Universidade de Aveiro Departamento de Geociências

Universidade do Porto Faculdade de Ciências
Departamento de Geociências, Ambiente e Ordenamento do Território

2015

ANA CRISTINA
PIRES DE OLIVEIRA

# ABORDAGEM INTEGRADA DE GEOENGENHARIA COSTEIRA EM AMBIENTES MARÍTIMOS

# INTEGRATED COASTAL GEOENGINEERING APPROACH FOR MARITIME ENVIRONMENTS

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Tese apresentada à Universidade de Aveiro (UA) e Universidade do Porto (UP), integrada no *programa doutoral em Geociências UA/UP*, para cumprimento dos requisitos necessários à obtenção do grau conjunto de Doutor em Geociências, realizada sob a orientação científica do Doutor Fernando Rocha, Professor Catedrático da Universidade de Aveiro e Coordenador do Centro GeoBioTec|UA e do Doutor Helder I. Chaminé, Professor Coordenador com Agregação do Instituto Superior de Engenharia do Porto (ISEP), Politécnico do Porto e membro investigador (FCT) do Centro GeoBioTec|UA

Apoio financeiro da FCT e do FSE no âmbito do POCI 2010 – Medida IV.3 e do QREN - POPH - Tipologia 4.1: SFRH / BD / 43175 / 2008

*À minha Avó Emília de Cassia, uma força da natureza!*

*Ao meu Avô António de Oliveira, serás para sempre o alicerce da família...*

*«Eu sou aquilo que perdi.» (Fernando Pessoa)*

**o júri**

presidente

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Doutor Tiago André Martins de Azevedo Abreu
*Professor Adjunto do Instituto Superior de Engenharia do Porto*

**agradecimentos / acknowledgements**

O presente trabalho resulta da conjugação de diversos apoios e incentivos dados à signatária, que desta forma, pretende expressar o seu agradecimento e reconhecimento a todos os que contribuíram para a elaboração da tese. / The present work results from the combination given to the author of several supports and encouragements, that wishes to express her acknowledgement and gratitude to those who contributed to the preparation of the thesis.

Ao Professor Helder I. Chaminé (ISEP), meu orientador científico, professor, mentor e "*Chefe*" de longa data: *for introducing me to a new "amazing world", the research...* Ao longo de 10 anos que me apresentou e iniciou a este mundo "duro" da investigação; ensinou-me a ter o espírito aberto, reflexivo, dinâmico, assertivo, rigoroso e que me viu "*crescer*" nessas dimensões e não só... Viu-me também amadurecer na vida como geo-profissional, investigadora e mulher... Agradeço profundamente por ter acreditado nas minhas capacidades, por incentivar a minha "*paixão*" pela investigação e para sempre querer saber mais e fazer melhor. Agradeço a amizade, as intensas conversas com "*cafeína*" por perto e, sobretudo, por ser o "*maciço rochoso*" em momentos mais difíceis da minha vida. Finalmente, agradeço a mensagem que nos transmitiu, desde o primeiro segundo, no orgulho em sermos Portugueses e que incutiu a toda a equipa, e assim demonstrarmos a nível internacional a qualidade das nossas descobertas... *As always, thank you so much for your continuous mentoring*...

Ao Professor Fernando Rocha (UA), pela orientação, apoio constante, exigência e voto de confiança já de muitos anos. Agradecida também pelo apoio logístico, enquadramento da investigação no Centro GeoBioTec|UA e por todas as facilidades no Departamento de Geociências da Universidade de Aveiro. Grata pela amizade, seriedade, calma e rigor; quase como um "*porto seguro*", pois em termos de dúvidas ou eventuais problemas que surgiram ao longo dos anos sempre me ajudou de forma discreta, pragmática, efectiva a ultrapassá-los. Muito obrigada, Professor.

Ao Professor Alberto Gomes (FLUP), pela troca de experiência nos temas cartográficos, SIG e de geomorfologia costeira, bem como pela cedência importante de dados e bibliografia. A relação científica vivenciada foi intensa e quase como a forte passagem de um "*tsunami*", com consequências em todos os momentos ao longo de um trabalho longo de investigação. Recordo os momentos quase cómicos que vivemos com um pouco de "*humor negro*" à mistura, característico do nosso "*Bertinho*".

Ao Professor A. Pérez-Albertí (USC), acima de tudo por nos ter deixado "*navegar*" pelo seu Atlântico desconhecido, mas que se tornou sereno... Agradeço o apoio incondicional não só em termos profissionais e científicos, mas também na minha vida pessoal, nas palavras sempre carinhosas nos longos "*chats*". Obrigada pela cedência de "*gigas e gigas*" de informação, de bibliografia e de contactos que muito foram úteis ao longo da tese*. Unha Aperta...*

Ao Professor F. Piqueiro (FEUP), pela partilha de dados, informações, experiência e por me ter deixado vivenciar um dos seus espectaculares e inesquecíveis "*voos adrenalínicos*". Agradeço a sua disponibilidade e capacidade de partilha ao longo destes anos de publicações.

À Professora Maria José Afonso (ISEP|IPP), pelo permanente apoio, incentivo e amizade, pela leitura crítica de uma versão inicial do manuscrito, bem como por todas as suas sábias e experientes palavras de coragem. Não existem palavras para lhe agradecer uma relação de amizade e respeito que dura há já tantos anos... "*Uma formiga atrevida / sem pedir qualquer licença / e satisfeita da vida / que certamente compensa / diligente despachada / pequenina como um trema / viu a porta escancarada / e irrompeu no meu poema (...)*" *(Poema inédito de Anthero Monteiro)* ...irrompeu na minha vida...

À Doutora Laura Guimarães (CIIMAR), que continuou sempre a receber-me no seu "porto" acolhedor com a sua característica compreensão, paciência e calma, sendo muitas vezes uma sábia conselheira que me tentava puxar para "*terra*".

Ao Professor José Martins Carvalho (TARH, Lda e ISEP|IPP), por me ter dado uma oportunidade profissional e de me ter incluído em muitos projectos reais. É um orgulho ter trabalho consigo, experiência profissional que jamais irei esquecer... Agradeço o apoio inicial quando comecei a trilhar este longo caminho na investigação, estarei sempre grata pela confiança dada e na "*fé*" que depositou em mim em termos de contribuição SIG e cartografia aplicada, em muitos trabalhos e projectos onde tive a oportunidade de colaborar.

Ao Professor J.C. Nunes (Departamento Geociências, Universidade dos Açores) pela cedência de diversos dados relativos à Ilha do Pico e por ter permitido a "navegação" ao longo do litoral Açoriano, sempre com a sua descontracção característica e optimismo.

To Professor Alan Trenhaile (University of Windsor, Canada) a top "*rocky shore*" of knowledge in terms of coastal geomorphology, morphodynamics and numerical modelling. Thank you for giving me the opportunity to work very closely with you. It was really a pleasure and an honour to work in such high level of research and standards.

À investigadora Engenheira Manuela Escarameia (HR Wallingford Ltd, UK), uma portuguesa em terras de "*Sua Majestade*" que me acolheu de uma forma tão simpática e sempre acessível, mostrando-me a "*casa*" em Wallingford de outra perspectiva e partilhando ideias.

Aos Engenheiros Araújo Lopes e Rui Rêgo da Empresa Irmãos Cavaco, S.A. (ICSA), que tornaram possível a visualização da construção de uma obra marítima, recolha de informação sobre ensaios laboratoriais e sobre os geomateriais (Marcação CE), bem como por todos os conselhos ao longo do trabalho, permitindo sempre os contactos certos. Um agradecimento muito especial ao Sr. Manuel Leite pelos magníficos passeios pela costa e por toda a explicação sobre o dimensionamento de estruturas de protecção costeiras.

To Dr. Sébastien Dupray (DREAL Languedoc Roussillon, France) for introducing me to new approaches related with coastal engineering and rock material characterisation. Thank you for sharing your experience and thoughts about armourstone applications in the CIRIA course (UK).

To EurIng Jonathan D. Simm (HR Wallingford Ltd, UK) for receiving me with so much enthusiasm in the annual Armourstone Meeting since 2010. Thank you for facilitating the exchange of news and views about the use of armourstone for coastal defences and breakwaters in the UK and all round the world and for the beautiful poems about the sea that you read and shared.

Aos Engenheiros E. Brògueira Dias, F. Santiago Miranda, A. Coutinho (Administração dos Portos do Douro e Leixões – APDL), por todo apoio ao longo da investigação e partilha de informação vital.

Ao Dr. José Turrado (Instituto de Estudos do Território, Galiza) pela cedência de ortofotomapas históricos e pela explicação e ajuda que deu sobre as bases cartográficas.

Ao Dr. Juan Lopez Bedoya (University of Santiago de Compostela) pela cedência de dados que muito ajudaram na análise espacial realizada ao longo dos sectores estudados da Galiza.

Ao Engº Filipe Fernandes, Engº José Cardoso Guedes e Sr. Manuel da Empresa SOLUSEL e ADIFER (Pedreira da Madalena, V.N. Gaia) pela autorização em tirar algumas fotos da pedreira, na cedência de dados e ensaios laboratoriais do material-rocha.

Ao Engº Nuno Faria, ex-Director de Serviço das Unidades Extractivas e Fabris, Pedreira V. P. Âncora, Aurélio Martins Sobreiro & Filhos, pela troca de informação, dados, fotografias e ensaios do material explorado na pedreira.

Ao Engº Ignacio, Empresa Hormigones de Xaras, S.L., Riveira (Pedreira de Vilar) pela cedência de ensaios do material explorado e por ter permitido a obtenção de fotografias da área de exploração.

Ao Marcos López (Director Comercial) e ao Fernando Salvado (Topógrafo), da Empresa CartoGalicia (A Coruña, Espanha) pela a aquisição e processamento das imagens LiDAR ao longo dos sectores da Madalena e Lajes do Pico na Ilha do Pico (Açores).

São devidos agradecimentos por apoios pontuais e decisivos em diversas e diferentes fases da investigação: Professora Maria Eugénia Lopes (ISEP), Professor Joaquim Borges Gouveia (DEGEI, UA) e ao Professor José Paulo Rainho (UTI, UA).

To Prof. Robin Lee Nagano (Miskolc University, Hungary) for the careful reading and final revision of the latest English version of the thesis; thank you so much for the "*fresh*" eyes…

To Patricia Nickson from B&B Marsh House (Shillingford, Wallingford, UK), for the warm way she received me at her house, for her "*hot tea and cookies*" at night and for the rides when I was at the Armourstone meeting.

To Lucy Wright (Institution of Civil Engineers – ICE) for the support and assistance given in the events, workshops and conferences that I attended. Thank you for all your help when I was so far away from home.

Ao meu amigo José Teixeira (GEOBIOTEC|UA / LABCARGA|ISEP / FLUP) ("*My Lord of the Maps*"), pela amizade, companheirismo e parceiro de tantos e tantos cafés... Agradeço o teu espírito de entreajuda em todos os momentos fulcrais, por vezes de desespero, até mesmo em momentos pessoais muito difíceis e complicados. A tua personalidade "*sem stress*" e o teu "*coolness*" fez com que o meu espírito mais "*rebelde ou agressivo*" serenasse. Vou-te ser sempre grata pela amizade quase fraterna que transmitiste e pelo apoio incondicional como colega de trabalho.

Aos antigos colegas "LABCARGUIANOS", Engª Patrícia Moreira, Engª Catarina Rodrigues e Engº Rui Santos Silva, por todo o apoio, quer no campo quer em gabinete. Sinto saudades de muita coisa pois passamos por muito, mas tenho saudades principalmente dos bons momentos nos intervalos onde muitas vezes me deram a força necessária para o trabalho futuro. Obrigada a todos!

À Liliana Freitas (LABCARGA|ISEP), a "*Baixinha*", companheira de saídas de campo, amiga e colega que me apoiou não só na fase final da minha tese mas também em momentos difíceis da minha vida, dando sempre uma palavra amiga e de conforto... Espero por ti na Ilhas Cíes na Galiza...

À aluna de Mestrado Ana Lúcia Costa por toda a ajuda no trabalho de campo e análise de dados, pela boa disposição no trabalho de campo elaborado sobre uma plataforma rochosa escorregadia...

To Stjepan Tomislav Rajcic (University of Zabreb, Croatia), ERASMUS student from FLUP, who provided useful data about geoforms and coastal geomorphology, with special focus on the geomorphology of the rocky beach of Lavadores (Gaia). We shared a "*scary*" moment with you, but fortunately everything went well…

À Mestre Isabel Malta Carvalho (UFP) pela leitura do inglês e pela ajuda inicial na revisão de alguns artigos, bem como à Dra. Rosa Dias pela tradução do catálogo da arte.

Ao Ricardo Matos pela ajuda na realização de um filme multimédia em 3D sobre a evolução da cartografia temática dos esporões de Espinho, agradeço a ajuda inicial e as sugestões que deu.

Ao Mestre José Amorim, estudante de doutoramento em História (FLUP), pelo contributo essencial que deu na arte e história como ferramentas possíveis na compreensão da evolução costeira, dando o seu contributo nesta área ainda pouco explorada. A tua capacidade de trabalho e gosto pelo trabalho de investigação são contagiantes, espero poder continuar a explorar contigo esta área em futuros trabalhos...

To geoscientist colleagues all around the world, with whom I have the opportunity to exchange ideas, suggestions and discuss some technical aspects of my research. For listening to me and for the long conversations by email I would like to express my gratitude to: William C. Haneberg (Fugro GeoConsulting, USA), Jim Griffiths (Plymouth University, UK), Jeffrey R. Keaton (AMEC Americas), Pinnaduwa Kulatilake (University of Arizona, USA), Bryan Curtis (Worthing Borough Council, UK), Andrew Bradbury (National Oceanography Centre Southampton, UK), Terry W. Sturm (Georgia Institute of Technology, USA), Alan Kwong (University of Hong Kong, Hong Kong), Madelon Burgmeijer (Delft University of Technology, The Netherlands), Alison Baptiste (Environment Agency, UK), Nigel Pontee (Halcrow Group Ltd., UK), Jonathan Rogers (Halcrow Group Ltd., UK), Emily A. Himmelstoss (USGS, USA) and many others… finally, my deeply gratitude to all publishers, editors, anonymous and non-anonymous reviewers that I encountered along the publication process…

Aos colegas de "*guerra*" política, nomeadamente, Sr. Emanuel Fonte, Sr. Adriano Freitas, Dr. Eduardo Rocha, Sr. Joaquim Leal, Dra. Elisabete Cardoso, Sr. Marco Reis, Dr. José Amorim, Sr. Miguel Brandão e Sr. Pedro Pires, por me terem apoiado, não só ao longo da campanha que coincidiu com a investigação, mas também ao longo do mandato ainda em curso, obrigada pela confiança e trabalho de equipa.

A todos os meus colegas e amigos do Coro Juvenil de S. Paio de Oleiros, por toda a compreensão e apoio ao longo deste período mais difícil e pelas minhas ausências. Em particular às minhas verdadeiras amigas de coração, Verinha, Catá e Elisabeth onde em momentos mas difíceis pude desabafar... à Belinha pelo apoio e ajuda, mesmo longe agradeço-te todo o incentivo...

Agradeço à Celina Capela pelo apoio, compreensão e por ter "*segurado o barco*" e o meu grupo coral em alguns momentos da minha ausência. Agradeço a sua força, incentivo, admiração e orgulho que sempre demostrou por mim...

Ao Professor Rui Soares, meu mestre de órgão de tubos, pela compreensão das minhas faltas e pelas palavras de apoio.

À Sandra Paiva pela infinita amizade e apoio moral ao longo deste meu percurso académico e profissional (sempre disponível, mesmo com a sua "*rebelde*" filha Maria). Agradeço também o contacto na Pedreira da Madalena.

À Belisa Geada pela tua amizade e pelas conversas serenas que sempre me tranquilizaram, agradeço o teu apoio e força ao longo desta fase final da tese.

Ao Engº Paulo Santos, Cristina e Aidita da *Papelicópia*, pela excelente execução na impressão e encadernação da tese, sempre com rigor e paixão no que fazem. Agradeço a vossa paciência ao longo dos vários anos que trabalhamos em conjunto.

Aos meus pais, irmãos e tios/padrinhos que sempre serão a minha "*estrutura de amarração*" durante toda a minha vida. Agradeço à minha confidente e melhor amiga "*Madrezita Sãozinha*", pois "*Mãe não tem limite, é tempo sem hora, luz que não apaga quando sopra o vento...*" *(Carlos Drummond de Andrade)*. Ao meu Pai Quim que é, e sempre será, o "*rochedo*" desta família. Aos meus sogros e cunhados pelo apoio e orgulho que têm demonstrado em mim. Ao meu Luís, que continuou a ser a minha "*muralha*" de defesa e aconchego, não existem palavras para agradecer o amor infinito, apoio incondicional e toda a dedicação que senti ao longo desta fase da escrita; perdoa-me as ausências e alienações. À Matilde, que eu seja motivo de orgulho para ti e que possas ver a tua "*Madita*" como um exemplo a seguir no futuro!

To the GeoBioSciences, GeoTechnologies and GeoEngineering Research Unit (GeoBioTec|UA) – University of Aveiro, and especially to Prof. Fernando Rocha, for financial support (UID/GEO/04035/2013): for the acquisition of high-resolution aerial photography and LiDAR, for attendance in several courses throughout the investigation, and for the contribution in the international conferences and seminars in which I took part.

To the Laboratory of Cartography and Applied Geology (LABCARGA|ISEP), School of Engineering (ISEP), Polytechnic of Porto, particularly to the Head of the Lab, Prof. Helder I. Chaminé for all the support provided in terms of using all the available resources and equipment, as well as for the acquisition and contribution of cartographic information, GIS data and bibliography (re-equipment program LABCARGA|IPP-ISEP|PAD'2007-08; HydroSPOT – European Space Agency|FLUP/ISEP/USC|ESA-ID5750; CARTGalicia project LABCARGA|ISEP–USC/2010-11) and the partially support of some conferences or meetings.

To all the successive directors of the Department of Geotechnical Engineering, School of Engineering of Porto (ISEP) (Eng. J. Sampaio, Prof. A.C. Galiza and Prof. J.A. Fernandes) and presidents of ISEP (Eng. V. Santos, Prof. J. Rocha), for their support throughout the whole research term.

To the Department of Geosciences, University of Azores, for all the support along the LiDAR data acquisition in Pico Island. To Pico Island Delegation of the Regional Secretary for Tourism and Transport of the Azores Regional Government for all the contribution in terms of georeferencing and differential correction process along Madalena and Lajes do Pico sites.

To Laboratory of Environmental Technology (Geomorphology Area), Institute of Technological Research, University of Santiago de Compostela (USC), to Prof. A. Pérez-Alberti and to Prof. F. Macias for allowing me to spend a few months in their institution to attend important workshops and develop my research work.

We are also grateful to the Xunta de Galicia (Consellería de Medio Ambiente, Territorio e Infraestructuras) which provided key information and funded this study in the scope of the POLGalicia project.

This thesis was partially funded by a PhD scholarship (SFRH/BD/43175/2008) from the Portuguese Foundation for Science and Technology (FCT), within the framework of the European Social Fund (FSE) as part of the "III Quadro Comunitário de Apoio" program.

*"(...) - As coisas da terra são esquisitas e diferentes - disse a Menina do Mar - Conta-me mais coisas da terra.*

*Então sentaram-se os dois dentro de água e o rapaz contou-lhe como era a sua casa e o seu jardim e como eram as cidades e os campos, as florestas e as estradas.*

*- Ah! como eu gostava de ver isso tudo - disse a Menina cheia de curiosidade.*
*- Vem comigo - disse o rapaz - eu levo-te à terra e mostro-te coisas lindas.*
*- Não posso porque sou uma Menina do Mar. O mar é a minha terra. Tu se vieres para o mar afogas-te. E eu se for para a terra seco. Não posso estar muito tempo fora de água. Fora de água fico como as algas na maré vaza, que ficam todas enrugados e secas. Se eu saísse do mar, ao fim de algumas horas ficava igual a um farrapo de roupa velha ou a um papel de jornal, destes que às vezes há nas praias e que têm um ar tão triste e infeliz de coisa que já não serve e que foi deitada fora e que já ninguém quer.*
*- Que pena que eu tenho de não te poder mostrar a terra! - disse o rapaz.*
*- E eu que pena tenho de não te poder levar comigo ao fundo do mar para te mostrar as florestas de algas, as grutas de corais e os jardins de anémonas!*

*E nessa manhã o rapaz e a Menina, enquanto nadavam na água, iam contando um ao outro as histórias do mar e as histórias da terra. Até que a maré subiu e despediram-se. (...)"*

A Menina do Mar (Sophia de Mello Breyner Andresen)

**palavras-chave** geoengenharia, geomaterais, gestão integrada costeira, geociências costeira, cartografia SIG, ambientes costeiros

**resumo**

Esta dissertação apresenta diversas abordagens metodológicas que integram um modelo de gestão costeira proposto, numa perspectiva interdisciplinar. O trabalho de investigação submetido é composto por uma série de publicações que abrangem diferentes perspectivas temáticas. A tese desenvolve abordagens integradas de geoengenharia costeira que estão intrinsecamente ligadas aos ambientes marítimos estudados. Desde praias arenosas e obras marítimas até às plataformas rochosas e arribas costeiras, este estudo incluiu trabalho de campo nos sectores de estudo entre Caminha – Figueira da Foz (NW Portugal) e na Galiza (NW Espanha). A investigação implicou também uma análise e caracterização geológica-geotécnica de pedra natural (enrocamento) e blocos artificiais (betão) aplicados em obras marítimas. O objectivo principal foi reavaliar e caracterizar os georrecursos e determinar a disponibilidade de enrocamento desde a sua origem (pedreira). Também foi importante diagnosticar in situ o grau de degradação/deterioração dos geomateriais tendo em conta o estado actual das obras de protecção costeira e prevendo trabalhos de monitorização e manutenção mais eficientes, possibilitando assim ter alguns benefícios económicos. Em termos de costa rochosa a abordagem incluiu o estudo dos blocos costeiros presentes ao longo da plataforma, mas também de todas as geoformas sob o ponto de vista da morfodinâmica costeira. Por um lado foi realizada uma análise à evolução da linha de costa em zonas arenosas sendo aplicada a extensão DSAS (Digital Shoreline Analysis System). Por outro lado a análise espacial e estatística realizada às arribas costeiras permitiram determinar zonas de susceptibilidade à erosão e zonas de risco. Todas estas investigações apresentam diferentes objectivos e resultados mas possuem um denominador comum entre eles que é a cartografia aplicada e os sistemas de informação geográfica (SIG). Desta forma, independentemente do ambiente costeiro em estudo, existe um sistema integrado que abrange uma série de metodologias propostas para o processo de investigação. Esta dissertação pretende dar um importante contributo para o estudo de diferentes ambientes costeiros, usando quase sempre as mesmas metodologias. Assim será possível a caracterização, monitorização e avaliação de obras de protecção costeira, costa e plataforma rochosas. Até mesmo propor ou recomendar estratégias de gestão para a orla costeira fundamentadas em questões sociais, económicas e ambientais, suportadas numa base SIG de planeamento e reforçado por decisões geo-cartográficas. De uma forma geral o desenvolvimento da cartografia aplicada envolveu seis fases que permitiram produzir mapas pormenorizados para cada ambiente costeiro: (1) imagens aéreas de alta resolução; (2) inspecção visual e monitorização sistemática; (3) elaboração de fichas de campo aplicadas; (4) avaliação in situ; (5) técnicas de amostragem; e (6) cartografia SIG. A tese envolve temáticas fundamentais que foram desenvolvidas ao longo das publicações científicas alcançadas, representando assim os resultados obtidos e discutidos. Essas temáticas estão directamente relacionadas com a arquitectura da tese: (i) cartografia aplicada à dinâmica costeira (incluindo uma análise histórica sobre a arte e cartografia antiga, usada como ferramenta para a evolução costeira e compreensão do litoral); (ii) avaliação geral dos georrecursos (o papel da cartografia no zonamento de georrecursos, avaliação e durabilidade de enrocamentos); (iii) aplicações à geoengenharia costeira e monitorização (o caso piloto de Espinho como campo experimental – NW Portugal); (iv) caracterização e estudo da costa e plataforma rochosas; (v) abordagens em ambientes mistos e costas arenosas; (vi) geociências costeira, cartografia SIG e levantamento fotogramétrico (geoengenharia costeira); e (vii) evolução cartográfica do litoral e estratégias para a gestão costeira (exemplo do Projecto CartGalicia – NW Espanha). Finalmente, todas estes temas foram essenciais para a proposta de modelos conceptuais e para perspectivar o futuro da gestão integrada da geoengenharia costeira.

**keywords** geoengineering, geomaterials, integrated coastal management, coastal geosciences, GIS mapping, coastal environments

**abstract** This dissertation introduces several methodological approaches which integrate a proposed coastal management model in an interdisciplinary perspective. The research presented herein is displayed as a set of publications comprising different thematic outlooks. The thesis develops an integrated coastal geoengineering approach which is intrinsically linked to the studied maritime environments. From sandy coasts and marine works to rocky platforms and sea cliffs, this study includes field work between Caminha – Figueira da Foz (NW Portugal) and Galicia (NW Spain). The research also involves an analysis and geological-geotechnical characterisation of natural rock (armourstone) and artificial units (concrete blocks) applied to coastal structures. The main goal is to contribute to the characterisation and re-evaluation of georesources and to determine armourstone suitability and availability from its source (quarry). It was also important to diagnose the geomaterials in situ concerning their degradation/deterioration level on the basis of the current status of the coastal protection works in order to facilitate more efficient monitoring and maintenance, with economic benefits. In the rocky coast approach the coastal blocks were studied along the platform, but also the geoforms were studied from a coastal morphodynamics point of view. A shoreline evolution analysis was developed for sandy coasts through Digital Shoreline Analysis System (DSAS) extension. In addition, the spatial and statistical analysis applied to sea cliffs allowed the establishment of susceptibility zones to erosion and hazardous areas. All of these studies have different purposes and results however, there is a common denominator – GIS mapping. Hence, apart from the studied coastal environment, there is an integrated system which includes a sequence of procedures and methodologies that persisted during the research period. This is a step forward in the study of different coastal environments by using almost the same methodologies. This will allow the characterisation, monitoring and assessment of coastal protection works, rocky coasts, and shore platforms. With such data, it is possible to propose or recommend strategies for coastal and shoreline management based on several justifications in terms of social, economic, and environmental questions, or even provide a GIS-based planning support system reinforced by geo-cartographic decisions. Overall the development of the applied cartography embraces six stages which will allow the production of detailed maps of the maritime environment: (1) high-resolution aerial imagery surveys; (2) visual inspection and systematic monitoring; (3) applied field datasheet; (4) in situ evaluation; (5) scanline surveying; and (6) GIS mapping. This thesis covers fundamental matters that were developed over the course of scientific publication and as a consequence they represent the results obtained and discussed. The subjects directly related to the thesis architecture are: (i) cartography applied to coastal dynamics (including an art historical analysis as a tool to comprehend the coastal evolution and the littoral zone); (ii) georesources assessment (the role of cartography in georesources zoning, assessment and armourstone durability); (iii) coastal geoengineering applications and monitoring (Espinho pilot site in NW Portugal as an experimental field); (iv) rocky coast and shore platform studies and characterisation; (v) sandy and mixed environment approaches; (vi) coastal geosciences GIS mapping and photogrammetric surveying (coastal geoengineering); and (vii) shoreline change mapping and coastal management strategies (the CartGalicia Project as an example – NW Spain). Finally, all of these thematic areas were crucial to generate the conceptual models proposed and to shape the future of integrated coastal coastal geoengineering management.

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*Cover illustration*: “The Espinho Fisherman” by J. Amorim, 2012

# PART I – INTRODUCTION AND BACKGROUND

*The Rainbow (1873), by Ivan Aivazovsky*

**Canção do Mar (Sea song)**

Ó mar / Oh sea
Ó mar / Oh sea
Ó mar profundo / Oh deep sea
Ó mar / Oh sea
Negro altar / Dark altar
Do fim do mundo / Of the end of the world

Em ti nasceu / In you were born
Ó mar / Oh sea
A noite que já morreu / The night that has already died
No teu olhar / In your sight

*Lyrics by Zeca Afonso, 1964*
*(Portuguese singer-songwriter)*

# CHAPTER 1 – GENERAL INTRODUCTION

Photo credits: Irmãos Cavaco SA (ICSA)

# 1. GENERAL INTRODUCTION

## 1.1. Context and motivation: the *5 G's*

*"On ne découvre pas de terre nouvelle sans consentir à perdre de vue, d'abord et longtemps, tout rivage" ("One doesn't discover new lands without consenting to lose sight of the shore for a very long time"), André P.G. Gide, 1925, Les faux-monnayeurs [The Counterfeiters]).*

This impressive quotation is a good way to start this dissertation and to clarify expectations at the beginning of the research. This was the core premise of the investigation, leading the dissertation to other fields by knowing that it is not possible to do anything original unless there is willpower to leave the "safety zone" of what has always been done.

It was with this idea in mind that the main goals of the thesis were set with a general purpose of studying maritime environments. The investigation of such environments had to involve many different fields that support all the research, as well as provide guidelines and background for the thesis design and methodological approaches. In addition, we considered the research surrounding as "the Matrix", i.e., an array with several key elements to study all possible relationships. This metaphor is not like the movie The Matrix (Andy Wachowski and Larry Wachowski [1999]) which describes a dystopian future and the real world is in fact a simulated reality or cyberspace contemplated by most humans. However, we decided to "take the red pill" and discovered that this cyberspace has several networks and integrates complex geo-systems (Figure 1). Starting with GEORESOURCES availability, its durability evaluation and quality control are important stages for the methodological approach developed along the thesis. Then, the core domains such as GEOLOGY, GEOTECHNICS and GEOMECHANICS are crucial for providing the conceptual basis of the study. Finally, it involves all the geoscientific related information that makes use of GEOTECHNOLOGIES including the application of Geographical Information Systems (GIS) technologies of various data from multiple sources.

In this section we would like to put the reader in perspective and to point to the main focus and the foundations of the research. This ongoing study, which was outlined some time before A. Pires became a PhD student at the University of Aveiro (UA), represents an encompassing study of maritime environments using coastal geosciences GIS mapping. Further details about the background and aims, as well as the applied methodological approaches, can be found in the scopes and objectives section presented later.

This investigation started in the academic year 2004/2005 when the student was finishing her five-year degree in Geotechnical and Geoenvironmental Engineering (School of Engineering [ISEP], Polytechnic of Porto), which included a one-year research project in Applied Geotechnics coupling Engineering Geosciences and Coastal Engineering (Pires 2005), advised by Professor Helder I. Chaminé (ISEP) and Eng. Fernando Santiago Miranda (APDL).

The approach was very preliminary, with the support of basic geoscientific software that was used to perform a systematic monitoring programme of maritime works using a geoengineering approach. Afterwards, several proceedings and papers were published about the preliminary cartographic procedures applied to coastal protection structures (e.g., Pires *et al*. 2006a, 2006b, 2007, 2010a).


**Figure 1.** The thesis matrix with the codification of the core G's for the development of the research: Georesources, Geology, Geotechnics, Geomechanics and Geotechnologies (inspired by "The matrix digital code" from the movie "Matrix").

In 2006, the student finished her Postgraduate Course in Geographical Information Systems (1 year) from the University of Porto (Department of Geography, Faculty of Arts, FLUP), with a final short project supervised by Professor Alberto Gomes (FLUP) and Professor José Martins Carvalho (ISEP). In 2007, she was awarded a Master's degree (2 years) in Minerals and Industrial Rocks (Geotechnics Area) from the University of Aveiro with a thesis entitled: *"Geoengineering and inspection of maritime works: from the raw material to the protection structure"* (Pires 2007), supervised by Professor Helder I. Chaminé (ISEP) and Professor Fernando Rocha (UA). At that time it was essential to improve the methodology and to seek enhanced software that permit the production of advanced coastal geosciences mapping.

In technological terms it was important to take that step, therefore from all the geotechnologies available we decided to explore the Geographical Information System (GIS) platforms. The development of such monitoring methodologies and GIS cartographic techniques allowed not only a better understanding of coastal dynamics but also geomaterial (natural rock and artificial blocks) evaluation at the quarrying sources along the studied areas (Pires & Chaminé 2007, Pires *et al.* 2008, 2009a). Pires & Chaminé (2007) exemplify the first results on geotechnical mapping evaluation of rock groynes (coastal protection works in Espinho area, NW Portugal), Appendix 1-A. The results published in Pires & Chaminé (2008a) and Pires *et al.* (2010b) which are available in Appendixes 1-B and 1-C respectively, display different approaches and show the GIS mapping evolution.

In the scope of geotechnologies this approach has gradually gained additional purposes. This fact stresses the need to establish links between University, Industry and Society in order to ensure environmental sustainability (Bieniawski 2010). Figure 2 illustrates the configuration to achieve the ideal solution between scientific knowledge, engineering and market cycles related with the engagements in R&D (Research and Development) projects. This flowchart takes into account creative entrepreneurship as the "driving force" to achieve technological development (Berkhout 2000, Berkhout & van der Duin 2007). Behind all that, there is an important issue to achieve, as stated by Prof. J. Borges Gouveia (UA): "Yes, we can measure it, we can improve it".

During the research it was really important to innovate but also to have the skills to delineate strategies aiming at entrepreneurship and effective management. As proposed by several authors (e.g., Allen 1977, Gouveia 2006, Timmons & Spinelli 2008, Von Stamm & Trifilova 2009, Bessant & Tidd 2011, Didion *et al.* 2012, Vasconcellos e Sá *et al.*, 2012) it is important to define a skilled management strategy that starts, commonly, with an idea followed by creation, design and improvement of a methodology until reaching sustainable development for a given product in environmental and ethical manners. In short, according to the Romanian sculptor Constantin Brancusi (1876-1957) *"simplicity is complexity resolved"*.

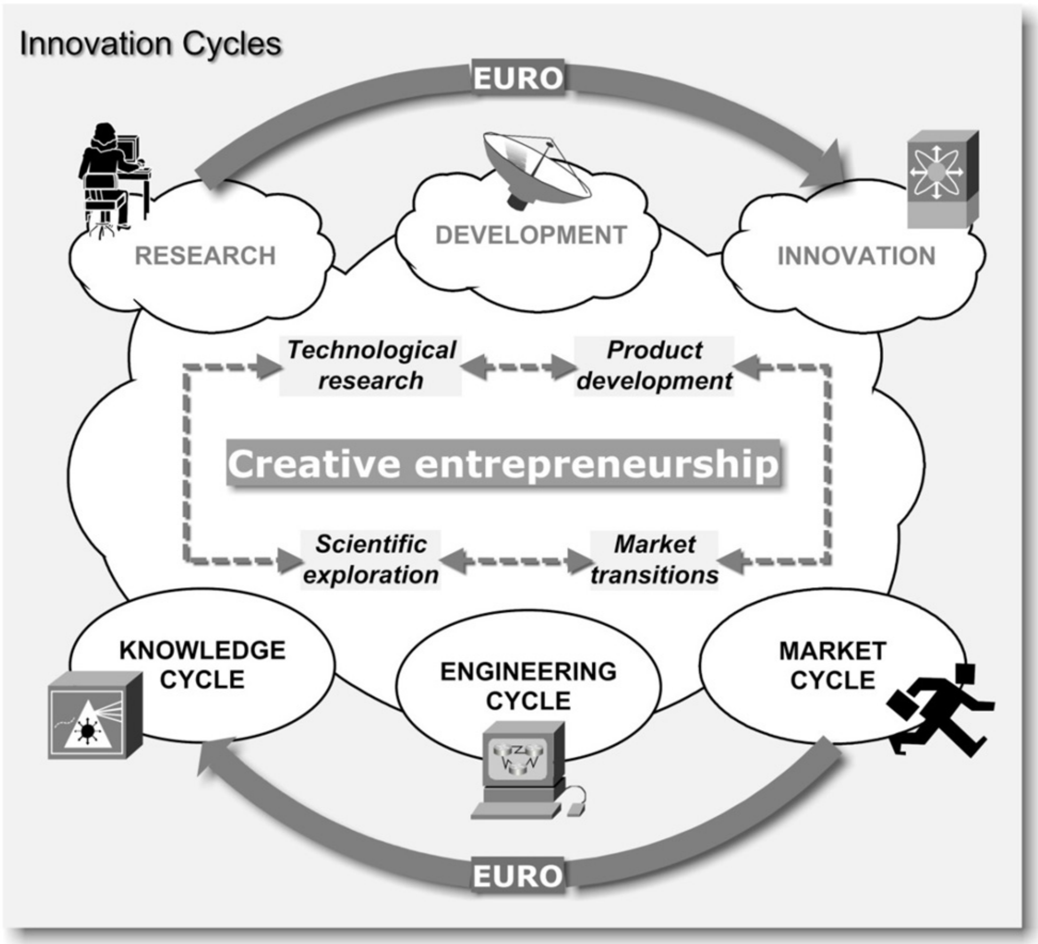



**Figure 2.** General flowchart describing the cyclic innovation model and the dynamics between research, development and innovation with knowledge, engineering and market cycles. Modifications in science, technology, industry and markets are constantly connected. Creative entrepreneurship is the main motivation in this configuration (adapted from Berkhout 2000, Berkhout & van der Duin 2007).

Figure 3 is a cubic image that represents the knowledge that must be protected and the different stages from the conception until a given product development. The knowledge stored in each individual is important to the creative process (Gouveia 2006, Bessant & Tidd 2011). However, the scientific community is increasingly working in interdisciplinary, multidisciplinary and transdisciplinary teams. In that line of thought this research approach follows very closely the holistic framework trend addressed by some authors such as Wickson *et al.* (2006), Kuhn (2012) and Wright (2012). Consequently, efforts were made to create synergies, know-how and skills interrelated with Geoengineering Sciences, Sea Engineering and Coastal Geosciences. During 2008-2010 protocols and networks were established with several universities, companies and agencies to carry out several core projects on integrated coastal zone management focused on geoengineering sciences (Figure 4).

The PETROCART, GISCOAST and CARTGALICIA projects were developed in a mixed academic and consultancy environment. In fact, these outstanding case studies were incorporated in this dissertation to test and improve a realistic methodological approach. Figure 4 shows how the different elements are associated with each other and lists the different stakeholders included in those projects. The R&D projects (2008-2013)[1] referred to shaped the main goals of the thesis. These projects also generated a database of cluster partners in the field of sea engineering.

As already mentioned the entrepreneurship involved undertaking innovations and incorporated different results. It is also important to publish and to disseminate the results of our research by several means. Appendix 2-A shows the leaflet of the School of Engineering|ISEP with general information about ISEP|IPP and Laboratory of Cartography and Applied Geology (LABCARGA). ISEP and UA institutions are *Oceano XXI* partners (Oceano XXI 2010) related to knowledge of the sea as a strategic investment and economic cluster. Additionally Appendix 2-B displays a multimedia CD (Figure 5) with the contents of the scientific activities ("Geology on summer") developed by the Laboratory of Cartography and Applied Geology (LABCARGA)/Department of Geotechnical Engineering, School of Engineering|ISEP and funded by "Ciência Viva" Programme (Ciência Viva 1996, Vargas & Noronha 2002). The summer activity related to the thesis consists of a 5-hour field trip to the Malaposta quarry (ICSA – Irmãos Cavaco S.A. Company based at Santa Maria da Feira council) followed by a tour at the Espinho groynes (NW Portugal) and the neighbouring beaches. Since 2005 the field trip normally takes place at the end of July and is led by Ana Pires and Helder I. Chaminé (ISEP) with the collaboration of ICSA geo-professionals and Alberto Gomes (FLUP).

[1] *The **PETROCart** project was carried out by the LABCARGA – Laboratory of Cartography and Applied Geology|ISEP and "Irmãos Cavaco SA" company (ICSA) related to rock georesources exploration (Central and North of Portugal) for hydraulics structures (LABCARGA|ISEP–ICSA/2007-08; PI: Professor Helder I. Chaminé), see details in Pires & Chaminé (2008b, 2009). The main partners were: Labcarga|ISEP and ICSA, with collaboration of the GGC – Geologia e Geotecnia, Consultores Lda. (LABCARGA 2008).*

*The **GISCoast** project aimed to develop a methodology for the assessment and management of coastal hydraulic structures in the Portugal mainland, focused on the source quality, durability and implementation of geomaterials, and to assess to what extent climate changes may affect the hydraulic structures and their material components (see details in Pires et al. 2009b). GisCoast (GIS mapping and durability assessment of geomaterials from hydraulic structures: implications for the coastal environment; PTDC/ECM/099187/2008; PI: Professor Helder I. Chaminé) resulted in an application proposal for FCT funding, for which the international evaluators state "the project is worth considering for funding". However, it was not supported, as FCT replied "not recommended for funding: in face of high competition for funding, this proposal did not reach a position to be funded"). The main partners were: GeoBioTec|UA, Labcarga|ISEP, INESC|Porto, ICSA, FEUP, IGOT|UL, CETMEF (France).*

*The **CARTGalicia** project was a joint project between the Laboratory of Cartography and Applied Geology|ISEP and the Laboratory of Environmental Technology (Geomorphology Area), University of Santiago de Compostela (LABCARGA|ISEP–ITE|USC/2010-11; PI: Professor Helder I. Chaminé) (LABCARGA 2011). The project aimed to study the coastal characterisation and evolution of Galicia. In addition, it also contributed to the master coastal management plan (POLGalicia) carried out by the Local Authorities (Xunta de Galicia, Consellería de Medio Ambiente, Territorio e Infrastructuras), see details in Pérez-Alberti et al. (2011, 2013a). In 2011 the project won the best communication prize: "GIS mapping and shoreline change analysis along the rocky coast of Galicia (NW Spain): preliminary approach" by Pérez-Alberti, Pires, Freitas, Rodrigues & Chaminé), given by ICE (Institution of Civil Engineers) scientific committee at the Coastal Management 2011 Conference, Belfast UK (15-16 November 2011). Dr. Alex Schofield, Chair of the ICE Organizing Committee wrote "I am delighted to announce that you have been selected as the winner of the ICE Coastal Management 2011 Poster Competition. This is a fantastic achievement of which you should feel extremely proud, especially given the extremely high standard of all of the poster presentations at this conference."*


**Figure 3.** The "knowledge cube" and the correlation between the innovating concept and the final product; from the characterisation / protection until the development.

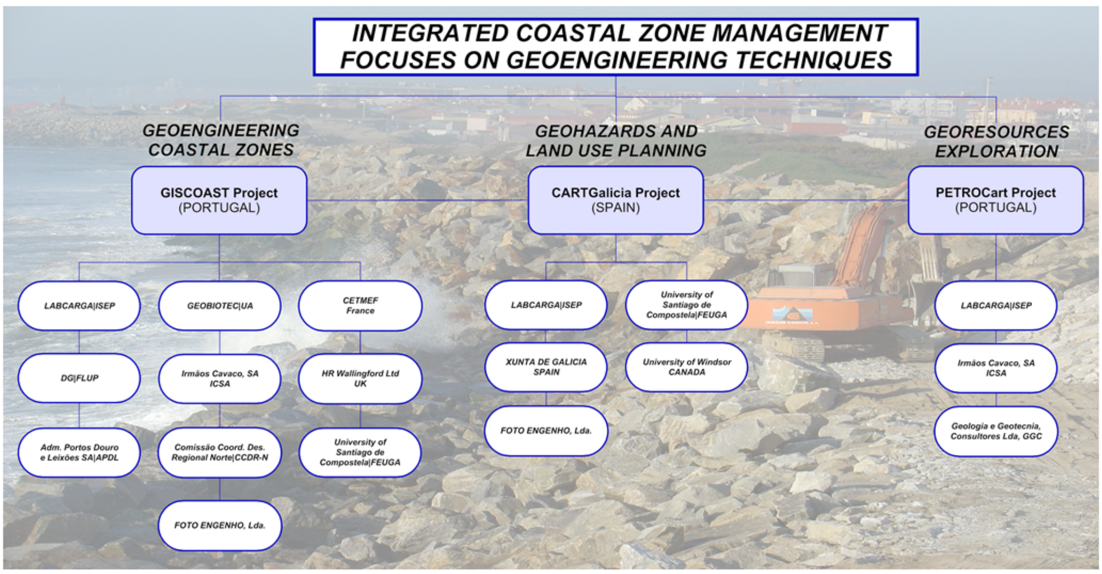



**Figure 4.** The institutional network of cooperation and R&D projects in a mixed academic and consultancy environment (2008-2013).


**Figure 5.** Ciência Viva Programme in Portugal ("Geology on summer / Geologia no Verão"), which assists projects with the purpose to encourage the hands-on in geoscience issues, as well as connecting experts, school communities and general public with a vision to an exchange of knowledge and resources. The CD-ROM is presented in Appendix 2-B (Chaminé *et al.* 2005-2013).

What has been accomplished with all the initiatives and activities during the PhD research? As we can see the current research has strong scientific connections to international partners and innovative entrepreneurship approaches. Nevertheless the most important input that this thesis could have is also the core of all the research; to establish a durable bond between the Research Units and Industry.

However, what was the motivation that drove us during this investigation? The main emphasis of this research is to develop a methodology in coastal geosciences GIS mapping. The integrated coastal zone management focused on geoengineering techniques presented in the main body of the thesis and addresses different approaches. These geoengineering approaches are intended to contribute to the design of hydraulic structures, coastal management projects and rock georesources related to coastal defences.

GIS mapping could improve the knowledge and skills of hydraulic engineers and coastal designers concerning the maritime environment. Besides, it can propose different outputs regarding the coastal management that may help decision makers and local authorities in their inventory, strategies and solutions.

The strong point of this thesis is the cartography associated with several geoengineering techniques. The study comprises more than geodatabases. The final output that is displayed in a map is more than an attractive graphic and is desirable to show some dynamics. The driving force along the research was to produce new maps involving several techniques, drawing the coastal dynamics and taking into account different variables (e.g. geology, geomorphology, topographic elements, forcing conditions, and/or geomaterial description). The ability and skill of making maps, or the so-called "Mapability" considered by Muehrcke (1990), is an interesting perspective because currently, we can make a lot of things possible in mapping with enhanced GIS technology. Both GIS and cartography can influence each other but the most important is that mapping could get the best of the relation (Muehrcke 1990, Navratil 2009). According to Hennig (2013) *"Contemporary cartography needs to be redefined according to today's challenges"* or perhaps tailoring the maps to our requirements and characteristics. The newly established "Neocartography Commission of the International Cartographic Association" (ICA 2011, Ruas 2011a, 2011b) stated that "*many examples of new and innovative mapping are being produced outside the normal orbit of existing cartographers or map producers. The term neocartographers is being used to describe map makers who may not have come from traditional mapping backgrounds, and are frequently using open data and open source mapping tools. Another difference is in the blurring of boundaries between map producers and map consumers. The availability of data and tools allows neocartographers to make their own maps, show what they want, and often be the intended audience as well – that is to say they may make the maps for themselves, just because they can. There is a real need for a discipline to be established to study this essentially undisciplined field of neocartography.".* This thesis does not claim to develop science in neogeography fields of map-making as proposed by several authors (emerging areas explored by Chilton 2008, 2011, Hennig *et al.* 2010, Hennig 2013). According to other authors (e.g., Liu & Palen 2010, Warf & Sui 2010) there has in fact been an exciting evolution of neogeography over the years with a fundamental role for scientists and cartographers and offering new demands.

The research presented herein follows the trends of neocartography to embrace an interest renovation in maps (Hennig 2013) and took into account cartographic representation in general along with the mapping process. Figure 6 shows the first slide of Dr. B. D. Hennig (University of Sheffield) published in September 2012. It is interesting to observe that in several ideas related to cartography and GIS mapping, the words that stand the most are: DIGITAL, MAPPING, NEW, DATA, CARTOGRAPHIC and MAP. This was the first slide of a presentation that can also be the last one which states the conclusions.

More than a decade ago former US Vice-President Al Gore came up with a vision of “Digital Earth”; “*(…) a multi-resolution, three-dimensional representation of the planet that would make it possible to find, visualize and make sense of vast amounts of geo-referenced information on physical and social environments*” (Gore 1999).

Craglia *et al.* (2012), inspired by that vision towards a new path, re-evaluates the development of Digital Earth (DE) as a system in continuous evolution. The *Digital Mapping*, *Digital Earth*, *GIS Applications*, *Geovisualisation*, *GIScience* or even the traditional *Cartography* are all “labels” of a broad approach which should include all aspects of visualising geospatial information (Hennig 2013).

Geographical Information Systems (GIS) had an important role in the thesis and represent an outstanding technology that is in constant development and is basically established as a mapping science. According to Goodchild (1992, 2004, 2010) GIScience is also an emerging concept with a wide field of applications. Therefore the research presented here assumed a multidisciplinary and holistic context (e.g., Drummond *et al.* 1997, Buckley *et al.* 2002, Vallega 2005, CIRIA *et al.* 2007, Sester *et al.* 2009, Rogers *et al.* 2010, Pires *et al.* 2014a) that will be described later in the integrated coastal engineering geosciences approach for GIS and photogrammetric surveying of dynamic maritime environments.


**Figure 6. “**From geovisualisation to neocartography: maps in a digital world” (Cover from the presentation slides created by Dr. Benjamin D. Hennig of the SASI Research Group|University of Sheffield [Views of the world 2009] published in September 2012). 

We have outlined the context and background but it is important to close this section by writing about how cartography has been influenced by geotechnologies overall; the progress of information and communication technologies and the geographical understanding (Brewer 2005, Konecný 2011). The term “adaptive cartography” became visible in 2003 related to mobile maps (Reichenbacher 2003, Sarjakoski & Nivala 2003).

Morita (2004) developed the idea of “ubiquitous mapping” in the beginning applied to mobile tools but now with several action fields. There is an enormous change between basic maps and thematic maps as proposed by Stanek *et al.* (2007) and Konecný (2011). Consequently, there was a need to shape and develop new cartographic elements and therefore the process of “ubiquitous mapping” inevitably involves interaction with the real world. The link between the current maps and the users or the practical applications of these maps is important to discuss, because basically maps should have a dynamic context with concrete purposes. The map design is set by the map’s context describing different approaches applied with adaptive cartography. This style of cartographic visualisation could solve several issues and it is useful in many cartographic fields (Fisher *et al.* 1993, Morita 2004, Dykes *et al.* 2005, Hrebícek & Konecný 2007). We need these research-based principles for correct representations from the same geodata source/core (Konecný 2011).

Figure 7 exemplifies the geodata and the elements of context usage (more details in Reichenbacher 2003, Stanek *et al.* 2007, Konecný 2011). As described in Konecný (2011) the context configuration defines:

- USER: the main target; who will read the map (skills, level, visual preferences of the user and profile);
- ACTION; the key question is why the map is produced and the particular information is described (spatial extent, features);
- SITUATION: the key issue is where the map is used and important characteristics such as time, location and orientation;
- TECHNOLOGY: this parameter indicates the map device constraints (display size and transfer rate) which do not always apply if there is no mobile device in the equation.

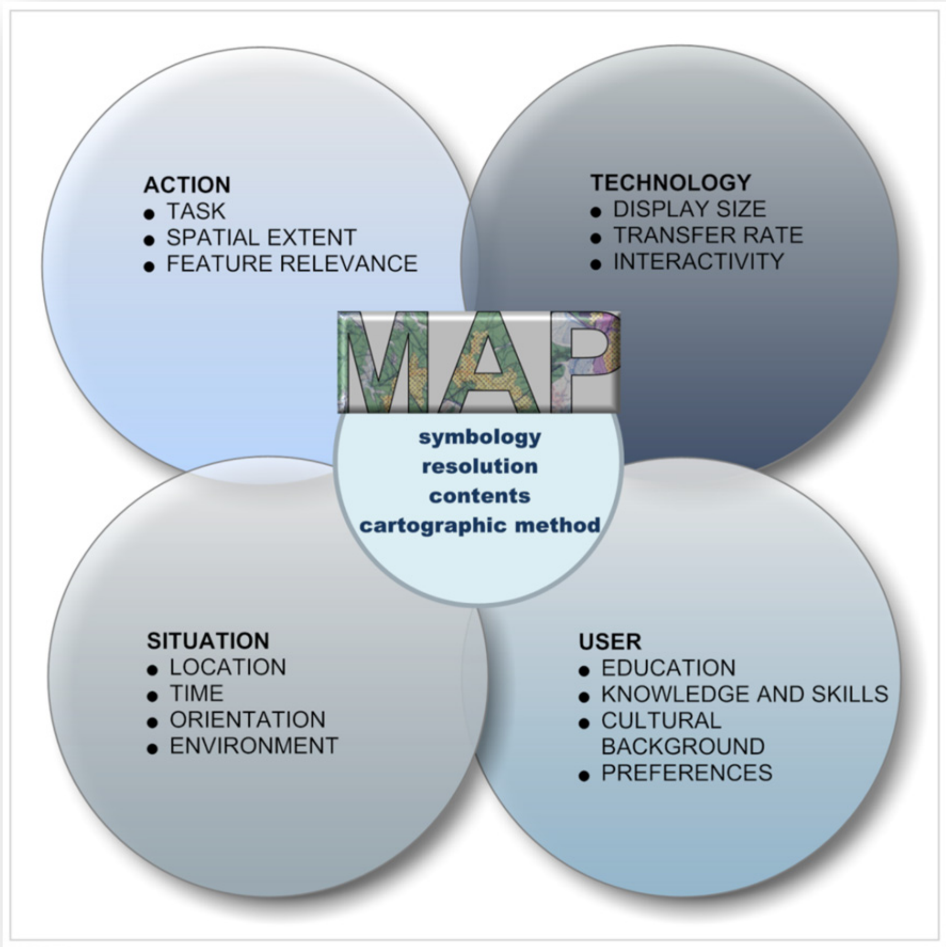



**Figure 7.** The cartographic context modifications in geovisualisation (adapted from Stanek *et al.* 2007, *in* Konecný 2011).

The thesis followed some of these principles, considering that GIS mapping played an important role along the research strategy. The applied cartography and GIS mapping were the connecting platform and the main drive which combined all the methodologies and techniques presented here. These were the core guidelines in order to integrate georesources assessment, geoengineering techniques and coastal zone management in this investigation.

This thesis had the main support of the R&D **Centre GeoBioTec** (Georesources, Geotechnics, Geomaterials Research Group)[2] at the **University of Aveiro** and the Consultancy Centre **Laboratory of Cartography and Applied Geology** (LABCARGA)[3] at the **School of Engineering** (ISEP), the **Polytechnic of Porto**. The spirit of cooperation between these Centres with engineering companies, industry, scientific institutions or other agencies made possible all the activities accomplished during the research and provided also the resources (materials and equipment) available during the fieldwork, laboratory and desk studies. The author holds a doctoral scholarship from the Portuguese **Foundation for Science and Technology** (FCT|SFRH/BD/43175/2008), evaluated by the civil and mining panel. In addition, support in several stages of research was made by the following institutions: University of Santiago de Compostela (Spain), University of Windsor (Canada), University of Porto (Faculty of Arts, Department of Geography), Irmãos Cavaco SA, FOTOENGENHO Lda, SOMAGUE SA, LNEC, CCDR-N (North Regional Coordination and Development Commission), APDL (Port Authority of Douro and Leixões), and CETMEF (France).

## 1.2. Scopes and objectives

The antiquity of coastal adaptations has gained renewed attention in the last several years as such coasts have long been important foci of human settlement (e.g., Bailey & Milner 2002, Bailey 2004, Bicho & Haws 2008, Haws *et al*. 2011, and references therein). As Bailey & Milner (2002) pointed out: *"…coastlines have been a primary focus for human settlement, population growth and dispersal from the earliest periods of prehistory, dynamic zones of cultural interaction and social change, and... they should not be viewed as marginal zones or barriers but as gateways to human movement, contact and cultural innovation…".*

Coastal environments are complex, and resource availability is not simply a function of climate. Sea level, oceanographic conditions, neotectonics and geomorphology have each played a role in determining the structure of coastal environments since Paleolithic time (Westley & Dix 2006, Haws *et al*. 2011). Pleistocene climatic instability caused rapid and large amplitude fluctuations in sea level that in turn led to continuous changes in coastal environments, such as the case of Iberia shoreline (e.g., Granja 1999, Dias *et al*. 2000, Araújo *et al*. 2003, Carvalho *et al*. 2006, Haws *et al*. 2011)

Climate change events and extreme weather, related to anthropic pressures and natural systems cyclicity, along with coastal erosion phenomena may have triggered the overall research. Moreover, the common domain is the shore marine environment.

*[2] The participation of this thesis was under the framework of the PEst-C/CTE/UI4035 (GeoBioTec|UA).*
*[3] The work was also assigned under the re-equipment program (LABCARGA|IPP-ISEP|PAD'2007-08) and PetroCart, CartGalicia and GisCoast projects.*

The coastal or maritime environment is one of the most dynamic and energetic interfaces between human society, ecosystems and environment sustainability (e.g., Green & King 2002, Fröhle & Kohlhase 2004, Populus *et al.* 2004, Wang 2009, Addo 2013). The proposed methodology places importance on anthropic intervention comprising the hydraulic structures, particularly the armour layer component (superficial and visible part) of the structures (Figure 8). The relationship between all the processes, elements and forcing conditions allowed the production of several thematic geoengineering maps, as well as a better understanding of the coastal morphodynamics. This approach was based on the concepts, terminologies and methods stated by Richards (1974), Woodroffe (2003) and Pavlopoulos *et al.* (2009) and interconnected with coastal geology, applied geomorphology and marine geotechnics. In addition, GIS coastal mapping is also related to the beach management and maritime engineering approaches presented in CIRIA *et al.* (2007) and Rogers *et al.* (2010).

In a shore marine environment there are natural elements and all of the coastal adjacent features, as well as the anthropogenic impacts which concern the hydraulic structures. All these components associated with rocky shores or mixed coasts are the main focus of the thesis. Consequently, all the elements and processes were taken into account in the mapping framework in sequence with the GIS-based project and settings. Figure 9 illustrates the analogy between the major scope and the component parts of a typical rock structure. Let us take as an example the design of a groyne, whih is a typical rock hydraulic structure. Firstly, we will have to include *GIS mapping* as the core and the basis of the research. Secondly, the under layer corresponds to *engineering geosciences* and finally the armour layer will be the *coastal dynamics*, as the main fields to sustain all the structure.

Overall the thesis outlines the application of geosciences cartography, engineering geology, applied geomorphology and marine geotechnics in an interdisciplinary methodology approach on complex marine environments. The research displays also the study of the geomaterial characterisation and should be considered a long-term approach. Likewise the study embraces cartographic GIS-based applications and techniques.

Regarding the hydraulic structures, these are significant assets that are essential to the economy of many coastal areas, the protection of harbours' infrastructures, and to shoreline erosion and stability control. For example, in the Portugal mainland there are about three hundred coastal protection structures identified along the coastline. Given their importance, it is of vital national interest to study their long-term stability and behaviour. Over 70% of these structures are groynes (i.e. beach control structures), revetments and seawalls, most of them built with rock as a primary material. Due to ageing (many are more than 50 years old) and the increasing population pressure along the coast, the maintenance management of these structures and their protective layer (the armour layer) is critical (LCPC 1989, CIRIA & CUR 1991, USACE 2003, CIRIA *et al.* 2007).

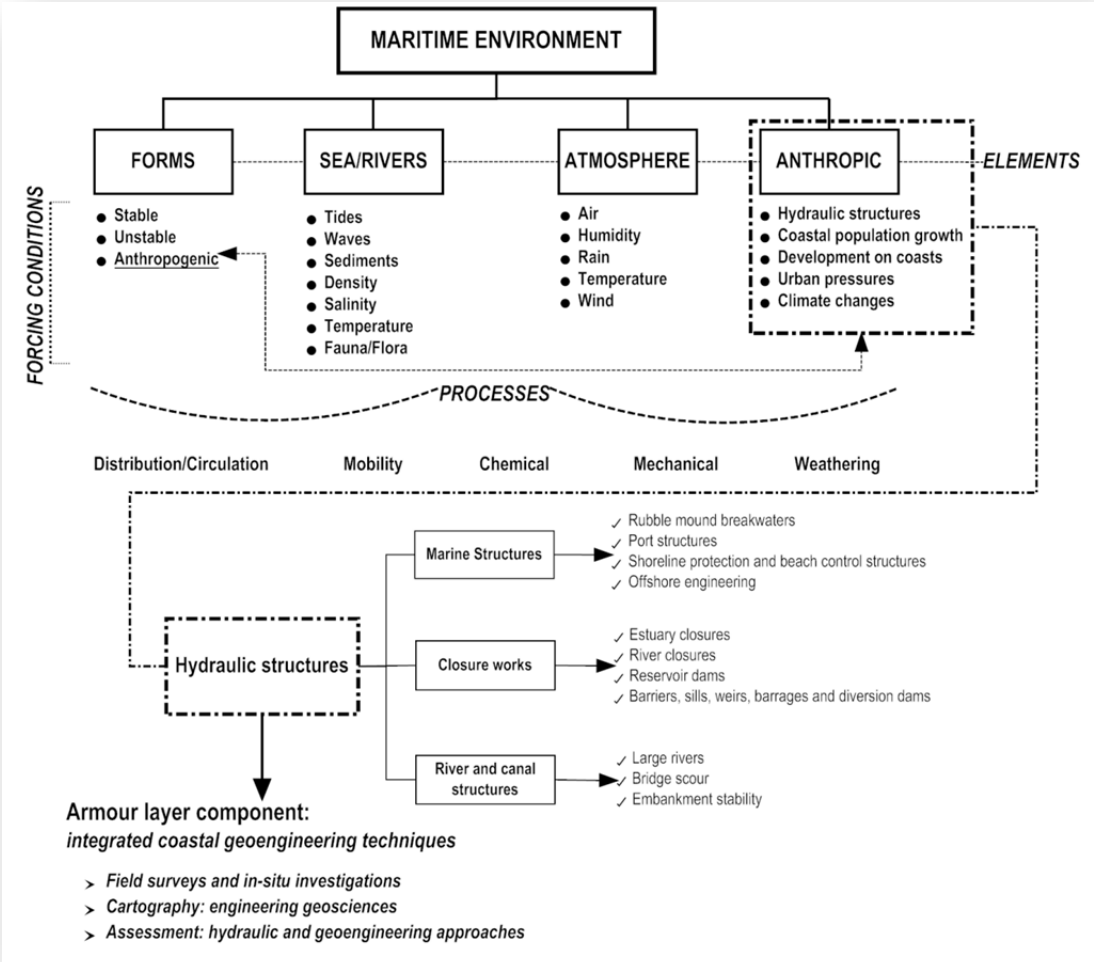



**Figure 8.** Conceptual framework and theoretical basis for an integrated coastal zone management [ICZM] focused on a geoengineering approach (Pires *et al. in press*).

In fact, asset management, i.e. the inspection, monitoring, repair, and rehabilitation of existing structures, represents nowadays the largest part of coastal works when compared to construction of new coastal defences in 'greenfield sites'. Modern monitoring techniques should allow a robust assessment of the condition of such structures (e.g. Rihouey *et al.* 2009, Papadopoulos *et al.* 2011, Infante *et al.* 2012, Al-Top 2013) and provide reliable technical information that would form the basis to predict the need for maintenance and rehabilitation works. In addition, geotechnical investigations carried out at the rock quarry sources should be incorporated in the assessment of material at the coast, since it forms part of investigations required to establish consistent geological and geomechanical assessment of armourstones. This comprises analysis of the in situ quarry rock masses, including the geometry and fracturing degree, and their petrophysical and mechanical properties, including weathering grade (e.g., Fookes & Poole 1981, Dinis da Gama 1996, Latham *et al.* 2006a, Pires & Chaminé 2009).

This information is particularly relevant for maritime structures, because the quality of the geomaterials used in their construction is known to influence the performance and lifetime of these structures (CIRIA *et al.* 2007). The schematic illustration of Figure 10 shows the cycle which integrates the applied cartography, inspection, modelling and quality assessment of geomaterials with geotechnical aspects. The monitoring of hydraulic structures does indeed play an important role in the thesis, as well as the rocky coast assessment.

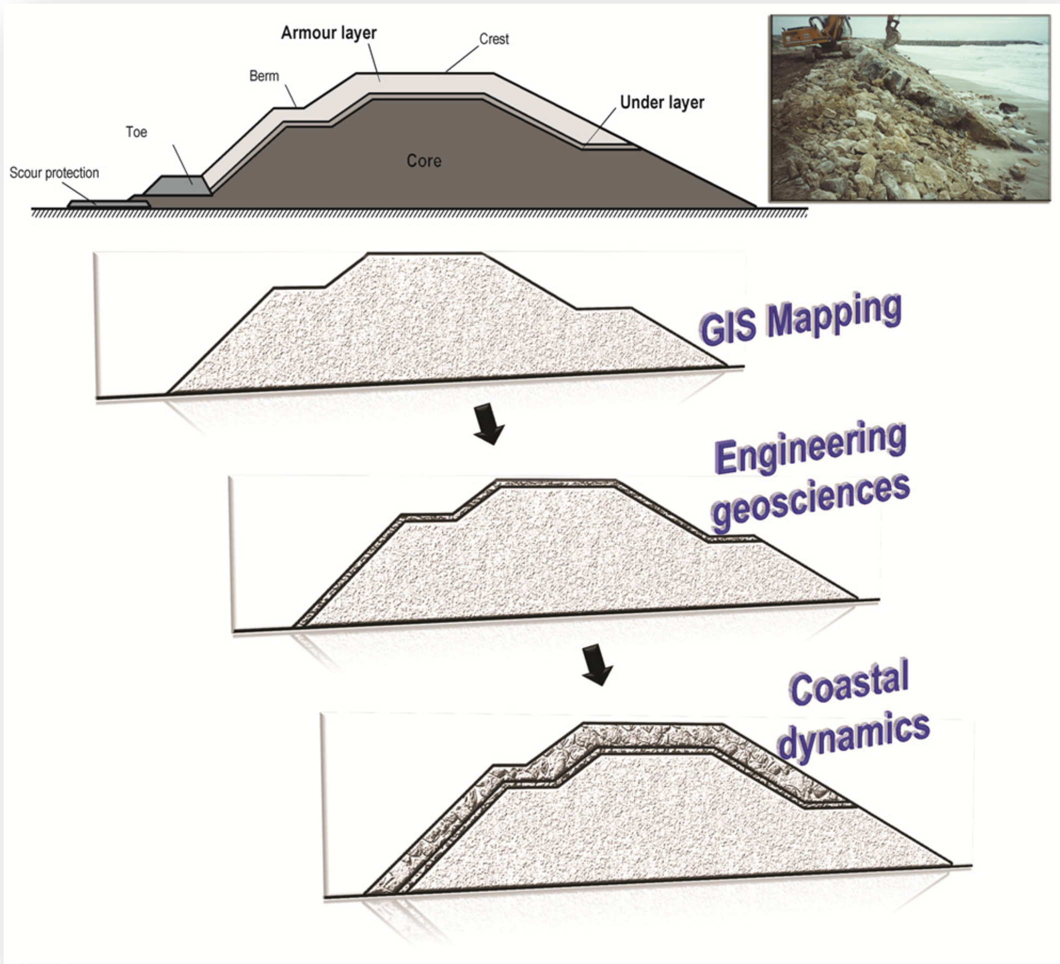



**Figure 9.** Major scope analogy using the component parts of a typical rock hydraulic structure.

Our investigation motto is the impressive quote of Leonardo da Vinci "*Water is the driving force of all nature*". The research will show an integrated coastal geoengineering approach for maritime environments providing a multidisciplinary study encompassing GIS-based cartography, engineering geosciences, rock mechanics and coastal zone sciences.

**Figure 10.** Schematic view of the coastal monitoring cycle: merging applied cartography, inspection, modelling and quality assessment of geomaterials with geotechnical aspects

The core goals of the thesis are presented in Figure 11, as well as the aims to be accomplished and the methodologies used.

This research focuses primarily on the strategic action fields listed below:

a) Coastal cartography and photogrammetry;
b) DSAS (Digital Shoreline Analysis System) application;
c) Study of rock-armourstone deterioration and durability;
d) Monitoring and inspections of hydraulic structures;
e) Structural and rock mechanics studies on shore platforms;
f) Integrated studies on coastal/shoreline management and territory planning.

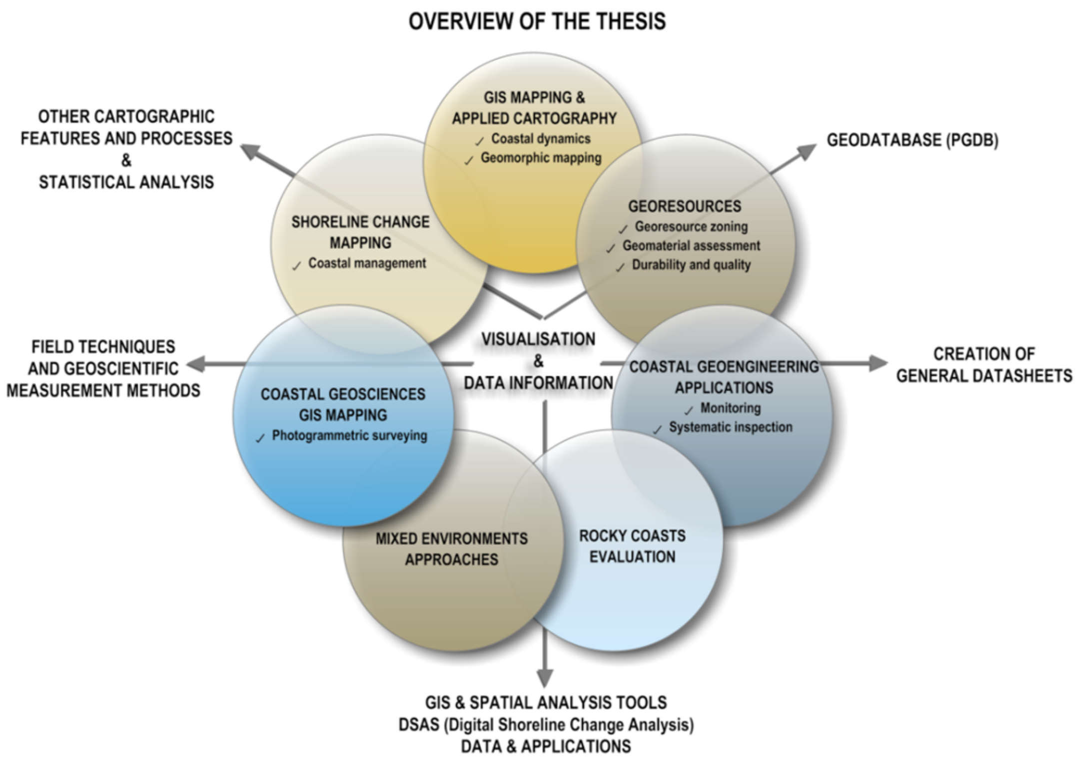



**Figure 11.** Schematic illustration of the scope of the thesis.

The overall working strategy involves the development and refinement of an applied methodology comprising the assessment and management of hydraulic structures durability, and including the characterisation of geomaterial at the quarry sources. The development of this integrated approach was the starting point to be extended in order to apply it globally to different maritime environments.

The thesis would like to answer these specific questions/aims:

1. What is the present condition of the hydraulic structures under study?
2. Which types of geomaterials are differentially involved in the structures' failures or damage and in what proportion?
3. Which are the more suitable areas/quarries for the potential extraction of durable armourstones?
4. Which factors influence the geomaterials behaviour and, thus, the performance and lifetime of the study structures?
5. How can the durability of armourstone layers influence coastal environments?
6. How can the shoreline evolution and cliff retreat be measured?
7. What are the consequences of erosion/accretion phenomena in the area in terms of coastal management and territory planning?
8. How can GIS mapping and cartography help to assess these coastal environments?
9. In what way can the integrated coastal geoengineering approach be related?

Answers to these questions will be obtained by accomplishing several tasks mainly interconnected with visualisation and data information (Figure 11):

- Collecting of information and selection of study areas;
- Geoengineering GIS databases;
- Creation of general datasheets;
- GIS and spatial analysis tools;
- Field techniques and geoscientific measurement methods;
- Other cartographic features and processes and statistical analysis;
- Integrated analysis of the results: an original methodology proposal for coastal geoengineering assessment.

These aims will be pursued by combining different techniques and tools, including aerial high-resolution imagery, field surveys and relational databases, evaluation of deterioration levels, geomechanical assessment of geomaterials, accuracy analysis of erosion and wear rates in geomaterials, and GIS modelling techniques.

The research has several innovative aspects that will bring results for and an original approach to the coastal assessment, and particularly to the characterisation of geomaterials, cartography of armour layers and rocky coasts evaluation. These include the use of GIS mapping and modelling techniques to support geo-monitoring coastal plans. Moreover, it takes advantage of an integrated approach employing different concepts to assess quality indicators for material armour layer and structure types or shoreline evolution and cliff retreat. The knowledge brought forth by this approach will provide insight into how the variables studied could be used in risk assessment and coastal management programmes.

## 1.3. Thesis architecture

The dissertation presented herein is displayed as a series of original papers published in peer-review and indexed international journals. Theses as papers are different from the conventional and traditional Doctoral thesis; however, we decided to create a “hybrid” version or style. Why “hybrid”? Because throughout the document the reader will understand that the thesis includes an extended introduction and background which sets out the context of the research, explains the organisation and structure of the thesis, the study area framework, material and methods and state of the art (Figure 12).

In this case, the thesis format includes a set of original papers that have been already published during the development of research or online first, in press, accepted for publication and submitted. The thesis by published work is based on papers that have been researched and written during the PhD course.

The multi-paper thesis has some advantages comparing with the traditional thesis. One of these benefits that should be emphasised is that all the chapters can stand alone. Therefore the reader can focus on a section or chapter of greater interest. Nevertheless, a thesis is more than a collection of papers. Despite the independent chapters, the dissertation is a thorough and coherent "story", in which each chapter is a fundamental part. Along the thesis the reader will confirm the strong link that all the papers have with each other and the logical and correct order in which they were put together.

In the results and discussion part concerned with the papers, the thesis will clearly have a different font and layout from the main document, because we will maintain the scientific journal format in which the article was submitted or published. Therefore, the so-called “stapler dissertation” may vary widely between the chapters. To keep the reader updated, before each chapter corresponding to a paper there will be a *summary/synopsis* which introduces the chapter and establishes its links to previous chapters, working almost like a brief presentation to each paper.

It should also be emphasised that regardless of the benefit from having several papers published during the research, all the investigation had to be redirected according to its flow but also according to the high standards of the journal and referees’ revisions.

The conceptual architecture diagram of the thesis and general assemblage is presented in Figure 12, individually explained in three main parts (*Parts I, II* and *III*).

We propose to “navigate” around the thesis structure and “take a dip” at the main scopes corresponding to each chapter (see also Figure 11 previously presented). The reader will see that each chapter corresponds to a paper which displays the main results related with the studied core fields (scopes).

In the first part of the document (*Part I*) the thesis framework is outlined (Figure 13). Firstly, the introduction and background part consists on the description of the context, scope and objectives as well as the generic characterisation of the study area. Secondly, a summary of the methodological approach is made. Finally, general concepts presented in the state of the art are related with the coastal systems and processes.

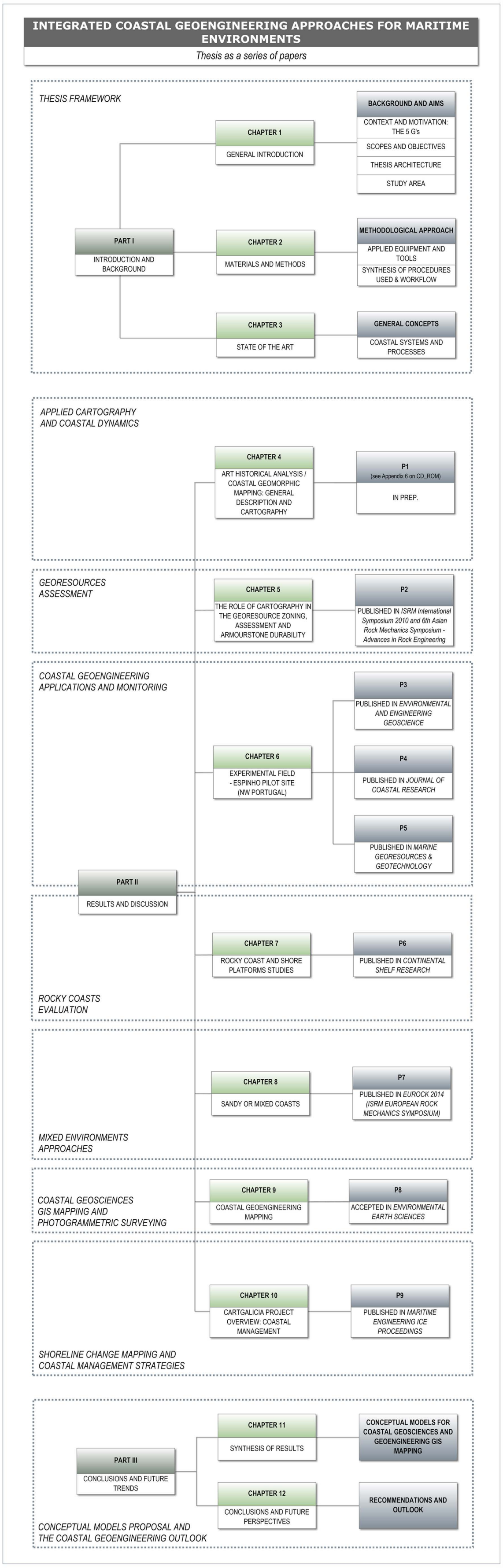



**Figure 12.** Conceptual architecture of the thesis and general assemblage.

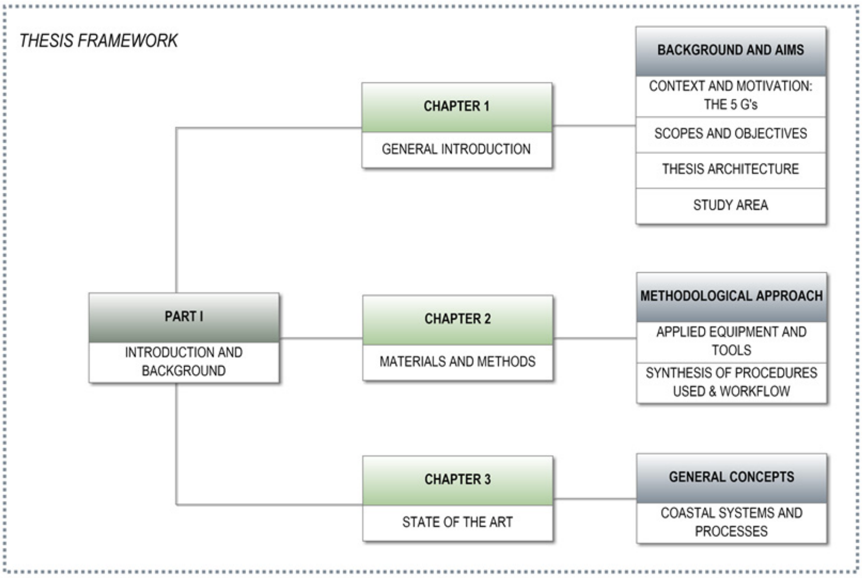



**Figure 13.** Crop and zoom of the thesis Part I – Introduction and background.

In the second part of the document (*Part II*) the results and discussion are revealed (Figure 14). Each chapter corresponds to a paper (submitted, accepted, in press/online first or published) as previously stated. Beside each paper the methodological approach and results/discussion are shown in the research fields of applied cartography and coastal dynamics; georesources assessment; coastal geoengineering applications and monitoring; rocky coast evaluation; mixed environments; coastal geosciences GIS mapping and photogrammetric surveying; shoreline change mapping and coastal management strategies.

These chapters constitute the core of the thesis in a coherent status. Table 1 synthesises the list of publications that have arisen from the work in the thesis, and the part of the document that it represents. Moreover, it is also presents the authors' contribution and tasks.

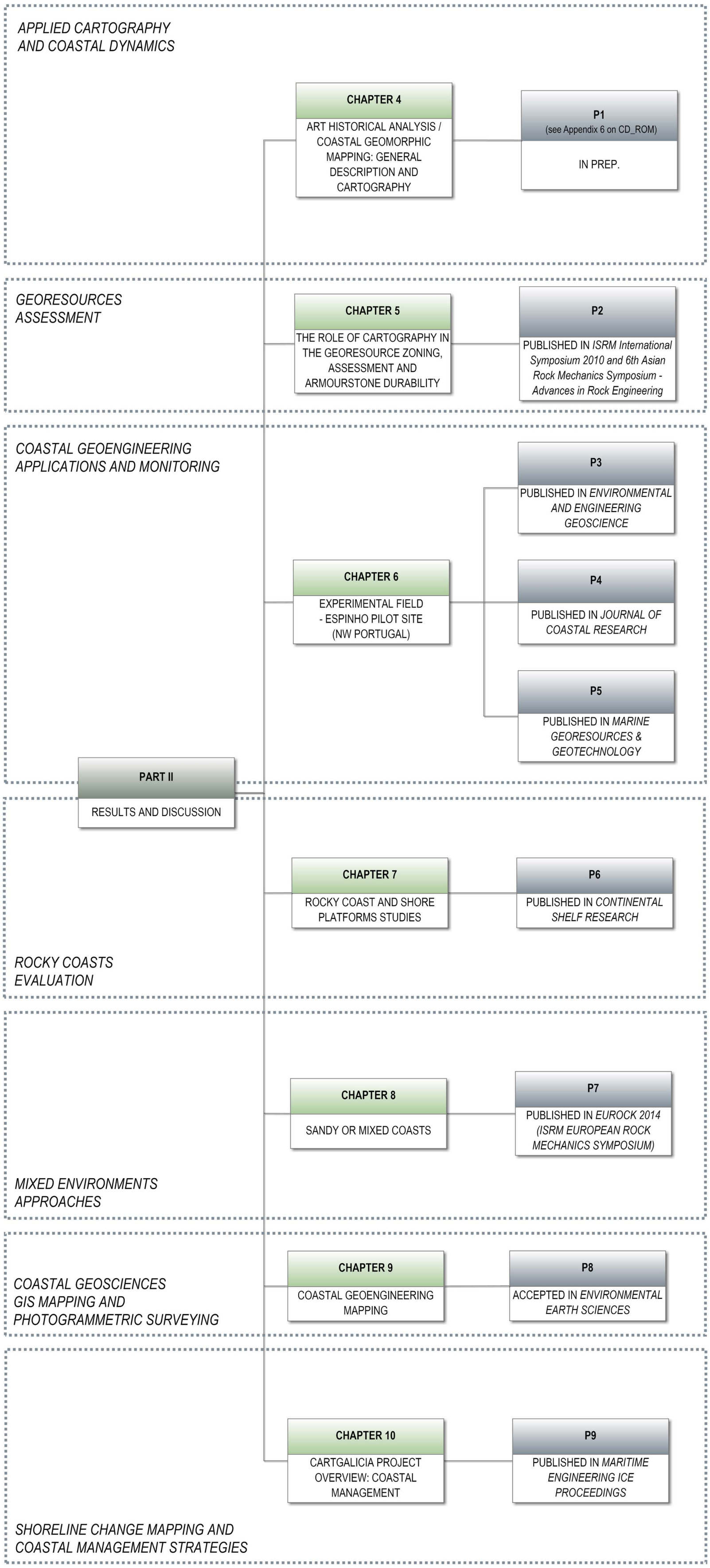



**Figure 14.** Crop and zoom of the thesis Part II – Results and discussion.

**Table 1.** Main indexed publications arising from this thesis.

| ID | Thesis chapter | Journal/Proceeding | Year | Publication title | Authors* | Publication status | Author contribution |
|---|---|---|---|---|---|---|---|
| P1 | 4 (Appendix 6) | - | 2015 | Catalogue – Art as a tool in coastal evolution<br>Brief history of Portuguese coastal art: insights through science | JCA, AP, HIC | In Preparation | JCA and AP designed the study. HIC gave inputs from coastal geomorphology and historical data. All authors contributed to data analysis, interpretation and discussed the results. JCA and AP wrote the manuscript with contributions from all authors. |
| P2 | 5 | ISRM International Symposium 2010 and 6th Asian Rock Mechanics Symposium - Advances in Rock Engineering | 2010 | Recognition of potential areas for the extraction of armourstone in maritime works (NW Portugal): coupling GIS mapping, geomaterial and geotechnics aspects | AP, HIC, FR | Published | AP and HIC designed the study. All authors contributed to data analysis, interpretation and discussed the results. AP and HIC wrote the manuscript with contributions from all authors. |
| P3 | 6 | Environmental & Engineering Geoscience | 2009 | Dynamics of coastal systems using GIS analysis and geomaterials evaluation for groins | AP, AG, HIC | Published<br>doi - 10.2113/gseegeosci.15.4.245 | AP and HIC designed the study. AG gave inputs from coastal geomorphology. All authors contributed to data analysis, interpretation and discussed the results. AP and HIC wrote the manuscript with contributions from all authors. |
| P4 | 6 | Journal of Coastal Research | 2009 | Cartography and assessment of hydraulic structures from Espinho coastal area (NW Portugal) using high-resolution aerial imagery surveys and a GIS interactive base | AP, HIC, AG, FP, FR | Published<br>http://www.jstor.org/stable/25738054 | AP and HIC designed the study. FP gave inputs from photogrammetry surveys. All authors contributed to data analysis, interpretation and discussed the results. AP and HIC wrote the manuscript with contributions from all authors. |
| P5 | 6 | Marine Georesources & Geotechnology | 2014 | Geo-engineering for the assessment of rock armour structures | AP, HIC, FP, FR | Published<br>doi - 10.1080/1064119X.2012.728684 | AP and HIC designed the study. FP gave inputs from photogrammetry surveys. All authors contributed to data analysis, interpretation and discussed the results. AP and HIC wrote the manuscript with contributions from all authors. |
| P6 | 7 | Coastal Shelf Research | 2012 | Shore platform boulders and boulder beaches in Galicia, northwestern Spain | APA, AT, AP, JLB, AG, HIC | Published<br>doi.org/10.1016/j.csr.2012.07.014 | APA and AT designed the study. JLB, AP, AG and HIC helped some stages of the fieldwork. All authors contributed to data analysis, interpretation and discussed the results. APA and AT wrote the manuscript with contributions from all authors. |
| P7 | 8 | EUROCK 2014 (ISRM European Rock Mechanics Symposium) | 2014 | Rock strength assessment and structural features analysis on rocky coasts | AP, HIC, APA, AG, FR | Published | AP and HIC designed the study. APA and AG gave inputs from coastal geomorphology. All authors contributed to data analysis, interpretation and discussed the results. AP and HIC wrote the manuscript with contributions from all authors. |
| P8 | 9 | Environmental Earth Sciences | 2015 | Combining coastal geoscience mapping and photogrammetric surveying in maritime environments (Northwestern Iberian Peninsula): focus on methodology | AP, HIC, FP, APA, FR | In press<br>doi: 10.1007/s12665-015-4936-z | AP and HIC designed the study. FP gave inputs from photogrammetry surveys. All authors contributed to data analysis, interpretation and discussed the results. AP and HIC wrote the manuscript with contributions from all authors. |
| P9 | 10 | Maritime Engineering | 2013 | Shoreline change mapping along the coast of Galicia (NW Spain) | APA, AP, LF, HIC | Published<br>doi - 10.1680/maen.2012.23 | APA, AP and HIC designed the study. LF helped some stages on GIS cartography. All authors contributed to data analysis, interpretation and discussed the results. APA, AP and HIC wrote the manuscript with contributions from all authors. |

**Authors' initials Ana Pires: AP; Helder I. Chaminé: HIC; Fernando Rocha: FR; Alberto Gomes: AG; A. Pérez-Alberti: APA; Alan Trenhaile: AT; Francisco Piqueiro: FP; Liliana Freitas: LF; J. López-Bedoya: JLB; José Carlos Amorim: JCA*

Throughout the writing process it was possible to develop some investigations related directly with the main scopes of the thesis, which are still in progress. These different subject areas, although they have not been presented as results, have been developed and studied during the research period. Some of the insights are presented as part of the discussion and conclusions section (according to the preliminary results of the field work and further analysis).

In particular, we are planning at least a few more scientific ISI articles to be submitted shortly:

- *The development of coastal geosciences mapping for maritime environments (Figueira da Foz groynes, Central Portugal), or geomorphic mapping that could be accessible in different framework levels or scales: from regional to local – that concerns Chapter 4 [Applied cartography and coastal dynamics]*
- *The geotechnical mapping techniques on coastal volcanic rock platforms using UAV LiDAR surveys in Pico Island, Azores – that concerns Chapter 4 [Applied cartography and coastal dynamics]*
- *A comparative study and statistical analysis of concrete blocks along maritime structures, in Vila Praia de Âncora breakwater and Espinho groyne – that concerns Chapter 8 [Mixed Environments Approaches]*
- *The coastal cliff retreat and morphodynamics in Galicia (N Spain), as well the evidence of differential mass movements in two studied sites As Lagoas and Estaca de Bares – that concerns Chapter 10 [Shoreline change mapping and coastal management strategies]*

Finally, in the third part of the document (*Part III*), the conclusions and future trends of the research are presented (Figure 15). Integration, analysis and synthesis of results from the main findings of the thesis were drawn together, establishing the significance of the work. Recommendations were made and the outlook shaped concerning the integrated coastal geoengineering approaches for maritime environments addressed during the PhD thesis. This chapter discusses the integration overview of all the results and highlights the achievements.

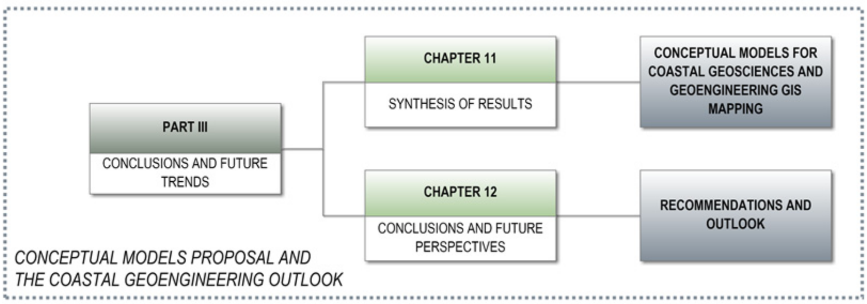



**Figure 15.** Crop and zoom of the thesis Part III – Conclusions and future trends.

The document skeleton presented herein is one of the multiple formats or styles to submit a PhD thesis. This layout could be greatly recommended for students that can benefit in scientific careers from having several papers published during their PhD studies. Furthermore, if the research is creative it may be perhaps a good way to prepare the thesis in an innovative way or even if the research area comprises distinct steps, subjects or mechanisms establishing the foundation for a series of publications (more details in Blunt & Souch 2008). All the important assumptions that were made by or in the study and how those assumptions might influence the results are included in the body of each paper.

## 1.4. Study area

### *1.4.1. A brief introduction*

This section presents a general framework of the study areas and sites. Obviously the local scale approach is fully characterised in the scientific papers. Therefore the regional mapping insights are provided in that section. In addition, a detailed description concerning the forcing conditions in the areas is presented. The environmental conditions have to be taken into account since the coast and the rock structures are determined by the hydraulic performance and structural response concerning the effects of physical processes (CIRIA *et al*. 2007).

The parameters obtained and generated by "*Puertos del Estado"* (Spanish Port System) site (*http://www.puertos.es/*) will be presented. They are divided into two main categories: real data and simulated data. The so-called REDEXT data (external network) are defined by the real data which are assured by Wavescan and SeaWatch buoys. This network couples, extends and updates the old RAYO and EMOD networks. The buoys of this network are characterised by being anchored away from the coastline at a great depth (more than 200 meters). Therefore, the wave actions of these sensors are not disturbed by local effects and each buoy provides representative observations of large coastal areas (more details in *http://www.puertos.es/*).

Concerning the records, they were divided in two basic types: WANA and SIMAR 44 were both generated and shared by *"Puertos del Estado"* (details in Mendoza-Ponce & Quintana 2009, and references therein). The provided parameters are: (i) significant wave height (Hs); (ii) maximum wave height (Hmax); (iii) peak period (T); (iv) direction; (v) mean speed and direction of currents; (vi) mean speed and direction of wind. The mean speed and direction of currents for simulated data is not available online; therefore we only have the real reference, as well as the maximum wave height (Hmax).

#### *1.4.2. Georesources site location*

Regarding the georesources assessment (*Chapter 5*) the coastal geoengineering issues are presented for a suitable selection and geomaterial characterisation concerning the geological and geotechnical quarry assessment (more details will be developed later in the paper). The progress of the research will show the results which comprise the evaluation of the quarry sources and the identification of potential areas for the extraction of armourstone of the quality and availability to supply maritime structures. Figures 16 and 17 display the location of the studied areas, including the selected counties and the georeferenced quarries. We should make it clear that the selected counties were clipped from a *buffer* previously defined as 70 km from the shoreline to the inner land.

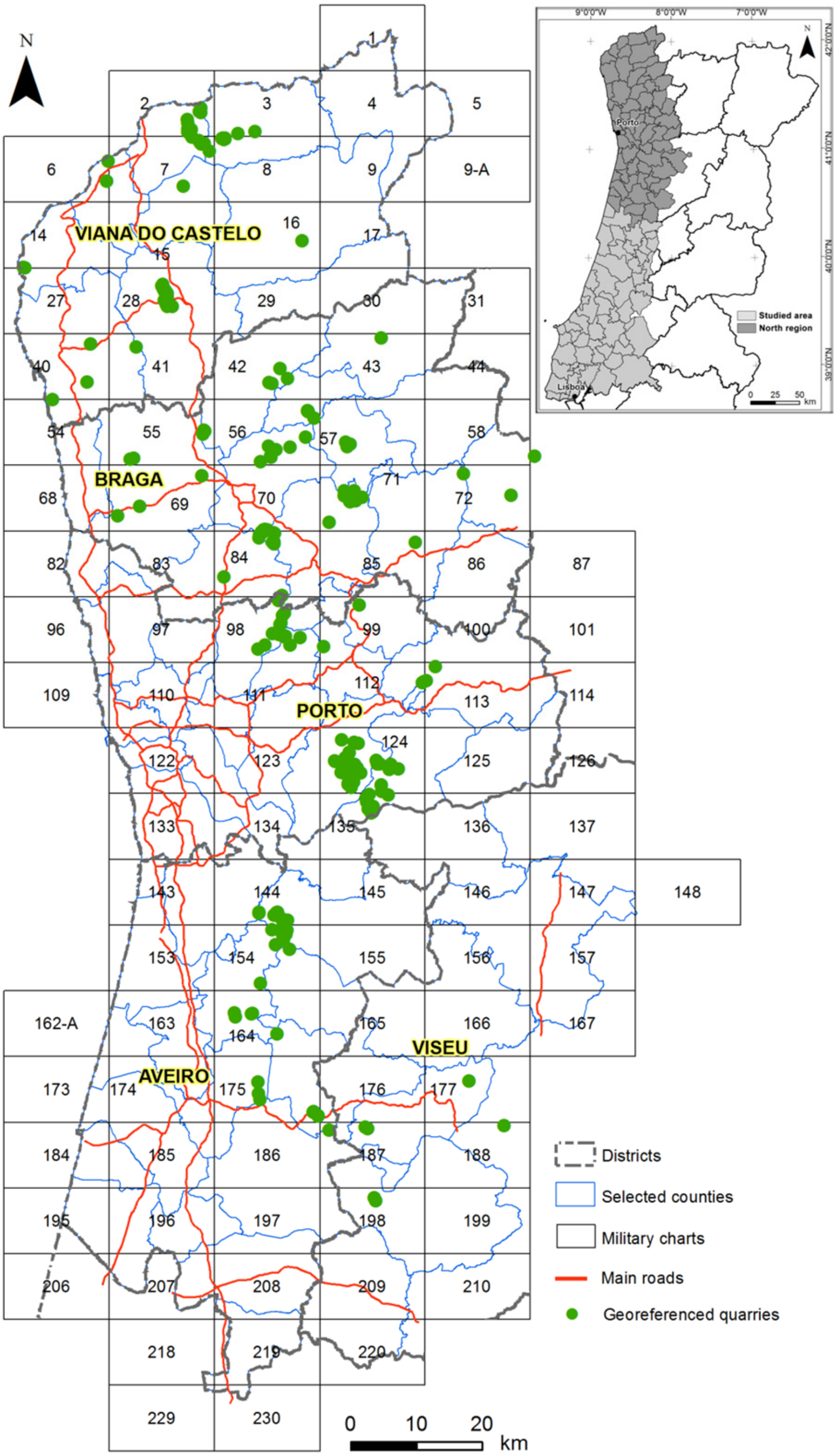



**Figure 16.** Location of rock quarry sources and selected counties in Northwest Portugal.

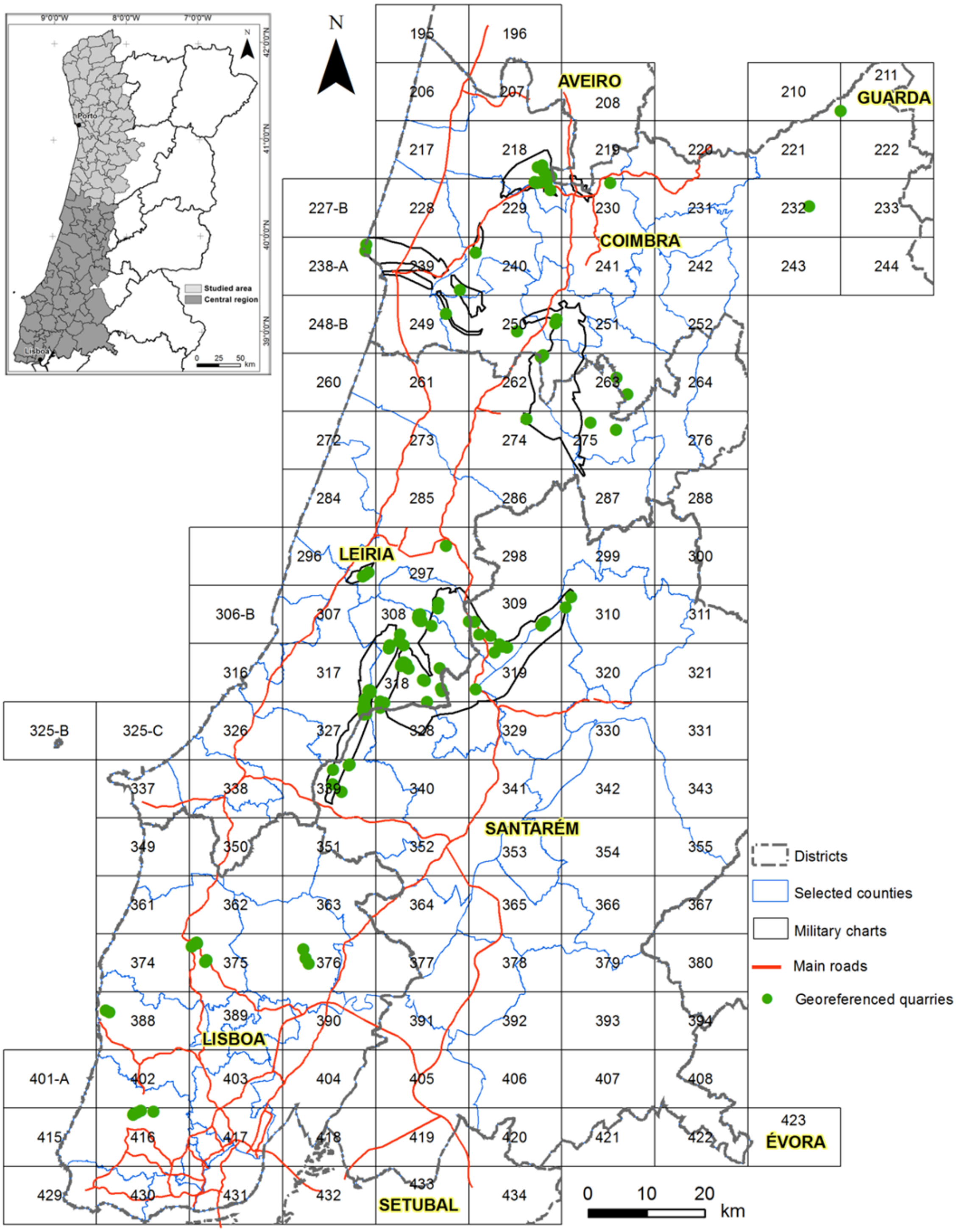



**Figure 17.** Location of quarries and selected counties in Central Portugal.

In total 966 quarries were identified (459 in NW Portugal and 507 in Central Portugal), georeferenced and distributed over a total area of 29,132 km$^2$ (14,010 km$^2$ in the Northwest regions and 15,122 km$^2$ in Central Portugal) (Table 2). More than 350 sites were selected, characterised and encompassed in the GIS database project with interactive support (e.g., hyperlinks for the datasheets, photos or essential information).

**Table 2.** Summary of the GIS database created and synthesis of results.

| Quantitative evaluation of the GIS project | Northwest Portugal | | Central Portugal | |
|---|---|---|---|---|
| | **Nr.** | **Area (km$^2$)** | **Nr.** | **Area (km$^2$)** |
| Selected counties | 85 | – | 71 | – |
| Georeferenced quarries | 459 | – | 507 | – |
| Visited and characterised quarries | 226 | – | 151 | – |
| Studied area | – | 14 010 | – | 15 122 |

### *1.4.3. Coastal study areas*

Concerning the techniques related to photogrammetric surveys, applied cartography, inspection of maritime structures and general coastal assessments the results and discussion section (*Part II*) put together the scientific papers which integrat several study cases (Figures 18 and 19). The studied key sites embrace a long stretch of coastline that involves a broad region of the north-west section of the Iberian Peninsula (Galicia and Portugal). Figure 18 displays the cartographic framework of the research areas of Spain and Portugal: a) As Lagoas and Estaca de Bares; b) Fisterra/Finisterre; c) Laxe Brava, Corrubedo and Aguiño; d) stretch between Baiona (Baredo) and A Guarda; e) Vila Praia Âncora; f) Lavadores (V. N. Gaia) and Espinho; g) Cova/Gala and Costa de Lavos.

The study comprises nine main areas, five sites in Spain labeled [G] and four sites in Portugal with [Pt] identification (Figure 19; see detailed description in Tables 3, 4 and 5). Except for [G1], [G2] and [G3], all of the areas have been subject to a collection of aerial imagery for the GIS-based platform using digital photogrammetry. This way, three flight operations were made: (i) areas [G4], [G5] and [Pt1]; (ii) areas [Pt2] and [Pt3]; (iii) area [Pt4]. Tables 3, 4 and 5 display an example of the high resolution imagery obtained and summarise the study areas' extension and a description of each sector, as well as the ground control points used for the georeferencing of the images.

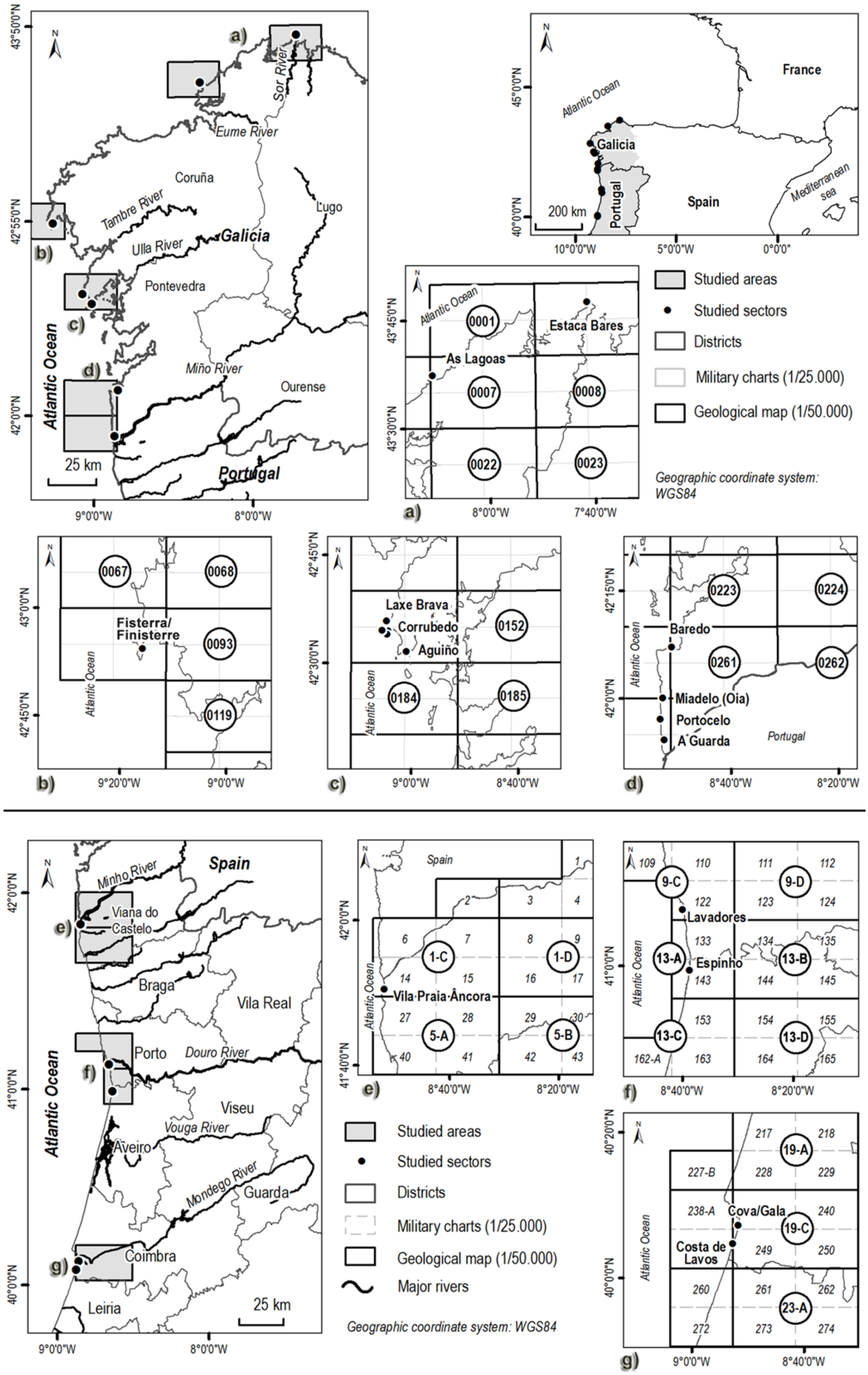



**Figure 18.** Cartographic framework of the research areas and sectors of Spain (Galicia) and Portugal (North and Central).

Figure 19 also contains the georeferenced position of the buoys (real and simulated data). In this type of research it is important to characterise the coastal region framework and the specific site features, such as: physical behaviour, hydraulic constraints and oceanographic forcing conditions.The region's coastline is considered very energetic, dynamic and heterogeneous (Dias *et al.* 2000, Veloso-Gomes *et al.* 2004, Pérez-Alberti *et al.* 2012). Consequently data from the buoys of the studied areas in terms of hydraulic conditions will be presented (Table 6 and Figures 20 to 28). The fieldwork and the accessed data spanned 4 years (2009-2012). However in the tables with medium significant wave height (Hs), maximum wave height (Hmax), peak period (T) and direction the time period begins since the beginning of the data record to identify atypical values that could correspond to storms.

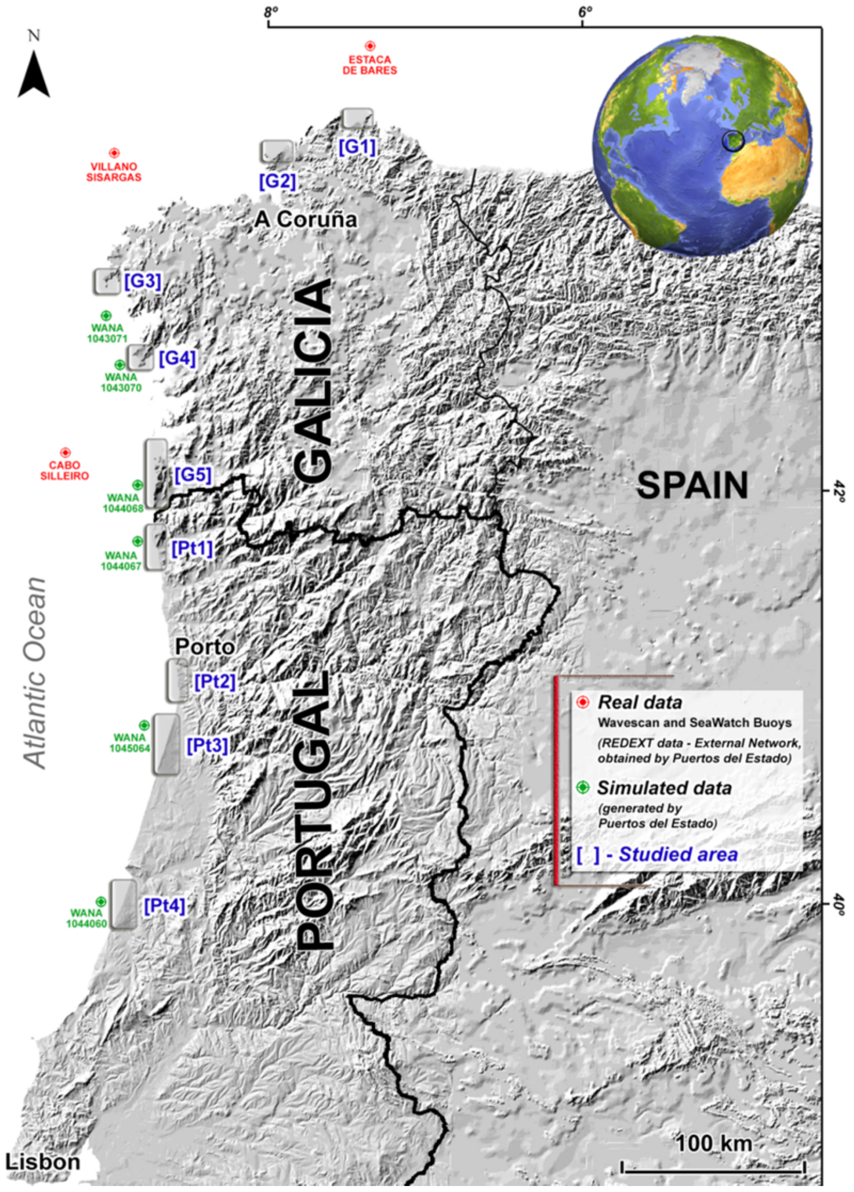



**Figure 19.** Studied sites – Galicia and North/Central Portugal – and selected sectors for the photogrammetric assessment and GIS applications in NW Iberian coastline; [Gx] Galicia sector and [Ptx] Portugal sector (more details in Tables 3, 4 and 5).

**Table 3.** Galicia (Spain) studied areas – description and characterisation with two examples of high resolution aerial imagery**.**

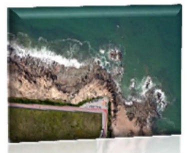
| Country | Studied sites [Area ID] | Type of coast | Studied sectors Nr. | Adjacent area (km) | Maritime structures in the area | Control points | Aerial view *(High resolution imagery or orthophoto/oblique aerial photograph)* |
|---|---|---|---|---|---|---|---|
| Spain | Ladrido – Estaca de Bares **[G1]** | Mixed coast | *1* rocky sector | 16 | 2 | n.a. |  |
| | As Lagoas **[G2]** | Mixed coast | *1* rocky sector | 20 | 0 | n.a. |  |
| | Fisterra/Finisterre **[G3]** | Mixed coast | *6* rocky sectors<br>*5* sandy beaches | 14 | 1 | n.a. |  |
| | Laxe Brava, Ribeira **[G4]** | Rocky coast and boulder beach | *1* boulder beach | 1,5 | 0 | 45 |  |

*(n.a. - not applicable because it used a different cartographic base from Xunta de Galicia)*

**Table 4.** Galicia (Spain) studied areas – description and characterisation with two examples of high resolution aerial imagery (*continuation*).

| **Country** | **Studied sites [Area ID]** | **Type of coast** | **Studied sectors Nr.** | **Adjacent area (km)** | **Maritime structures in the area** | **Control points** | **Aerial view** *(High resolution imagery or orthophoto)* |
|---|---|---|---|---|---|---|---|
| Spain | Corrubedo, Ribeira **[G4]** | Rocky coast and boulder beach | *3* rocky platforms<br>I – Faro Corrubedo<br>II – Punta Corrubedo<br>III – Punta Couso/Corrubedo | 7 | 4 | 40 |   |
| | Aguiño, Ribeira **[G4]** | Mixed coast | *1* groyne<br>*1* rocky platform<br>I – Aguiño groyne<br>II – Aguiño platform | 1 | 1 | 40 |   |
| | Baiona (Baredo), Pontevedra **[G5]** | Rocky coast with boulders | *1* rocky coast | 2 | 3 | 35 |   |
| | Oia, A Guarda **[G5]** | | *1* rocky coast | 5 | 2 | 30 |   |

**Table 5.** NW Portugal studied areas – description and characterisation with two examples of high resolution aerial imagery.

| Country | Studied sites [Area ID] | Type of coast | Studied sectors Nr. | Adjacent area (km) | Maritime structures in the area | Control points | Aerial view (*High resolution imagery or orthophoto*) |
|---|---|---|---|---|---|---|---|
| Portugal | Vila Praia de Âncora **[Pt1]** | Mixed coast | *1* breakwater<br>*1* rocky platform<br>I – V.P.Âncora groyne<br>II – Caminha rocky coast | 4 | 2 | 35 |   |
| | Lavadores, V.N. Gaia **[Pt2]** | Rocky coast with boulders and sandy beaches | *1* rocky platform | 2,5 | 3 | 45 |   |
| | Espinho, Aveiro **[Pt3]** | Sandy coast | *4* groynes<br>*1* seawall<br>I – Marinha<br>II – Marinha seawall<br>III – Carreira de Tiro<br>IV – Casa Branca<br>V – Paramos ETAR | 5 | 7 | 200 |   |
| | Cova and Lavos, Figueira da Foz **[Pt4]** | Sandy coast | *2* groynes<br>I – Lavos<br>II – Cova | 5 | 9 | 75 |   |

***Galicia and Portugal coastline: a general overview*[4]**

The NW Iberian coastline is depressed by several rivers, inlets and bays. The shoreline has a coastal and maritime environment that is very dynamic, heterogeneous and mixed (e.g., Trenhaile *et al.* 1999, Dias *et al.* 2000, Pérez-Alberti *et al.* 2012, Pires *et al.* 2013, Pires *et al.* 2014b). From a rocky shore or platforms to a diversified environment, the region comprises sandy beaches and coastal protection works (Pires *et al*. 2014a). The maritime works that can be found along the coast between Portugal and Spain cover a wide range of structures, such as harbours, breakwaters, groynes, jetties, seawalls or mixed solutions (Figure 8). In rocky shores several geoforms were described along the coast and platforms, like boulders which in some places of Galicia have a very energetic and dynamic performance (Trenhaile *et al*. 1999, Blanco-Chao *et al*. 2007, Pérez-Alberti *et al*. 2012). A good example of boulder beaches is the case of [G4] area which comprises the Laxe Brava site (Figure 19 and Table 3).

The A Coruña, Vigo, Leixões, Aveiro and Figueira da Foz are the main commercial ports in the study area. There are other small ports for protection and fishing which are used by small craft and fishing vessels (NGA 2011).

On the Galician coast ([G3], [G4] and [G5] areas) the wind system in winter usually has a SW trend, while in spring and summer the wind has predominantly N and NW directions (NGA 2011, Puertos del Estado 2012). However, with strong winds from S or SW, currents can come from the north, reaching a mean velocity of 40 cm/s (NGA 2011, Puertos del Estado 2012) (Figures 21c and 22c). The wind regime over the Galician coast may present different directions and values depending on two different situations: winter and summer (NGA 2011, Puertos del Estado, 2012). In winter the predisposition induces SW winds on the coast. However, in spring and summer the wind blows predominantly from the N and NW directions (McClain *et al.* 1986, Penabad *et al.* 2008) (Figures 21d and 22d for real data and Figures 23d, 24d and 25d – WANA 1043071, WANA 1043070 and WANA 1044068 – for simulated data). Sousa *et al.* (2011) registered a more variable wind regime during the winter reaching a maximum of 14 m/s (meteorological stations) and 18 m/s (oceanic stations, for the year of 2001). During the summer the highest speed in 2001 was 7 m/s (at meteorological stations) and 13 m/s (all points) (for further information see Sousa *et al.* 2011). It is also interesting to observe that for the [G1] and [G2] areas and for the Estaca de Bares buoy (Figure 20) in the North of Galicia different directions of currents are presented that also come from SE direction and regarding the wind parameter, it has likewise a predisposition of SW or NE directions.

Table 6 shows the mean significant wave height (Hs), maximum wave height (Hmax), peak period (T) and direction (º) for the real data buoys (Puertos del Estado 2012). The most surprising values are the maximum wave height (Hmax) that registered 20.6 m in 2009 (Table 6a, Estaca de Bares buoy); 21.9 m in 2010 (Table 6b, Villan-Sisargas buoy) and 19.1 m in 2010 (Table 6c, Cabo Silleiro buoy).

[4] The information in this subsection is partially based on Pérez-Alberti *et al*. (2013a) and Pires *et al*. 2014a.

**Table 6.** Mean significant wave height (Hs), maximum wave height (Hmax), peak period (T) and direction (º) for the real data buoys (Puertos del Estado 2012).

**a** **Estaca de Bares buoy (between 1996 - 2012)**

| Month | *Hs* (m) | *T* (s) | Direction (º) | Year | *Hmax (m)* | *T* (s) | Direction (º) | Year |
|---|---|---|---|---|---|---|---|---|
| January | 12.8 | 12.5 | 284 | 2009 | 20.6 | 12.5 | 283 | 2009 |
| February | 9.5 | 14.3 | 305 | 2006 | 17.0 | 12.5 | 339 | 2001 |
| March | 12.9 | 14.3 | 312 | 2008 | 19.7 | 15.4 | 323 | 2008 |
| April | 9.1 | 13.4 | 315 | 2001 | 14.5 | 13.4 | 327 | 2001 |
| May | 7.1 | 13.3 | 311 | 1997 | 12.8 | 12.5 | 295 | 2002 |
| June | 6.1 | 12.5 | 326 | 1999 | 8.5 | 12.5 | 322 | 2002 |
| July | 5.3 | 10.5 | 310 | 2001 | 9.5 | 12.5 | 287 | 2007 |
| August | 6.9 | 14.3 | 304 | 2008 | 10.4 | 13.4 | 311 | 2008 |
| September | 8.9 | 14.3 | 304 | 2000 | 16.7 | 14.3 | 311 | 2000 |
| October | 9.5 | 14.3 | 312 | 2003 | 15.2 | 13.2 | 312 | 2003 |
| November | 11.1 | 16.7 | 302 | 2000 | 16.2 | 14.3 | 325 | 2009 |
| December | 11.2 | 15.3 | 320 | 2007 | 17.5 | 16.7 | 323 | 2007 |

**b** **Villano-Sisargas buoy (between 1998 - 2012)**

| Month | *Hs* (m) | *T* (s) | Direction (º) | Year | *Hmax (m)* | *T* (s) | Direction (º) | Year |
|---|---|---|---|---|---|---|---|---|
| January | 13.5 | 14.3 | 296 | 2009 | 19.4 | 14.3 | 296 | 2009 |
| February | 10.0 | 13.4 | 281 | 2011 | 17.0 | 14.3 | 286 | 2011 |
| March | 12.6 | 14.3 | 323 | 2008 | 18.0 | 14.3 | 326 | 2008 |
| April | 8.3 | 16.6 | 319 | 2012 | 14.2 | 11.1 | 315 | 2004 |
| May | 8.8 | 13.4 | 290 | 2006 | 15.3 | 12.5 | 297 | 2006 |
| June | 6.0 | 14.3 | 316 | 1999 | 8.2 | 7.1 | 45 | 2009 |
| July | 5.5 | 12.5 | 292 | 2007 | 9.9 | 10.0 | 312 | 2009 |
| August | 6.3 | 14.3 | 313 | 2008 | 10.3 | 10.0 | 319 | 2004 |
| September | 6.7 | 12.5 | 302 | 1999 | 11.4 | 12.5 | 312 | 1999 |
| October | 10.2 | 14.3 | 309 | 2003 | 16.8 | 14.3 | 314 | 2003 |
| November | 11.7 | 14.3 | 324 | 2010 | 21.9 | 14.3 | 329 | 2010 |
| December | 10.9 | 12.5 | 309 | 2006 | 17.9 | 16.7 | 340 | 2007 |

**c** **Cabo Silleiro buoy (between 1998 - 2012)**

| Month | *Hs* (m) | *T* (s) | Direction (º) | Year | *Hmax (m)* | *T* (s) | Direction (º) | Year |
|---|---|---|---|---|---|---|---|---|
| January | 11.0 | 14.3 | 301 | 2009 | 17.4 | 14.3 | 302 | 2009 |
| February | 10.4 | 16.7 | 299 | 2007 | 18 | 16.7 | 303 | 2007 |
| March | 10.9 | 14.3 | 324 | 2008 | 17 | 14.3 | 326 | 2008 |
| April | 7.5 | 15.4 | 329 | 2012 | 11.9 | 16 | - | 2000 |
| May | 8.2 | 12.5 | 300 | 2006 | 13 | 12.5 | 301 | 2006 |
| June | 4.7 | 12.1 | - | 1999 | 8.5 | 8.3 | 309 | 2003 |
| July | 5.4 | 12.5 | 296 | 2007 | 8.3 | 12.5 | 302 | 2007 |
| August | 6.6 | 14.3 | 310 | 2008 | 10.6 | 14.3 | 311 | 2008 |
| September | 7.8 | 14.2 | - | 2000 | 11.5 | 13.5 | - | 2000 |
| October | 10.3 | 16.6 | 317 | 2003 | 15.4 | 14.3 | 319 | 2003 |
| November | 10.8 | 14.3 | 331 | 2010 | 19.1 | 14.4 | 332 | 2010 |
| December | 11.1 | 16.0 | - | 1998 | 18.3 | 16 | - | 1998 |

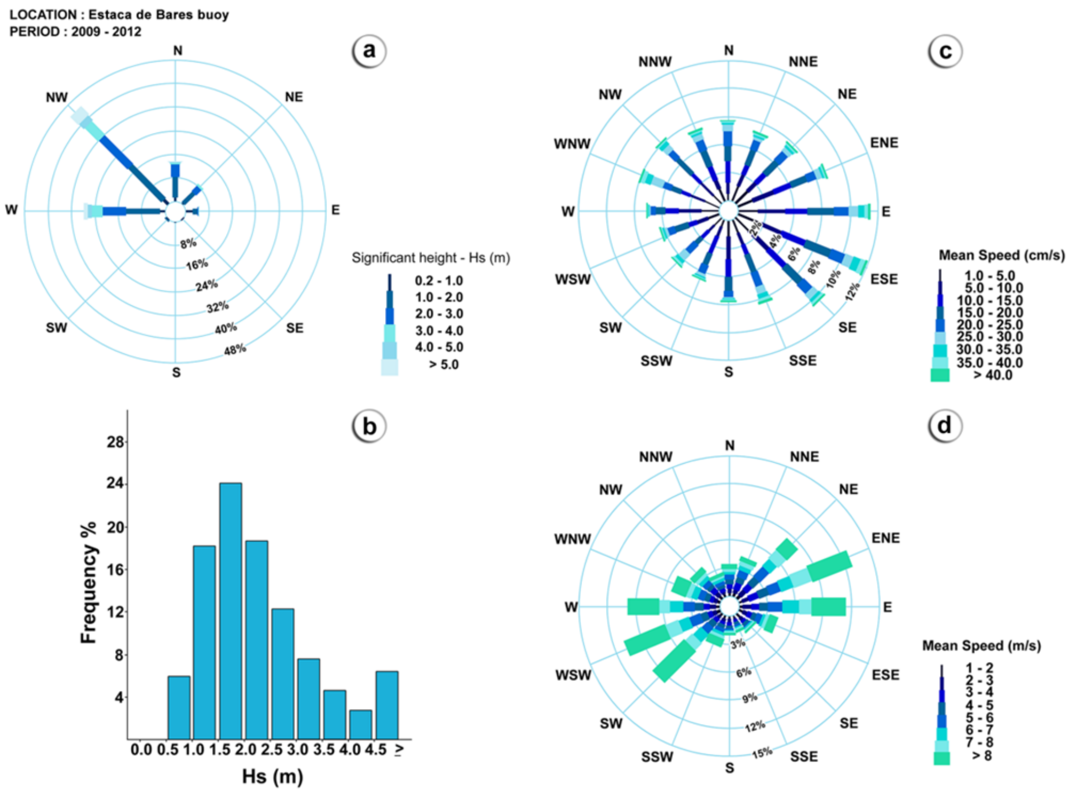



**Figure 20.** Estaca de Bares buoy: a) mean significant wave height (Hs); b) significant wave height frequency (%); c) currents mean speed and direction; d) wind mean speed and direction (Puertos del Estado 2012).

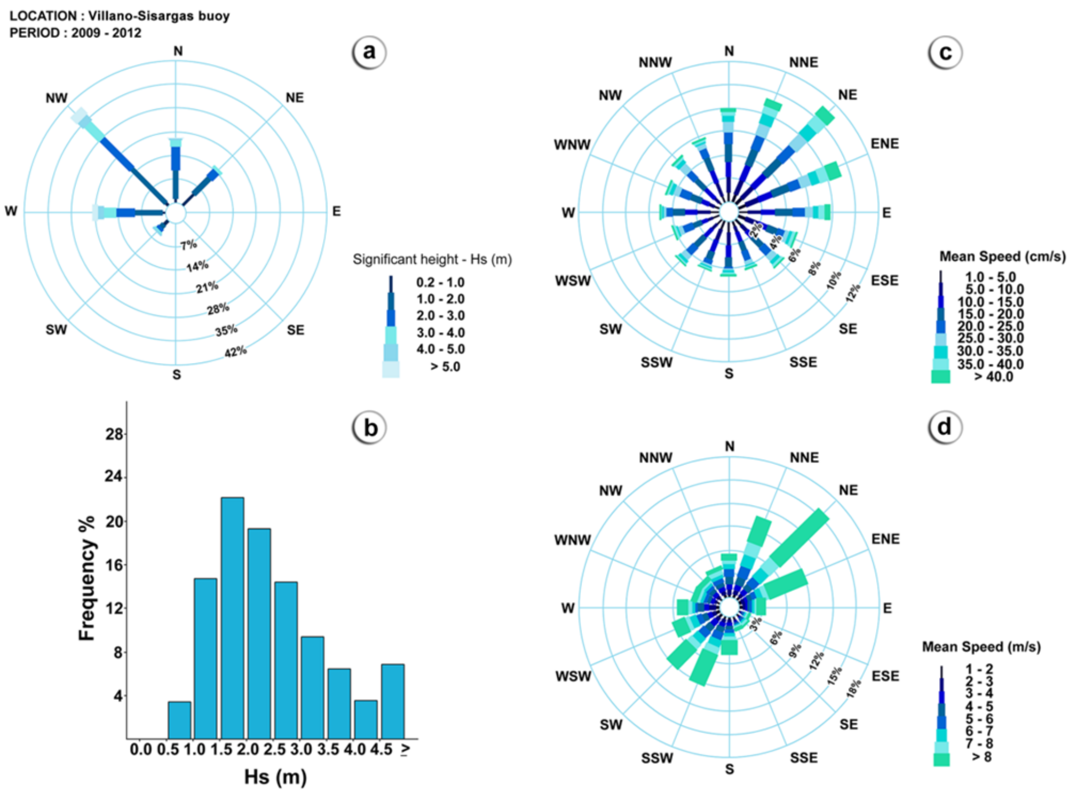



**Figure 21.** Villano-Sisargas buoy: a) mean significant wave height (Hs); b) significant wave height frequency (%); c) currents mean speed and direction; d) wind mean speed and direction (Puertos del Estado 2012).

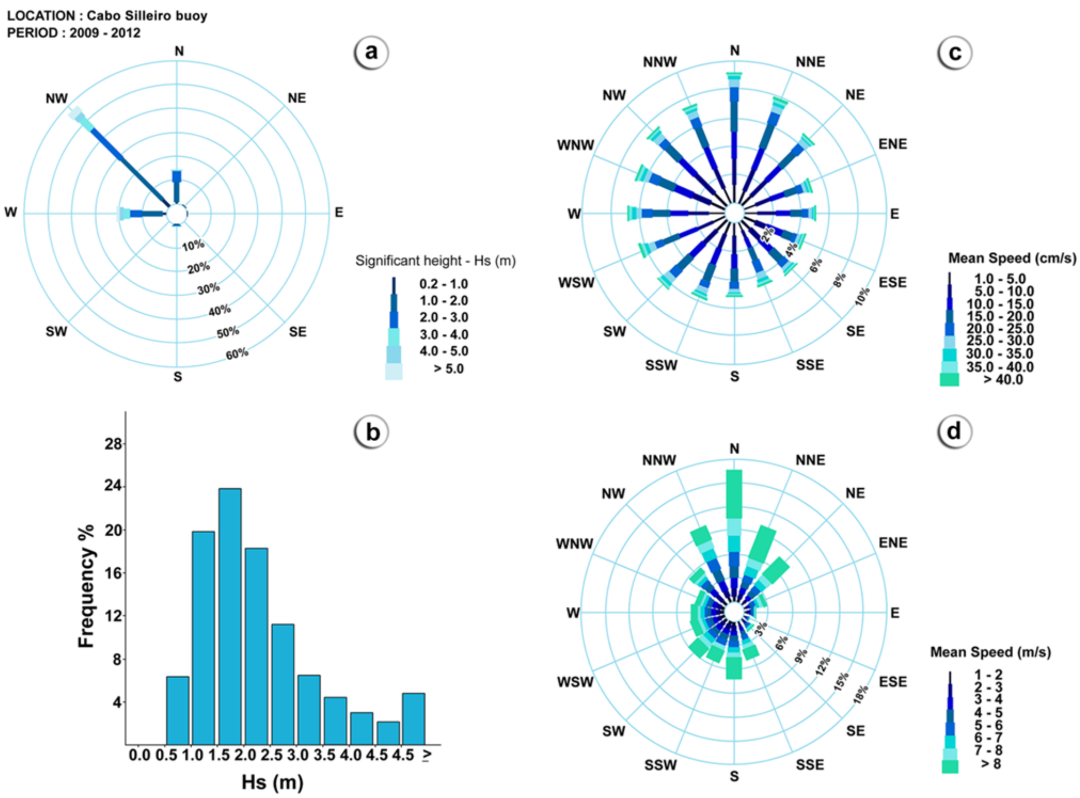


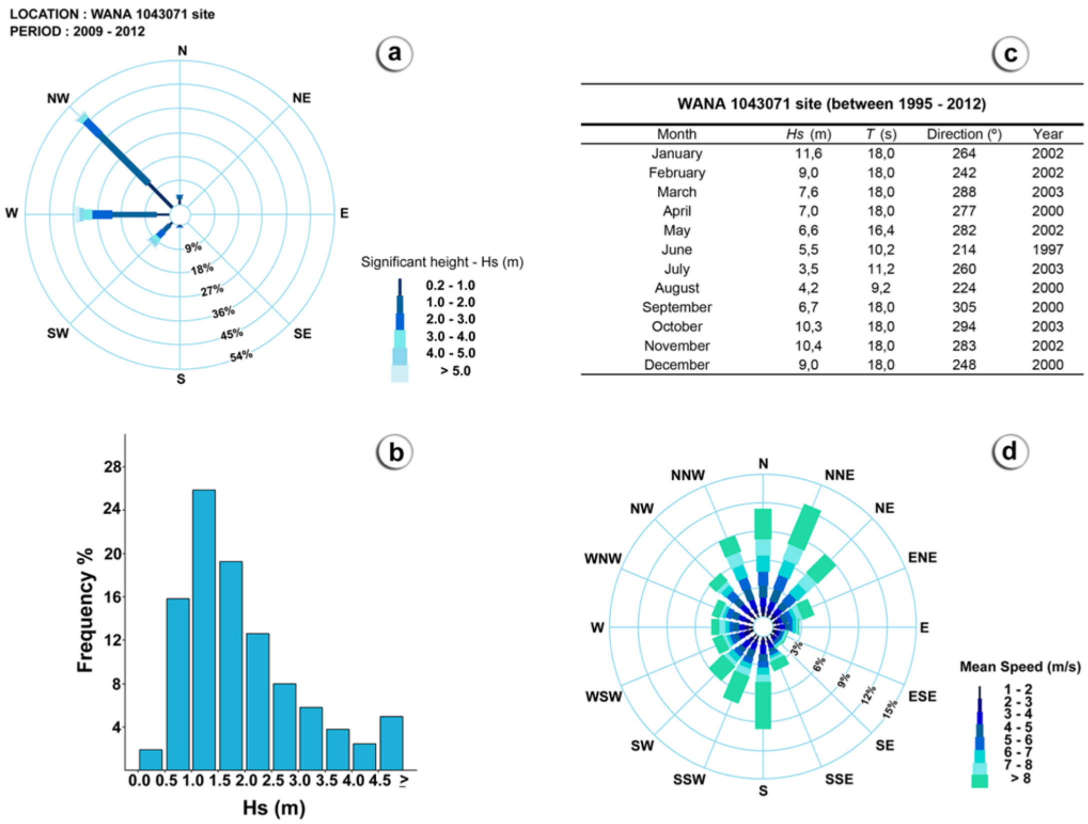

**Figure 22.** Cabo Silleiro buoy: a) mean significant wave height (Hs); b) significant wave height frequency (%); c) currents mean speed and direction; d) wind mean speed and direction (Puertos del Estado 2012).

In all Galicia's coastline has around 2,100 km of extension, including several islets and over 380 hydraulic works along the coast (POLGalicia 2010). The Galician mainland close to the studied area [1] is dominated by a mesotidal environment with a mean tide length of 2.5 m and a spring tidal range between 3.75 and 4 m (Pérez-Alberti *et al.* 2012, 2013a). Galicia has a really distinctive and active coastline because [G1] and [G2] areas are cliffed coasts with different geological, geomorphological and topographical features and landslide movements associated with these features. The Fisterra/Finisterre area ([G3]), locally known as the Costa da Morte ("Death Coast"), is characterised not only by a cliffed coast but also by sandy beaches and coastal protection strutures. Ribeira's area ([G4]) is mainly a rocky coast with a few mixed systems along the littoral zone such as sandy beaches and dunes. The stretch between Baiona (Baredo) and A Guarda ([G5] area) is characterised by a mixed coast with several maritime works (groynes, ports, jetties and breakwaters) but is also highlighted by a rocky coast with boulders and megaboulders.

Generally the dominant winds coming off the coast of Portugal are between N and NW, except in the winter, when the prevailing wind regime direction is from SW and is stronger than in the summer. According to I.H. (1990, 2005) in the [Pt1] area (Viana do Castelo station, between 1961-1990) we have values with a range of 2 m/s to 3 m/s for orientations of N and NW, but we frequently also register values of 1.5 m/s for NE winds and 3 m/s for SW winds.

Along the [Pt2] and [Pt3] areas (Porto/Pedras Rubras station, between 1961-1990) the most frequent winds are from N and NW with a range between 3.5 m/s and 5 m/s. In the central zone comprising [Pt4] area (Cabo Carvoeiro station, between 1961-1990) the medium value range is 5 m/s mainly with N direction. These values are in accordance with the wind graphics presented in Figures 26d, 27d and 28d (WANA 1044067, WANA 1045064 and WANA 1044060).

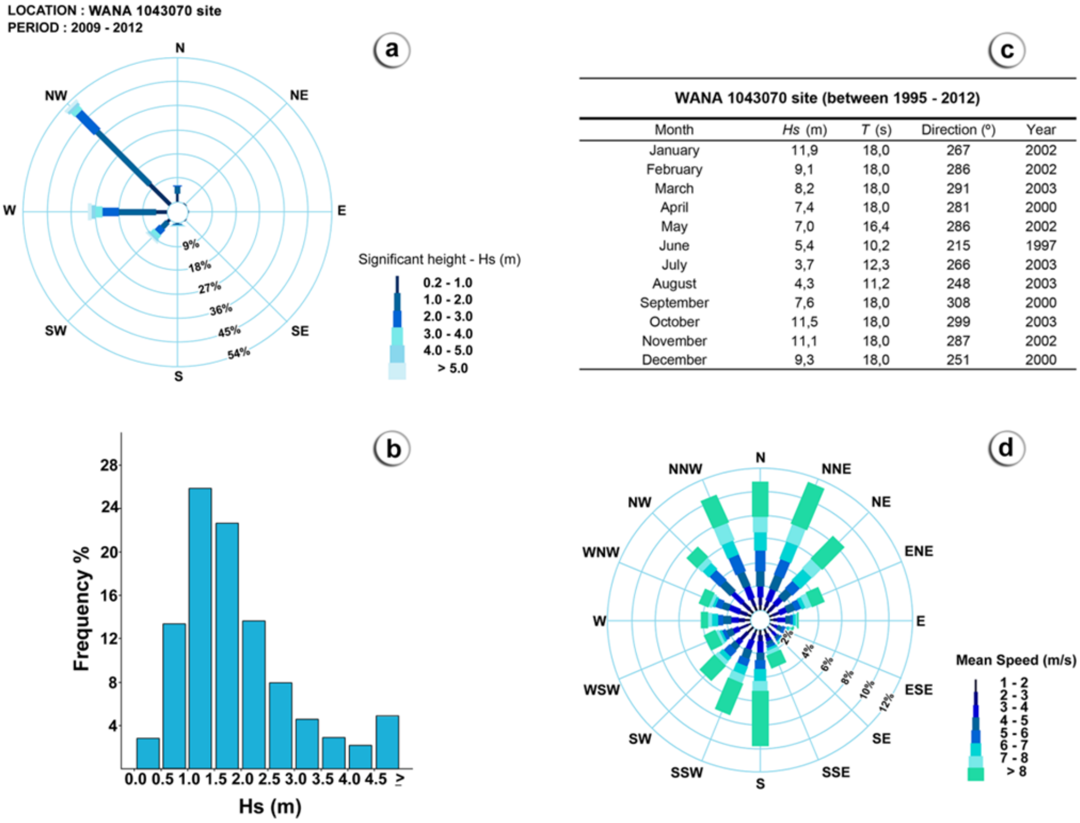
The total length of the Atlantic coast of Portugal mainland is more than 800 km of extension. With about 290 hydraulic works along the coast, 70% of them are groynes and seawalls (Pires *et al*. 2009a). The studied area [5] is also characterised by a mixed coastal system comprising sandy beaches and groyne fields with approximately 5 km of extension. Regarding the forcing conditions, the system is characterised by semi-diurnal tides (with amplitudes of 2-4 m). In general, significant wave heights range from 2 m to 3m and storm significant wave heights are greater than 8 m (once per year). Finally, the wave directions are dominated by W and NW, with some events from SW (Pires *et al.* 2009a, 2013) and with typical values  between 20-30 cm/s and sometimes exceeding the 40 cm/s of current velocities in the winter (I.H. 1990, 2005). From a rocky coast ([Pt1] area) to a sandy coast ([Pt3] and [Pt4] areas) Portugal displays also a mixed environment with a rocky coast with boulders and mega boulders, sandy beaches and maritime structures ([Pt2] area).




**WANA 1043071 site (between 1995 - 2012)**

| Month | *Hs* (m) | *T* (s) | Direction (º) | Year |
|---|---|---|---|---|
| January | 11,6 | 18,0 | 264 | 2002 |
| February | 9,0 | 18,0 | 242 | 2002 |
| March | 7,6 | 18,0 | 288 | 2003 |
| April | 7,0 | 18,0 | 277 | 2000 |
| May | 6,6 | 16,4 | 282 | 2002 |
| June | 5,5 | 10,2 | 214 | 1997 |
| July | 3,5 | 11,2 | 260 | 2003 |
| August | 4,2 | 9,2 | 224 | 2000 |
| September | 6,7 | 18,0 | 305 | 2000 |
| October | 10,3 | 18,0 | 294 | 2003 |
| November | 10,4 | 18,0 | 283 | 2002 |
| December | 9,0 | 18,0 | 248 | 2000 |

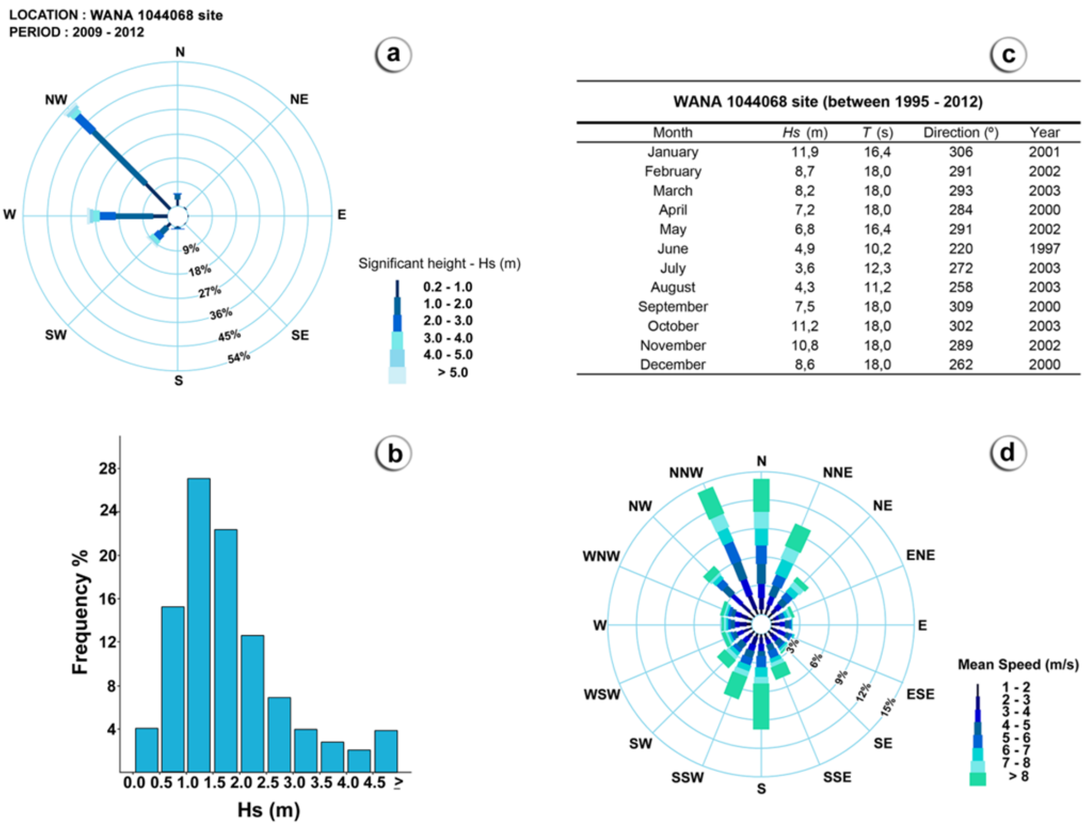
**Figure 23.** WANA 1043071 buoy: a) mean significant wave height (Hs); b) significant wave height frequency (%); c) significant wave height (Hs), peak period (T) and direction (º); d) wind mean speed and direction (Puertos del Estado 2012).




WANA 1043070 site (between 1995 - 2012)

| Month | *Hs* (m) | *T* (s) | Direction (º) | Year |
|---|---|---|---|---|
| January | 11,9 | 18,0 | 267 | 2002 |
| February | 9,1 | 18,0 | 286 | 2002 |
| March | 8,2 | 18,0 | 291 | 2003 |
| April | 7,4 | 18,0 | 281 | 2000 |
| May | 7,0 | 16,4 | 286 | 2002 |
| June | 5,4 | 10,2 | 215 | 1997 |
| July | 3,7 | 12,3 | 266 | 2003 |
| August | 4,3 | 11,2 | 248 | 2003 |
| September | 7,6 | 18,0 | 308 | 2000 |
| October | 11,5 | 18,0 | 299 | 2003 |
| November | 11,1 | 18,0 | 287 | 2002 |
| December | 9,3 | 18,0 | 251 | 2000 |

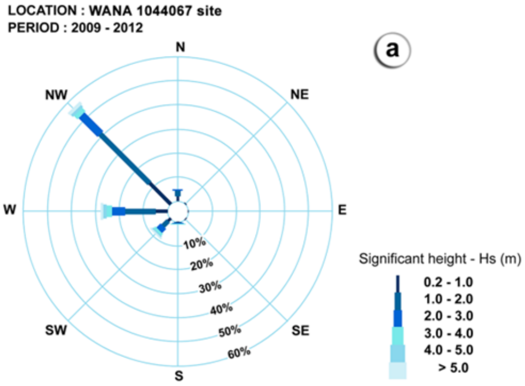
**Figure 24.** WANA 1043070 buoy: a) mean significant wave height (Hs); b) significant wave height frequency (%); c) significant wave height (Hs), peak period (T) and direction (º); d) wind mean speed and direction (Puertos del Estado 2012).




WANA 1044068 site (between 1995 - 2012)

| Month | *Hs* (m) | *T* (s) | Direction (º) | Year |
|---|---|---|---|---|
| January | 11,9 | 16,4 | 306 | 2001 |
| February | 8,7 | 18,0 | 291 | 2002 |
| March | 8,2 | 18,0 | 293 | 2003 |
| April | 7,2 | 18,0 | 284 | 2000 |
| May | 6,8 | 16,4 | 291 | 2002 |
| June | 4,9 | 10,2 | 220 | 1997 |
| July | 3,6 | 12,3 | 272 | 2003 |
| August | 4,3 | 11,2 | 258 | 2003 |
| September | 7,5 | 18,0 | 309 | 2000 |
| October | 11,2 | 18,0 | 302 | 2003 |
| November | 10,8 | 18,0 | 289 | 2002 |
| December | 8,6 | 18,0 | 262 | 2000 |

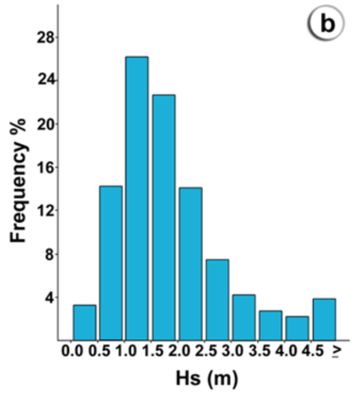
**Figure 25.** WANA 1044068 buoy: a) mean significant wave height (Hs); b) significant wave height frequency (%); c) significant wave height (Hs), peak period (T) and direction (º); d) wind mean speed and direction (Puertos del Estado 2012).




c

**WANA 1044067 site (between 1995 - 2012)**

| Month | *Hs* (m) | *T* (s) | Direction (º) | Year |
|---|---|---|---|---|
| January | 12,2 | 16,4 | 307 | 2001 |
| February | 8,7 | 18,0 | 293 | 2002 |
| March | 8,3 | 18,0 | 293 | 2003 |
| April | 7,2 | 18,0 | 285 | 2000 |
| May | 6,8 | 16,4 | 293 | 2002 |
| June | 4,7 | 10,2 | 220 | 1997 |
| July | 3,7 | 12,3 | 275 | 2003 |
| August | 4,3 | 11,2 | 262 | 2003 |
| September | 7,7 | 18,0 | 311 | 2000 |
| October | 11,5 | 18,0 | 304 | 2003 |
| November | 10,8 | 18,0 | 291 | 2002 |
| December | 8,7 | 13,5 | 286 | 2000 |



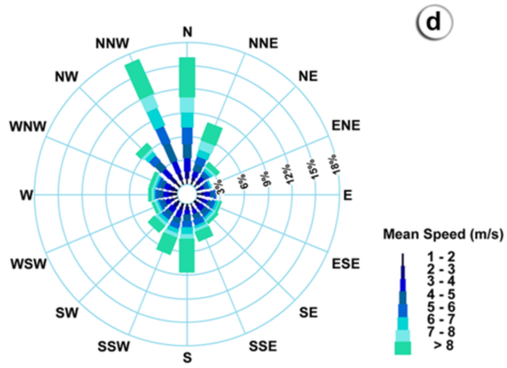
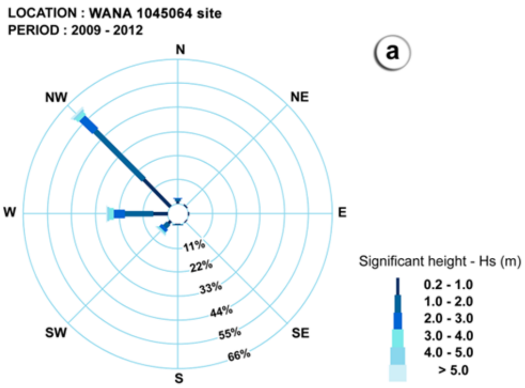



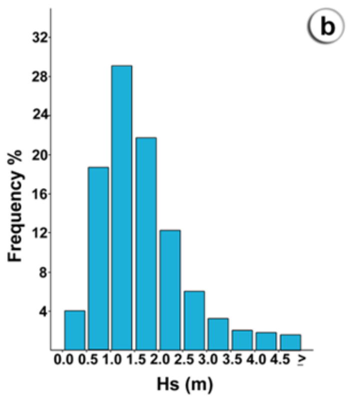

**Figure 26.** WANA 1044067 buoy: a) mean significant wave height (Hs); b) significant wave height frequency (%); c) significant wave height (Hs), peak period (T) and direction (º); d) wind mean speed and direction (Puertos del Estado 2012).




c

**WANA 1045064 site (between 1995 - 2012)**

| Month | *Hs* (m) | *T* (s) | Direction (º) | Year |
|---|---|---|---|---|
| January | 10,6 | 14,9 | 305 | 2001 |
| February | 7,8 | 18,0 | 296 | 2002 |
| March | 7,8 | 18,0 | 294 | 2003 |
| April | 6,5 | 18,0 | 290 | 2000 |
| May | 6,2 | 16,4 | 296 | 2002 |
| June | 4,1 | 13,5 | 273 | 2003 |
| July | 3,5 | 8,3 | 332 | 2011 |
| August | 4,1 | 11,2 | 273 | 2003 |
| September | 6,8 | 18,0 | 311 | 2000 |
| October | 10,5 | 18,0 | 304 | 2003 |
| November | 9,8 | 18,0 | 294 | 2002 |
| December | 8,7 | 13,5 | 287 | 2000 |



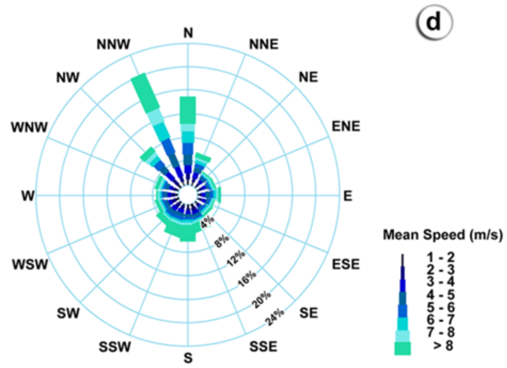
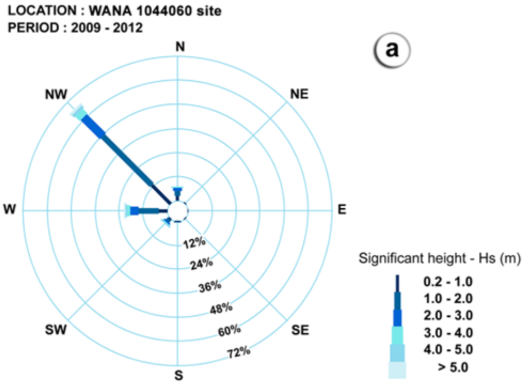
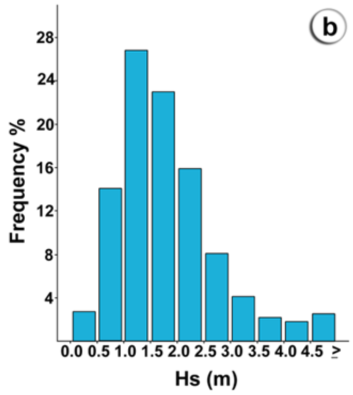




**Figure 27.** WANA 1045064 buoy: a) mean significant wave height (Hs); b) significant wave height frequency (%); c) significant wave height (Hs), peak period (T) and direction (º); d) wind mean speed and direction (Puertos del Estado 2012).




c

| WANA 1044060 site (between 1995 - 2012) | | | | |
|---|---|---|---|---|
| Month | *Hs* (m) | *T* (s) | Direction (º) | Year |
| January | 10,3 | 16,4 | 320 | 2001 |
| February | 8,2 | 16,1 | 293 | 2011 |
| March | 7,9 | 18,0 | 298 | 2003 |
| April | 8,3 | 14,9 | 315 | 2000 |
| May | 6,3 | 16,4 | 302 | 2002 |
| June | 4,0 | 9,1 | 338 | 2010 |
| July | 3,8 | 8,6 | 340 | 2011 |
| August | 4,0 | 11,2 | 284 | 2003 |
| September | 7,4 | 18,0 | 317 | 2000 |
| October | 11,3 | 18,0 | 312 | 2003 |
| November | 10,6 | 18,0 | 313 | 2003 |
| December | 8,4 | 13,5 | 296 | 2000 |



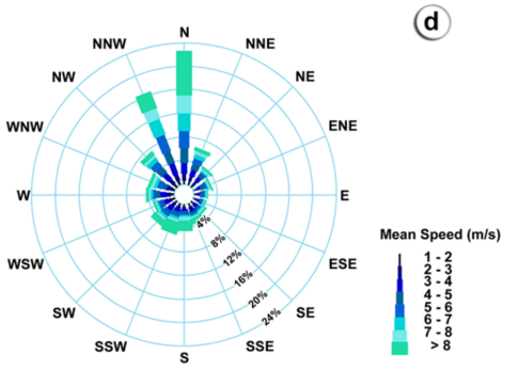




**Figure 28.** WANA 1044060 buoy: a) mean significant wave height (Hs); b) significant wave height frequency (%); c) significant wave height (Hs), peak period (T) and direction (º); d) wind mean speed and direction (Puertos del Estado 2012).

Through graphical display this section generally is intended to describe some of the hydraulic parameters of the studied areas and to include the influence of physical conditions such as currents and winds, which are important to characterise the region. All the described areas are included in *Part II* of the thesis regarding the results and the discussion section. In summary the relationship between the studied areas and the chapters (original research papers) is listed below:

- [G1] and [G2] areas: considered in Chapter 10 conclusions, still in progress;
- [G3] area: considered in Chapter 10;
- [G4] area: considered in Chapter 7, 8 and 9;
- [G5] area: considered in Chapter 7;
- [Pt1] area: considered in Chapter 8 conclusions, still in progress;
- [Pt2] area: considered in Chapter 8;
- [Pt3] area: considered in Chapters 4, 5, 6, 8 and 9;
- [Pt4] area: considered in Chapter 4 conclusions, still in progress.

These studied areas and specific sites have been studies using different approaches and methodologies, which will be described in the next chapter.

# CHAPTER 2 – MATERIALS AND METHODS

*Photo credits: A. Pires*

# 2. MATERIALS AND METHODS

## 2.1. Methodological approach

As mentioned before, the results and discussion sections consist of sets of research papers. Thus the investigation development is an important part of the thesis. Until the thesis is submitted to the examination board or even till the last manuscript is reviewed by the advisors, there is long path to approval (Figure 29). Jorge Gabriel Cham[5] illustrates very well in an ironic approach the framework of several graduate students (MSc), PhD students and/or post-PhD researchers (first published in 1997, *http://www.phdcomics.com/*). The selection of an attractive research project and become a researcher is a challenging decision. We have to try to keep the balance between our skills, pragmatism and creativeness. It is a demanding path, particularly if we decided to publish within the PhD term of the research. There will be a stage when the PhD crosses over the "*Matrix*" and goes beyond what it is possible to do, because it is almost like a "virus" in our system that only lets us survive until we reach the better solution of our scientific project.

**Figure 29.** ***"****The origin of theses":* how everything begins and how it is finished (PhD Comics 1997).

The published papers acting as part of a thesis have unavoidably to be submitted to scientific journals which are indexed with an impact factor. There are several indexing services and evaluation systems available (Figure 30).

[5]*Jorge Cham: creating PhD Comics [ http://www.ibiology.org/ibiomagazine/issue-2/jorge-cham-creating-phd-comics.html ]*

However, one of the most important main research platforms for Science and Technology fields is the *Thomson Reuters Web of Knowledge* or *Web of Science* (the so-called ISI index, Thomson Reuters 2013)[6]. The *Science Citation Index* (SCI) – and also the *SCI Expanded* – was an achievement that was in our mind thoughout this overall process because the choice of the journal and where to publish is very important. A good choice of journal can really make the difference in publishing or not. Abstracting and indexing is important, but we cannot be indifferent to the aims and scopes of each journal.

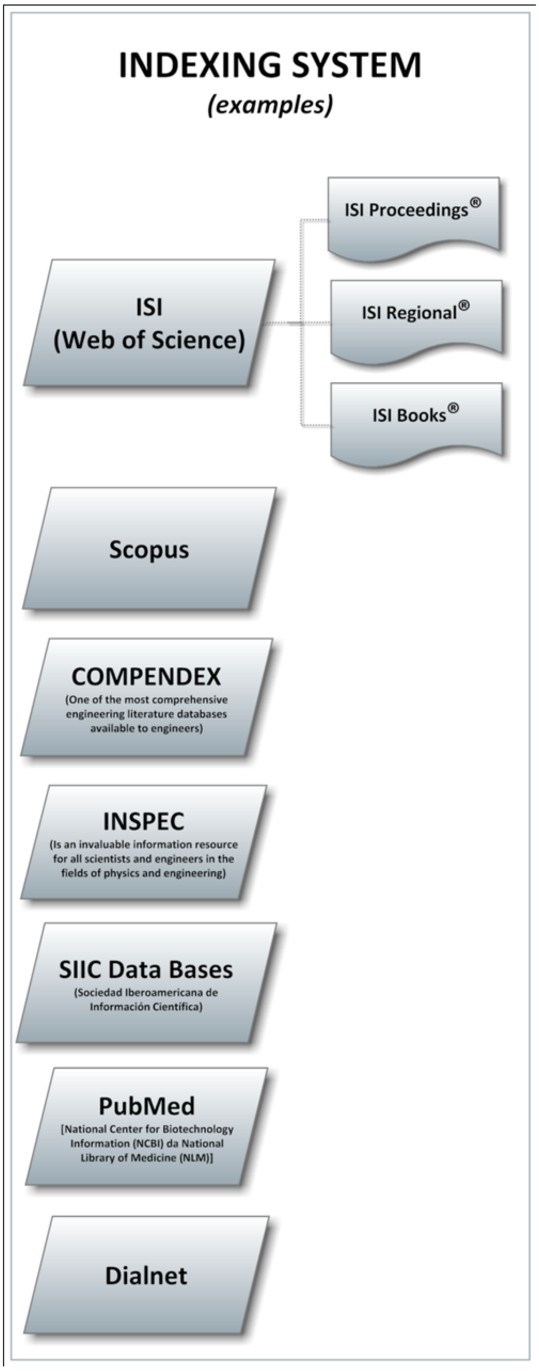



**Figure 30.** Indexing services and systems available: some international examples.

[6] *http://thomsonreuters.com/*

At the beginning of the current study we decided to publish the on-going research. Consequently the hierarchy and the publication pyramid approach presented in Figure 31 makes perfect sense: i) at the core level there is, commonly, a rigorous peer reviewer system (e.g., a typical hierarchical journal system: editor-in-chief, associate editors, advisory board, editorial board, and referees); ii) abstracts, proceedings, full papers conference, and book chapters are in the foundation of the pyramid; iii) the peak covers scientific articles (revision paper, original paper or technical note). A young researcher initiates, generally, the practice of scientific writing in abstracts and conference proceedings until achieving original journal papers or chapters of books (e.g., Smith 1998, Crawford *et al.* 2000, Feibelman 2011).

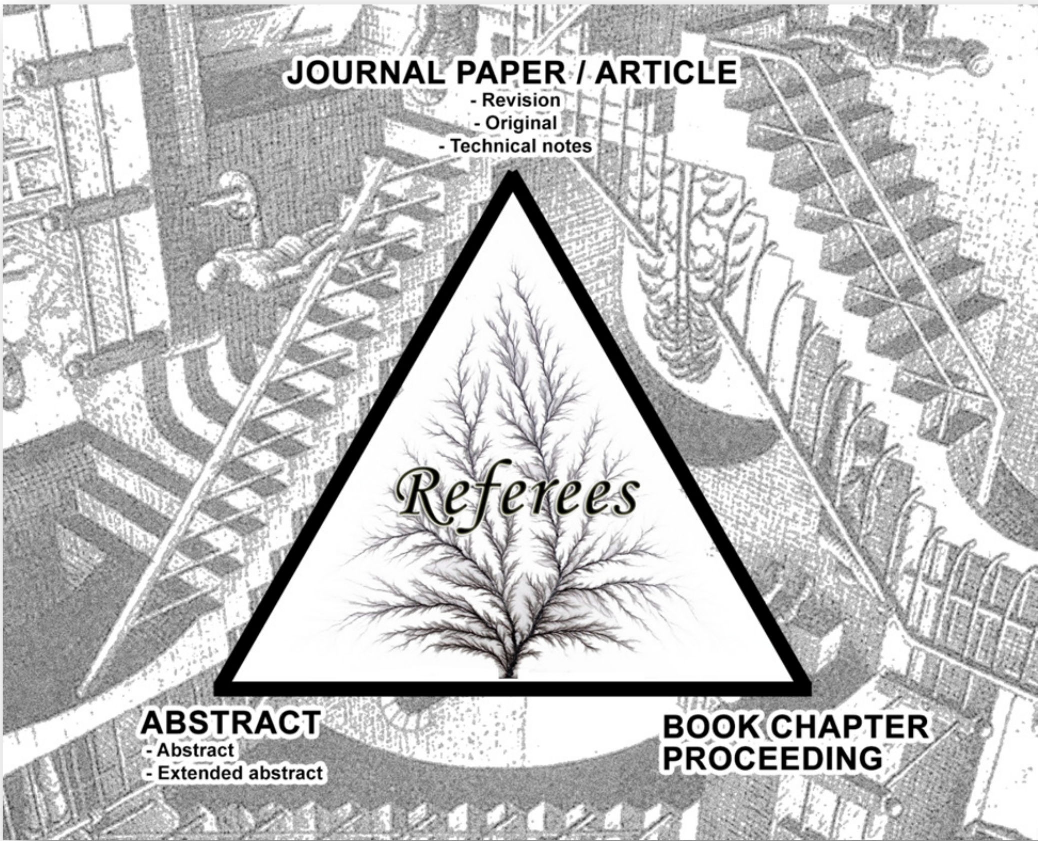



**Figure 31.** The publication pyramid and hierarchies: from the abstract to the proceedings, book chapters and journal papers.

The methodological approach is intrinsically related to the investigation and science work flow-line. By focusing on an academic career, it is expected for the candidate to develop a scientific program that comprises several goals, different methodologies and leads to find the solutions for scientific questions.

From the first steps of the researcher as an undergraduate student, we will tailor gradually our future research skills as an expectation of post-doc researcher position achievement. Therefore the research methods are vital in any R&D program. The key issue to a successful research project lays in a recurrence cycle: the process of returning again and again to the research questions, methods, and data, which leads to new ideas, revisions and improvements (Bencze & Hodson 1999). As stated by Professor Emeritus George Springer (Stanford University): "*It is really important to do the right research as well as to do the research right. You need to do 'wow' research, research that is compelling, not just interesting".* That impressive quotation is also essential to enlighten the scope and objective of any topical research to improve the quality and lucidity of the overall research (Katzoff 1964). According to Feibelman (2011), another important issue is: "*It is important that your focus be on problems and not on techniques or specialised tools. The latter come and go and as a researcher you want to be able to shift your approaches as needed to solve the more fundamental problems*".

It is easy to think of research as a gradual or mechanical process. Nevertheless we have to be open-mind to change and address such research to both academia and industry. As Smith (1998) reported: "*Interdisciplinary research is no substitute for good disciplinary training during the greater part of a graduate career. It is advisable, however, to seek exposure to interdisciplinary activities in graduate as well as postdoctoral training since most researchers engage in interdisciplinary research during their professional careers*".

In conclusion, there is not a single formula for developing a successful research study, but it is important to understand that the research process is cyclical and continuous, as well as a permanent interactive process. Nagaoka *et al.* (2010) argue there is a significant part of the research project motivated by the "pursuit of fundamental principles or understandings" but also by "solving specific issues in real life".

Based on this assumption the knowledge creation process in science is really an important step in experimental research. All processes start with assertive observations, descriptions, followed by raising questions, measurements and recording all the data (Davis 1973). Then we analyse, deduce, understand, delineate and discuss the findings and the results (Barnes 1995, Saaty 2008, Smith *et al.* 2011). Finally, we communicate the main conclusions or display in tables and map the analysis, interpretation and evaluation made: *observe, analyse, discuss and communicate*.

These approaches were the core and the starting point for the research development essentially because we needed to publish and to communicate our results to the scientific community. If we think in general approaches and methods to use in research we can have the following four types of development models (Figure 32).

From the basic modelling (fieldwork and desk studies), conceptual ground modelling (geologic and/or geomorphological models with engineering parameters), numerical modelling (based on mathematical modelling, i.e., probabilistic, deterministic or stochastic approaches) to the experimental modelling, the research methods along the investigation development are shaped (e.g., Griffiths & Stokes 2008, Keaton 2013a, Chaminé *et al.* 2013a,b and references therein). All the models must be robust, calibrated and supported on a permanent back-analysis scale based on a logical understanding of the real ground behaviour (Dinis da Gama 1983, Chaminé *et al.* 2013a,b).

The modelling types are displayed as a cyclical process of four types of models (Davis 1973, Barnes 1995, Saaty 2008, Smith *et al.* 2011). Ultimately, when developing a research thesis project the good approach is "*swimming*" alongside the whole modelling types. It is important to reach the experimental modelling and then return to the field to verify the assumptions and corroborate the results.

*And then… it starts all over again…*

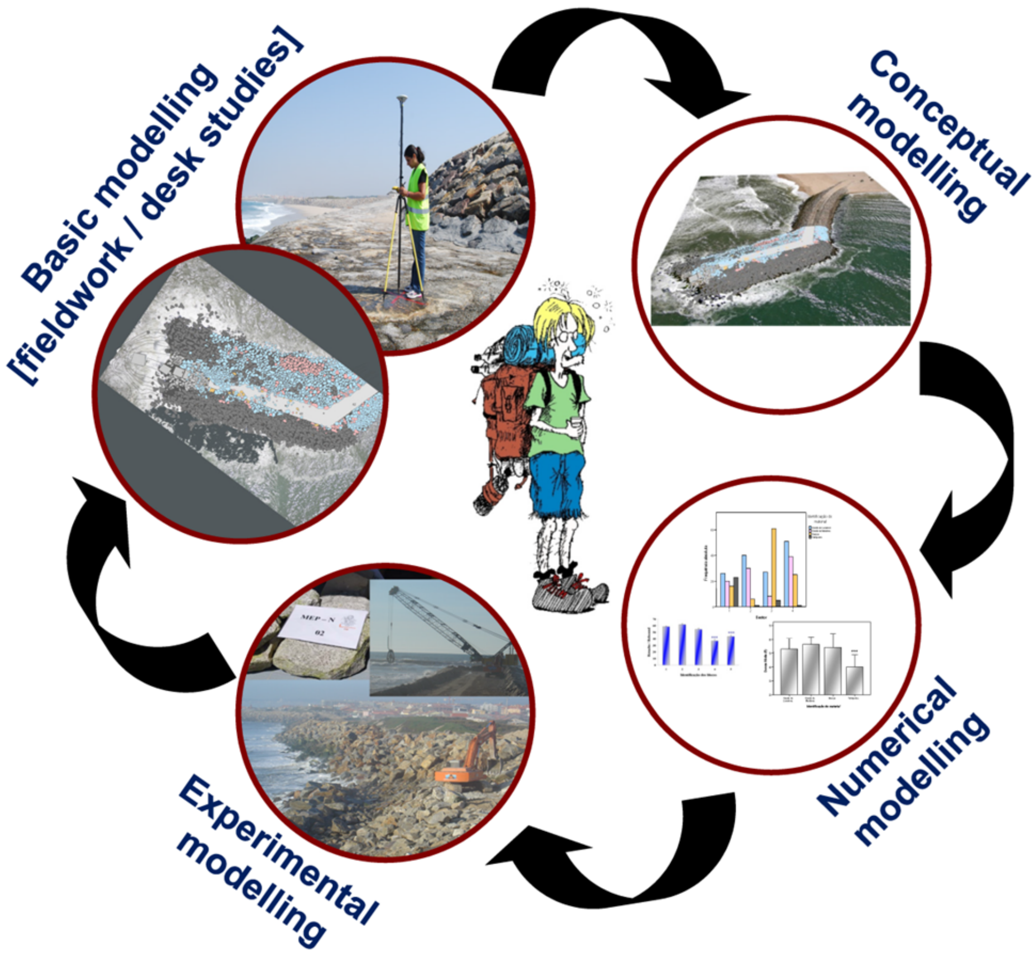



**Figure 32.** Research methods and modelling types along the investigation process and development.

### *2.1.1. Equipment, software and tools*

The purpose of this section is to outline the software, equipment and tools used in fieldwork and desk studies. The basic equipment for fieldwork is the following: geologist hammer, compass, digital camera and fiberglass tape measure (Figure 33). However, the use of netbooks or notebooks, tablets and iPADs is also increasing in geosciences fieldwork, and therefore they were included in the list of basic tools (Clegg *et al.* 2006, Donatis & Bruciatelli 2006, Knoop & Pluijm 2006, Brown & Sprinkel 2007, Donatis *et al.* 2008, Wooster Geologists 2009). Figures 34a to 34d show different aspects of using the tablet during the thesis fieldwork. The portable multiparametric tester kit is normally used in hydrology field studies to measure the water parameters: pH, temperature and electrical conductivity (e.g. Assaad *et al.* 2004, Moore 2011). However this equipment was simply used to measure the pH/temperature of sea water and water in pot-holes in shore environments (Figure 34e and 34f).


**Figure 33.** Basic equipment applied in the fieldwork.

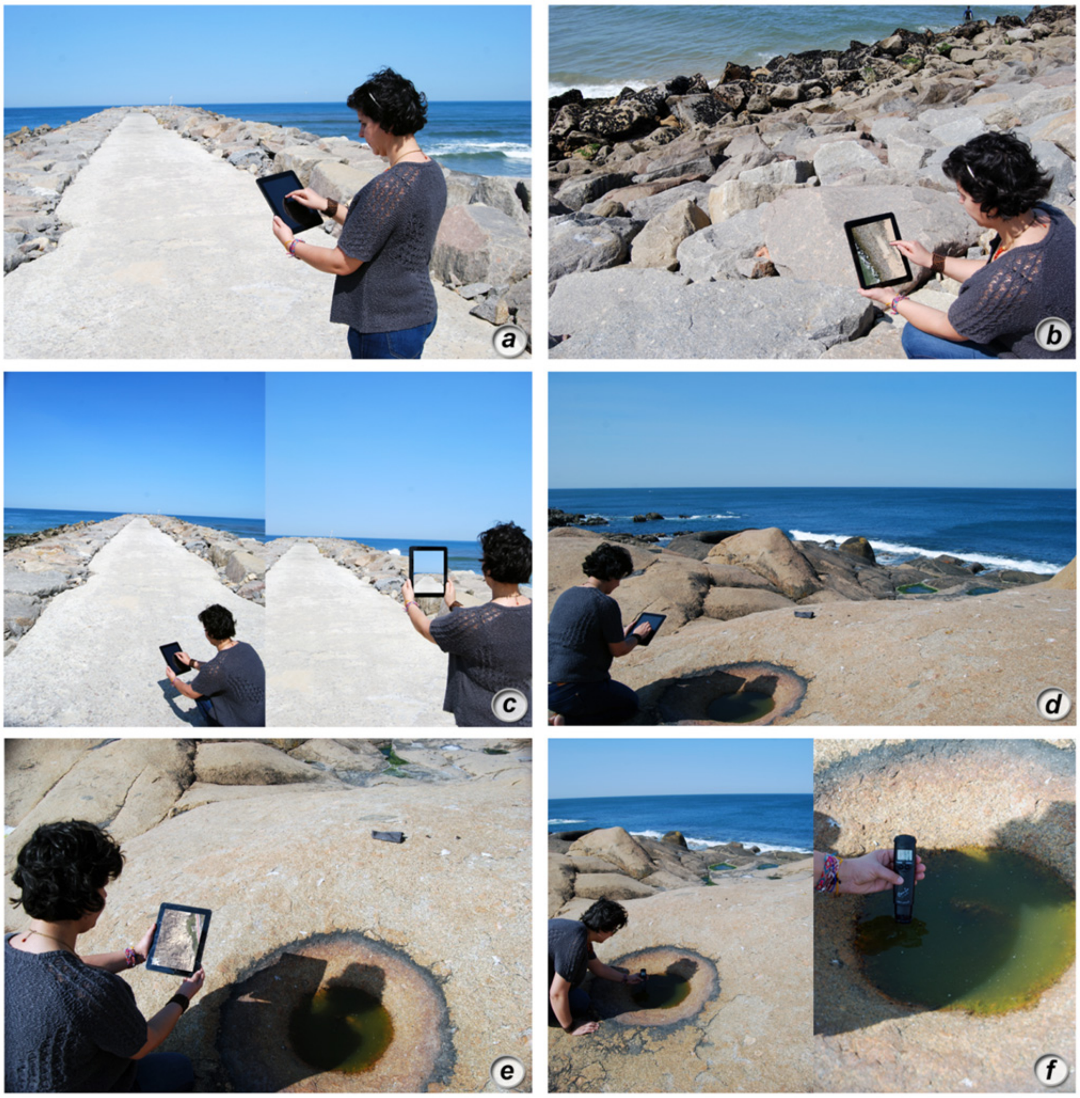


**Figure 34.** Using the tablet in coastal geoengineering fieldwork (a – e) and measuring the pH/temperature of water in pot-holes in rocky coasts with the portable multiparametric tester kit (f).

The next set of figures (Figures 35 to 42) will display the handling of tools and equipment, as well as a brief description of the applicability. The software presented herein has been purchased and licensed by LABCARGA|ISEP – Laboratory of Cartography and Applied Geology, as well as all the equipment and tools used during the research term.

***Strater – Golden Software®***

*Strater* is a stratigraphic well log, borehole and cross section plotting software for geoscientists (Strater 2004, Golden Software 2013). The package allows users to create high-quality professional representations of subsurface data with different designs and layouts available. The improved user interface enhances the data visualisation and creates professional reports (Figure 35). At the beginning of the research (Pires & Chaminé 2007) *Strater* was used to organise and systematise all the data and information collected in the material characterisation process (e.g. lithology, weathering grade, uniaxial compressive strength).

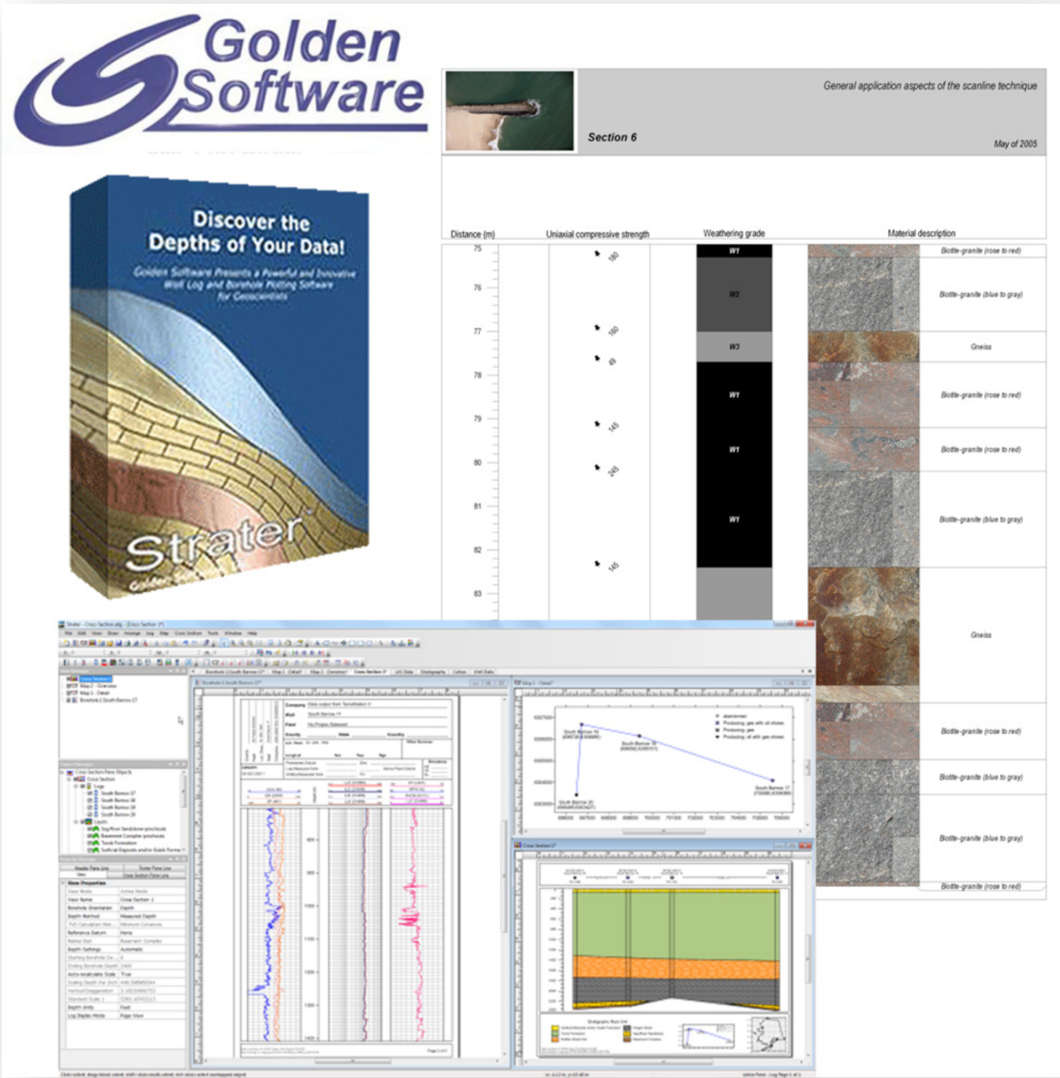



**Figure 35.** User interface software package of *Strater* and the report of coastal application in groynes.

***Dips – Rocscience®***

*Dips* is essentially a stereonet analysis program used in the interactive analysis of orientation-based geological data (Rocscience 2013). As shown in Figure 36, the program is skilled with many applications in the analysis of structural geology data. *Dips* is also related to the structural analysis of fabric structures and rock engineering analysis. The package allows the study of any orientation-based data. According to Rocscience (2013) the software is designed for the analysis of different features (e.g. kinematic analysis toolkit for planar, wedge, toppling analysis; graphical interactivity; dip vector and intersection plotting; fuzzy cluster analysis).

*Dips* software (currently at version 6) is basically used in our project to process the orientation-based data analysis from the measured discontinuities in fractured rocky coasts.

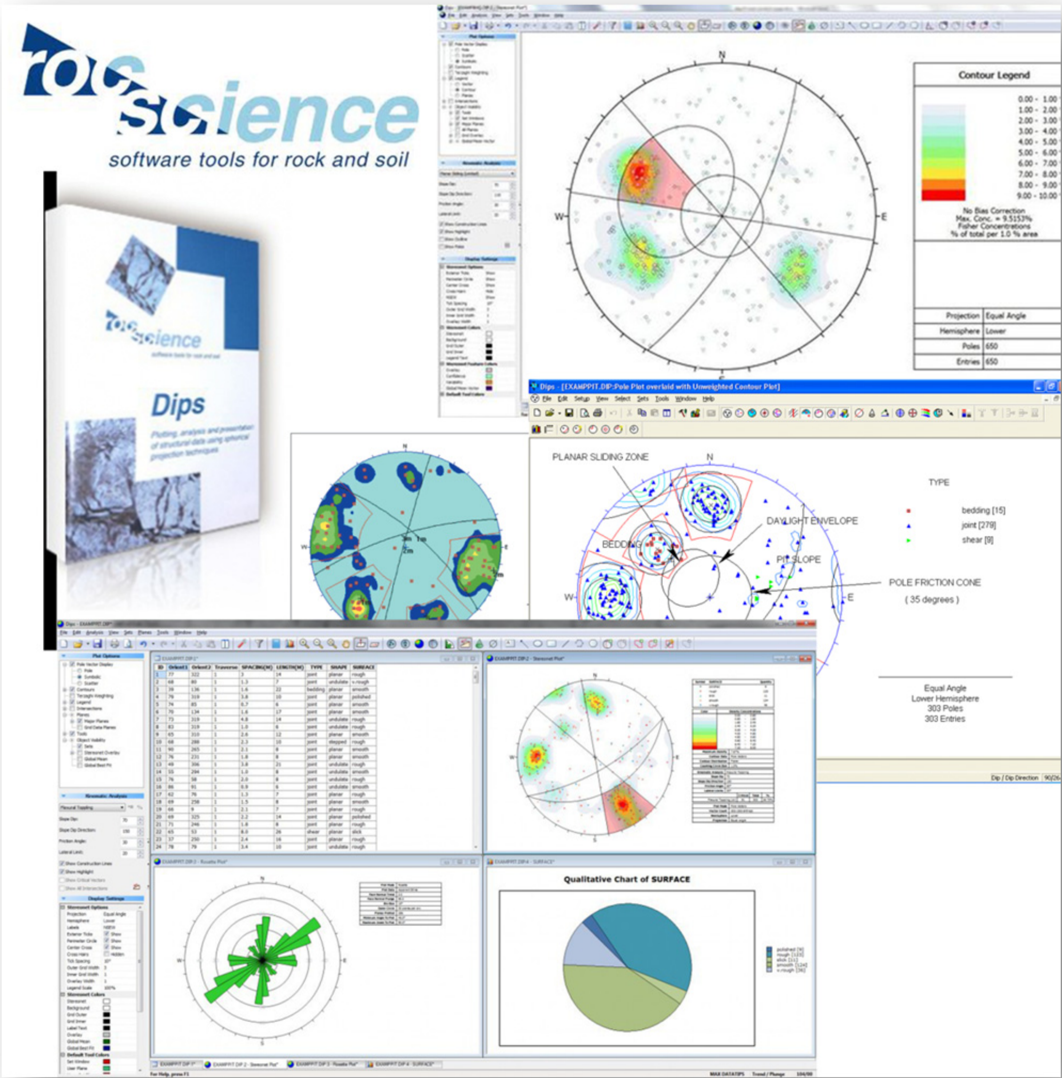



**Figure 36.** The software potential presented by Dips and its distinctive functions.

***<u>OCAD – The smart software for cartography</u>®***

*OCAD* is a CAD-based program for drawing maps of all types and related to digital cartography. This software is applied to geosciences broadly and it is also an important geoinformatics tool. The software is easy to handle and is prepared with a set of several symbols already implemented as well as specific cartographic drawing and editing tools (OCAD 2013). *OCAD* is more than a map drawing software. The program is very powerful for producing any kind of maps and has interesting package features. *OCAD* was used throughout the thesis and during the creative process of maps and cartography. Moreover it was also applied to vectorise and/or improve images or figures (Figure 37).

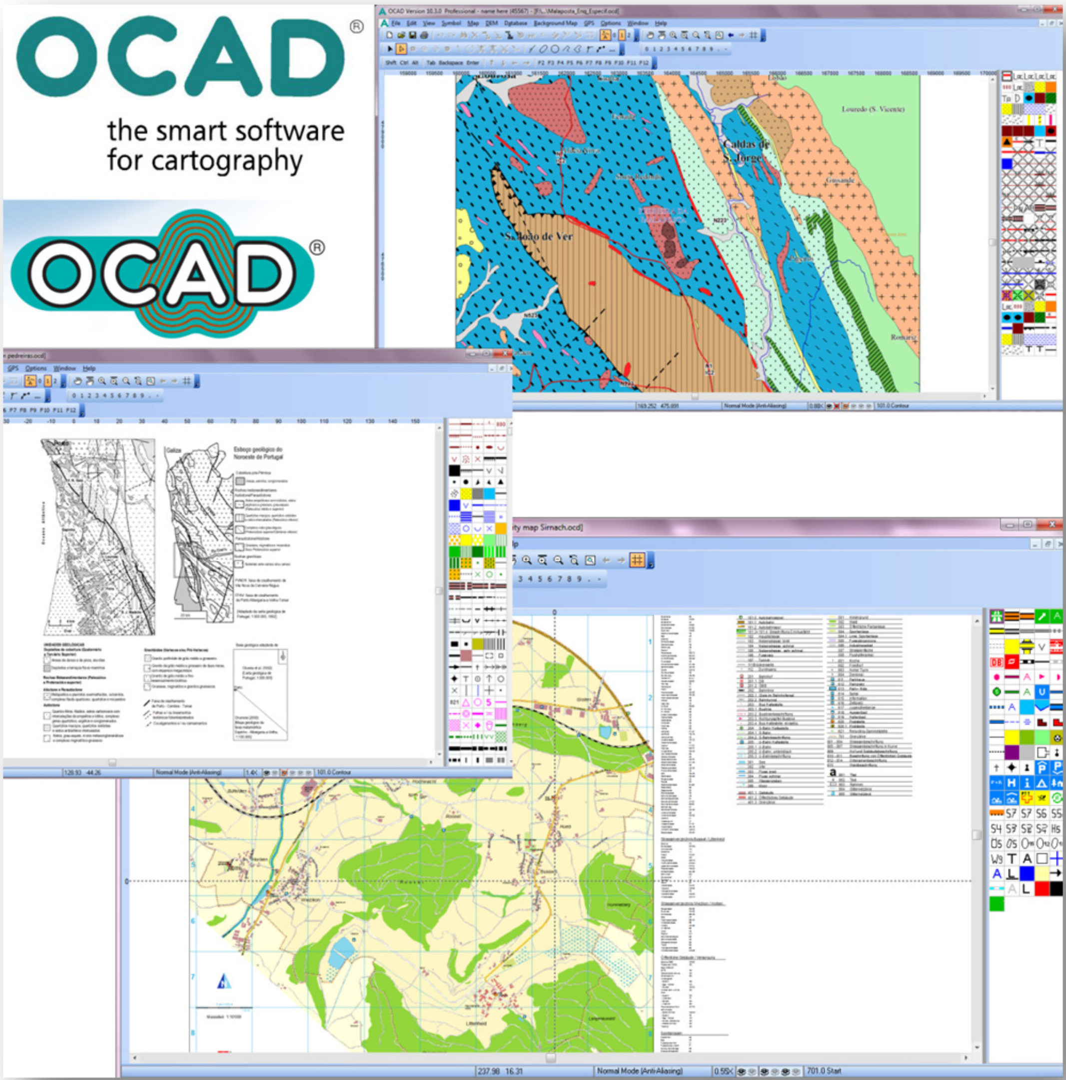



**Figure 37.** Different types of applications using the software and the *OCAD* user interface.

***<u>ArcGIS – Esri</u>®***

*Esri* (Environmental Systems Research Institute) is an American company specialised in producing solutions for the geographic information field. The initial mission of *Esri* was focused on organising and analysing geographic information to support planners and natural resource managers in environmental decision making at different levels. *Esri*'s mapping software integrates hardware, software, data and human capital with a geographic component. *Esri* invented the "shapefile" after using the "coverage" for many years. The GIS (geographic information systems) application of *ArcGIS* helps the user to understand and visualise data and to make decisions based on the best information and analysis (Esri 2013). It has the ability to create regional, local, detailed maps, qualify features, quantify features and display the temporal evolution, and many others (Figure 38).

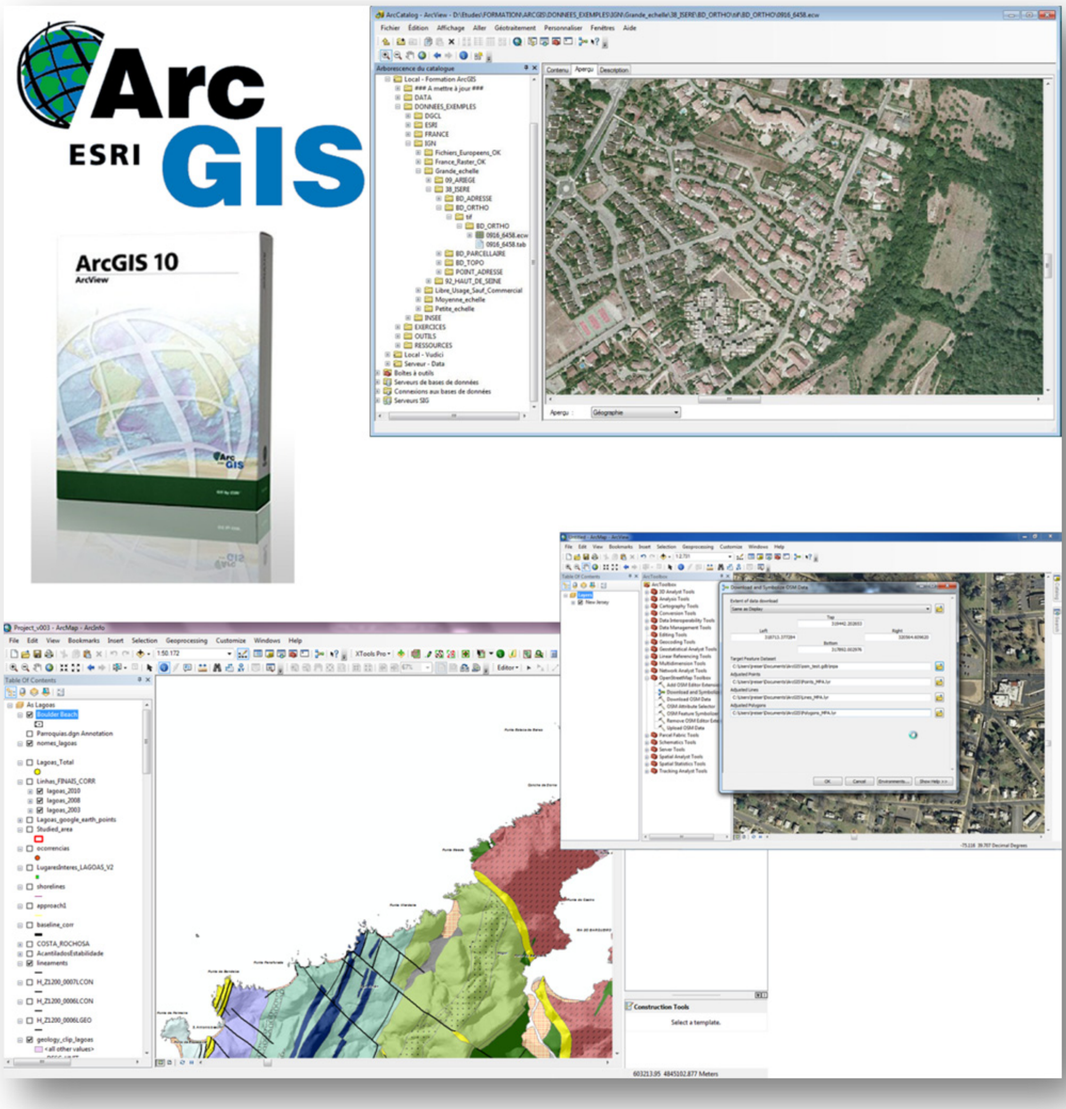



**Figure 38.** The software interface with a few examples of its plentiful applications and *ArcGIS* procedures.

This software package also allows you to use a number of extensions related to spatial analysis, 3D analysis or coastal dynamics (Burke *et al.* 2001, Thieler *et al.* 2005, Esri 2013). Currently the *ArcGIS* fields of actions are enormous and used individually or by several types of organisations (companies, schools, higher education, and research). *ArcGIS* can be utilised in several main areas, such as planning and analysis; asset or data management; operational awareness and field workforce (Esri 2013). *ARCGIS* was the main program used for the so-called GIS mapping creation, GIScience and geo-cartography development. However there are many open source software programs available for students and researchers such as GRASS GIS (GRASS GIS 1998), gvSIG (gvSIG 2011), Quantum GIS (Quantum GIS 2013) and many others.

***GPS GeoExplorer (GeoXH) – Trimble*®**

The use of GPS (Global Positioning System) and a high-accuracy GIS data collection system is crucial in spatial data acquisition. It provides specific services in several scientific areas like geosciences and geoengineering by supporting diverse research studies. When high levels of accuracy and minimal errors are needed, the solution may involve the use of high-accuracy GPS providing centimeter accuracy (about 30 cm to 40 cm). However, using differential correction this accuracy could achieve 10 cm to 15 cm, assuming optimal conditions of signal reception and data quality from the reference stations. But if the extra edge in accuracy is required, it is possible to collect data with *Trimble* TerraSync™ software (Trimble 2013).

The high-tech equipment *Trimble* (models GeoXH™ and GeoXT™, equipped with external antenna and software Pathfinder® Office) is ideal for the development of collaborative research and development (R&D) and specialised consultancy services (Figure 39). *Trimble* GPS proved to be a fundamental tool because the georeferencing process of maps is the base for good GIS cartography. Using this equipment it was possible to collect control points along the study area or site to improve this process. *Trimble* was also important to gather all the measured data in the fied and included in the GIS project (e.g. start and end points of studied profiles; maritime structures georeferencing; boulder and geoforms location; georeferencing of rocky platforms profiles and monitoring points). Some aspects of the *Trimble* GPS applications will be displayed later.


**Figure 39.** *Trimble* GPS model GeoXH™ incorporating the external antenna. Also displayed is the interface of the *Trimble* GPS Pathfinder® Office software, which is a powerful and accessible package of GNSS (Global Navigation Satellite System) postprocessing tools.

### ***Schmidt hammer – Proceq®***

*Proceq*'s Schmidt hammers are the most broadly used portable measuring instruments for a rapid assessment of the condition of a concrete structure. The hammer was originally developed in the late 1940s (Schmidt 1951) for non-destructive testing of concrete, and began to be used in the characterisation of rock materials from the 1960s (Poole & Farmer 1980, Goktan & Ayday 1993, Aydin & Basu 2005, Aydin 2009). It currently is extensively applied to evaluate the uniaxial compressive strength of the rock material. In general this evaluation is made on the basis of laboratory or field tests (e.g. ISRM 1978a, 1981, Poole & Farmer 1980, Goktan & Ayday 1993, Katz *et al.* 2000, Al-Harthi 2001, Kahraman 2001, ASTM 2001, Kahraman *et al.* 2002).

There are many types of equipment and models available (Figure 40) from original to digital hammers. Additionally, the equipment recommends a PC application available only for digital hammers. All the data and information can be downloaded via the powerful Hammerlink software® (Silver Schmidt) and via ProVista software® (Digi Schmidt, Figure 40).

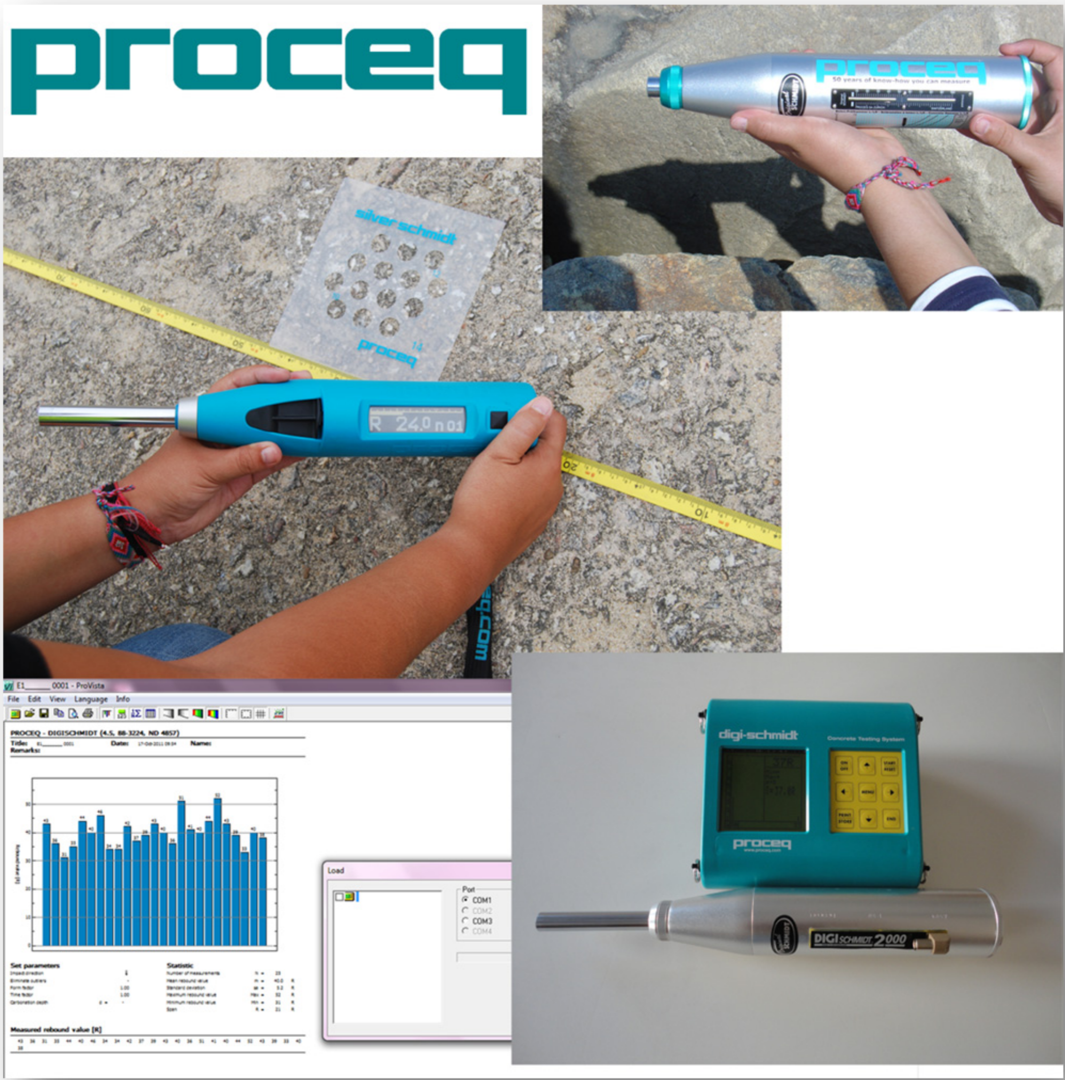



**Figure 40.** From top to bottom: Original Schmidt, Silver Schmidt and Digi Schmidt hammers. General overview of the ProVista software® allowing connections and data download from the Digi Schmidt hammer.

The *Proceq* hammers hit the concrete or the rock material at a defined energy whereas its rebound is dependent on the hardness of the material and is measured by the instrument (Proceq 2013a, 2013b, 2013c). Normally the Original Schmidt is available in models with different impact energies, and each test hammer is designed for a specific test application in order to meet the needs of the users to investigate a wide range of material types and sizes.

We used the type L/LR Original Schmidt, which operates with significantly lower impact energy, as well as the Silver Schmidt type ST L with a reduced impact energy. The Digi Schmidt type ND was used only for concrete armour units. According to different authors (ISRM 1978a,b, Amaral *et al.* 1999) the recommended type of hammer when testing rock material is type L; however, ASTM (2001) does not impose the type of hammer. In field tests, Aydin & Basu (2005) note that the right positioning of the hammer is to place it to be perpendicular to the tested surface, consequently minimising errors due to oblique impacts. There are many approaches proposed for the number of tests that are necessary for the geomechanical analysis (ISRM 1978a,b, ISRM 1981, ASTM 2001, ISRM 2007). According to these authors 10 hammer impacts (Rebound – R) are usually required and the 5 lowest values are eliminated. However other authors suggest a range of 25 to 30 samples to become statistically significant and valid (Good & Hardin 2006, Marques de Sá 2007). The values of rebound are then converted to strength values by the mean of a Miller diagram (Miller 1965, González de Vallejo & Ferrer 2011) (Figure 41). Table 7 displays the proposed classification in terms of uniaxial compressive strength according to different authors (Bieniawski 1973, ISRM 1981, BS 5930 1999).

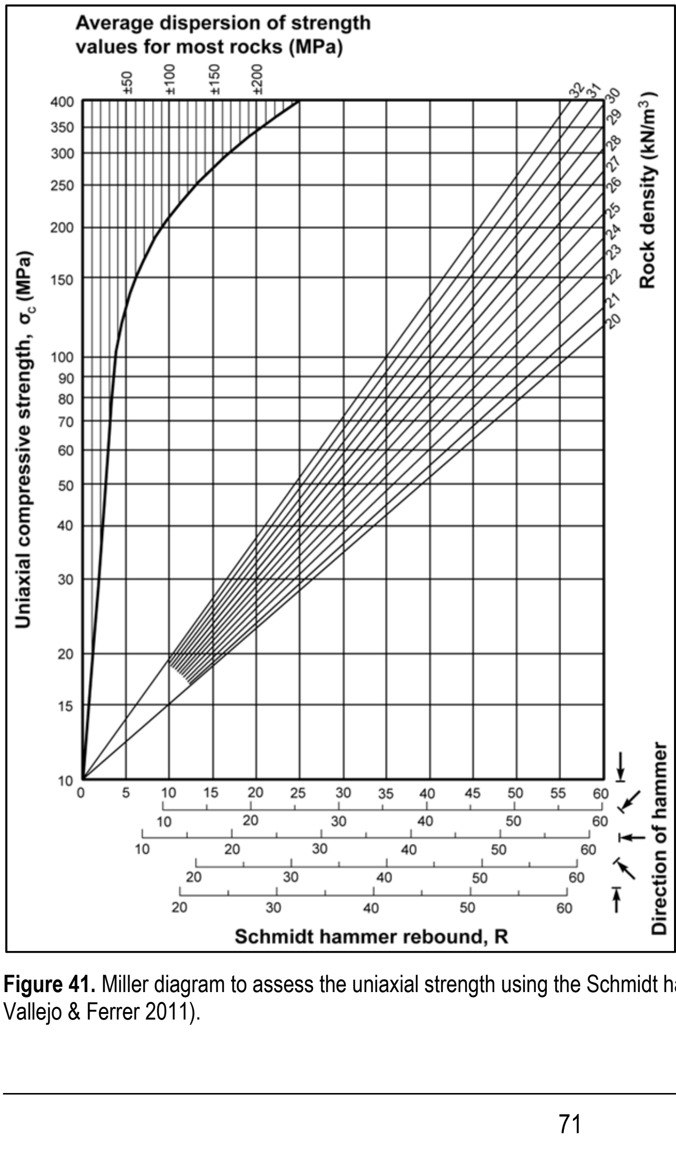



**Figure 41.** Miller diagram to assess the uniaxial strength using the Schmidt hammer (adapted from Miller 1965; *In*: González de Vallejo & Ferrer 2011).

**Table 7.** Rock classification by uniaxial compressive strength (UCS) (adapted from ISRM 1981, González de Vallejo & Ferrer 2011).

| Uniaxial compressive strength (MPa) | ISRM (1981) | BS 5930 (1999) | Bieniawski (1973) | Examples |
|---|---|---|---|---|
| < 1 | Soils | | | |
| < 1.25 | Very weak | Very weak | Very low | Salt, mudstone, silt, marl, tuff, coal |
| 1.25 - 5 | | Weak | | |
| 5 - 12.5 | Weak | Moderately weak | | |
| 12.5 - 25 | | Moderately strong | | |
| 25 - 50 | Moderately strong | | Low | Schist, shale |
| 50 - 100 | Strong | Strong | Medium | Schistose metamorphic rocks, marble, granite, gneiss, sandstone, porous limestone |
| 100 - 200 | Very strong | Very strong | High | Hard igneous and metamorphic rocks, highly cemented sandstone, limestone, dolomite |
| > 200 | | Extremely strong | Very high | Quartzite, gabbro, basalt |
| > 250 | Extremely strong | | | |

The fields of action are broader and therefore this type of equipment is also applied in different maritime environments like rocky coasts, coastal boulders and shore platforms (e.g. Goudie 2006, Viles *et al.* 2011).

***Equotip – Proceq®***

Equotip is another type of equipment from *Proceq* which was released in the 1970s (Proceq 1977). This is a versatile portable metal hardness tester which offers extended capabilities. The instrument is based on the principle of Leeb impact and the measure of hardness used in the Equotip method is the hardness value L, invented by *Proceq* (Proceq 1977, Verwaal & Mulder 1993, Hack 1993, Kompatscher 2004). The equipment allows data to be downloaded/uploaded from/to a PC using Equolink, the linking software for Proceq (Proceq 2013d) (Figure 42).


**Figure 42.** *Proceq*'s Equotip equipment general overview and the interface of Equolink, the linking software.

Throughout the years Equotip has also been applied in rock surfaces (e.g. Kawasaki *et al.* 2002, Kawasaki & Kaneko 2004, Aoki & Matsukura 2007, 2008). It is also worth emphasising that Equotip is increasingly being used in distinctive geomorphological contexts and using different approaches (e.g. Viles *et al.* 2011, Pérez-Alberti *et al.* 2013b). Appendix 3 points out the importance of Equotip in testing rock and concrete strength and is also effective not only in rock but also in concrete. The application note anticipates the role of durability on geomaterials for coastal geoengineering and geomorphology (Proceq 2012). Equotip is one of the most efficient types of equipment in different environments and methodological approaches but also in different types of materials and surfaces.

***GeoTech|CalcTools: ScanGeoData|BGD and SchmidtData|UCS***

GeoTech|CalcTools merges the ScanGeoData|BGD and SchmidtData|UCS geotechnical spreadsheet applications. This database is developed in MS. Excel® advanced features related tobasic rock mass description (Fonseca *et al.* 2010, Galiza *et al.* 2011, Pinheiro *et al.* 2014, and references therein). The main purpose is to organise and gather all the collected field data in a single geodatabase (GeoTech|CalcTools) comprising different parameters on the basic geotechnical rock mass description and geological characteristics (Figure 43).

The general database was used in this study to record and analyse all the information gather regarding the shore platforms assessment. It was also used on the orientation-based data collected in fractured rocky coasts.

The GeoTech|CalcTools application carried out a geological, geotechnical and geomechanical characterisation for discontinuities and rock mass features or properties including different elements, specifically:

i. *General description of the outcrop;*
ii. *Basic structural geology description;*
iii. *Weathering grade;*
iv. *Basic geotechnical description of discontinuities (ISRM 1981);*
v. *In situ geomechanical evaluation.*

The platform allowed us to control and analyse all type of measurements acquired, especially along the rocky coasts and shore platforms studied.

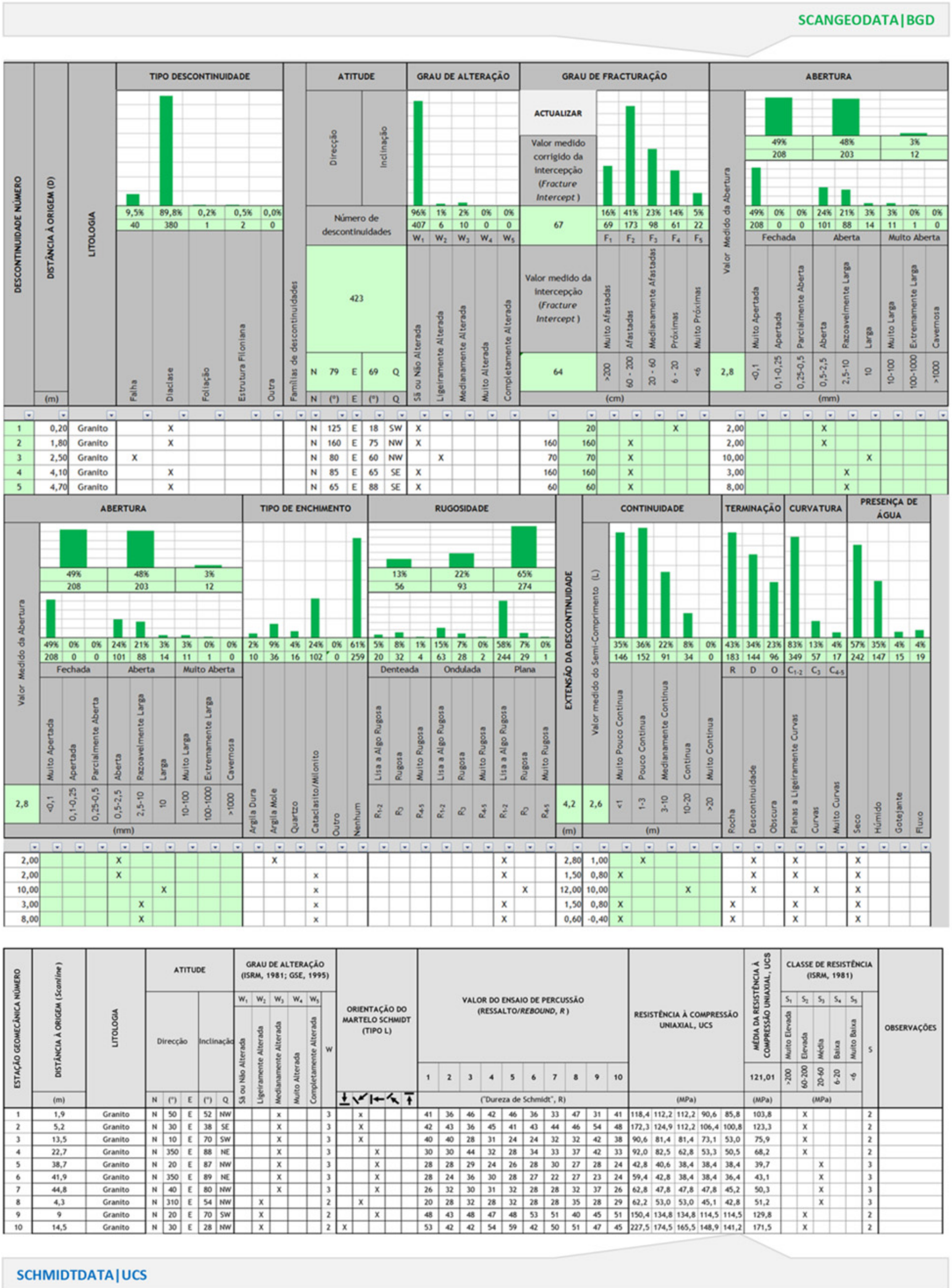



**Figure 43.** General overview of the database architecture: structure, studied parameters and characteristics, analysis and assessment (Fonseca *et al.* 2010, Galiza *et al.* 2011).

### *2.1.2. Synthesis of procedures used & Workflow*

In this section we present a brief retrospective of the research. This section is very important to establish the link between all the procedures used. There was a sequence of procedures and methodologies that persisted during the research period, almost like a common denominator. Unquestionably GIS mapping is intrinsic to this investigation, but there is an integrated system already tested on maritime environments. Figure 44 lists the main stages or procedures proposed for this research process.

The approach is a step forward to the study of different coastal environments by using almost the same methodologies. Consequently, it will allow the characterisation, monitoring and assessment of coastal protection works, rocky coasts, and shore platforms. It can even be utilised to propose or recommend strategies for coastal and shoreline management based on several justifications with social, economic and environmental issues or even a GIS-based planning support system reinforced by geo-cartographic decisions.

The development of the applied cartography embraces six stages, which will allow the production of detailed maps of the maritime environment (Figure 44):

A. *High-resolution aerial imagery surveys;*
B. *Visual inspection and systematic monitoring;*
C. *Applied field datasheet;*
D. *In situ evaluation;*
E. *Scanline survey;*
F. *GIS mapping.*

The research process is illustrated, in particular some aspects of the fieldwork are shown. A "portfolio" displaying a selection of selected images will be presented. Each set of images will show the work in interdisciplinary complex environments, application of geological cartography, and engineering geosciences methods in coastal systems contexts and areas.

Figures 45 to 65 will feature the research strategy from innovative technologies, namely mapping and surveying high-precision GPS systems, GIS software extensions and in situ geomechanical tests (in particularly, the Schmidt hammer non-destructive portable testing instrument or Equotip equipment), to the basic and classic methods of fieldwork.

In each paper (*Part II*) a specific and applied materials and methods section is given correspondent to each studied site. Herein the methologies will be synthesised and illustrated in general applications and examples of the studied areas and sites.

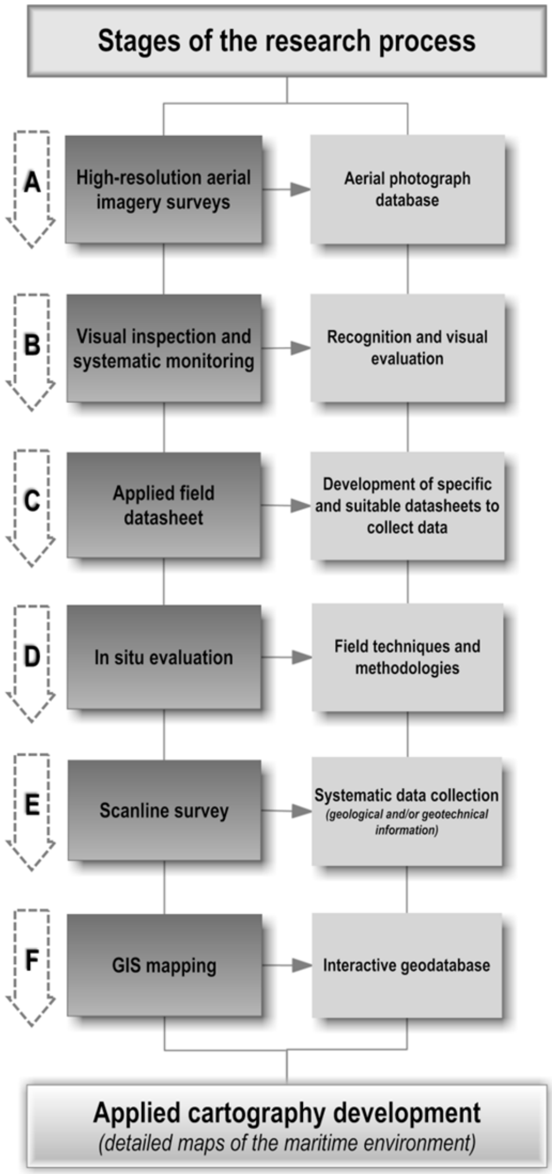



**Figure 44.** Flowchart with the main stages or procedures of the research process.

***<u>Stage A: High-resolution aerial imagery surveys</u>***

First of all the quality of the geospatial data and imagery acquisition is an important step in the research process. All the images are a fundamental part of the GIS platform/project in raster format. The investigation procedure takes advantage of high resolution imagery by means of an airborne platform and photogrammetric techniques coupled with applied cartography. These images were used to set up a georeferenced GIS database. The methodological integrative procedure was therefore a coupling between coastal geosciences GIS mapping and high-resolution digital imagery suitable for maritime environments evaluation in general (Pires *et al.* 2009c, Pires *et al.* 2014a).

The proposed system is composed of two fundamental subsystems that are supported by the same common navigation system, running on a rugged embedded PC: the flight guidance system and the image acquisition system (Figure 45). High-end digital single lens reflex (D-SLR) camera was used which enable high resolution images (at least 21 megapixels) at high frame speeds (several frames per second during continuous shooting). A trigger signal was fed to the embedded PC each time a picture was taken and a time tag was recorded.

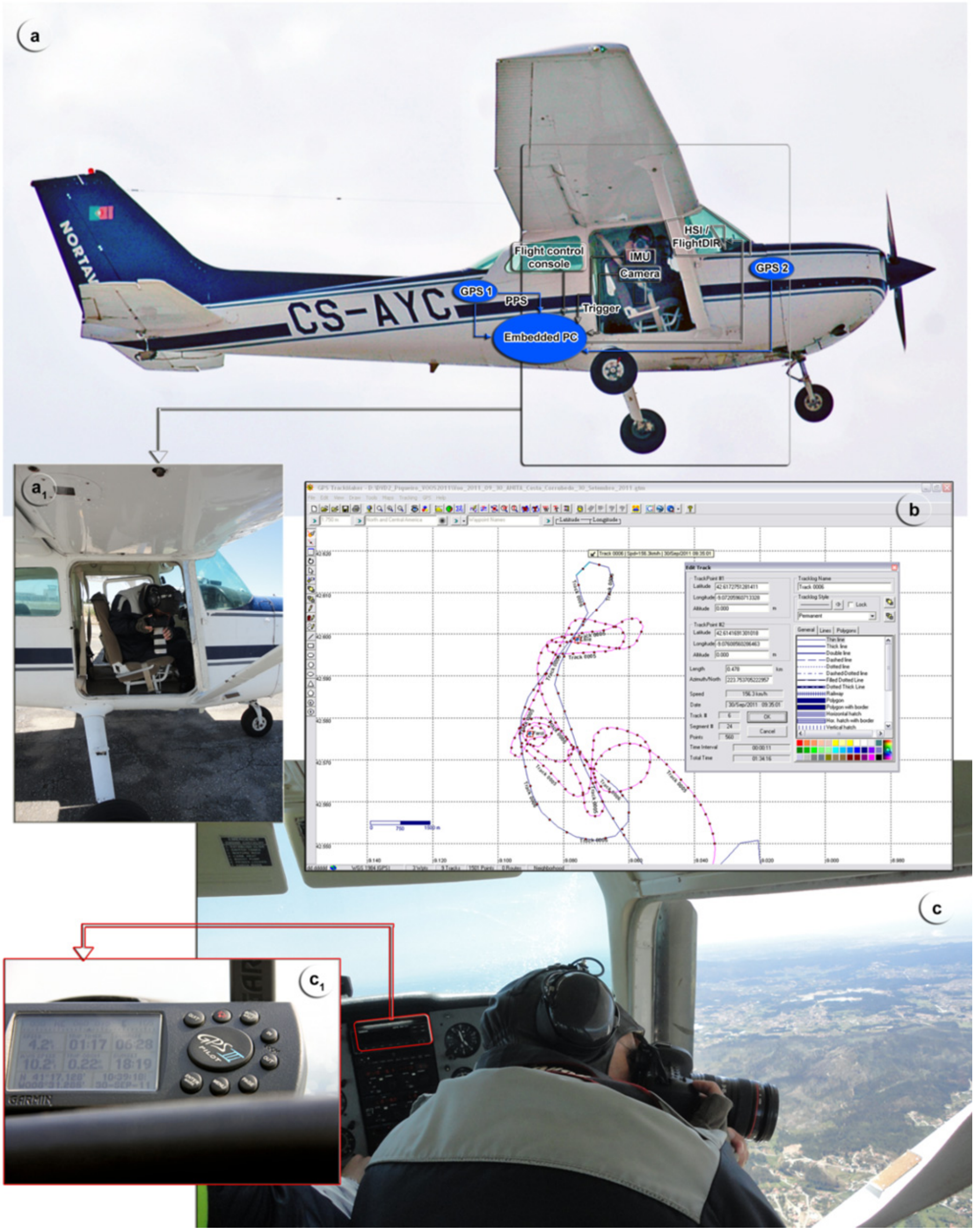



**Figure 45.** Main components involved in the image acquisition process: (a) system architecture description and ($a_1$) flight conditions; (b) GPS tracker software; (c) general photos of the flight and ($c_1$) the navigation panel and GPS image.

The IMU data related to the camera orientation was logged together with the time stamps relative to each measurement. Its main purpose was to compute the camera orientation, through integration of its acceleration and angle rate measurements with the GPS derived positions.

This system can be used on a small aircraft (in this case on a Cessna C172) without any physical or aerodynamic changes to the airframe, other than the simple removal of the right door. Equipment and flight costs are particularly relevant in this type of application (e.g., Teunissen 1995, Silva *et al.* 2001, Gonçalves & Piqueiro 2004, Cunha *et al.* 2006). Besides the equipment installed in the aircraft, a reference station was also established for each mission, enabling differential processing of the GPS receivers on board the aircraft relative to the ground station, thereby enhancing their precision (Figure 45) (for further details see Pires *et al.* 2009c, Pires *et al.* 2014a).

The image process acquisition is exemplified in Figure 46, showing the overall imaging experience and the different perspectives of the flight (from below and above).


**Figure 46.** Overall imaging experience: (a) perspective from below; (b) and (c) perspectives from above.

Finally the final outputs ant the results are displayed in Figure 47 with some examples of the high resolution imagery.


**Figure 47.** High resolution imagery final results and outputs (courtesy: FotoEngenho Lda and Prof. F. Piqueiro): (a), (b) and (c) images from Corrubedo, Aguiño and A Guarda respectively (NW Galicia); (d), (e) and (f) images from V. Praia de Âncora, Espinho and Figueira da Foz (Portugal) respectively.

Currently, the UAV (Unmanned Aerial Vehicle) technologies, commonly known as a drone, have evolved into an important tool for the acquisition of LiDAR images and data (Jordan 2015), as reflected in Chapter 9 which shows an example. Furthermore, UAV technologies and LiDAR data also have been applied throughout the research developed in Pires *et al.* 2015, for further details see Appendix 4.

***Stage B: Visual inspection and systematic monitoring***

Apart from high resolution imagery the inspection and monitoring of coastal environments is a simple and effective way to evaluate a given area or site. This can be accomplished by surveying the studied site (e.g. maritime structure, rocky coast, shore platform) or viewing it from a boat or an airplane. Aerial imagery and digital photogrammetric techniques are frequently used to compare images and detect changes during a specific time span. However this stage concerns visual inspections, which are always made above-water, and which allow us to observe different aspects of the maritime work components or specific zones along the site.

The most used and basic photographic method is the comparative photography set, which is a photographic survey technique. Photographs of the same view are repeated in each survey and the images compared to detect differences or even just to spot and control some features along the studied area (Santos *et al.* 2003, USACE 2003, CIRIA *et al.* 2007). As proposed and tested by Pires (2007), the main goals were to assess the structures' status/evolution and to get better information on the "in-situ" behaviour, thus leading to better projects of similar works in the future. Figures 48 and 49 show a set of pictures and some of the results of the inspection/monitoring made in this research on coastal protection structures.

This inspection technique enables the detection of changes in the maritime structure (Santos *et al.* 2003, Pires 2007), namely: (i) broken elements; (ii) changes in the placement of blocks or displaced blocks; (iii) breakage and cracking; (iv) concrete disintegration or corrosion; (v) symptoms of deterioration in the blocks; and (vi) deterioration of the armour layer and signs of potential problems (Figure 48).

This type of visual inspection is always complemented with photographs of the inspected structure according to a plan of view points and angles established for each structure. The field campaigns are carried out at low tide to have the maximum length of slope visible. Moreover all the inspections should occur in good weather and calm sea to be able to have the best conditions and safely move over the structures' components. Therefore it is important to understand the surroundings and be exposed to the coastal environment (Figure 49).


**Figure 48.** Visual observation of Espinho field groynes (NW Portugal): (a) displaced stones and differences along the armour layers component; (b) and (c) potential problems and breakage and cracking; (d) and (e) corrosion of the concrete material or symptoms of deterioration; (f) concrete material broken armour units.

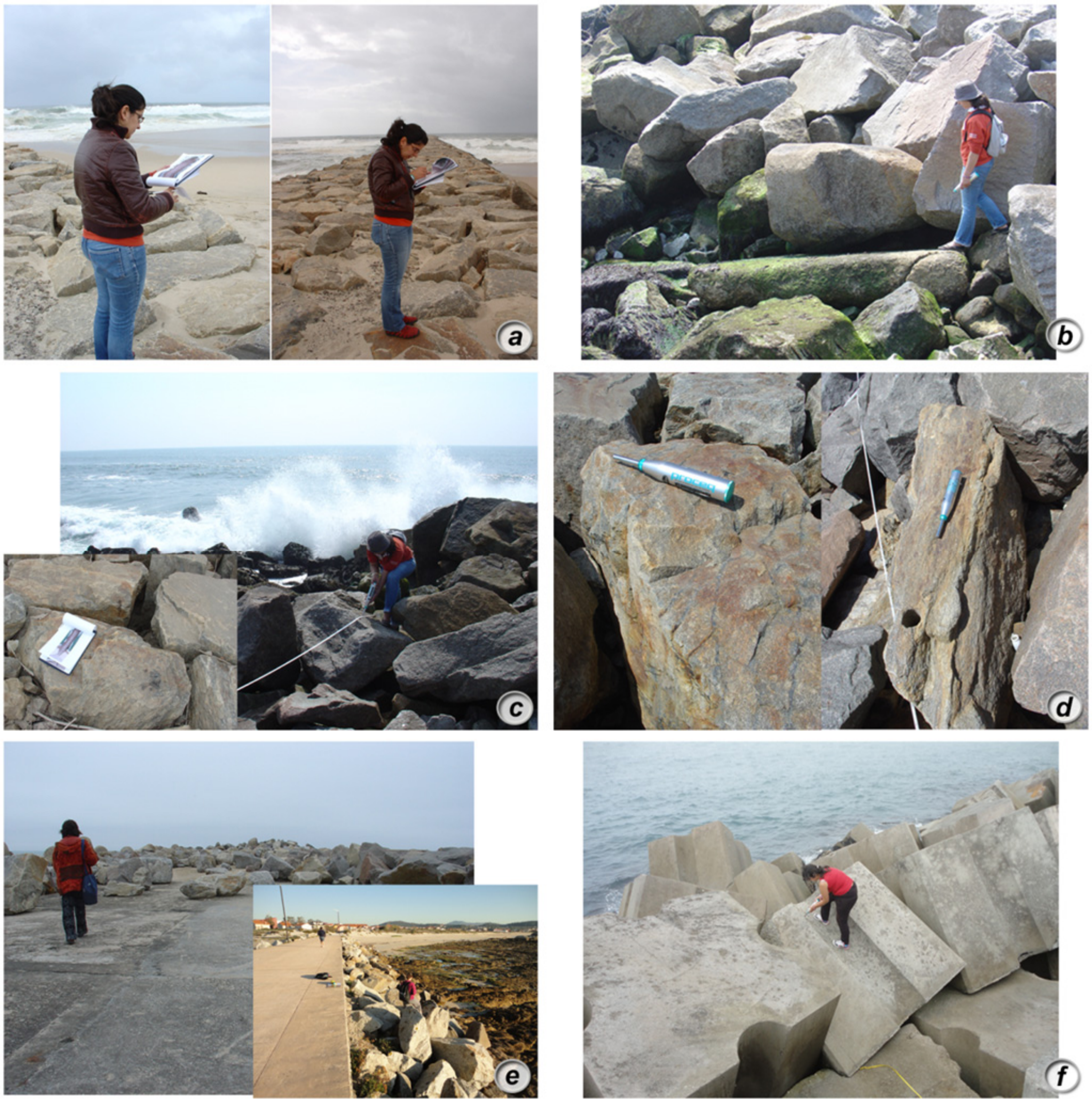


**Figure 49.** The overall monitoring along the maritime structures (Espinho, Vila Praia de Âncora): from the basic observation (a, b, e) to several applications of methods and tools to evaluate each sector (c, d, f).

This type of approach can also be applied to other maritime environments such as rocky coasts, shore platforms or boulders beach. It was possible to evaluate the studied area in terms of mobility and boulder stability analysis. The movement of boulders was determined and each one of the clasts was identified by accomplishing this systematic inspection and survey of the area (Figure 50).

**Figure 50.** Boulder monitoring and systematic observation to trace the movement and displacement of blocks with markers (Laxe Brava, NW Galicia, Spain); visual inspection applied to rocky coasts and boulders beach.

USACE (2003) proposes that a monitoring plan should provide and include enough flexibility in scheduling to accommodate the irregularity of severe storms. Hence, carrying out walking inspections after major storm events will allow the assessment of maritime structures exposed to damage. Figure 51 shows the case of the severe weather in February 2011. The storm occurred in the entire northwest coastal area of Portugal, from Porto to Aveiro. The Furadouro and Cortegaça sites are some of the examples of how the damage took place, as well as the quick repair/reinforcement actions or emergency interventions along the coast (Figure 51).

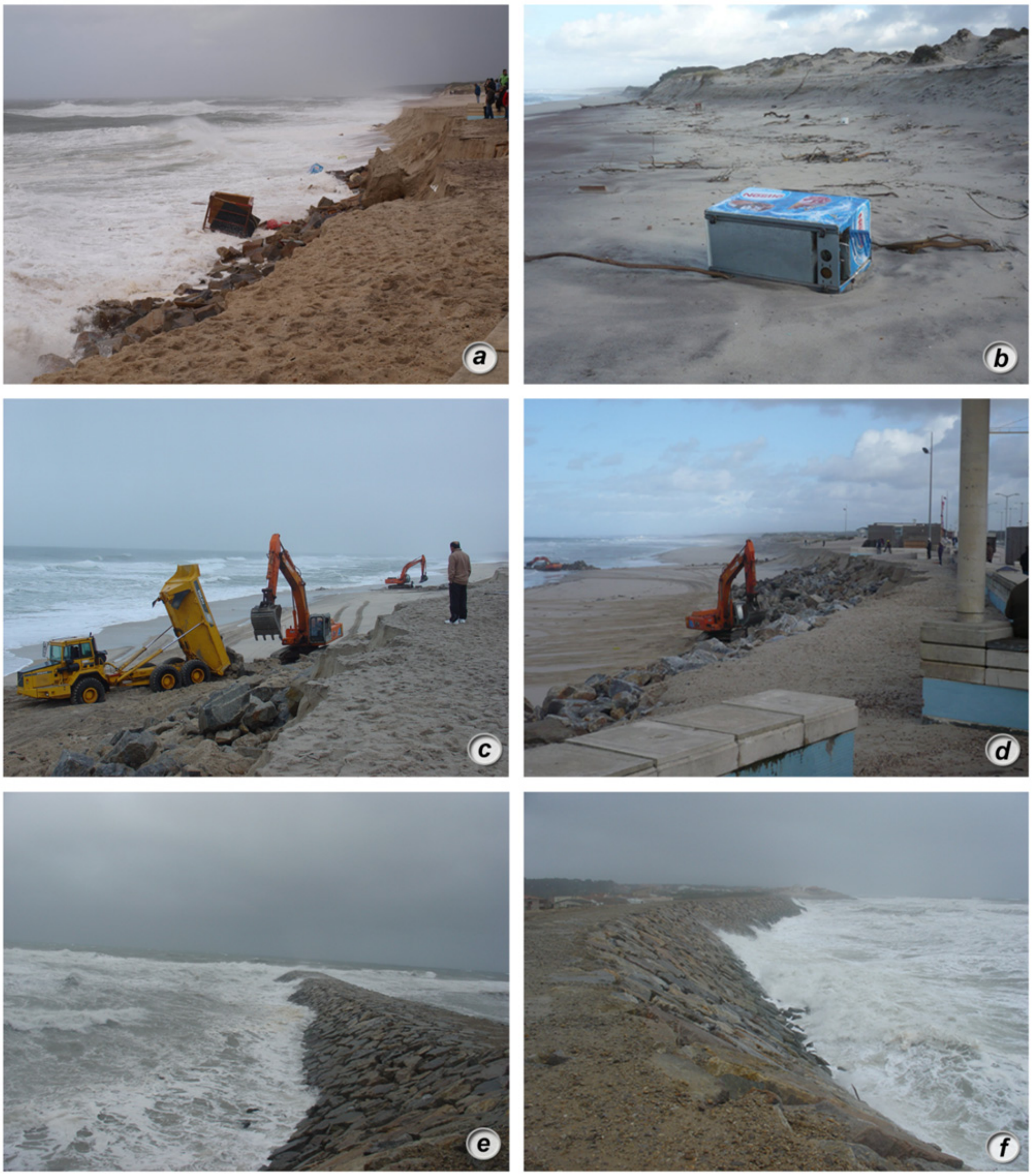



**Figure 51.** Monitoring and understanding trends in extreme storms (February 2011): Furadouro (a to d) and Cortegaça (e, f) examples; some of the events that occurred and the repair/reinforcement actions or interventions along the coast.

***Stage C: Applied field datasheet***

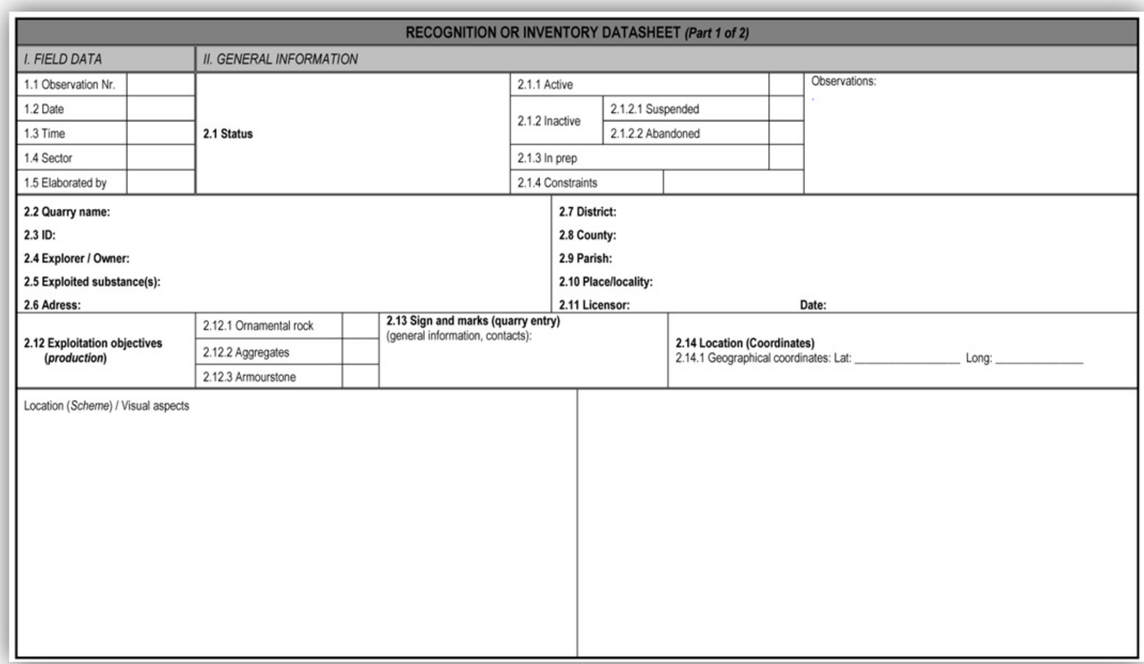
This stage comprises the development of specific and suitable field datasheets to collect data. This type of recording and registering data is a methodology already used in several scientific areas (USACE 2003, CIRIA *et al.* 2007, González de Vallejo & Ferrer 2011, Chaminé *et al.* 2013a,b and references therein). Hence the principle, essence and main aims applied were the same: to define and list parameters/features to register in order to characterise and study the area or site.

These systematic data collections synthesise and summarise all the gathered data in the fieldwork. It will be a good way of creating a geodatabase of information to assemble and consolidate in the desk studies.

In this stage it is displayed the different field datasheets created for each type of maritime environment and each type of research: (i) quarry evaluations; (ii) maritime structure assessments; (iii) boulder beach characterisations; and (iv) geoform identifications. The proposed datasheets will be displayed in the following figures. Moreover, Appendix 5 will show one detailed datasheet filled out for each type of research as an example from the studied areas or sites (examples of the quarry, maritime structure, boulder and geoform datasheets).

*Quarry characterisation*

The quarry datasheet was created and included in the GIS project to identify potential areas for the extraction of armourstone (more details in Pires & Chaminé 2008b, Pires *et al.* 2010a). The main purpose of this quarry inventory was to create a suitable database with different levels of information (Figures 52, 53 and Appendix 5-A).



**RECOGNITION OR INVENTORY DATASHEET** ***(Part 1 of 2)***

| I. FIELD DATA | | II. GENERAL INFORMATION | | | | Observations: |
|---|---|---|---|---|---|---|
| 1.1 Observation Nr. | | **2.1 Status** | 2.1.1 Active | | | |
| 1.2 Date | | | 2.1.2 Inactive | 2.1.2.1 Suspended | | |
| 1.3 Time | | | | 2.1.2.2 Abandoned | | |
| 1.4 Sector | | | 2.1.3 In prep | | | |
| 1.5 Elaborated by | | | 2.1.4 Constraints | | | |

**2.2 Quarry name:**
**2.3 ID:**
**2.4 Explorer / Owner:**
**2.5 Exploited substance(s):**
**2.6 Adress:**
**2.7 District:**
**2.8 County:**
**2.9 Parish:**
**2.10 Place/locality:**
**2.11 Licensor:** **Date:**

| **2.12 Exploitation objectives (*production*)** | 2.12.1 Ornamental rock | |
|---|---|---|
| | 2.12.2 Aggregates | |
| | 2.12.3 Armourstone | |

**2.13 Sign and marks (quarry entry)** (general information, contacts):

**2.14 Location (Coordinates)**
2.14.1 Geographical coordinates: Lat: ________________ Long: ______________

Location (*Scheme*) / Visual aspects

**Figure 52.** Datasheet for the inventory and assessment of quarries (Part 1).

It was important to make the most of this inventory, and therefore we compiled general information and features about the quarry (Figure 52), as well as information concerning the recognition and visual inspection made (Figure 53).

| RECOGNITION OR INVENTORY DATASHEET *(Part 2 of 2)* | | | |
|---|---|---|---|
| *III. INVENTORY/RECOGNITION AND VISUAL INSPECTION* | | | |
| **3.1 Geological aspects or geology:** | | | |
| **3.2 Topographical aspects or topography:** | | | |
| **3.3 Surrounding area characterisation** | 3.3.1 Inaccessible | | Observations: |
| | 3.3.2 Great difficulty in accessing | | |
| | 3.3.3 Partially accessible | | |
| | 3.3.4 Accessible | | |
| | 3.3.5 Good accessibility | | |
| **3.4 Rejected material** | 3.4.1 Yes | | Observations: |
| | 3.4.2 No | | |
| **3.5 Slime dams existence** | 3.5.1 Yes | | |
| | 3.5.2 No | | |
| **3.6 Overall assessment** | 3.6.1 Without interest | | Observations |
| | 3.6.2 With interest | | |
| | 3.6.3 With great interest | | |
| **3.7 Observations** | | | |

**Figure 53.** Field datasheet for the inventory and assessment of quarries (Part 2).

*Maritime structure assessment*

During field surveys a geotechnical datasheet was created (with several updates) for the assessment of structures' armour layer, as well as for the recognition and visual evaluation of the rock material (Pires 2005, Pires *et al.* 2006a, Pires 2007, Pires & Chaminé 2007, Pires *et al.* 2009c, Pires *et al.* 2014a).

Several parameters were registered along a sampling scanline on the block materials (Figure 54 and Appendix 5-B), such as lithological heterogeneity, petrophysical and geomechanical features plus the weathering grade (ISRM 1978a,b, GSE 1995). The classification for the assessment of the degradation grade of the constitutive materials was also used (further details in Pires 2007, Pires *et al.* 2014a), which is based on visual observation of breakage and cracking, and disintegration or corrosion of the concrete material.

| Geological characterisation - Armour layer (general evaluation) | | | | | | |
|---|---|---|---|---|---|---|
| Structure ID: | | | Type of structure: | | | |
| Geomaterial description | | | | | | |
| Geomaterial *ID* | | | | | | |
| Colour | | | | | | |
| Weathering grade (natural rock) - *W* | | | | | | |
| Degradation grade (artificial block) - *D* | | | | | | |
| Texture/Structure | | | | | | |
| Observations | | | | | | |

| Scanline direction: | Date: | Time: |
|---|---|---|

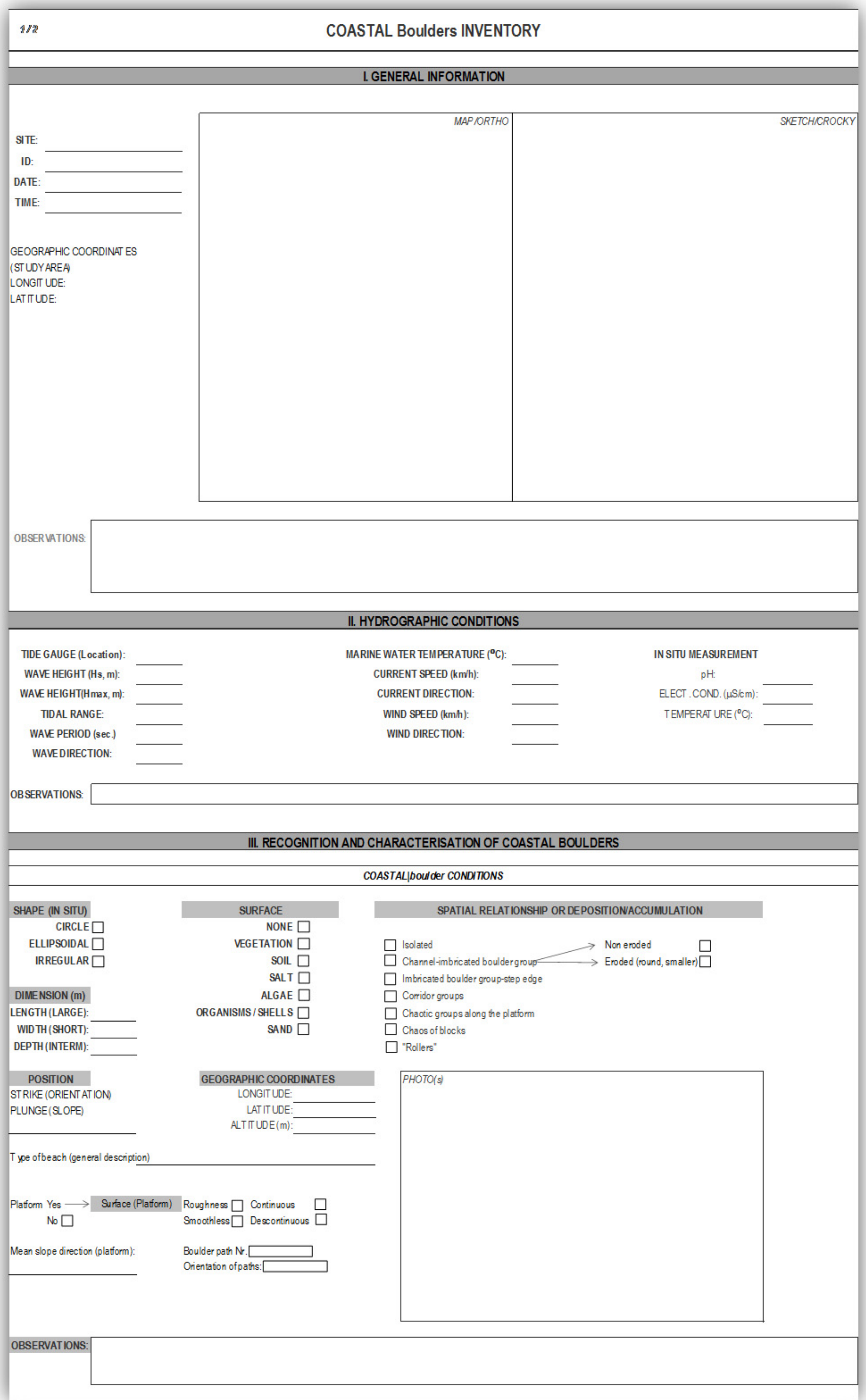
| Segment number: | Scanline scheme |
|---|---|
| Section (m): | |

| *Schmidt hammer rebound values (R)* | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Station nr. | | Results | | | | | Station nr. | | Results | | | | |
| Origin distance (m) | | | | | | | Origin distance (m) | | | | | | |
| Geomaterial *ID* | | | | | | | Geomaterial *ID* | | | | | | |
| Weathering grade (*W*) | | | | | | | Weathering grade (*W*) | | | | | | |
| Degradation grade (*D*) | | | | | | | Degradation grade (*D*) | | | | | | |
| | | | | | | | | | | | | | |

**Figure 54.** Field datasheet created for the evaluation and inspection of block materials (natural rocks and concrete blocks).

*Boulder beach evaluation*

The boulder datasheet was created to study not only the geometric form of coastal boulders but also to create an inventory of the different types of boulders (Figures 55, 56 and Appendix 5-C). It was also important to understand the complex spatial relationship between the blocks, arrangement, accumulation, dimensions, shape and position in the platform. Equally important is the boulder strength evalution by means of equipment previously presented, for example the Schmidt hammer or Equotip to assess the hardness of each block (Pérez-Alberti *et al.* 2012, Proceq 2012).


1/2

COASTAL Boulders INVENTORY

I. GENERAL INFORMATION

MAP/ORTHO

SKETCH/CROCKY

SITE:
ID:
DATE:
TIME:

GEOGRAPHIC COORDINATES
(STUDY AREA)
LONGITUDE:
LATITUDE:

OBSERVATIONS:

II. HYDROGRAPHIC CONDITIONS

TIDE GAUGE (Location):
WAVE HEIGHT (Hs, m):
WAVE HEIGHT(Hmax, m):
TIDAL RANGE:
WAVE PERIOD (sec.)
WAVE DIRECTION:

MARINE WATER TEMPERATURE (ºC):
CURRENT SPEED (km/h):
CURRENT DIRECTION:
WIND SPEED (km/h):
WIND DIRECTION:

IN SITU MEASUREMENT
pH:
ELECT. COND. (µS/cm):
TEMPERATURE (ºC):

OBSERVATIONS:

III. RECOGNITION AND CHARACTERISATION OF COASTAL BOULDERS

COASTAL|boulder CONDITIONS

SHAPE (IN SITU)
CIRCLE ☐
ELLIPSOIDAL ☐
IRREGULAR ☐

SURFACE
NONE ☐
VEGETATION ☐
SOIL ☐
SALT ☐
ALGAE ☐
ORGANISMS / SHELLS ☐
SAND ☐

SPATIAL RELATIONSHIP OR DEPOSITION/ACCUMULATION
☐ Isolated
☐ Channel-imbricated boulder group → Non eroded ☐ / Eroded (round, smaller) ☐
☐ Imbricated boulder group-step edge
☐ Corridor groups
☐ Chaotic groups along the platform
☐ Chaos of blocks
☐ "Rollers"

DIMENSION (m)
LENGTH (LARGE):
WIDTH (SHORT):
DEPTH (INTERM):

POSITION
STRIKE (ORIENTATION)
PLUNGE (SLOPE)

GEOGRAPHIC COORDINATES
LONGITUDE:
LATITUDE:
ALTITUDE (m):

PHOTO(s)

Type of beach (general description)

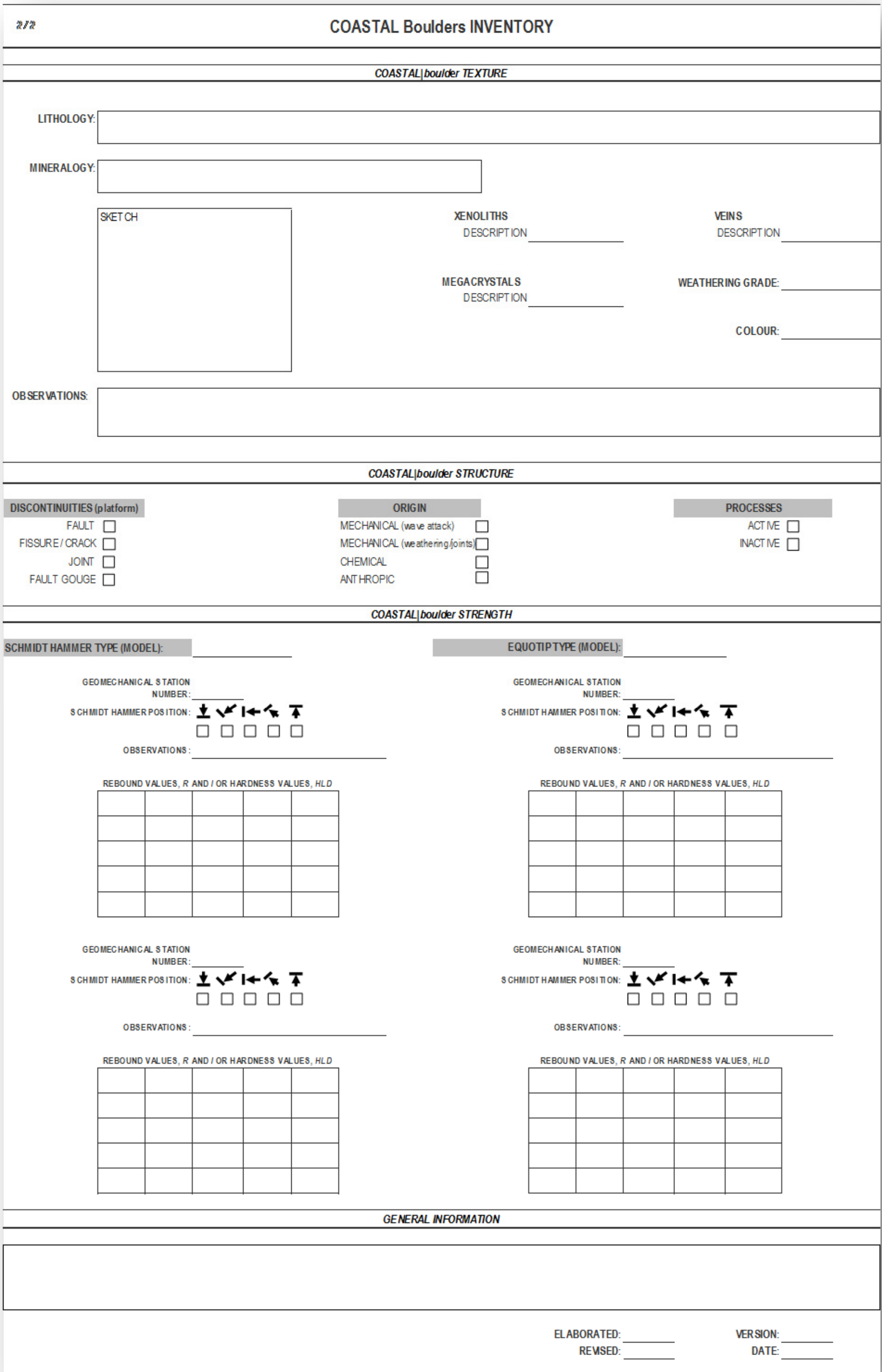
Platform Yes → Surface (Platform) Roughness ☐ Continuous ☐
No ☐ Smoothless ☐ Descontinuous ☐

Mean slope direction (platform):

Boulder path Nr.:
Orientation of paths:

OBSERVATIONS:

**Figure 55.** Field datasheet for the evaluation of boulders (Part 1).



2/2

COASTAL Boulders INVENTORY

COASTAL|boulder TEXTURE

LITHOLOGY:

MINERALOGY:

SKETCH

XENOLITHS
DESCRIPTION

VEINS
DESCRIPTION

MEGACRYSTALS
DESCRIPTION

WEATHERING GRADE:

COLOUR:

OBSERVATIONS:

COASTAL|boulder STRUCTURE

DISCONTINUITIES (platform)
FAULT ☐
FISSURE / CRACK ☐
JOINT ☐
FAULT GOUGE ☐

ORIGIN
MECHANICAL (wave attack) ☐
MECHANICAL (weathering/joints) ☐
CHEMICAL ☐
ANTHROPIC ☐

PROCESSES
ACTIVE ☐
INACTIVE ☐

COASTAL|boulder STRENGTH

SCHMIDT HAMMER TYPE (MODEL):

EQUOTIP TYPE (MODEL):

GEOMECHANICAL STATION NUMBER:
SCHMIDT HAMMER POSITION: ☐ ☐ ☐ ☐ ☐
OBSERVATIONS:
REBOUND VALUES, *R* AND / OR HARDNESS VALUES, *HLD*

GEOMECHANICAL STATION NUMBER:
SCHMIDT HAMMER POSITION: ☐ ☐ ☐ ☐ ☐
OBSERVATIONS:
REBOUND VALUES, *R* AND / OR HARDNESS VALUES, *HLD*

GEOMECHANICAL STATION NUMBER:
SCHMIDT HAMMER POSITION: ☐ ☐ ☐ ☐ ☐
OBSERVATIONS:
REBOUND VALUES, *R* AND / OR HARDNESS VALUES, *HLD*

GEOMECHANICAL STATION NUMBER:
SCHMIDT HAMMER POSITION: ☐ ☐ ☐ ☐ ☐
OBSERVATIONS:
REBOUND VALUES, *R* AND / OR HARDNESS VALUES, *HLD*

GENERAL INFORMATION

ELABORATED:
REVISED:
VERSION:
DATE:

**Figure 56.** Field datasheet for the evaluation of boulders (Part 2).

*Geoform characterisation*

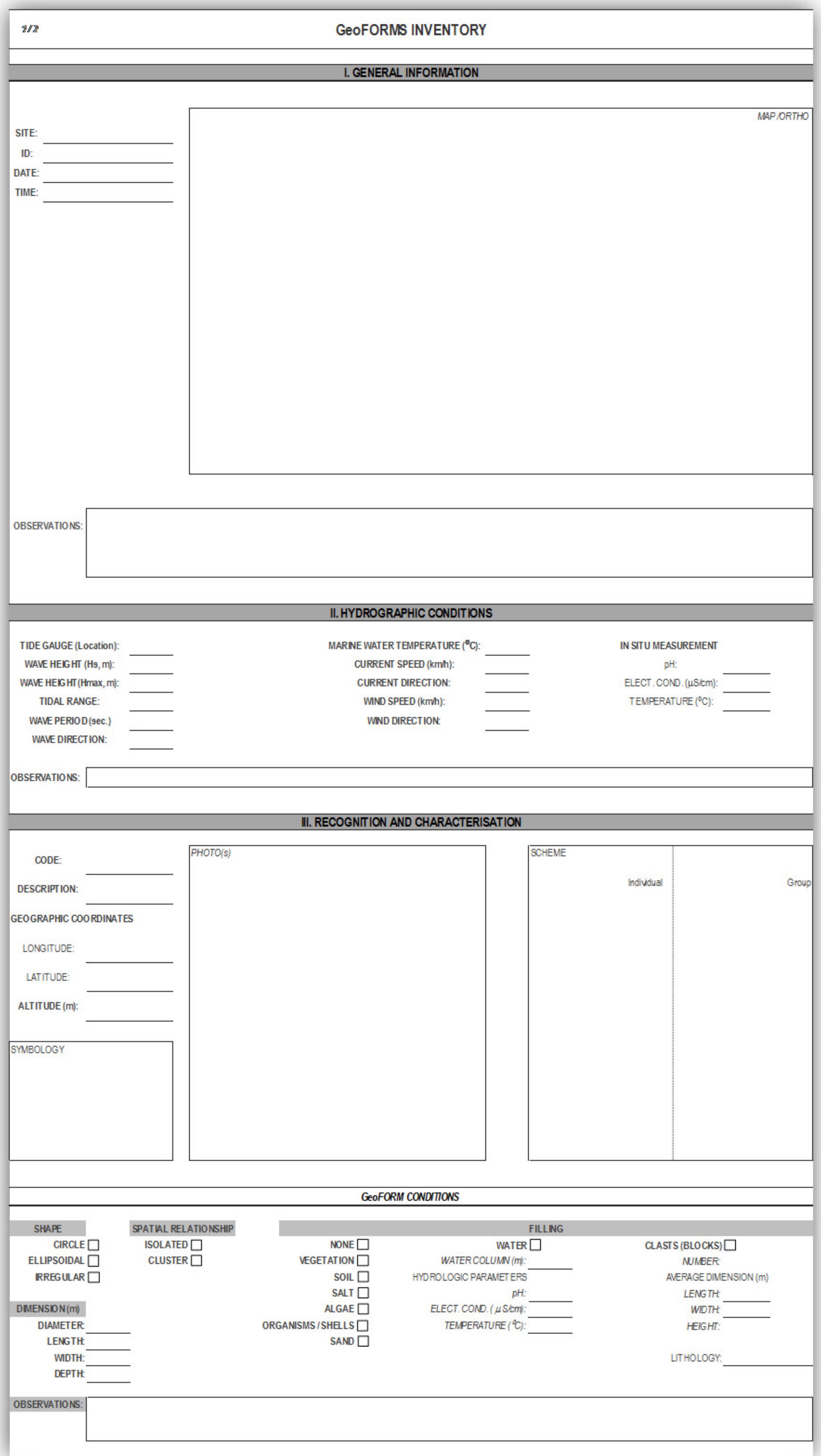
The geoform datasheet was developed because at some point there was a need to assess rocky coasts and shore platforms (Goudie 2004, Madden *et al.* 2008). These sorts of coastal environments comprise numerous but very distinctive coastal forms that are worthwhile to study and characterise. This is a field datasheet very similar to the previous one (boulder beach evaluation), however more broad in terms of coastal geoforms that can occur in different maritime environments. It should be emphasised that the datasheets displayed have been adapted to coastal pot-holes (Figures 57, 58 and Appendix 5-D). This type of record system can be adapted to whatever we decided to study or assess.

To assess the geoforms it was important to register several parameters, from general information to specific details related to the coastal forms, namely:

i. *General information about the hydrographic conditions;*
ii. *Recognition and characterisation;*
iii. *Spatial conditions;*
iv. *Texture;*
v. *Structure;*
vi. *Strength.*

*Support datasheets*

The support datasheets displayed in Figures 60 and 61 suggest applications for additional data or information. The design of a field datasheet was very useful to systematise the collected data concerning only the rebound/hardness values to assess the strength of boulders/geoforms (Figure 59) or any type of studied environment to register the Schmidt hammer and Equotip data obtained (Figure 60). In addition, the datasheet requires general information like the location, scanline orientation, lithology, date and profiles ID (Figure 60). The measurement parameters are also important information to be taken into account regarding the block characterisation before the strength evaluation.



1/2 GeoFORMS INVENTORY

I. GENERAL INFORMATION

SITE:
ID:
DATE:
TIME:

MAP/ORTHO

OBSERVATIONS:

II. HYDROGRAPHIC CONDITIONS

TIDE GAUGE (Location):
WAVE HEIGHT (Hs, m):
WAVE HEIGHT (Hmax, m):
TIDAL RANGE:
WAVE PERIOD (sec.)
WAVE DIRECTION:

MARINE WATER TEMPERATURE (ºC):
CURRENT SPEED (km/h):
CURRENT DIRECTION:
WIND SPEED (km/h):
WIND DIRECTION:

IN SITU MEASUREMENT
pH:
ELECT. COND. (µS/cm):
TEMPERATURE (ºC):

OBSERVATIONS:

III. RECOGNITION AND CHARACTERISATION

CODE:
DESCRIPTION:
GEOGRAPHIC COORDINATES
LONGITUDE:
LATITUDE:
ALTITUDE (m):

SYMBOLOGY

PHOTO(s)

SCHEME
Individual
Group

GeoFORM CONDITIONS

SHAPE
CIRCLE
ELLIPSOIDAL
IRREGULAR

SPATIAL RELATIONSHIP
ISOLATED
CLUSTER

DIMENSION (m)
DIAMETER:
LENGTH:
WIDTH:
DEPTH:

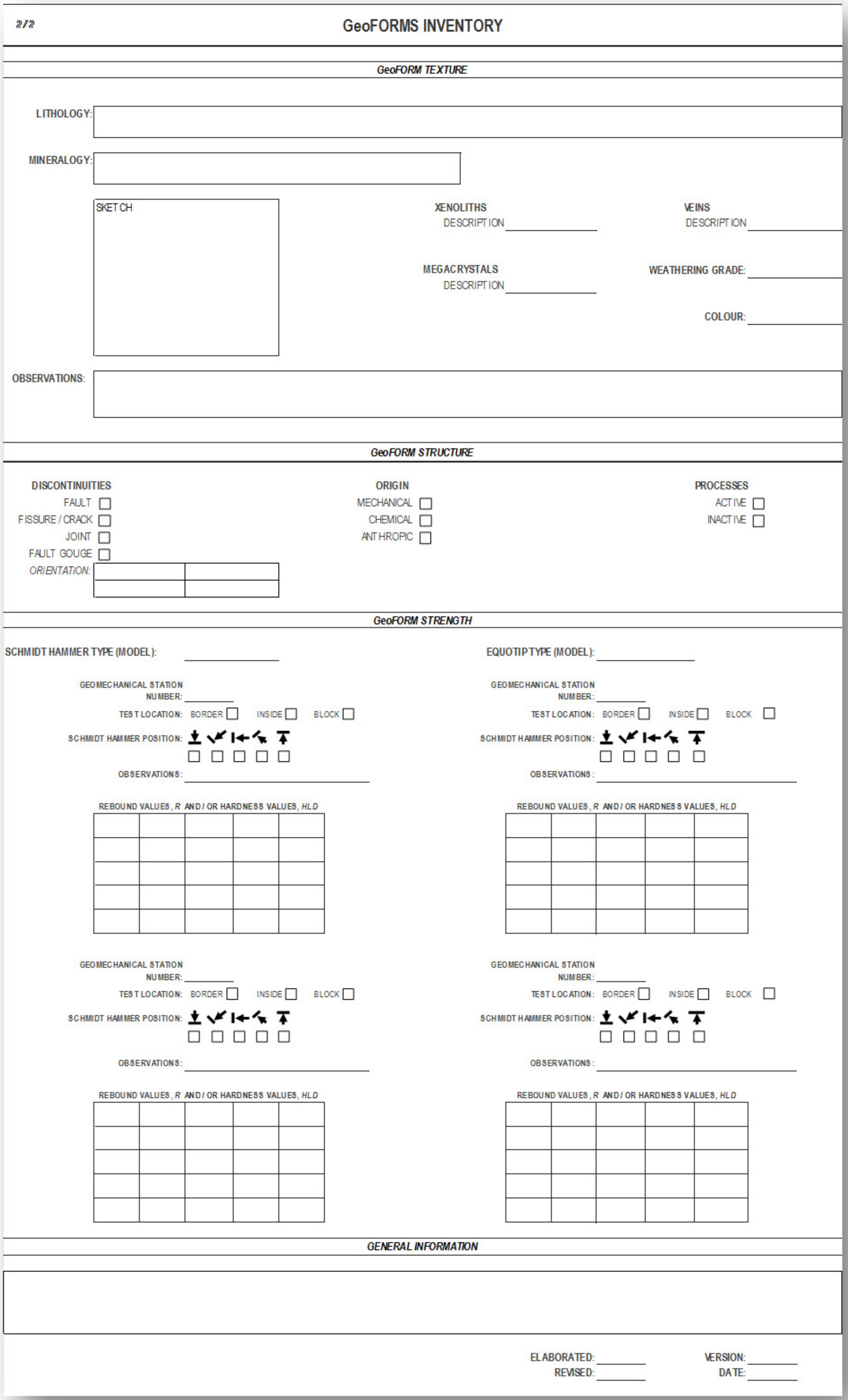
FILLING
NONE
VEGETATION
SOIL
SALT
ALGAE
ORGANISMS / SHELLS
SAND

WATER
WATER COLUMN (m):
HYDROLOGIC PARAMETERS
pH:
ELECT. COND. (µS/cm):
TEMPERATURE (ºC):

CLASTS (BLOCKS)
NUMBER:
AVERAGE DIMENSION (m)
LENGTH:
WIDTH:
HEIGHT:
LITHOLOGY:

OBSERVATIONS:

**Figure 57.** Field datasheet for the geoforms inventory and characterisation (Part 1).



2/2

GeoFORMS INVENTORY

GeoFORM TEXTURE

LITHOLOGY:

MINERALOGY:

SKETCH

XENOLITHS
DESCRIPTION

VEINS
DESCRIPTION

MEGACRYSTALS
DESCRIPTION

WEATHERING GRADE:

COLOUR:

OBSERVATIONS:

GeoFORM STRUCTURE

DISCONTINUITIES
FAULT ☐
FISSURE / CRACK ☐
JOINT ☐
FAULT GOUGE ☐
*ORIENTATION:*

ORIGIN
MECHANICAL ☐
CHEMICAL ☐
ANTHROPIC ☐

PROCESSES
ACTIVE ☐
INACTIVE ☐

GeoFORM STRENGTH

SCHMIDT HAMMER TYPE (MODEL):

EQUOTIP TYPE (MODEL):

GEOMECHANICAL STATION NUMBER:
TEST LOCATION: BORDER ☐ INSIDE ☐ BLOCK ☐
SCHMIDT HAMMER POSITION: ☐ ☐ ☐ ☐ ☐
OBSERVATIONS:
REBOUND VALUES, *R* AND / OR HARDNESS VALUES, *HLD*

| | | | | |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

GEOMECHANICAL STATION NUMBER:
TEST LOCATION: BORDER ☐ INSIDE ☐ BLOCK ☐
SCHMIDT HAMMER POSITION: ☐ ☐ ☐ ☐ ☐
OBSERVATIONS:
REBOUND VALUES, *R* AND / OR HARDNESS VALUES, *HLD*

| | | | | |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

GEOMECHANICAL STATION NUMBER:
TEST LOCATION: BORDER ☐ INSIDE ☐ BLOCK ☐
SCHMIDT HAMMER POSITION: ☐ ☐ ☐ ☐ ☐
OBSERVATIONS:
REBOUND VALUES, *R* AND / OR HARDNESS VALUES, *HLD*

| | | | | |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

GEOMECHANICAL STATION NUMBER:
TEST LOCATION: BORDER ☐ INSIDE ☐ BLOCK ☐
SCHMIDT HAMMER POSITION: ☐ ☐ ☐ ☐ ☐
OBSERVATIONS:
REBOUND VALUES, *R* AND / OR HARDNESS VALUES, *HLD*

| | | | | |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

*GENERAL INFORMATION*

ELABORATED:
REVISED:
VERSION:
DATE:

**Figure 58.** Field datasheet for the geoforms inventory and characterisation (Part 2).

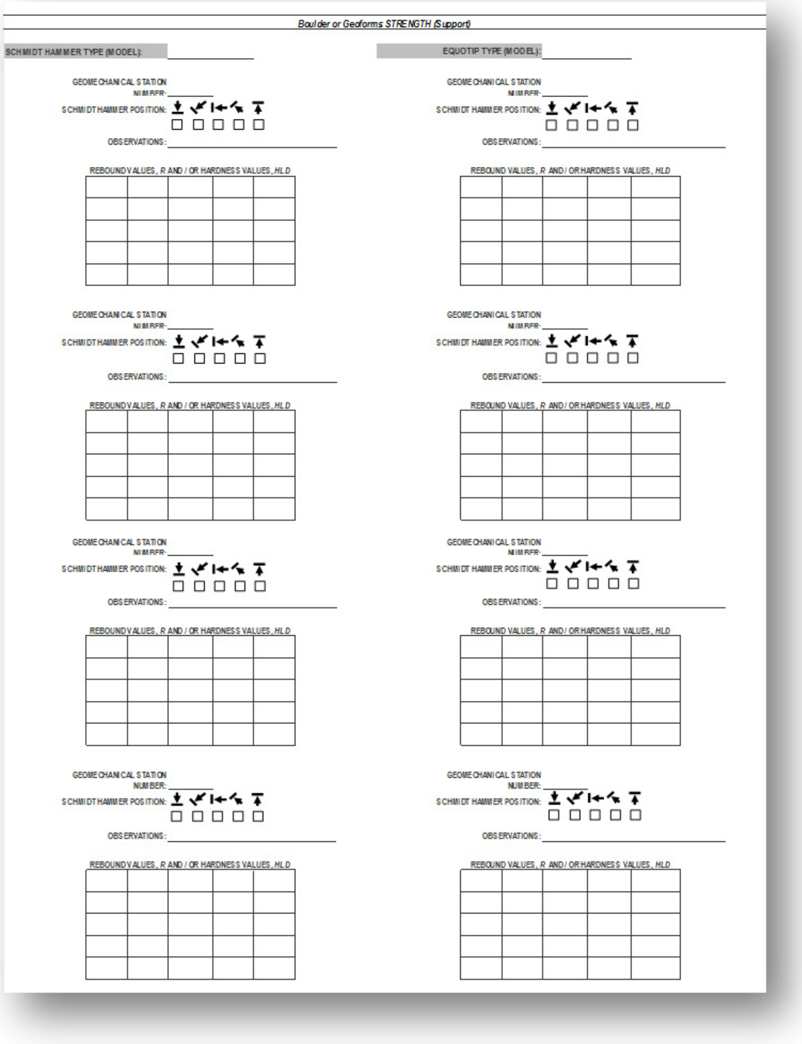



**Figure 59.** Support field datasheet for additional data or information applied to the strength/hardness assessment of boulders or geoforms.

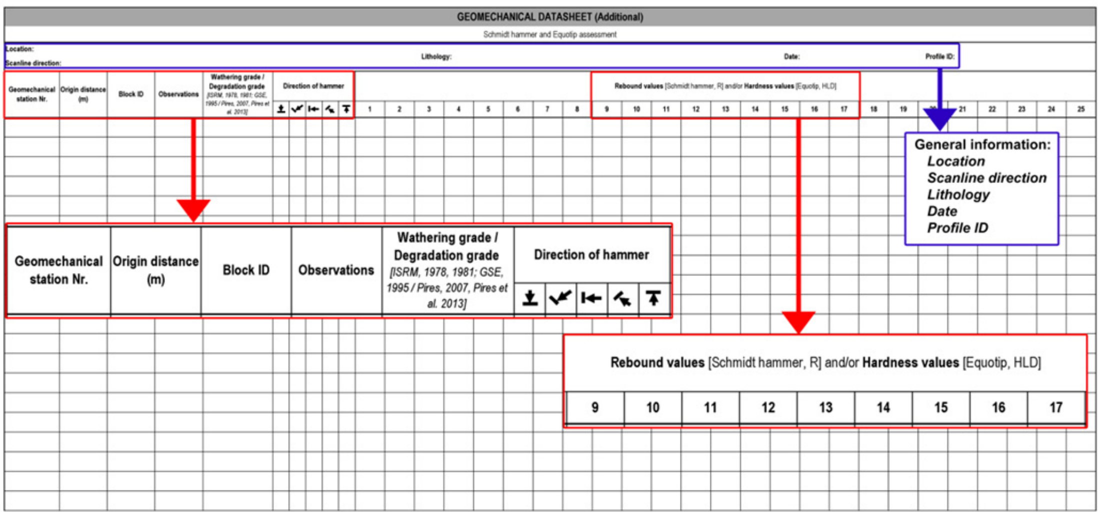



**Figure 60.** Support field datasheet for additional data or information applied to any type of studied environment to register the rebound or hardness values respectively obtained from Schmidt hammer and Equotip instruments.

***Stage D: In situ evaluation***

Stage D comprises in situ evaluations which concerns to diverse field techniques and methodologies (Figures 61 to 63). This stage is well illustrated by the high-accuracy GIS data collection system (Figure 61), the use of different Schmidt hammer models (Figure 62) and the Equotip application (Figure 63).

Overall the *Trimble®* GPS technology provided georeferencing information along the maritime structures and rocky shores for aerial imaging, which was integrated in the GIS project. It was also used to perform walkover surveys along scanlines to record information on the overall condition of the structures, including any obvious block movements, changes in the profile or type of lithology (Figure 61).

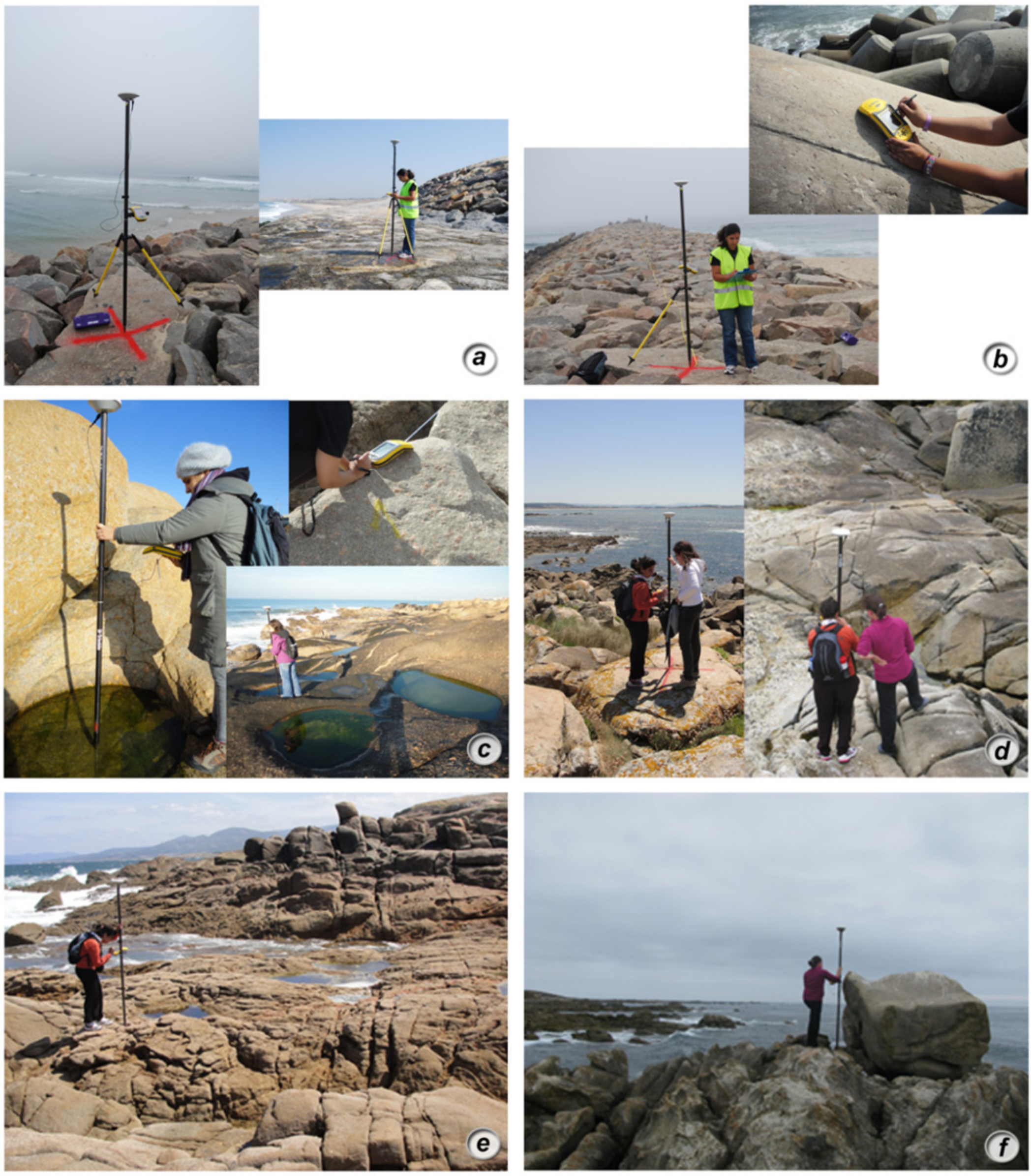



**Figure 61.** Trimble GPS technology: several aspects of the field technique applied to georeference coastal features or monitoring.

The in situ evaluation starts with the maritime structures GPS monitoring and georeferencing the control points on natural/concrete blocks (Figure 61a,b, Espinho site, NW Portugal); geoforms georeferencing such as coastal pot-holes or coastal boulders (Figure 61c, Lavadores site, NW Portugal); rocky coast evaluation (Figure 61d,e, Corrubedo, NW Galicia) and mega-boulder/mega-block georeferencing (Figure 61f, Oia – A Guarda, NW Galicia).

The Original Schmidt hammer, Silver Schmidt and Digi Schmidt were also applied to assess the rebound and the uniaxial compressive strength of blocks (Figure 62).

**Figure 62.** Several applications in situ of the Original Schmidt hammer, Silver Schmidt and Digi Schmidt at the studied sites.

The Original Schmidt hammer was applied on natural rocks (Figure 62a) and concrete blocks (Figure 62b). It was also used in rocky platforms and coastal boulders (Figure 62c). An example of Silver Schmidt being used on natural/concrete blocks and shore platforms is illustrated in Figure 62 (d,e). Finally the Digi Schmidt was applied to concrete blocks such as antifer cubes or tetrapods (Figure 62f).

Equotip equipment was also employed to measure hardness and the strength in different coastal environments (Figure 63). It was also applied in coastal boulder evaluation (Figure 63a,b), shore platforms and rocky beaches (Figure 63c) or even in maritime structures, more specifically on concrete blocks (Figure 63d,e,f).

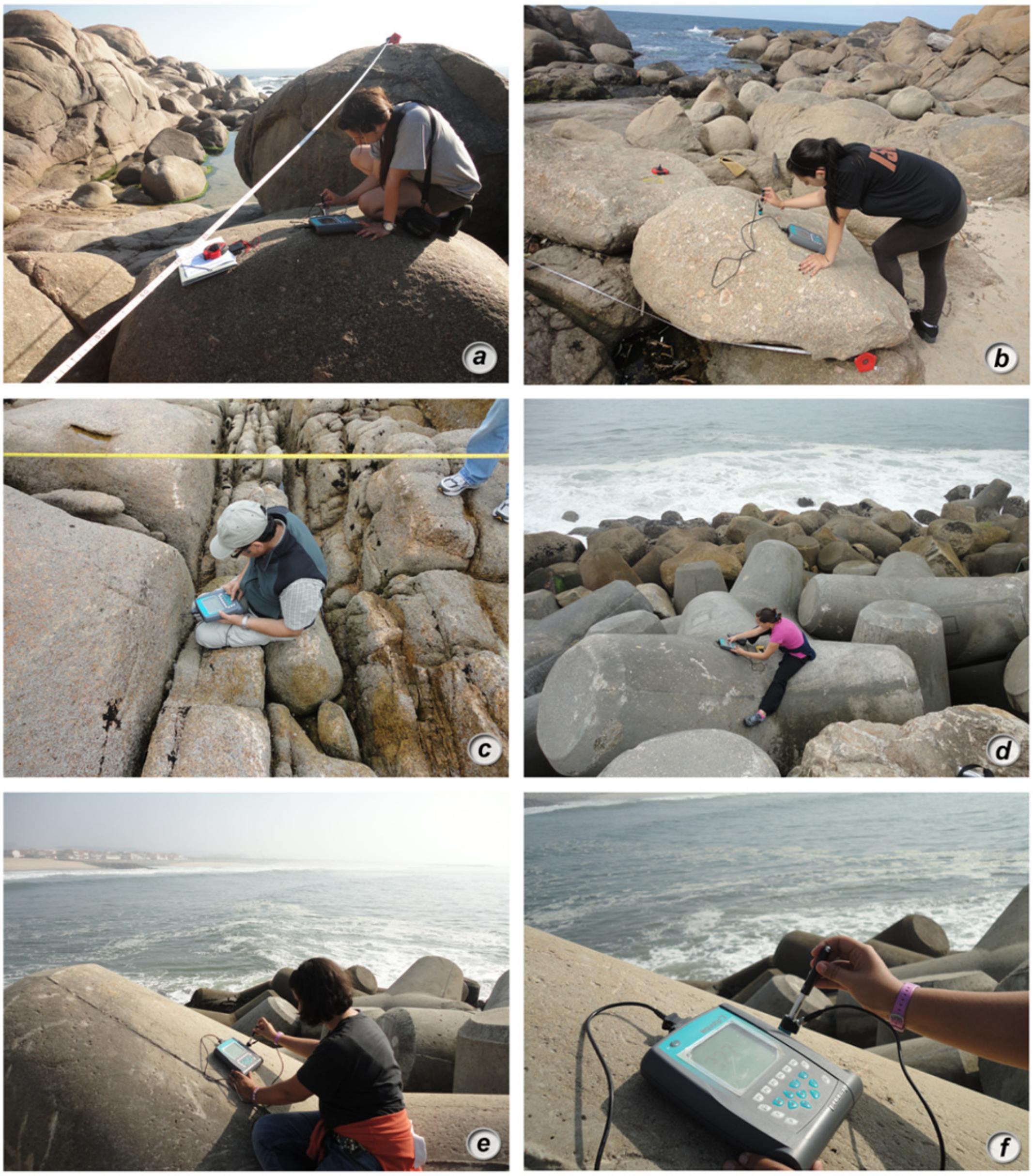



**Figure 63.** The Equotip equipment application in different coastal environments.

***Stage E: Scanline survey***

Sampling along a scanline is an accurate and fast method for representative data compilation (e.g., Dinis da Gama 1995, Chaminé & Gaspar 1995, Chaminé *et al.* 2001, Martins *et al*. 2006, Chaminé *et al*. 2013b). In this particular work the scanline was applied with a different approach providing support for the characterisation of the blocks or discontinuities intersected by the fiberglass tape measure. This stage represents the systematic data collection in terms of geological and/or geotechnical information. The following figures show the scanline technique applied to maritime structures (Figure 64) and to rocky coasts or shore platforms (Figure 65). Figure 64 shows that we can have longitudinal or transverse profiles (e.g. cross-sections being held in the head area of the groyne) and several visual inspections can be performed for each studied site according to the scanlines established.


**Figure 64.** The scanline technique applied to maritime structures.

In addition, some relevant parameters must be collected, such as the scanline sections, lithology, weathering grade, petrophysical characteristics and geomechanical features of block materials. In the case of the study of rocky coasts and discontinuities analysis, a rock mass description and evaluation are performed (Figure 65).

In summary, Figure 64 (a,b) displays different aspects along the crown wall of a groyne (Espinho site, NW Portugal). Similarly this technique can be used along seawalls (Figure 64c, Espinho site, NW Portugal). It is also used in other types of groynes in terms of lithology such as limestones (Figure 64d,e, Figueira da Foz, Central Portugal). Or we even use the scanline technique on other components like the armour layer of a maritime structure (Figure 64f, Aguiño groyne – Corrubedo, NW Galicia).


**Figure 65.** The scanline technique applied to rocky coasts and shore platforms.

***Stage F: GIS mapping***

This stage is the result of all the procedures and methods applied and previously presented. The GIS mapping, applied cartography and final outputs will be presented in *Part II* of the thesis as well as in *Part III*. It should also be emphasised that these results were obtained mainly in four research categories and interests: georesources, maritime structures, rocky coasts and coastal management.

***The workflow***

This chapter culminates with two fundamental workflows that represent the synthesis of all the methologies/procedures implemented and how they interrelate with each other. Some concepts and terminologies will be broadly developed in the state of the art chapter, and therefore here we will only try to show the main steps and phases behind the core of the research.

This research has two fundamental roles: geomaterial characterisation and coastal management. It seems that they are not connected but if we establish a bridge between the integrated coastal geoengineering techniques with the GIS mapping and cartographic data developed, we will find the same perspective in terms of implications on coastal management and planning.

The "*modus operandi*" established an interdisciplinary connection between geoengineering concepts for the planning of maritime structures and beach management (e.g., USACE 1984, LCPC 1989, USACE 2003, CIRIA *et al.* 2007, Rogers *et al.* 2010). The conceptual flowcharts presented here (Figures 66 and 67) were planned and based on these authors' recommendations and terminologies and on the proposed basic geotechnical description of rock masses, the so-called BGD (see details in ISRM 1981). These workflows also used a series of techniques and methods with the eventual purpose of identifying the geomaterials' source and studying its implications in terms of durability (previously described by Fookes & Poole 1981, Fookes 1991, Poole 1991, Lienhart 1998, Pope & Curtis 2005, Latham *et al.* 2006a,b).

On the other hand, the GIS project includes quarry assessment in order to identify potential areas for the extraction of armourstone. As shown in Figure 66, all obtained data from the literature review and fieldwork were inserted in the GIS database, allowing the user to view all levels of information and generate 3D modelling, spatial and network analysis. During this process of data integration there were necessarily two phases: (i) geomaterial characterisation of the hydraulic structure's armour layer and (ii) geomaterial characterisation at the extraction sites (quarries). The geomaterial characterisation and assessment workflow (Figure 66) also shows a set of images with different aspects of the applied techniques/fieldwork and the stages of the rock project; from the suitable choice of the material, handling and transport at the quarry to the construction process (Pires & Chaminé 2009, Pires *et al.* 2010a), resulting ultimately in the coastal geoengineering approach and an understanding of what is important to highlight.

Then again we also have other types of maritime environments such as rocky coasts, shore platforms and cliffs. Although we already showed the existence of some common points in the procedures and methodologies applied, the perspective and final results in this type of studies are a little different (Figure 67).

There are some aspects to take into account in a coastal dynamics study and in shoreline management projects (Pérez-Alberti *et al.* 2013a). First of all, the site investigations are in a complex coastal environment, very dynamic and sometimes with mixed features. This type of research is more connected or related to coastal management. It is always necessary to make a thorough evaluation/characterisation of the surrounding area to define results and propose strategies/measures.

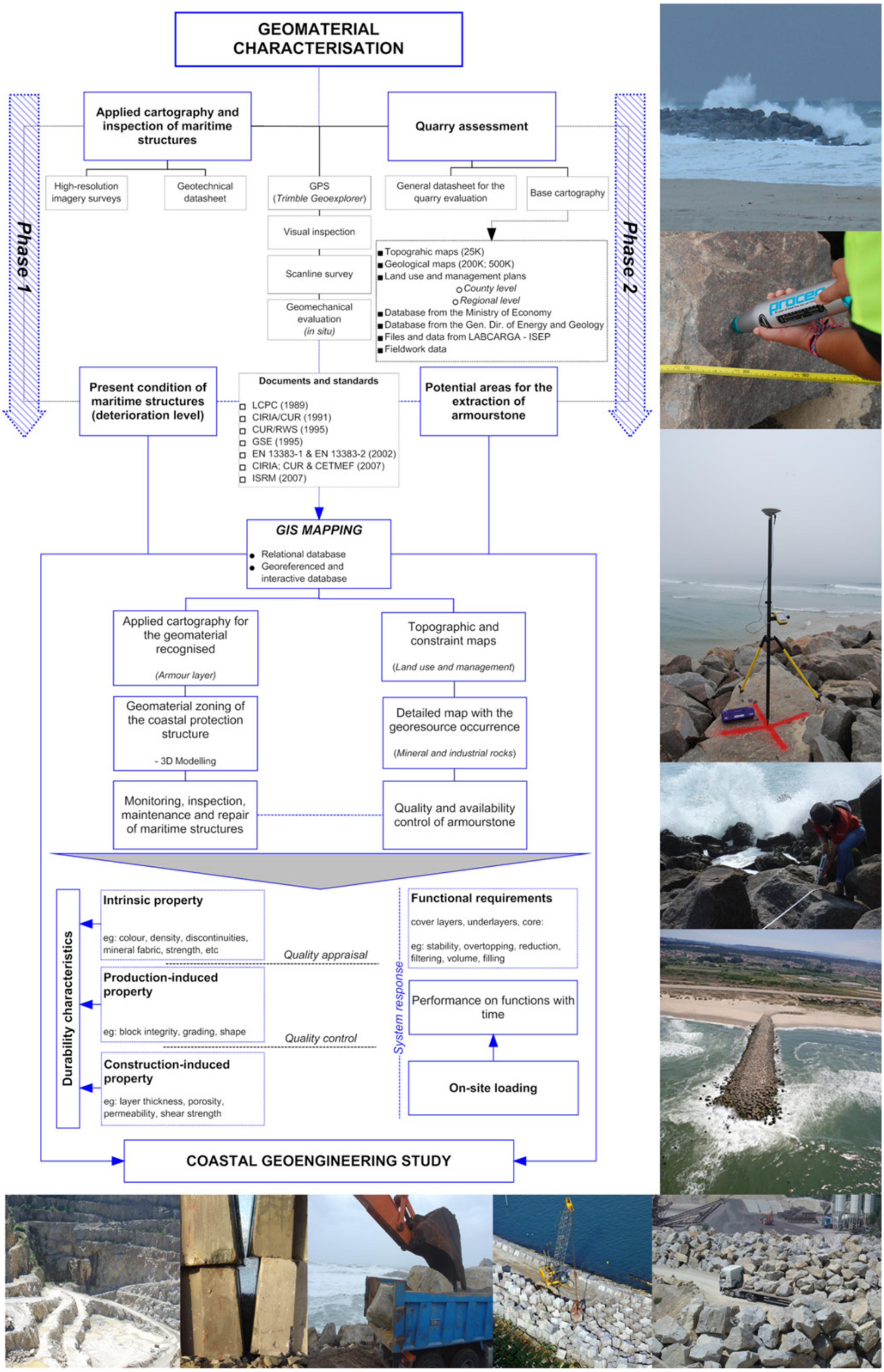



**Figure 66.** Conceptual flowchart for the coastal geoengineering research (updated from Pires & Chaminé 2009, Pires *et al.* 2009c, Pires *et al.* 2009d); some images with different aspects of the applied techniques/fieldwork and the stages of the rock project; from the suitable choice of the material, handling and transport at the quarry to the construction process.

The applied cartography is of great importance in that it will be the main platform for the decision support system for integrated coastal management in the studied areas. It is better to deal with the data separately for sandy and rocky areas; therefore this methodology is able to better evaluate the coastline evolution or the cliff retreat values. Other available techniques or software can be used. In the end of the research stage a statistical analysis can also aim the research and help to outline a conceptual model. Susceptibility, vulnerability or geohazard maps will be accomplished with the help of all these data, proposing and contributing strategies and actions to shoreline management plans (Figure 67).

Of course there are many methodologies available and the workflow must always be adapted to the reality of the study area. Nevertheless, both workflows have to be adapted to the investigation needs or to achieve the objectives earlier defined.

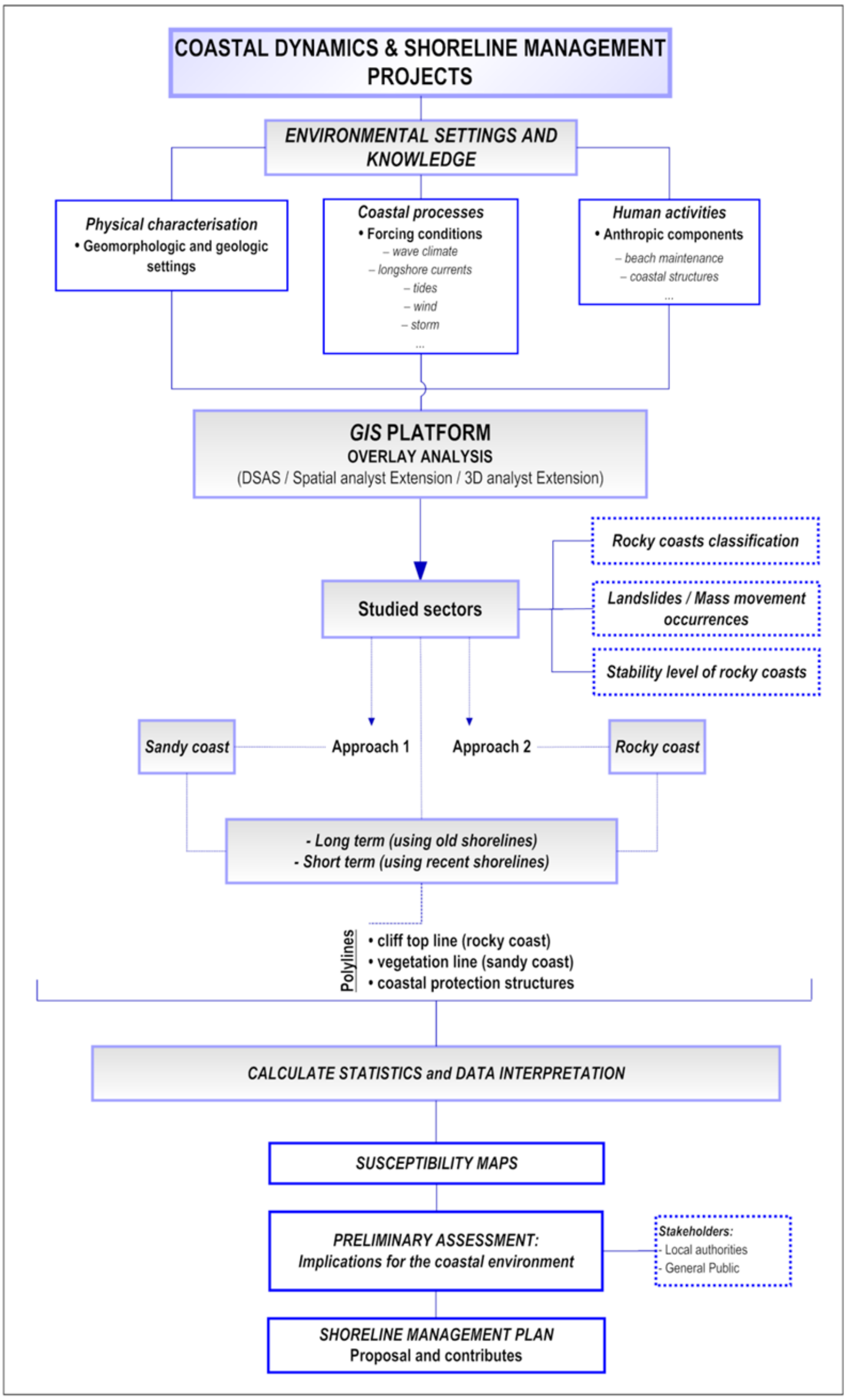



**Figure 67.** Conceptual flowchart for the study of the dynamics of coastal system: shoreline management plans overview (adapted from Pérez-Alberti *et al.* 2013a).

# CHAPTER 3 – STATE OF THE ART

*Illustration by M. Yardin (Laboratoire régional de Saint-Brieuc, in LCPC 1989)*

# 3. STATE OF THE ART

## 3.1. Introduction

This chapter contains a brief overview of general concepts regarding coastal systems and processes. The presented published papers (*Part II*) already include a comprehensive coverage of the relevant literature, moreover a short section within the introduction chapter which overviews (and references) key ideas from the literature was also included.

The assumptions made in Chapters 1 and 2 stated explicitly (i) the theory under investigation, (ii) the phenomena under investigation, (iii) the instruments and equipments, (iv) the methodologies, (v) the analysis, (vi) the capability to find the implications, and (vii) the participants in the study.

The contents displayed herein contain the reasons that led us to consider such investigations and also introduce a critical review of selected literature. More importantly, this chapter comprises a clear statement of the significance of the thesis aims, identification of gaps in knowledge and the relationship of the bibliography to the research program. All this issues became part of a set of interrelated concerns with the brief overview of the literature and the thesis theme: “Integrated coastal geoengineering approach for maritime environments”. Therefore, Chapter 3 was shaped and its main organization is shown in Figure 68.

The conceptual schema layout consists of general concepts about the coastal systems and processes divided into five sections: (i) the historical context of coastal areas, the importance of coastal engineering and coastal science, and the causes of shoreline erosion, (ii) integrated coastal zone management, including the coastal area and the littoral processes, (iii) the social context, presenting a case study and examples of how to include people in coastal management, (iv) characterisation of coastal environments and systems, as well as the types of hydraulic structures, and (v) the georesources and geomaterials related to marine structures.

Finally, the last and the most important section is about coastal geoengineering strategy and how all of the sections previously presented show the culmination of several factors that will help to understand the coastal dynamics and prepare the reader for the approach submitted in the thesis.

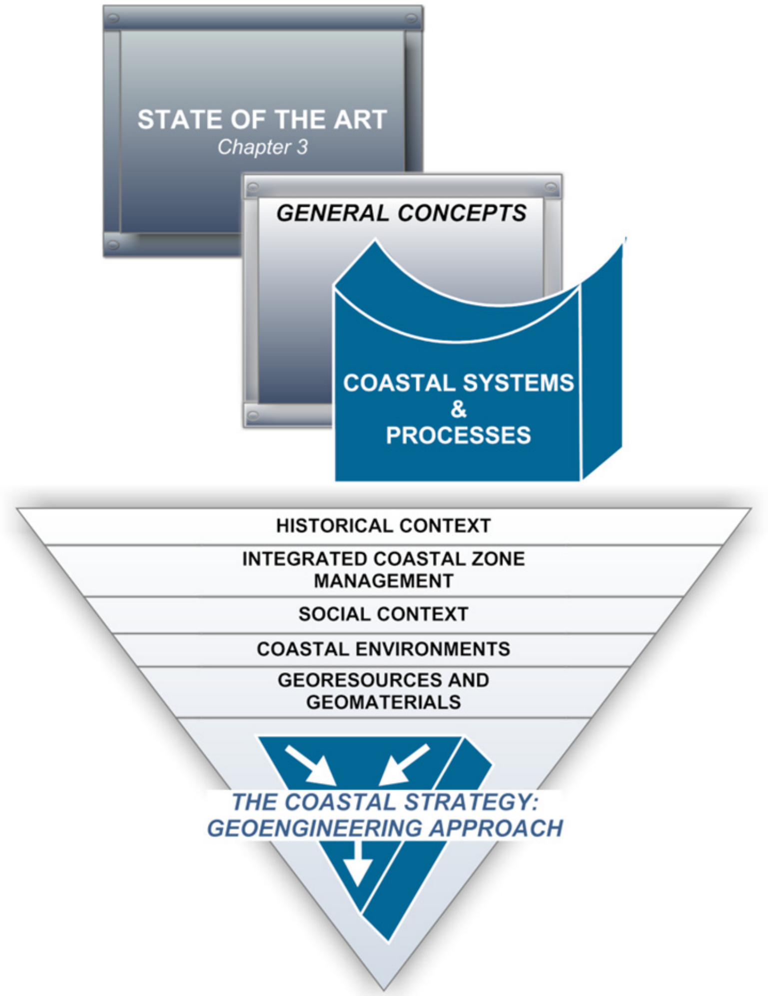



**Figure 68.** Conceptual schema layout of Chapter 3.

## 3.2. Historical context

### *3.2.1. The ocean*

"*We know that when we protect our oceans we're protecting our future*" (Clinton, 2000/2001: 1573). That impressive quotation addresses an interesting issue about the privileges of mankind living on the blue planet, the Earth. So a question can be raised; why does the current society not have this ability? Nearly 71% of the planet's surface is covered by ocean (Trenberth & Stepaniak 2004, NOAA 2013a). In fact, all the oceans contribute energy, food, mineral resources, and play an increasing role in recreation and tourism (Woodroffe 2003, Moan 2004). But they also provide means for transportation or other infrastructures related to industrial activities and offshore technologies, as shown in Figures 69a and 69b with some structures for various functions.

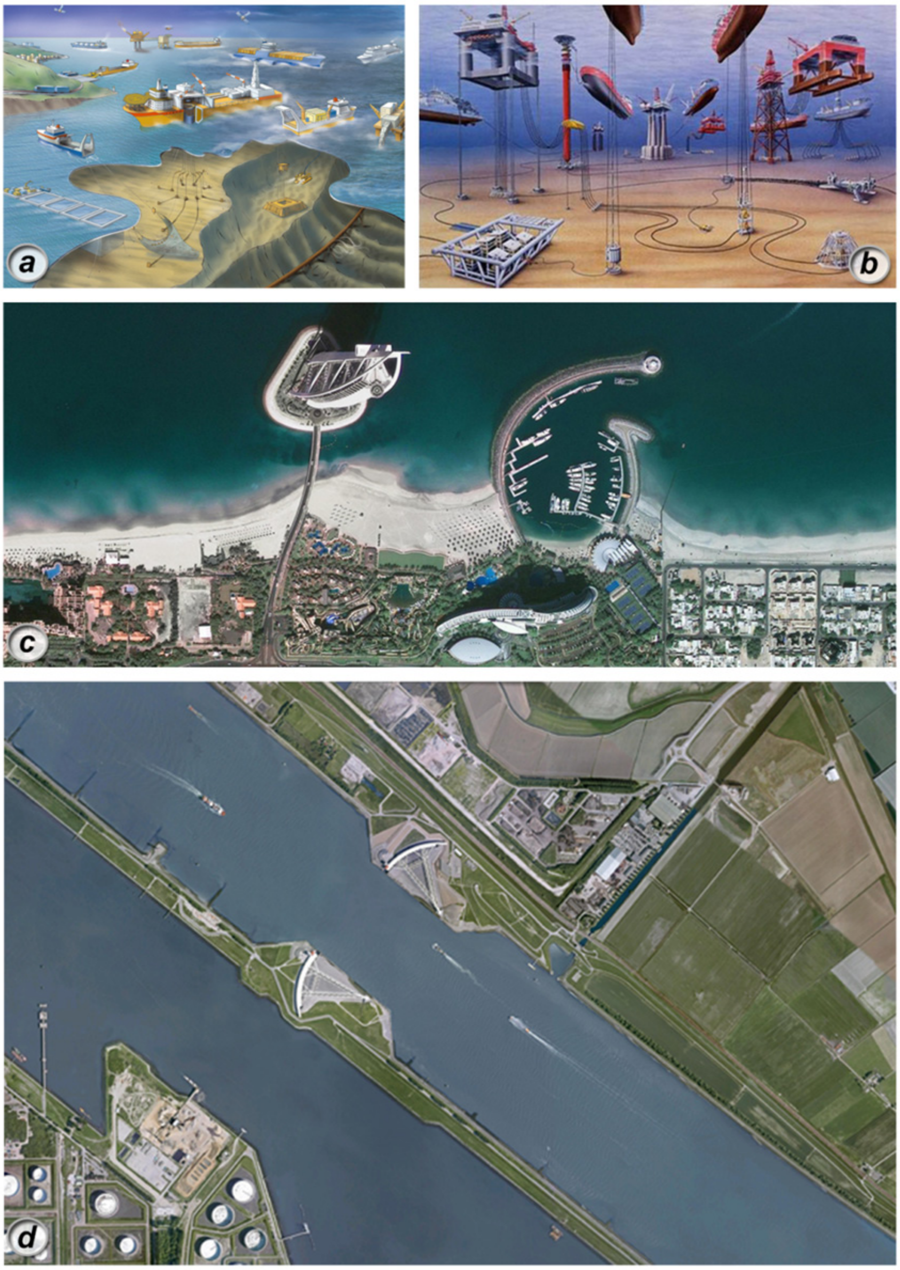


**Figure 69.** Sketches of marine structures and their various functions [a, b] (Moan 2004, SINTEF 2013, respectively); coastal protection works along the Jumeirah Beach Resort, Dubai [c] (ATKINS 2013); hydraulic structures of Maeslantkering, Netherlands [d] (Google Earth Pro, accessed August 2013).

The diversity of these types of technologies really shows the sea of opportunities for innovation, especially in the growing field of design practice in offshore geotechnical engineering, which has diverged from onshore practice over the last 30 years (Chaney & Fang 1986, Poulos 1988, Gerwick 2007, Dean 2009, Randolph & Gourvenec 2011, Bogossian 2012). The main market is the gas and oil industry, with subsea – offshore pipelines – and floating production systems – risers, umbilicals and power cables (Figures 69a and 69b) (Moan 2004, SINTEF 2013).

Nonetheless, humanity has always had the ability to conceptualise inspired and outstanding engineering works and create innovative structural designs over the decades. Figures 69c and 69d show two of the numerous amazing examples of other kind of maritime structures.

The coastal protection works in Jumeirah Beach Resort Development, Dubai are displayed in Figure 69c (ATKINS 2013). Palm Jumeirah represents one of the many iconic architectural structures of Dubai and is part of the enigmatic mega-project that was created on a global scale to symbolise its national identity (for further details about the project and coastal management see: Smit *et al*. 2005, Stive 2005, Orrill 2006, Darmaki 2008, Kubat *et al*. 2009 and references therein).

Maeslantkering is another kind of hydraulic structure (Figure 69d). It is situated between Hoek van Holland and Maassluis, up to the confluence of the rivers Oude Maas and Nieuwe Maas, Netherlands. Figure 69d shows an aerial view of the storm surge barrier that can move automatically with a massive weight to resist large forces applied by water during storms (for further details see: Samyna *et al*. 2007, Aerts 2013 and references therein). According to CIRIA *et al*. 2007, Maeslantkering is an astonishing example of one of the types of closure works designated as flow control structures.

Nothing is impossible for humankind, sometimes with drastic consequences for coastal regions. There is indeed an ocean of “endless possibilities”. The different purposes as well as the opportunities that the sea offers, such as energy, food, transport and more, are indicated in Figure 70. The flowchart synthesises a knowledge-based maritime cluster with marine activities and illustrates the global relief model of Earth's surface. All the subjects appear to be linked to this relationship between seas and territory but also with the concept of maritime clusters (Moan 2004, Pinto & Cruz 2012). The theory of industry clusters has progressively generated substantial interest among the scientific community, policy makers, industry leaders and the media (IOC 2012).

This concept was sourced to Alfred Marshall´s *Principles of Economics*, which was first published in 1890 (IOC 2012). According to Marshall (1890), “*agglomeration advantages were supposed to be linked to three sets of localization economies: a pooled market for workers; availability of specialized inputs and services; and technology spillovers*”. The cluster model is a valuable tool to explain, synthesise and promote economic growth by creating a basis for increased competitiveness. There are diverse “*actors*” that can have different definitions; therefore this concept is used widely in varying contexts, including the maritime context (Doloreux & Shearmur 2009, OCEANO XXI 2010, KIMERAA 2011, IOC 2012, Pinto & Cruz 2012). Figure 70 illustrates the integrated work established within technology, science and management with the prospects services (food, energy, transport or another benefits). The commercial achievement and the success of marine technology in the future essentially depend on economic, management and logistic quality (Moan 2004). Assessment and implementation of relevant enabling technologies (information, communication, automatic control, materials, fabrication and logistics) is required to improve the value and the competitiveness of the final product. Consequently an important concern in this maritime network is how to be competitive by using enabling technologies in addition to suitable and accurate technology (Moan 2004, KIMERAA 2011, IOC 2012, Pinto & Cruz 2012).

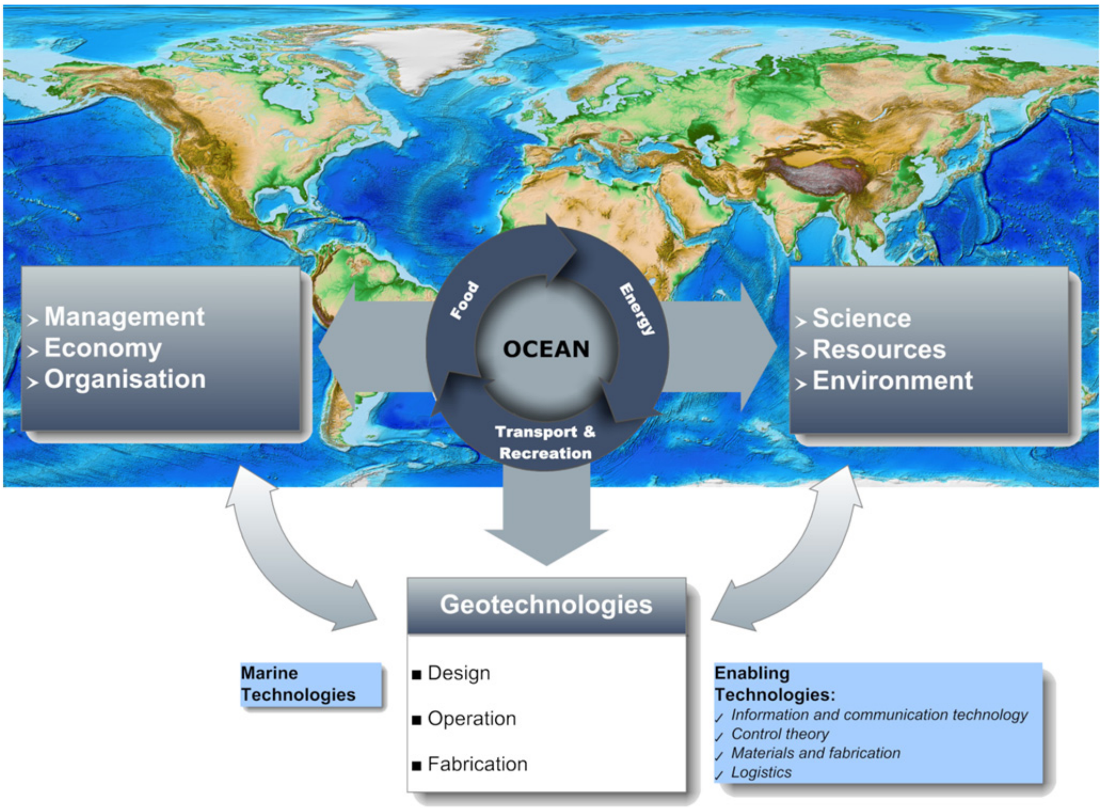



**Figure 70.** Knowledge-based maritime cluster and marine activities (adapted from Moan 2004, KIMERAA 2011, IOC 2012, Pinto & Cruz 2012); the image presented is the *ETOPO1* 1 Arc-Minute global relief model of Earth's surface that integrates land topography and ocean bathymetry, developed in 2008 by the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), USA (for further details see Amante & Eakins 2009; NOAA 2013b).

### *3.2.2. Climate change, sea level rise and coastal erosion*

"*Do you want me to tell you what I think, Yes, do, I don't think we did go blind, I think we are blind, blind but seeing, blind people who can see, but do not see*" (from *Blindness* by José Saramago, 1997: 326). We challenge the reader to be involved and try to "see the sea" from a geoengineering approach. It is not easy to write about a technical subject and to expect that the reader is absorbed all the time. Therefore, like Truman Capote (American short-story writer, novelist and playwright, 1924-1984) states, "*(...) the greatest pleasure of writing is not what it's about, but the inner music that words make*". We hope that the following text succeeds in "making music" regarding the state of the art, without repeating the contents of the papers in *Part II* of the thesis. Hopefully we will tell a short story about climate change, oceans, coasts, maps, geoengineering and how they integrate with each other in coastal studies and analysis.

Regarding coastal processes issues, they must be addressed within a global climate change and erosion problems framework, because these phenomena are the main triggers in terms of coastal hazards, risk of extreme events or disasters. Moreover these problems can lead to new developments in techniques and different approaches to shoreline analysis/assessment related to coastal management.

Nearly all coasts are complex in terms of geologic history, and consequently, the nature and associations of their current features are equally complex (Inman & Nordstrom 1971). As described by the same authors, these features outline complex associations of tectonic development which are adjusted by the joint actions of several agents and processes (marine, terrestrial and organic). All these agents and processes are subject to the effects of the large variations in sea level during the late Pleistocene, commonly known as the Holocene epoch (Inman & Nordstrom 1971). During this same epoch the continental shelf was the main area under active littoral processes (USACE 1995, Davis 2002, Stewart 2008). It is important to introduce and summarily describe the sub-sea features previously defined by the International Hydrographic Organization (IHB 1953). Figure 71 displays a model of the ocean floor summarising and presenting the most important features of the ocean floor, taking into consideration the definitions proposed by Sverdrup *et al*. (1942), Shepard (1973), Dietrich *et al*. (1980), USACE (1995), Woodroffe (2003), Stewart (2008).

There are indications of additional evidence for vertical movements of land and sea due to the exploration of remote parts of the world (for further details about the historical perspective of global tectonics please see Woodroffe 2003). In fact, Darwin (1842) described marine fossils at several hundred metres above sea level and observed this rapid uplift on the coast of South America (Woodroffe 2003, Schwartz 2005, Bird 2008, 2010).

The continental drift proposed by Wegener (1915) and subsequently the so-called theory of plate tectonics is considered the most important geologic discovery of the twentieth century (e.g., Pichon 1976, Wyllie 1976, Ribeiro 2002, Kearey *et al*. 2009, Frisch 2011, Foulger 2010), explaining many aspects of the Earth's crust dynamics and providing the framework for coastal development (Davis 2002, Woodroffe 2003). The classic paper that discusses and relates plate tectonics and coastal evolution is endorsed to Inman & Nordstrom (1971), which provided several models and foundations for coastal development (Davis 2002, work and discussion is based largely on that paper and its general concepts; see also recent work by Duarte *et al*. 2013). In general this plate-tectonic background supported a broad classification of continental coasts proposed by Inman & Nordstrom (1971); on a major scale, coasts are categorised as collision coasts or trailing-edge coasts, depending on whether they are active plate margins or passive mid-plate locations (Davis 2002, Woodroffe 2003, Schwartz 2005, Bird 2008).

Long term vertical and horizontal displacements of land relative to sea level are influenced by the plate-tectonic setting. The variations occurring in the level of the sea have effects on the coast, even on what way the land is abraded by marine processes (Davis 2002, Harff & Meyer 2008). These can be decoded from terraces, shelves or from sequences of sediments that have been deposited in the same situations.

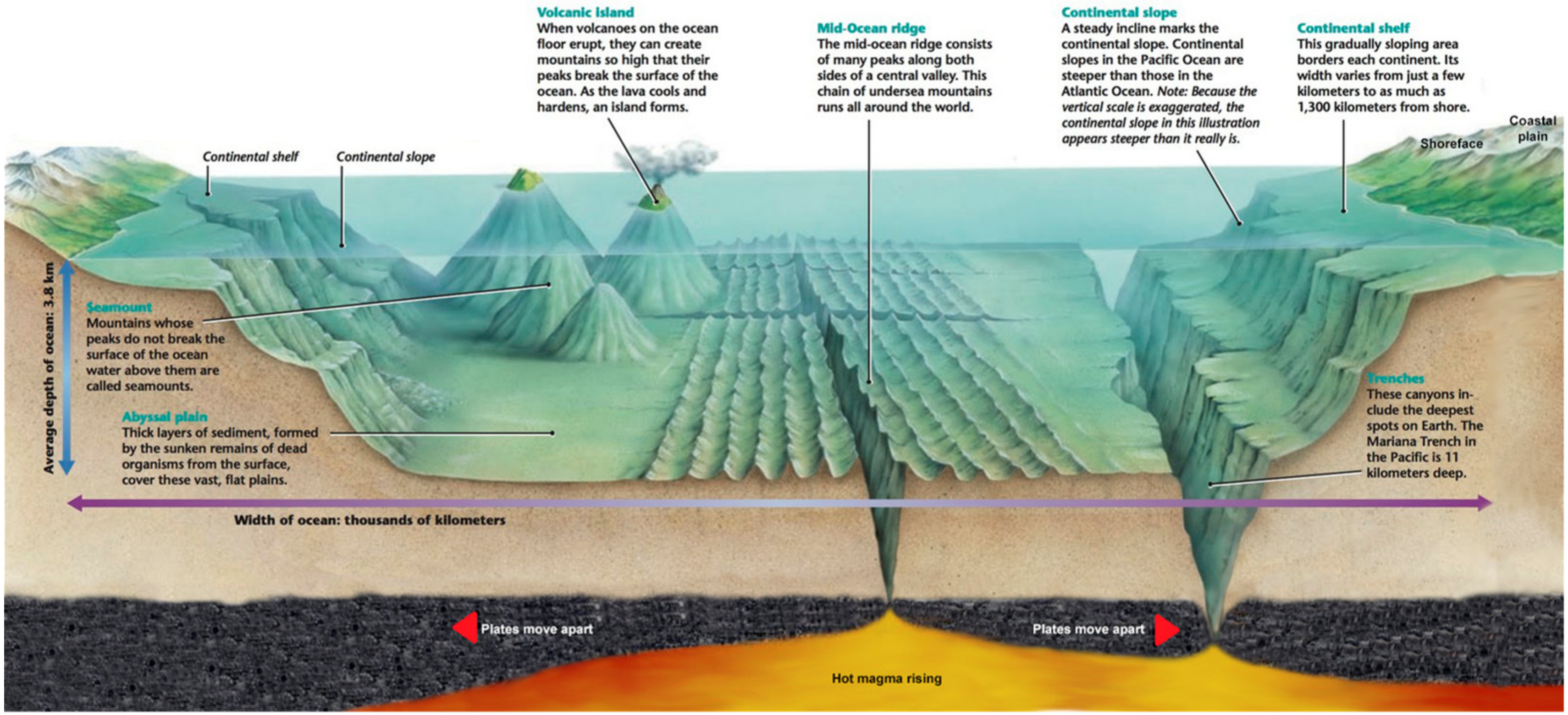



**Figure 71.** Schematic section through the ocean showing principal features of the sea floor (figure not to scale, great vertical exaggeration) (adapted from USACE 1995, Stewart 2008 and the diagram model base adapted from MRTRENT 2011).

Due to such evidence, the significance of sea level changes at geological time scales, especially through the Quaternary, has been widely accepted and several studies have been published all around the world and about the Iberian Peninsula region (e.g. Pérez-Alberti 1991, Trenhaile *et al*. 1999, Dias *et al*. 2000, Muñoz Sobrino *et al*. 2005, Carvalho *et al*. 2006, Alonso & Pagés 2007, Harff & Meyer 2008, Costas *et al*. 2009, Martínez-Cortizas *et al*. 2009, Azevêdo & Nunes 2010, Leorri *et al*. 2013). The study and record of sea level changes has been increasingly refined for the Quaternary (Carter 1988, Woodroffe 2003, Bird 2008).

According to Woodroffe (2003) the vertical displacement between land and sea involves three main components: (1) tectonic movements (result of compressive stress and strain in or between lithospheric plates); (2) sea level variations superimposed on these (predominantly as a result of ocean-volume changes associated with extension and contraction of ice sheets during the Quaternary); and (3) flexural adjustments of the crust, termed isostasy (in response to imposition and redistribution of water, ice, rock and sediment).

Coastal lithology (type of rock) and sediments (fragmented material resulting mainly from rocks) have an important role, since it is sediment flow in response to processes that shapes coastal morphodynamics. Moreover, antecedent landforms apply an influence on the morphology of the coast as sea level changes (Woodroffe 2003, Bird 2008, Bird 2010). Paleoenvironmental reconstruction is essential to provide insights into past coastal morphology and how coastal landforms have changed (Moullade *et al*. 1988, Davis 2002, Woodroffe 2003, Bird 2008, Bird 2010, Jalut *et al*. 2010). As stated by Bicho *et al*. (2011), "*Coastal zones are no longer dismissed as marginal areas full of "fall-back" resources of limited economic value. Instead, coastal zones are being recast as primary eco-niches for humans from the earliest periods of prehistory to the present*."

Eustasy is also an important concept to take into consideration. However, it is a concept shrouded in contradictions and different points of view (see more details in the research of Mörner 1980, 1986, 1996, 2004). By tradition the word eustasy has been used to denote changes in the oceanic level as opposed to changes in the crustal level (Mörner 2004). Initially, it was assumed that changes in the ocean level were identical all over the globe and coasts were rebuilt from postglacial sea level rise, which was primarily assembled into one eustatic curve (Woodroffe 2003). Hence, eustasy was defined as "*simultaneous changes in global sea level*" (e.g. Fairbridge 1961). But the pattern of sea level change differed from place to place, implying that there is no global eustatic curve and that every region must present its own "*regional eustatic curve*" (Mörner 1976, 1986). Therefore, Mörner (1986) proposed a redefinition of the concept "*eustasy*" to represent "*changes in ocean level (regardless of causation)*". Consequently and according to Mörner (1976, 2004) it was then understood that changes in the ocean level are not simultaneous and similar all over the world, but differential and sometimes even opposed (Mörner, 1976, 2004).

All these relationships concerning plate tectonics are relevant and should be analysed on a range of scales, from overall variation over geological time scales (Woodroffe 2003, 2007). Furthermore, the analysis and the link to future ongoing sea level rise over coming decades may result from global warming, as suggested during the years and throughout several investigations (e.g. Gutenberg 1941, Vilas *et al*. 1991, Domingues *et al*. 2008, Ferreira *et al*. 2008, Smith 2010, García *et al*. 2012, Taborda & Ribeiro 2015).

In fact, climate affects the rate at which terrestrial and oceanographic processes operate, and is intrinsically linked to sea level change. On the other hand, these relative changes of sea level somehow confine the shoreline position, the geomorphological processes, influencing how the coast is "sculptured" at a different level of scales (Woodroffe 2003, Schwartz 2005, Bird 2008, Bird 2010).

In terms of present and future sea level trends, it is important to emphasise the importance of sea level as a boundary condition acting as a constraint on the coastal system. In addition, the subject related to sea-level rise at shorter time scales as a consequence of anthropogenic actions has gained new significance and is a growing concern in relation to global environmental change, which is predicted to result from the enhanced greenhouse effect (Barth & Titus, 1984, Woodroffe 2003).

Broadly speaking and according to the IPCC (2007a,b, 2012), climate change refers to "*a change in the state of the climate that can be identified (e.g. by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer*". These alterations can occur due to natural internal processes or external forces, or to persistent anthropogenic changes in the composition of the atmosphere or in land use. In Article 1 of the United Nations Framework Convention on Climate Change (UNFCCC), climate change is defined as: "*a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods*". As a result, UNFCCC makes an explicit distinction between climate variability deriving from human activities and from natural causes, modifying the atmospheric composition (IPCC 2007a,b, 2012).

The anthropogenic drivers, impacts and responses to climate change, and their relations are represented in the schematic framework of Figure 72. Initially the information was mainly available to describe the linkages clockwise (e.g. to derive climatic changes and impacts from socio-economic information and emissions), according to IPCC (2007a). However, with improved understanding of these connections, it is now possible to assess the links also counterclockwise (e.g. to evaluate possible development paths and global emissions restrictions that would reduce the risk of future impacts that society may wish to avoid) (IPCC 2007a, Mcgranahan *et al.* 2007).

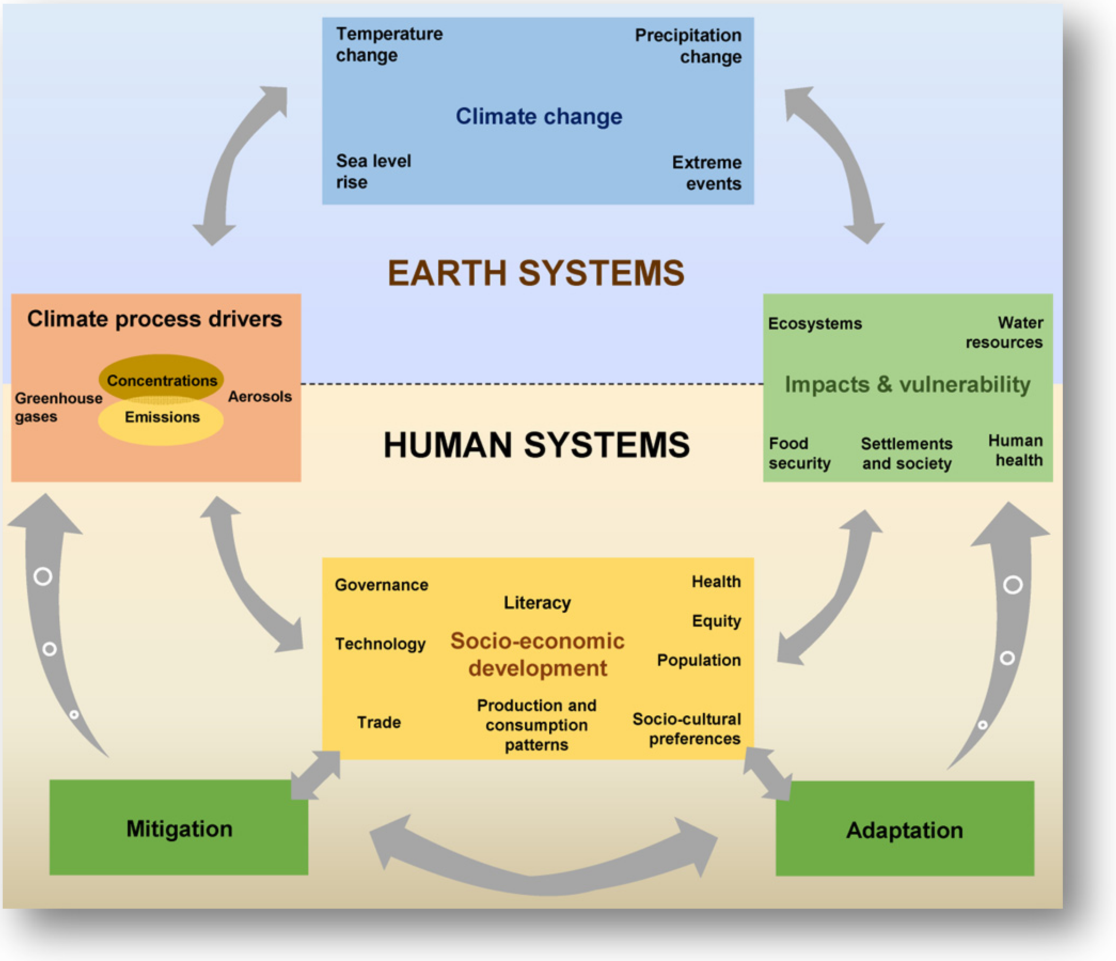



**Figure 72.** Schematic framework representing the link between the anthropogenic drivers, impacts and responses to climate change (adapted from IPCC 2007a).

Regarding the concept of sea level, as stated by EEA (2004), EUROSION (2004), IPCC (2007a,b, 2012), sea level can change, in both a global and local perspective. Changes in sea level can be caused by changes in the shape of the ocean basins, in the total mass of water and in water density. In global warming the factors that lead to sea level rise include an increase in the total mass of water from the melting of land-based snow and ice, and changes in water density from an increase in ocean water temperatures and salinity changes (EEA 2004, EUROSION 2004, IPCC 2007a,b, 2012, NASA 2013a). Finally, according to the same authors, relative sea level rise occurs where there is a local increase in the level of the ocean relative to the coast that might take place because of ocean rise and/or land level subsidence.

Global warming, climate changes and sea level changes are conflicting issues and we can probably say that there is no consensus or unanimity in terms of scientific achievements, research analysis or even in terms of concepts, theories and models. On the one hand, Oreskes (2004) pronounces that there is a consensus about climate changes; on the other hand Walter (2007) asks: "*Consensus? What Consensus? Among climate scientists, the debate is not over*".

This situation shows that this scientific harmony is absent, which has been the topic of several research works (e.g. Doran & Zimmerman 2009, Anderegg 2010). NASA (2013b) debates with several scientists, institutions, organisations and societies, reaching a final decision: "*Observations throughout the world make it clear that climate change is occurring, and rigorous scientific research demonstrates that the greenhouse gases emitted by human activities are the primary driver*" (statement on climate change from 18 scientific associations in 2009). Furthermore NASA (2013b) makes available information on what federal agencies are doing to adapt to climate change (C2ES 2012) and in this way is raising awareness concerning this topic.

Among the most worrying of the presented impacts of climate change is an increase in civil conflict as people compete for diminishing resources such as arable land and water, as described by Solow (2013). Until recently, most works about the relationship between climate change and security were highly hypothetical and speculative, according to Gleditsch (2012). However the latest statistical studies reporting a connection between climate and civil violence have attracted attention from the press and policymakers (Solow 2013). So far, the assessment reports by the IPCC and other authors (IPCC 2007a, 2007b, 2012, Blunden & Arndt 2012) offer little or no guidance on this matter (Gleditsch 2012). But at this point the stakes are too high not to try to do something; "*civil conflict keeps poor countries poor and, if climate change turns out to be an important contributor to such conflict, it would be costly indeed*", as reported by Solow (2013). However, outlining the climate topic as a security problem might influence the perceptions and sensitivities of the actors and "*contribute to a self-fulfilling prophecy*" (Gleditsch 2012).

We believe it is necessary to focus on climate change education, progressive work towards an integrated coastal science, and multisciplinary/interdisplinary research. These approaches should prepare the public, stakeholders or government to face extreme events and disasters with solutions and strategies with regard to coastal management, and likewise develop climate change adaptation (IPCC 2012). Climate change education is redirected in NOAA's long term goal of "*an informed society anticipating and responding to climate and its impacts*" (NSC 2011, NOAA 2013c). The agency is working with the public to develop a broader climate literacy perception, to comprehend climate change and to make more informed choices (NOAA 2013c). In addition, this methodology proposes an "ecletic" path along these concepts, knowledge and experiences on climate events.

Regardless of the incongruent aims for climate change education, several federal agencies have agreed on a shared definition of climate literacy (NSC 2011). Therefore, the fundamental principles of climate, developed by 13 US federal agencies, science and education organisations, defines a climate-literate person as someone who "*understands the essential principles of Earth's climate system, knows how to assess scientifically credible information about climate, communicates about climate and climate change in a meaningful way, and makes informed and responsible decisions with regard to actions that may affect climate*" (U.S. Climate Change Science Program 2009).

NSC (2011) also emphasises that the crucial point in climate literacy is that knowing more about science is not enough to accomplish the final aim of informed decision making and actions. There is clearly a great challenge to education systems that demands a long-term commitment in trying to “solve the puzzle” in relation to the impacts of climate change all around the world (NSF 2009).

It is important to establish strategies and propose approaches to manage the risks of extreme events and disasters due to advance climate change adaptation, but also to establish methodologies and key factors and standard references for policymakers and scientists (EEA 2004, EUROSION 2004, IPCC 2007a,b, Blunden & Arndt 2012, IPCC 2012, NOAA 2013c, Committee on Guidance for NSF on National Ocean Science Research Priorities: Decadal Survey of Ocean Sciences *et al.* 2015).

The severity of impacts from climate extremes is related not only to the extremes themselves but also to exposure and vulnerability. Therefore, adverse impacts are denominated disasters when they produce wide destruction and cause severe alterations in the normal operation of communities or societies (IPCC 2007a,b, 2012). Figure 73a shows the impact of natural climate variability, anthropogenic climate change on climate extremes, other type of weather and climate events that can contribute to disasters, plus the exposure and vulnerability of human society and natural ecosystems (IPCC 2012). Figure 73a also reflects the role of key elements such as exposure and vulnerability, interactions between disasters and development. Disaster risk management and adaptation to climate change can lead to a reduction in exposure and vulnerability to weather and climate events and consequently to a reduction in disaster risk, as well as increased resilience to the risks that cannot be excluded (IPCC 2012). The development of greenhouse gas emissions, anthropogenic climate change and the potential for mitigation of anthropogenic climate change are equally essential processes in this cycle (IPCC 2012).

This risk management cycle assesses a wide range of approaches and complementary adaptation, reducing risks of climate extremes and disasters and increasing resilience to remaining risks as they differ with time (Figure 73b). Although mitigation of climate change is not focused upon in the approaches, coupling adaptation and mitigation could considerably reduce the risks of climate change (IPCC 2012).

The geographical distribution of notable climate anomalies and events occurring around the world can be accessed at NOAA (2013d); Figure 74 displays a 2011 example. This image is a worldwide synthesis which comprises the weather and climate events, engaging them into accurate historical perspective, providing information on the trends, variability and state of the climate system’s many phenomena, featuring several global-scale variables. It is possible to observe that the massive influence of La Niña cooling (El Niño–Southern Oscillation, ENSO) across much of the climate system was persistent during 2011. The assessment of the La Nina impact is distributed among climate’s many disciplines and across its many regions, but with different approaches and sensitivities (a more detailed analysis about the state of the climate in 2011 can be found in Blunden & Arndt 2012).

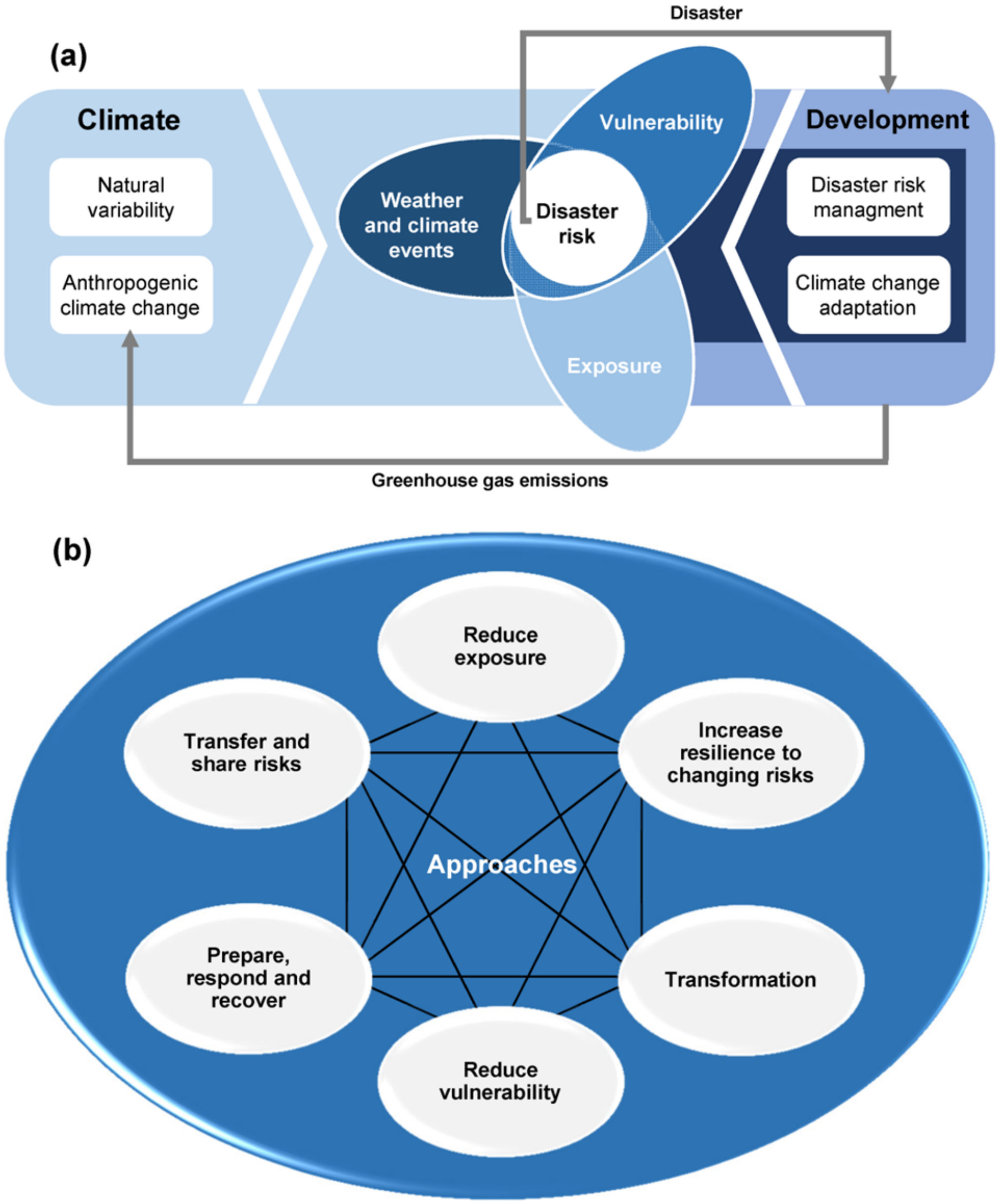



**Figure 73.** Schematic illustration of adaptation and disaster risk management approaches for a changing climate: (a) key concepts involved in disaster risk management and climate change adaptation, and the interaction of these with sustainable development; (b) adaptation and disaster risk management approaches for reducing and managing disaster risk in a changing climate (adapted from IPCC 2012).

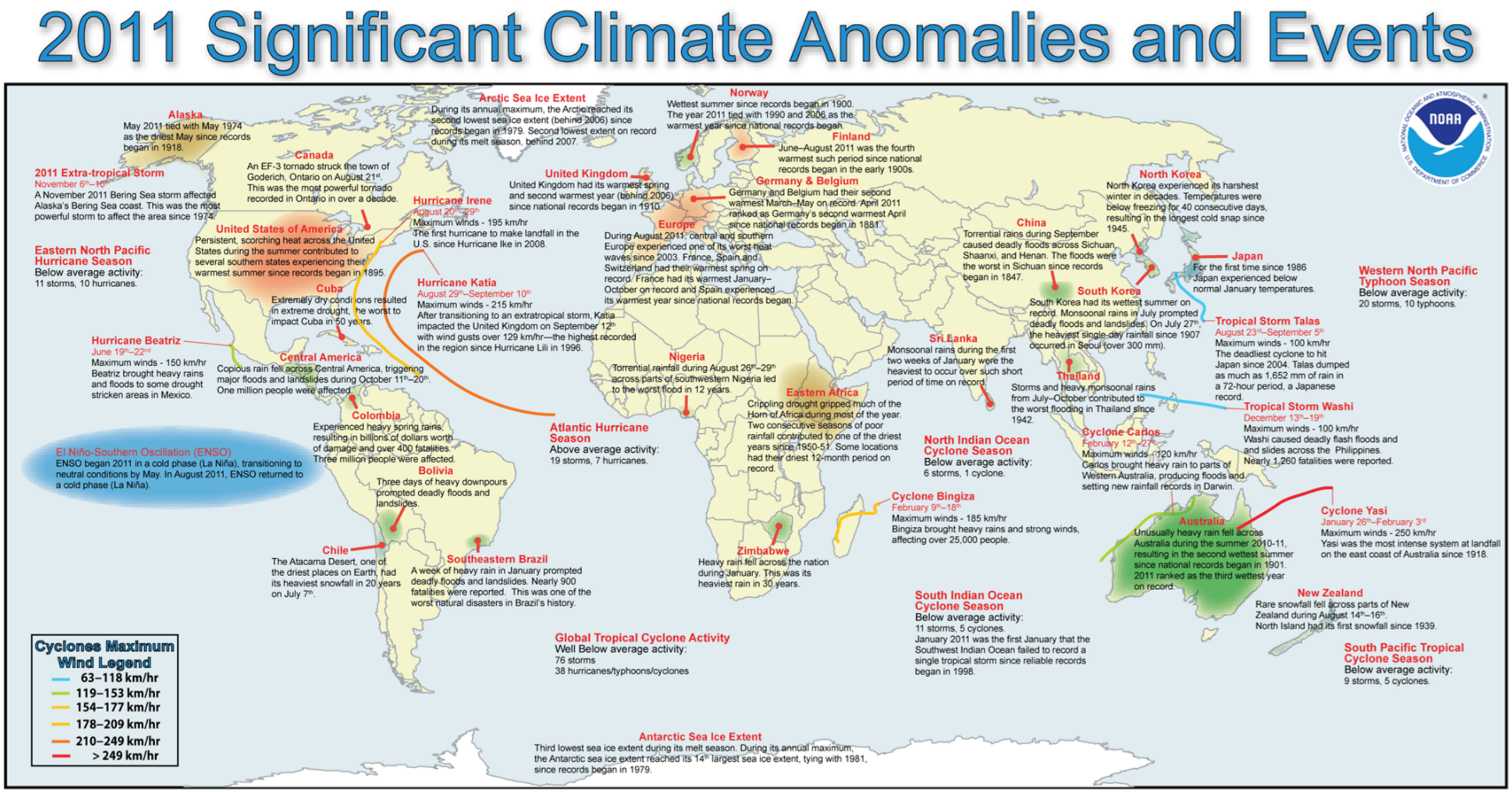



**Figure 74.** Geographic-al distribution of notable climate anomalies and events occurring around the world in 2011 (data available online at NOAA 2013d).

Above were discussed the main reasons or causes for an increasing problem along the shorelines all over the world: coastal erosion. According to the USACE (1984) and EUROSION (2004) coastal erosion outcomes from a combination of several causes and factors – natural and/or man-induced – which have different time and space patterns and are of different natures (reversible, non-reversible, continuous or incidental; EUROSION 2004). In addition, doubts still persist about the interactions of the forcing conditions or agents, as well as on the significance of non-local causes of erosion (USACE 1984 and EUROSION 2004).

These natural and man-induced causes of erosion are listed in Table 8, which summarises and highlights the possible sources responsible for coastal erosion (based on the USACE 1984 and EUROSION 2004 terminologies, perspectives and approaches).

Before adopting any method of coastal protection, it is vital to recognise and understand both the short- and long-term causes of erosion. If we do not succeed in doing so, the shore protection measures applied could really accelerate the process of erosion. All of these causes need to be profoundly analysed to understand long-term consequences. Natural causes can occur as a result of the shoreline response to natural effects, and man-induced effects occur when human activities have an impact on the natural system (USACE 1984). These negative impacts can be activated by a lack of understanding or on the other hand can be improved by balanced coastal zone management. Coastal engineers must struggle to understand the dynamics of the natural system and try to reduce the negative impacts by designing projects which work in harmony with nature (McHarg 1992, USACE 1984).

Figure 75 shows a scheme comprising the main processes that influence and contribute to shoreline variation. This figure synthesises the forcing conditions, processes and nearshore behavioural factors that must be considered. As described by Thornton et al. (2000) the focus of the research was on the interaction of fluid (including wind) processes with developing coastal morphology. We decided to change the geomorphology focus of Thornton et al. (2000) and generalise the diagram by showing that all the included processes represent variables for shoreline change analysis (Figure 75). The response of the nearshore is also a function of sea level, climate, sediment fluxes and anthropogenic effects, and contributes to coastal erosion, modifying the coastline configuration.

Finally, to conclude this section, it is important to make a brief reference to Environmental Impact Assessment (EIA) or Environmental Assessment (EA). In Europe, coastal erosion driven by human activities has overcome the coastal erosion driven by natural factors (EUROSION 2004). As stated before, the main incomes from the growing impacts of small and medium-sized projects have repercussions on man-induced coastal erosion. Progressively, practitioners, competent authorities and project developers are paying more attention to Environmental Impact Assessment (EIA) (CIRIA & CUR 1991, EUROSION 2004).

**Table 8.** Synthesis of the natural factors of coastal erosion human induced factors of coastal erosion (adapted from USACE 1984 and EUROSION 2004).

*Causes of erosion*

| Natural factors | |
|---|---|
| ***Element*** | ***Brief description*** |
| Sea level rise | A long term rise in sea level relative to the land exists in many areas of the world. This rise results in a slow, long term recession of the shoreline, partly due to direct flooding and partly as a result of profile adjustment to the higher water level. |
| Variability in sediment supply to the littoral zone | Changes in the world's weather pattern that cause lacks (e.g. rainfall, precipitation) can result in a reduction in the occurrence of floods on rivers supplying sediment to the coastal zone. |
| Waves | Waves are generated by offshore and near-shore winds, which blow over the sea surface and transfer their energy to the water surface. As they move towards the shore, waves break and the turbulent energy released stirs up and moves the sediments deposited on the seabed. The wave energy is a function of the wave heights and the wave periods. |
| Winds | Winds act not just as a generator of waves but also as a factor of the landwards move of dunes (Aeolian erosion). |
| Tides | During high tides, the energy of the breaking waves is released higher on the foreshore or the cliff base (cliff undercutting). Macro-tidal coasts (i.e. coasts along which the tidal range exceeds 4 meters), all along the Atlantic sea, are more sensitive to tide-induced water elevation than mesa- or micro-tidal coasts. |
| Near-shore currents | Sediments scoured from the seabed are transported away from their original location by currents. In turn the transport of (coarse) sediments defines the boundary of coastal sediment cells, i.e. relatively self-contained systems within which (coarse) sediments stay. Currents are generated by the action of tides (ebb and flood currents), waves breaking at an oblique angle with the shore (long-shore currents), and the backwash of waves on the foreshore (rip currents). |
| Storms | Storms result from raised water levels (known as storm surge) and highly energetic waves induced by extreme winds. Combined with high tides, storms may result in catastrophic damage such as that along the North Sea in 1953. Beside damage to coastal infrastructure, storms cause beaches and dunes to retreat, or may considerably undermine cliff stability. In the past 30 years, a significant number of extreme historical storm events have occurred that severely damaged the coast. |
| Longshore sediment transport | Sand is transported alongshore by waves breaking at an angle to the shore. If the sediment carrying capacity of the longshore current generated by these waves exceeds the quantity of sediment naturally supplied to the beach, erosion of the beach results. |
| Slope processes | The term “slope processes” encompasses a wide range of land-sea interactions which eventually result in the collapse, slippage, or topple of coastal cliff blocks. These processes involve on the one hand terrestrial processes such as rainfall and water seepage and soil weathering (including alternating freeze/thaw periods), and on the other hand the undercutting of cliff base by waves. |
| Vertical land movements | Vertical land movement – including isostatic rebound, tectonic movement, or sediment settlement – may have either a positive or negative impact on coastline evolution. |

| Man-induced factors | |
|---|---|
| ***Element*** | ***Brief description*** |
| Coastal artificialisation (hard defences) | Coastal artificialisation may be defined as the engineering of the waterfront by way of seawalls, dykes, breakwaters, jetties, or any hard and rock-armoured structures that aim at protecting infrastructure or other assets landwards of the coastline from the assault of the sea. Such structures modify coastal sediment transport patterns through 3 major processes: (i) trapping of sediment transported alongshore and a sediment deficit downdrift due to the fact that contrary to “natural” coastlines, hard structures do not provide sediment for the alongshore drift; (ii) incoming wave reflection by hard structures that hampers energy dissipation and augments turbulence resulting in increased cross-shore erosion. This phenomenon has been paradoxically boosted along those coastal stretches where seawalls have been built precisely to counteract coastal erosion; (iii) wave diffraction, which is the alteration of the wave crest direction due to the vicinity of seaward structures (such as jetties or breakwaters). This alteration results in wave energy being either diluted in some places (less impact on the coastline) or concentrated in some other places (more impact on the coastline and subsequent erosion). |
| Land reclamation | The impact of land reclamation projects undertaken in the 19th and first half of the 20th century on coastal erosion has become obvious only in the last few decades. Within tidal basins or bays (where land reclamation projects are easiest to undertake), land reclamation results in a reduction of the tidal volume and therefore a change in the ebb and flood currents transporting sediments. |
| River water regulation works | Carried out for purposes such as for land reclamation, the impact of water flow regulation works on coastal processes has been highlighted only recently, as such impacts probably become visible only after several decades. Damming has led to intensively sealed water catchments locking up millions of cubic metres of sediments per year. |
| Dredging | Dredging activities have intensified in the past 20 years for navigational purposes (the need to keep the shipping routes at an appropriate water depth), construction purposes (an increasing amount of construction aggregates comes from the seabed), and since the 1990s for beach and underwater nourishment. Dredging may affect coastal processes in a variety of ways: (i) by removing from the foreshore materials (stones, pebbles) which protect the coast against erosion; (ii) by contributing to the sediment deficit in the coastal sediment cell; (iii) by modifying the water depth, which in turn results in wave refraction and change of alongshore drift. |
| Vegetation clearing | A significant number of cases have highlighted the positive role of vegetation in increasing the resistance to erosion in sandy coasts and environments. With the same idea, changes in land use and land cover patterns that tend to reduce the vegetation cover on the top of cliffs may increase infiltration of water and undermine the cliff stability. |
| Land subsidence from removal of subsurface resources | The removal of natural resources underlying the coastal zone, such as gas, oil, coal, and groundwater, may cause subsidence of the beach. This has the same effect as a sea level rise. |

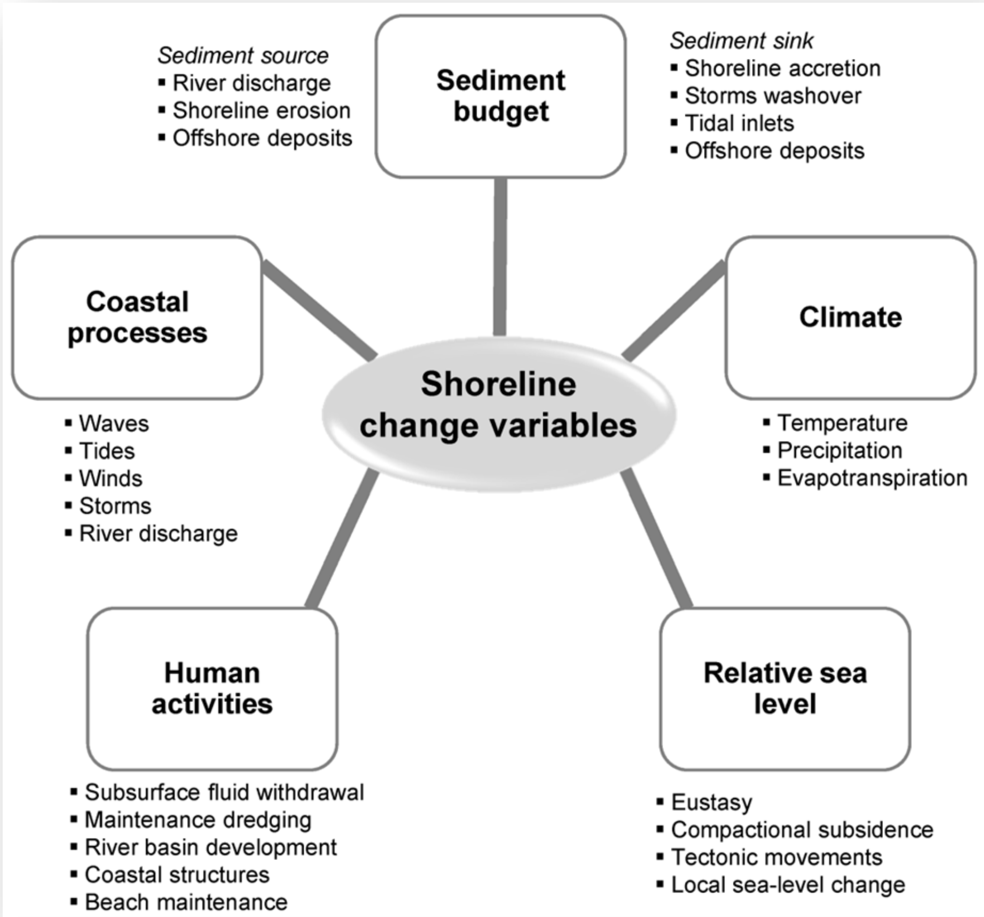



**Figure 75.** Processes that influence and contribute to shoreline variation (adapted from Thornton *et al*. 2000).

According to CIRIA & CUR (1991), shoreline engineering works may affect (or be affected by) the social and natural environment in which they are placed. Moreover, some studies take into account the effect of climate changes when designing new coastal structures in order to fulfil the established functional and stability criteria during their life cycle. These reports also indicate that in a few decades some existing coastal structures may loose part of their functionality and stability (Olabarrieta *et al*. 2007, Dupray & Simm 2008). Figure 76 illustrates some of the variables, factors and processes (described before) with the typical aspects of the environment. This figure draws attention to the relevance of EIA/EA projects. EA should be an integral part of the design process and it would be more beneficial for the EA to begin at the conceptual stage of a coastal project (CIRIA & CUR 1991). The figure lists different aspects: (i) geomorphology, landscape and physical geology processes (climate, erosion, drainage, sediment transport); (ii) ecology (flora and fauna); (iii) social and economic features; (iv) human sensory characteristics (noise, visual disturbance); (v) cultural, historical, and archaeological perspectives; and (vi) water, air and soil factors (pollution, contamination) (Figure 76) (CIRIA & CUR 1991).

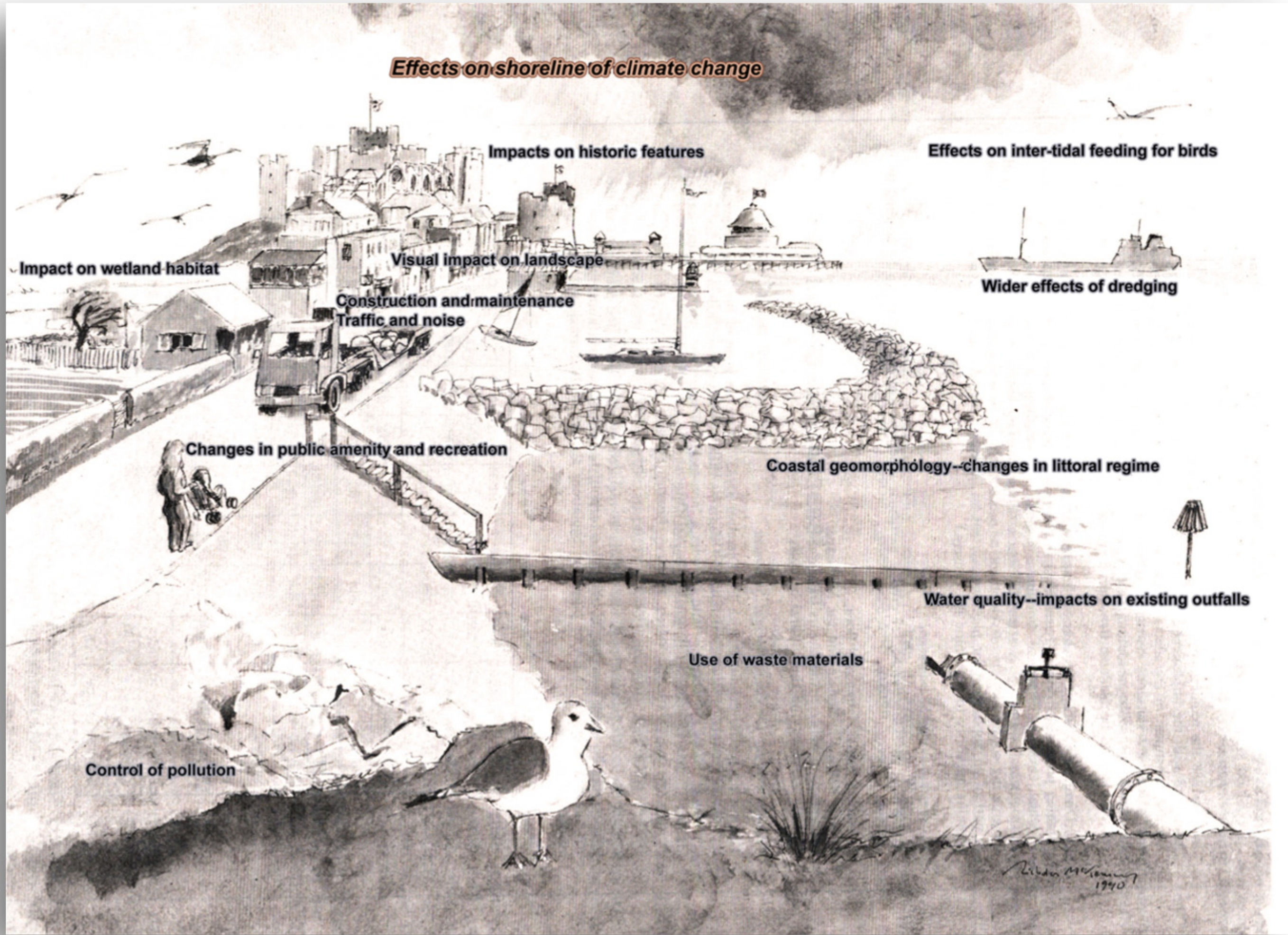



**Figure 76.** Typical coastal environmental impacts and shoreline engineering works distresses (adapted from CIRIA & CUR 1991).

### *3.2.3. Cartography and maps*

"*There are several other sources of enjoyment in a long voyage, which are of a more reasonable nature. The map of the world ceases to be a blank; it becomes a picture full of the most varied and animated figures. Each part assumes its proper dimensions: continents are not looked at in the light of islands, or islands considered as mere specks, which are, in truth, larger than many kingdoms of Europe. Africa, or North and South America, are well-sounding names, and easily pronounced; but it is not until having sailed for weeks along small portions of their shores, that one is thoroughly convinced what vast spaces on our immense world these names imply*" (Charles Darwin 1839, Voyage of the Beagle; *in* Keynes 2001).

Because maps were an important tool throughout this thesis and since they are one of the oldest forms of human communication, we would like to dedicate a short section to an outline of a history of cartography. The main goal is not to accomplish a very exhaustive study of the historical aspects of mapping, as this is not the central focus in the thesis; however, it is important to build a framework and to ensure background knowledge to understand the historical perspective and how all the elements integrate with coastal science, including the ocean. Fortunately, the history of cartography has already been the topic of a systematic and thorough study. The History of Cartography Project was a research, editorial, and publishing development which draw international attention to the history of mapping. This project resulted in the publication of a multi-volume series on the history of cartography (Harley & Woodward 1987, 1992, 1994, Woodward & Lewis 1998, Woodward 2007). The publication comprises 3 volumes (5 books) with all the information about the foundation of cartography, first maps, and considerable number of illustrations, examples and a gallery of plates. This research has an interdisciplinary approach embracing scholars in the arts, science, and humanities, considering previously ignored aspects of cartographic history and assessing the importance of maps for the historical study of society. According to Harley & Woodward (1987), maps "*constitute a common language used by men of different races and tongues to express the relationship of their society… to a geographic environment*". Hence cartography (in a broad sense the discipline and art of making maps) has been an integral part of human history for thousands of years and has progressed enormously (Okada *et al*. 2008).

Like painting, mapmaking predates both number systems and written language. Primitive people created maps for orientation in both the living environment and the spiritual worlds (Okada *et al*. 2008). These visual representations in assemblage unwrapped new potentials for focusing on visualising new scenarios, re-creating the past, coordinating actions and making decisions. Maps help us make sense of the universe at different scales, connecting the nonconcrete with the concrete by overlaying implications on the world and remembering what is important, and help us to explore possible configurations of the unknown (Okada *et al*. 2008).

From cave paintings to ancient maps of Babylon, Greece, and Asia, and right into the 21st century, people have created and used maps as tools to help them define, explain, and navigate through the world. Just as was done with maps of stone, wood, and animal skins, we currently manipulate software tools that control maps as modern views generated from several data, layers and annotations (Okada *et al*. 2008). Maps can be applied to make several configurations perceptible, and represent a significant step forward in intellectual and culture development, whether sketched on a napkin or modeled in software (Okada *et al*. 2008).

Friendly & Denis (2001) created an interesting project about the history of thematic cartography, statistical graphics, and data visualisation. Their study displays the milestones in the graphic representation of quantitative information interconnected with histories of thematic cartography, statistical graphics, and data visualisation, which are "tangled" with each other (Friendly & Denis 2001). They relate the earliest stones placed in geometric diagrams with the mapmaking to aid in navigation and exploration. It is a crosswalk throughout the first maps, the techniques and instruments for precise observation and measurement of physical quantities (16th century); analytic geometry, theories of errors of measurement, the birth of probability theory, and the beginnings of demographic statistics and "political arithmetic" (17th century); the birth of statistical thinking and analysis, visual thinking (diagrams, nomograms, graphics), and the growth of thematic cartography for maps and visual representations (over the 18th and 19th centuries); the intensification of statistical thinking (19th century); and developments in technology (20th century) (for further details see Friendly & Denis 2001). These findings provide several types of information: (i) chronological benchmarks and information about geographical features and insights; (ii) confirmation of the universal nature of mapping; (iii) help in elucidating cultural differences and influences; (iv) valuable data for tracing conceptual evolution in graphic presentations; (v) data to enable the examination of relationships to more "*contemporary primitive*" mapping (Harley & Woodward 1987, Friendly & Denis 2001, Okada *et al*. 2008).

"*The eyes are not responsible when the mind does the seeing*" (Publilius Syrus, 85-43 BC; *in* Okada et al. 2008). Let us begin with the oldest known map. There are several claimants for this honour and searching for the earliest forms of cartography is a continuing effort of considerable interest and fascination.

Figure 77 shows two of the oldest maps documented. One of the most famous artifacts presented as the oldest cartographic effort is the Babylonian map inscribed on a clay tablet (Figure 77a). These type of maps developed by the Babylonians usually vary in scale (ranging from small scale to regional, local or large scale images) displaying the world conceptions. These cartographic relics show detailed interpretations which can have conflicting evaluations relating to their design, age, and meaning or implication (Dias 2004, The British Museum 2013). The exterior part of the tablet is inscribed with a map of a district bounded by two ranges of hills and bisected by a watercourse. The sexagesimal system of mathematical cartography developed by the Babylonians is also illustrated and outlines the earliest known model of a topographic map (Harley & Woodward 1987, Dias 2004, The British Museum 2013).

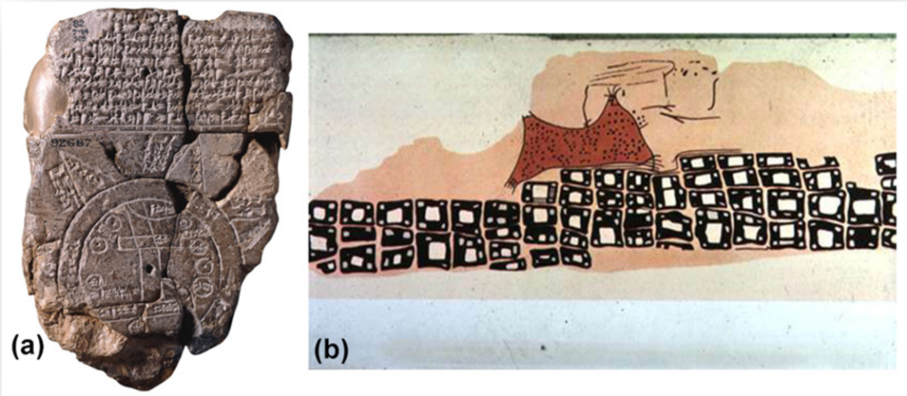



**Figure 77.** The oldest maps? (a) Babylonian world map (c. 700-500 BC), British Museum, UK (image available in The British Museum 2013); (b) Konya town map (c. 6200 BC), Museum at Konya, Turkey (image available in Friendly & Denis 2001).

The image clearly shows Babylon surrounded by a circular landmass showing several cities such as Assyria, Urartu and others. These cities are delimited by a "*bitter river*" (Oceanus), with seven islands arranged around it so as to form a seven-pointed star. This world map is believed to be a symbolic rather than an accurate exemplification of the world for the Babylonians. The area shown is described as a circular shape surrounded by water, which is in accordance with the religious image of the world in which they believed (Harley & Woodward 1987, Dias 2004, The British Museum 2013).

Conversely, though the Babylonian clay tablet map described previously has been the largely accepted "*earliest known map*".,the map-form discovered in the early 1960s by James Mellaart in Ankara (Turkey) during an excavation in Anatolia is also an important cartographic artifact (Figure 77b). This old map, although less distinctive and on a much larger scale, represents a wall painting that is approximately 2.7 m in length. According to several authors (Harley & Woodward 1987, Friendly & Denis 2001, Dias 2004, Okada *et al*. 2008) as well as James Mellaart, this map describes a town plan, matching *Çatalhöyük* (Anatolia) itself, showing the overfilled structured design of the settlement and displaying about 80 buildings. Behind the town a volcano is shown with volcanic rocks falling down the slopes of the mountain, and others are being thrown from the erupting cone above which “blazes” a cloud of smoke and ashes (Harley & Woodward 1987, Friendly & Denis 2001, Dias 2004, Okada *et al*. 2008).

Obviously, the Babylonian symbols inscribed on the clay tablet or even the *Çatalhöyük* map do not represent the initiation of cartographic history. There are many others that will claim this honor and investigation into the early development of cartography will continue to document such geographical spatial concepts with a reasonable probability of further success. This positivity is justified by the fact that the materials used during these periods were more durable elements, for example, metal, clay, ceramics or stone, as opposed to later cartographic objects made of more fragile materials such as wood or paper.

Figure 78 displays the first maps of the world. Anaximander, one of the earliest Greek thinkers and philosophers (c. 610-546 B.C.E.), is recognised for creating one of the first maps of the world (Figure 78a). This map has a circular form and exposes the known lands of the world gathered around the Aegean Sea at the center and all surrounded by the ocean (Harley & Woodward 1987, Dias 2004). Based on Anaximander's map of the world, a Greek historian, Hecataeus of Miletus (c. 550-476 B.C.E.), created a corrected and enlarged version (Figure 78b). This Greek historian defined the regions of the world reaching as far north as Scythia and to Asia in the east. He was also the author of the geographical survey of countries and populations of the known world, describing Egypt in particularly detail (Harley & Woodward 1987, Dias 2004).

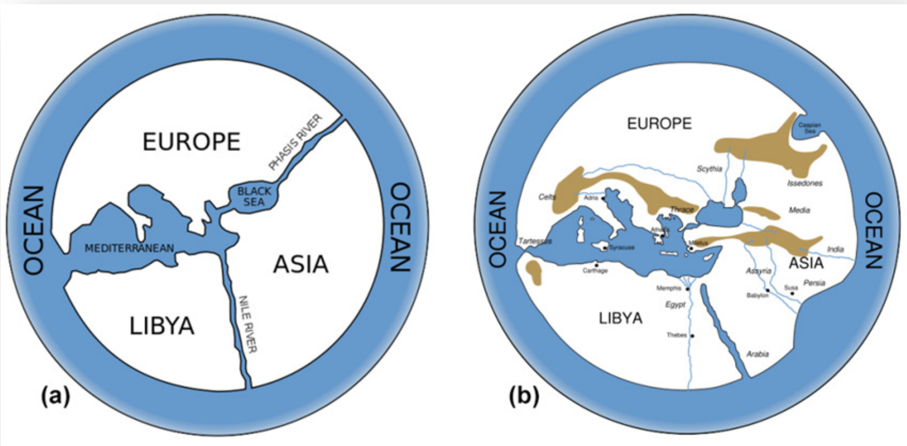



**Figure 78.** The first world maps? (a) Anaximander world map (c. 610-546 BC); (b) Hecataeus of Miletus world map based in the previous map from Anaximander (c. 550-476 BC) (images from Amusing Planet 2012, adapted from the original maps).

To conclude our brief survey, Posidonius (c. 150-130 BC), a Greek philosopher, published a work about the ocean and its contiguous areas (Figure 79). This work, besides being a global representation of geographical questions, also helped to promote his concepts about the internal connections of the world, to show how all the forces had an effect on each other and also how these interdependences are intimately related to human life, politics or personal circles (Harley & Woodward 1987, Dias 2004).

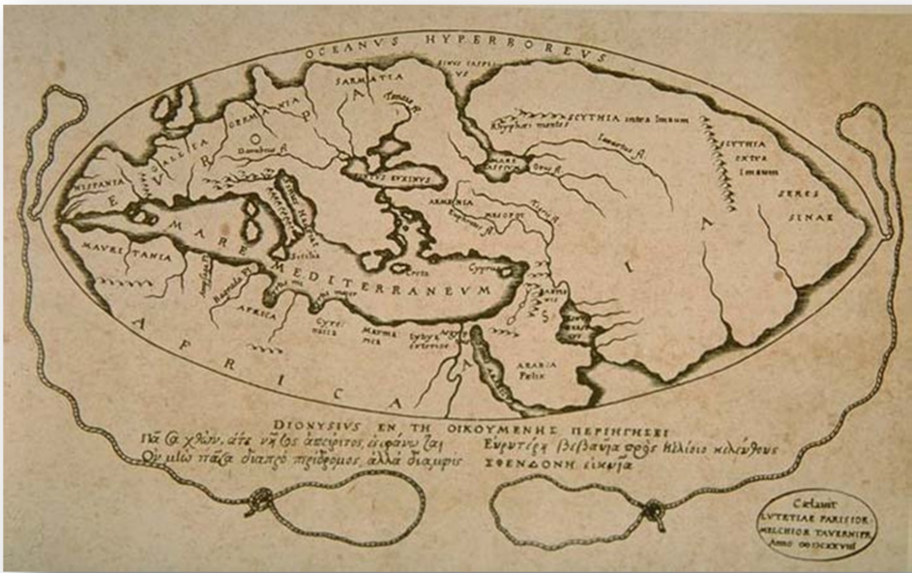



**Figure 79.** The first map which conceptualised the ocean (Posidonius, c. 150-130 BC) (image available in Amusing Planet 2012).

"*Maps have been used to make visible and legitimate the invisible complex environmental knowledge, needs and claims of people disenfranchised and misrepresented*" (Rocheleau, *in* Brosius *et al*. 2005: p. 328). There are several early world maps and cartographic pieces that could be listed. However the maps presented herein are some of the most important and scientifically recognised maps. There are different purposes for these maps but a shared meaning: to communicate.

"*Não é pois a grandeza territorial das nações, nem mesmo a riqueza do seu solo, que lhes dá o carácter de nações comerciais. É a sua situação, a sua configuração, as suas condições naturais, a índole dos seus povos, e principalmente o seu contacto com o mar, por onde podem ter acesso e comunicar-se com o estrangeiro pelo meio mais económico, que lhes dão esse carácter*", (Loureiro 1904: p. 27). This means more or less that: "*It is not the territorial greatness of nations, nor even the richness of their soil, which gives them the character of trading nations. It is their situation, their configuration, their natural conditions, the soul of their people, and particularly their interaction with the sea, where they can have access and communicate overseas by the economic income that will give them that attraction*".

The ocean, the sea and the coast…we have always been fascinated by the coast and the study of the coast is probably as old as any study. For example the term "delta" originates from the Greek capital letter "D," (Δ) which was thought to resemble the triangular shape at the mouth of the Nile River, and even the Greek historian Herodotus observed this similarity of its shape to the Greek word "delta" (Woodroffe 2003).

But the first real scientific interest in coasts initiated in the context of navigation beyond the Mediterranean in the post-Renaissance period. Global exploration such as geological or biological investigations were frequently extensions of the survey work carried out by naturalists and followed by the analysis of hydrographers like Bellingshausen or Wharton (Woodroffe 2003).

The scientific work of Leonardo da Vinci (1452-1519) was nearly unknown during his lifetime and remained unknown until the 19th century. He made important achievements and discoveries in many fields (biology, geology, mathematics, engineering, anatomy, military, architecture, painting, sculpture, music, arts, etc.), but also contributed to physical geography and geology, including land surveying and mapping. His cartographic contributions are acknowledged and he actually drew beautiful and accurate maps with a variety of purposes throughout his life (Blevins 2010). Perhaps we can say that he was a painter, a land surveyor and a master in cartography too, since he had an unusually curious mind and outstanding polyfaceted personality. According to Blevins (2010) Leonardo, like so many great skilled persons, earned his living through the art of measuring and mapping the land. He had the power to visualise, observe and to work the nature scenes on the scale of entire rock mountainous valleys or water dynamics, in order to create maps or landscapes (Blevins 2010).

A few examples of Da Vinci's work shows that he was attracted to coastal plans and other type of studies, in general related with water (Figure 80). The Val di Chiana map (Figure 80a) indicates the changes in elevation by using colour. Likewise the image of the accurate shoreline portrayed by Da Vinci illustrates his plan for draining the coastal Pontine Marshes in Italy in the 15th century (Figure 80b). And then we also have other sketches comprising water investigations (Figures 80c and 80d). Therefore Blevins (2010) claims that: "*Leonardo's second Florentine period, 1500 to 1516, [age 48-64], was perhaps the most productive period of his life. Leonardo's maps from that period show geographical details with a degree of accuracy far beyond anything attempted by the cartographers of his time. He used washes of different intensities to follow the contours of mountain chains, different shades representing different elevations, and he pictured the rivers, valleys, and settlements in such a realistic manner that one has the eerie feeling of looking at the landscape from an airplane.*"

The approaches involved more than recreation of images. There seem to be a more deep and mystic aspirations in his work. Da Vinci's motivation in exploring cartographic techniques and applying these techniques to landscape representation and the nature of the landscapes painted by him has long been debated (Kemp 2011, Pezzutto 2011, 2012). Pezzutto (2011, 2012) dedicated his research to the comparison of maps and landscapes created by Da Vinci; for example the *Mona Lisa* provides the exceptional opportunity of a painted landscape corresponding to a particular location that was mapped by that artist in the Val di Chiana map (Figure 80a); or also Leonardo's *Annunciation*, *Madonna of the Yarnwinder* and *Virgin and Child with St Anne and Lamb* that shown landscapes that match other features and locations (for further details about the methods applied and analysis see Pezzutto 2011, 2012).


**Figure 80.** Examples of Da Vinci work with coastal plans and water studies: (a) Da Vinci, Val di Chiana (1502-3); (b) bird's-eye-view of sea coast, Roman southern coast, coastal Pontine Marshes in Italy (c. 1515); (c) Studies of water (1509-11); (d) Studies of water (c. 1513) (Credits: Royal Collection, Windsor; available at Web Gallery of Art 2013).

The prevailing opinion of art historians is that these paintings or maps represent a synthesis of contrasting elements (Kemp 2011), but opposed to this opinion there is a theory that they represent particular locations (Pezzutto 2011, 2012). Nevertheless, Da Vinci has demonstrated his skills and innovative techniques as a cartographer. He also revealed a particular sensitivity or awareness in cosmology, in his case the knowledge of the earth as a complex sphere (Pezzutto 2011, 2012). There are many examples of this concept found in his notes and drawings and even his notebooks.

These transcriptions anticipated the heliocentric universe of Copernicus, indicating the level of his knowledge of cosmology: "*The earth is not in the centre of the Sun's orbit nor at the centre of the universe, but in the centre of its companion elements, and united with them. And anyone standing on the moon, when it and the sun are both beneath us, would see this our earth and the element of water upon it just as we see the moon, and the earth would light it as it lights us*" (Da Vinci 2003).

In conclusion, Da Vinci invented and improved surveying tools and presented cartographic techniques that are currently applied. Exhaustive and accurate land measurements were performed and many complicated cartographic "master works" were created. The painter, naturalist and surveyor are main characteristics which shaped the "*single enquiring mind*" (Blevins 2010). According to Blevins (2010), Leonardo da Vinci was an astonishing land surveyor and cartographer; however he was one of us, despite being the "*Master of Earth*". Presently map-makers, surveyors and geomatic engineers have a respected and unique heritage in terms of art, science, geography and history (Blevins 2010).

The development of cartography and maps are related to the progress made in military operations, geography, geology, engineering geosciences and topography, in broad terms. The reader should be aware that in military operations and war history, there are important scientific basis, methodologies and techniques in cartography that have developed over the years. The use of road or strategic maps in battles, from Ancient Rome to the World Wars and up to today, meets the demands of military or administrative organisations. Throughout time, these maps or charts were all created by skilled surveyors and military engineers using up-to-date instruments and surveying principles, to improve military efficiency and to support military strategies. Baker (1996-2011) presents a collection of maps with accessible examples for anyone who wishes to research the places of interest to the British Army of World War I. Two categories of maps are available: campaign and battle maps. This is historical research compiled from books and "odd places", as stated by the author (Baker 1996-2011). From basic cartographic techniques in to advanced maps, battle lines and movements of forces during war are shown, as sketch and trench maps, using topographic features, geographic elements, strategies or plans, toponomy, natural watercourses, geomorphology, geological resources, etc.

In 1959, Dwight D. Eisenhower (in Caldwell *et al*. 2004) declared at the White House that: "*The principles of war are not, in the final analysis, limited to any one type of warfare, or even limited exclusively to warfare itself … but, principles as such can rarely be studied in a vacuum; military operations are drastically affected by many considerations, one of the most important of which is the geography of the region*". It is necessary to adopt a geo-perspective in this matter, because physical conditions, geography, geology, hydrogeology and many others are important scientific fields in military processes (e.g., Kiersch 1998, Caldwell *et al*. 2004, Haneberg 2004, Rose & Clatworthy 2008a,b, Rose & Rosenbaum 2011 and references therein).

These fields of research are naturally connected with each other and the first recognised military operation using geological-based guidelines was in 1813, when Professor von Raumer analysed the terrain of Silesia for the Prussian General von Blucher (Kiersch 1998). Many other studies and developments were followed by other pioneers that improved cartographic techniques and geologic and geomorphological maps in military approaches (Rose & Clatworthy 2008b). And then others drew attention to the importance of engineering geology and geoscience (Kiersch 1998, Rose & Rosenbaum 2011). According to Haneberg (2004), geology and topography have placed important restrictions on military operations since the beginning of organised warfare. As indicated by Haneberg (2004), these are important fields of action because: the movement of troops on foot, on horseback, or in motorised vehicles can be slowed down by the topographic and soil conditions; the bedrock type and strength are important factors in the construction of the camp base; the availability of groundwater supplies can control the location; and mountainous terrain can provide good cover to guerilla forces or small groups of operatives. Since the Napoleon's invasion of Egypt in 1798, the use of people with knowledge in geology has been reported. Hence throughout the nineteenth century (for example at the Battle of Gettysburg in 1863) geological and topographical considerations were recognised and had an important part in military operations (Haneberg 2004).

What is important to retain from this is that the use of geologic information became common during World War I and World War II, and for instance they even created a military geology branch in the United States Geological Survey (Haneberg 2004). The continuous growth of these research areas (geology, geography, hydrogeology, engineering, GIS applications and GIScience, remote sensing, photogrammetry, etc.) over the years has allowed cartographic methods and mapmaking to expand to other fields of action and to higher levels of conception, visualisation, outputs and difficulties.

During the 20$^{th}$ century maps developed exponentially. The more advanced technologies we have, the more excellent the maps that will be generated. From the several devices available in the market, more accurate data and surveying, to the photogrammetry techniques, it is possible to perform more accurate mapping. In the last decades we can benefit from the rugged computers, high resolution GPS or even tablets or iPAD’s that make it possible to create maps in real time. On the other hand we also have remote sensing approaches which allow an outstanding quality of satellite imagery, geospatial information and geovisualisation (e.g. LANDSAT, SPOT), sweeping almost the entire Earth with current maps. Therefore, presently we work with maps and live in a digital world exposed to constant evolution. This progress in cartography is displayed in Figure 81, which gives a brief overview of some of the major trends affected by the digital technology that started to transform the discipline in the 1960s (Views of the world 2009, Hennig *et al*. 2010, Hennig 2013). In addition, we can report the progress from the general reference maps which entertain and build new branches until the modern cartography.

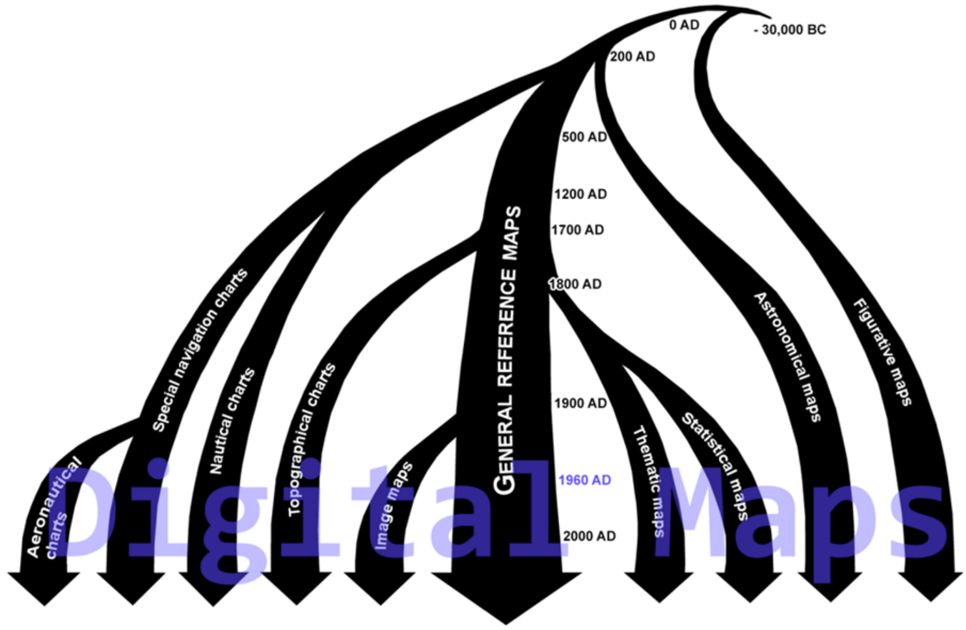



**Figure 81.** Evolution of cartography and maps (adapted image from the presentation slides created by Dr. Benjamin D. Hennig of the SASI Research Group|University of Sheffield [Views of the world 2009] published in September 2012).

Modern cartography points out that the concern with design begins to be significant, and despite the fact that GIS dominion has ignored design in the past, we are now aware that a map must "talk". It is necessarily an elegant display of the geographic data which is as important as the data itself (Peterson 2009). In a modern cartography approach we can not forget the terms *multimedia* and *World Wide Web* (WWW). In recent years, great progress has been made in cartography and map-making but the most amazing step is the level of world projection of our maps. Coupling media with an interactive linking structure, we achieve multimedia cartography, enhancing the user experience. Multimedia is interaction with multiple forms of media supported by the computer (Cartwright *et al*. 2007). As defined by Cartwright *et al*. (2007), multimedia cartography is best defined as a world atlas, which gathers in book format a collection of maps and is a reference to people. "*The atlas has been a window to the world for millions of people. It is consulted when one needs to know where something is located or something about a region of the world. The atlas forms the basis for how people conceive the world in which they live*" (Cartwright *et al*. 2007). The atlas is our computer, our image, our maps… The World Wide Web (WWW) broadcasts geospatial data and according to (Kraak & Brown 2001) only few in the geosciences field have not (yet) found a use for the WWW. In this process a map plays an important and emerging role and has multiple functions. Moreover to search and publish geospatial data it is required to have an accetable geospatial infrastructure. Currently, maps are also applied to navigate, to map cyberspace and to map websites (Kraak & Brown 2001).

### *3.2.4. Art in coastline evolution*

"*Facile credo, plures esse Naturas invisibiles quam visibiles in rerum universitate. Sed horum omnium familiam quis nobis enarrabit? et gradus et cognationes et discrimina et singulorum munera? Quid agunt? quae loca habitant? Harum rerum notitiam semper ambivit ingenium humanum, nunquam attigit. Juvat, interea, non diffiteor, quandoque in animo, tanquam in tabulâ, majoris et melioris mundi imaginem contemplari: ne mens assuefacta hodiernae vitae minutiis se contrahat nimis, et tota subsidat in pusillas cogitationes. Sed veritati interea invigilandum est, modusque servandus, ut certa ab incertis, diem a nocte, distinguamus.*" ("*I easily believe that in the universe the invisible Natures are more numerous than the visible ones. But who will clarify for us the family of all these natures, the ranks and relationships and criteria and functions of each of them? What do they do? In what places do they dwell? The human mind has always searched for the knowledge of these matters but has never acquired it. Meanwhile, I do not deny that it is from time to time useful mentally to picture in the mind, as on a tablet, the image of a larger and better world, so that our minds, preoccupied with trivial matters of everyday life, does not shrink excessively and subside entirely into petty ideas. We must however be careful about the truth and keep a sense of proportion, so that we may discriminate between the certain and uncertain, day from night."), Thomas Burnet, Archaeologiae Philosophicae sive Doctrina Antiqua de Rerum Originibus, Libri Duo: Londini, 1692, pp. 68, in Coleridge 2013).*

This short section is supported by a catalogue which is the main document of this segment (Chapter 4, see Appendix 6 on CD-ROM). Many historical elements and data were compiled in this catalogue about "art as a tool", accessible as a publication in Chapter 4 (see Appendix 6 on CD-ROM) of the thesis. Also some aspects were analysed in detail of several Portuguese paintings or other associated media by different authors related with coast, sea, shoreline or coastal features and elements. Art in coastline evolution shows general aspects of coastal changes but from a different perspective: *art as a science or science as art*? This is the question raised when we appreciate art or a painting which involves coastal features. These paintings could "tell a story", working as an instrument in support of the understanding of coastal change.

The history and evolution of the coastline of many countries and regions, such as England, Scotland, Wales and even Portugal, tells a story of a seafaring nation and illustrates how shore forms are a central resource in economic, environmental and social terms. Over the years there has been increasing attention given to establishing a sustainable framework for the management of coastal zones. This type of approach will improve the cooperation between stakeholders in what has become known as integrated coastal zone management (McInnes & Stubbings 2010a). Many tools are available to understand how the coastline has changed over time and coastal scientists often use sophisticated monitoring systems. However, according to McInnes & Stubbings (2010a), there are few locations where accurate records of coastal change exist before the middle of the 20$^{th}$ century and actually aerial photography of the coastline only exists from the early 1940s (one exception is the coasts of England).

Therefore, only not fully used tools can presently contribute to our understanding of long term coastal evolution. For example, the methodology applied in the works of McInnes (2008, 2010), McInnes & Stubbings (2010a,b) and McInnes & Benstead (2013a,b) takes advantage of historical resources such as old maps, photographs, landscape paintings, watercolour drawings, engravings, postcards and literary accounts. These sorts of records will certainly allow comparisons of changes in morphology and land use patterns including coastal developments over the years.

"*Earth as art*" is a good example available which proves that is very interesting to observe and analyse Earth's artistic beauty in the patterns, shapes, colours, and textures of the land, or even oceans, ice, and the atmosphere (Friedl & Yuen 2012). Using modern technology and environmental satellites in orbit around the planet, the measured images show more than what is visible to the naked eye (Friedl & Yuen 2012). According to the authors the beauty of Earth is rich with creativity that varies from the bizarre to the transcendent, and these were the factors that led the authors to explore earth as art and NASA (National Aeronautics and Space Administration) to publish this attractive compilation of images.

If we are developing a coastal study it is necessary to use all the necessary means to support our research. The use of cartographic evidence for assessing coastal change is a practice that may be complicated by the type of source applied and this could jeopardise our work (Baily & Nowell 1996, Bannon *et al*. 2010). According to Bannon *et al*. (2010) only historical maps, charts and literature have traditionally been used as potential sources of information for analysing long-term morphodynamics of coastal systems. However, these sources of information can contain errors which should not be ignored when originating quantitative estimates of coastal indicators. As survey techniques, methodologies and mapping standards improve, and so it is natural that the reliability of the information set on maps changes through time. Therefore supplementary sources of information are important in coastal assessments (Bannon *et al*. 2010).

McInnes (2008, 2010) was first interested in recording the art and history of the Isle of Wight (UK) by means of books, prints and photographs. McInnes (2010) makes available an attractive collection of images. Some of the book designs are based on the "*arts and crafts*" style of the nineteenth century with elaborated decoration, with high quality paper to ensure the quality of images (McInnes 2010). But this investigation was soon extended to other study sites using different approaches and developing new methodologies of analysis to understand coastal change (McInnes & Stubbings 2010a,b, McInnes & Benstead 2013a,b).

McInnes explores a new type of research developed to thoroughly consider art and history in coastal evaluation. There were verified old paintings and images, comprising landscape paintings, watercolour drawings and engravings. These elements helped to study the variances in coastline evolution and identify coastal components with relevance to landscape assessments, environmental change and the history of coastal development (McInnes 2008).

This type of research has never before been accomplished for the Portuguese coast or specific sites along it. Nevertheless it seems to be an interesting methodology of coastal assessment and coastal evolution analysis that has drawn our attention, resulting in the art catalogue considered in Chapter 4 (publication in prep.) (see Appendix 6 on CD-ROM).

### 3.3. Integrated coastal zone management

There is no doubt that the coast plays an important role in global transportation and is the most popular tourist destination around the world. The shoreline is where "the land meets the sea", and it is continually changing (Woodroffe 2003).

During the years coastal scientists "walking by the shore", have tried to understand the shoreline in relation to the processes that shape it, and its interrelationships with the contiguous superficial marine and terrestrial hinterland environments (Carter 1988, Woodroffe 2003, Bird 2008). Those factors encourage the need for Integrated Coastal Zone Management (ICZM), because of its possible use in identifying coastal management issues to take into account in policy strategies, measures and planning.

Many definitions or explanations of what ICZM or ICM is can be found in publications, but a good definition may be that of Cicin-Sain & Knecht (1998): "*Integrated coastal management (ICM) can be defined as a continuous and dynamic process by which decisions are taken for the sustainable use, development, and protection of coastal and marine areas and resources. ICM acknowledges the interrelationships that exist among coastal and ocean uses and the environments they potentially affect, and is designed to overcome the fragmentation inherent in the sectoral management approach. ICM is multi-purpose oriented, it analyzes and addresses implications of development, conflicting uses, and interrelationships between physical processes and human activities, and it promotes linkages and harmonisation among sectoral coastal and ocean activities*".

According to Post & Lundin (1996) theoretically a wide number of sciences are involved in Integrated Coastal Zone Management, including Law, Oceanography, Sociology, Economics, Planning, Geology, Geography, Physics, Ecology, Chemistry and Engineering. Hence we can say that ICZM is a holistic approach to researching and studying coastal areas in every scientific branch, including the participation of different entities and also to ensure public awareness.

The conditions for planning in coastal areas have changed considerably in the last few decades. As stated before, numerous interests like tourism or environmental concerns have gained importance. Therefore, other functions have to be considered in coastal defense planning besides safety, and to do so integrated coastal zone management is essential (Post & Lundin 1996, Cicin-Sain & Knecht 1998, Kay & Alder 2002, EUROSION 2004).

Still in line with the European project (EUROSION 2004), when it comes to legislation specifically covering ICZM, no explicit legal instruments have been developed in many countries (e.g. on the Baltic Sea) and this reflects the situation throughout Europe. There is a specific need to cover ICZM through existing legal means because this implementation will always require planning decisions. ICZM allows for the establishing of “rules”, policies and strategies which will handle problems or future interventions in coastal areas through basic concepts, guidelines and theoretical procedures by putting them into practice.

The legislation relating to ICZM is all quite recent. In the Baltic Sea area, several ICZM programs have been initiated. Every country in the Baltic area is somehow engaged in ICZM and these projects are being carried out everywhere. However, integrated coastal zone planning is still in a very early stage in the Baltic Sea area, and in most countries the implementation of ICZM is experimental (EUROSION 2004). For example in Portugal, Veloso-Gomes *et al*. (2008) published a work that mentioned the proposals made in the report “Basis for a National Strategy for Coastal Zone Management” prepared for the Portuguese Ministry of Environment, Territorial Planning and Regional Development. The final version of that report was presented in June 2006 (Veloso-Gomes *et al*. 2007) and the work describes the ICZM framework followed by a discussion of concepts and presents nine primary principles, eight principal objectives, and 37 strategic options. Also it was important to clarify some coastal zone concepts and designations (in Portuguese: *litoral, costa, faixa costeira, faixa litoral, orla costeira, zona costeira, zona litoral, área/região costeira*). Therefore the working group designed for this program (Veloso-Gomes *et al*. 2007, 2008) was forced to define the following concepts which did not have any consensus about their physical, political, economic and social boundaries:

- Littoral (*Litoral*) – covering the whole EEZ shoreline and all the terrestrial area influenced directly or indirectly by the sea;
- Coastal Zone (*Zona costeira*) – the stretch ranging from the 200 m depth line to the interior as far as tides, waves or winds reach and have an influence;
- Coastal Stretch (*Orla costeira*) – a stretch of coast which is under the direct influence of sea activity;
- Coastline (*Linha de costa*) – reference line defined as the intersection between the mean height of sea level and land.

ICZM is more than an environmental policy; ICZM also aims to improve the economic and social well-being of coastal zones and help them develop their full potential as modern, vibrant communities (EUROSION 2004). In the coastal zone, these environmental and socio-economic goals are intrinsically interconnected. Important issues of Europe’s coastlines are: (i) badly planned tourist developments; (ii) decline of the fishing industry; (iii) poorly conceived transport networks; (iv) increasing urbanisation; (v) erosion; (vi) pollution and (vii) habitat destruction (EUROSION 2004).

EUCC (2013) highlights and documents the importance of coastal zones, and also includes a proposal for strategies; recommendations and programs with seven principles of good coastal zone management clearly identified:

1) *Take a wide-ranging view of inter-related problems (thematic and geographic) – a broad "holistic" perspective;*
2) *Use a long-term perspective; allow for unforeseen future developments;*
3) *Local specificity: base decisions on highly quality of data and information;*
4) *Try to work with natural processes;*
5) *Participatory planning: involve all stakeholders;*
6) *Support and involve all relevant administrative bodies;*
7) *Make use of a range of instruments (laws, plans, economic instruments, information campaigns, voluntary agreements, promotion of good practices, etc.).*

Sustainable solutions for managing coastal erosion are what every coastal program wishes to achieve. Progressively ICZM will be used as a tool in organisation and legislation. When it comes to legislation specifically covering ICZM, at present no European country has developed explicit legal instruments. Consequently ICZM has to be shielded through existing legal means. Planning and/or Building Acts are the predominant national instruments, given the fact that the implementation of ICZM will always require planning decisions (EUROSION 2004, EUCC 2013).

The main questions on ICZM for the analysis of the regional sea context and issues such as policy options implemented, strategies or approaches adopted to combat erosion are extensively discussed in the European project (EUROSION 2004). The generic policy options presented are addressed in Chapter 10 (shoreline change mapping and coastal management strategies) in this thesis, where a literature review about several approaches and decisions is given. In this section we will only show a diagram with the five generic policy options that can incorporate the concept of ICZM: (1) do nothing; (2) hold the line; (3) move seaward; (4) managed realignment and (5) limited intervention (more details in EUROSION 2004). Once again we draw the reader's attention to Chapter 10 which covers this subject in a broader perspective and presents other types of policies or strategies based on this principle.

These concepts or the five technical solutions put erosion in the perspective of other issues in the coastal zone; however, habitat protection and water quality recovery are other issues that could use ICZM as a tool, according to EUROSION (2004). In addition, different approaches could be applied, such as (EUROSION 2004): (i) a proactive methodology, which refers to a policy of anticipating erosion processes (when technical measures or plans such as management plans or flood warning systems are adopted to prevent erosion or minimise the expected effects of erosion); or (ii) a reactive approach, which refers to the policy of carrying out coastal defence measures to reduce the effects of existing erosion processes.

The scheme displayed in Figure 82 illustrates the decision process of finding a suitable technical solution in the case of sedimentary coasts, dealing with either acute or structural erosion (EUROSION 2004). This flow diagram shows the options in terms of technical analysis or technical solutions/measures. The selection of an option to deal with any erosion or flooding problem depends on a chain of factors beginning with the value of the land or property threatened; the values at stake in coastal areas (such as people, property and associated economic values; ecological and cultural values) define the need for intervention; finally once these values are assessed, the selection of the most appropriate solution(s) can be made. Coastal protection measures can generally be divided between hard and soft measures (EUROSION 2004): (i) hard engineering measures include the construction of solid structures designed to fix the position of the coastline; and (ii) soft measures are planned to work with the natural processes.

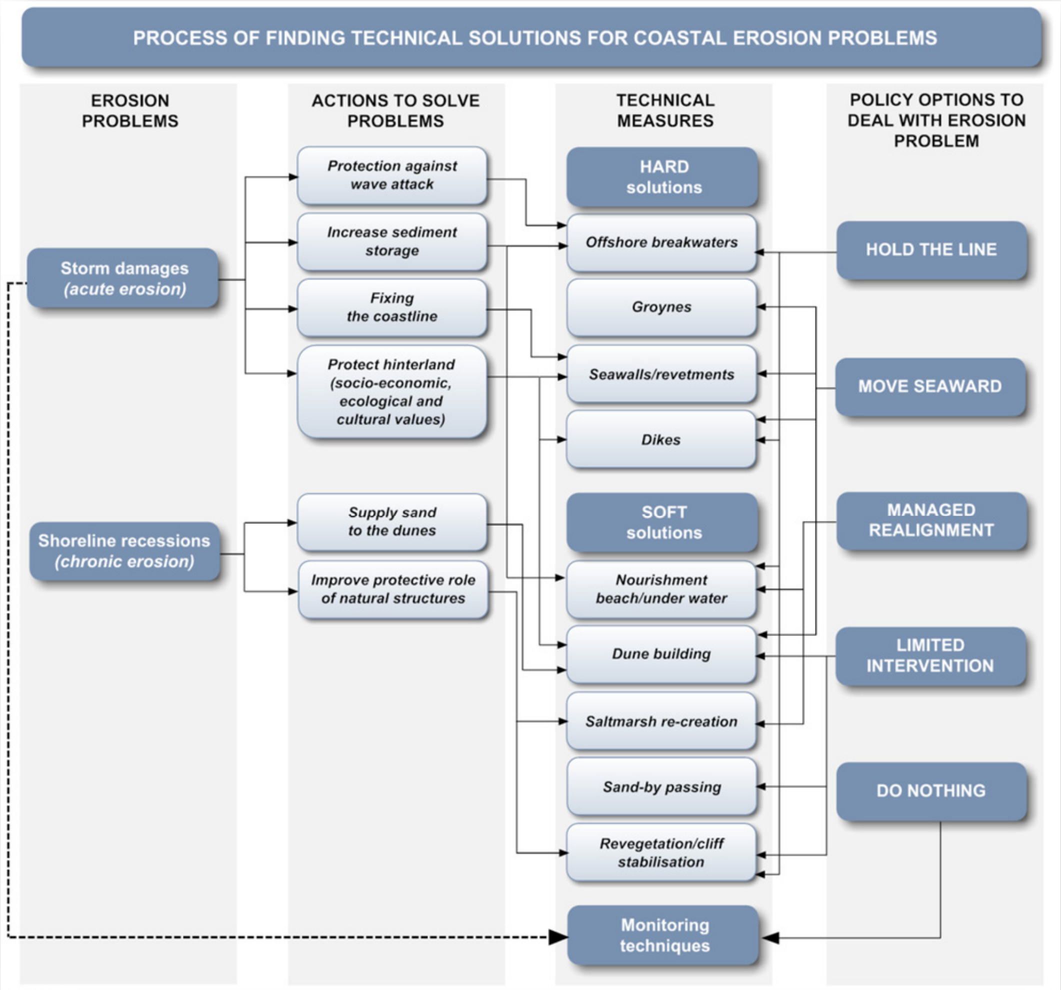



**Figure 82.** Flow diagram and organisation of the possible technical solutions to be implemented in the management process for integrated coastal zones (adapted from EUROSION 2004).

There are significant differences between these solutions, since soft solutions allow the natural dynamic behaviour of the coastal area to occur and thus the coastline may change over time (EUROSION 2004, ANCORIM 2013). The application of possible measures will differ according to the local situation, type of coast or physical circumstances (diversity); nevertheless it is required to recognise the best option(s) (the most efficient and cost effective). In order to achieve this, a balanced knowledge is needed of the scale of the problem and the causes of erosion or flooding under which the optional measures are to be applied. For example, when the erosion problem is caused by a net longshore transport, a seawall is generally not a sufficient solution. Another example concerning cliff protection: the geology, location and orientation of the bedding planes (and other geostructures) will determine the type of erosion (rock fall, toppling failure, wedge failure, slide, rotational slump or flow) and thus the appropriate type of protection required.

In general the success and failure factors of technical measures depend on diversity and the combination of the type and causes of erosion, the measures themselves and the surrounding physical conditions (EUROSION 2004).

### *3.3.1. Temporal and spatial scales: diverse perspectives*

This section is related to coastal evolution, which in turn is the product of morphodynamic processes that occur in response to changes in external conditions (Cowell & Thom 1994, Woodroffe 2003, 2007, EUROSION 2004). Therefore it is important to understand how coastal morphodynamics operate within a hierarchy of temporal and spatial scales. We will display four different approaches from different authors that show the same problem but with a single conceptual scheme or conceptual scenarios that shows their point of view.

According to Cowell & Thom (1994) the mutual influence between forms and processes can be seen as changes in the spatial and temporal distribution of sediment volumes (Figure 83). This approach to morphodynamics involves geological processes such as erosion, transport and accumulation, and they are induced by aerodynamic or hydrodynamic forces (e.g., Carr 1980, Carter 1988, Cowell & Thom 1994, Carter & Woodroffe 1997).

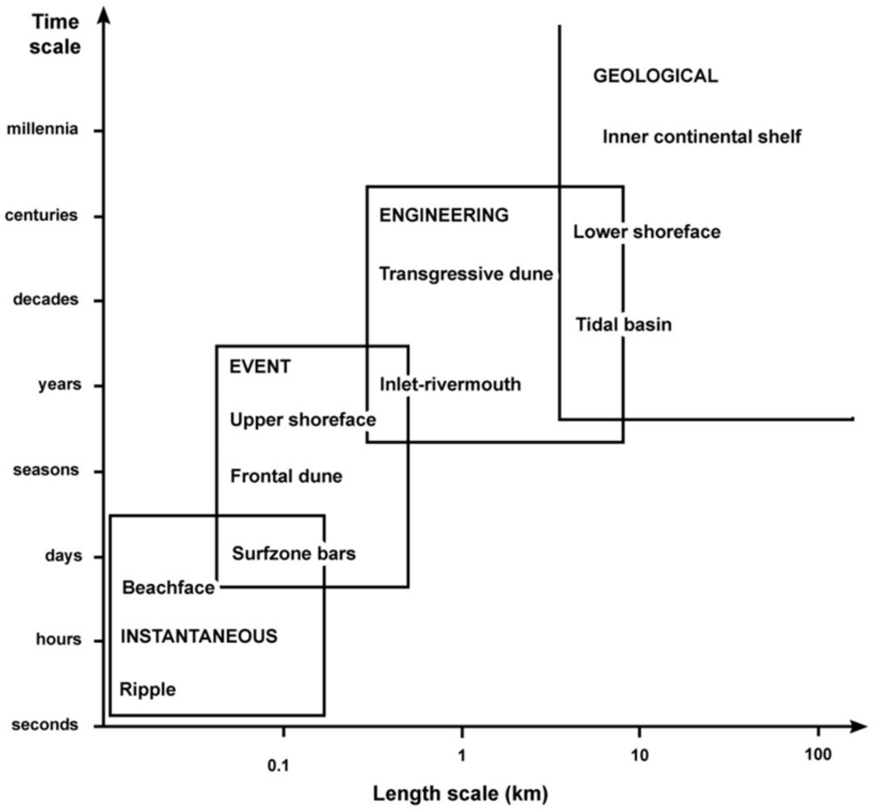



**Figure 83.** Temporal and spatial scales related with morphodynamics and geological processes (adapted from Cowell & Thom 1994).

Woodroffe (2003) concluded that there are advantages in viewing individual coasts over a range of different time scales. Based on the previous framework by Cowell and Thorn (1994) he defined a different representation (Figure 84). According to Woodroffe (2003) the smallest scale is an “instantaneous” time scale over which the principles of fluid dynamics apply, governed by the laws of physics, but operating randomly. We could conceivably monitor in “real-time” the details of sediment entrainment and the complexities of turbulent flow, including processes such as the deposition of individual bedform laminae, with a view to understanding the coastal system perfectly at this scale. The “event” time scale is concerned with recurrent sequences of processes, such as a tidal cycle with rising, slack and ebbing conditions, storm or flood events, and seasonal variations (Carr 1980, Carter 1988, Cowell & Thom 1994, Carter & Woodroffe 1997). At the event scale, “instantaneous-scale” processes are averaged to gain an understanding of morphological response to single events or perturbations, such as a single storm. The coast appears to be more or less balanced during “non-events”, but adjusts to a perturbation or event and coastal landforms are the cumulative creation of numerous events (and “non-events”) (e.g., Cowell & Thom 1994, Komar 1998, Masselink & Hughes 2003, Woodroffe 2003, 2007, EUROSION 2004).

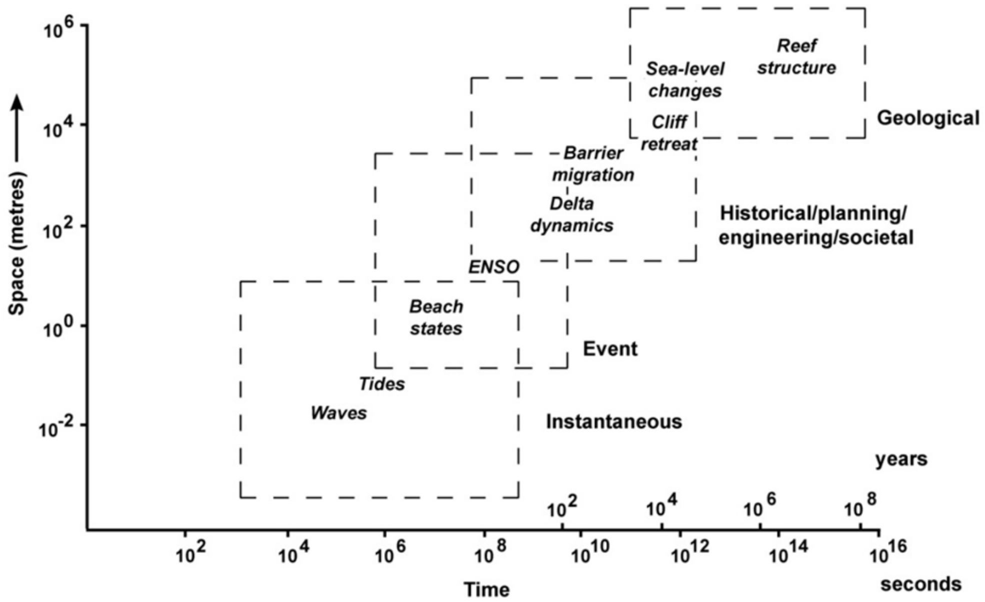



**Figure 84.** The representation of space and time scales appropriate for the study of coastal morphodynamics and the schematic representation of examples of coastal systems or patterns of variation and their general position in terms of space-time scales (based on Cowell & Thom 1994 and adapted from Woodroffe 2003).

On the other hand coastal erosion results from a combination of various factors, as explained previously, both natural and human induced. These factors have different time and space patterns and have different natures – continuous or incidental, reversible or non-reversible (EUROSION 2004). Moreover, the interactions of forcing agents, as well as the significance of regional causes of erosion remain uncertain. The different coastal types determine the modification in resistance against erosion. For example, hard rock coasts hardly erode, while soft cliffs and sedimentary coast are much less resilient. Consequently, various natural factors (with diverse time and spatial scales) redesign the geologically formed coastal morphology (EUROSION 2004). Figure 85 summarises natural factors responsible for coastal erosion and focuses on the time and space patterns within which these factors operate. It is important to highlight that "distance" has to be understood as the geographical extent in which the factor action takes place, or takes place with a relatively stable intensity. Instead "time" reflects the temporal extent in which the factor occurs and causes erosion (EUROSION 2004).

The scheme (after Cowell & Thom, 1994) in terms of coastal morphodynamics which operates within a hierarchy of temporal and spatial scales was improved. These improvements are shown schematically in Figure 86 with examples from reef systems as an illustration. According to Woodroffe (2007) time is usually considered as linear and progressive, but in some cases it can be circular or cyclic. The smallest scale is the "instantaneous" scale, including the time frame within which individual waves occur where the physics of fluid dynamics apply (Figure 86) and is best surveyed at a very local spatial scale.

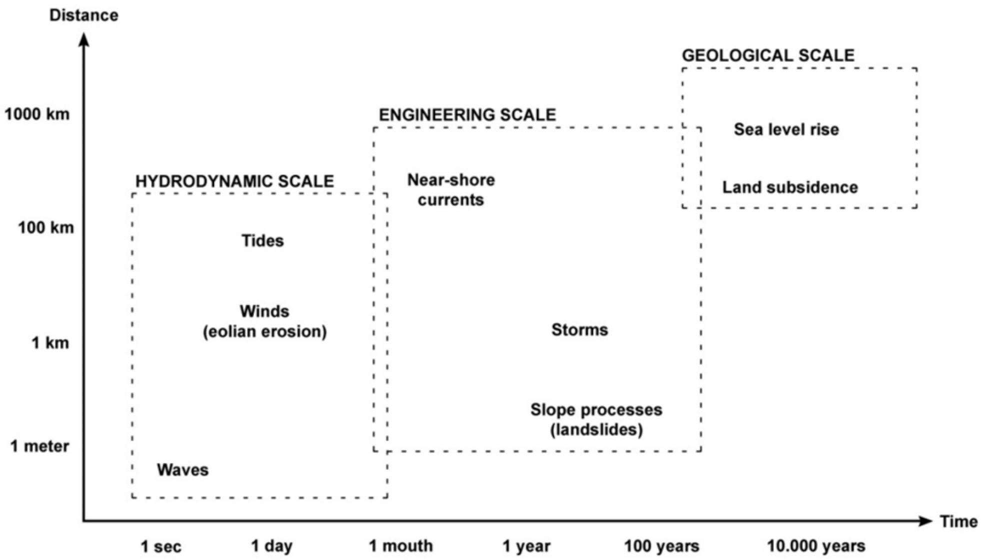



**Figure 85.** Time and space patterns of natural factors of coastal erosion (adapted from EUROSION 2004).

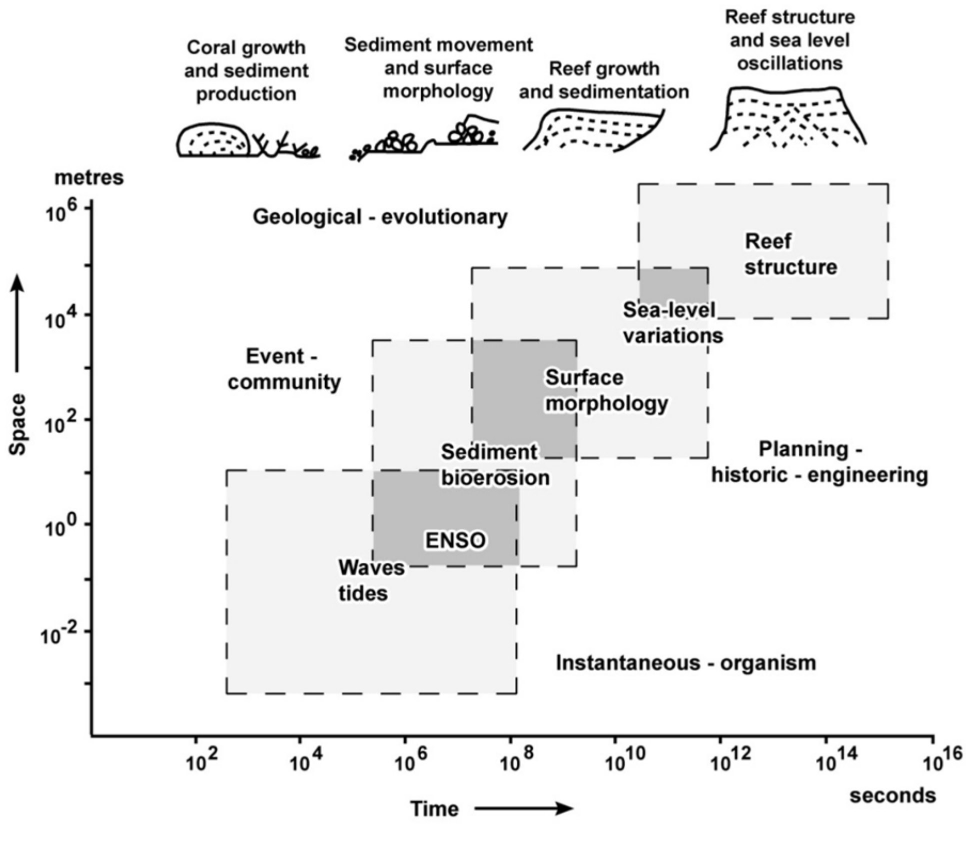



**Figure 86.** Temporal and spatial scales (adapted from Woodroffe 2007).

In the situation of a reef, the instantaneous scale comprises the physical processes under an individual wave and the biological processes which enable the coral to grow and so produce sediment (more details in Woodroffe 2007). The "event" scale is a longer time scale, at which a perturbation occurs and the system responds. In the case of reefs it is processes at the event scale, such as tropical storms, which have the greatest control on the surface morphology of reefs, detaching and breaking coral colonies and building rubble ridges. The effects of a period of high wave energy have a similar impact on reefs. The beach responds to the storm (high wave energy) by changing state and then recovers from this event towards its pre-storm state (a measure of its resilience). This event scale is described as "short-term" by Brunsden (2002), and in geomorphology he regards predictive inferences at this scale to be informed guesses at best. The following level of research concerns regional scales over decades to centuries. In the case of reefs (Figure 86), changes at this scale are preserved in the pattern of reef growth and sedimentation. The long-term designated by Brunsden (2002) is a time scale of particular significance in the context of human societies. It has been variously referred to as the "historic", "engineering" or "planning" time scale (Komar 1998, Masselink & Hughes 2003, Woodroffe 2003) because it is the scale over which we know from historical records that there have been changes, and which is of special significance in terms of planning or engineering projects.

Brunsden (2002) considers that any attempt to forecast at these scales can be thought of as "predictions"; the coastal system's wide behavioural patterns may be known but cannot be predicted with confidence. The largest scale is the geological time scale and the global spatial scale. This is the time scale of millennia, extending to millions of years. The geological time scale embraces important broad trends with very significant implications; for example Quaternary variations in sea level have seen significant movements of the shoreline (vertically or horizontally). Nevertheless, the processes at work at these time scales may be undetectable in everyday management of coastal systems (Woodroffe 2003).

It is interesting to analyse the images which represent particular conceptual scenarios. The first schemes are more related with coastal morphodynamics and processes (Figures 83 and 84). Alternatively the structure displayed in Figure 85 concerns coastal engineering aspects, erosion problems and how natural factors affect the coastal morphology through time and space. Finally Woodroffe (2007) links physical with biological processes to recognise the differences in the response of coastal systems, but everything is also related with geological processes and morphodynamics (Figure 86).

Sometimes it is not only a problem of scale; the diverse perspectives and point of views that every one of us could have – as a scientist, geomorphologist, geographer, engineer, geologist, etc. – may also have an effect. Keaton (2013a) for instance, tells us that geologists and engineers view the world in complementary but different ways. Science pursues a way to explain all observed details, while engineering tries to find the design with specific objectives and multiple restrictions (Keaton 2013a).

This last point has been the primary source of "geologist–engineer jokes" because of the different way each observes the world. See Keaton (2013a) for an example:

"*(...) An engineer and a geologist who have worked together on several projects are on their way to a field site. The engineer is frustrated at not being able to get a straight, unqualified answer from the geologist. The engineer driving the car sees a pasture on the side of the road in which an isolated brown cow is standing. The engineer realizes that this setting provides an opportunity to ask the geologist a question so simple that the geologist might give a straight answer.*

*Engineer: "I am going to ask you a simple question about that brown cow in the pasture ahead."*

*Geologist: "Okay."*

*Engineer: "What colour is that cow?" The geologist studies the cow is they drive past.*

*Geologist: "The colour of that cow looks like 10YR 3/4."* [7]

*Engineer: "What?!"*

*Geologist: "Brown … on this side."*

As stated by Keaton (2013a), the point of this "geologist–engineer" joke is that the geologist first delivered information using a term that the engineer did not recognise and then qualified the information because of the observational nature of geology. The origin of the conflicting views of the world from geologists and engineers is embedded in the contrast between science and engineering.

The relationship between geology, engineering geology, and engineering can be illustrated with a timeline that begins with the earth's history and extends to the future past the engineering design life (Figure 87). According to Keaton (2010) the geologist is considered a historian and looks back to the beginning of earth history. In turn the engineering geologist (or applied geologist) is considered a predictor and is concerned with looking back into earth history focusing on the most recent 10,000 years for some applications. The engineering geologist also looks into the future to a time outside the design life of planned facilities. Finally, the engineer (like, geological engineer, geotechnical engineer, civil engineer, mining engineer) is considered a designer and looks back to the beginning of construction, and into the future as far as the design life of the planned facility (Keaton 2010).

[7] *Bt horizon soil: Moist colour is 10YR 3/4. Texture is clay or clay loam.*

It is fascinating how different background and scientific interests could influence our perspectives and consequently our directions and approaches to research. For that reason and to conclude this section, it is essential to make a last comment about conceptual models and about dynamic layouts in terms of maps or cartography. Hopefully, nowadays any skilled geo-professional (e.g., geologist, engineering geologist, engineering geomorphologist, geological engineer, geotechnical engineer, mining engineer, civil engineer, or military geologist/engineer) engaged in the practice of applied geosciences must keep this in mind to reduce all intrinsic geological uncertainties and variabilities (Chaminé *et al*. 2013b). According to De Freitas (2009) the safest way through such uncertainties relies on good case histories, which should be on the desk of every geo-professional and used as frequently as the electronic calculator.

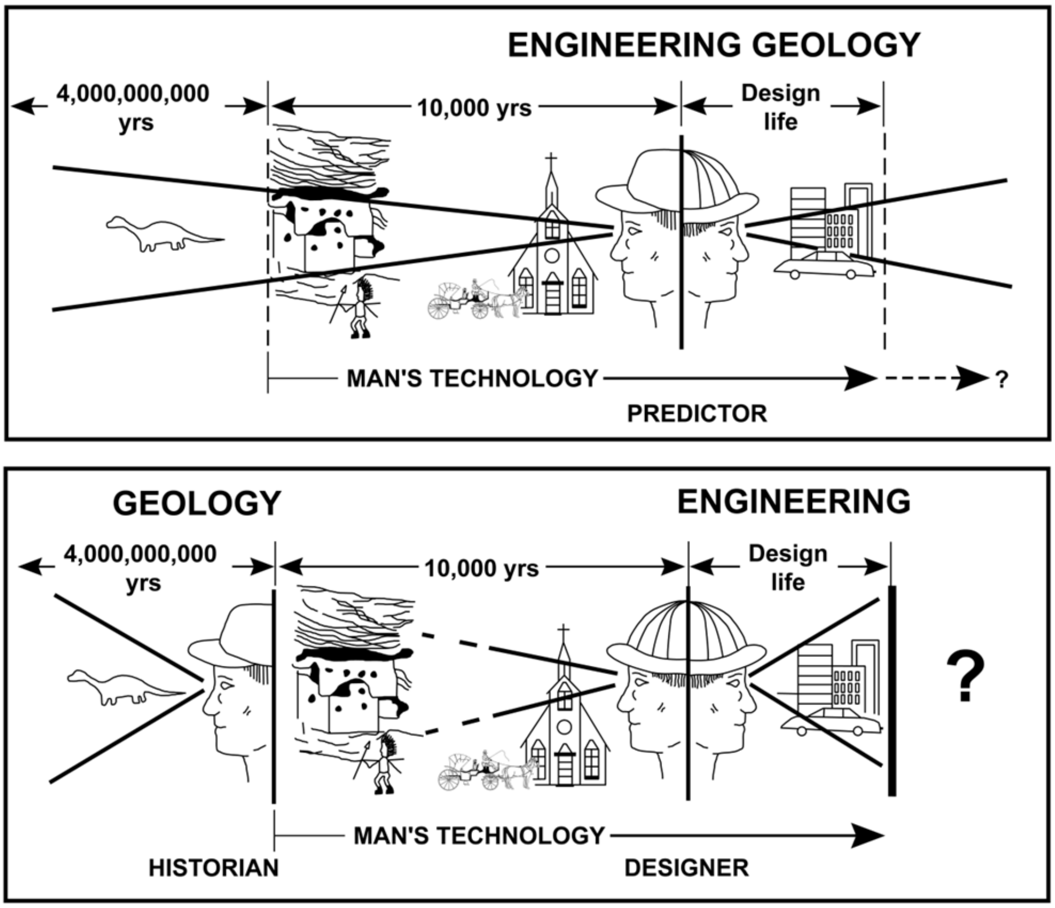



**Figure 87.** Views and perspectives of geology, engineering geology, and engineering (adapted from Keaton 2010 which was modified from illustration provided by Christopher C. Mathewson, Texas A&M University).

In the thesis and publications presented in Part II (Results and Discussion) it is common to conceptualise an integrative model which involves all aspects of the research or the methodological processes. Understanding the complexity of Earth systems is possible through the use of ground models (Griffiths & Stokes, 2008). Thus, a typical site characterisation should be outlined based on Earth systems analysis which form the core for building models to create scenarios using different approaches (e.g., Griffiths & Stokes 2008, Keaton 2013a, Chaminé *et al*. 2013,a,b and references therein).

These schemes could have different representations, models, flowcharts, quantitave or qualitative data, diagrams or mixed concepts and ideas. They are very much inspired by several authors that use this type of site modelling in different contexts: coastal morphodynamics, engineering geology, engineering geomorphology, mining geotechnics, hydrogeomorphology, or groundwater exploration (e.g. Fookes 1997, Woodroffe 2003, Fookes *et al*. 2005, 2007, Griffiths & Stokes 2008, Smith *et al*. 2011, Barton 2012, Teixeira *et al*. 2013, Chaminé *et al*. 2013a,b). Besides these scientific fields we have also been inspired by coastal geomorphological features and applied cartography (e.g. Vanney & Mougenot 1981, Sunamura 1992, Paskoff 1994, Peña Monné 1997, Trenhaile 1997, Vanney & Ménanteau 2004).

These are the main reasons to closely relate this thesis to integrative approaches and techniques, including different fields of research. Once again the integrated coastal management (ICZM) we mentioned before could integrate many features, dynamics and processes without going through numerical or physical models. These conceptual models represent a conclusive interpretation that can only have advantages if incorporating multidisciplinary teams. Thus, by interacting with several elements this will improve the site conceptual model displayed in the end.

## 3.4. Social context

### *3.4.1. Sociological perspective in coastal management*

This subsection makes perfect sense in the state of the art chapter. After all, integrated coastal zone management involves a wide number of sciences including sociology. Moreover, the concerns of other management responses, such as the adaptation to coastal change, are actively being encouraged, as well as development and implementation of the necessary adaptation strategies, such as: (i) relocation of communities or assets; (ii) using innovative resilience measures for individual properties; and (iii) education and engagement activities (like those proposed by Frew 2012, Moore 2012). Multidisciplinary cooperation between the natural sciences, engineering sciences and social sciences is very difficult to apply but necessary at some point.

The term transdisciplinarity previously analysed (Wickson *et al*. 2006, Kuhn 2012, Wright 2012), is proposed here in order to enhance the fact that without doubt the outcomes and outputs of integrated projects move beyond any of the disciplines involved, as suggested by Visser (2004).

Throughout history coasts have been the primary habitat for humanity. It is coastal cities and towns with fishing communities which have been the main target for innovation (Glavovic 2013a). Nevertheless, those technological innovations jeopardise coastal communities with unsustainable practices. As a result, coasts are the "battle zone" in humanity's struggle to learn to live sustainably in the face of global change.

Coastal and shoreline management plans are gradually forced to integrate the concept of sustainable territorial development in coastal areas management system models (Vivacqua et al. 2009, Schmidt *et al*. 2012, Glavovic 2013a). Likewise the awareness of coastal processes analysis will increase the liaison between the sea and man-made structures and the impact that cliff erosion has on the supply of beach material (Frew 2012, Moore 2012). This fact leads us to question the importance and long-term sustainability of "defence at all costs". For this reason different decisions, strategies or solutions were taken into account and some changes were made in the approach to coastal management (Frew 2012). Several strategies for sustainable development could be reflected in different action fields, for example the two main features considered by Jorge (2010), namely: (1) the biophysical features of the territory and the settlement patterns which structure and organise the space; (2) the economic and socio-cultural dimensions, like the characteristics and activities of families, relationship with agriculture and fisheries, use of natural resources, land ownership, the material and symbolic value of land and the participation of local actors. Furthermore, a thorough analysis of the socio-environmental conflicts in the studied areas will confirm the complex challenges facing stakeholders (investors) who support a new approach to development local planning and coastal management (Jacomel 2012). Thus, the constant and determined search for more substantial investments in political-ecological research, on socio-environmental conflict mediation as well as the reinforcement of territorial governance systems in coastal areas is essential (Vivacqua *et al*. 2009).

Another important topic is the regional governance implemented by each country. According to Glavovic (2013a) "*governance is more than government and refers to the interactions of actors from the state, civil society and the private sector to solve societal problems through power sharing, social coordination and collective action innovation*". As stated by Glavovic (2013a,b): "*Governance innovations have done little to stem the tide of unsustainable coastal activities*". It seems to be a paradox because new innovations are always necessary to correct the failures of the past. It is necessary to enable and invest in governance processes to encourage good practices, reflection, diversity, dialogue, research and planning. So why is it so problematic to organise adequate joint actions for coastal sustainability? Once again Glavovic (2013a,b) helps to answer this problem by tracking down coastal and shoreline management toward a wider setting of developing and multidimensional governance. Coherent governance innovation is also imperative to rethink and reinforce business and technology that lead to social transformation for coastal sustainability.

Coastal management might help this transition by being reconceptualised as a transformative practice of deliberative coastal governance with a foundation which embraces four deliberative outcomes (Figure 88): (i) shaping human and social capital by knowledge, enhanced attitudes and skills; (ii) simplifying community-oriented action and improving institutional capacity and decision-making; (iii) the previous actions enable the population judgment for problem-solving; and finally (iv) building more cooperative communities (Glavovic 2013b).

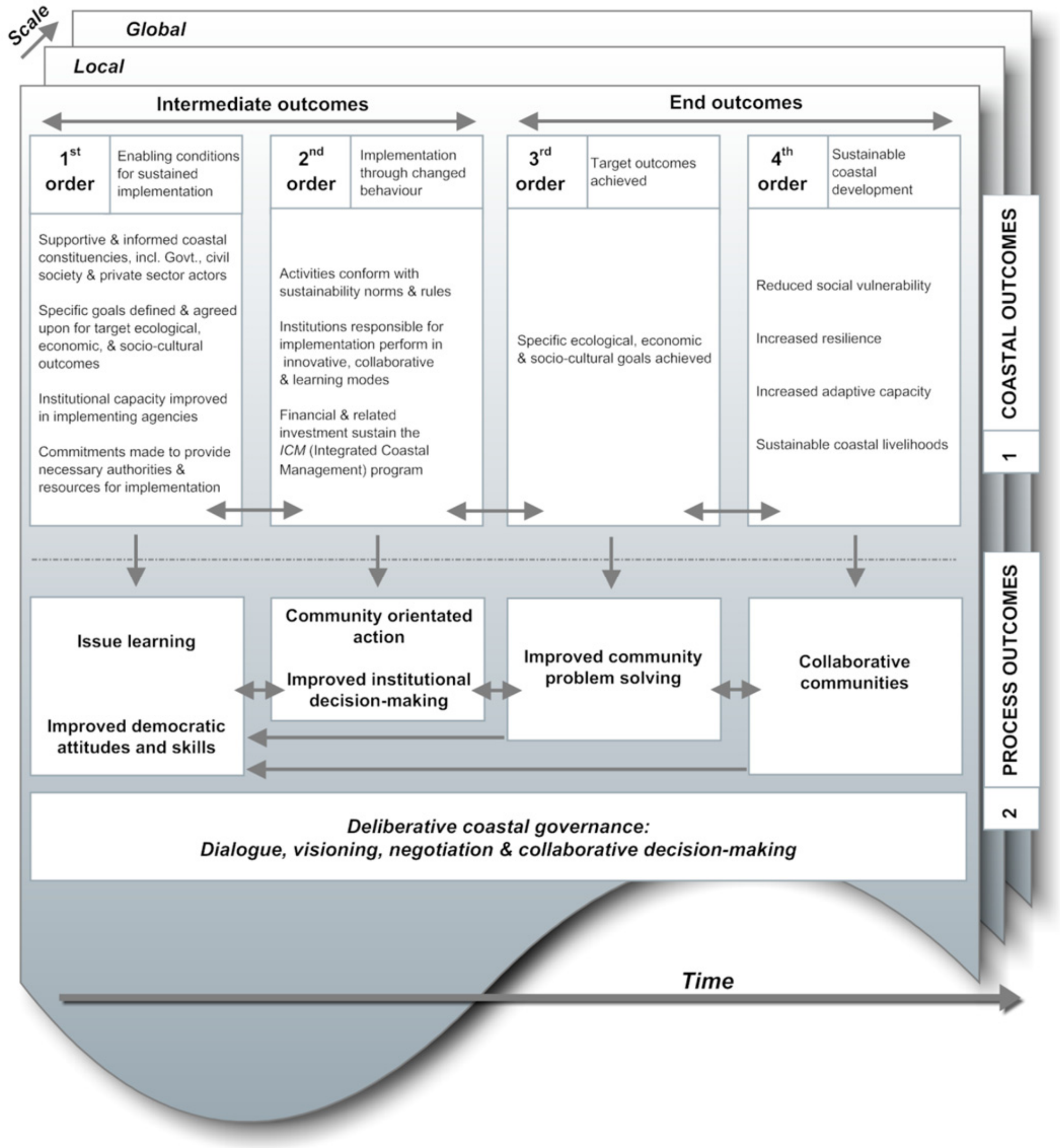



**Figure 88.** Deliberative coastal governance process flowchart (adapted from Glavovic 2013b): four orders of outcomes are emphasised and interconnected; the outcomes progress sequentially similar to a platform for understanding intermediate and end coastal outcomes.

This type of framework can be adapted and applied in other geographical settings and other coastal environments to develop innovative sustainability paths and help to solve coastal issues (for further details about the coastal and process outcomes see Glavovic 2013b and references herein). The deliberative groundwork of process outcomes synthesised in Figure 88 supports the coastal outcomes outlined by Olsen *et al*. (2009).

There are several factors to take into consideration in a coastal management project. Nevertheless, social issues are significant, particularly in areas where the relationship between the sea and people is very close, almost like a "love and hate" bond. Additionally we would like to draw attention to the fact that this subsection provides a brief outline of the emerging research in marine sociology (Ning'er 2011). Perhaps we can say that Europe is providing a background to the ongoing "*Marine Century*," showing that marine strategies will be more effective in the long term as people in marine countries improve their awareness of the association with the sea and increase their knowledge related to the management of marine problems, as proposed by Ning'er (2011) and Governo de Portugal (2013). Ning'er (2011) also discusses the impact of marine strategies on sociological research, because according to this author *"marine strategies are deeply social, and sociology may provide some insights into understanding the relationship of people, communities, regions, and nations between the sea and themselves".* This is an emerging concept which is worthwhile in marine countries and societies. Marine sociological studies are very relevant to coastal management strategies. Therefore, coupling continuous marine sociological research in coastal areas with other scientific fields will help us understand and manage marine social problems. For that reason, it is essential to consider the sociology research agendas in marine countries (Ning'er 2011, Governo de Portugal 2013).

After the Indian Ocean tsunami of December 2004 it was important to ask "how resilient is your coastal community"? This concept of resilience is another intricate notion intimately connected or related with the coastal sociological context, it has to be! The flexibility and durability of a particular coastal community cannot be quantitatively measured, but can be evaluated and analysed. The effects of the variations due to population growth in coastal areas, vulnerability or climate change, place the communities at increasing risk from coastal hazards such as tsunamis, severe storms, shoreline erosion and cliffs retreats (U.S. IOTWS 2007, Diego *et al*. 2012, IPCC 2012, Schmidt *et al*. 2012). According to U.S. IOTWS (2007) all of these facts have led to the question of how to increase community resilience. Because of the numerous types of hazards in coastal areas the only possible response involves a holistic, integrated and long term approach. Diego *et al*. (2012) has performed research in two Portuguese coastal cities to understand what makes some cities more vulnerable and less resilient to natural hazards. Coastal areas have many resources but also have vulnerability. Therefore, vulnerability and resilience concepts seem to be interrelated, with importance to the geographic variation of this social factor. The vulnerability factors and features which allow response and recovery from the hazard impact have to be identified, and may influence disasters or even catastrophes (more details in Diego *et al*. 2012).

There are many important elements, stages and actions to reduce risk, accelerate recovery and adapt to change (U.S. IOTWS 2007). The main concerns when assessing resiliency are described in Figure 89a with the network of actions and approaches depending on the resiliency level. Moreover, as stated by U.S. IOTWS (2007), the risk from coastal hazards is characterised by the frequency of occurrence and severity of the hazard (Figure 89b).

As illustrated in Figure 89b, tsunamis are typically uncommon events with moderate to severe consequences; however, flooding may occur frequently, while severe flooding may be an occasional event; coastal erosion may be a chronic event with minor consequences or, coupled with other hazards, may result in severe impacts on the coast (U.S. IOTWS 2007). According to Keaton (2010) the concept of a "disaster cycle" has changed in engineering geology field (Figure 89c). In the beginning people settle in a region because of natural resources or transportation routes without recognising that hazardous processes (e.g. earthquake or hurricane) occur relatively infrequently. A hazard strikes and causes a certain amount of damage which might not be considered as a disaster if this damage is limited or populations deal with such adversity by cleaning up the debris and returning quickly to an operative state.

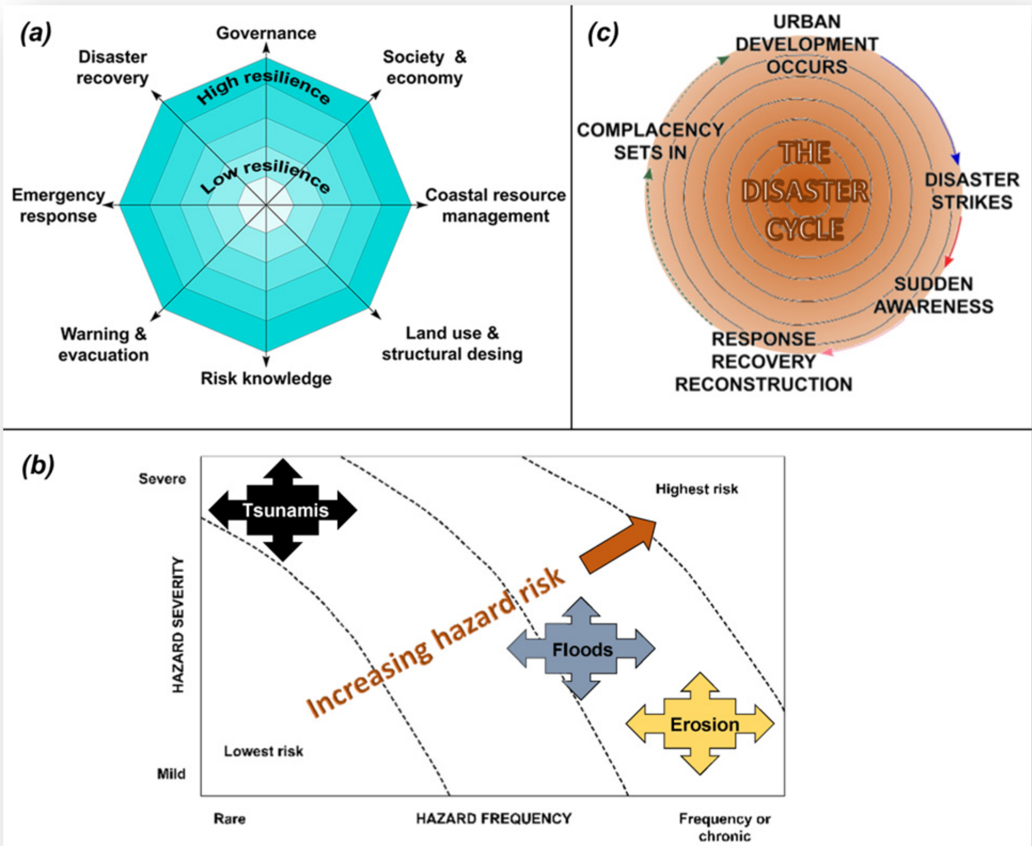



**Figure 89.** (a) Network resiliency assessment: planning processes and procedures; (b) risks from coastal hazards as a function of hazard frequency and severity (adapted from U.S. IOTWS, 2007); (c) the disaster cycle (adapted from Keaton 2010 which was modified from a concept by Christopher C. Mathewson, Texas A&M University).

Many countries in terms of good practices (including methods and tools) are increasingly adopting a diverse range of approaches to manage disaster risk and adapting climate change, with the purpose of creating a secure society. Figure 90 lists the incremental action and includes a visual representation of the approaches, summarising policies and strategies for policymakers. According to IPCC (2012) the efforts made in building this culture of safety comprise several elements: (i) methods associated with assessing and communicating risk; (ii) reducing "climate-related" disaster risks; (iii) transferring and sharing residual risks; and (iv) managing the impacts of disasters holistically, as disaster risks can never be reduced to zero. Consequently, it is important to point out that the approaches, methods, and tools discussed here are complementary, frequently overlapping, and can be pursued simultaneously (IPCC 2012).

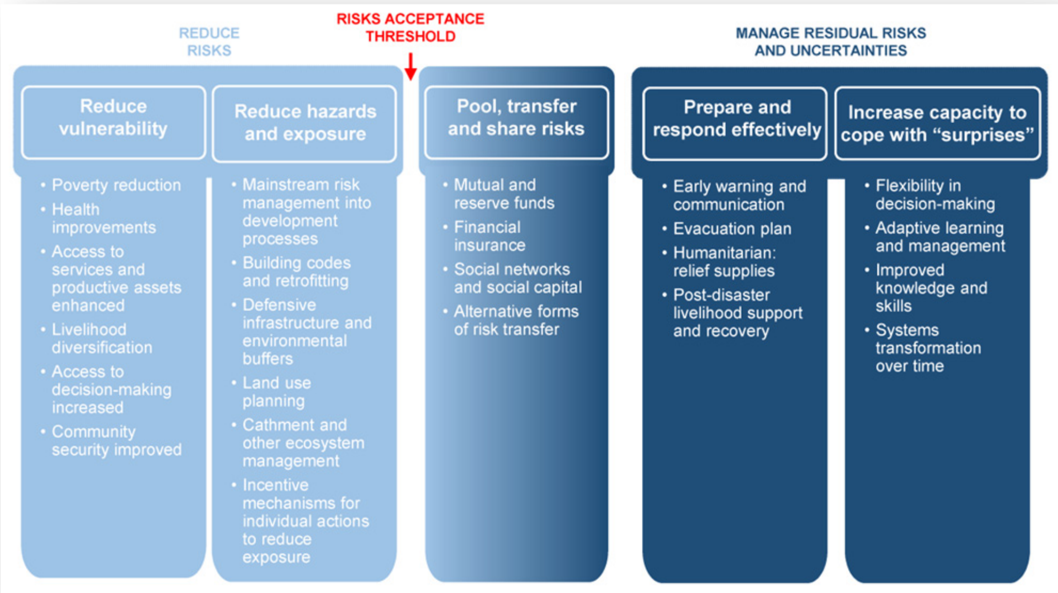



**Figure 90.** Complementary response measures for observed and projected disaster risks supported by respective institutional and individual capacity for making informed decisions (adapted from IPCC 2012).

### *3.4.2. Espinho fishing community (NW Portugal) – a case study*[8]

In Portugal there are several areas buffeted by sea invasions, coastal erosion and severe storms. The Portuguese coastal zone, where more than 80% of the population and assets are concentrated, is one of Europe's most vulnerable regarding coastal erosion (Schmidt *et al*. 2012). The fall of cliffs, shoreline retreat and the construction of new coastal defenses have required substantial funds in infrastructure and protection measures.

[8] *This research has been developed in Rocha et al. 2014.*

The following case is an example of one of the most vulnerable sites in Portugal in terms of coastal erosion and sea invasions and how the "engagement" between local fishing community and coastal projects are extremely important.

"*N ka ten di agraba di mar pamodi tudu ki ten e mar ki dau*" means "*I cannot hold a grudge against the sea, because all that I have the sea has given me*" (Cape Verdean proverb *in* Almeida 1996). Is this a good way to express how the love and hate relationship between man and sea is? We believe so, particularly in the Espinho (NW Portugal) local community such as among the fishermen who work the coastal areas of these waters. The local fishermen state that: "*Espinho nasceu entre a terra e o mar...*" ["*Espinho was born between the land and the sea...*"]. There is a feeling of conformance and apparent "harmony" of those who have survived the continuous sea "fights". This sociological perspective already addressed by Pires (1996) and Pires (2007), was made with the single purpose of highlighting the fishermen's effort and tenacity. Furthermore we want to show the great passion for the sea that "stole" parents, sons and themselves, without displaying any fear or terror. It is in fact among the grains of sand of the salty water that we find the coastal protection structures; systems that have had the virtue of defending the beach from the attacks of dominant North – South and Southwest – Northeast currents. These structures have become an integral part of their lives and have become "family" of these communities.

The Espinho case shows the link between *governance – stakeholders – contractors – researchers – local community* as a necessary management strategy and more, such as the holistic synergy already proposed by Frew (2012) and other authors mentioned above. It defined a "social mesh" embracing a platform or a project which comprises different vectors and combines social aspects, economic factors, culture and heritage with activities, upgrading the traditions in fishing communities, to somehow forget and accept the sea invasions and the hard solutions like coastal protection structures (e.g. groynes, seawalls) as well as the reinforcement and requalification of the urban areas and the improvement in the seashore area. Espinho is mainly a maritime area principally in the Marinha area (Figure 91). Its origin lies in the abundance of fish, in particular of sardines. Espinho beach is a charming beach and it has an ancient fishing tradition. Here it is still possible to watch the Art of "Xávega", which is a traditional fishing form based on bulls' strength to recover the nets and which uses rowing boats sometimes carrying 15 men (Figure 92). The abundance of sardines contributed to the increase of the fishing campaigns, and to the development of the canning industry, expanding this industry in the first half of the 20th century. The decades later were essentially marked by the growth of the tertiary sector of the economy, in particular the services linked to tourism.

**Figure 91.** Some aspects of the Marinha (Silvalde, Espinho) site and the coastal activities (photos by A. Pires, 2007).

Sea invasions in Espinho have been common news, documented since 1869 (Lima 1979, 1982), as evidenced by several historical documents (Figures 93 and 94). Indeed, the first reported erosion dates back to 1860 (Ortigão 1876), and old maps show that the urban area of Espinho was much larger, extending further seaward to positions that have since been lost to the sea (Bandeira de Melo 1870, 1900, *in* Teixeira Lopes 1995). The continuous retreat and advance of the Espinho shoreline several metres landward and seaward led to the construction of the first defenses in 1909, but by 1911, these had been naturally destroyed. Since then several protection structures have successively been put in place to protect the city (Perdigão 1931, Mota Oliveira and Martins 1991, Mota Oliveira *et al*. 2000, Trigo Teixeira 2003).

Figures 95 and 96 illustrate not only the occurrence of some disastrous episodes of sea invasions in the Espinho region but also some evidence of the construction of protection works. This historical compilation of events demonstrates the importance of coastal research in the area.

**Figure 92.** Representative figures of fishing activity and the Art of "Xávega" (ancient fishing tradition) between Espinho and Ovar, NW Portugal (Lopes & Lopes 1995).

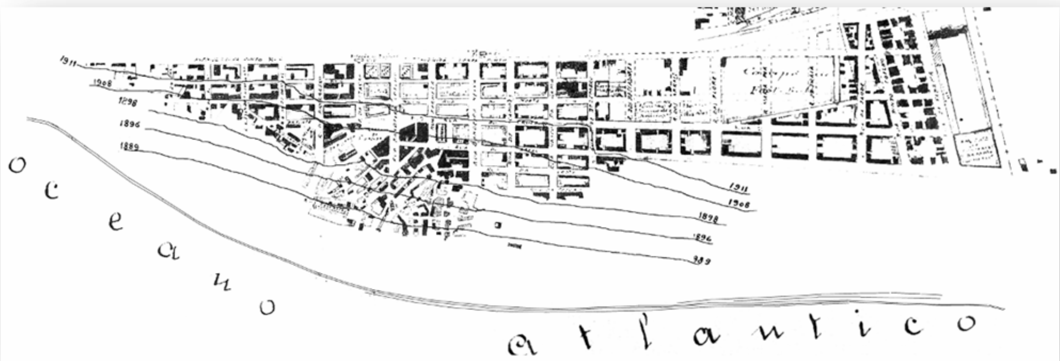



**Figura 93.** Extract of the schematic plant created by J. C. Lopes in 1933 (Espinho City Council Archives, unpublished).


**Figura 94.** Old maps used for the reconstitution of the urban cluster of Espinho in the 19th century: a) plant commissioned by the first City Council to Bandeira Lima in 1900 (*in* Teixeira Lopes 1995); (b) topographic map performed by Bandeira of Melo in 1870 and offered to S.M. da Feira City Council (*in* Teixeira Lopes 1995).

Pires *et al*. (2007) compiled several documents and information about Espinho coastal history, sea invasions and interventions made along the shoreline (Figures 95 and 96). This study was based on historical research and a detailed analysis of aerial photos of the littoral processes of Espinho (NW Portugal), as well as on field inquiries among the local population. The data gathered allowed an analysis of the Espinho dynamic coastal system since the 19th century, and the inference of its evolution as a useful tool for the management of the coastal urban landscape. A historical reconstitution of the location of coastal protection structures was first carried out, which comprised a cartographic representation of buildings, streets and sea line invasions. Actual and historical events related to coastal erosion and urban landscape management were georeferenced and represented by using GIS (geographical information systems) tools.

The use of an interactive interface provided a simple and easy way to perform queries on the existence and occurrence of coastal protection structures since 1889. Susceptibility maps of sea invasions were then produced through spatial analysis. This research was important to gather knowledge on past events and to predict the location of the actual coastal line if no groynes had been constructed. The study takes advantage of GIS tools to contribute to the understanding of the geomorphological dynamics of Espinho. Furthermore, it provided a sound basis for monitoring and management of the coastal zone, namely in the planning of security measures concerning the eventual occurrence of disastrous scenes of sea invasions (further details in Pires *et al*. 2007).


**Figure 95.** Historical images and examples from the Espinho shoreline (Espinho City Council Archives, c. 1960).

**Figure 96.** Compilation of images used to verify the occurrences identified on the GIS based project in Pires *et al.* (2007) research; some examples of the sea invasions, destruction of buildings, reinforcement of marine works; several types of coastal interventions and solutions held along the shoreline (Espinho City Council Archives, 1958-1960).

The main protagonist of this irreparable damage and chaos is the sea with numerous shoreline attacks, putting to the test the resistance, ingenuity and the effort of the entire Espinho population that seem to have already discredited the popular saying: "*o que a terra tirou, o mar há-de buscar*" ["*what the land took, the sea will fetch*"].

Therefore the population sought solutions for halting the momentum of the sea. Pires (1996) in her sociological framework expressed the opinion of the fishing community in Espinho, particularly their emotional state. The main goal was to understand what their perceptions and concerns were regarding the present status of the coastal protection structures, their understanding and expectations in regard to their resilience to coastal vulnerabilities. Also, at the time, it was important to identify the socio-economic conditions of the fishing sector and get to know the reasons for the construction of a coastal harbour in Espinho city. This was an often discussed issue, not only by the competent authorities and experts, but most of all by the fishermen who had always struggled for that coastal work to moor their fishing boats.

Over the years there have been successive onslaughts of the sea, causing terrible human and material damage. The loss was particularly high among the fishing class, whose homes were and still are close to the sandy beach. These constructions, due both to their fragility and the proximity of the sea, were the first to dive into the waves, as soon as the water invaded the beach. Here real disasters resulted, since the destruction of the houses involved not only the eviction of their residents, but also the loss of goods such as: nets, boats, and other materials related to *faina pesquera*. The fishermen themselves are the greatest victims and declare that "*we have to take risks to survive*". Some confess also that do not even know how to swim. In fact, Espinho always had an intimate relationship with the sea, a mix of love and hate, because since the beginning of the second half of the last century, the sea that does not deny plenty and enables the growth of important seaside resorts was the same sea that had invaded, successive times, destroying neighbourhoods and ruining large quantities of sand.

Fishing communities and fishermen are well documented in Portugal, since this is a country with an extensive coastline with so many coastal resources (Dias *et al*. 1994, Veloso-Gomes *et al*. 2006, Delicado et al. 2012, Santos *et al*. 2012). Figure 97 displays a few pages extracted from the Aveiro Archive (A.D.A. 2000) well documented with some interesting historical aspects about these communities. This archive could be considered a good example of how these historical compilations could help us to understand coastal processes and events. Therefore, with a history of sea invasions causing terrible human damage and destruction of assets, this local community of Espinho was a perfect place to put integrated coastal zone management (ICZM) into within a marine sociological perspective.


ARQVIVO DO DISTRITO DE AVEIRO

N.º 130

Abril, Maio e Junho

AVEIRO

1967

OS PESCADORES POVEIROS NOS «MARES» DE AVEIRO

**Figure 97.** Extract and assemblage of a few pages from the Aveiro Archive (CD-compilation) showing several historical information, data, diverse text material and details about the fishing community and the fishermen (A.D.A. 2000).

Between 1997 and 2001 the fishing community of Marinha (Espinho) was involved in a local project designated “Programa de Reabilitação Urbana da Marinha – PRUM” (in Portuguese), “Program of Urban Rehabilitation of Marinha”. In the course of this project and during this period, the community worked as a live laboratory and as an experimental field. The integrated coastal approach involved several fields of action: politics, socio-economics, sociology, ethnography, education, culture, music, photography, coastal engineering, general planning of public space, requalification and restoration of buildings and environmental improvement in the seashore area. This multidisciplinary project to “reform” the seaside has resulted in a special mention of the Espinho region in 2002 (PUBLIC SPACE 2013).

Figure 98 reveals the faces and some activities of this fishing community. It allso shows the results of the photography workshop accomplished along the project.


**Figure 98.** The faces and everyday activities from Espinho fishermen community. Photography workshop from the Program of Urban Rehabilitation of Marinha (PRUM) in Silvalde (ESPINHO 2009).

There were many workshops developed alongside the project in numerous areas. Apart from the engineering works and requalification, the most important question was this interaction between the fishing community, the sea and the technical aspects related with marine works and coastal design.

The main questions are: (i) how to link the public with the issues of coastal erosion; (ii) how to minimise the population responses towards situations of risk and coastal vulnerability; and finally (iii) how to increase the resilience to extreme events. It is necessary to engage the public with the engineers, scientists, contractors, other stakeholders, etc. We believe that the Espinho project was a case that succeeded. Undoubtedly this program structured a coastal management plan, coupling engineering design with societal context. This project allowed the weaving of different strands carried out by applying a holistic methodology, using a number of professionals and experts and directly affecting the public. It was actually a live laboratory where we had the opportunity to see the implications of the final results. We also took conscious note of the significance of integrating coastal management approaches with social background into maritime environments.

### 3.5. Coastal environments

Coasts are defined by their singular geological features or by the geological event that formed them. As stated previously, the coast comprises a complicated and dynamic transition between the marine environment and the terrestrial environment. It also includes a wide range of areas, topographies, and geologic settings (Davis 2002). Within the coast we can discover beaches, barrier islands, tidal inlets, coastal estuaries and lagoons, rocky coasts, and reefal and glaciated coasts (Woodroffe 2003, Davis 2002).

The nature and form of the coastal system at any part of the world is influenced by several factors and those usually associated with coastal morphodynamics are (e.g., Trenhaile 1987, Woodroffe 2003, Davis 2002): (i) waves; (ii) tides; (iii) wind; and (iv) the additional matter of severe storms. The progression of plate tectonics and sea level change are also significant but less generally considered.

The worldwide distribution of general coastal types is quite diverse. The most extensive is the rocky coasts that make up about two-thirds of the world's shorelines. This diversity also includes coral reef coasts and barrier island coasts, comprising only about 10%, with deltas, estuaries, and glacial coasts covering most of the rest of the coastlines (e.g., Trenhaile 1987, 2002, Davis 2002, Granja 2002, Woodroffe 2003, Schwartz 2005, Bird 2008, Naylor *et al*. 2010, Trenhaile 2011a,b, Stephenson *et al*. 2013).

There are many different kinds of classification that have been applied to coasts in attempts to characterise dominant features in terms of modes of evolution, geographic occurrence and physical or biological properties (e.g. Suess 1888, Cotton 1952, Johnson 1919, Shepard 1948, Valentin 1952, Owens 1994, Finkl 2004). According to Finkl (2004) the characterisation or classification of natural coastal environments were wide-ranging in scope but needed specificity while other specialised systems were narrowly focused, providing irregular coverage of genesis units for coastlines of the world. As a result, Finkl (2004)'s research integrates a systematic approach to consider in the development of a comprehensive scheme for coastal classification. The increasing availability of GIS information and frameworks, particularly digital formats, endorse integrated and systematic approaches to coastal classification. It is required to apply sophisticated solutions to correspond and interconnect problems in the littoral zone.

Climatic factors can determine the nature of some coasts but there are many other parameters necessary in order to categorise the so-called geomorphic units (Trenhaile 2011a, Trenhaile *in press*). The proposed approach by Finkl (2004) employs discriminating criteria for hard rock and soft rock coasts that are related to the antiquity of littoral landforms and divided by chronometric parameters. Table 9 presents the comparison between the materials, processes, forms, or coastal environmental properties that are considered in some selected classification systems and compared to Finkl (2004)'s study.

**Table 9.** Comparison between some selected classification systems which consider several properties such as materials, processes, forms or coastal environment (adapted from Finkl 2004).

| **Authors** *(Year)* | *Suess* *(1888)* | *Cotton* *(1952)* | *Johnson* *(1919)* | *Shepard* *(1948)* | *Valentin* *(1952)* | *Owens* *(1994)* | *Finkl* *(2004)* |
|---|---|---|---|---|---|---|---|
| **Features** | | | | | | | |
| *Geodynamics* | **H** | **H** | | **L** | | | **H** |
| *Tectonics* | **H** | **H** | | **L** | | | **H** |
| *Structure (faults, folds)* | **H** | **L** | **L** | **L** | **L** | | **L** |
| *Relative sea level change* | | **H** | **H** | **H** | **L** | | **L** |
| *Marine processes* | | | | **H** | **L** | | **H** |
| *Terrestrial processes* | | | **L** | **H** | **L** | | **H** |
| *Shoreline position* | | **L** | **L** | **L** | **H** | | |
| *Materials* | | | **L** | **L** | | **H** | **H** |
| *Form (Morphology)* | | | **L** | **L** | | **H** | **H** |
| *Environmental* | | | | | | **L** | **L** |
| *Organic* | | | **L** | **L** | **L** | **L** | **L** |
| *Erosion–deposition* | | | | | **L** | **L** | **H** |
| *Climate* | | | | | | | **L** |
| *Polygenesis* | | **L** | **H** | **L** | | | **H** |
| *Tides* | | | | | **L** | **L** | **L** |
| *Anthropomorphic* | | | | | | **L** | **L** |

H=Parameter or characteristic considered at a high (prominent) level in the classification system. Such consideration is usually explicit but may be implicit based on recent interpretations. L=Parameter or characteristic considered at a lower (subordinate) level in the classification system or the concept is implied or inferred. Blank=Parameter or characteristic not specifically considered or inferred in the classification system.

The developed approach to a new comprehensive classification system by Finkl (2004) is thus proposed for the coastal fringe, a buffer zone 5 to 10 km wide across the shoreline, which incorporates all important parameters necessary to categorise geomorphic units that can be mapped at meaningful scales.

Finkl (2004)'s work is an excellent study in terms of its literature review and in the following pages we synthesise all the categories of coastal classification comprised in that study. In this thesis none of the classification systems were used but it was important to categorise the type of coasts studied and comprehend the classifications available to coastal researchers. Also it is important to draw the attention to the conception of systematic approaches (whatever the purpose and goals of the research), which are one of the principles of this thesis.

Finkl (2004) states "*a classification system reflects the level of perception of research and understanding of natural bodies (morphological features) in terms of process and form*". In the essence of this study Finkl (2004) cited the line of thought by Kubiena in 1948 (*in* Finkl 2004) where he briefly highlighted this relationship to the soil science community: "*Show me your [classification] system and I will tell you how far you have come in the perception of your research*." This comment is relevant to contemporary coastal science and researchers are still attempting to apprehend the relationship between form, function, time, and space in one of the most dynamic environments on Earth (Finkl 2004). Thus all the terminologies, classifications, and morphodynamic models are approximations in a given time and place. Still regarding this matter Finkl (2004) described the current status using the forecast by Russell (1967 pp. 84, *in* Finkl 2004) which remarked that "*Much of the literature on sea coasts is concerned with classification of shoreline types, but to me this is both unfortunate and premature. Taxonomy should follow, rather than precede, the acquisition of more precise and factual information than we now possess... I think we know altogether too little about coasts to line up examples and shove them into appropriate pigeonholes*". Though this statement is factual in certain aspects, the coastal geomorphology field has positively advanced in terms of understanding, mainly in the areas of morphodynamics and modelling but also in terms of GIS applications, mapping, applied cartography and 3D modelling. Finkl (2004)'s compilation and research is summarised in the flowcharts illustrated in Figures 99 to 101.

Indeed, coastal environments are explored but they display extensive areas of study. The coastal environments covered by this thesis include four categories: (1) rocky coasts; (2) sandy coasts; (3) mixed environments; and (4) marine structures (Figure 102). The thesis publications cover applications of rock and concrete block to two types of structures: groynes and seawalls. Figures 103 and 104 exemplify with aerial images some of the coastal environments addressed here and the types of coasts illustrated.

**COASTAL CLASSIFICATION - Type of coasts**
***(Literature review by Finkl 2004 – Summary)***

**I. PROCESS-RELATED COASTAL CLASSIFICATION**

**1) Geotectonic systems (geodynamic processes)**

- Suess (1888)
  - ✓ *Atlantic type (transverse) coasts*
  - ✓ *Pacific (longitudinal) type coasts*
- Cotton (1918)
  - ✓ *Stable regions*
  - ✓ *Mobile regions*
- After Cotton (1952)
  - ✓ *Classification of coasts based primarily on the geodynamic stability of coastal regions and secondarily on features related to relative sea level change*
- Fairbridge (1992); updated reformulation Fairbridge (2004)
  - ✓ *Suggested two basic categories of environmental setting*
    - *- Primarily – geotectonic province*
      1. Active (convergent)
      2. Taphrogenic (mainly strike-slip) plate margins
      3. Passive plate margins (Sedimentary Coasts)
      4. Passive plate margins
      5. Active plate margins and back-arc basins
      6. Semistable platforms, dominated today by wind and meteorological tides and by geostrophic current dynamics
      7. Oceanic fracture-zone volcanic complexes and seamount-related atolls
    - *- Secondarily – climatic province*
      1. High Arctic
      2. Sub-Arctic
      3. West-coast westerly
      4. East-coast westerly
      5. Subtropical and trade wind

**2) Sea-level change (eustatic processes)**

- Dana (1849): *recognised the influence of submergence on the coastal outline*
- Richthofen (1886); Suess (1888); Gulliver (1889); Davis (1898): *considered submergence and emergence criteria in coastal description*
- Daly (1926, 1934, 1938): *work on the glacial control of sea level, in relation to the formation of coral atolls and other features, drew attention to oscillations of sea level resulting from glacial–interglacial cycles*
- After Johnson (1919)
  - ✓ *Classification of coasts based on processes related to changes in relative sea level, i.e. interpretation of features associated with the present coast in relation to the most evident or prominent change in land-sea movement*

**3) Marine modification and terrestrial inheritance**

- Shepard (1937, 1948, 1973): *abandons the high-level classificatory submergent-emergent dichotomy of previous workers by (1) placing submergent coasts at a lower level in the classification and (2) suggesting that emergent coasts can be ignored*
- After Shepard (1948)
  - ✓ *Classification of coasts as:*
    1. Primary (coasts shaped mainly by terrestrial agencies)
    2. Secondary (modified by marine processes)
- Shepard (1973): *modified and elaborated his classification, but retained its basic structure*

**4) Coastal erosion (shoreline retreat) and deposition/accretion (shoreline advance)**

- After Valentin (1952)
  - ✓ *Classification of coasts in relation to shoreline advance (by emergence or sediment accumulation) or retreat (by submergence or erosion)*

**II. SPECIAL PURPOSE COASTAL CLASSIFICATIONS**

**1) Regional or reconnaissance classification of cold region coasts in Canada for sensitivity to oil spill clean-up**

- After Owens (1994)
  - ✓ *Classification of shoreline types on the basis of materials and coastal configuration*

**2) Regional classification of subtropical coasts in Florida for sensitivity to oil spill clean-up**

- After SFRPC (1984)
  - ✓ *Classification of shoreline types in southeastern Florida based on environmental sensitivity to soil spill and cleanup*

**3) Environmental Sensitivity Index Mapping**

- Battista & Monaco (1996)
  - ✓ *The most widely used approach in the United States, NOAA's Environmental Sensitivity Index (ESI), systematically compiles information for coastal shoreline sensitivity, biological resources, and human-use resources. ESI maps identify sensitive resources before an oil spill occurs so that protection strategies and clean-up procedures can be designed in advance. Also these maps include geomorphological classification of shoreline types that are integrated with other coastal resources that help define risk during oil spills*

**Figure 99.** Summary and compilation of the literature review about coastal classifications in Finkl (2004) (part 1 of 3).

## II. SPECIAL PURPOSE COASTAL CLASSIFICATIONS

### 4) Classification of oceanic islands, exclusive of coral reefs

- After Nunn (1994)
  - ✓ *A genetic classification of oceanic islands*
- Scott & Rotondo (1983)
  - ✓ *The model proposed explains the origins of all major types of island found on the Pacific lithospheric plate where tens of thousands of seamounts are scattered over the oceanic crust of the plate surface*

### 5) Classification of coral reefs and reef islands

- Darwin (1842)
  - ✓ *Coral reefs are still divided into three main types:*
    1. Fringing reefs
    2. Barrier reefs
    3. Atolls
- An initial classification by Fairbridge (1950, 1967) was elaborated by Maxwell (1968)
- Hopley (1982): *proposes the development of GBR (Great Barrier Reef, Australia) coral reefs for Quaternary*
- Guilcher (1988): *additionally considers bank reefs and patch reefs to be special types*
- Hopley (1988)
  - ✓ *Classification of shelf coral reefs and associated geomorphic features.*

- Stoddart & Steers (1977) Reviewing literature on reef islands, suggest that cays and low wooded islands of the GBR show greater morphological variety than reef islands of any other coral reef region.
- After Stoddart et al. (1978)
  - ✓ *Classification of reef islands of the Great Barrier Reef*
- After Guilcher (1988)
  - ✓ *Classification of the main reef types*

### 6) Classification of beaches and beach geomorphology

- Carter & Orford (1984); Wells (1996): *shingle or gravel beaches*
- Jennings & Shulmeister (2002): *consider the Iribarren number, beach width, average grain size, and storm berm height as discriminating factors in the classification of gravel beaches*
- Hardisty (1990): *for sandy beaches, the orthogonal system of classification extends from the landward limit of the swash to the depth at which wave action ceases to be competent to transport noncohesive seabed sediment*

#### 6.1) Wave-dominated beach types

- Short (1975): *first comprehensive classification of beach types (morphodynamic states) and change*
- Wright & Short (1984); Short (1993): *modified version*
- After Wright et al. (1982); Short (1993, 1999)
  - ✓ *Classification of morphodynamic beach types, based on the prevailing nature of a beach, including the waves and currents, extent of the nearshore zone, width and shape of the surf zone with its bars and troughs, and the dry subserial beach. This comprehensive classification of wavedominated, micro-tidal beach types, first developed for the New South Wales coast, is now used worldwide where the tidal range is less than 2m*

**Reflective Beaches**

-

#### 6.2) Intermediate Beaches

- Short (1993, 1999)
  - ✓ *Low tide terrace (LTT) beaches*
  - ✓ *Transverse bar and rip (TBR) beaches*
  - ✓ *Rhythmic bar and beach (RBB) types (e.g. Benedet et al. 2004)*
  - ✓ *Longshore bar and trough (LBT)*

#### 6.3) Dissipative beaches

- Taylor & Stone (1996)

#### 6.4) Tide-dominate beach types

- Masselink & Short (1993)
  - ✓ *Developed the beach morphodynamic classification scheme using four morphodynamic variables: breaking wave height and period, the high tide sediment fall velocity, and the mean spring tide range*

### 7) Classification of coastal dune morphology

- Bagnold (1941): *contributions*
- Landsberg (1956); Cooper (1958); Olsen (1958): *cited papers*
- Short & Hesp (1982): *explored the morphodynamic status of dunes*
- Sherman & Hotta (1990): *process-based studies of coastal dunes*
- Short & Hesp (1982); Stewart & Davidson-Arnott (1988); Martinez & Psuty (2004): *recent advances in dune geomorphology include the linking of shoreline morphodynamics to dune formation*
- Hosier & Cleary (1977); Sorensen & Mccreary (1985): *the development of storm-driven cyclic models of environmental change for low barrier dunes*
- Horikawa et al. (1986); Hotta (1988): *for re-evaluation of many of the long-accepted transport formulae*
- Nordstrom et al. (1990): *for further consideration about coastal dune morphology*
- Psuty (1988, 1994); Martinez & Psuty (2004): *coastal dune forms are essentially a function of sediment budget where the dune-beach sediment budget evolves, and through feedback mechanisms, new dune forms emerge. Leakage in the system contributes to local site diversity but the balance between the regional beach budget and regional foredune budget maintain the dune-beach morphological system; the range of coastal dune forms is conceptualized by Martinez & Psuty (2004) in terms of a foredune developmental sequence that pars foredune and beach sediment budgets*

**Figure 100.** Summary and compilation of the literature review about coastal classifications in Finkl (2004) (part 2 of 3).

## II. SPECIAL PURPOSE COASTAL CLASSIFICATIONS

### 8) Classification of rocky coasts (cliffs and platforms)

- Isakov (1953); Emery & Kuhn (1982); Sunamura (1992)
- Bird (1976)
  - ✓ *Subdivision of the subhorizontal-platforms into two distinctive types according to the platform elevation:*
    1. High-tide platform
    2. Low-tide platform
- Trenhaile (1987); Griggs & Trenhaile (1994)
  - ✓ *Type-A platforms are most common in macrotidal environments and Type-B platforms in meso- and microtidal regions*

## III. CLASSIFICATION OF COASTAL AND MARINE ENVIRONMENTS

*Note: the previous classification (II), focused on physical processes and morphological development of coastal morphologies, shapes and forms. This classification considers alternatives to the initial physically-based approach that considers forms and processes*

- Terrestrial biotic provinces are classified, for example, by Udvardy (1975), Axelrod (1958), and Areces-mallea et al. (1999) - on the basis of vegetation
- Coastal classification is largely by physical landforms and physical processes (e.g. Cotton 1954; King 1966; Bird 1976; Dolan et al. 1972, 1975)
- Other approaches focusing on nearshore continental and oceanic island environments – based on the water column and underlying benthic substrate together to form an integrated habitat unit – (e.g. Zacharias et al. 1998; Zacharias & Roff 2000; Allee et al. 2001) / opposed to deeper water environments (e.g. Greene et al. 1999)
- Lind (1969) and Furmanczyk et al. (2002): *provide insight into coastal landscape classification by applying a linear approach*
- *that differentiates natural components in unit-segments of coast*
- Dolan et al. (1972, 1973): *provide insight into initial attempts to develop comprehensive classifications of coastal/marine environments*
  - ✓ *Process zones across-the-coast include: (1) the deep water zone of the outer continental shelf; (2) shallow water zone of the inner continental shelf; (3) zone of intense shoaling and breaking (surf zone); (4) zone of extreme wave energy dissipation (surge zone); (5) zone of maximum tidal and atmospheric*
- Dolan et al. (1973): *the process of classification along the coast is divided into four steps: (1) analysis of the process; (2) mapping the distribution of geologic materials; (3) analysis of biotic systems in the vicinity of the coast; and (4) integration and assembly of these subunits of the classification. Analysis of the atmosphere is based on air mass climatology whereas oceans are characterized by the analysis of water masses. The materials context is stratified via the information gained through analysis of coastal landforms. This provides the information needed to integrate the principal units of the coastal interface with the ocean and atmosphere. The third part of the classification, verification of the regimes, subregimes, and interface units, is achieved through analysis of biotic provinces. The final phase is the integration of all three subunits of the classification*
  - ✓ *The process context yields the first two levels of the classification:*
    1. atmospheric regimes
    2. oceanic subregimes
- Method of coastal land systems mapping
  - ✓ *Christian & Stewart (1953); Brink et al. (1966); Speight (1968):* is one method where a "land system" consists of a recurring pattern of landforms, soils, and vegetation. The lower order "land facets" which make up the land system are described but not mapped. The concept of a land system has been adapted to coastal conditions extent along the southeast coast of the Florida peninsula in the Broward Coastal Zone (BCZ)
  - ✓ *Finkl (1994):* Finkl approach follows the land-system surveys of the C.S.I.R.O. (Commonwealth Scientific and Industrial Research Organization, Australia) (e.g. Christian & Stewart 1953, 1968; Beckett & Webster 1965; Brink et al. 1966)
- Ecological classification of coastal environments (Wolfe 1990): *Florida Springs Gulf-coast ecological classification of native biological communities (although there are many examples of ecological characterisation of localised coastal environments, experience with the Florida Spring Coast illustrates the technique*

## IV. COASTAL CLASSIFICATION AND MAP LEGENDS: GLOBAL AND CONTINENTAL SCALES

- Bird & Schwartz (1985): *encyclopedic compilations*
- Schwartz (1982); Snead (1982): *relevant topics discussed here*
- National Atlas of the United States (1970): *classificatory units used to designate properties of coastal segments, including suggestions for additional units to accompany the original map units*
- Gorshkov (1979): *summary of the Russian coastal classification and mapping units as displayed in the Atlas of the World Oceans*

## V. A PROPOSED NEW SYSTEM OF COASTAL CLASSIFICATION BASED ON GEOMORPHOLOGICAL SITE CHARACTERISATION

### Structural organisation of the new unified geomorphological coastal classification system

- Suess (1888); Johnson (1919); Cotton (1952); Valentin (1952); Shepard (1973); Owens (1994): *analysis of their previous works*
- Finkl 2004: *organisational structure of considerations for a proposed approach to a comprehensive coastal classification based on morphological units that are hierarchically subdivided in terms of rock type, age, geodynamics, climate, relief, erosional-depositional forms, and relief elements*

**Figure 101.** Summary and compilation of the literature review about coastal classifications in Finkl (2004) (part 3 of 3).

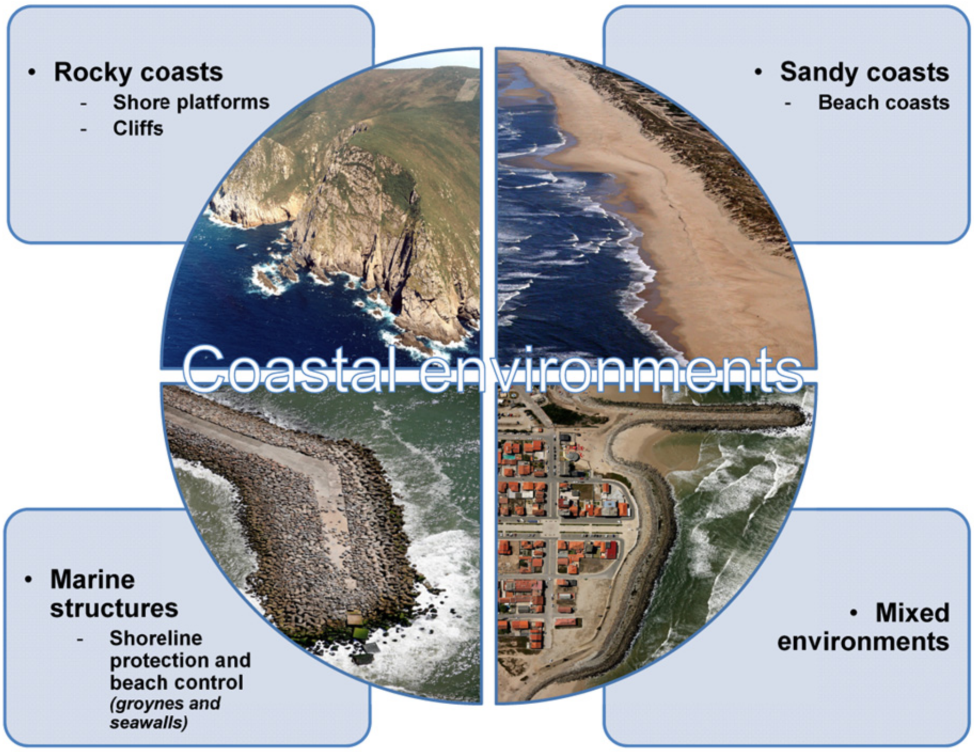



**Figure 102.** Coastal environments considered in this thesis.

To understand these coastal environments it is important to be aware that there are several complex interacting processes involved which are continually modifying rocks and sediments (USACE 1995). As stated by Dean & Dalrymple (2004), to understand coastal processes (including near shore flows and the resulting sediment transport) and to have the skill to change this understanding into operational engineering measures the following factors are required: (i) a blend of analytical capability; (ii) an interest in the workings of nature; (iii) the ability to interpret many complex and sometimes apparently conflicting pieces of evidence; and (iv) experience gained from studying a variety of shorelines and working with many coastal projects.

There are many definitions and terminologies related to coastal geology, coastal engineering and morphodynamics applied to the characterisation of coastal zones. The next images (Figures 105 and 106) show different perspectives, as well as a general description of the coastal zone definitions and subdivisions. Such broad terms as “coast” and “shoreline” are also defined below. Figure 105 displays the typical beach profile and several coastal types and subdivisions. Figure 106 shows the general features for rocky coasts according to different authors. It should be noted that USACE (1995) describes the rocky coast as a bluff (which is a cliff or headland with an almost perpendicular face) while other authors use the terminology of a cliff (land rising abruptly for a considerable distance above the water or surrounding land) (according to the coastal terminology and geologic environments from USACE (2003)).

**Figure 103.** Examples of the coastal environments considered in this thesis: (a) boulders beach in Corrubedo (NW Spain); (b) rocky platform in Lavadores (NW Portugal); (c) coastal cliff in Ortigueira (N Spain); (d) coastal cliff in As Lagoas (N Spain). (image credits: a,c, d - Xunta de Galicia; b - FotoEngenho).

**Figure 104.** Examples of the coastal environments considered in this thesis: (a) sandy beach and field of groynes in Espinho (NW Portugal); (b) mixed environment (sandy beach, groynes and seawall) in Cortegaça (NW Portugal); (c) mixed environment (rocky coast, sandy beach and groyne) in Aguiño (NW Spain); (d) mixed environments in Vila Praia de Âncora and Douro River (NW Portugal). (image credits: FotoEngenho).

Indeed these coastal zone features are very difficult to define because temporal variability or continuous changes between features make delineation of the boundaries sometimes unclear (USACE 1995, 2003). Moreover, nomenclature is not standardised, and numerous authors describe the same features using different names. Even with the same name, the proposed boundaries may differ significantly. This ambiguity is especially evident in the terminology and zoning of shore and littoral areas (Figures 105 and 106).

The following concepts present a suggested coastal zone definition and subdivision according to USACE (1995) and based essentially, but not exclusively, on geological criteria. Still according to USACE (1995) and other authors (e.g. USACE 1984, CIRIA & CUR 1991, USACE 2003, Woodroffe 2003, CIRIA *et al*. 2007), sometimes these concepts and terminologies does not necessarily coincide with other geological based zonings or those established by other disciplines. Coastal zone geology differs greatly from place to place, and must be adapted to the coastal morphodynamic context. Therefore, in a very dynamic coast flexibility, a good description and illustrations are necessary, as well as suitable cartography, for the coastal characterisation of a given study site or region.

According to USACE (1995) the coastal zone can be defined "*as the transition zone where the land meets water, the region that is directly influenced by marine or lacustrine hydrodynamic processes. The coastal zone extends offshore to the continental shelf break and onshore to the first major change in topography above the reach of major storm waves.*"

The coastal zone can be divided into three subzones (Figures 105 and 106): (a) coast; (b) shore; and (c) shoreface. Thus in the USACE (1995) context we define the following coastal elements:

a) Coast: "*the coast is a strip of land of indefinite width that extends from the coastline inland as far as the first major change in topography. Cliffs, frontal dunes, or a line of permanent vegetation usually mark this inland boundary. On barrier coasts, the distinctive back barrier lagoon/marsh/tidal creek complex is considered part of the coast. The seaward boundary of the coast, the coastline, is the maximum reach of storm waves.*"
b) Shore: "*the shore extends from the low-water line to the normal landward limit of storm wave effects, i.e., the coastline. Where beaches occur, the shore can be divided into two zones: backshore (or berm) and foreshore (or beach face). The foreshore extends from the low-water line to the limit of wave uprush at high tide. The backshore is horizontal while the foreshore slopes seaward. This distinctive change in slope, which marks the juncture of the foreshore and backshore, is called the beach or berm crest.*"

c) Shoreface: "*the shoreface is the seaward-dipping zone that extends from the low-water line offshore to a gradual change to a flatter slope denoting the beginning of the continental shelf. The continental shelf transition is the toe of the shoreface. Its location can only be approximately marked due to the gradual slope change. Although the shoreface is a common feature, it is not found in all coastal zones, especially along low-energy coasts or those consisting of consolidated material. The shoreface, especially the upper part, is the zone of most frequent and vigorous sediment transport.*"

Throughout the centuries ocean and land explorations have taken place on ships around the world and therefore at this dynamically active intersection of land and the oceans, humans have been building structures throughout history. Ports and harbours have always served as bases for naval forces and as a way to access upland trade routes or major centres of civilization (Dean & Dalrymple 2004). So it was inevitable that mankind would use their coastlines to built fortified ports as coastal defences.

In Britannia the fascinating Saxon Shore forts are more than fortified ports, they were also essential links in a provincial logistical system concerned with troop movements and the exploitation of natural and agricultural resources (Fields 2006). Over the course of time man has built these fortified ports to protect themselves against seaborne threats, as in the case of the USA (McGovern & Smith 2006). The marine structures presented here are more than shoreline protection and beach control structures (e.g. groynes and seawalls). They work like "castles of defense" that protect us from our enemies, which in this case are the waves on the sea and storms.

More recently, coastlines are used for recreation and tourism and have become more important economically. According to Dean & Dalrymple (2004) coastal development is "*taking the form of homes and businesses*". Populations and built environments in coastal watersheds are growing rapidly, with 55% of the US population already living within 80 km of the coast (NOAA 2013e). Between Central Portugal and North Galicia there are five main commercial ports: A Coruña, Vigo, Leixões, Aveiro and Figueira da Foz. There are other small ports for protection and fishing which are used by small craft and fishing vessels (NGA 2011). In overall Galicia's coastline has around 2,100 km of extension, including several islets and over than 380 hydraulic works along the coast (POLGalicia 2010). The total length of the Atlantic coast of Portugal mainland is more than 800 km of extension, with about 290 hydraulic works along the coast, 70% of which are groynes and seawalls (Pires *et al.* 2009a).

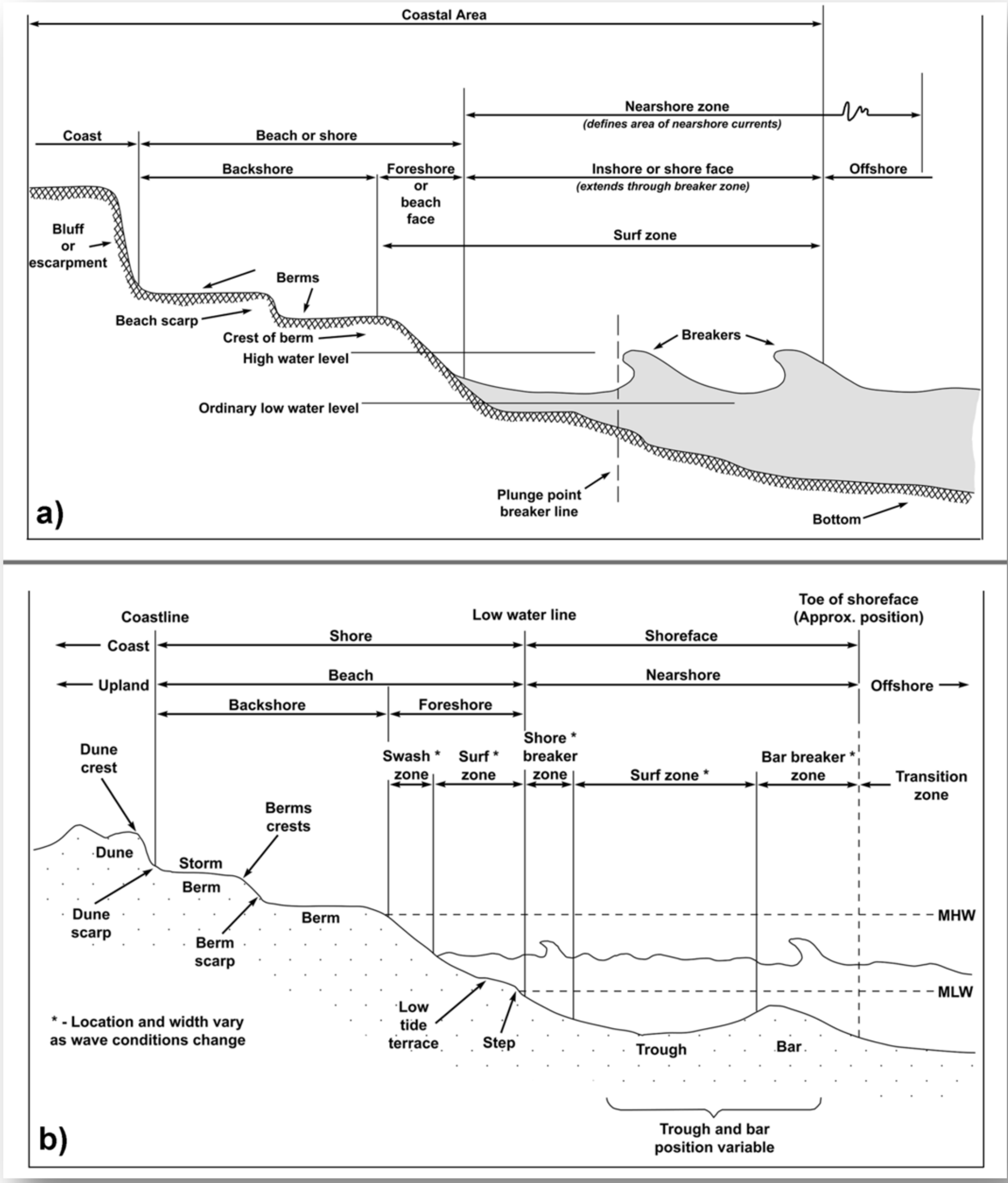



**Figure 105.** Definition of terms and features describing the coastal zone: (a) typical beach profile according to Dean & Dalrymple (2004) and adapted from USACE (1984); (b) typical beach profile according to USACE (1995).

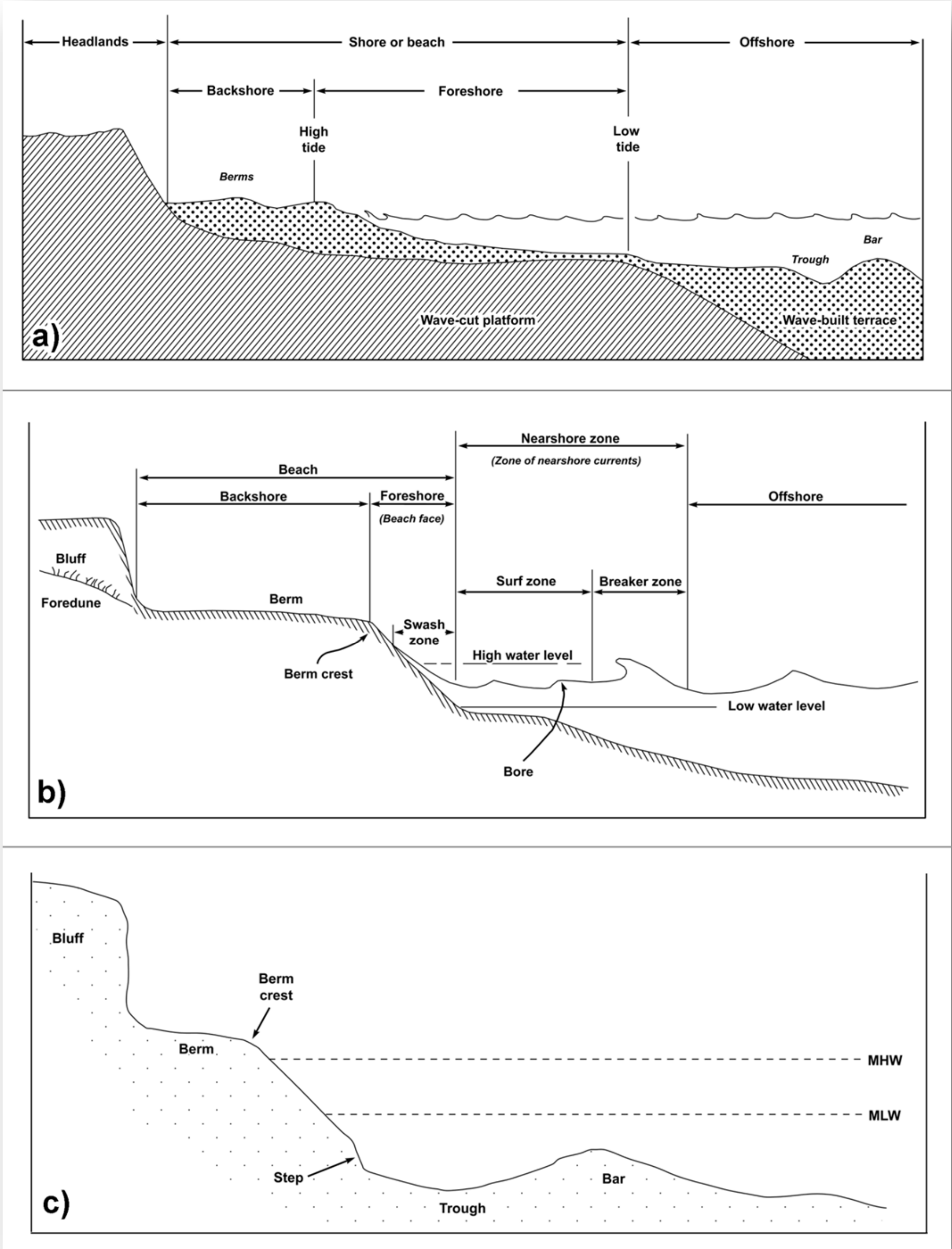



**Figure 106.** General shore features of rocky coasts: (a) typical profile according to Fairbridge (1968); (b) typical profile according to Trenhaile (1987, 1997) and using Komar's (1998) definition of the nearshore; (c) typical profile according to USACE (1995).

It is possible to verify that this shoreline development is causing an increasingly important conflict with the natural coastal processes. Dean & Dalrymple (2004) stated that there are indeed many historical examples of engineering works that have interfered with sediment transport processes (affecting the beach in terms of erosion or large accumulations of sand) and, associated with structural damage, have made some facilities inoperable.

In many coastal areas the fight against the sea is cruel and hard, always in a tentative effort to achieve an "artificial" way of stabilising the coastline.. Coastal defences are simply temporary and "palliative" resources for addressing the impacts of coastal erosion, giving sometimes an incorrect sensation of security to coastal populations (Granja & Pinho 2012). But at the same time it is necessary to turn to this type of solution, and when planning and designing marine structures, and in particularly rock structures, it is necessary to apply fundamental principles. These "codes" essentially handle the planning and design process and certainly any stage in the asset life cycle (CIRIA *et al*. 2007). Figure 107 shows the first stages of coastal projects and the steps in the design process.

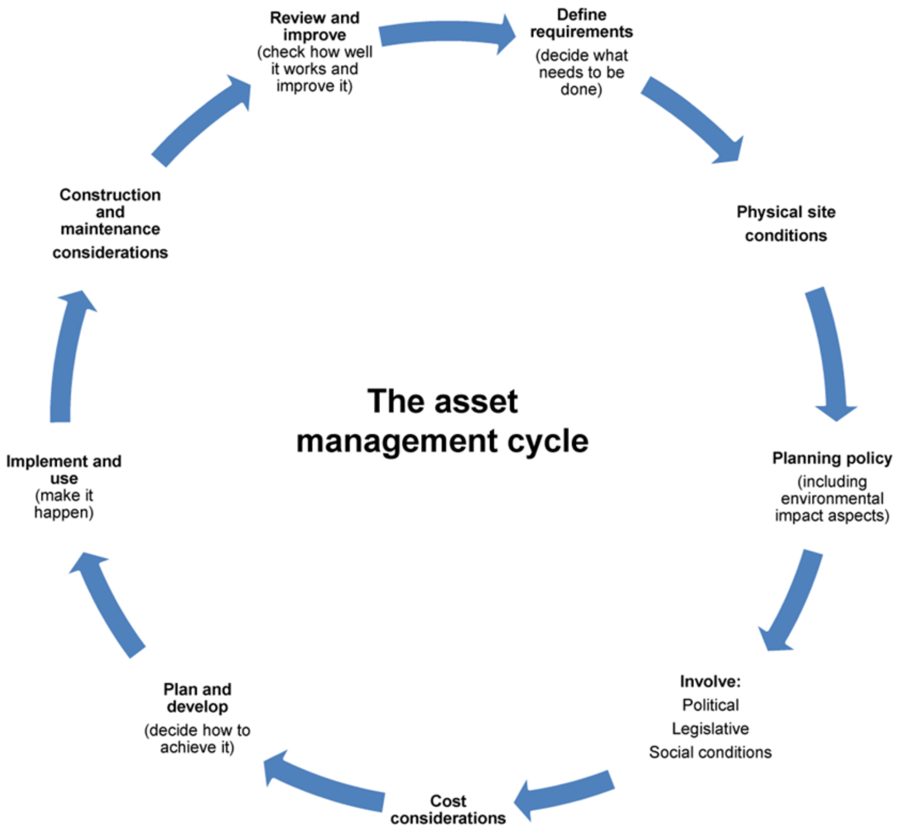



**Figure 107.** The asset management cycle (adapted from CIRIA & CUR 1991 and CIRIA et al. 2007).

As a part of the thesis research it was necessary to perform a zoning of the rock structure, so it is important to define all the component parts and functions in general terms (Figure 108). According to CIRIA *et al*. (2007) the functions of component parts comprise two categories related to: (1) the primary function of the structure; (2) maintaining the physical integrity of the structure. Figure 109a illustrates the key component parts of a breakwater, which are also listed in Table 10 along with the primary functions they perform. The core of a breakwater not only has the purpose of preventing or significantly attenuating wave transmission but also provides support to the armour layer and overall geotechnical stability.

Each component of the structure has a particular function, critical to the overall performance and suitability. The most critical elements for rock structures are generally: (i) stability of the cover layer; (ii) a safe foundation to minimise settlement; (iii) toe protection to prevent undermining; and (iv) a suitable crest for protection (CIRIA *et al*. 2007). The typical failure mechanisms which are relevant for this type of structure are given in Figure 109b.

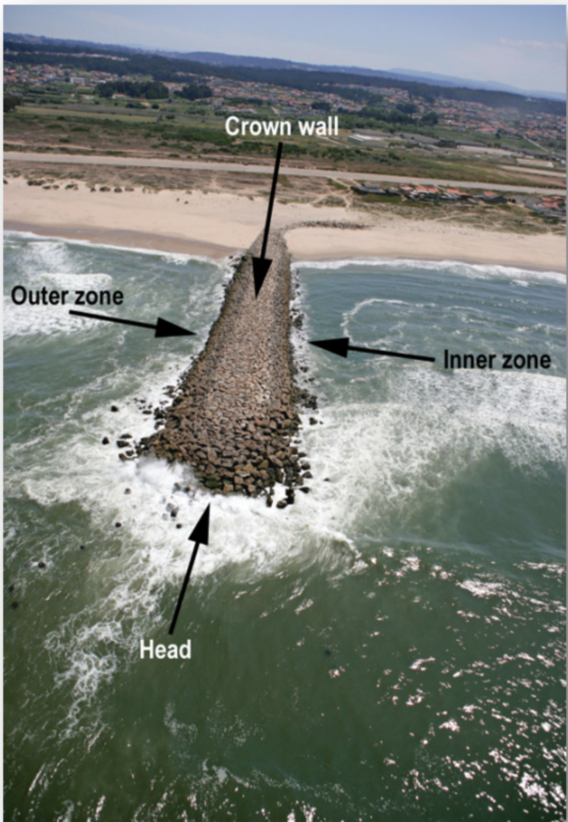



**Figure 108.** The component parts of a typical rock structure (e.g. groyne). Photo credits: FotoEngenho.

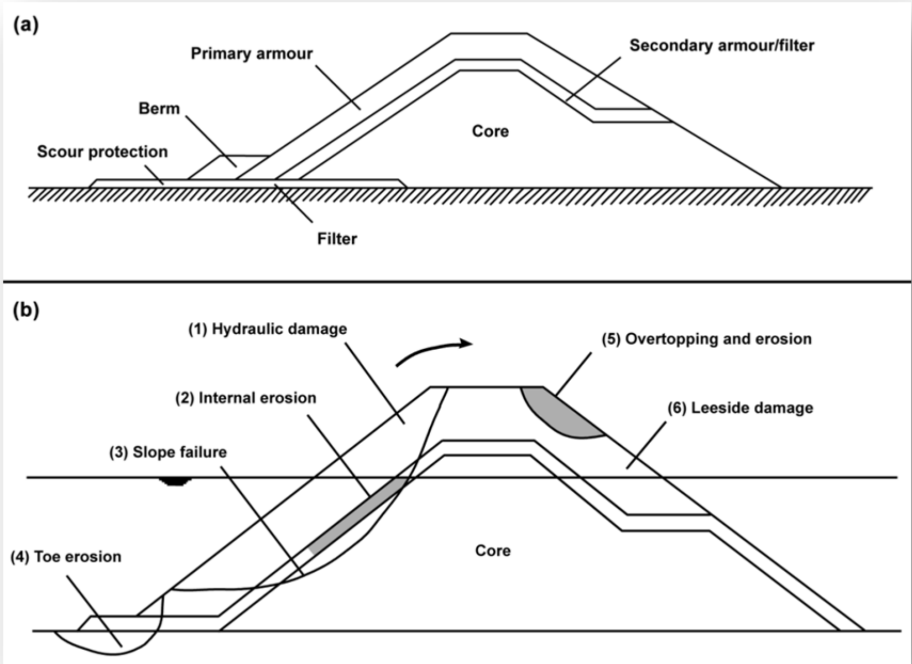



**Figure 109.** (a) Cross-section of a typical rubble-mound breakwater (adapted from CIRIA & CUR 1991); (b) failure mechanisms of a rubble-mound breakwater (adapted from CIRIA & CUR 1991).

In terms of exposure zones for coastal structures it is important to recognise environmental influences of the forcing conditions are applied to which parts of the structure. According to CIRIA & CUR (1991), four approximate exposure zones can be distinguished (Figure 110).

A range of scenarios should be considered in the design of hydraulic structures in terms of failure modes and regarding the system and its responses to hydraulic loading (waves). Some degradation or even failure of the structure or elements of the structure may occur as a result of the loading generated and related to normal functioning of the structure in service and also to ultimate or accidental situations (CIRIA & CUR 1991, CIRIA *et al*. 2007).

Each of the failure modes shown in Figure 111 should be considered in the design of rock structures; howeve,r the degree to which these are relevant will diverge for different structures, locations and design scenarios (CIRIA & CUR 1991, CIRIA *et al*. 2007). Also very often these failure modes are interconnected (e.g. settlement of the structure may increase overtopping, which may in turn cause instability of the inner (rear-side) slope of the structure). In Table 11 a summary is presented of these failure mechanisms and their principal loading parameters with cross-reference to Figure 111 (for further details see CIRIA & CUR 1991, CIRIA *et al*. 2007).

**Table 10.** Functions of typical component parts of a rock structure (adapted from CIRIA *et al*. 2007).

| **Component** *(see figures 108 and 109)* | **Function** |
|---|---|
| *Scour protection* | • Prevents erosion and undermining of the toe |
| *Core* | • Attenuates wave transmission<br>• Supports armour layer and underlayers<br>• Provides geotechnical stability |
| *Berm* | • Attenuates wave action, run-up and overtopping<br>• Provides additional geotechnical stability |
| *Toe* | • Provides stable footing to armour layer |
| *Secondary armour / Filter / Underlayer* | • Acts as a filter<br>• Protects subsoil/core from erosion<br>• Provides in-plane drainage<br>• Regulating or levelling layer that provides appropriate surface for armour layer placement<br>• Separates armour from smaller sized materials and reduces hydraulic gradient into subsoil/core |
| *Primary armour / Armour layer* | • Prevents erosion of underlayer and core by wave action<br>• Dissipates wave energy |
| *Crest (not shown in figures)* | • Attenuates wave overtopping<br>• Allows access for maintenance |
| *Crown wall* | • Attenuates wave overtopping<br>• Allows access for maintenance<br>• Provides support for facilities such as cabling and pipework |
| *Roundhead (not shown in figures)* | • Terminates the structure in a stable manner<br>• Diffracts waves |

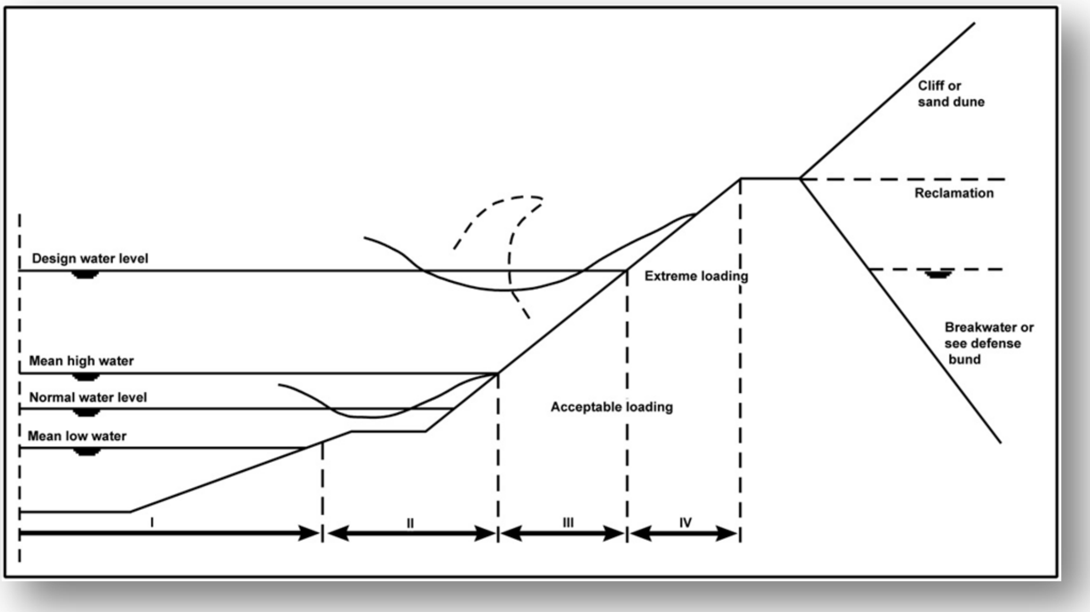



**Figure 110.** Exposure zones on coastal structures (adapted from CIRIA & CUR 1991): Zone I is permanently submerged; Zone II is the zone between MLW and MHW where the ever-present wave loading of low intensity is of importance for the long term behaviour of the structure; Zone III is the zone between MHW and the design level and can be heavily attacked by waves but the frequency of such attacks reduces as one goes higher up the slope; finally Zone IV is the zone above design level, where there should only be wave run-up and overtopping.

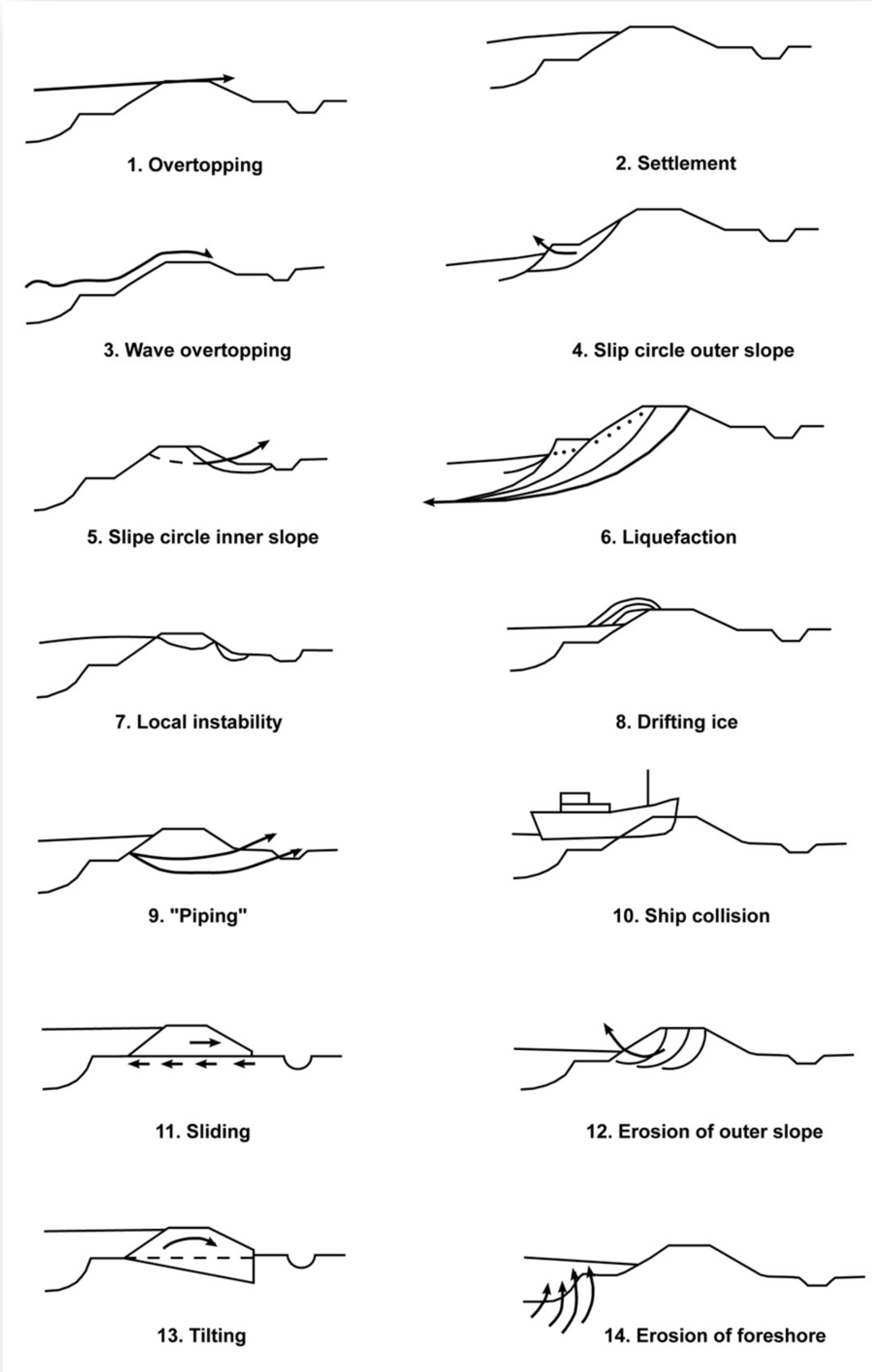



**Figure 111.** Typical failure modes of rock structures (adapted from CIRIA & CUR 1991).

One of the solutions of the "do something" option is to build shoreline protection and beach control structures such as groynes or breakwaters (Figure 112). As indicated before there are many solutions available regarding the design of coastal protection works, including groynes, breakwaters, seawalls, jetties and beach recharges (USACE 2003, CIRIA & CUR 1991, CIRIA *et al*. 2007). According to Simm *et al*. (1996): (i) groynes are shore normal structures designed to reduce longshore transport and retain beach material; (ii) detached breakwaters are shore parallel structures designed to dissipate wave energy and reduce the level of wave activity at the shore; (iii) sills are detached structures that may also be used to form a continuous shore parallel submerged breakwater (or sill) designed to reduce offshore losses by supporting the toe of the beach (for more details about marine structures, closure works, river and canal structures see CIRIA 1990, CIRIA & CUR 1991, Kamphuis 2000, USACE 2003, Reeve *et al*. 2004, CIRIA *et al*. 2007).

**Table 11.** Functions of typical component parts of a rock structure (adapted from CIRIA *et al*. 2007).

| Mechanism | Principal loading parameters | Ref. in Fig. 111 |
|---|---|---|
| **Overtopping** | *Waves* – height, period<br>*Water levels* | 1, 3 |
| **Settlement, tilting** | *Weight* – specific density of materials; saturation degree; pore water pressure; time | 2, 13 |
| **Slope instability** | *Water levels* – differential water levels<br>*Waves* – weight of construction materials; pore pressures; slope angle | 4, 5 |
| **Sliding of structure** | *Weight of structure or elements* – weight of construction materials; pore water pressures (influenced by wave height and period); slope angle | 11 |
| **Movement of rock cover** | *Waves* – height, period, angle of incidence<br>*Currents* – turbulence, velocities<br>*Ice* – layer thickness and drift intensity | 7, 12 |
| **Migration of sub-layers** | *Water level changes* – waves, ship-induced water movements, other dropping water levels; hydraulic gradients; internal flow velocities | 7, 12 |
| **Piping** | *Hydraulic gradients* – internal channel flow velocities | 9 |
| **Erosion of foreshore** | *Waves* – height, period<br>*Currents* – velocities, turbulence | 14 |
| **Liquefaction** | *Waves* – height and period<br>*Earthquakes* – acceleration, frequency; number of loading cycles; pore water pressures; (relative) shear stress amplitude | 6 |

Planning rock works is not the main goal of the thesis, however, and in conclusion, it is important to recognise the importance of several factors in the design of hydraulic structures (according to USACE 1995 and CIRIA *et al*. 2007):

- Study site morphodynamics;
- Physical conditions (climatic and forcing conditions);
- Specification of functional requirements and structure service lifetime;
- Establishment of the statistics of local short-term and long-term sea states as well as estimation of possible geomorphological changes;
- Selection of design levels for hydraulic responses: wave run-up, overtopping, wave transmission, wave reflection;
- Consideration of construction equipment and procedures, and of availability and durability of materials;
- Selection of alternative structure geometries to be further investigated (e.g., composite caisson structures, rubble structures with and without crown walls);
- Identification of all possible failure modes for the selected structures (e.g., armour layer displacement);
- Selection of design damage levels for the identified failure modes;
- Conceptual design of the structural parts based on the chosen design levels for failure mode damage and hydraulic responses (e.g., determination of armour layer block size and crest height for a breakwater);
- Evaluation of costs of the alternative structures and selection of preferred design(s) for more detailed analysis and optimisation;
- Detailed design including economical optimisation and evaluation of the overall safety of the structure;
- Wave-structure interaction (hydraulic responses, loads and response of structural parts);

It is important to always take into account the uncertainty and make an effort to achieve reliability in the design, because this will influence the further stages in a coastal project or in a rock project.

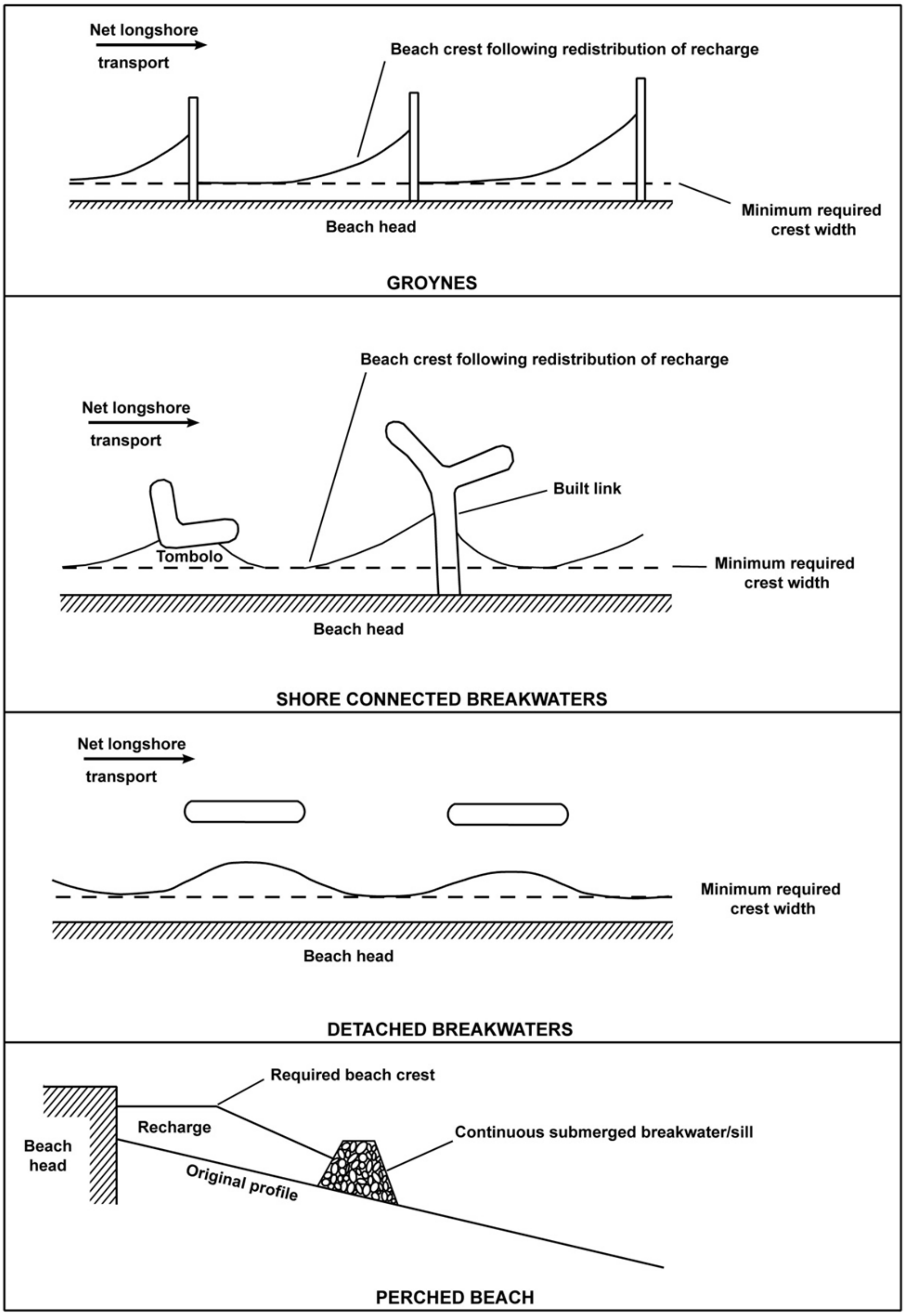



**Figure 112.** Schematic diagram of engineering options: groynes (adapted from Simm *et al*. 1996).

## 3.6. Georesources and geomaterials in hydraulic structures

In the words of Carson (1955): "*understanding comes only when, standing on a beach, we can sense the long rhythms of Earth and Sea that sculptured its land forms and produced the rock and sand of which it is composed*".

This section is comprised of brief remarks about the rock engineering project in coastal protection works. Moreover, it is important to make some mention of source rock quarrying and about the materials available for such kind of hydraulic structures. The rock project process is iterative, dynamic and should be addressed in a logical and inclusive development at the concept design stage before preliminary design is started (Figure 113). This may include a preliminary assessment process in parallel by one or more potential contractors. Therefore the process should consider available material sources, specification requirements, site conditions and available transport (CIRIA *et al*. 2007). After the detailed design the contractor also will work out the best choice of rock source, transport method, construction method, and the total cost. According to CIRIA *et al*. (2007) and CIRIA & CUR (1991) the contractor will experience additional cycles of iteration and improvement to conclude the plan for handling of materials.

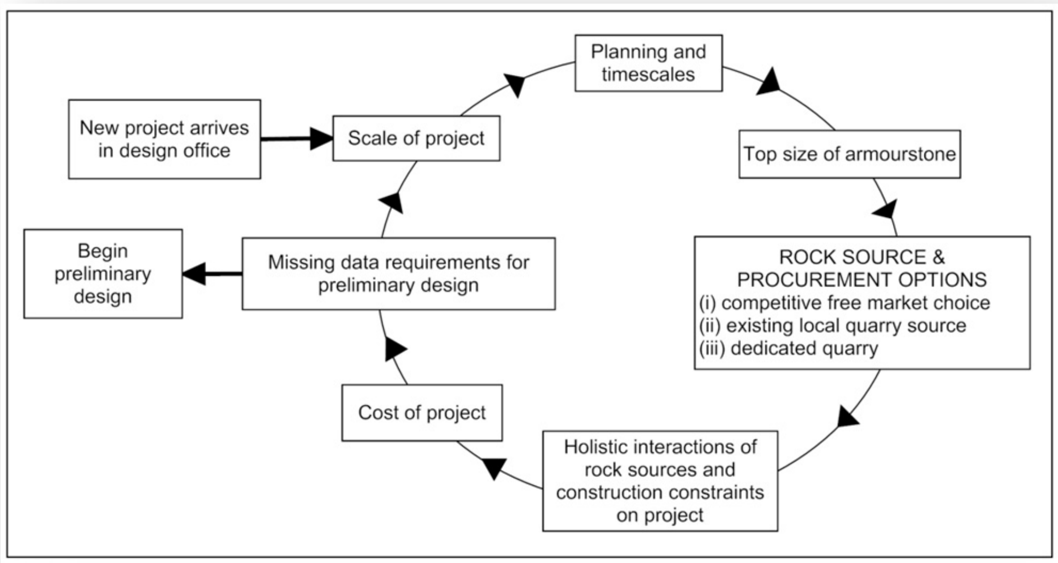



**Figure 113.** Flow diagram of materials consideration process to be applied at concept stage (adapted from CIRIA *et al*. 2007).

Overall, the project should always be developed on the basis of coastal engineering, engineering geoscience, and geomaterial characterisation, by preference on the georesource site, as well as on the location of the hydraulic structure.

These concepts in geotechnical and geoengineering fields are important for rock characterisation and a subject of interest to many researchers (e.g., Fookes & Poole 1981, Poole *et al*. 1983, Poole 1991, Fookes 1991, Latham 1991, Lienhart 1998, Smith *et al*. 2001, Dupray *et al*. 2004, Latham *et al*. 2006a,b, Pires & Chaminé 2007, Pires et al. 2009a,b,c, and references therein), which have proved to be of extreme importance in this thesis. It is also important to highlight the importance of quarry characterisation of rock material quality, which is fundamental for a viable and sustainable rock project. Figure 114 displays a few examples of different types of quarries, involving different geological environments and features, dissimilar materials explored and final purposes.


**Figure 114.** Type of rock quarries and some examples of the georesources available: (a) granite quarry for aggregate/armourstone (Malaposta quarry, S. João de Ver, NW Portugal); (b) granite quarry for aggregate/armourstone (Madalena quarry, Canidelo, Gaia, NW Portugal); (c) granite quarry for ornamental rock (Bouça dos Castros quarry, Braga, NW Portugal); (d) granite quarry for aggregate (Vilar quarry, Ribeira, NW Galicia); e) limestone quarry for aggregate (Cabo Mondego Norte, Figueira da Foz, Centre Portugal); and f) limestone quarry for ornamental rock (Alenquer quarry, Lisbon, Central Portugal); (Photo credits: A. Pires and J. Teixeira).

During the study we take a stand in respect of rock material evaluation, from its rock source quarrying until the completion of the marine project (LCPC 1989, CIRIA & CUR 1991, CIRIA *et al*. 2007). In this sense, the geotechnical investigations also should establish consistent geologic-geomorphological, geotechnical and geomechanical information of the in situ quarry rock mass, including the geometry of the geological units, and their physical and mechanical properties (Fookes & Poole 1981, Smith *et al*. 2001). The proposed methodology essentially focused on concepts like durability, integrity, deterioration and availability, topics on which several authors have been working in past years (e.g., Poole *et al*. 1983, Poole 1991, Fookes 1991, Latham 1991, Lienhart 1998, Dupray *et al*. 2003, Dupray 2005, Latham *et al*. 2006a,b,c, Pires *et al*. 2010a, and references therein).

From the geoengineering point of view, which has been constantly been clarified, and within a scientific context, impacts caused by the construction of large structures and incorrect land use along the coastal areas require comprehensive geological, geomechanical studies and engineering solutions for their mitigation. Since coastal zones are considered highly dynamic and spatially variable, coastal protection structures are important features in this kind of environment to be taken into account within a successful coastal maintenance program or management strategy.

The central considerations for the implementation of a suitable rock project are its scale and the availability, the quality, the durability and the life cycle of construction materials (LCPC 1989, Poole 1991, Lienhart 1998, Dupray *et al*. 2003, Latham *et al*. 2006a,b,c, CIRIA *et al*. 2007). Moreover, the criteria for the selection of raw material are its petrophysical properties and strength, adaptability, cost, handling requirements, maintenance requirements, and environmental impact (Fookes & Poole 1981, Dibb *et al*. 1983, Fookes 1991, Keaton 2013b). Also the knowledge of past material performance in similar coastal projects is an important consideration for the study of coastal structures to ensure maintenance and predict repair/rehabilitation works (USACE 2003, Pope 2005). In addition, coastal protection structures require continuing maintenance to ensure acceptable performance. In addition, a management strategy plan for the deterioration level evaluation and the present condition of these structures is essential.

According to the specific framework and hydraulic environment, different methods and types of structures may be used to protect coastal areas. These fall into two categories (CIRIA *et al*. 2007): marine works and closure works. Marine works are intended to prevent shoreline erosion and hinterland flooding. In fact, coastal defences are vital, among others, to the maintenance of trade and economic development. Natural and durable rock is one of the main materials employed in marine construction works to prevent scour and erosion. According to CIRIA *et al*. (2007) at least 10 million tonnes of armourstone are used each year across Europe, in constructionworks valued at nearly 1 billion euros.

Figures 115 and 116 show specific examples of materials that can be used in marine structures, from natural rock (armourstone) to concrete armour units. Once the rock sources and procurement options for armour layer materials are identified, the required armourstone may not be available or may not be the most cost-effective option. As an alternative to the use of quarried rock in the marine environment, concrete armour units (prefabricated concrete elements) can be a competitive option, especially when heavy armouring is required (CIRIA & CUR 1991, CIRIA *et al*. 2007, Dupray *et al*. 2010). A wide variety of types of unit is available (Figure 116). More information about the use of concrete in maritime engineering can for example be found in Dupray *et al*. (2010).

There are additional alternatives to primary quarried rock to be considered for use in hydraulic structures, including wood or recycled and secondary materials or residues (Masters 2001). More information on these alternatives can for example be found in Brampton *et al*. (2004).


**Figure 115.** Types of geomaterials applied in marine structures: (a) and (b) armourstone (natural rock) and concrete armour units (artificial blocks): tetrapods (c) and antifers (d) (Photos by A. Pires).

In line with several authors (e.g. USACE 2003, CIRIA *et al*. 2007, Dupray *et al*. 2010) the concrete armour units can be categorised into four varieties (Figure 116): (1) *massive concrete units* (parallelepiped, cube, grooved cube with hole and antifer); (2) *bulky concrete units* (acropod, haro, core loc and Seabee); (3) *slender concrete units* (tetrapod and dolos); and (4) *multi-holes units* (shed and cob) which are not represented in the image.

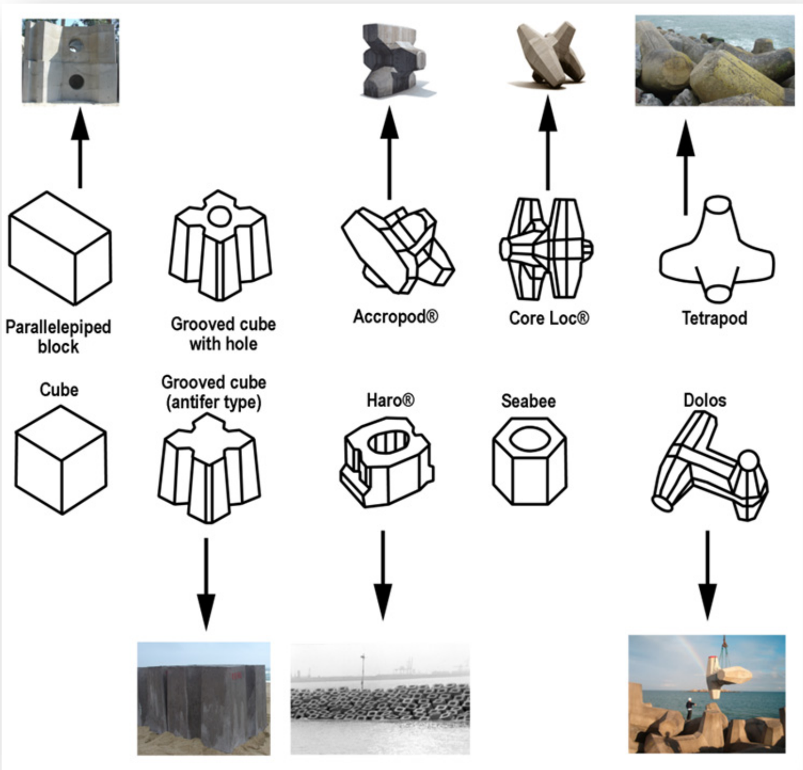



**Figure 116.** Examples of concrete armour units (adapted from USACE 2003, CIRIA *et al*. 2007).

In general, the main functions of materials in hydraulic structure are to: (i) provide volume filling; (ii) provide a foundation and a filtering system; and (iii) protect the structure against wave or current action and scouring (CIRIA *et al*. 2007).

The application of each different material has also consequences (not necessarily hydraulic) that are important to designers. According to CIRIA *et al*. (2007) these distinct applications may carry advantages or disadvantages (e.g. visual appearance, durability, permeability to groundwater, ease of construction, flexibility, availability, effectiveness, access, maintenance, public safety, hygiene and cost).

Table 12 summarises the hydraulic functions in terms of the different types of materials that may be provided during the course of the coastal project.

**Table 12.** Hydraulic functions (adapted from CIRIA *et al*. 2007).

| Function | Natural armourstone | Concrete armour units | Gabions | Alternative granular materials |
|---|---|---|---|---|
| | Type of material | | | |
| Volume fill | *** | - | - | ** |
| Filtering | *** | - | * | * |
| Armouring | *** | ** | ** | * |

*** usually ideal, ** suitable for this function, * may be used to provide this function; a requirement under specific conditions, - not suitable

According to Fookes (1991) the concept of geomaterial can be stated as *"processed or unprocessed soils, rocks or minerals used in the construction of buildings or structures, including man-made construction materials manufactured from soils, rocks or minerals"*. In addition, armourstone is defined as a coarse aggregate used in hydraulic structures and other civil works (according to EN 13383-1 2002, EN 13383-2 2002, Trmal & Dupray 2006, CIRIA *et al*. 2007). This category of rock materials used in coastal defence works is subject to environmental conditions which differ, both in severity and type, from those encountered in other situations. Design requirements also include elements specific to coastal engineering structures and these aspects must be given due consideration in the selection and specification of the rock.

The two most important groups of properties of rock for use in coastal engineering are geometric properties – shape, size and grading – and physical properties – which includes density and factors relating to mechanical strength, resistance to abrasion, porosity and durability (Poole 1991, Wang *et al*. 1991a, 1991b, 1991c). Another important parameter to take into account is rock erosion and scour along the structure, which is a rock-water interaction phenomenon (Latham 1998, Smith 1999, Feng *et al*. 2013, Keaton 2013b).

The failure mechanisms which affect the structure have already been mentioned and illustrated. However, Figure 117 schematises the principal failure modes of rock structures and the rock system associated with hydraulic and structural responses to allow a better understanding. "*Failure can be simply defined as the exceedance of a predefined limit state, which occurs when the loading exceeds the strength*" (CIRIA & CUR 1991). When excess loading occurs, a failure response of the structure (or component parts of it) can be defined. These failures can take place during construction stage, operation stage or both. The typical loading and responses are related to wave height and displacement, and both loading and response are functions of time. There are forcing conditions affecting the rock system (loading and strength) which in turn will have a response, that depending on the functional requirements could result in failure.

The schematic illustration in Figure 117 represents the response model is applied to elements of the structure (stones, sublayers) or to the structure as whole. These concepts are related to the previous section about coastal environments and coastal structure behaviours (Figure 111 and Table 11).

Besides, all of these processes involved on the design, construction, maintenance and repair of the structures are intrinsically connected with the material selected regarding its geological-geotechnical characteristics and geomechanical properties. The structure response and the functional requirement will be at stake.

According to CIRIA *et al*. (2007), there are undeniably large quantities of rock quarrying applied to marine projects for example: Hong Kong Airport (an estimated 9.3 million tonnes per year over five years); the Iceland breakwater (1,847,000 tonnes of quarried rock, 80% of which was core material and 20% armourstone); or in contrast the Scotland bridge pier scour protection scheme (4,200 tonnes of armourstone, though river training works may use just a few hundred tonnes of armourstone or gabions).

According to several authors (e.g. Winkler 1973, LCPC 1989, Fookes & Poole 1981, CIRIA *et al*. 2007) it is always necessary to consider several features in the coastal project equation, including the assessment of quarried rock; its production and its processing. This will certainly provide vital economic success and a good understanding of hydraulic design to the project.

The availability and procurement of armourstone is not an easy process because every site condition and rock type is distinctive. Therefore, potential or prospective rock sources need to be evaluated and harmonised with their purpose at the site (CIRIA *et al*. 2007). The rock types available are various and according to CIRIA *et al*. (2007) it is possible to divide rocks into the following categories depending on their mode of formation (Figure 118):

- Igneous – *formed by the crystallisation and solidification of a melted magma;*
- Sedimentary – *formed by sedimentation and subsequent lithification of mineral grains, either under water or more rarely on an ancient land surface;*
- Metamorphic – *formed by the effect of heat and pressure on igneous, metamorphic or sedimentary rocks for geological periods of time, resulting in new minerals and textures developing within the pre-existing rock.*

In short, rocks are formed in a continuous geodynamic cycle (involving numerous internal and external processes) throughout geological time, that result for engineering purposes (e.g., Smith *et al*. 2001, Price 2009, De Freitas 2009, Chaminé *et al*. 2013b) in hard rocks (unweathered, strong and durable), soft rocks (weak and easily deformable) and soils (unconsolidated sedimentary deposits overlying bedrock) (Figure 118).

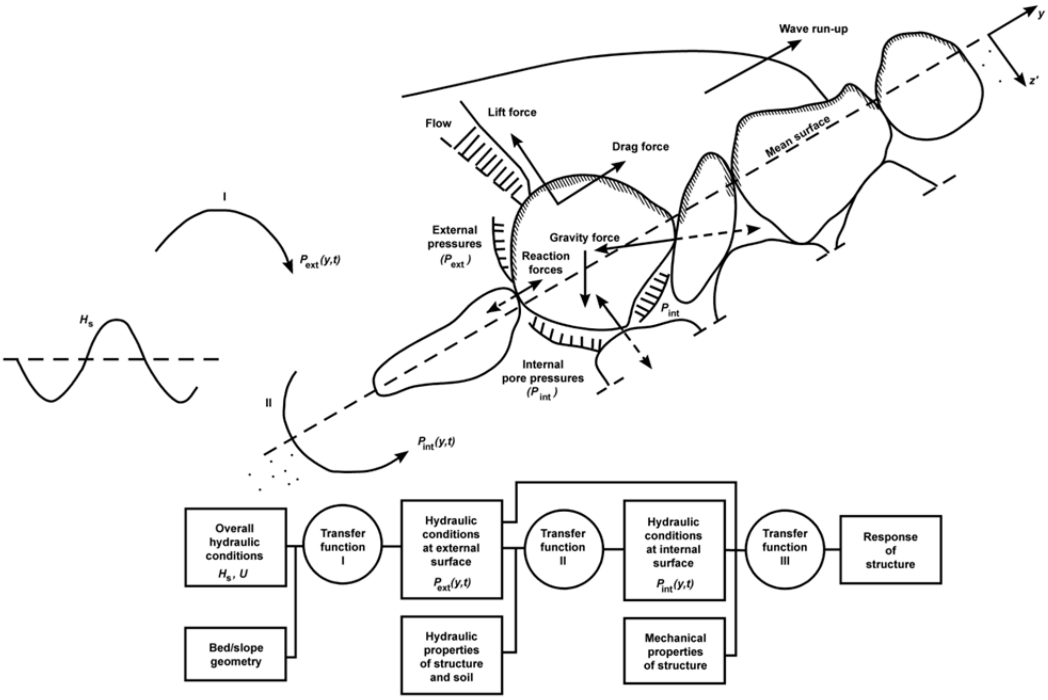



**Figure 117.** A rock system and its responses to hydraulic loading (waves) [Hs – significant wave height; U – horizontal depth mean current velocity] (adapted from CIRIA *et al*. 2007).

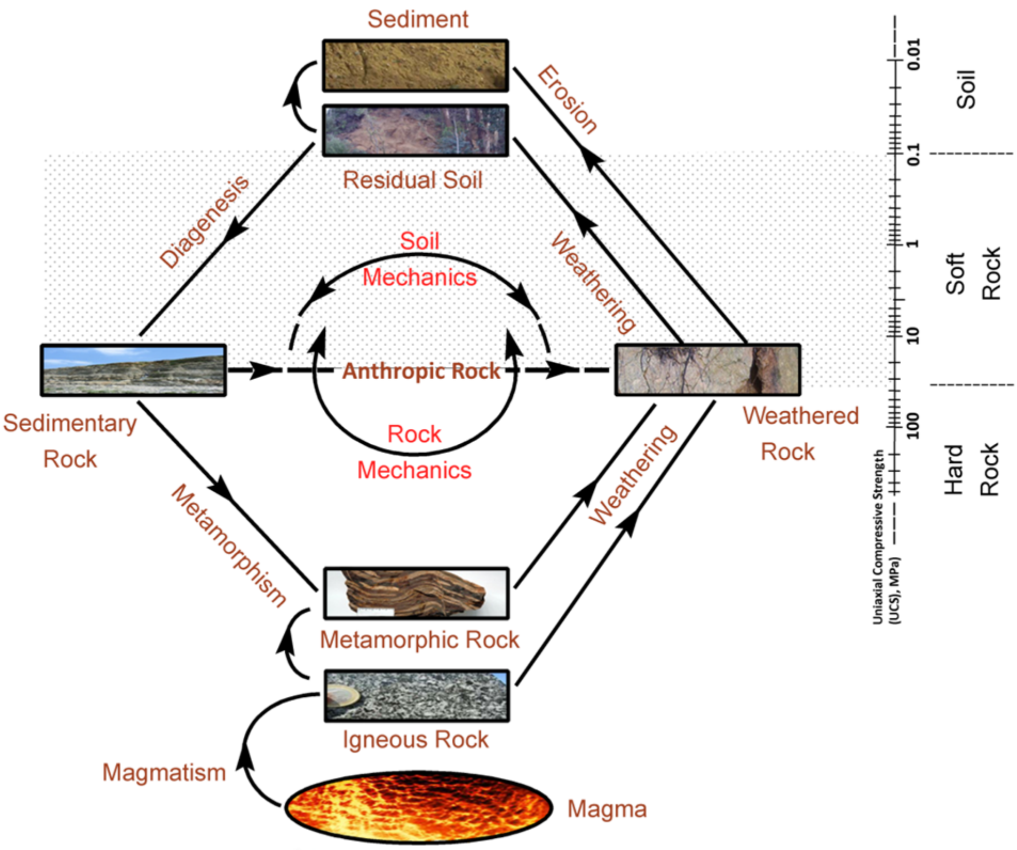



**Figure 118.** The rock cycle in the perspective of the engineering geosciences framework: an outlook for rock mechanics and soil mechanics issues (adapted from Dobereiner & De Freitas 1986). Anthropic rocks is a collective term for those rocks made or modified or moved by humans (Underwood 2001). After Chaminé *et al*. (2013b).

These categories on the other hand may be split into 20 rock types in hydraulic structures, with comparable characteristics which are presented in a general summary form as shown in Table 13.

**Table 13.** Generalised evaluation of the use of unweathered rock in hydraulic structures (adapted from CIRIA *et al*. 2007).

| Rock | | Use | | | Property | | |
|---|---|---|---|---|---|---|---|
| Group | Type | Armour | Filter | Core | Density ($t/m^3$) | Maximum size | Shape |
| Igneous | Granite | * | * | * | 2.5 - 2.8 | HG | Equant |
| | Diorite | * | * | * | 2.6 - 3.1 | HG | Equant |
| | Gabbro | * | * | * | 2.8 - 3.2 | HG | Equant |
| | Ryolite | * | * | * | 2.3 - 2.8 | LG | Irregular to equant |
| | Andesite | * | * | * | 2.4 - 3.1 | LG | Equant |
| | Basalt | * | * | * | 2.5 - 3.1 | HG | Equant |
| | Syenite | * | * | * | 2.6 - 2.9 | HG | Tabular to equant |
| Sedimentary | Quartzite | * | * | * | 2.6 - 2.8 | HG | Tabular to equant |
| | Sandstone | ! | * | * | 2.3 - 2.8 | LG | Tabular |
| | Siltstone | ! | ! | * | 2.3 -2.8 | LG | Tabular |
| | Shale | ! | ! | * | 2.3 - 2.7 | LG | Tabular |
| | Limestone | * | * | * | 2.3 - 2.7 | HG | Tabular to equant |
| | Chalk | ! | ! | * | 1.5 - 2.3 | LG | Equant |
| Metamorphic | Slate | x | x | * | 2.7 - 2.8 | LG | Tabular |
| | Phylite | x | x | * | 2.3 -2.7 | LG | Elongated |
| | Schist | ! | ! | * | 2.7 - 3.2 | LG | Elongated to tabular |
| | Gneiss | * | * | * | 2.6 - 2.8 | HG | Equant |
| | Marble | * | * | * | 2.7 - 2.8 | HG | Equant |
| | Serpentinite | * | * | * | 2.5 - 2.6 | LG | Irregular |
| | Eclogite | * | * | x | 3.3 - 3.6 | HG | Irregular |

* suitable for use; ! Specific attention to ensure suitability; x not suitable
CG: Coarse grading; LG: light grading; HG: heavy grading

Each family of rock has essentially similar characteristics, so that the engineering properties of these rock types can be synthesised in Table 14. The features in Table 14 refer only to fresh rock. Geological weathering, which is not always identifiable by simple visual inspection, can often seriously reduce the quality of the rock concerned (CIRIA & CUR 1991). It is possible to verify that the specific weight values of rocks vary widely, with porosity data for particular rocks (giving average values for some rocks) and uniaxial compressive strength (UCS) values for different types of rock. Some values are not available (n.a.) for certain rocks.

**Table 14.** Some generalised engineering characteristics of unweathered common rocks: porosity and strength values (adapted from González de Vallejo & Ferrer 2011).

| | Typical values for unit weight and porosity of rocks | | Strength values for fresh intact rock | | |
|---|---|---|---|---|---|
| | | | Uniaxial compressive strength (MPa) | | Tensile strength (MPa) |
| **Fresh rock** | ***Unit weight (KN/m$^3$)*** | ***Porosity (%)*** | Average values | Range of values | |
| *Andesite* | 22-23.5 | 10-15 | 210-320 | 100-500 | 7 |
| *Amphibolite* | 29-30 | - | 280 | 210-530 | 23 |
| *Anhydrite* | n.a. | n.a. | 90 | 80-130 | 6-12 |
| *Basalt* | 27-29 | 0.1-2 | 80-200 | 60-350 | 5-25 |
| *Chalk* | 17-23 | 30 | n.a. | n.a. | n.a. |
| *Coal* | 10-20 | 10 | n.a. | n.a. | n.a. |
| *Diabase* | 29 | 0.1 | 240-350 | 130-365 | 55 |
| *Diorite* | 27-28.5 | - | 180-245 | 120-335 | 8-30 |
| *Dolorite* | n.a. | n.a. | 200-300 | 100-350 | 15-35 |
| *Dolomite* | 25-26 | 0.5-10 | 60-200 | 50-350 | 5-25 |
| *Gabbro* | 30-31 | 0.1-0.2 | 210-280 | 180-300 | 14-30 |
| *Gneiss* | 27-30 | 0.5-1.5 | 60-200 | 50-250 | 5-20 |
| *Granite* | 26-27 | 0.5-1.5 (0.9) | 70-200 | 50-300 | 7-25 |
| *Greywacke* | 28 | 3 | 100-150 | 80-220 | 5.5-15 |
| *Gypsum* | 23 | 5 | 25 | 10-40 | 1-2.5 |
| *Limestone* | 23-26 | 5-20 (11) | 60-140 | 50-200 | 4-30 |
| *Marble* | 26-28 | 0.3-2 (0.6) | 120-200 | 60-250 | 6-20 |
| *Marl* | n.a. | n.a. | 30-70 | 20-90 | - |
| *Mudstone* | 22-26 | 2-15 | 20-40 | 10-90 | 1.5-10<br>0.5-1* |
| *Quartzite* | 26-27 | 0.1-0.5 | 200-320 | 100-500 | 10-30 |
| *Rhyolite* | 24-26 | 4-6 | n.a. | n.a. | n.a. |
| *Salt* | 21-22 | 5 | 12 | 5-30 | - |
| *Sandstone* | 23-26 | 5-25 (16) | 55-140 | 30-325 | 5-20 |
| *Schist* | 25-28 | 3 | 30-60 | 20-160 | 2-5.5 |
| *Shale* | 25-27 | 0.1-1 | 40-150 | 30-200 | 7-20 |
| *Siltstone* | n.a. | n.a. | - | 35-250 | 2.7 |
| *Tuff* | 19-23 | 14-40 | - | 10-46 | 1-4 |

*(*) Along lamination planes.*

Rock engineers deal with large volumes of rock which will contain variable amounts of fluid in their network discontinuities, such as joints, fractures, faults, sedimentary or tectonometamorphic surfaces (bedding planes, schistosity, shear zones, folds, etc.) and vein structures. These natural rock structures render the fabric of the rock mass discontinuous (Zhang 2005, Price 2009). The general term "discontinuity" in rock engineering refers to any break in the rock continuum having little or no tensile strength (Hudson & Cosgrove 1997). Intact rock refers to the unfractured blocks (ranging from a few millimetres to several metres in size) between discontinuities in a typical rock mass (Zhang 2005).

The basic techniques of field mapping, engineering geosciences and rock mechanics (see details in Chaminé *et al*. 2013b) must be applied at the given study rock quarrying site (Figure 119).

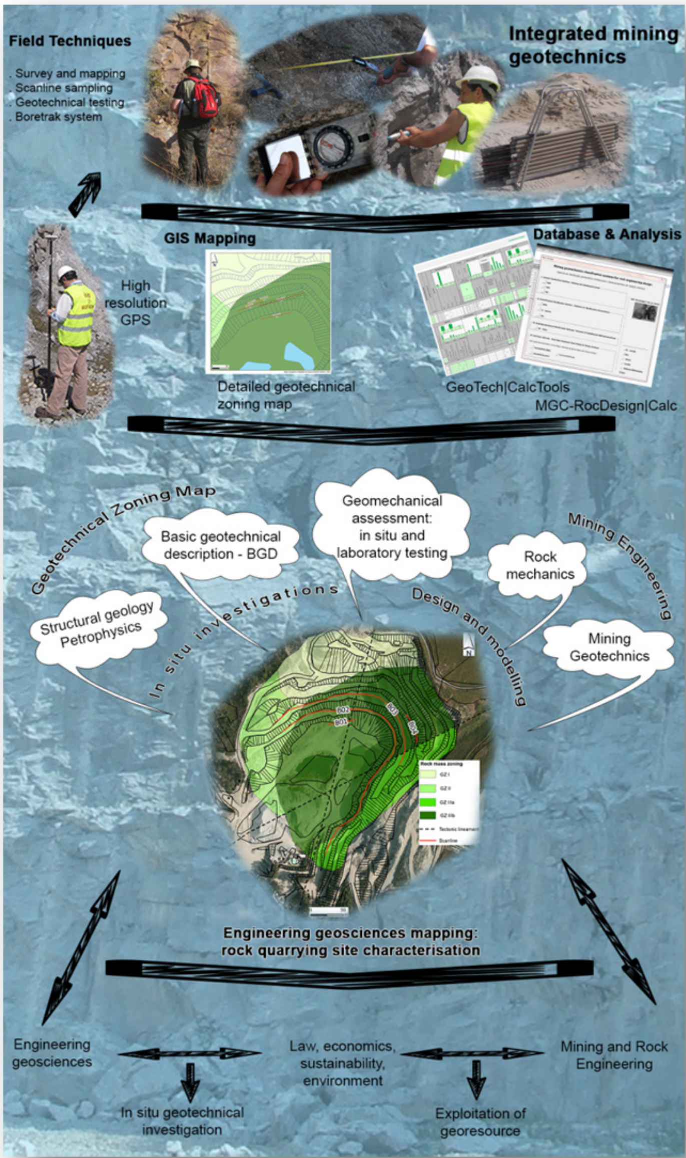



**Figure 119.** Engineering geosciences mapping on rock quarrying site activities: a general outlook on an integrated georesources exploitation framework. This integrative approach allows the basic geotechnical description of rock masses and establishes an engineering geosciences zoning map. The scanline sampling technique is applied to the study of free rock mass faces on different benches of the quarry to characterise the rock mass discontinuities and to define the in situ block size (after Chaminé *et al.* 2013b).

The discontinuities of the rock mass are also important parameters to take into account in quarry evaluation, as well as in the right choice of the material (e.g., Hudson & Cosgrove 1997, Brady & Brown 2004, CIRIA *et al.* 2007, González de Vallejo & Ferrer 2011). Quarrying occurs in an in situ rock mass, comprising intact rock and discontinuities cutting through it; both e factors are important for production and application of armourstone.

These modes of origin result in a small number of typical discontinuity patterns within the rock masses, as illustrated in Figure 120. According to CIRIA *et al*. (2007) discontinuities could have geological or geomorphological origin (natural discontinuities) or could be generally induced by extraction techniques, such as blasting ("artificial" discontinuities). The engineering geology field commonly uses special terminology (e.g. ISRM 1981, Blyth & De Freitas 1984, Harrison & Hudson 2000, U.S.D.I.B.R. 1998, Price 2009, González de Vallejo & Ferrer 2011) to cover a variety of discontinuities. Usually discontinuities are characterised by several geological and geotechnical features: origin, orientation, persistence, fracture degree, weathering grade, seepage, strength walls, and infill material (ISRM 1981).

In accordance with CIRIA *et al*. (2007) the evaluation of the discontinuity pattern (rock mass) will provide the following crucial information: (i) the block sizes in the rock mass prior to production, also called "*In situ Block Size Distribution*" (IBSD) (Wang *et al*. 1990, Wang *et al*. 1991a,b, Lu & Latham 1999) ; (ii) the likelihood and distribution of weathering in both the rock mass and the armourstone produced; (iii) the expected block shape of light and heavy armourstone pieces (Figure 120); (iv) the likelihood of armourstone integrity problems for light or heavy grading.

The discontinuity pattern may be analysed: (i) from free rock mass face outcrops (when accessible); or (ii) by drill cores or borehole logs, which can provide typical spacing information in the borehole direction and the Rock Quality Designation – RQD index (see Zhang & Einstein, 2000, for details).

The weathering grade of the rock is related with the exposure of the rock over long periods of geological time to the climatic conditions at the Earth's surface and involves mechanical disintegration and/or chemical decomposition acting together (ISRM 1978a,b, GSE 1995, Mottershead 1997, Ng *et al*. 2001, Caricato *et al*. 2011, Palmström & Stille 2010). The weathering profiles of rock are influenced by climate and this situation is illustrated in Figure 121, which represents typical quarries in three different climates: north-western European, tropical hot-wet and hot arid regions (CIRIA *et al*. 2007).

Rock degradation processes may have taken place very slowly over geological timescales, due to physical, chemical and biological weathering or hydrothermal alteration processes. Depending on the degree to which this degradation has occurred, the general properties expected for a fresh specimen as given in Tables 13 and 14 may not apply. For example, weathering over many thousands of years may have developed an abundance of microcracks in the mineral fabric of an igneous rock, and originally strong interlocking minerals may have been altered or completely replaced by weaker ones such as clays.

The weathering profiles existing within the rock face being excavated require suitable identification (Fookes 1980, Palmström & Stille 2010). As a general rule, the igneous and metamorphic rocks (formed in conditions of high temperature and pressure) display the greatest predisposition to well-developed weathering profiles, while the sedimentary rocks break down less easily because they were formed at conditions of temperature and pressure existing at the Earth's surface, which are probably similar to the climatic regime they experience at the present ground surface (Fookes 1980, CIRIA *et al*. 2007).

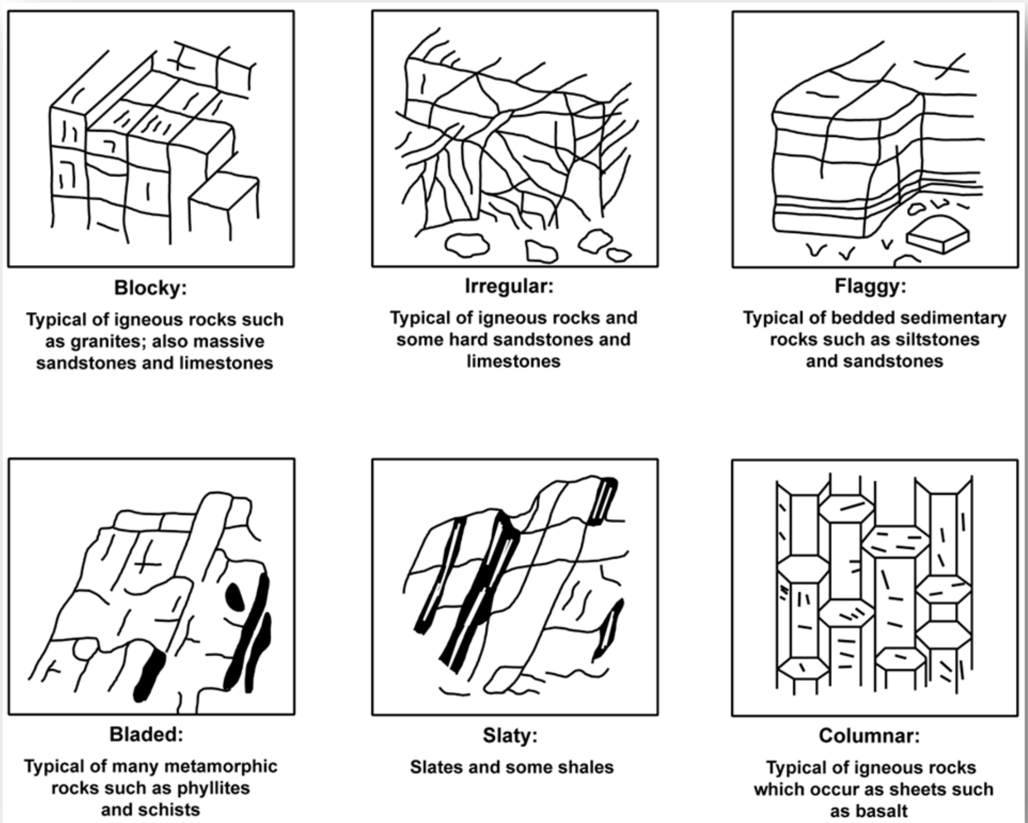



**Figure 120.** Idealised sketches of common discontinuity patterns in natural outcrop forms (adapted from CIRIA *et al*. 2007).

Figure 121 shows three quarries in an extremely simplified form. Quarry No. 1 (right-hand) portrays an igneous rock quarry in north-western Europe. According to CIRIA *et al*. (2007) the Pleistocene ice advances have planed off much of the existing residual soil and weakened weathered rock to leave fairly fresh rock, generally containing only faint to slight weathering grades of material (immediately prior to the current geological processes operating on the Earth's surface). Frequently this rock is crushed near the surface by freeze-thaw cycles and it may be covered with glacial or post-glacial debris (Fookes 1980). Quarry. No. 2 (centre quarry) shows the same rock in a tropical hot and wet climate. In this location, physical flattening by ice during the Ice Ages did not occur, and therefore a thick development of residual soil still exists. The soil passes down into highly weathered rock, which in turn passes down into less weathered and finally into fresh rock. In such a quarry the various grades of weathering can easily be seen and recognised. Finally, Quarry No. 3 (left-hand) portrays a limestone quarry in a hot desert climate. The rock is usually fairly porous and weakened some metres below the existing ground surface by leaching, but has a thick hardened surface duricrust composed of calcrete (the specific type of duricrust formed by the upward leaching of a limestone bedrock) (CIRIA & CUR 1991, CIRIA *et al*. 2007).

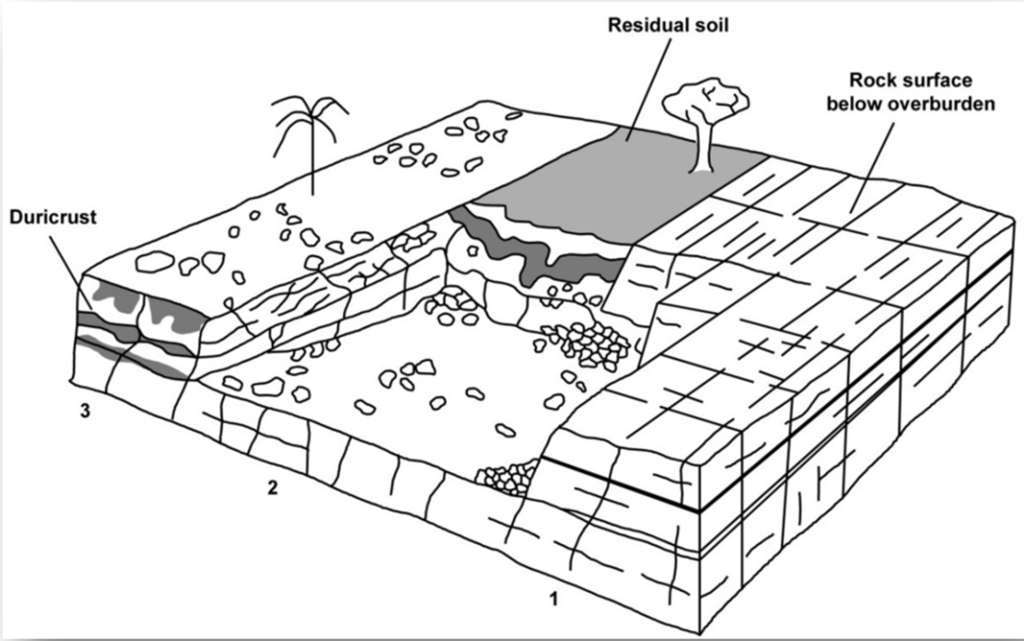



**Figure 121.** Three idealised quarries showing different types of weathering (adapted from CIRIA *et al*. 2007).

The next paragraphs will succinctly outline guidelines for the use of rock in hydraulic engineering and propose some strategies which are important to rock and coastal projects (based on CIRIA *et al*. 2007 and information taken from CIRIA (2009) training course notes about "*the use of rock in hydraulic engineering: materials, construction and maintenance*"). The purpose of the next topic is to work almost like a step-by-step quick guide that is useful to understand essential subjects in rock projects, as well as synthesise the main concepts behind the architecture of rock armour structures.

**The use of rock in hydraulic engineering**

**1. European approach to armourstone**

Standards and codes

*EN13383 part 1 requirements*

*EN 13383 part 2 test methods*

*Annex ZA: CE marking for hydraulic application*

National informative standard

Other guidance: The Rock Manual (CIRIA *et al*. 2007)

**Euro-standard EN 13-383**

Scope: *natural, secondary and recycled armourstone used for hydraulic work and other civil engineering application. Does not cover core materials and concrete armour units*

Objective: *define properties that should be declared by the producer to legally allow trading of armourstone on the EC and national markets. This is embodied by the "CE Marking"*

**CE Marking**

The CE declaration and marking is done by the producer, through:

- *ITT : Initial Type Tests*
- *FPC : Factory Production Control*

Test results are declared by the producer

- *A standard category (defined by criteria)*
- *A Declared value or Declared category*
- *A No Requirement Category*
- *"NPD" (No Performance Determined), if the property is not compulsory in the country where it is sold - it may be tested for other markets*

**2. Armourstone production / selection**

The following aspects should be considered:

- *How to clean efficiently the muckpile / rock face*
- *How to select heavy armourstone at the rock face*
- *How to produce smaller armourstone (<300kg)*
- *How to fit the production of smaller armourstone in the rest of the production*

*"The right tool for the right job"*

In summary, select:

- *Equipment or machine type and size*
- *Tool size*

as a function of the:

- *Armourstone size*
- *Armourstone quantity*
- *Lead time*
- *Distance in the quarry.*

**3. Construction with armourstone**

Rock in marine construction

Approaches to marine construction will vary with:

- *Transport and origin of the stones*
- *Placing requirements and conditions*

The site conditions

will control:

- *Access on site for deliveries*
- *Work*

Public safety – to be aware

will affect working conditions:

- *Tidal work?*
- *In the dry?*

Site conditions and access

- *Sea deliveries or land based deliveries*
- *Marine based operation or land based operation?*

Health and safety

- *Implementation is contractor's responsibility*
- *Designer's responsibility to consider during design*

Rock quality

- *Is it a problem during construction?*
- *Is there a risk of rock breakage?*
- *Can we drive over the armourstone?*

Transport & delivery & placing – sea

- *Placement – working from sea*
- *Transport – Sea*
- *Land based deliveries*
- *Large Rock Sizes – Wire loops in stones*

Working from land – long reach

- *Working conditions*
- *Size of machines should be increased with regard to the actual reach required during the work*

Transport and placing of concrete units

On the use of geotextiles

Can be used as an alternative to under layers and can provide benefits for toe design

Advantages:

- *Savings in material cost, layer thickness*
- *Reduces differential settlement*
- *Can be quick to lay*

Challenges:

- *In deep water or areas of high current is often difficult (not impossible) to lay*
- *Protection during placement from plant needed*
- *Care needed when placing rocks on top*

Surveying
Layer thickness and design
Model construction
Specifications

**4. Armourstone integrity**

Armourstone types of breakage
- Minor breakage:
  - *Crushing mechanism*
  - *Loss of mass < 10%*

  *Assessed by tests on:*
    - *Small scale specimens*
    - *On the mineral fabric*
- Major breakage: deserves full-scale investigation
- Effects of armourstone breakage – analysis
- How / when / what for?
  - *Sonic velocity test:*
    - *As control test of deliveries*
    - *To confirm deliveries have a consistent integrity, with ref. to Drop-Test or Full-Scale Splitting test*
  - *Drop test:*
    - *As pre-contract type >> pass / fail test*
    - *To confirm production is suitable for deliveries*
  - *Full-Scale Splitting test :*
    - *As initial type test >> qualification test*
    - *To assess the effect of existing discontinuities on the grading during construction/service*

**5. Durability and maintenance**

Quality / durability
- Degradation mechanisms
  - *Location of the structure / position of the stone viz. water level*
    - *Weathering: freeze and thaw, salt crystallisation, wetting/drying, thermic cycles*
    - *Attrition and impacts from beach*
  - *Type of structure*
    - *Movement in the cover layer and impacts*
  - *Rock mass heritage*
    - *Decay and mineralogical changes, stress release*

Durability will affect design properties:
- *$M_{50}$ (Mass of particle for which 50% of the granular material is lighter)*
- *Interlocking*
- *Filtering capacity*

The loss of performance kinematic varies with the degradation mechanism:
- *Wear is progressive and affect interlocking which affects $M_{50}$*
- *Breakage or disintegration affect $M_{50}$ and may be sudden*

During design, maintenance scenario should be envisaged and durability scenario should be considered:
- *Excellent durability: no maintenance or related to extreme events*
- *Good durability: condition based maintenance*
- *Lower durability: over-design to allow for degradation / anticipate when restoration is required*

Quality evaluation: quarry and in-situ
- Rating of the various relevant properties
  - *Indicative scale:*
    - *Excellent - ideal and sometimes available. No risk of degradation.*
    - *Good - better than average. In normal situations, no specific attention needed.*
    - *Marginal - lower than average. Without specific attention, the attribute may lead to significant degradation.*
    - *Poor - much lower than average. If possible, the use of the material should be avoided.*

Quality evaluation: laboratory tests

Global evaluation – multicriteria approach
- *Global approach*
- *Indicative approach*
- *Rating of properties depending on their role (quality rating assessment worksheet, after Lienhart 1998)*
  - *Essential = more than 90%*
  - *Important =80%-90%*
  - *Equal =70%-80%*
  - *Minor = 50%-70%*
- *Allows a rational comparison of rock sources*
- *Quarry*
- *AS (armourstone pieces): Integrity*
- *Rock*
  - *Physical properties*
  - *Static strength*
  - *Dynamic strength*
  - *Wear*
  - *Weathering*

Service prediction for wear

Originally developed for pure attrition:

- *With the mill abrasion test – correlated for MDE (Micro-Deval test)*
- *Adapted to take into account other mechanisms*
  *>> X-factor*
- *Extrapolated for global AQD (Armourstone quality designation) approach for the Rock Manual*
  *>> ks versus AQD relation*

**6. Alternative to loose stone**

Why look into alternatives?

1. when the top size is not available
2. when top size is available but would lead to significant overproduction or extreme lead time
3. when limited durability does not allow to use top size
4. when recycling is possible it may be financially interesting

Concrete armour units

- *Cubes and antifer cubes*
- *Hollow units*
- *Shaped « slender » or « legged » units*
- *Bulky units*

Concrete armour units: design parameters

- $D_{n50} = D_n$
- *Modification of slope angles*
- *Under layer to be checked with the unit designer*
- *Mass density*
- *2350 to 2400 kg/m$^3$*
- *May increase up to 3000 kg/m$^3$*
  >> implication with regard to smaller size/greater number to cover the same area/fabrication costs
- *Reference to EN 206 (concrete) and others including EN 197 (cements)*
- *Strength is critical since units are generally not reinforced:*
  > Minimum early age strength for demoulding
  > Minimum strength for handling/stacking
  > Minimum strength for handling/placing

Quality control prior placing is critical:

- *Mould quality*
- *Ad hoc concrete mixing and target concrete quality at fresh and hardened state*
- *Compaction/vibration*
- *Demoulding*
- *Curing*
- *Cracking and re-handling…*

Durability of concrete units is critical:

- *sulphate resisting cement*
- *source suitable aggregates : ASR risks, quality of heavy aggregates*
- *avoid thermal problems:*
  - *cracking : CEM III, low heat of hydration, replacements, large size aggregates*
- *delayed ettringite (DEF)*

Recycled and secondary

- *recycled armourstone: armourstone that is recycled as armourstone*
- *recycled material used as armourstone*
- *secondary material used as armourstone*

Alternative – recycled materials

- *EN 13383 applies also to this alternative, in particular properties as construction material grading, density, strength, durability-investigate in particular the variability*
- *Ad hoc chemical investigation should be considered with regard to leaching and any other possible environmental risk for the operatives, environment*
- *Ad hoc durability / stability investigation should be considered >> production process and quality control should be adapted accordingly*

Alternative – gabions

Gabion stone

- *Typically CM 90/180 mm or 90/130 mm*
  >> can be produced direct from crusher of aggregate quarry and screening

LA (Los Angeles) used as an indicator and CS60 (Cast steel ornament) minimum should be used

Mass density should be known for design

Absorption should be limited to 0.5 or durability against F&T (Resistance to freezing and thawing) verified

Alternative – grouted armourstone

- *Fully penetrated, e.g. used as revetment*
- *Partial penetration e.g. used as toe*
- *Used for transition*
- *Consider:*
  - *Grouting base – cementitious or asphaltic*
  - *Grouting product – grout/mastic/cement/concrete*
  - *Grouting pattern*
  - *Consider structure related aspect including roughness, permeability, filtering, flexibility*
  - *Construction and durability*

Alternative - geotextile
- *Consider:*
    - *Function, including separation/filtration/transmission/reinforcement/protection*
    - *Type, include woven and non-woven*
    - *Other properties, including durability, extensibility, resistance to puncture, etc.*
    - *Construction aspect, in particular underwater*
    - *Specifying*

**7. Implications of selecting a quarry**

Selection of an armourstone source

*Small scale project: < 50.000 t*
- Established source – quickly available – free market – local source

*Medium scale project: < 500.000 t*
- Existing source(s) – generally need some preparation/adaptation and specific equipment's – free market – regional sources

*Large scale projects: > 500.000 t (or 1.000.000 t)*
- Existing source(s) or dedicated quarries to be opened – lead time may be long for planning permissions/purchase equipment/starting production – national or international sources – utilisation of all gradings is critical

Selection parameters:
- Access to the quarry/to the site: sea/waterways/rail/road
- Type of market: free market or dedicated quarry
- Type of armourstone: oversized from aggregate, scrap stone, specific production
- Travel distance: on site, local, regional, national, abroad
- Lead time: week(s), month(s), year(s)
- Key armourstone properties: top size, quantities needed (vs. quantities required) and waste, quality and durability
- Organisation of the quarry and equipment: pre-selection / set aside; dedicated armourstone area / track or bottom; dedicated equipment or not

Intrinsic properties: a quarry inheritance
- Intrinsic properties of the armourstone are inherited from the rock properties:
    - *Rock type and petrography*
    - *Mass density*
    - *Porosity and water absorption*
    - *Colour*
    - *Strength and durability*

Shape: a quarry inheritance
- Shape is controlled by the pattern of discontinuities and affected by extraction/production

Aspect ratio and blockiness
Size(s): a quarry inheritance
Integrity: a quarry inheritance
Durability: a quarry inheritance

**8. Quarry yield and gradings**

*What do we have?*
*What we want?*
*How do we make it happen?*
- Quarry yield assessment
    - *In situ discontinuity analysis*
    - *IBSD (In situ block size distribution) prediction*
    - *BBSD (Blast modelling and quarry yield) prediction*
    - *Quarry yield assessment*
    - *Selection/production*

- Phase 1: *In situ discontinuity analysis*
  It aims at assessing:
    - *The various discontinuities affecting the rock mass*
    - *Their characteristic "orientation" in space*
    - *Their "persistence" and their "spacing"*

  How?
    - *On drill-cores*
    - *Scan-line measurements*
    - *In situ discontinuity analysis scanline*
- Phase 2: *IBSD prediction*
- Phase 3: *Quarry yield prediction and blasting*
    - *Several models exists based on the Rosin-Rammler equation for mass distribution of blasted materials*
    - *Factors – inherited (to cope with):*
        - Discontinuities spacing and orientation
        - Density, elasticity and strength of the rock
        - Presence of water in blast holes, fractures and joints
        - Spatial variations of geology and rock types in general
    - *Factors – controllable (for adaptation):*
        - Drill holes (diameter, pattern), accuracy (position, orientation)
        - Type & strength of explosive
        - Distribution of explosive in holes
        - Firing sequence or delay timing

- *How to improve the quarry yield?*
  - Low specific charge ( down to 0.11 to 0.25 kg/m$^3$)
  - Reduce the spacing to burden ratio (≤ 1)
  - Burden larger than discontinuity spacing
  - Increase the stemming length (≥ burden)
  - One raw blasting – one shot blast or large delays
  - Intermediate bench height
  - Bottom charge or decked charge
  - "Gas" rather than "fragmentation" explosive
  - Etc.

- Phase 4: *quarry yield assessment*
  - *Quarry yield assessment is essential to:*
    - Estimate actual production during optimisation stage
    - Control on-going production
  - *It can be performed using:*
    - Selection /screening data: non continuous data, costly
    - Image analysis: ! Fines & relative method
    - Direct scanline or photo scanline: ! Fines & relative method

*****

**ENROCHEMENT (ARMOURSTONE)**

«*ensemble de blocs de roche extraits en carrière, de forme quelconque, mais de poids imposé, pouvant aller jusqu'à plusieurs centaines de kilos, et utilisés pour la protection des parties immergées des ouvrages d'art*»

«*ils servent à protéger les constructions submergées contre les affouillements. Ils s'emploient dans les ports pour préserver les disques et les jetées. On les utilise aussi en avant des murs de quais de cours d'eau au courant violent. Ces roches ou ces blocs sont le plus souvent coulés irrégulièrement au fond de l'eau; parfois, ils sont posés côte à côte suivant une direction déterminée, de façon à former une plate-forme servant de base aux constructions à bâtir*»…

(Grand Larousse Encyclopédique, *in* LCPC 1989)

This definition of "armourstone" shows how underestimated the application of natural rocks was in coastal projects. As proven previously in this section, these types of materials are the basis of construction and feature singularities as well as intrinsic geological and geotechnical properties that must be taken into account.

### 3.7. The coastal strategy: geoengineering approach

Rock engineering is both an important basis and very useful to the development of applied projects in engineering, therefore the teaching of these concepts should benefit from a multidisciplinary and diversified approach (e.g. Rocha 1971, 1981, Mello Mendes 1985, Oliveira 1986, 1987, Wittke 1990, Brady & Brown 2004, Hoek 2007, Palmström & Stille 2010, Chaminé *et al*. 2013b). From the mid-20$^{th}$ century the mechanical behaviour of rock material was viewed with special interest. Consequently and firstly the area called soil mechanics acquired a separate status (e.g. Terzaghi 1925, 1943, Terzaghi *et al*. 1996). The rock mechanics developed particularly in the last 50 years (Müller 1969, Rocha 1971).

Mello Mendes (1967/1968) considers the concept of geomechanics as a broad designation and states that this concept deals with the mechanics that describe a material's rheological behaviour. A more assertive perception is presented by Dinis da Gama (1995), in which geomechanics quantitatively analyses the phenomenon of rock strain considering the mechanical properties of rock masses. Later designations of engineering geology and engineering geomorphology result from the wish to possess knowledge about the geological or geomorphological characteristics of the site where engineering works will be designed or areas identified as potential geohazards and at risk (e.g., Legget 1939, Oliveira 1987, Hatheway *et al*. 2004, Fookes *et al*. 2007, Culshaw *et al*. 2008, Griffiths & Stokes 2008, Keaton 2010, Chaminé *et al*. 2013b).

Other authors tracked these concepts, sometimes contradictorily, pursuing the "maturation" of the studied scientific fields and increasing their knowledge about these ideas. Therefore the words of Záruba (1970) are still contemporary: "(…) *the engineering geologist should be very sober in his conclusions, to keep painstakingly to the objective facts and avoid even the most ingenious inferences. Compared with a theoretical geologist, whose bold hypotheses concerning, for example, continental drift or the tectonic structure of the mountains will be verified in the distant future. The engineering geologist is handicapped by having his work checked immediately by a civil engineer with a measure in hand. (..). Moreover, as the intermediary between natural forces and human works the engineering geologist should always be aware that nature cannot be confined within our simplified rules and may have some unpleasant surprises in stock for us*."

Nascimento (1990) states the formal recognition of geotechnics as an autonomous scientific field occurred in 1948 when the international journal *Géotechnique* from the Institution of Civil Engineers (ICE) was first launched. Chaminé *et al*. (2013b) argues this modern scientific area is currently applied and recognised by a myriad of geo-professionals (e.g., applied geologist, engineering geologist, engineering geomorphologist, geological engineer, geotechnical engineer, mining engineer, civil engineer, or military geologist/engineer). Regarding this, Figure 122 represents a modern overview of the interdisciplinary and multidisciplinary scientific field called *Geotechnics*, which can be practiced by several types of professionals and in most situations encompassing expert teams with complementary skills. Engineering geoscience is concerned with the application of geology and geomorphology in engineering practice (Chaminé *et al*. 2013b).

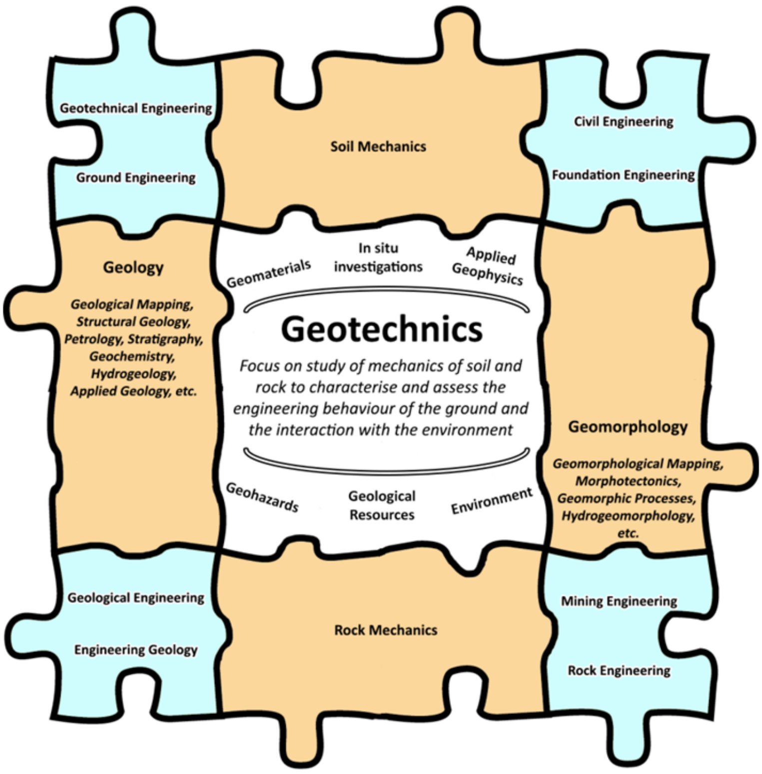



**Figure 122.** A modern overview of Geotechnics: major scientific areas – geosciences (geology and geomorphology), soil mechanics and rock mechanics – and practitioners (after Chaminé *et al*. 2013b).

Presently, there is a new domain arising, even more integrative and "eclectic", designated by the name geoengineering (CERF 1994, Bock 2006). But even more recently we also have the concept of geoengineering sciences (Manoliu & Radulescu 2008, McCabe *et al*. 2012).

This dichotomy – engineering geosciences *vs* geoengineering – has been widely addressed in several works (e.g., Manoliu & Radulescu 2008, McCabe *et al*. 2012, Chaminé *et al*. 2013a,b). Based on these geoengineering science and education conceptions we decided to update this concept in order to adapt it to coastal management. Hence a new integrated coastal geoengineering approach for maritime environments was proposed, which is the "heart" and leading foundation of this thesis. Also it was important to incorporate in a broader sense coastal geosciences and geoengineering GIS mapping to this final equation resulting in conceptual models.

The strategy present herein shows the bottom line of the conceptual schema layout of Chapter 3. The efforts made by this approach to include several topics/issues are recognised during the course of this dissertation, scientific research and publications. This will support the understanding of coastal dynamics and apply these integrated concepts in terms of multidisciplinary methodology.

Coastal geoengineering strategy has a different mechanism which works as a jigsaw puzzle (Figure 123). This mechanism is composed of different pieces that fit perfectly and where each has their individual role and own place. We have the main or the primary pieces (engineering geoscience, geotechnologies, georesources and GIScience) that derivate to the secondary pieces complementing the jigsaw puzzle. We can clearly observe that the puzzle is incomplete and fragmented because these scientific fields are always in continuous evolution, as well as because innovative techniques, methods and tools are constantly being developed.

At the final stage we can say that each geo-professional can work in any research area or field with their own perspective and self-perception, concerning their study site, which could be pragmatically applied to different end-uses (Chaminé *et al*. 2013a,b).

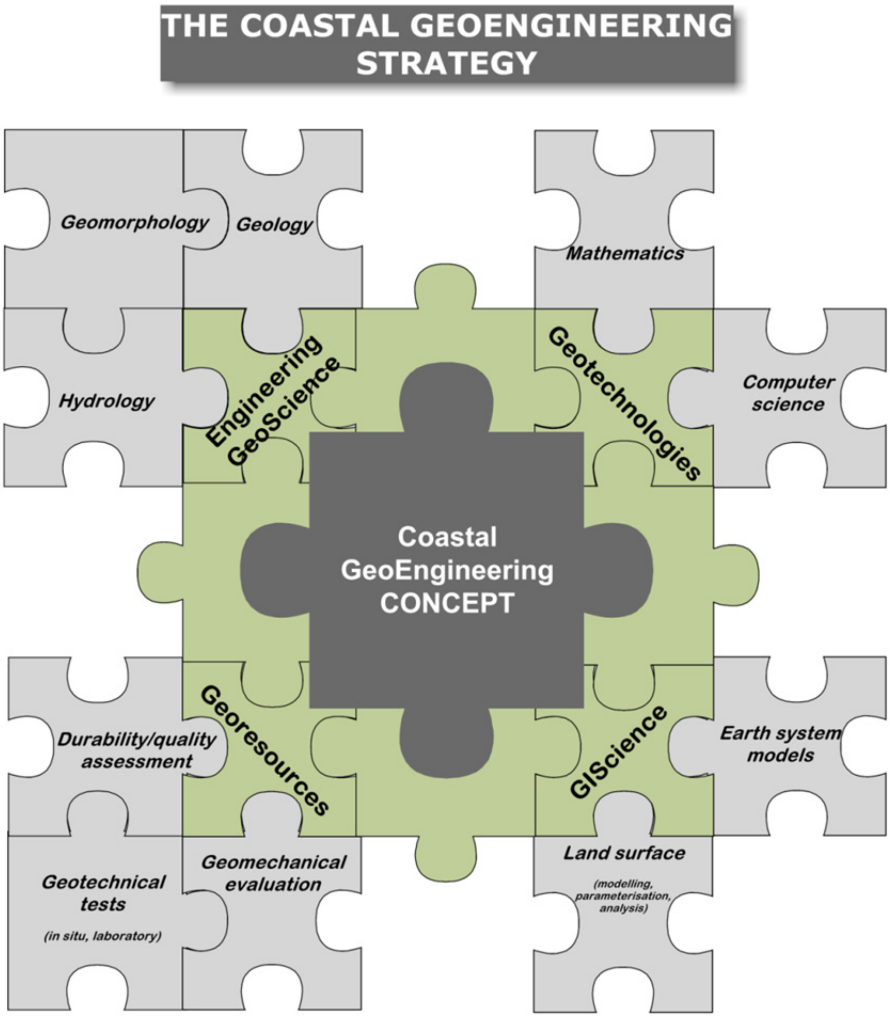



**Figure 123.** The jigsaw puzzle as a model with coastal geoengineering strategy and architecture.

# PART II – RESULTS AND DISCUSSION

*Photo credits: A. Pires*

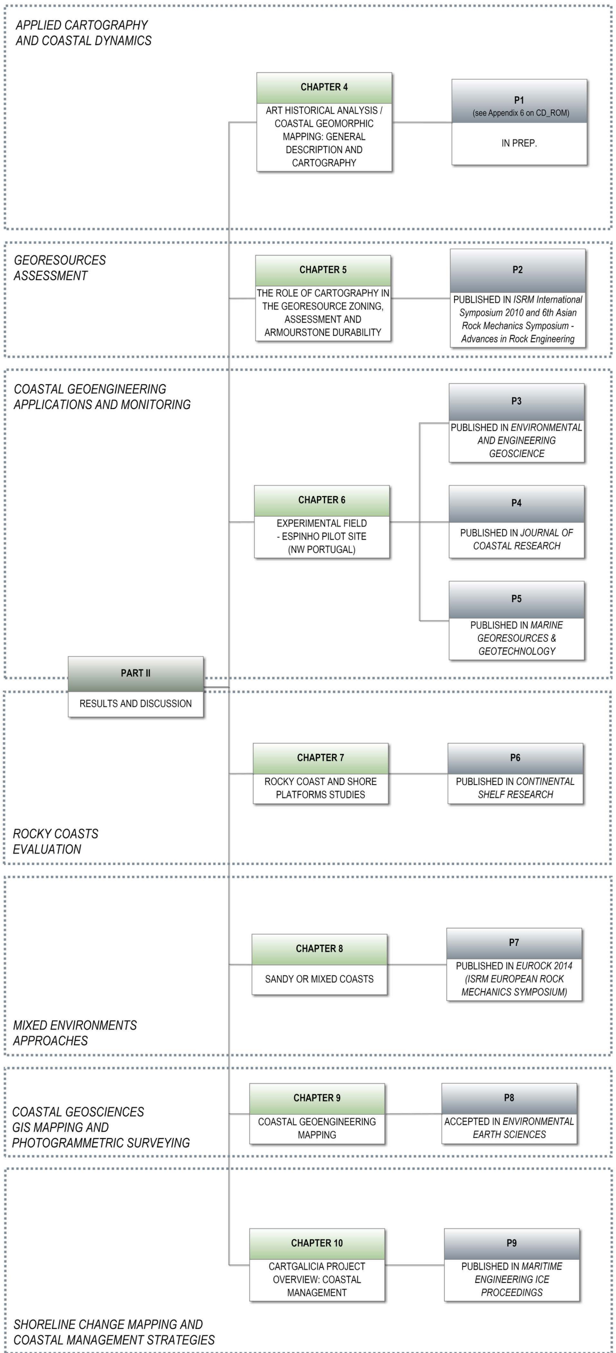
«Lá longe, longe, no meio do mar, a água é tão azul como as pétalas das centáureas, pura como o vidro mais transparente, mas tão profundo que seria inútil tentar ali lançar âncora, sendo necessário, para medir a distância do fundo à superfície, empilhar uma quantidade infinita de campanários de igreja, uns postos sobre os outros.
É ali que vive o povo do mar. (...)»

«Far out in the ocean, where the water is as blue as the prettiest cornflower, and as clear as crystal, it is very, very deep; so deep, indeed, that no cable could fathom it: many church steeples, piled one upon another, would not reach from the ground beneath to the surface of the water above.
There dwell the Sea King and his subjects. (...)»

*The Little Mermaid by Hans Christian Andersen (1836)*

# PUBLICATIONS

## PART II ORGANISATION AND GUIDE



# CHAPTER 4

# P1

(see Appendix 6 on CD-ROM)

## SYNOPSIS

*The aim of this research was to contribute to, and support, the coastal evolution knowledge in historical terms. The work enveloped a thorough compilation of several Portuguese elements from the coastline and other examples. It was also accomplished a specific analysis about the coastal systems and dynamics for some of the examples or sites presented. This analysis was also performed to the elements/characteristics of the paintings or images. This catalogue is an interesting historical research, but is also a different perspective of analysing coastal dynamics. Art in coastline evolution shows how paintings, stamps, images, pictures, can "tell us a story" about the coastal areas/sites acting like an instrument in support of the understanding of coastal change. The reader will travel between different places, characteristics, dynamics and beautiful images related with the coastline. The evolution of cartographic visualisation in the digital era is also displayed with the aid of numerous charts, maps and aerial images showing the improvement of cartographic techniques from the past to the future. The coastal geomorphic mapping, general description and cartography are presented in old maps, charts, photographs, pictures until the innovative techniques to acquire high resolution aerial imagery. This work emphasises the fact that man, on the coast, is intrinsically related to the sea, fishing, boats,... There is almost like a hate-love relationship with this sea that surrounds us in magnificent baths in the Sun, but is also responsible for cruel attacks on the coast. All these events were the main trigger to inspire thousands of artists and improve methodologies/technologies related to cartography, GIS mapping and acquisition of high resolution aerial imagery to analyse the coastal dynamics and evolution.*

# CATALOGUE – ART AS A TOOL IN COASTAL EVOLUTION

# Brief history of Portuguese coastal art:
## Insights through science

J. C. AMORIM, A. PIRES, H. I. CHAMINÉ

# CHAPTER 5

# P2

## SYNOPSIS

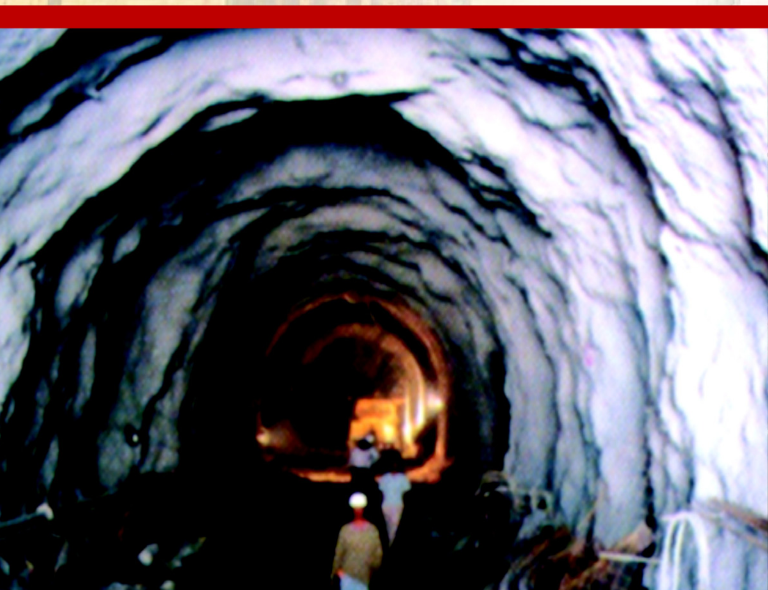
*This research addresses the georesources assessment topic. In this work, using guidelines and procedures for the evaluation of rock materials, it was possible to develop a GIS-based methodology that establishes a bridge between specific geological construction materials (geomaterials) and the design of coastal protection structures. The main goal of this work was the application of GIS tools and concepts to the study of Espinho coastal zone (NW Portugal). This involved creation of GIS-based monitoring project to gather information on all coastal works located along Espinho shoreline, focusing especially on the geotechnical mapping evaluation of the geomaterials used in groynes, based on lithology, weathering grade, and stiffness of the rock materials. This work present a methodology for the assessment and management of coastal hydraulic structures, focused on the quality, durability of protective rock-based materials and including the characterisation of geomaterials at the sources (quarries). The development of the research had two main phases: (i) the field survey, applied cartography and inspection of maritime structures and (ii) the geological and geotechnical quarry assessment. This study reports results from the second phase which comprises the evaluation of quarries and the identification of potential areas for the extraction of armourstone with quality and availability to supply maritime structures. It was proposed a zoning of the NW Portugal region and taken into account some features like the land use and management, urban and settlement plans, geological setting, geotechnical and geomechanical description/typification of the rock masses. There were identified 459 quarries, georeferenced and distributed in a total area of 14.010km2. More than 200 sites were selected, characterised and included in the GIS database project with interactive support (e.g. hyperlinks for the datasheets, photos or essential information). A total area of 4,1% was calculated, including relevant geological conditions and comprising existent quarries (active/inactive) or new places (suitable or predictable areas). Discussion looks forward in future research trends based on network analysis for the choice of the best route from the quarry to the coastal work. However, the present work will show that the geo-engineering GIS project can provide critical information for analysis and decision-making about each structure. A multidisciplinary perspective must be adopted providing a cost-effective method useful to the incorporation of important concepts (durability and integrity) in geo-monitoring coastal plans and highlighting GIS coastal projects.*

# ISRM International Symposium 2010
# and
# 6th Asian Rock Mechanics Symposium

## Advances in ROCK ENGINEERING

**23-27 October 2010, New Delhi, India**

## Proceedings



*Editors:* Dr. K.G. Sharma • Dr. T. Ramamurthy • V.K. Kanjlia • A.C. Gupta

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*23-27 October, 2010, New Delhi, India*

# RECOGNITION OF POTENTIAL AREAS FOR THE EXTRACTION OF ARMOURSTONE IN MARITIME WORKS (NW PORTUGAL): COUPLING GIS MAPPING, GEOMATERIAL AND GEOTECHNICS ASPECTS

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***Abstract :*** *This work introduces the coastal geo-engineering issues for a suitable selection and geomaterial characterisation of quarries. The development of the research had two main phases: (i) the field survey, applied cartography and inspection of maritime structures and (ii) the geological and geotechnical quarry assessment. This study reports results from the second phase which comprises the evaluation of quarries and the identification of potential areas for the extraction of armourstone with quality and availability to supply maritime structures. It was proposed a zoning of the NW Portugal region and taken into account some features like the land use, urban and settlement plans, geological setting, geotechnical and geomechanical description/typification of the rock masses. 459 quarries were identified, georeferenced and distributed in a total area of 14.010km$^2$. More than 200 sites were selected, characterised and included in the GIS database project with interactive support (e.g. hyperlinks for the datasheets, photos or essential information). A total area of 4,1% was calculated, including relevant geological conditions and comprising existent quarries (active/inactive) or new places (suitable or predictable areas). A multidisciplinary perspective must be adopted providing a cost-effective method useful to the incorporation of important concepts (durability and integrity) in geo-monitoring coastal plans and highlighting GIS coastal projects.*

## 1. INTRODUCTION

### 1.1 Importance of coastal geo-engineering in geomaterial characterisation

Presently, concepts in geotechnical and geo-engineering fields are important for rock characterisation and subject of interest by many researchers ([1]). For the design and/or maintenance of coastal defence works the application of analysis methods and technologies related with these domains, are essential (e.g., [2]; [3]; [4]). From the geo-engineering point of view, and within a scientific context, impacts caused by the construction of large structures and incorrect land use along the coastal areas, require comprehensive geological, geomechanical studies and engineering solutions for their mitigation. The coastal zone is considered highly dynamic and spatially variable ([5]) and therefore, coastal protection structures are important features in this kind of environment to take into account during a successful coastal maintenance program or management strategy. During the coastal structure's life it is necessary maintenance and repair works, hence, natural and durable rock is one of the main geomaterials employed in maritime works.

The definition of geomaterial is: *"processed or unprocessed soils, rocks or minerals used in the construction of buildings or structures, including man-made construction materials manufactured from soils, rocks or minerals"* ([6]; [7]). Related with the previous concept, the armourstone designation is defined as a coarse aggregates used in hydraulic structures and other civil works (according to [8] and [9]). This category of rock materials used in coastal defence works are subject to environmental conditions which differ, both in severity and type, from those encountered in other situations. Design requirements also include elements specific to coastal engineering structures and both these aspects must be given due consideration in the selection and specification of the rock. The two most important groups of properties of rock for use in coastal engineering are the geometric properties of shape, size and grading and the physical properties which include density and factors relating to mechanical strength, resistance to abrasion, porosity and durability ([7]). The present study emphasises the importance of rock material, which requires a previous study of its availability, quality and also a monitoring plan, maintenance and repair of the structure, as an integral part of life cycle management (e.g., [10]; [11]; [9]). In addition, another purpose is the mapping and systematic inspection to characterise the natural and artificial blocks which constitute the rock armour structures. Furthermore, the geomaterials were traced back to their origin (i.e., the extraction quarries) in order to typify and better evaluate the evolvement of the whole structure since its construction. When accurately performed this characterisation, constitutes an early stage establishment of the quality of the rock material, which is fundamental for a viable and sustainable rock project. The use of geographical information systems (GIS) provides ideal platforms for acquiring all the coastal information and its analysis to monitor coastal zones progression and defence (e.g., [12]; [13]). In this work, using guidelines and procedures for the evaluation of rock materials, it was possible to develop a GIS-based methodology that establishes a bridge between specific geological construction materials (geomaterials) and the design of coastal protection structures. The main goal of this work was the application of GIS tools and concepts to the study of Espinho coastal zone (NW Portugal) supported in previous studies ([4]; [14]; [15]; [16]; [17]). This involved creation of GIS-based monitoring project to gather information on all coastal works located along Espinho shoreline, focusing especially on the geotechnical mapping evaluation of the geomaterials used in groynes, based on lithology, weathering grade, and stiffness of the rock materials.

## 2. SITE INVESTIGATION PROCEDURES

### 2.1 Objectives and methodology

This study approaches a fundamental question related with the assessment of hydraulic structures, i.e., inspection, repair and rehabilitation of existing structures. It was developed a GIS mapping project that integrated different layers of information and methodologies for the assessment and management of maritime works, focused on the geomaterials quality applied. The main goal of this research involved the development and improvement of the methodology previously implemented for the present condition evaluation of maritime structures (deterioration level) and the geomaterial characterisation traced back to their origin ([4]; [18]; [14]; [15]; [16]). Primarily, there were studied 5 sectors from the coastal area of Espinho (NW Portugal) comprehending 4 groynes and 1 seawall in order to characterise and evaluate several parameters, namely: type of geomaterial and geological and geomechanical characteristics ([19]; [20]). Afterwards, visual inspections were carried out to the head zone of the groynes for the general evaluation in which it was intended to analyse and register the structure's present condition (details in [15]). All the gathered data was inserted in the GIS project and allowed the conception of a detailed map with the geomaterials recognition and the 3D modelling of the structure. Figure 1 presents the conceptual flowchart applied to this study. On the one hand, the applied cartography and inspection of maritime structures and the different methods/techniques used to analyse the deterioration level along the armour layer. The assessment of the conservation status of marine structures enabled the development of methods and procedures for the systematic monitoring of maritime works, identifying and proposing intervention areas in the structure. On the other hand, the GIS project also included the quarry assessment in order to identify potential areas for the extraction of armourstone. As shown in Figure 1, all obtained data from the literature review and fieldwork were inserted in the GIS database, allowing the user to view all levels of information and generate 3D modelling, spatial and network analysis. During this process of data integration there were necessary 2 phases: (i) the geomaterial characterisation along the hydraulic structure's armour layer and (ii) the geomaterial characterisation along the extraction sites (quarries). For the first phase further details can be found in previous work ([4]; [18]; [14]; [16]). In this work it is presented the exploratory approach for the GIS mapping project of the second phase (quarry assessment) in order to emphasise the importance of quality control and geotechnical evaluation of armourstone. To implement and process all the GIS data, there were used different levels of information (Figure 2) with distinct purposes: (i) location of the sites and georeferencing, (ii) analysis and study of the surface geology, (iii) detailed map of mineral and industrial rocks occurrences using the constraints map, (iv) quarries inventory for the studied area.

### 2.2 Study area

The project for cartography and GIS covers a pilot site that combines the study of the coastal protection structures of Espinho (NW Portugal), and the sites for rock extraction which eventually could provide armourstone for the hydraulic structures mentioned. The municipality of Espinho is located in the Portuguese Northwest coast, facing the North Atlantic Ocean and belongs to the district of Aveiro. Situated approximately 16km to the South of Porto, the groyne field from Espinho region includes 5 study sectors, illustrated in Figure 3.

From the geomaterial characterisation in the Espinho coastal area it was possible to trace back the source of the rock material applied. The location of the armourstone quarries is presented in Figure 3 (A and B in the map). The "Quinta do Moinho" quarry is currently an old open pit mine that started the exploitation labour in 1971 by SOLUSEL Company. The main resource purpose of this quarry was aggregates but also an important armourstone supplier of many coastal protection works along the NW of Portugal with the production of biotitic granites.

The "Malaposta" quarry is licensed since 1976 by Irmãos Cavaco SA Company (ICSA), which is one of the industry leaders in hydraulic works. The ICSA Company growth in the 80's decade and is strongly connected to the Maritime and Port Workmanships intervention. The extracted geomaterial is an orthogneiss for aggregate and armourstone ([21]).

## 3. RESULTS AND DISCUSSION

### 3.1 Coupling GIS mapping, geomaterial and geotechnics aspects

*3.1.1 Applied cartography and inspection of maritime works*

Based on the described methodology for phase 1, different geomaterials were recognised, such as: natural rocks (granite and gneiss) and artificial materials (concrete or a mixed material, i.e., concrete + aggregates or tetrapods). This applied cartography provided an evaluation of the current condition of the structure and the revetment material status. A detailed mapping of the rock blocks was prepared with the support of the aerial photographic database. Afterwards, for the 5 studied sectors, more than 20.000 block materials on the structure's superficial section (armour layer) were vectorised in a GIS base. This approach allowed obtaining thematic maps of the structures useful to evaluate different geomechanical (based on the recommendations of the [22]; [23]; [24]; [25] and [26]) and geotechnical parameters. From the results obtained, there are substantial indicators of the need for repairing/maintenance works in some components of the studied structures (5 sectors).

*3.1.2 Quarry characterisation and recognition of potential areas for the extraction of armourstone*

For the analysis and data processing of phase 2, two distinct bases were built: a relational and a georeferenced GIS databases. The first database was compiled in *Ms. Office Access*, enabling queries to explore all the information which is organised by districts and counties. The georeferenced database with the locations of all the quarries identified, is connected to the GIS project and comprises not only general information but also the datasheets for the quarries evaluation and the respectively hyperlink to the sites, cartographic bases, images, orthophotos, and another features. Therefore, the geographic database is functional, interactive and constantly updated. Table 1 synthesises all the information analysed with 459 indentified quarries distributed in a total area of 14.010km$^2$. The GIS platform allowed determining potential areas for the extraction of armourstone, as a result of all the related data of the inventoried quarries and other layers previously described that were incorporated in the final project (Figure 4).

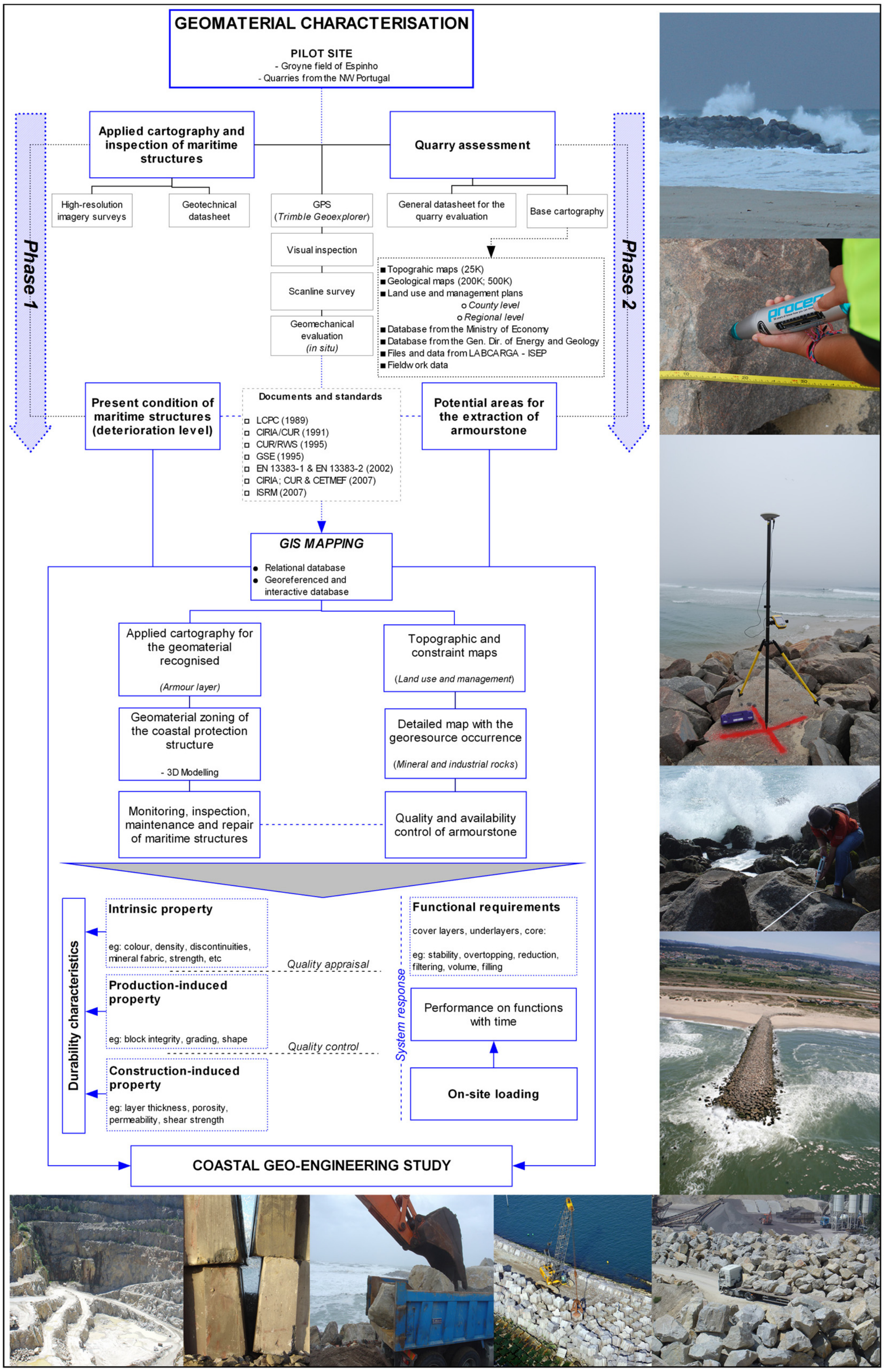


Figure 1 – Conceptual flowchart for the coastal geo-engineering research (adapted from [14]; [15]; [16]); some images with different aspects of the applied techniques/fieldwork and the stages of the rock project; since the suitable choice of the material, handling and transport at the quarry until the construction process.

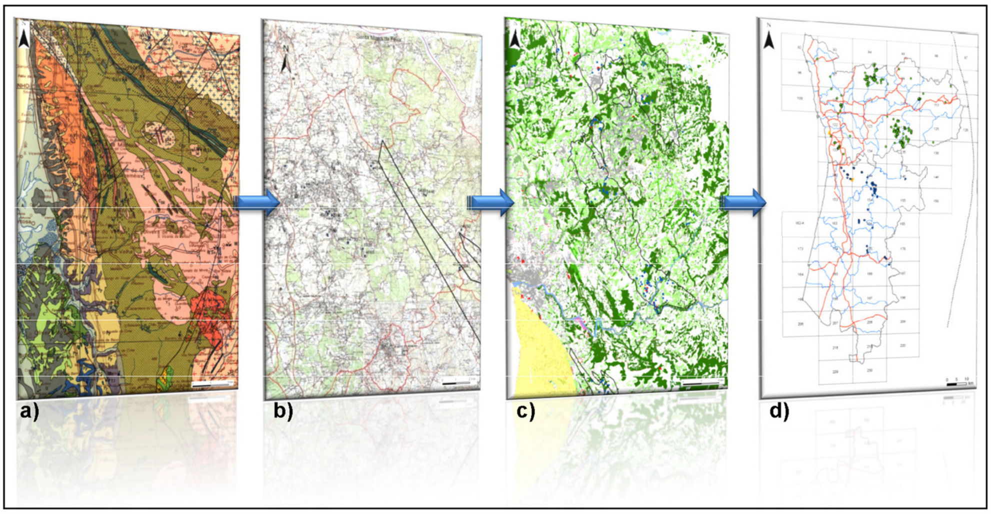


Figure 2 – Representation of the different layers of information implemented in the GIS database; a) analysis and study of the surface geology (adapted from the Geological Map of Portugal, 1:500.000 scale, S.G.P., 1992), b) location of the sites and georeferencing (topographic base: extract from the Military Map of Portugal, 1:25.000 scale, IGeoE), c) detailed map of mineral and industrial rocks occurrences using the constraints map (land use) and d) quarries recognition.

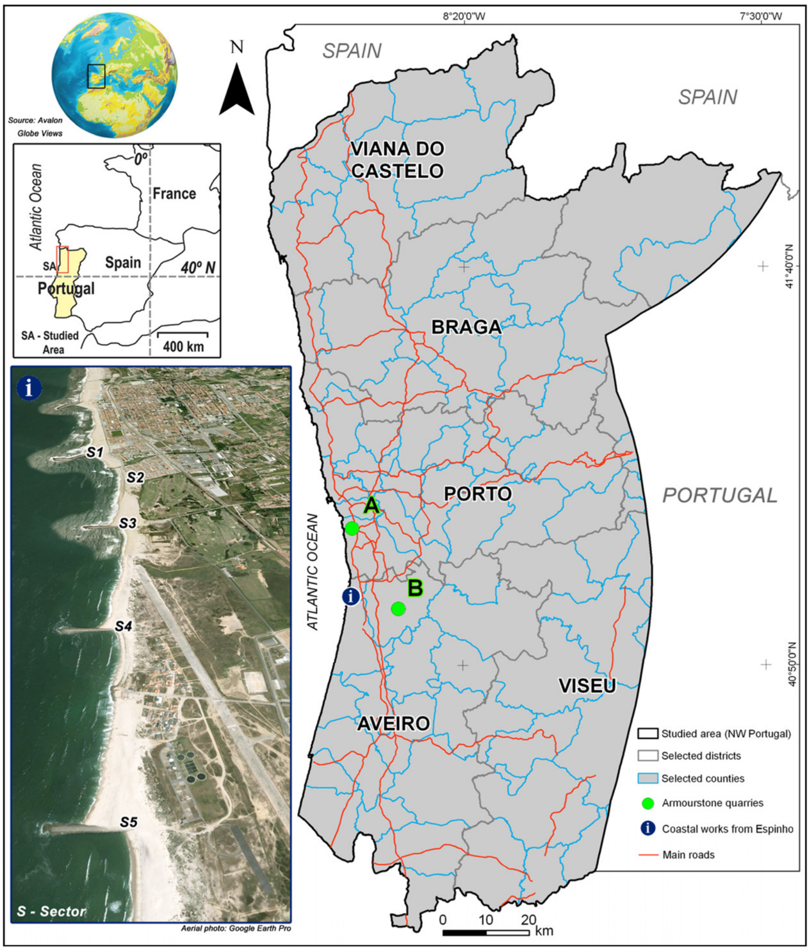


Figure 3 – Studied area (NW Portugal); location of Espinho region with the groyne field along the coast and the 5 sectors studied; A and B: location of the 2 dedicated quarries of armourstone that supplied the hydraulic structures of Espinho.

Table 1 - Summary of the created GIS database and synthesis of results.

| Quantitative evaluation of the project | NW Portugal | | |
|---|---|---|---|
| | **Nr.** | **Area (km$^2$)** | **(%)** |
| Selected counties | 85 | – | – |
| Georeferenced quarries | 459 | – | |
| Characterised quarries | 226 | | |
| Studied area | – | 14.010 | 100 |
| Potential areas for the extraction of armourstone | – | 1.432 | 10,2 |
| Suitable zones without major constraints (in terms of land use) within the potential areas | – | 579 | 40,4 |
| Total area with suitable conditions for the armourstone extraction | – | – | 4,1 |

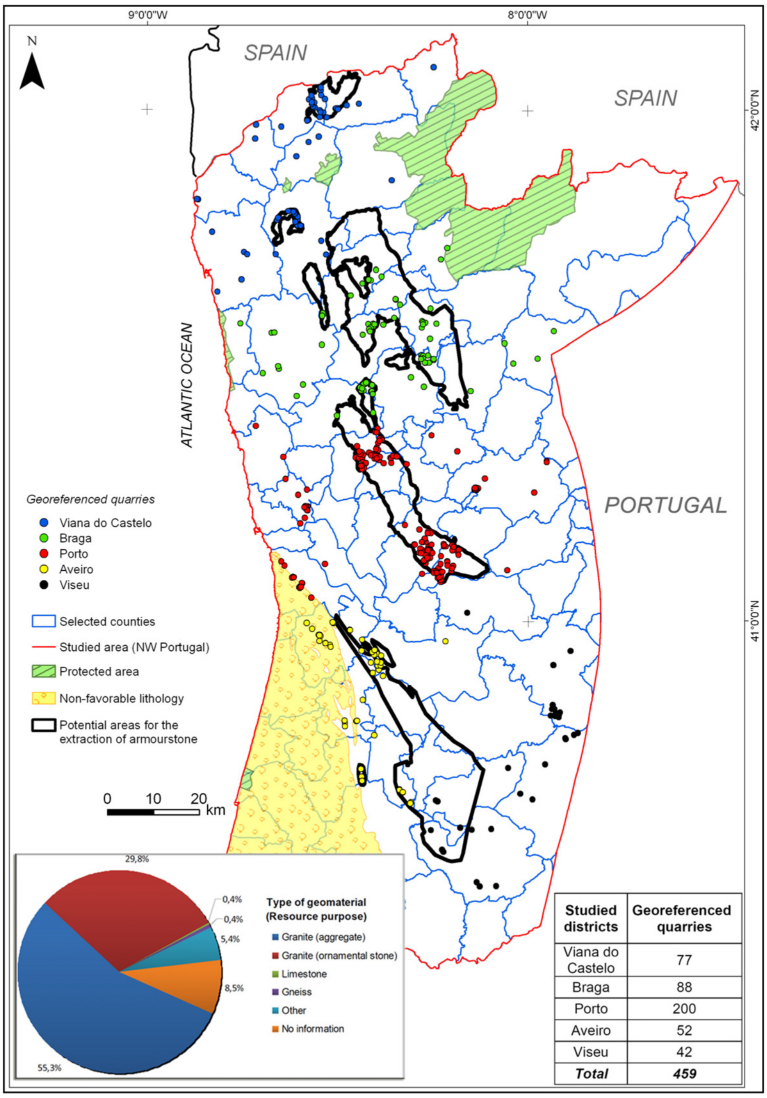


Figure 4 – Synthesis map for the studied area (NW Portugal); georeferenced quarries for the 5 districts, potential areas for the extraction of armourstone and a graphic that summarises the type of geomaterial studied and resource purpose.

## 4. CONCLUDING REMARKS

According to the obtained results, a methodological characterisation of the rocks is crucial to determine the deterioration level and the structures' present condition. This approach uncovered the need for maintenance works in some of the studied structures, and of eventual changes in their design. Monitoring, visual inspection, applied cartography and GIS tool assumed a very important role in a coastal management plan. This methodology allowed the zoning of coastal protection structures, evaluating the deterioration level and assessing the conservation status. This study revealed that in areas of high deterioration levels (with high loads), presented less strength relatively with areas of low deterioration level. Consequently it was possible to select areas that will suffer reinforcement or repair works and keeping protection costs at a low level.

Moreover, it gives further support to the importance of establishing the availability, the geotechnical quality and durability of geomaterials to be used in a particular site at an early stage (quarries) when considering design options. Furthermore, the created database for the quarry assessment could be very useful as well as all the information incorporated in the GIS tool. The system potential features included georeferenced databases, applied cartography, interactive data, different levels of interrelated information and even statistical, spatial or network analysis. Besides, allowed to define potential areas for the extraction of armourstone which comprises existent quarries or new places (suitable or predictable areas). After the results analysis, it was possible to verify that the percentage of total area with suitable conditions for the armourstone extraction, without any kind of restrictions, it was 4,1% for the NW Portugal pilot-sites. This exploratory approach applied to the GIS mapping project wishes to contribute to the national inventory of exploitation areas for minerals and industrial rocks, with different status (active/inactive) and different purposes (ornamental stone, aggregate or armourstone).

This investigation is still in progress to provide more detailed information on the most appropriated geomaterials, namely regarding the rock mechanic properties required in relation to the design, and additional test procedures that are usually applied to assess quality and durability of these materials before and during construction. The applied counterpart will result in the elaboration of guidance for use in this area, under the scope of European standards and codes. Those results of the project may also be important for scientific areas such as coastal and hydraulic engineering, coastal geomorphology and geotechnical engineering.

## ACKNOWLEDGEMENTS

This work was funded by doctoral scholarship from Portuguese Foundation for Science and Technology (FCT) to A. Pires (SFRH/BD/43175/2008). This work was also performed under the financial support from LABCARGA-IPP-ISEP|PAD'2007/08. We are grateful to North Regional Coordination and Development Commission (CCDR-N) and Regional Directorate of the Economy (DRE-N) that has kindly contributed to this study and provided key information. We gratefully acknowledge to A. Mota Freitas (SOMAGUE) and A. Lopes (ICSA) for their collaboration during preliminary investigations. To S. Dupray (CETMEF), E. Brògueira Dias (APDL/ISEP), A. Gomes (FLUP), R. Teixeira (CCDR-N) for helpful comments that greatly improved the purpose of our research.

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## KEYNOTE LECTURES AND ABSTRACTS

*Editors:* Dr. K.G. Sharma • Dr. T. Ramamurthy • V.K. Kanjlia • A.C. Gupta


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*ISRM International Symposium 2010 and 6th Asian Rock Mechanics Symposium - Advances in Rock Engineering, 23-27 October, 2010, New Delhi, India*

# RECOGNITION OF POTENTIAL AREAS FOR THE EXTRACTION OF ARMOURSTONE IN MARITIME WORKS (NW PORTUGAL): COUPLING GIS MAPPING, GEOMATERIAL AND GEOTECHNICS ASPECTS

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**Abstract:** Along the Portuguese shoreline there are more than 300 coastal protection structures identified and it is essential to study their long term stability and behaviour. In addition, due to ageing (many are more than 50 years old) and the increasing population pressure along the coast, management and maintenance of these structures and its protective component (the armour layer) is critical. Presently, concepts in geotechnical and costal geo-engineering fields are important for rock characterisation. Therefore, from the geo-engineering point of view, and within a scientific context, impacts caused by the construction of large structures and incorrect land use along the coastal areas, require comprehensive geological, geomechanical studies and engineering solutions for their mitigation.

This work present a methodology for the assessment and management of coastal hydraulic structures, focused on the quality, durability of protective rock-based materials and including the characterisation of geomaterials at the sources (quarries). Different techniques and tools were combined, including aerial high-resolution imagery, field surveys and relational databases, evaluation of deterioration levels, geomechanical assessment of geomaterials, GIS mapping and modelling techniques.

The development of the research had two main phases: (i) the field survey, applied cartography and inspection of maritime structures and (ii) the geological and geotechnical quarry assessment. This study reports results from the second phase which comprises the evaluation of quarries and the identification of potential areas for the extraction of armourstone with quality and availability to supply maritime structures. It was proposed a zoning of the NW Portugal region and taken into account some features like the land use and management, urban and

settlement plans, geological setting, geotechnical and geomechanical description/typification of the rock masses. There were identified 459 quarries, georeferenced and distributed in a total area of 14.010 km$^2$. More than 200 sites were selected, characterised and included in the GIS database project with interactive support (e.g. hyperlinks for the datasheets, photos or essential information). A total area of 4,1% was calculated, including relevant geological conditions and comprising existent quarries (active/inactive) or new places (suitable or predictable areas).

Discussion looks forward in future research trends based on network analysis for the choice of the best route from the quarry to the coastal work. However, the present work will show that the geo-engineering GIS project can provide critical information for analysis and decision-making about each structure. A multidisciplinary perspective must be adopted providing a cost-effective method useful to the incorporation of important concepts (durability and integrity) in geo-monitoring coastal plans and highlighting GIS coastal projects.

This research was funded by doctoral scholarship from Portuguese Foundation for Science and Technology (FCT) granted to A. Pires (SFRH/BD/43175/2008).

**Keywords:** coastal geo-engineering; geomaterial; GIS mapping; rock evaluation; deterioration level.

# CHAPTER 6

# P3

## SYNOPSIS

*This is the first of three publications about Espinho pilot site (NW Portugal) – experimental field. The present study takes advantage of GIS tools to contribute to the knowledge of the geologic and geomorphological dynamics of Espinho (NW Portugal) shoreline. Firstly, a GIS-based monitoring project was compiled, which gathers information on all coastal works located along Espinho shoreline, focusing especially on construction, monitoring, and repairing aspects. Secondly it was performed a geological and geomorphological characterisation and overview of the studied area. The shoreline change was analysed using the ArcGIS extension entitled Digital Shoreline Analysis System (DSAS). The approach adopted in this work contributes to improving our knowledge on the dynamics of Espinho shoreline. It provides a solid base to easily forecast and model shoreline displacements over the years and to identify main areas of erosion/accretion. This work also puts emphasis on the importance of performing geotechnical characterisations of coastal protection structures to diagnose their degree of damage and/or deterioration and plan more efficient maintenance works. Our results indicate a general trend of erosion to the South of Espinho coastal area and an accretion trend to the North. Along this coastal stretch there are also several hydraulic works that influence the coastal erosion process and this can easily be shown by the accretion that occurs in the north areas of obstacles (e.g., groynes) and erosion in the south ones. The geotechnical characterisation of Paramos groyne allowed to define three main zones for the armour block materials, i.e., Zones I, II/III, and IV, which show, respectively, very-low, medium to high, and low deterioration levels. The study also provides information valuable in extending the average lifetime of Espinho coastal protection structures and recommends some solutions to minimise the situation. Some proposed solutions, can be accomplished through several processes: recuperation of the dune systems; collaboration with other institutions with littoral jurisdiction; identification and definition of the areas which are more vulnerable to erosion and implementation of preventive measures; implementation of the coastal defence programmes; intervention in priority areas (e.g., Espinho); additional studies to find adequate interventions. The so-called hard coastal defences are indispensables and there is not, at the moment, any plan to remove the existing groynes, sea walls and other hydraulic structures. Hence maintenance works or even rearrangement of their original design is likely to continue. Also artificial sand nourishment operations might also be included as possible solutions to the erosion problem affecting this coastal stretch.*

# Environmental & Engineering Geoscience


## Dynamics of Coastal Systems Using GIS Analysis and Geomaterials Evaluation for Groins


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**Key Terms:** ***Coastal Dynamics, Hydraulic Structures, Geomaterials, Coastal Geoengineering, GIS***

## ABSTRACT

**Shoreline change in the Espinho area (northwest Portugal) is a chronic problem. The present study takes advantage of geographical information system (GIS) tools to contribute to the knowledge of the geologic and geomorphological dynamics of the Espinho shoreline. A GIS-based monitoring project was compiled, which gathers information on all coastal works located along the Espinho shoreline, focusing especially on construction, monitoring, and repair aspects. Shoreline change was analyzed using the ArcGIS extension "Digital Shoreline Analysis System" (DSAS) to understand this important aspect of coastal management. This work also emphasizes the importance of geotechnical assessment of coastal protection structures in diagnosing their degree of damage and/or deterioration so that one can plan more efficient maintenance works. Our results indicate a general trend of erosion to the south and accretion to the north of the Espinho coastal area. Geoengineering characterization of the Paramos groin defines three main zones for the armor block materials (i.e., Zones I, II/III, and IV), which show, respectively, very low, medium to high, and low deterioration levels.**

## INTRODUCTION

Coastal areas represent a dynamic environment of vital importance to human society. Over 40 percent of human settlements are located near the coast—a proportion that is still increasing (Carter, 1988). The sustainable management of coastal areas depends on gathering proper knowledge and understanding of the coastal development and combining it with relevant information to develop effective tools with which to aid the decision-making process. Coastal zone management and coastal defense are central fields of interest all over the world, and effective management of coastal zone dynamics is a key issue of research (Taveira Pinto, 2003; MAOTDR, 2008). Carter (1988) subdivides coastal management into the three broad areas of policy, planning, and practice. Most coastal management issues, he suggests, "raise conflict between various coastal user and interest groups." These conflicts may include disputes between jurisdictions over access to key resources, conflicts between sectors of society about the allocation of these resources, conflicts between human use of the coast and the ecological requirements of other components of the coastal system, and conflicts arising through misunderstanding or underestimating the operational requirements of natural coastal processes such as sediment movement, shoreline erosion, etc. Nowadays, in recognition of the many problems that have arisen in the past through inappropriate use and management of the coast, a new, more "environmentally oriented" ethos of coastal management is emerging, one that is based on more holistic, transdisciplinary, and integrative principles and that aims at sustainable management of coastal resources. This new philosophy depends, however, on a thorough understanding of the entities and relationships at work in the coastal system, which in turn demands a solid base of data and information to be harnessed in support of decision making. Thus, for these and many other reasons, coastal scientists, engineers, and administrators are increasingly looking for new developments in information technology, tools, and methodologies that might assist them in their work (Carter, 1988; McCleese, 2000).

One crucial part of any successful coastal maintenance program is its monitoring (McCleese, 2000). The complexity and scope of a monitoring effort can vary widely, from simple periodic on-site visual inspections at the low end of the scale to elaborate and expensive long-term measurement programs at the other extreme. The most important aspect of any monitoring and inspection program is the careful determination of the purpose of this issue. Without a clear definition of the monitoring goals, resources and instruments will not be used in the most beneficial manner, and it is likely that the information gathered will be insufficient to accurately evaluate the project and to recommend appropriate maintenance programs.

One of the most important aspects of coastal management and planning programs that requires further investigation is shoreline dynamics. This term includes not only the progression and erosion of coastlines, but also protection against erosion. The latter is a complex problem, for which different methods and coastal structures may be used to protect the shoreline, according to the specific framework. Groins are among the most common structures built for erosion control. These are transverse coastal structures, the function of which is to intersect the waves to minimize their erosive power; they are also designed to regulate littoral sediment transport in order to stabilize the beach (Gomes, 1977; USACE, 2002). Normally groins are built in groups designated as groin fields. These coastal defense works may be integrated with longitudinal constructions, and in some cases they may be artificially nourished (LCPC, 1989; CIRIA/CUR, 1991; USACE, 1995; and CIRIA et al., 2007). As a result of their characteristics, these structures are designed under the assumption that maintenance and repair work will be needed during the life of the structure (USACE, 1990; Silva, 1996; and Santos et al., 2003). Geographical information systems (GIS) provide ideal platforms for acquiring coastal information and for analysis of this data with an eye toward monitoring coastal zone progression and defense. GIS are highly suitable for analyzing geologic and geomorphological data, revealing trends and interrelationships that would be more difficult to discover in tabular format. Moreover, GIS allow policy makers to easily visualize problems in relation to coastal erosion and the condition of existing protection structures for effective resource utilization.

In Portugal, the coastal zone of Espinho is situated on the western Atlantic shoreline of the Iberian Peninsula. In this area, the erosion phenomena are usually intense and have been well known since the 19th century. To protect this part of the Portuguese shoreline several structures have been constructed—the majority during the past. In Portugal, several public institutions share the responsibility for coastal zone management, which sometimes gives rise to overlapping or ineffective actions (MAOTDR, 2008). Nevertheless, the prime legal authority can be identified as being the Ministry for Towns, Territorial Planning and Environment, especially through the Portuguese Water Institute (INAG) and the Institute for Nature Conservation and Biodiversity (ICNB). In fact, INAG and ICNB together have jurisdiction over all of the Portuguese coastal zones, except for the areas under harbor jurisdiction.

The main goal of this work was the application of GIS tools and concepts to the study of the Espinho coastal zone. This involved the creation of a GIS-based monitoring program to gather information on all coastal works located along the Espinho shoreline, focusing especially on construction, monitoring, and repairing aspects. A long-term estimation of the erosion and accretion rates in several different locations was then performed using GIS extension tools. This analysis allowed us to make predictions on future displacements of the Espinho shoreline. Finally, a geotechnical mapping evaluation of the rock blocks used in groins from the Espinho shoreline was carried out, based on lithology, weathering grade, and stiffness of the rock materials.

## STUDY AREA

Espinho is a municipality in the Aveiro district, situated on the North Atlantic coast approximately 16 km south of Porto city, the second largest urban area in Portugal (Figure 1). The town of Espinho has a total area of 21.1 km$^2$ and a population of 33,701 inhabitants (census 2001; after PDM [2004]), including five parishes (Espinho, Anta, Guetim, Silvalde, and Paramos); about 20,000 of the inhabitants are concentrated in the urban seafront of Espinho (Veloso Gomes et al., 2002, 2006b; PDM, 2004).

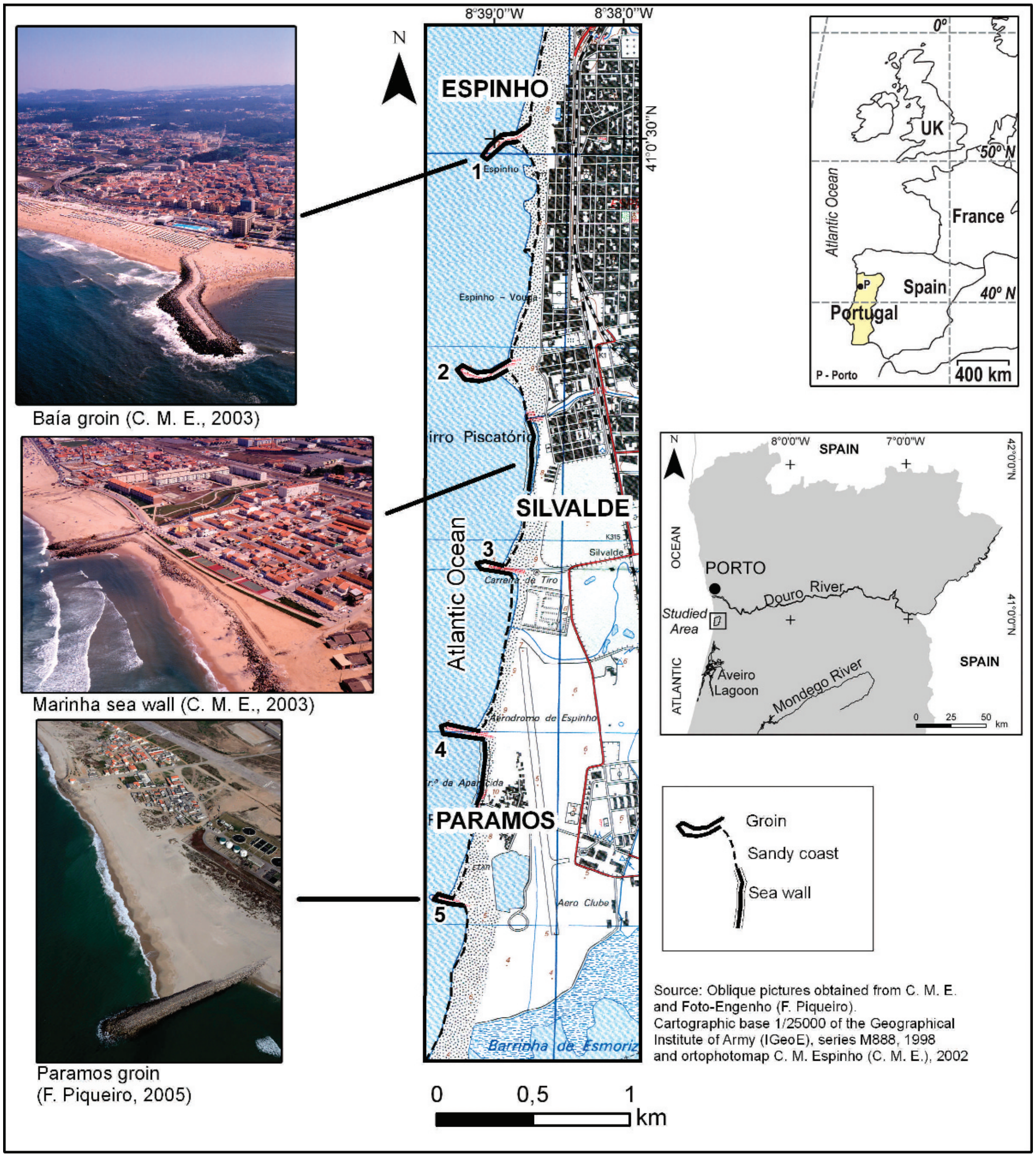


Figure 1. Espinho coastal study area.

Coastal erosion in Espinho has been popular news, recorded since 1869 (Lima, 1979, 1982), as evidenced by several historical documents (Figure 2). Indeed, the first reported erosion dates back to 1860 (Ortigão, 1876), and old maps show that the urban area of Espinho was much larger, extending further seaward to positions that have since been lost to the sea (Bandeira de Melo, 1870, 1900, in Lopes [1995]). The continuous retreat and advance of the Espinho shoreline several meters landward and seaward led to the construction of the first defenses, in 1909, but by 1911, these had been naturally destroyed. Since then several protection structures have successively been put in place to protect the city (Perdigão, 1931; Mota Oliveira and Martins, 1991; Mota Oliveira et al., 2000; and Trigo Teixeira, 2003). Figure 2 illustrates not only the occurrence of some disastrous episodes of sea invasions in the Espinho region but also some evidence of the construction of protection works. This historical compilation of events demonstrates the importance of coastal research in the area.

Presently, two large groins, one in the north and another in the south, and two seawalls comprise the main structures protecting the seafront of Espinho,


Figure 2. Historical images of early 20th century from the Espinho shoreline (Espinho City Council Archives).

and the situation is considered to be stable. The main erosion problems persisting in the downdrift area are due to lack of sediment transport. The most vulnerable area in terms of erosion is the urban seafront of Paramos (Veloso Gomes et al., 2003), located in between Espinho and Esmoriz. The main problems identified in this narrow strip are due mostly to sandy coastal areas that have no natural rock protection, where continuous erosion results in destruction of almost all sand dunes (Dias et al., 2000). Table 1 summarizes the main characteristics of the groins from the Espinho region and the designations used for each coastal structure (see Figure 1), along with the types of different approaches studied.

## Geological and Geomorphological Overview

The regional geology of the Espinho area is related to two different Iberian geotectonic domains: metasedimentary and crystalline bedrock, belonging to the Ossa-Morena Zone (Chaminé, 2000; Chaminé et al., 2003), and the northern part of the Lusitanian sedimentary cover, a tectonic basin developed like an aulacogen during Meso-Cenozoic times (Araújo et al., 2003; Gomes et al., 2006, 2007; and Gomes, 2008).

The shaping of coastal landforms has been influenced by a range of morphogenic factors. While some coastlines have changed little over the past 6,000 years, most have advanced or retreated, and some have shown alternations of advance and retreat (Bird,

Table 1. *Summary of the main characteristics of groins in the Espinho region (compiled data from SOMAGUE [1980] and Veloso Gomes et al. [2002]).*

| Protection Structure Designation (present study) | ID* | Type of Coastal Structures | Location | Construction Date | Length (m) | Groins | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Geotechnical Evaluation | Evaluation (SNIR*Lit*, 2002) | DSAS Study |
| 1 | Structure 1/1 | Groin | Espinho | 1918/1981/1983 | 350 | X | X | X |
| 2 | Structure 2/2 | Groin | Espinho | 1981/1983 | 400 | X | X | X |
| — | — | Seawall | Espinho | — | 400 | | X | |
| 3 | Structure 3/3 | Groin | Espinho | 1981/1983 | 300 | X | X | X |
| 4 | Structure 4/4 | Groin | Paramos | 1981/1983 | 280 | | X | X |
| — | — | Seawall | Paramos | — | 100 | | X | |
| 5 | —/5 | Groin | Paramos | 1985 | 280 | X | X | X |

DSAS = Digital Shoreline Analysis System.
*Identification (ID) according to SOMAGUE (1980)/Veloso Gomes et al. (2002).

1997). The Portuguese coast between the city of Espinho and Mondego cape is undergoing morphological changes (Dias et al., 2000). One of the most common characteristics of this littoral stretch is the so-called littoral platform (Araújo, 2002), encompassing different altitudes and bordered from the inland by a contrasting straight relief (Figure 3). The littoral platform ranges from 75 m in elevation (on the north, close to Ave River) to 130 m in elevation (at the south) and drops down toward the sea like a staircase (Brum Ferreira, 1983). This platform is bounded to the east by a step relief (i.e., the marginal relief) (Araújo, 1991) and is a regional fault scarp related to the Porto-Coimbra-Tomar shear zone (Chaminé, 2000; Gomes, 2008). This planation surface is generally covered with several outcrops of Plio-Pleistocene deposits (Teixeira et al., 1962). This platform has been considered a stable staircase of old marine deposits, indicative of the eustatic fluctuations. However, recent studies bring new insight that many of these deposits have a continental origin (Granja et al., 1999; Araújo, 2002).

## MATERIALS AND METHODS

Three different cartographic sources were used for the study of the Espinho coastal zone: (i) the Pre-project Planning for the execution of the coastal protection structures in Espinho region presented by SOMAGUE (1980); (ii) the Espinho City Council cartographic base of 1993 (scale 1/5,000); and (iii) the 2002 ortophotomap of Espinho City Council. Two other additional sources of information were used to elaborate the GIS-based monitoring project: (a) the monitoring data available at SNIR*Lit*—National Information System of Littoral Resources (SNIR*Lit*, 2002)—and (b) the basic information on coastal works from the Espinho region previously compiled by Pires (2005, 2007) and Pires et al. (2006, 2007). The latest records on the Espinho coastal zone available in SNIR*Lit* date back to 2002. The information on the coastal works includes data related to the design features of the structures (e.g., location, cost, length) as well as their actual condition, eventual pathologies, and needed repairs. These information sources were georeferenced, and all the data were rectified before vectorization using more than 20 control points. The vectorization was used to represent beach areas, protection structures, and bathymetric information (0.0 and +5.0 m.s.l., mean sea level).

The study of the variation of the Espinho shoreline focused on the analysis of the coastal dynamics and the spatiotemporal changes of coastal morphology for the period between 1993 and 2002 and took advantage of the Digital Shoreline Analysis System (DSAS) extension. DSAS is the most user-friendly and powerful tool currently available for measuring the shoreline displacement. It was originally developed by Thieler and Danforth (1994) using loosely coupled programming techniques. The current versions use the ArcView Avenue Macro language, which converted the tool into an extension of ArcView 3.3. Within an ArcView environment, DSAS can benefit from other GIS capabilities of ArcView, such as importing of shapefiles, coverages, and grids, as well as editing and changing projections. The latest version of DSAS can be downloaded freely from the U.S. Geological Survey web page (Thieler et al., 2005). DSAS is an extension that enhances the normal functionality of ESRI ArcGIS software and enables users to calculate shoreline rate-of-change statistics from a time series of multiple shoreline positions. The extension was designed to aid in historic shoreline change analysis (Bailey and Gatrell, 1995). DSAS is also useful for data sets that use polylines as a representation of a feature's position at a specific point in time, such as the forward limit of a glacier; river channel boundaries, and land use and land cover maps. DSAS works by generating

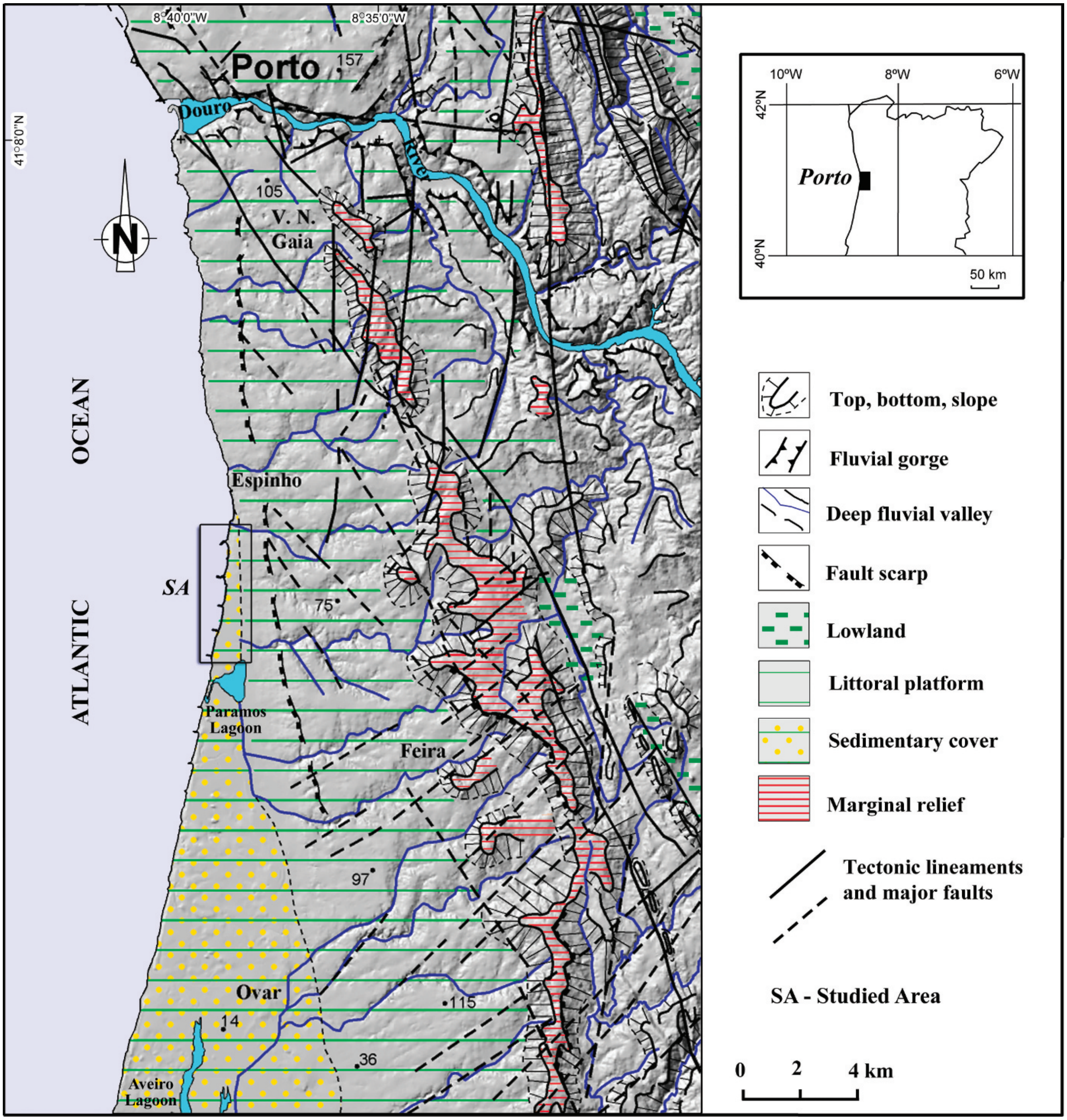


Figure 3. Geomorphological outline of Espinho region, South of Porto city, northwest Portugal (adapted from Gomes et al. [2006, 2007] and Gomes [2008]). Shadowed image relief of the studied area, generated from digitization of elevation contour lines of the 1:25,000 scale. Ground resolution is 10 m.

orthogonal transects at a user-defined separation and then calculating rates of change and associated statistics that are reported in an attribute table. The DSAS tool requires user data to meet specific field requirements: (i) the baseline is the starting point for all transects and is therefore one of the most important components of the shoreline change analysis process; (ii) the baseline must be contained in a single shapefile (and therefore is a single feature class once imported into the geo-database); and (iii) the user should take the time to manually edit and smooth the baseline depending upon the particular study area.

Several statistical methods are available to estimate annual erosion rates and to forecast shoreline positions, such as end point (EP), linear regression, time-series analysis, and geostatistics. The EP rate (EPR) was used in this work and was calculated by dividing the distance of shoreline movement by the time elapsed between the earliest and latest measurements (i.e., the oldest and the most recent shoreline). The major advantage of the EPR is its ease of computation and minimal requirement for shoreline data (two shorelines). The major disadvantage is that in cases in which more than two shorelines are available, the information about shoreline behavior provided by additional shorelines is neglected. Thus, changes in sign or magnitude of the shoreline movement trend or cyclicity of behavior may be missed. For the Espinho coastal area we determined eight zones representing different beach areas, and we also vectorized the lines to evaluate displacement of the head zone of the groins. The DSAS extension was then applied to assess the evolution of the shoreline according to the parameters indicated in Figure 4. The methodology applied in the present study combines several field techniques and various types of inputs/tools (Figure 4), establishing an interdisciplinary connection of geoengineering concepts and an analysis of coastal dynamics for the planning of maritime structures.

The geotechnical mapping evaluation of the groin of Paramos (Espinho shoreline) was performed according to a previously established methodology (Pires et al., 2006, 2009; Pires and Chaminé, 2007, 2009). This methodology is based on the recommendations and terminology of the *Manual of the Use of Rock in Coastal and Shoreline Engineering* from CIRIA/CUR (1991) and CIRIA et al. (2007) as well as on the proposal of geologic and geotechnical characterization of rock masses by ISRM (1978a,b, 1981) and the Geological Society Engineering Working Group (1995). A geotechnical datasheet was used for the recognition and visual evaluation of the rock material constituting the groin. A georeferenced GIS database for this structure was then set up using the data collected and aerial images of the area (Gonçalves and Piqueiro, 2004; Cunha et al., 2006; and Pires et al., 2009). A detailed mapping of the rock blocks constituting the structure was then prepared using the aerial photographic database. Afterwards, more than 5,000 block materials on the groin's superficial section (armor layer) were vectorized into a GIS base. Sampling along a scanline is an accurate method for the systematic collection of geological and/or geotechnical information (e.g., ISRM, 1981; Dinis da Gama, 1983, 1995; and CIRIA et al., 2007). Moreover, in several geologic-geotechnical situations it is the easiest and fastest way to collect data. This approach allowed us to obtain thematic maps of the Paramos groin armor layer that were useful for evaluating various geotechnical parameters (ISRM, 1978b, 1981; Pires and Chaminé, 2007, 2009 [and references therein]). This assessment was also supplemented with walkover surveys carried out to record (with the aid of photographs and high-accuracy GIS data collection system Trimble Geoexplorer GPS) not only the overall condition of the structure, including any obvious rock movements, but also changes in the groin profile, type of lithology, etc.

These visual evaluations were supported by the use of the inspection datasheet, where the most important aspects and parameters were registered, including lithology, weathering grade, petrophysical characteristics, and geomechanical features of block materials (Fookes and Poole, 1981; Lienhart, 1998). For the evaluation of the uniaxial compressive strength of rocks and materials (concrete) in the groin, the Schmidt Hammer technique was used (e.g., Katz et al., 2000; Kahraman, 2001). This methodology was further refined through the application of GIS tools (e.g., Burke et al., 2001) and was used to create thematic geotechnical zoning maps of the block groins (e.g., Zuquette and Gandolfi, 2004; Pires et al., 2009).

## RESULTS AND DISCUSSION

Within the scope of the present work, an interactive GIS-based monitoring project was created for the coastal zone of Espinho. This information system represents the actual condition of the Espinho shoreline as well as the state of degradation of the existing coastal protection structures (Figure 5). It includes a spatial representation of all groins and seawalls from Espinho, and it also stores all the relevant elements, specifications, and photos obtained during the process of information gathering. In brief, it assembles specific data on the following issues: (i) coastal protection structure identification; (ii) present condition of the coastal protection structures with hyperlinks to photos by SNIR*Lit*; (iii) a geotechnical assessment of the coastal protection structures, including observed pathologies and indications on the eventual need of future repairs; and (iv) technical specifications, such as the kind of structures, type, location, year of construction, length, volume of blocks used in the construction, and costs. The information system developed in the GIS environment is useful for long-term accumulation of coastal data, while allowing for easy and accurate measurement and forecast of shoreline displacement.

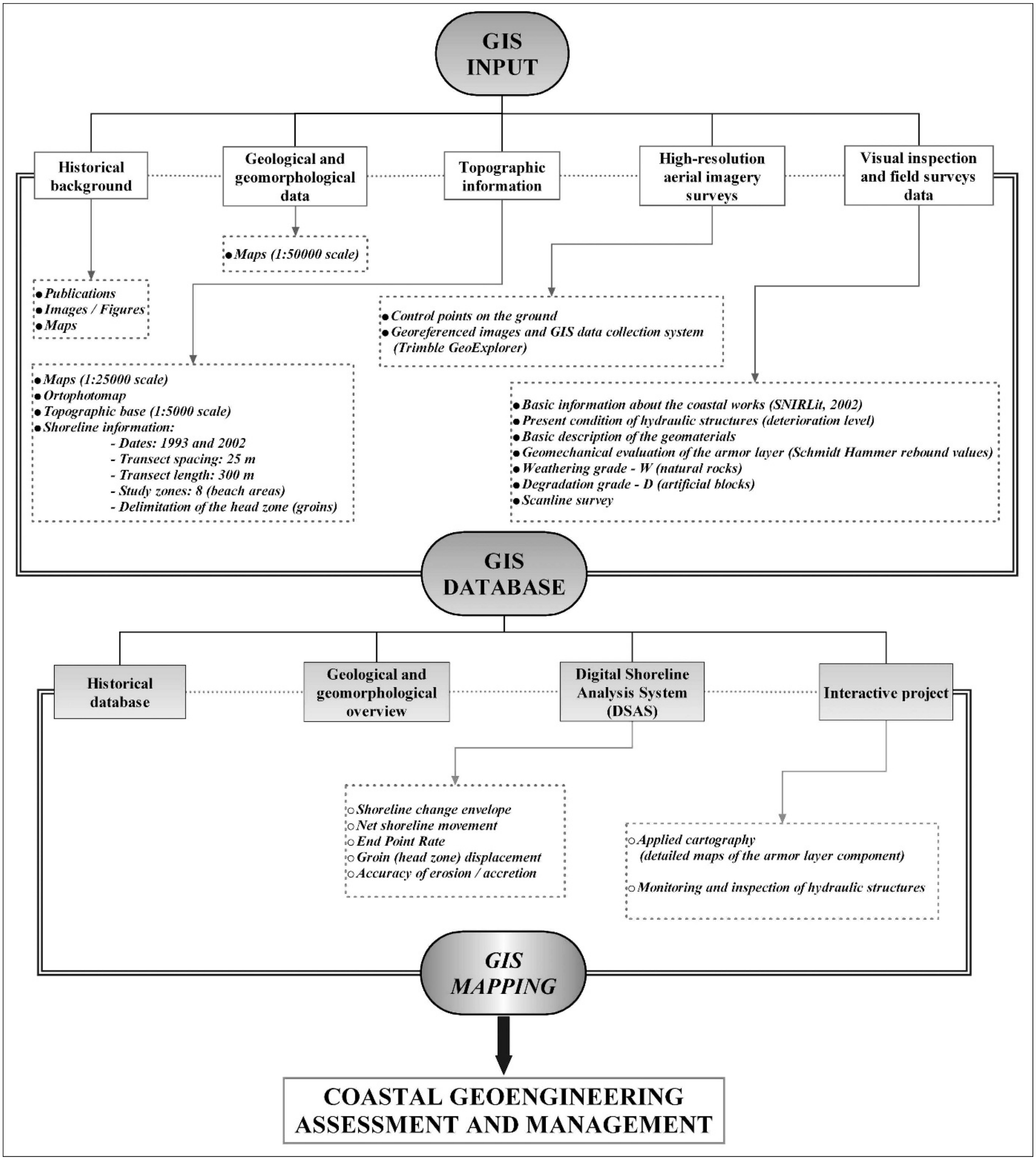


Figure 4. Conceptual flowchart for the dynamics of coastal geoengineering system assessment.

Estimation of the rates of erosion and accretion along the study area was performed for the 9-year period using the positions of the Espinho shoreline in 1993 and 2002. According to the results obtained, zone 4 (south of Marinha groin) shows a general trend of erosion. In agreement with this, the main accretion area is located in the north (zones 1 to 3). Figure 6 represents the beach areas that were studied and the corresponding values of erosion or accretion, as determined by the transect methods employed by

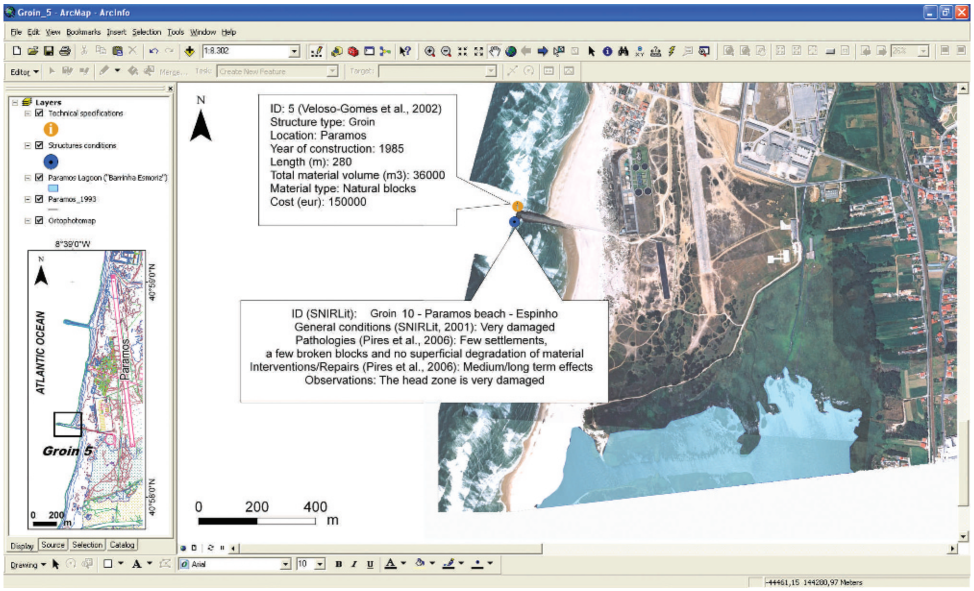


Figure 5. GIS database: an example of the type of information recorded for the Paramos groin (groin 5).

DSAS. The results indicate a general trend of erosion for the south of Espinho, with an average rate of 2.72 m/yr, whereas the mean rate of accretion estimated for the north of the study area is 3.21 m/yr. This figure shows very well the advance of the sea in the Paramos region (south of Espinho), which is one of the most affected sectors. These results are in agreement with those estimated by Dias et al. (1994) and Dias (2005) using other methodologies and for different temporal periods. These authors report a mean erosion rate of 3.8 m/yr for the period between 1870 and 1954, a value close to that obtained in the present work for a temporal interval of just 9 years. We also estimated the areas of land loss or gain for each zone (Figure 7a). This estimation was based on polygon vectorization for each section, with subsequent determination of the area of the polygons (Moran, 2003).

Within the Espinho coastal zone, the area of accretion has been estimated at about 60,000 $m^2$/yr (Figure 7b), corresponding to 56 percent of the total affected area. These results are in agreement with those reported by other authors (e.g., Dias et al., 1994; Veloso Gomes et al., 2006a; and MAOTDR, 2008), who concluded that although the measures implemented in the Espinho area efficiently protect the northern part of the coast, they are ineffective in protecting its southern part. The displacement/settlement of blocks for the head zone of the groins is exemplified for groin 2, which shows movement or the destruction of this zone in the period ranging from 1993 and 2002 (Figure 8). Of the five groins studied, only groin 1 did not present visible settlements. Groin 4 underwent maximum change, with about 1,800 $m^2$ of settlement during the study period, and groin 5 had the lowest change, at 233 $m^2$. Groins 2 and 3 present values showing approximately 900 $m^2$ of displacement.

The use of the method of transects from DSAS extension offered a flexible way to analyze Espinho coastal dynamics. Although based on just two shorelines and a short elapsed time, the method employed by the DSAS extension was powerful enough to confirm the marked evolution of the coastline during this period, clearly indicating the areas showing considerable erosion and accretion changes. Furthermore, ArcGIS embedded functions were instrumental in estimating (i) the total area affected by coastal advance and retreat and (ii) the annual average erosion and accretion rates.

Geotechnical mapping and evaluation of the Paramos groin involved inspection and assessment of post-construction works. Considering that the geologic nature and engineering properties of the materials used to construct coastal engineering structures are critically important to the success and longevity of the structure (e.g., Dupray, 2005; Latham et al., 2006a,b), a lithological map of the armor layer of Paramos groin was first prepared. More than 5,000 rock materials were vectorized, and the different geomaterials were identified (Table 2): for example, natural rocks (granite and gneiss) and artificial materials (concrete or a mixed material [i.e., concrete + aggregates]).

The applied cartography provided an evaluation of the current condition of the structure and of the status of the revetment material. The Schmidt Hammer rebound values provided an estimate of the uniaxial compressive strength of block armor materials along the crown wall of the structure,

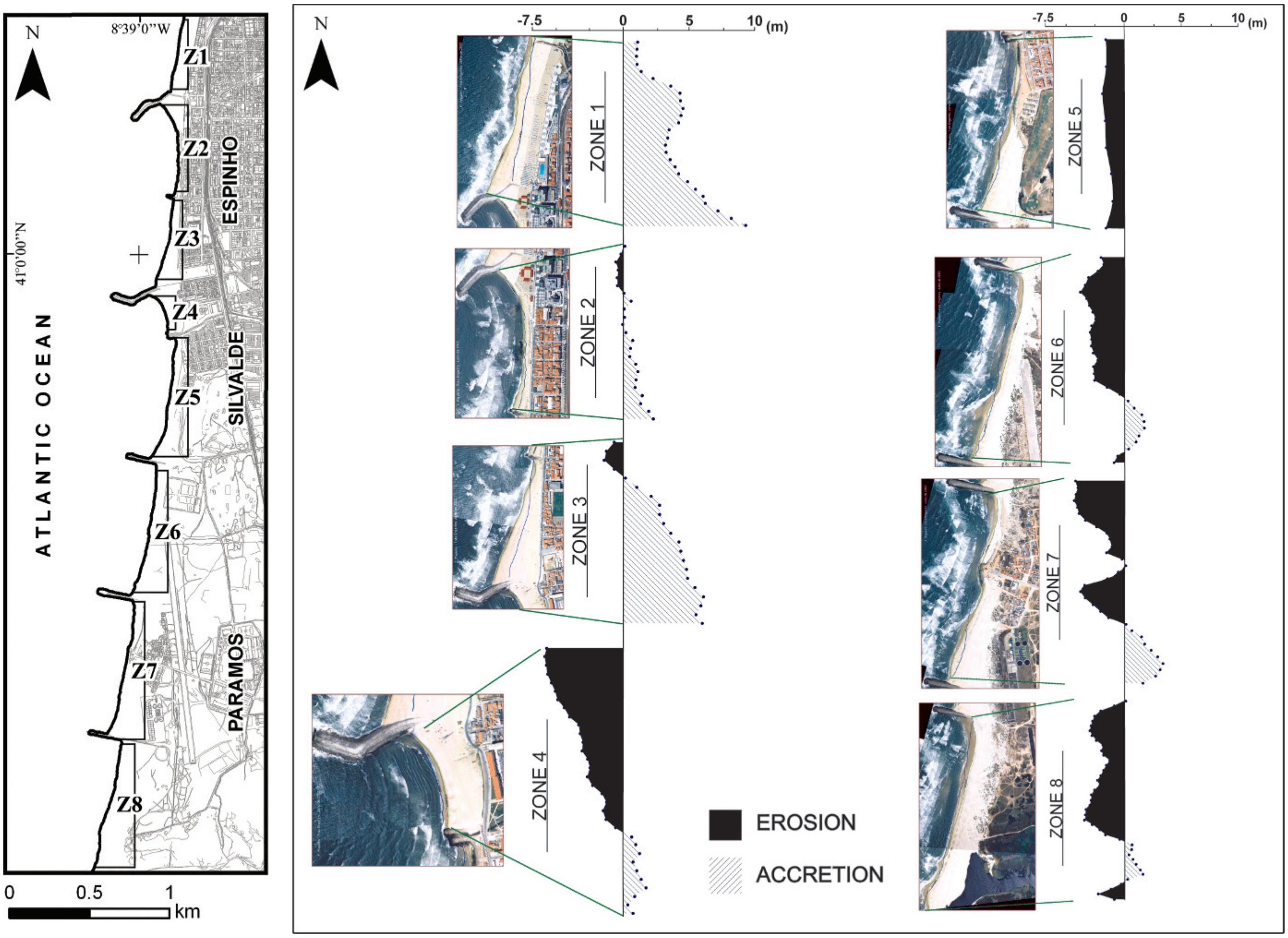


Figure 6. DSAS application on the beach zones studied in the Espinho area: EPR (end point rate) quantification.

according to ISRM (1981). The cross-check of all geotechnical and geomechanical parameters obtained, particularly petrophysical features, weathering grade, and uniaxial compressive strength, allowed us to classify the Paramos armor block material in terms of its degree of deterioration (Figure 9a). Zone I (ZI) corresponds to the crown wall, which shows the maximum strength (ranging from 195 to 250 MPa).

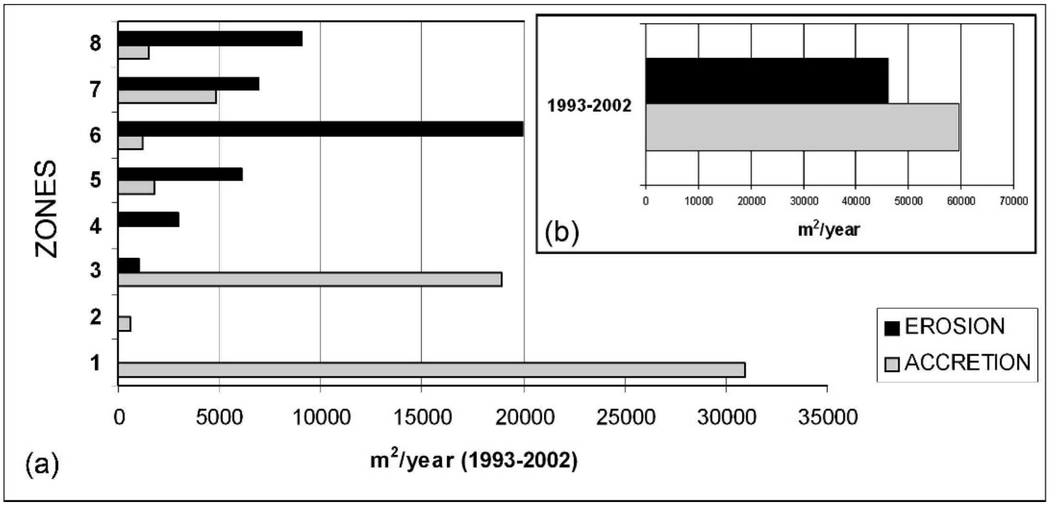


Figure 7. Estimated areas of land loss or gain. (a) Beach zones (1 to 8) area variation; (b) Espinho total area variation.

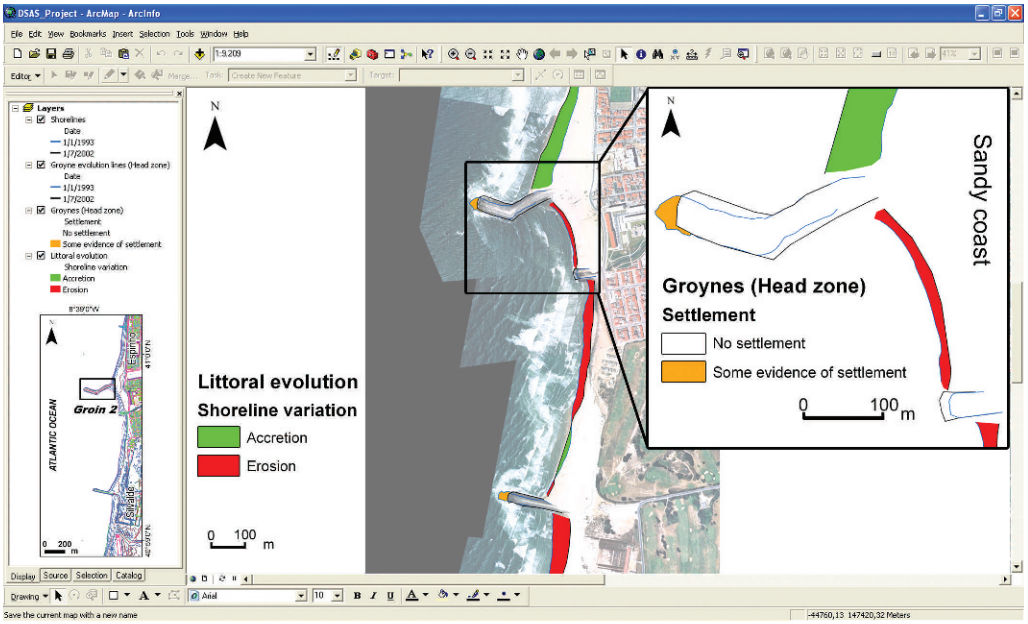


Figure 8. GIS project and application of DSAS extension on Espinho coastal dynamics: example of the settlement studied for groin 2.

This zone is predominantly composed of medium- to fine-grained reddish-rose granite. Zones II (ZII, inner) and III (ZIII, head) have the same lithologic characteristics, namely medium-grained grayish-blue biotitic granite, with intermediate values of strength, ranging from 150 to 195 MPa. Finally, zone IV (ZIV) corresponds to the outer zone, with the lowest strength values (ranging from 120 to 150 MPa). This zone mainly comprises yellowish biotitic orthogneisses with feldspar mega-crystals. Based on the described methodology, an example of the lithological characterization obtained is presented for Paramos groin (Sector 5) in Figure 9b.

Table 3 synthesizes the geotechnical features of the armor block material classification and the present deterioration level of Paramos groin. In this case, for zones I, II/III, and IV, the deterioration levels are, respectively, very low, medium to high, and low.

The methodology used for the geotechnical mapping and assessment of the block materials from Espinho coastal protection structures proved to be an easy, fast, and economical way to assess the status of coastal protection structures (details in Pires and Chaminé [2007, 2009]). Furthermore, this methodology provides a geological-geotechnical characterization useful for groin management. The main results of both the applied cartography developed in a georeferenced GIS base and the evaluation of the deterioration level of the groin materials reinforce the need for careful planning in this kind of work. Because the cost of production and

Table 2. *Geomaterials recognized along the superficial layer and studied characteristics for the five sectors.*

| | Geomaterial Characterization | | | |
|---|---|---|---|---|
| Description | Granite | Granite | Biotite-orthogneiss | Concrete |
| Color | Grayish-blue | Reddish-rose | Yellowish-brown | Gray |
| Weathering grade (W) (GSE, 1995; ISRM, 2007) | $W_1$–$W_3$ | $W_1$–$W_3$ | $W_1$–$W_{3-4}$ | — |
| Degradation grade (D) | n.a. | n.a. | n.a. | $D_1$–$D_4$ |
| Texture/structure | Medium grained | Medium to fine grained | Coarse to medium grained | n.a. |
| Observations (geological units, from Chaminé [2000]) | Granitic facies, essentially biotitic, grayish-blue, medium grained (Canidelo quarry, "Lavadores" granite) | Granitic facies, reddish-rose, medium to fine grained (Canidelo quarry, "Lavadores" granite) | Biotite orthogneiss (quartz and large feldspar megacrystals) has a strong foliation and a strong shear fabric (Malaposta quarry, "Lourosa" Unit) | Blocks with concrete and aggregates |

n.a. = not applicable.

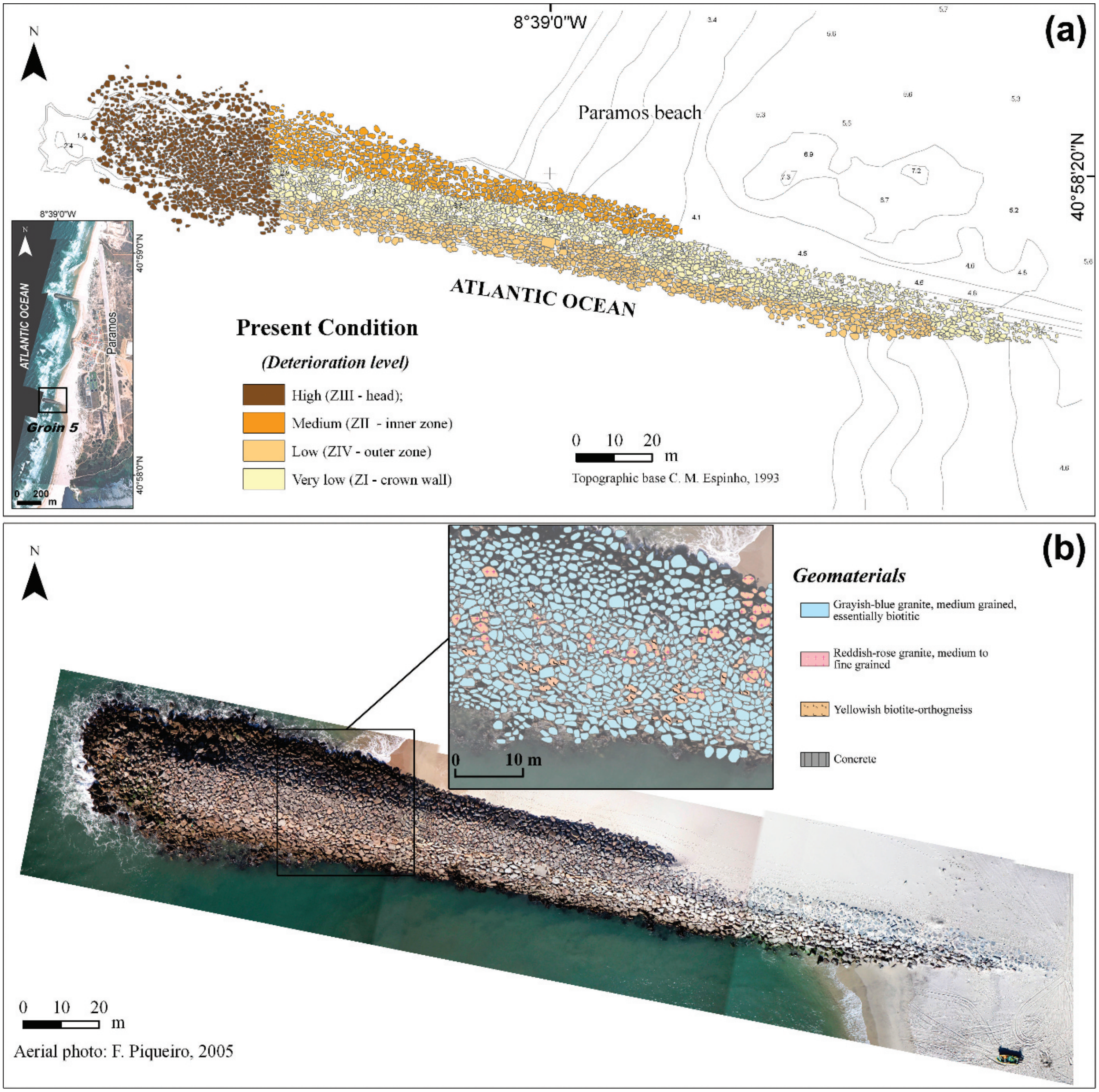


Figure 9. (a) Armor block materials zonation, a tentative synthesis map: deterioration level and structure present condition; (b) Applied cartography from Paramos groin.

Table 3. *Results of the field assays and the visual inspection.*

| Designation | Weathering Grade (W) (ISRM, 1981; GSE, 1995) | Uniaxial Compressive Strength (MPa) (ISRM, 1981) | Present Condition (deterioration level) |
|---|---|---|---|
| ZI | $W_1$ | 195–250 [$S_1$] | Very low |
| ZII/ZIII | $W_{1-2}$ | 150–195 [$S_2$] | Medium/high |
| ZIV | $W_3$ | 120–150 [$S_2$] | Low |

Z = zone; ZI = crown wall; ZII = inner zone; ZIII = head; ZIV = outer zone.

transportation of the very large quantities of rock often required for coastal and shoreline structures is an essential consideration when selecting a particular design solution, it is important to establish the availability and quality control of rock materials at their point of origin or location of extraction until the project is completed. Further studies to provide more detailed information on the geological materials and the material properties in relation to the design requirements and to apply standard test procedures to assess the quality and durability of these materials before and during construction (Pizarro et al., 2005) are in progress. At the same time, there is also a need to evaluate the structure condition after the construction (i.e., for monitoring and maintenance perspectives).

Several generations of Espinho residents have been living under the threat of coastal hazards. They have thus developed some feeling for coastal erosion, and their general opinion on the coastal defenses of the city of Espinho is that these structures are essential to holding back the sea and enlarging beach dimensions (Soares de Carvalho, 1995; EUrosion, 2004). The Espinho shoreline is a very dynamic coastal stretch, with historic and natural erosion events that may possibly become aggravated in the future, necessitating calls for careful and continued monitoring studies. Such studies may help us to avoid the undesired consequences of possible future aggravations of the erosion process.

## CONCLUDING REMARKS

In conclusion, the approach adopted in this work contributes to improving our knowledge of the dynamics of the Espinho shoreline. It provides a solid base from which to easily forecast and model shoreline displacements over the years and to identify main areas of erosion/accretion.

The approach used to propose a coastal evolution for this area indicates that the recession of coastline is occurring in the form of erosive wave propagation from north to south. Along this coastal stretch there are also several hydraulic works that influence the coastal erosion process, and this can easily be shown by considering the accretion that occurs in the northern areas of obstacles (e.g., groins) and the erosion that occurs in the southern areas.

The main erosion problems, which exist in the southern area (downdrift), are due to lack of sediment transport. The most vulnerable area in terms of erosion is the urban seafront of Silvalde/Paramos (zones 4 to 8). Several large groins protect the downdrift of Paramos, and the Coastal Management Plan considers the probable retreat of this urban seafront as a future measure of managed realignment predicted for the Portuguese west coast (Taveira Pinto, 2003). Consequently, the main problems in this stretch are due to (i) sandy coast with no natural rock protection; (ii) extended erosion problems, with the destruction of the dunes; (iii) large groins and sea walls; and (iv) the erosion existing in the urban seafront of Silvalde/Paramos (considering the retreat of this urban seafront).

In addition, according to the results obtained, a methodological characterization of the geomaterials is crucial to determine the deterioration level and the structures' present condition. This approach uncovered the need for repair/maintenance work in some parts of the study area or for eventual changes in their design. Moreover, the GIS tools provided an easy and very useful way of handling large data sets and, most importantly, of visualizing the results in a way that facilitates the rapid perception of the status of the structures and, thus, the decision-making processes. In the present case, according to the evaluations performed, replacement of the primary armor layer of the head of the structures would increase the effectiveness and modification of the longevity of the structures. The results also indicate that for some of the sectors, alterations to the design of the structures would help minimize deterioration of the structures due to erosion. Figure 9a revealed that the head and inner zones have high and medium deterioration levels, respectively, and that they are significantly susceptible to waves and current events. These two zones comprise geomaterials that do not possess high compressive strength and are also subject to the currents and wave propagations, mainly from north to south, that facilitate the overall damage to the structures. For the five groins studied it was clear that the head zone has the highest level of deterioration and is the most susceptible component of the hydraulic structures, and it was also evident that during the construction and design of these structures, material selection was not based on the type of rock, quality, durability, and other characteristics, which the contractor should have taken into consideration. As a result, the methodology developed provides a geotechnical characterization that is useful in the planning of maritime repair works. Moreover, this methodology gives further support to the importance of establishing the availability and the geotechnical quality and durability of geomaterials to be used at a particular site at the time of extraction from quarries when one is considering geoengineering design options (e.g., Lienhart, 1998; Latham et al., 2006a,b; and Manoliu and Radulescu, 2008). On the other hand, there is also a concern for evaluating the structural condition of protection work after the construction for monitoring and maintenance.

The study also provides information valuable in extending the average lifetime of Espinho coastal protection structures. The costs of such structures, their expected behavior, as well as the consequences of their failure do justify on-site geotechnical investigations designed to help in decision making.

This research is still in progress to provide more detailed information on the most appropriate geomaterials (namely with regard to the rock mechanic properties required in relation to the design) and standard test procedures that are usually applied to assess quality and durability of these materials before and during construction. In this area, the illegal occupation/use of the maritime public domain is common, and there is no cartographic record of the areas of the public shoreline domain, which makes the management of these areas very complicated. To achieve results for the proposed actions or measures, it is essential to study and adequately program the interventions in the littoral region. Thus, there are three essential objectives: (1) to encourage technical scientific studies on the littoral; (2) to identify the areas at risk and take preventive measures; and (3) to protect the areas at risk.

Some proposed solutions can be accomplished through the following processes: recuperation of the dune systems; collaboration with other institutions with littoral jurisdiction; identification and definition of the areas that are more vulnerable to erosion and implementation of preventive measures; implementation of the coastal defense programs; intervention in priority areas (e.g., Espinho); and additional studies to find adequate interventions. The so-called hard coastal defenses are indispensable, and at the moment, there is not any plan to remove the existing groins, seawalls, and other hydraulic structures. Hence, maintenance works, or even rearrangement of the original design of the structures, is likely to continue. In addition, artificial sand nourishment operations might also be included as possible solutions to the erosion problem affecting this coastal stretch.

## ACKNOWLEDGMENTS

This project was developed within the scope of a trainee period of a GIS post-graduation course (FLUP) performed by A. Pires at the Laboratory of Cartography and Applied Geology (Labcarga-ISEP) and GeoBioTec Centre (University of Aveiro). This work was performed with the financial support of Labcarga-IPP-ISEP|PAD'2007/08. This research was also funded by a doctoral scholarship from the Portuguese Foundation for Science and Technology (FCT) to A. Pires (SFRH/BD/43175/2008). We gratefully acknowledge R. Sousa (CME), A. Mota Freitas (Somague), A. Lopes (ICSA), F. Santiago Miranda (APDL), F. Piqueiro (FEUP), P. Freire (LNEC), F. T. Rocha (UA), and S. Dupray (Cetmef) for useful information; their comments greatly improved the focus of our paper. We acknowledge W. C. Haneberg, N. S. Levine, S. E. Hasan, and an anonymous referee for constructive reviews that helped to improve the clarity of the manuscript; in addition, we thank editor A. Shakoor for all the support.

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# P4

## SYNOPSIS

*This is the second publication about the experimental field studied and displays a methodological article. This study was carried out to develop a systematic methodology for the analysis of coastal protection structures in a GIS database project. This work contributes to ameliorate the efficiency of monitoring and maintenance, in an economically beneficial mode. Low-level aerial surveys were conducted from a light aircraft, providing high-resolution digital images suitable for armour layer integrity analysis. Combining photogrammetric and field techniques, this research aims to define an applied cartography for geomaterials characterisation in hydraulic works. This research comprehends different phases: i) visual inspection; ii) field techniques to study geologic-geotechnical features; iii) in situ measurement of geomechanical parameters; and iv) development of GIS mapping and assessment of the block materials. The GIS project incorporates high-resolution aerial imagery surveys and the results of the field techniques applied for the structures' cartography. The interactive base included the pilot case presented in this work, from Espinho coastal area (NW Portugal), which comprises five sectors. This guidance may be helpful during pre-design or planning assessments, supported by coastal geoengineering concepts. It also generates useful knowledge for repairing recommendations and conceptual coastal management. This research was the preliminary study to develop a systematic methodology since the acquisition of high resolution aerial imagery until the coastal monitoring in hydraulic structures.*

Proceedings of the 10th
Volume II

# INTERNATIONAL COASTAL SYMPOSIUM ICS 2009

Journal of Coastal Research
Special Issue 56

Published by:
Coastal Education and Research Foundation [CERF],
and Centro de Estudos de Geografia e Planeamento Regional [e-GEO],
FCSH - UNL

Edited by: Carlos Pereira da Silva

| Journal of Coastal Research | SI 56 | 1572 - 1576 | ICS2009 (Proceedings) | Portugal | ISSN 0749-0258 |
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# Cartography and Assessment of Hydraulic Structures from Espinho Coastal Area (NW Portugal) Using High-Resolution Aerial Imagery Surveys and a GIS Interactive Base

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**ABSTRACT**

PIRES, A.; CHAMINÉ, H. I.; GOMES, A; PIQUEIRO, F.; MIRANDA, F. S. and ROCHA, F. T., 2009. Cartography and assessment of hydraulic structures from Espinho coastal area (NW Portugal) using high-resolution aerial imagery surveys and a GIS interactive base. Journal of Coastal Research, SI 56 (Proceedings of the 10th International Coastal Symposium), 1572 – 1576. Lisbon, Portugal, ISSN 0749-0258.

This study was carried out to develop a systematic methodology for the analysis of coastal protection structures in a GIS database project. This work contributes to ameliorate the efficiency of monitoring and maintenance, in an economically beneficial mode. Low-level aerial surveys were conducted from a light aircraft, providing high-resolution digital images suitable for armour layer integrity analysis. Combining photogrammetric and field techniques, this research aims to define an applied cartography for geomaterials characterisation in hydraulic works. This research comprehends different phases: i) visual inspection; ii) field techniques to study geologic-geotechnical features; iii) in situ measurement of geomechanical parameters; and iv) development of GIS mapping and assessment of the block materials. The GIS project incorporates high-resolution aerial imagery surveys and the results of the field techniques applied for the structures' cartography. The interactive base included the pilot case presented in this work, from Espinho coastal area (NW Portugal), which comprises five sectors. Based on the described methodology, different geomaterials were recognised, providing an evaluation of the current condition of the structure and the revetment material status. The results obtained allowed to define a geomaterial zonation for the structures' armour layer, according to the type of rock source, weathering/degradation grade and *in situ* geomechanical tests. Also, the outcome established by these results indicates the need for repairing/maintenance works in some parts of the studied structures. This guidance may be helpful during pre-design or planning assessments, supported by coastal geoengineering concepts. It also generates useful knowledge for repairing recommendations and conceptual coastal management.

**ADITIONAL INDEX WORDS:** *Geomaterials, Photogrammetry, Deterioration level, Coastal geoengineering*

## INTRODUCTION

The coastal protection strategies in a project must necessarily include a rational balance between the activities of management strategy plan and the adjustments to the natural systems (USACE, 2003). Impacts caused by the construction of large structures and incorrect land use require comprehensive geotechnical approaches and engineering solutions for their mitigation (MANOLIU and RADULESCU, 2008). In this study the importance of geological and geotechnical concepts for the coastal planning of hydraulic structures are illustrated. It is also emphasised the importance of rock material, which requires a previous study of its availability, quality and also a monitoring plan, maintenance and repair of the structure, as an integral part of life cycle management (*e.g.*, LCPC, 1989; SILVA, 1996; CIRIA/CUR, 1991; USACE, 2003). In addition, another purpose is the mapping and systematic inspection of these structures to characterise the natural and artificial blocks which constitute these structures. Furthermore, the geomaterials were traced back to their origin (i.e., the extraction quarries) in order to typify and better evaluate the evolvement of the whole structure since its construction. The use of GIS (Geographic Information System) databases is currently considered a useful tool that provides scientific background to evaluate parameters used as well as the results produced. In this work, using guidelines and procedures for the evaluation of rock materials, it was possible to develop a GIS-based methodology that establishes a bridge between specific geological construction materials (geomaterials) and the design of coastal protection structures. In addition, the technique for the acquisition of high-resolution aerial imagery surveys permitted the development of a geo-database and an input for the GIS mapping project.

For projects that involve quarry stone armour units, good specifications are essential for the performance of the hydraulic structures. The geotechnical investigations accomplished in this study, also aim at establishing reliable geological and geomechanical features of the in situ quarry rock mass, including the geometry of the geological units, and their physical and mechanical properties (FOOKES and POOLE, 1981).

It is presented the photogrammetric technique for the acquisition of aerial images taken by a light aircraft. These vertical images were used to assess the detailed cartography and the GIS geo-database. Digital SLR off-the-shelf photographic cameras have achieved performance levels today that compare to professional photogrammetric equipment, at a fraction of the cost. Together with navigation equipment (GPS and inertial) and a light aircraft, they offer an attractive perspective for high resolution and local area airborne photogrammetry applications. In this type of applications, equipment and flight costs are particularly relevant (*e.g.*, TEUNISSEN, 1995; SILVA, CHILRO and CUNHA, 2001; CUNHA, SILVA and PIQUEIRO, 2006).

This work aimed to be a contribution to coastal geoengineering, by developing new methodologies (i.e., applied cartography to coastal revetment structures and the acquisition of aerial imagery, which also includes a GIS mapping and geotechnical characterisation of armourstone quarries) for the rock material evaluation since its origin (quarry) until the project.

## STUDY AREA

The coastal area under study is located in the Portuguese Northwest coast, facing the Atlantic Ocean. It belongs to Espinho, a municipality from the district of Aveiro, situated approximately 16km to the South of Porto (MAOTDR, 2008). The groin field from Espinho area includes five sectors along ca. 5km length (Figure 1).

The Espinho town has a total area of 21.1km$^2$ and a population of about 33.000 inhabitants, including 4 more parishes (Anta, Guetim, Silvalde and Paramos), about 20.000 of which are concentrated on the urban seafront of Espinho.

## METHODOLOGY

The methodology for the cartography and assessment of coastal protection structures includes a characterisation of rocks and combines field techniques with different types of tools, establishing an interdisciplinary connection of geoengineering concepts for the planning of maritime structures (*e.g.*, LCPC, 1989; CIRIA/CUR, 1991; USACE, 2003; CIRIA, CUR and CETMEF, 2007). It is based on the recommendations and terminology of the "Manual of the Use of Rock in Coastal and Shoreline Engineering" from CIRIA/CUR (1991) and CIRIA, CUR and CETMEF (2007), as well as on the proposed basic geotechnical description of rock masses, the so-called BGD (see details in GSE, 1995; ISRM, 2007,). It also used a series of techniques and methods previously described by FOOKES and POOLE (1981) and LATHAM, LIENHART and DUPRAY (2006), with the final purpose of identifying the geomaterials' source and studying its implications in terms of durability. Furthermore, GIS tools were used to create a platform for the integration of all available data on digital maps. This platform and its corresponding geo-relational database allowed not only, data assessment, processing and visualization, but also its analysis and interpretation as a support to decision-making processes in the coastal geoengineering field. Aerial images of the area were used to set up a geo-reference GIS database. A detailed mapping of the rock blocks was then prepared with the support of the aerial photographic database. The proposed system for the images acquisition is constituted by two fundamental subsystems that are supported by the same common navigation system, running on a rugged embedded PC: the flight guidance system and the image acquisition system exemplified in Figure 2A(i). The pictures are taken using a high-end digital single lens reflex (D-SLR) camera that is able to acquire high resolution pictures (21 mega pixels) at high frame rates (several frames per second at continuous shooting). Each time a picture is taken a trigger signal is fed to the embedded PC and a time tag is recorded. The IMU data related to the camera orientation is logged together with the time stamps relative to each measurement. Its main purpose is to compute the camera attitude, through integration of its acceleration and angle rate measurements with the GPS derived positions. This system can use a small aircraft for operation (in this case an aircraft model CESSNA C172). There is no need for physical or aerodynamic changes to the airframe or even any change in the slight envelope or certification other than the removal of the right door. Although it might seem strange, this is a common and easy procedure in this

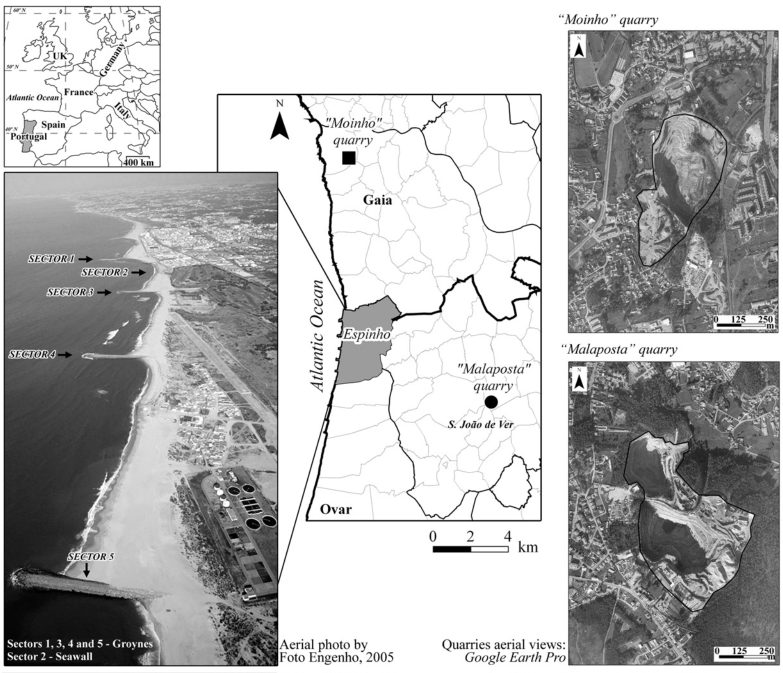



Figure 1. Location from the five sectors studied (Espinho region, NW Portugal) and quarries geomaterials extraction sites.

type of aircraft. Figure 2A(ii) illustrates this description. Besides the equipment installed in the aircraft a reference station is also established in the surveyed for each mission, enabling differential processing of the GPS receivers on board the aircraft relative to the ground station enhancing their precision (for further details see CUNHA, SILVA and PIQUEIRO, 2006). A geotechnical datasheet was then created for the recognition and visual evaluation of the rock material (Figure 2B). A detailed mapping of the rock blocks was prepared with the support of the aerial photographic database. Afterwards, for the five sectors studied, more than 20.000 block materials on the structure's superficial section (armour layer) were vectorised in a GIS base. Sampling along a linear scanline, which is an accurate and fast method for the systematic and representative collection of geological and/or geotechnical information (PIRES *et al*., 2006; PIRES and CHAMINÉ, 2007, 2008), was then used. Walkover surveys were performed along the scanlines established with the aid of the aerial photographs and high-accuracy GIS data collection system (Trimble Geoexplorer), to obtain and record information on the overall condition of the structure, including any obvious block movements, changes in the profile, type of lithology, etc. These visual evaluations were supported by the use of the inspection datasheet where, the previous data, and other important aspects and parameters were registered, namely scanline segments, lithology, weathering grade, petrophysical characteristics, geomechanical features of block materials. Additionally, a meticulous study of the quarry control that provides the rock materials, i.e., gneissic and granitic rocks in the surroundings of the study area, was carried out. For the evaluation of the uniaxial compressive strength of rocks and materials (concrete), the Schmidt Hammer technique was used (e.g., ISRM, 2007). This approach allowed us to obtain thematic maps of the structures armour layer useful to evaluate different geologic and geotechnical parameters.

## RESULTS AND DISCUSSION

Based on the described methodology, an example of the geomaterial characterisation obtained is presented for Marinha groyne and seawall (Sector 1 and Sector 2). The lithological maps of the armour layer of Marinha groyne and seawall, comprises more than 2.300 and 4.200 vectorised geomaterials, respectively (Figure 3). Different geomaterials were recognised (Table 1), such as: natural rocks (granite and gneiss) and artificial materials (concrete or a mixed material, i.e., concrete + aggregates or tetrapods). This applied cartography provided an evaluation of the current condition of the structure and the revetment material status. The Schmidt hammer rebound values obtained allowed to estimate the uniaxial compressive strength of block armour materials along the crown wall of the structure. Through the cross-check of all geotechnical and geomechanical parameters, particularly the petrophysical features, the weathering grade and the uniaxial compressive strength, it was possible to define deterioration levels and a corresponding zonation for the block materials of the structures' armour. The application of this zonation is exemplified for Sector 4. The table in Figure 3 synthesises the geotechnical features of the zonation in relation to the deterioration level (Sector 4). For Zones I, II, and III the deterioration levels are, respectively, low, medium and high. Zone I and II correspond to the crest and inner/outer zones, respectively, and show the maximum rebound values.

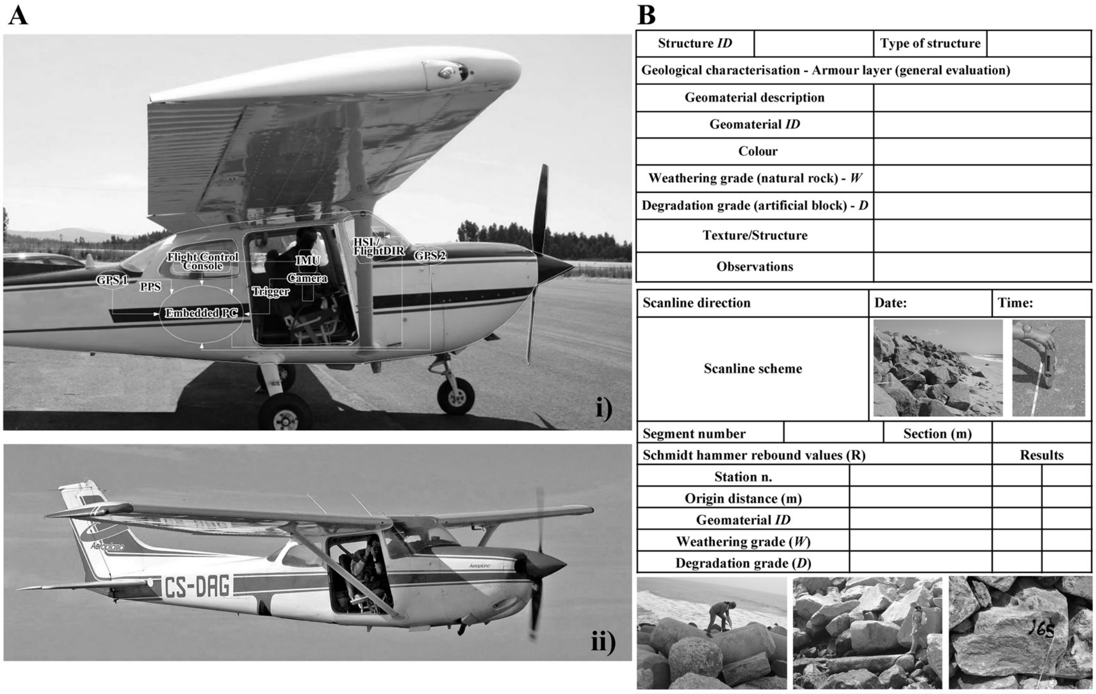
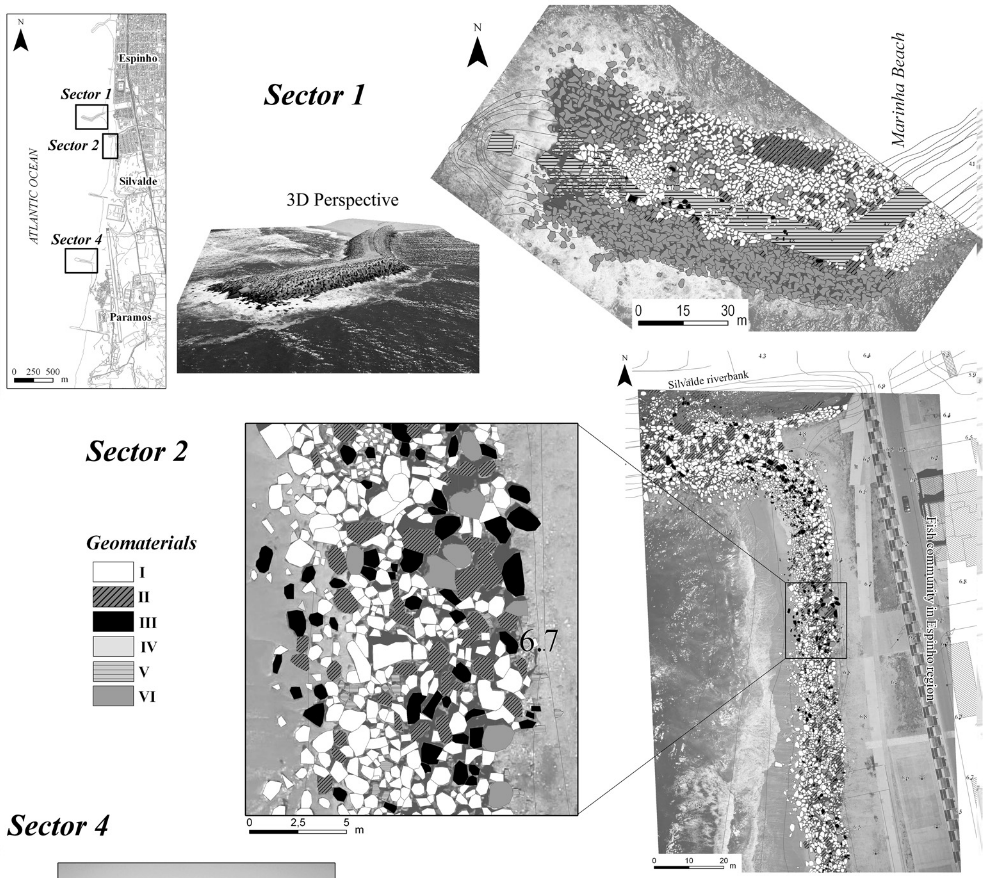
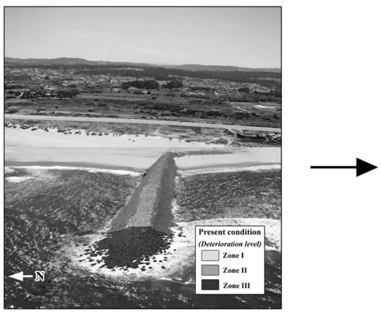



Figure 2. A(i) - Aircraft and system functional diagram (adapted from CUNHA, SILVA and PIQUEIRO, 2006); A(ii) - Mission operation; B - Datasheet created for the evaluation and inspection of block materials and some aspects of the field technique applied (adapted from PIRES and CHAMINÉ, 2007).




Sector 4




| Armour layer zonation [Designation] | Rebound values range (R) | Predominant geomaterial / Weathering grade (W) / Degradation grade (D) | Present condition (Deterioration level) |
|---|---|---|---|
| *Zone I [crest]* | 55 to 60 | orthogneiss / $W_{1\text{-}2}$ to $W_3$ | Low |
| *Zone II [inner and outer zones]* | 55 to 60 | orthogneiss / $W_{1\text{-}2}$ to $W_3$ | Medium |
| *Zone III [head]* | 20 to 45 | tetrapod / $D_3$ to $D_4$ | High |

Figure 3. Applied cartography from Marinha groyne and seawall (Sector 1 and 2), for explanation, see Table 1; Application of the coastal geomaterial zonation proposed to the armour block materials of Sector 4.

Table 1: Geomaterials recognised along the superficial layer and studied characteristics for the five sectors (*n.a.* – not applicable).

| | *Geomaterial characterisation* | | | | | |
|---|---|---|---|---|---|---|
| *Description* | Granite | Granite | Biotite-orthogneiss | Garnetiferous Micashist | Concrete | Tetrapod |
| *Geomaterial ID* | I | II | III | IV | V | VI |
| *Colour* | Greyish-blue | Reddish-rose | Yellowish-brown | Yellow reddish | Gray | Gray |
| *Weathering grade (W) (GSE, 1995; ISRM, 2007)* | $W_1$-$W_3$ | $W_1$-$W_3$ | $W^1$-$W^{3\text{-}4}$ | $W_2$-$W_4$ | - | - |
| *Degradation grade (D)* | *n.a.* | *n.a.* | *n.a.* | *n.a.* | $D_1$-$D_4$ | $D_1$-$D_4$ |
| *Texture/Structure* | Medium grained | Medium to fine grained | Coarse to medium grained | Coarse grained | *n.a.* | *n.a.* |
| *Observations* | - "Lavadores" granite<br>- Essentially biotitic | - "Lavadores" granite | - "Lourosa" Unit<br>- High-tectonised lithology | - Metasedimentary rock ("Lourosa" Unit)<br>- High-tectonised lithology | - Concrete path along the structure crest<br>- Blocks with concrete and aggregates | *n.a.* |

The area encompassing these zones is predominantly constituted by orthogneisses. Zone III corresponds to the area of the head, showing the lowest rebound values. It is mostly constituted by tetrapods and is the area with the highest deterioration level. The results obtained with this methodology indicate the need for repairing/maintenance works in some parts of the studied sectors. In the present case, according to the evaluations performed, replacement of the primary armour layer of the head of the structures would increase the effectiveness and prolong the longevity of the structures. The results also suggest that for some of the sectors, alterations to the design of the structures would help minimise the deterioration of the structures due to erosion.

## CONCLUDING REMARKS AND OUTLOOK

This study presents, in a coastal geoengineering perspective, a methodological proposal for the assessment of the preservation status of geomaterials from coastal protection structures. The work was based on the inspection and assessment of hydraulic structures after workmanship, through the measurement of its structural state and of geomechanical parameters. According to the results obtained, a methodological characterisation of the rocks is crucial to determine the deterioration level and the structures' present condition. This approach uncovered the need for maintenance works in some of the studied structures, and of eventual changes in their design. The methodology developed provides a geotechnical characterisation useful for the planning of maritime repair works. Moreover, it gives further support to the importance of establishing the availability and the geotechnical quality and durability of geomaterials to be used in a particular site at an early stage (extraction areas, i.e., quarries) when considering design options. The GIS tools provided an easy and very useful way of handling large datasets and, most important, of visualising the results in a way that facilitates the rapid perception of the status of the structures under evaluation, and thus the decision-making processes. The inclusion of this methodology in monitoring plans, complemented with photogrammetry technique and aerial imagery survey, could therefore contribute to improve the landscape protection and management, helping to control urban seafront extensions while keeping protection costs at a low level. This investigation is still in progress to provide more detailed information on the most appropriated geomaterials, namely regarding the rock mechanic properties required in relation to the design, and additional test procedures that are usually applied to assess quality and durability of these materials before and during construction.

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## ACKNOWLEDGEMENTS

This work was performed under the financial framework of LABCARGA-IPP-ISEP|PAD'2007/08. This research was also funded by scholarship from FCT to AP (SFRH/BD/43175/2008). We acknowledge the anonymous referees for constructive reviews that helped to improve the clarity of the manuscript.

# P5

## SYNOPSIS

*This is the last publication which closes the cycle about Espinho pilot site (NW Portugal) and experimental field. This work deals with the problem of assessing armourstone structures focusing on strengthening the combination of geo-marine techniques and geotechnical properties. The research has two main purposes: (i) to establish an integrative coastal geo-engineering approach for better assessment of the hydraulic structures; and (ii) to draw attention to the importance of quarry evaluation in order to improve armourstone quality and durability. Several studies have demonstrated the relevance of a holistic approach to coastal design issues. The suggested approach couples GIS-based mapping with geo-engineering techniques assessment along five pilot sectors of the Espinho coastal system in Northwestern Portugal. This investigation allowed us to propose zoning a coastal structure according to its degree of deterioration, geomechanical properties and geomaterial status. Replacement of the primary armour layer in only selected sections or components of the structure will reduce the cost of maintenance, repair and reinforcement work. All the gathered data about the preservation status of the armour layer and the quarry inventory have been compiled in a powerful GIS geo-database. The paper argues for the wider use of combination of coastal geo-engineering and GIS analysis in planning the monitoring and/or maintenance of marine works using armourstone. This paper is the compilation of all the collected data from Espinho area and shows the well-established connection between the georesources and the coastal protection structures that this thesis aims to emphasise.*

*Marine Georesources & Geotechnology*, 32:155–178, 2014

ISSN: 1064-119X print/1521-0618 online
DOI: 10.1080/1064119X.2012.728684

# Coastal Geo-Engineering Techniques for the Assessment of Rock Armour Structures

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*This work deals with the problem of assessing armourstone structures focusing on strengthening the combination of geo-marine techniques and geotechnical properties. The research has two main purposes: (i) to establish an integrative coastal geo-engineering approach for better assessment of the hydraulic structures; and (ii) to draw attention to the importance of quarry evaluation in order to improve armourstone quality and durability. Several studies have demonstrated the relevance of a holistic approach to coastal design issues. The suggested approach couples GIS-based mapping with geo-engineering techniques assessment along five pilot sectors of the Espinho coastal system in Northwestern Portugal. This investigation allowed us to propose zoning a coastal structure according to its degree of deterioration, geomechanical properties and geomaterial status. Replacement of the primary armour layer in only selected sections or components of the structure will reduce the cost of maintenance, repair and reinforcement work. All the gathered data about the preservation status of the armour layer and the quarry inventory have been compiled in a powerful GIS geo-database. The paper argues for the wider use of combination of coastal geo-engineering and GIS analysis in planning the monitoring and/or maintenance of marine works using armourstone.*

Received 4 June 2012; accepted 24 July 2012.

We gratefully acknowledge A. Lopes (ICSA), A. Mota Freitas (SOMAGUE), F. Santiago Miranda and E. Broguèira Dias (APDL) for their collaboration during preliminary investigations. Thanks are also due to A. S. Trenhaile (Windsor University, Canada), A. Pérez-Alberti (Santiago de Compostela University, Spain), A. Gomes (Porto University, Portugal) and S. Dupray (CETMEF, France) for helpful discussions that helped to improve the clarity of the manuscript.

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Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/umgt.

**Keywords** coastal management, geo-marine techniques, geomaterials, rock armour structures

## Introduction

Coastal areas represent a dynamic environment of crucial importance to human society, where many people come regularly for seaside recreation. Approximately half of the world's population is living in coastal regions, and coastal changes will continue to be much affected by human impacts (Eurosion 2004, Bird 2008, Dupray and Simm 2008). Coastal erosion has always existed and has contributed throughout history to shape European coastal landscapes. However, the human influence, particularly due to urbanisation and economic activities, has turned coastal erosion and flooding from a natural phenomenon into an emerging problem of concern (Carter 1988, Taveira Pinto 2003, Eurosion 2004).

It is also important to emphasize the great social impact that climate changes have been generating in the last few years, which led the scientific community to issue warnings about the potential impact of climate changes on coastal regions. It is noteworthy that the most recent studies on climate changes were focused only on expected sea level variations and their likely effects. However, changes in some other variables such as the wave climate could create great damage along the coast (Olabarrieta et al. 2009). Moreover, some studies stress the need to take into account the effect of climate changes when designing new coastal structures in order to fulfil the established functional and stability criteria during their life cycle. These reports also indicate that in a few decades some existing coastal structures may lose part of their functionality and stability (Olabarrieta et al. 2009, Dupray and Simm 2008). Relevant data and information gathered by the Eurosion project (2002–2004) revealed that while, historically, many hard constructions were built to protect assets at risk (Eurosion 2004), they provided an effective solution only in the short term; their long-term effectiveness was mostly unsatisfactory. According to Eurosion (2004) there are no miracle solutions to counteract the adverse effects of coastal erosion and the best results have been achieved by combining different types of coastal defences including hard and soft solutions. Nevertheless, this is a restrictive point of view that bases the response on an engineering solution. A socio-economic approach should also be considered by rethinking the use of coastal spaces and more appropriate planning including retreating from the most threatened areas when required.

In general, groynes are among the most common structures built for erosion control. This type of structure, which usually runs normal to the beach and may extend out to the limit of the surf zone, has been widely used in many countries (Schwartz 2005, Sorensen 2006). Many groynes are built in groups, known as groyne fields, and their length, height and spacing vary depending on the purpose they were meant to serve (USACE 2002).

Groynes are constructed very often to (1) maintain the beach behind them, and (2) control the amount of sediment moving alongshore. Because modern coastal engineering practice includes a perspective that incorporates the stability of downdrift beaches, groynes are normally constructed along with beach nourishment, so that sediment is impounded by the groynes (USACE 2002, Schwartz 2005, Sorensen 2006, Rogers et al. 2010). These structures are designed with the understanding that maintenance and repair works will be needed during the structure's life. However, it is important to stress that the general case does not really integrate long-term management or repair strategies. The cost benefit analysis, for instance does not combine the fact that maintenance costs should be available to defense structure (e.g., Silva 1996, USACE 2002, Santos et al. 2003).

Coastal protection strategies must ensure that there is a rational balance between the activities of the management plan and the required adjustments to the natural system (USACE 2002). Over the last few decades, the importance of the rock geotechnics of the materials engineering geosciences, and geo-engineering issues for coastal defense works has been recognized as essential to their design and/or maintenance (e.g., Fookes and Poole 1981, Latham 1991, Poole 1991, Nakase and Tsuchida 2002, Latham et al. 2002, 2006b, Dupray 2005, Pires and Chaminé 2007, Manoliu and Radulescu 2008, Rato et al. 2008, Haneberg 2009, Pires and Chaminé 2009, Özvan et al. 2011). Geographical information systems (GIS) provide platforms for acquiring coastal information and analysis. Moreover, GIS allows policy makers to easily visualize problems in relation to coastal erosion and the condition of the existing protection structures for effective resource utilization (e.g., Bailey and Gatrell 1995, Burke et al. 2001, Green and King 2003, Crous et al. 2004, Pires et al. 2009a and 2009b, Pérez-Alberti et al. 2011).

The main issues for a rock project are its scale (size of the structure and blocks), as well as the availability, quality and handling of materials (Fookes and Poole 1981, Latham 1991, Lienhart 1998, Dupray et al. 2004, Latham et al. 2006a and 2006b, Rato et al. 2008). In addition, this type of project should include a holistic approach and in general, should consider the technical, environmental and construction site consequences of using different materials from several sources (CIRIA et al. 2007). Planning and designing rock works should also involve the characterization and the study of the in situ conditions of the geomaterial in the quarry and on an armour structure. This must link or combine with other important stages such as design, construction, monitoring, inspection, maintenance and repair works. The availability, geotechnical quality and durability of geomaterials to be used at a particular site should follow the legal procedures of CE Marking, under the scope of European standards and codes such as EN 13383-1 (2002), and be determined at an early stage while considering design options.

Natural and durable rock is one of the main materials employed in marine construction works to prevent scour and erosion. According to CIRIA et al. (2007), at least 10 million tonnes of armourstone are used each year across Europe, in construction works valued at nearly 1 billion Euros. In addition, coastal protection structures need continued maintenance to ensure that they perform satisfactorily. In many cases, structures survive well beyond their intended service life because they have been well-maintained or were over-designed initially (USACE 2002). Nowadays it is very difficult to predict service life of rock material in coastal environments.

A management strategy is needed for the evaluation of structure deterioration and condition and to predict required repair/rehabilitation work (e.g., LCPC 1989, CIRIA/CUR 1991, Silva 1996, USACE 2002). However, there is a limited guidance on designing repairs to deteriorating structures (PIANC 1998, 2004). Construction techniques for a specific coastal project are influenced by several factors (e.g., availability of suitable equipment, contractor experience or environmental exposure). Moreover the engineers' practical experience can be very important. In general, performance monitoring may be needed to validate the procedures and to spot problems before serious damage can occur in these situations (CIRIA et al. 2007). There are four main categories of armour layer repair (CIRIA et al. 2007): (1) spot replacement of broken or dispersed armour stones or concrete armour units; (2) overlaying existing armour layers; (3) replacing armour layers and (4) rebuilding the structure. The approach proposed aims at identifying armouring degradation to allow repair before deterioration is too advanced and to determine the optimum timing for simple repair of the armouring layer.

In this work, a geo-engineering GIS-based methodology, using high-resolution aerial imagery, was developed using guidelines and procedures for the evaluation of rock materials (e.g., LCPC 1989, USACE 2002, CIRIA et al. 2007). This methodology was applied to the Espinho coastal zone in northwestern Portugal (see Pires and Chaminé 2007, Pires et al. 2009a and 2009b, and references therein). The study focused on geotechnical mapping evaluation of the rock blocks used in groynes, based on lithological heterogeneity, weathering grade, and stiffness of the rock materials, in order to consider how construction material properties might influence the design of coastal protection structures. The geomaterials were also traced back to their origin (i.e., rock sourcing quarries) in particular to investigate changes that have occurred since their exposure to marine environments. This step is essential to allow further study of the rock intrinsic properties (e.g., mass density, porosity, water absorption), as described by CIRIA et al. (2007). Different properties may need to take into consideration the different phases in the life cycle of the armourstone; at the quarry prior to extraction, or after many years in service. However, this is not applicable for concrete armour units.

Additionally, for projects that involve quarrystone armour units, good specifications are essential for the performance of the hydraulic structures (Fookes and Poole 1981, Dibb et al. 1983, Latham 1991, Dinis da Gama 1995, Pires and Chaminé 2009). In this sense, the geo-engineering investigations accomplished in this study also aim at establishing reliable geological and geomechanical features for the in situ quarry rock mass, including the geometry of the geological units, petrophysical properties and size/shape of armourstone blocks. However, in the current research, more emphasis was given to the geomaterial in situ assessment in the armour layer of the coastal structure and only the general features of the quarries were represented in the GIS database. In short, this study has two major purposes: (1) to explain the different methodologies used to assess the deterioration condition of hydraulic structure and (2) to draw attention to the importance of quarry evaluation in order to improve armourstone quality and durability.

## Site Investigation

### *The Portuguese Coast: Brief Outlook*

The Atlantic coast of Portugal is more than 800 km long, and plays an important role in the economic, social and political life of the nation. There are about 290 coastal protection structures along the coast, of which over 70% percent are groynes and seawalls (INAG 2009). Coastal erosion is becoming an increasing problem in several areas because of rising sea level and the encroachment of urban populations on the coast (Veloso-Gomes et al. 2007). Some erosion can be attributed to inappropriate human action (construction of dams, harbour breakwaters, navigation channels, and dredging works) and ineffective coastal management policies in the past.

Hydraulic structures are usually built with natural stones and/or artificial concrete blocks of different shapes (Costa et al. 1996). Most of these works are made with stones with weights of up to 12 t, which are available in most Portuguese

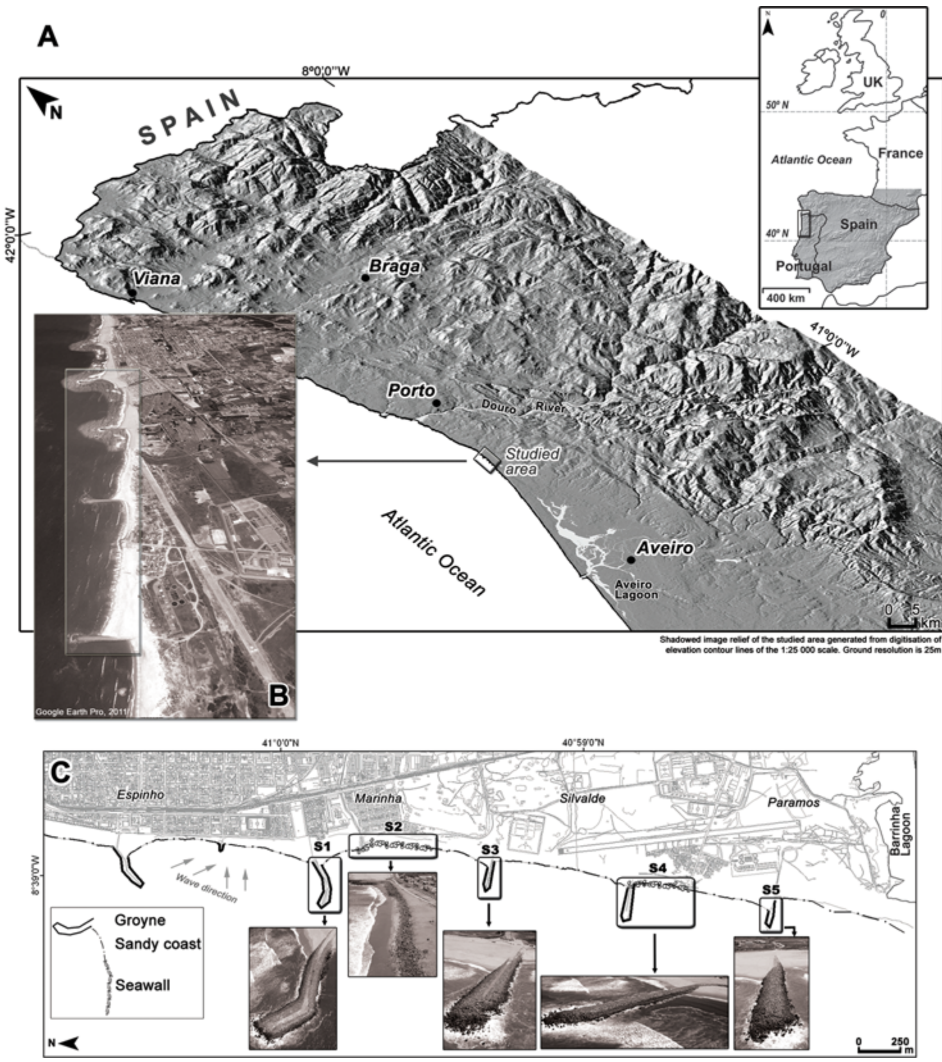



**Figure 1.** A - Location of Espinho region (NW Portugal); B - Aerial view of the pilot site and location of the 5 sectors (Google Earth Pro, accessed in 2011); C - Groyne field along the coast and the 5 sectors studied.

quarries. Concrete blocks are also used (tetrapods and cubes are the most employed) with weights of between 15 t and 90 t, blocks of this latter value being restricted to the construction of breakwaters (Veloso-Gomes et al. 2007). In Portugal, it is expected that major repairs will have to be undertaken on the these structures every eight to twelve years (Veloso-Gomes and Taveira Pinto 2000), and that maintenance will be necessary every two years, depending on the intensity and frequency of storms.

### *The Pilot Site: Espinho Area (NW Portugal)*

The study area is in Espinho, a municipality in the district of Aveiro on the Portuguese Atlantic coast, approximately 16 km south of Porto (MAOTDR 2008).

**Table 1.** Summary of the main characteristics of the maritime works, from Espinho region (compiled data from SOMAGUE 1980, Veloso-Gomes et al. 2002)

| Studied sectors | Name (ID) | Type of structure | Location | Construction date | Length (m) | Volume of blocks used ($m^3$) | Cost at the time of construction (€) |
|---|---|---|---|---|---|---|---|
| - | | Groyne | Espinho | 1918/1981/1983<br>1981/1983 | 350 | 112 637 | 704 234 |
| 1 | Marinha | Groyne | | 1981/1983 | 400 | 121 477 | 742 830 |
| 2 | Marinha | Seawall | | No data available | 400 | No data available | |
| 3 | Carreira de Tiro | Groyne | Silvalde | 1981/1983 | 300 | 36 431 | 181 935 |
| 4 | Casa Branca | Groyne | Paramos | 1981/1983 | 280 | 36 431 | 181 935 |
| - | | Seawall | | No data available | 100 | No data available | |
| 5 | Paramos (ETAR) | Groyne | | 1985 | 280 | 36 000 | 150 000 |

Besides the interesting coastal system that Espinho has, the studied pilot site also has one of the oldest histories of problems related to coastal erosion in Portugal (e.g., Veloso-Gomes et al. 2004, Pires et al. 2009b and references therein). Erosion has been a major problem in the area since at least the 19th century (Mota Oliveira and Martins 1991). Several protective structures have been constructed in the past. Today, two sea walls and two large groynes, one in the north and the other in the south, constitute the core of the field of groynes protecting the seafront of Espinho, and the situation is considered to be stable.

The town of Espinho has a population of about 33,000, about 20,000 of which are concentrated on the urban seafront (Veloso-Gomes et al. 2002, 2006). The coastal system described in this study comprises a groyne field, which can be subdivided into five sectors, approximately 5 km in length (Figure 1, Table 1). The environmental coast conditions are characterized by semi-diurnal tides (amplitudes between 2 m and 4 m); significant wave heights range between 2 m and 3 m; storm significant wave heights exceeding 8 m (once per year); the most frequent wave periods range between 8 s and 12 s; west and northwest wave directions dominate, with also some occurrences from southwest (IHRH 2003, Rosa-Santos et al. 2009).

This case study of the Espinho region includes GIS-based recognition and characterization of the armourstone quarries, as well as data and other relevant information on the studied extraction areas and the rock used in the armour structures. Figure 2 shows the GIS project and the rock characterization from the two quarries that provided armourstone for the coastal structures at Espinho.

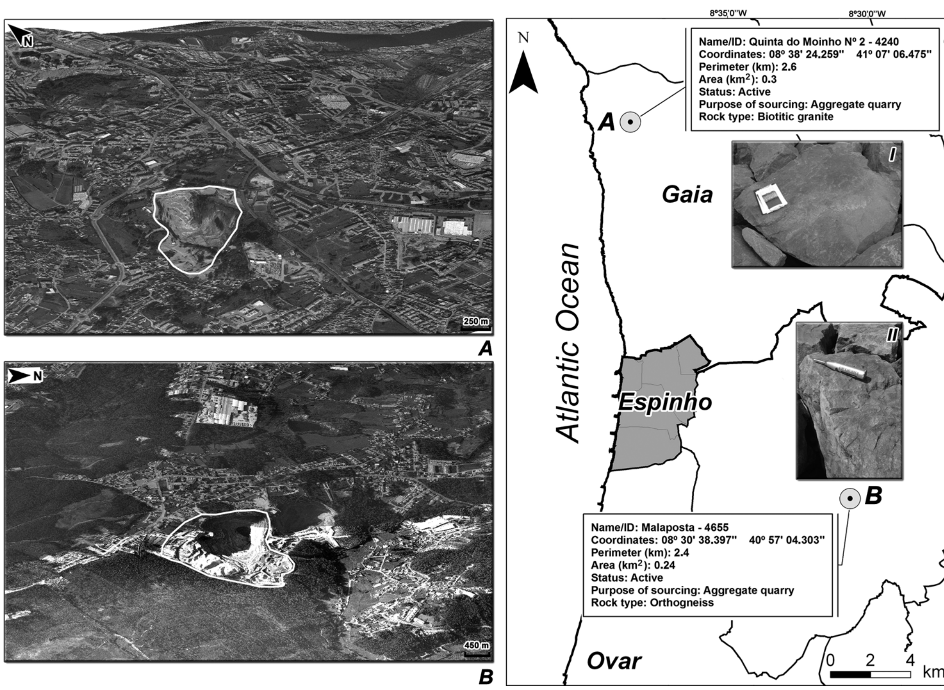



**Figure 2.** Main characteristics of the studied rock quarries; A - 3D perspective of the "Quinta do Moinho" granitic quarry (Canidelo, Gaia); B - 3D perspective of the "Malaposta" gneissic quarry (Lourosa); I – View of the biotitic granite; II – View of the orthogneiss.

## Methodologies and Techniques

The research was carried out to develop a systematic methodology for the analysis of the condition of the coastal protection structures as well as the degradation of constitutive materials in a GIS database project (Figure 3 and Figure 4) and particularly rock armour structures. The GIS project incorporated high-resolution aerial imagery and field survey and data acquisition. The methodology presented is a combination of different materials and techniques refined throughout the research work (e.g., Pires and Chaminé 2007, 2009, Pires et al. 2009a). The research encompasses several geo-engineering techniques allowing a new approach for the assessment and monitoring of coastal structures.

The new approach is synthesized in a flowchart (Figure 3) and illustration (Figure 4) showing the different stages that were carried out in this study.

### *High-Accuracy GPS Measuring and Photogrammetry in Light Aircraft*

Trimble GPS GeoExplorer® XH technology provided georeferencing information on the maritime structures and in the quarries for aerial imaging, which was integrated in the GIS project (Stage A, Figure 4). High-accuracy GPS was also used to perform walkover surveys along scanlines to record information on the overall condition of the structures, including any obvious block movements, changes in the profile, type of lithology, etc.

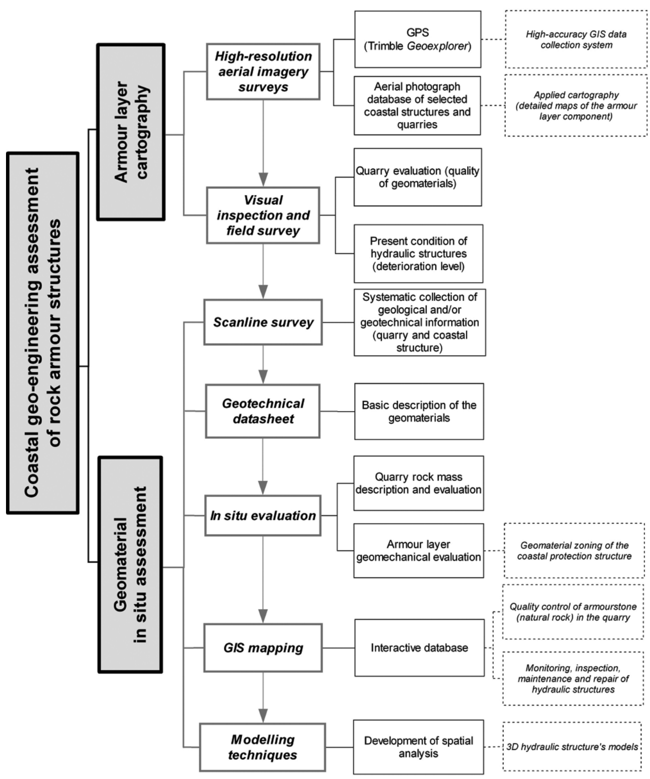
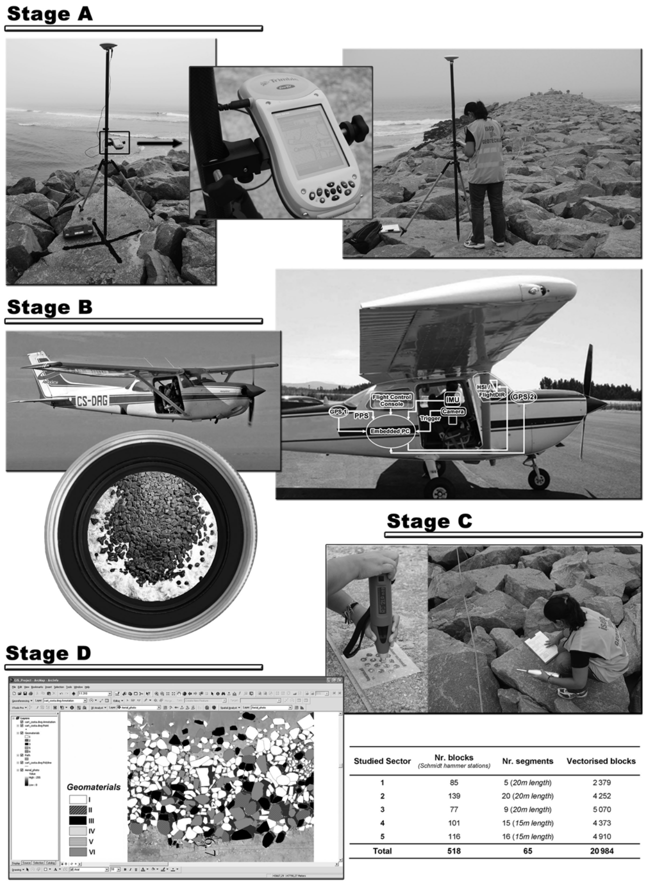



**Figure 3.** Conceptual flow chart for coastal geo-engineering assessment.




| Studied Sector | Nr. blocks (*Schmidt hammer stations*) | Nr. segments | Vectorised blocks |
|---|---|---|---|
| 1 | 85 | 5 (*20m length*) | 2 379 |
| 2 | 139 | 20 (*20m length*) | 4 252 |
| 3 | 77 | 9 (*20m length*) | 5 070 |
| 4 | 101 | 15 (*15m length*) | 4 373 |
| 5 | 116 | 16 (*15m length*) | 4 910 |
| **Total** | **518** | **65** | **20 984** |

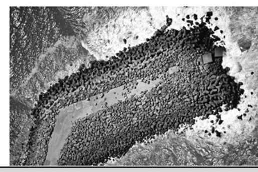
**Figure 4.** Some geo-engineering techniques carried out along this study: Stage A - high-accuracy GPS measuring; Stage B - photogrammetry in light aircraft; Stage C - visual inspection and in situ evaluation; Stage D - integrating GIS geo-mapping, geomaterials and geotechnical testing for the assessment of rock armour structures.

Aerial images of the area were used to set up a geo-reference GIS database (Stage B, Figure 4). The proposed system for the image acquisition is composed of two fundamental subsystems that are supported by the same common navigation system, running on a rugged embedded PC: the flight guidance system and the image acquisition system (Stage B, Figure 4). The pictures were taken using a high-end digital single lens reflex (D-SLR) camera that was able to acquire high-resolution images (21 mega pixels) at high-frame speeds (several frames per second during continuous shooting). Each time a picture was taken a trigger signal was fed to the embedded PC and a time tag was recorded. The inertial measurement unit (IMU) data related to the camera orientation was logged together with the time stamps relative to each measurement. Its main purpose was to compute the camera attitude, through integration of its acceleration and angle rate measurements with the GPS-derived positions (Figure 4, Stage B). This system can be used on a small aircraft (in this case on a Cessna C172) without any physical or aerodynamic changes to the airframe, other than the simple removal of the right door. Equipment and flight costs are particularly relevant in this type of application (e.g., Teunissen 1995, Silva et al. 2001). Besides the equipment installed in the aircraft, a reference station was also established for each mission, enabling differential processing of the GPS receivers on board the aircraft relative to the ground station, thereby enhancing their precision (for further details see Cunha et al. 2006).

### *Visual Inspection and in Situ Evaluation*

During field surveys a geotechnical datasheet was prepared for the assessment of structures' armour layer as well as for the recognition and visual evaluation of the rock material (Figure 5). Several parameters were registered along a sampling scanline on the block materials, such as lithological heterogeneity, petrophysical and geomechanical features as well as weathering grade (ISRM 1978a and 1978b, GSE 1995) or degradation grade of the constitutive materials (Pires 2007). With

| Sector/Name | 1/Marinha |
|---|---|
| Type of structure | groyne |
| Nr. blocks *(Schmidt hammer stations)* | 85 |
| Nr. segments | *5 (20m length)* |

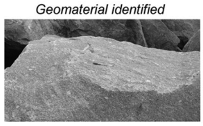


| *General evaluation - Armour layer* | |
|---|---|
| Geomaterial description | Granite |
| Geomaterial *ID* | 1 |
| Colour | Greyish-blue |
| Weathering grade (natural rock) *W* | $W_1$ |
| Degradation grade (artificial block) *D* | n.a. |
| Texture/Structure | Medium grained |
| Observations | - |

| Scanline direction: N 288° E | Date: 8th, June 2005 | Time: 15h |
|---|---|---|
| Scanline scheme | | |

| Segment number | 1 | Section (m) | 0-20 |
|---|---|---|---|

*Geomaterial identified*



Schmidt hammer rebound values (R)

| Station nr. | Scanline origin distance (m) | *Results* | |
|---|---|---|---|
| | | 58 | 62 |
| | | 60 | 52 |
| 2 | 3,4 | 62 | 50 |
| | | 55 | 56 |
| | | 51 | 53 |

**Figure 5.** Geotechnical datasheet created for the evaluation and inspection of geomaterials with example entries.

**Table 2.** Categories defined for the degradation grade evaluation of concrete blocks (adapted from Pires 2007)

| Category (degradation grade, D) | Classification | Description |
|---|---|---|
| $D_1$ | Very good condition | Blocks in good condition and no breaks |
| $D_2$ | Good condition to slightly damaged | A few breaks and some corrosion (*superficial holes are visible*) |
| $D_3$ | Damaged | Many breaks and much corrosion |
| $D_4$ | Very damaged | Blocks heavily deteriorated or broken |
| $D_5$ | Extremely damaged | Blocks highly deteriorated or broken |

regard to the degradation grade for artificial blocks, Table 2 shows a class ranging $D_1$ to $D_5$, i.e., from a block in very good condition to one that is extremely damaged. This classification is based on visual observation of breakage and cracking, and disintegration or corrosion of the concrete material (Pires 2007).

The Classical Schmidt Hammer was used to determine the hardness of the geomaterials (rebound values are correlated with a graphical chart with the uniaxial compressive strength, which depends on the unit weight of the block and the inclination of the hammer and test surface) (Stage C, Figure 4) (e.g., Katz et al. 2000, Kahraman 2001, ISRM 2007). Sampling was conducted along a scanline survey, which is an accurate and fast method for the systematic and representative collection of geological and/or geotechnical properties (Pires and Chaminé 2007, Figure 5).

A detailed study was made of the quarries that provide gneissic and granitic rock. More than 400 quarries were identified and georeferenced in NW Portugal, within 50 km of the coast. From the studied quarries, 200 were selected, characterized and included in the GIS database. A datasheet was prepared to characterize the rock masses and armourstones by visual inspection and in situ evaluation during field survey (see Pires and Chaminé 2009). The GIS database incorporated the studied quarries with interactive support (e.g., hyperlinks for the datasheets, photos or essential information). The database included the "Quinta do Moinho" and "Malaposta" sourcing quarries from the studied pilot site (see Figure 2).

### *Integrating GIS Mapping, Geomaterials and Geotechnical Properties*

GIS tools and ArcGIS (ESRI®) extensions were used to create a platform for the integration of all the data gathered on digital maps and to create 3D models of the structures. The methodology established an interdisciplinary connection between geo-engineering concepts for the planning of maritime structures (e.g., LCPC 1989, CIRIA/CUR 1991, USACE 2002, CIRIA et al. 2007). It was based on the recommendations and terminology of the "Manual of the Use of Rock in Coastal and Shoreline Engineering" from CIRIA/CUR (1991) and CIRIA et al. (2007), as well as on the proposed basic geotechnical description of rock masses, the so-called BGD (see details in ISRM 1981). It also used a series of techniques and methods previously described by Fookes and Poole (1981) and Latham et al. (2006a), with the eventual purpose of identifying the geomaterials' source and studying its implications in terms of durability.

Detailed mapping of the rock blocks was then conducted with the support of the aerial photographic database. Afterwards, for the five sectors studied, more than 20,000 block materials on the structures' superficial section (armour layer) were vectorized in a GIS mapping base. The GIS platform and the modelling techniques permitted thematic maps of the structure's armour layer to be obtained in order to evaluate different geological and geotechnical parameters (Stage D, Figure 4). All the results generated geotechnical maps that facilitated the identification of deterioration levels (of the constitutive materials of the stones/blocks) and armour layer zoning of the structures (Pires et al. 2009a). The deterioration level represents a qualitative evaluation of the present status of the structure. This rating is based not only in the fieldwork surveys (data acquisition) as well as in the applied cartography and anticipates the actual condition of the superficial blocks that are the armour layer constituents.

### *Statistical Analysis*

One-way analysis of variance, ANOVA, (Davis 1986) was used to test the hypothesis that there are significant differences between the means of the rebound values for the different geomaterials along the groynes' armour layer. To allow an overall comparison of results from these stones/blocks, it is important to stress that this comparison makes sense because all of them are more or less exposed to comparable wave action and sea action. Prior to the analysis of variance, normality and homogeneity of variances assumptions were checked using the nonparametric Kolmogorov-Smirnov test and Levene's test of equality of error variances, respectively. All values obtained are presented as the mean and corresponding standard error, by the type of block. The relative frequency of the different block materials in each sector was analyzed using a Chi-square test. In all statistical tests the level of significance was set at 0.05.

## Results and Discussion

Different geomaterials were identified based on the described methodology, (Figure 6 and Table 3), providing a measure of the current condition of the structure and of the status of the revetment material. Figure 6 provides examples of geomaterial in situ assessment for the Marinha groyne (Sector 1), for the Marinha seawall (Sector 2), and for the Casa Branca groyne (Sector 4). The geomaterials (Table 3) included natural rocks (granite, gneiss and micashist) and artificial materials (concrete or a mixed material, i.e., concrete + aggregates or tetrapods).

The Schmidt hammer statistical data are shown in Table 4. Figure 7 shows the results for the rebound values and the geomaterials tested for each sector, and the global evaluation of the Espinho coastal system. Geomaterial 2 (reddish-pink granite) had a value of $57 \pm 0.51$ (mean $\pm$ SEM), compared with a value that was 25% lower for geomaterial 6 (tetrapods) (Table 4). The rebound values allow a comparison to be made between the rock hardness and the behaviour of the different type of blocks, although it was also important to cross-check the statistical study with visual observations of the geomaterials (geological classification, weathering grade, etc.) along the armour layer.

There are statistically significant differences between the rebound values for the geomaterials ($F_{(5,512)} = 35.5$, $p < 0.001$). In general block types 4, 5, and 6

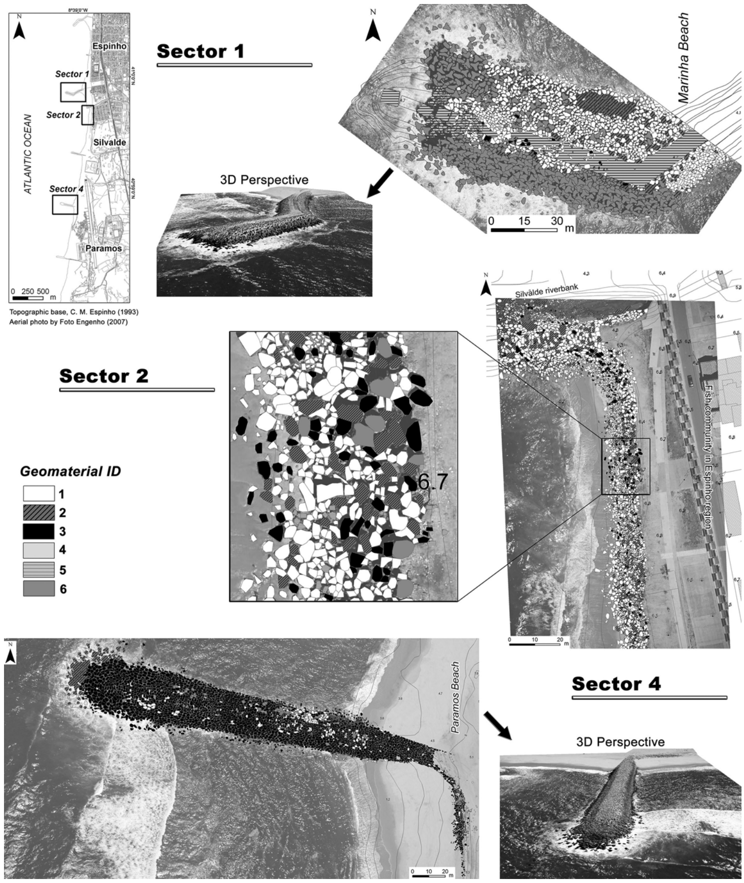



**Figure 6.** Geomaterial recognition and detailed cartography of Marinha groyne and seawall (Sector 1 and 2), for explanation, see Table 3; a proposed coastal zoning for the superficial layer of Sector 4.

had the lowest values of rebound and the most significant differences with the other geomaterials. Differences were also significant between sectors 4 and 5, which were composed predominantly of gneisses (60%) and granites (78%), respectively (Figure 7 b4 and b5). On the other hand, Sector 1 has a greater frequency of blocks 6, and Sector 3 of blocks 3, compared with other sectors (Figure 7 b1 and b3, respectively). Blocks 4 (micashist) were found in only low quantities in Sector 2, and we consequently eliminated from the second analysis. For this crosstab analysis, four groups were considered: (G1) geomaterial 1, (G2) geomaterial 2, (G3) geomaterial 3 and (G4) geomaterial 5 and 6. In group four (G4), which consisted of artificial blocks, the relative frequency of the materials for each sector were significantly different between groups (Pearson Chi-Square test, $\chi^2_{(12,0.05)} = 147.5$, $p < 0.001$).

Table 5 synthesises the geotechnical features of the zoning in relation to the deterioration level, but it also provides a general evaluation of the structures' armour layers as well as the diagnosis and proposed need for repair for each sector. This table was derived from all the visual inspections along the armour layer of the studied sectors, as well as from the combination of qualitative/quantitative parameters

**Table 3.** Geomaterials recognized along the superficial layer and studied characteristics for the five sectors (*n.a.* – not applicable)

| Geomaterial characterization | | | | | | |
|---|---|---|---|---|---|---|
| Geomaterial ID | 1 | 2 | 3 | 4 | 5 | 6 |
| Description | **Granite** | **Granite** | **Biotitic orthogneiss** | **Garnetiferous Micashist** | **Concrete** | **Tetrapod** |
| Colour | Greyish-blue | Reddish-pink | Yellowish-brown | Yellow brownish | Grey | Grey |
| Weathering grade [W] | $W_1 - W_3$ | $W_1 - W_3$ | $W_1 - W_{3\text{-}4}$ | $W_2 - W_4$ | – | – |
| Degradation grade [D] | *n.a.* | *n.a.* | *n.a.* | *n.a.* | $D_1 - D_4$ | $D_1 - D_4$ |
| Texture/Structure | Medium grained | Medium to fine grained | Coarse to medium grained | Coarse grained | *n.a.* | *n.a.* |
| Density (kN/$m^3$) | 26,5 | 26,5 | 26 | 27 | 24 | 24 |
| Observations (details in Chaminé, 2000) | Biotitic granite, greyish-blue, medium grained (Canidelo quarry) | Granite, reddish-pink, medium to fine grained (Canidelo quarry) | Biotitic gneiss (quartz and large feldspar megacrys-tals) has a strong shear fabric (Mala-posta quarry) | Porphyroblastic garnet-biotite micaschist highly tectonised (Mala-posta quarry) | Concrete path along the structure crest: blocks with concrete and aggregates | *n.a.* |

**Table 4.** Synthesis of statistical data analysis of the Schmidt hammer rebound values obtained

| | | Schmidt hammer stations | | Rebound (R) | | | |
|---|---|---|---|---|---|---|---|
| Sector | Geomaterial ID | Nr. blocks (N) | Nr. blocks (%) | Mean | Median | Std. Deviation | Std. Error of Mean |
| 1 | 1 | 26 | 31 | 55.8 | 56.3 | 5.38 | 1.05 |
| | 2 | 20 | 24 | 58.2 | 59.1 | 4.42 | 0.99 |
| | 3 | 16 | 19 | 55.0 | 54.7 | 5.23 | 1.31 |
| | 5 | 3 | 4 | 41.8 | 41.6 | 2.91 | 1.68 |
| | 6 | 20 | 24 | 41.5 | 41.9 | 7.65 | 1.71 |
| | *Total* | *85* | *100* | *52.3* | *53.4* | *8.76* | *0.95* |
| 2 | 1 | 49 | 35 | 58.5 | 59.2 | 7.94 | 1.13 |
| | 2 | 11 | 8 | 61.7 | 61.2 | 4.81 | 1.45 |
| | 3 | 41 | 29 | 54.3 | 56.2 | 12.51 | 1.95 |
| | 4 | 14 | 10 | 36.6 | 35.9 | 10.62 | 2.84 |
| | 5 | 23 | 17 | 43.4 | 44.4 | 9.60 | 2.00 |
| | 6 | 1 | 1 | 42.6 | 42.6 | – | – |
| | *Total* | *139* | *100* | *52.7* | *55.2* | *12.44* | *1.06* |
| 3 | 1 | 40 | 52 | 53.9 | 56.1 | 9.40 | 1.49 |
| | 2 | 30 | 39 | 57.7 | 59.1 | 4.73 | 0.86 |
| | 3 | 6 | 8 | 49.5 | 53.8 | 10.67 | 4.36 |
| | 5 | 1 | 1 | 39.4 | 39.4 | – | – |
| | *Total* | *77* | *100* | *54.8* | *56.4* | *8.39* | *0.96* |
| 4 | 1 | 27 | 27 | 54.2 | 56 | 7.38 | 1.42 |
| | 2 | 8 | 8 | 57.4 | 57.2 | 3.16 | 1.12 |
| | 3 | 61 | 60 | 56.9 | 58.2 | 9.20 | 1.18 |
| | 5 | 2 | 2 | 35.7 | 35.7 | 21.35 | 15.10 |
| | 6 | 3 | 3 | 36.0 | 42 | 13.26 | 7.66 |
| | *Total* | *101* | *100* | *55.2* | *57* | *9.74* | *0.97* |
| 5 | 1 | 51 | 44 | 50.3 | 51.6 | 6.78 | 0.95 |
| | 2 | 39 | 34 | 54.5 | 56 | 5.50 | 0.88 |
| | 3 | 25 | 22 | 47.9 | 50.2 | 10.41 | 2.08 |
| | 5 | 1 | 1 | 31.0 | 31 | – | – |
| | *Total* | *116* | *100* | *51.0* | *52.4* | *7.91* | *0.73* |
| **Global evaluation** | 1 | 193 | 37 | 54.4 | 55.6 | 8.12 | 0.58 |
| | 2 | 108 | 21 | 57.0 | 57.7 | 5.29 | 0.51 |
| | 3 | 149 | 29 | 54.2 | 55.8 | 10.57 | 0.87 |
| | 4 | 14 | 3 | 36.6 | 35.9 | 10.62 | 2.84 |
| | 5 | 30 | 6 | 42.2 | 43.1 | 9.74 | 1.78 |
| | 6 | 24 | 5 | 40.8 | 42 | 8.19 | 1.67 |
| | ***Total*** | *518* | *100* | *53.1* | *55* | *9.94* | *0.44* |

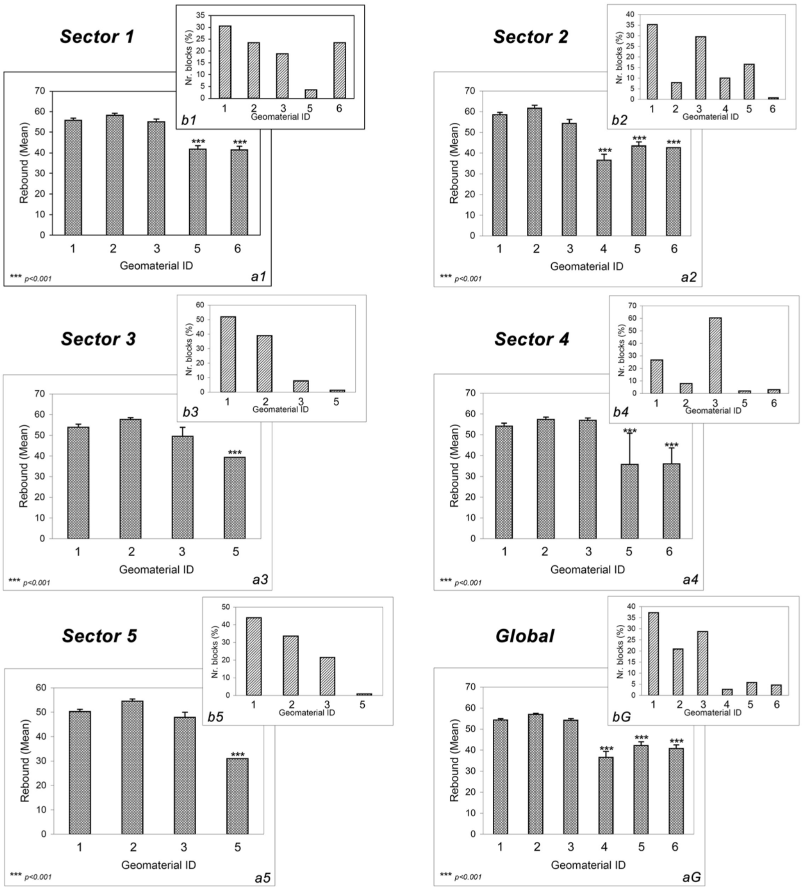



**Figure 7.** (a$x$) Mean and the respectively standard error of the mean, for the rebound values obtained for each sector and for the global survey; (b$x$) Nr. of geomaterials (relative frequency, %) recognized and studied for each sector and for the global analysis ($^{***}p < 0.0001$).

and all the collected data (e.g., Schmidt Hammer values, degradation level, weathering grade). Analysis of the overall deterioration (damage) level of the hydraulic structures indicates the present condition and the need for repair. Figure 8 presents the proposed zoning for Sectors 1 to 5. From the assessment carried out along the armour layer and from the Rock Hammer rebound values (see Table 5), it was determined that the concrete blocks had the lowest values (<30 MPa) and that the reddish-pink granite had the highest values (≅200 MPa). In general, all the sectors with a predominance of reddish-pink granite had low deterioration levels (weathering grade, $W_{1\text{-}2}$), whereas zones with a predominance of artificial blocks had high deterioration levels (degradation grade, $D_{4\text{-}5}$). Regarding the components of the structures, it is evident that the head zone is more deteriorated than the other parts of the structures. The head and, to a lesser extent, the inner zones have, in general, medium to high deterioration levels, and they are susceptible to wave and current events. In general, these two parts of the structures comprise geomaterials that do not possess high compressive strength (<130 MPa) and are also susceptible to sea forcing agents. It is visible that the side of the structure exposed to main wave action has more

**Table 5.** Zoning proposed after the in situ geotechnical evaluation and the visual inspection carried out (values obtained for each sector studied)

| Sector | Zoning [Component part] | Predominant geomaterials/ Weathering grade (W)/ Degradation grade (D) | Schmidt Rebound hammer values range (R) | Uniaxial Compressive Strength, MPa | Deterioration level | Present condition of the structure armour layer | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | General evaluation | Diagnosis | Repair needs |
| 1 | ZI [East outer zone] | Reddish-pink granite (2)/$W_1$ | 55–60 | 180–240 | ***Low*** | Heavily to highly deteriorated | Many displacements; many broken blocks; very damaged and much corrosion | Urgent repair |
| | ZII [West outer zone] | Greyish-blue granite (1)/$W_{1\text{-}2}$ | 50–55 | 140–180 | ***Medium*** | | | |
| | ZIII/ZIV/ZV [Head/Inner zone/Crown wall] | Tetrapod (6)/$D_3$ to $D_{4\text{-}5}$ | 30–42 | 40–80 | ***High*** | | | |
| 2 | ZI [South jetty/North seawall] | Greyish-blue and reddish-pink granite (1 and 2)/$W_1$ to $W_{1\text{-}2}$ | 57–63 | 200–280 | ***Low*** | Heavily to highly deteriorated | Many displacements; many broken blocks; very damaged and much corrosion | Urgent repair |
| | ZII [South seawall] | Orthogneiss and micaschist (3 and 4)/$W_2$ to $W_3$ | 33–55 | 55–200 | ***Medium*** | | | |

(*Continued*)

**Table 5.** Continued

| Sector | Zoning [Component part] | Predominant geomaterials/ Weathering grade (W)/ Degradation grade (D) | Schmidt Rebound hammer values range (R) | Uniaxial Compressive Strength, MPa | Deterioration level | Present condition of the structure armour layer | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | General evaluation | Diagnosis | Repair needs |
| 3 | ZI [Outer zone] | | | | | Slightly deteriorated | A few broken blocks; a few displacements and a few breaks | Careful observation is required |
| | ZII [North head] | Reddish-pink granite (2)/$W_1$ | 55–60 | 180–240 | ***Low*** | | | |
| | ZIII [Crown wall] | Concrete (5)/$D_2$ to $D_3$ | 25–45 | 30–90 | ***Medium*** | | | |
| | ZIV [South head] | Greyish-blue granite (1)/$W_{1\text{-}2}$ | 50–55 | 140–180 | ***High*** | | | |
| | ZV [Inner zone] | | | | | | | |
| 4 | ZI [Crown wall] | Orthogneiss (3)/ $W_{1\text{-}2}$ to $W_3$ | 55–60 | 180–240 | ***Low*** | Slightly to heavily deteriorated | A few broken blocks; a few displacements and a few breaks | Careful observation is required |
| | ZII [Inner and outer zones] | | | | ***Medium*** | | | |
| | ZIII [Head] | Tetrapod (6)/$D_3$ to $D_4$ | 20–45 | 25–90 | ***High*** | | | |
| 5 | ZI [Crown wall] | Reddish-pink granite (2)/$W_1$ | 54–57 | 170–200 | ***Very low*** | Deteriorated | Some broken blocks; some displacements and some evidence of settlement | Repair is advised |
| | ZII [Inner zone] | Greyish-blue granite and orthogneiss (1 and 3)/$W_2$ to $W_3$ | 46–48 | 100–125 | ***Low*** | | | |
| | ZII [Outer zone] | Greyish-blue granite (1)/$W_{1\text{-}2}$ | 49–51 | 130–145 | ***Medium*** | | | |
| | ZIV [Head] | | | | ***High*** | | | |

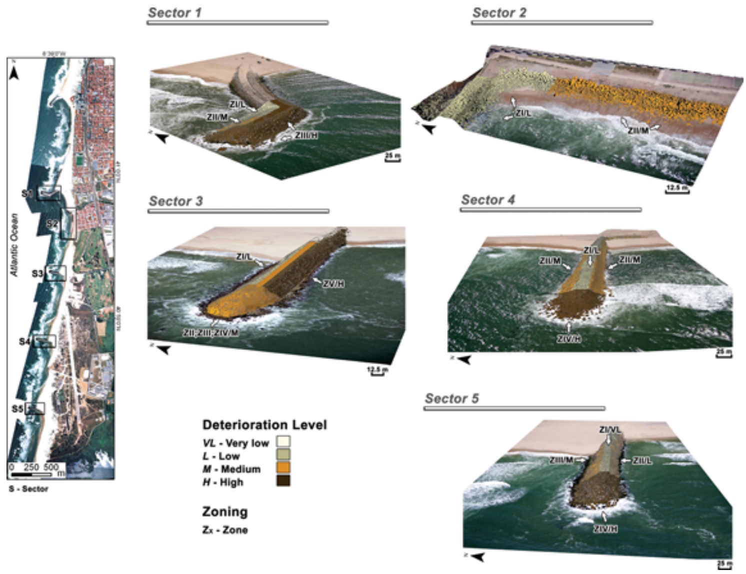



**Figure 8.** Application of the coastal geo-engineering zoning proposed for the rock armour structures of Espinho region (5 sectors).

energetic waves as opposed to the less exposed part. This is because on the lee side or more protected is located in shallower waters that lead to wave breaking and thus less energetic waves.

Therefore, according to the evaluations that were performed, replacement of the primary armour layer of the head of the structures would increase the effectiveness and prolong the longevity of the structures. The results obtained with this methodology also indicate the need for repairing/maintenance works in some parts of the studied sectors. As shown in Table 5, Sectors 1 and 2 need urgent repair and are the most deteriorated structures. The results also suggest that for some of the sectors, alterations to the design of the structures would help to minimize deterioration due to erosion. This study emphasizes the need for a management strategy to evaluate the deterioration and present condition of coastal structures in order to direct and plan appropriate maintenance, and repair/rehabilitation work, and to minimize the overall cost.

## Conclusions and Outlook

The Espinho coast is very dynamic and exposed to severe wave action and erosive forces. It has been experiencing erosion for a long time and the prospect of even greater erosion in the future requires that it be carefully monitored. This study was concerned with the identification and assessment of factors that may extend the life of coastal protection structures (further details in Pires et al. 2009b). The methodology that was developed proved to be a fairly easy, fast, and economical way to evaluate the status of maritime works. The tested procedures confirmed the need for maintenance on some of the studied structures and/or eventual changes in their design.

The main conclusions were:

1. In addition to the application of geo-engineering techniques, coastal engineering projects could include the development of GIS-based geo-cartography in the assessment of hydraulic structures in order to benefit from the following advantages: build a database with all the gathered information that can be always updated, including several data and features at the same time in one GIS-project, creating thematic cartography;
2. Maritime structural zoning map, based on the analysis of geological, geotechnical and geomechanical properties (eg. lithological and petrophysical features, weathering grade/degradation grade, rock strength, etc.) and GIS mapping allows repair programs to be directed to selected parts of groynes and other structures, at a reduced cost;
3. GIS databases and geomaterial assessment of coastal structures, as well as engineering geosciences of the quarry and inventory are important inputs to strategic decision making with reference to selection of quarries sources in the future and also with reference to determine optimum timing of repair. At a local-scale it is important to identify the availability of armourstone and active quarry locations.

According to USACE (2002), one of the hardest questions to answer is: ‘‘When should a structure or coastal project be repaired or rehabilitated?’’ This depends on what functions are served by the project and how critical the structure is in comparison with other structures in need of repair. Perhaps now, it is also important to ask: ‘‘Which component of the structure should be repaired or rehabilitated?’’ The data from the armour layer condition evaluation are used to produce recommendations for maintenance or additional inspection. Outputs from the type of damage evaluation presented in this paper will permit the generation of a matrix of the most appropriate geomaterials for repair. Such a matrix should take into account both the rock mechanical properties required for the design and the application of appropriate (additional) test procedures for the assessment of material quality and durability both before and during construction.

## Funding

This research was funded by doctoral scholarship from Portuguese Foundation for Science and Technology (FCT) to A. Pires (SFRH/BD/43175/2008). This work was performed under the framework of the PEst-C/CTE/UI4035/2011 (GeoBioTec|UA), re-equipment program (LABCARGA|IPP-ISEP|PAD’2007/08) and GISCOAST research line (LABCARGA|ISEP/GeoBioTec|UA).

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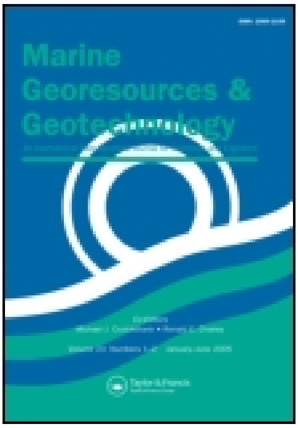


Marine Georesources & Geotechnology

# Coastal Geo-Engineering Techniques for the Assessment of Rock Armour Structures

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Accepted author version posted online: 27 Mar 2013.Published online: 21 Feb 2014.

# CHAPTER 7

# P6

## SYNOPSIS

*This research is related to rocky coasts evaluation and shore platforms analysis. Boulder accumulations are common on the granitic shore platforms of Galicia, northwestern Spain. Measurements were made of the long axis length of more than 800 boulders, and additionally of the short and intermediate axes of 340 of these boulders, as well as their orientation and gradient. There were two study areas. Because of greater joint density, the boulders on the Barbanza Peninsula are generally a little smaller than those in southern Galicia with, respectively, mean long axis lengths of 0.98 and 1.14 m, and masses of 1.06 and 1.59 t. Joint density and orientation also account for the occurrence of very coarse boulders and megaclasts in southern Galicia. The distribution and extent of the deposits and boulder imbrication and orientation testify to the high levels of wave energy produced by north-westerly and westerly storms in this region. Although the boulders, as well as the underlying shore platforms, were inherited, in part, from previous interglacial stages, some boulder detachment and movement is occurring today during storms, when significant deep water wave heights exceed 8 to 10 m. Despite some abrasion of the shore platforms, the primary role of large boulder accumulations is protective. The effect of sediment on shore platforms has been neglected, but this study suggests that, because of arrested development under thick accumulations, platform gradient in areas with abundant sediment increases with the grain size of the material. The occurrence and type of sediment on shore platforms may therefore help to explain the distribution of sloping and subhorizontal platforms under different morphogenic and geological conditions. The main conclusions of the paper are that the large boulders to megaclasts are being moved across the shore platforms of Galicia by large storm waves, to elevations extending well above the present high tidal level; these boulders play an important erosional, and probably most importantly, protective role in the evolution of the shore platforms, especially where they are adjusting to the present level of the sea; the sediments in transport-limited environments play an important, albeit neglected, role in the development of shore platforms; and because of the effect of large amounts of sediment in arresting platform development, and the relationship between sediment grain size and equilibrium slope, shore platform gradient tends to increase with the coarseness of the sediment.*

Continental Shelf Research 48 (2012) 122–137

Contents lists available at SciVerse ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Research papers

# The effect of boulders on shore platform development and morphology in Galicia, north west Spain

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ARTICLE INFO

*Article history:*
Received 22 February 2012
Received in revised form
19 July 2012
Accepted 22 July 2012
Available online 1 August 2012

*Keywords:*
Boulders
Sediment
Shore platforms
Galicia
Storms

ABSTRACT

This paper is concerned with the effect of sediment accumulation on shore platform development. Boulder accumulations are common on the granitic shore platforms of Galicia, northwestern Spain. Boulders are produced by erosion of shore platforms and of cliffs consisting of cold-climate deposits from the last glacial period. Measurements were made of the long axis length of more than 800 boulders, and additionally of the short and intermediate axes of 340 of these boulders, as well as of their orientation and gradient. There were two study areas. The boulders on the Barbanza Peninsula are generally a little smaller than those in southern Galicia with, respectively; mean long axis lengths of 0.98 and 1.14, and masses of 1.06 and 1.59 t. There are also some isolated, very coarse boulders and megaclasts in southern Galicia. The distribution and extent of the deposits and boulder imbrication and orientation testify to the high levels of wave energy produced by northwesterly and westerly storms in this region. Although the boulders, as well as the underlying shore platforms, were inherited, in part, from previous interglacial stages, some boulder detachment and movement is occurring today during storms, when significant deep water wave heights exceed 8 to 10 m. Despite some abrasion of the shore platforms, the primary effect of large boulder accumulations is protective. The role of sediment on shore platforms has been neglected, but this study suggests that because of arrested development under thick accumulations, platform gradient in areas with abundant sediment increases with the grain size of the material. The occurrence and type of sediment on shore platforms may therefore help to explain the distribution of sloping and subhorizontal platforms under different morphogenic and geological conditions.



## 1. Introduction

Much of the more than 100 year old debate on the origin of shore platforms has been concerned with the relative contributions of wave and weathering processes on the development of subhorizontal ($<1^\circ$) shore platforms in New Zealand and southeastern Australia, and sloping (1 to 5°) shore platforms around the north Atlantic (Bartrum, 1916; Hills, 1971; Kennedy et al., 2011; Trenhaile, 1987, 2011; Stephenson et al., in press). Therefore, much of the classical literature has been concerned with the effect of climate and wave regimes on shore platform gradient. Conversely, in the last few decades, it has been shown that there is a moderately strong relationship between mean regional platform gradient and tidal range (Trenhaile, 1987, 1999), which has been supported by the results of mathematical modeling (Trenhaile, 2000, 2001, 2003). The relationship between shore platform gradient and tidal range may reflect the tidally distributed expenditure of wave energy within the intertidal zone, and the way that tides control immersion and exposure frequencies and durations, and consequently the intensity and spatial variability of weathering processes (Trenhaile, 2003, 2004a). Apart from modelling, which suggested that platforms with large amounts of beach material tend to be narrower and steeper than bare platform surfaces (Trenhaile, 2005), the possible role of sediment, ranging from boulders to sand, on shore platform development has not been considered. This material may, depending on its mobility, protect or abrade the platform surface, and it also influences weathering processes by retaining moisture against the underlying rock surface.

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0278-4343/$ - see front matter 
http://dx.doi.org/10.1016/j.csr.2012.07.014

Boulders are common on shore platforms cut into granite, basalt, chalk, limestone, and other rocks with well-spaced discontinuities, particularly in exposed areas with high wave energy (Blanco Chao et al., 2007; Knight et al., 2009; Hall, 2011; McKenna et al., 2011; Knight and Burningham, 2011; Stephenson and Naylor, 2011). Most recent interest in boulders, however, has been concerned with the debate over whether they were emplaced by paleo-tsunami or storm waves (Nott, 2004; Paris et al., 2011), and most work on shore platforms has been conducted on largely bare rock surfaces without much sediment or debris (Trenhaile, 1987, 2011; Stephenson et al., in press). There has been only limited interest in rock coasts as sedimentary environments (Felton, 2002; Noormets et al., 2004) and consequently, despite an evident dynamic relationship between erosional and depositional landforms and processes, they have usually been treated as distinct entities in the coastal literature.

Boulders can be eroded from cliffs and shore platforms, carried to the foreshore by mass movements, or released by the erosion of glacial or other Quaternary deposits (Oak, 1984; McKenna, 2005; Chen et al., 2011). Boulders eroded from ancient cliff deposits may have been previously rounded by fluvial processes, whereas boulders dislodged from rock outcrops can be rounded by wave abrasion or by pre- or post-erosional spheroidal weathering. In addition to rounded forms, there are often angular boulders that are either too large to be mobile or have not moved sufficiently to become rounded because of recent detachment or topographical trapping, sheltering, or wave divergence.

The purpose of this paper was to determine the effect of boulders on the development and morphology of shore platforms, based on work conducted in Galicia, northwestern Spain. The study was designed to:

a) investigate the occurrence and characteristics of boulders and boulder accumulations on the shore platforms;
b) determine the degree, if any, to which the boulders are mobile and therefore playing an active abrasional or other role in platform development, or inactive and simply protecting the underlying platform surface; and
c) study the effect of boulder accumulations on shore platform development and morphology.

## 2. The study areas

The Galician coast is in a metamorphic belt of Precambrian to Silurian age consisting of slates, schists and quartzites, and late-Variscan granites and granodiorites (Llana-Fúnez, 2001). The rocks are generally deeply fractured and were weathered under tropical conditions in the Tertiary (Nonn, 1966; Pérez Alberti, 1991). The coast is mesotidal, with a mean range of 2.5 m and a maximum of approximately 4.0 m. Galicia has the most energetic wave climate on the Iberian Peninsula. Deepwater waves of 1.0 to 2.5 m in height account for approximately 80% of the yearly total, and over 5.0 m for 3% of the total (Puertos del Estado, 2011). The largest waves occur during autumn and winter when low-pressure systems generate storms with westerly, northwesterly, and southwesterly winds; significant wave heights of 11.6, 13.5, and 12.6 m were recorded in November 2010, January 2009, and March 2008, respectively (Fig. 1; Table 1).

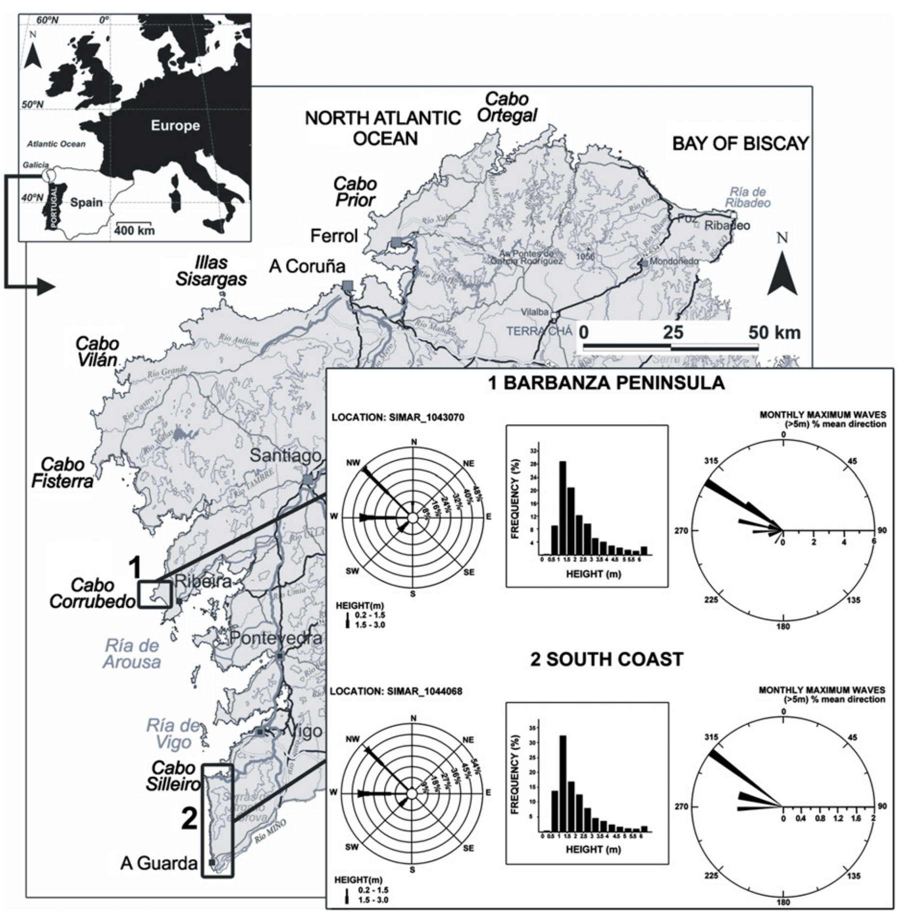


Fig. 1. Location, and mean wave height, frequency, and direction in the two study areas in Galicia, northwestern Spain.

**Table 1**
Monthly maximum significant wave height ($H_s$) and peak period ($T$) for 2010 and January and February 2011 (Puertos del Estado).

| Month | $H_s$ (m) | $T$ (s) | Direction (°) |
|---|---|---|---|
| January | 5.7 | 14.3 | 282 |
| February | 9.1 | 14.3 | 297 |
| March | 8.5 | 12.5 | 290 |
| April | 6.0 | 11.8 | 311 |
| May | 4.0 | 7.6 | 240 |
| June | 3.5 | 8.4 | 358 |
| July | 5.0 | 11.7 | 302 |
| August | 3.9 | 24.8 | 334 |
| September | 3.5 | 7.2 | 40 |
| October | 7.7 | 15.4 | 290 |
| November | 11.6 | 16.6 | 322 |
| December | 6.1 | 10.6 | 39 |
| January | 8.2 | 15.4 | 266 |
| February | 10.0 | 18.2 | 281 |

Data are from the Villano Buoy, 43°29.4′N, 9°12.6′W, at a depth of 386 m.

Abandoned sea caves filled with marine isotopic stage (MIS) 2 and 3 (mid- to late Weichselian) sediment, elevated cliff–platform junctions, and ancient beach deposits suggest that sea level was about 2 to 3 m higher than today's during MIS 5 (Eemian interglacial) (Trenhaile et al., 1999; Blanco Chao et al., 2003). Consequently, modern coastal processes are modifying a variety of inherited and relict landforms, including cliffs, shore platforms, and boulder deposits. Some shore platforms in Galicia have already acquired gentle gradients ( < about 3°) and they slope seawards with a graded morphology that appears to be well adjusted to the present level of the sea, whereas others retain extensive elevated sections with deeply incised channels. Shore platforms are essentially bare in places but most are characterized by a variety of boulder accumulations ranging from isolated clasts up to boulder deposits that extend over the entire rock surface.

This study focussed on two areas (Figs. 1 and 2). The Barbanza Peninsula lies between the Ria de Muros e Noia and the Ria de Arousa. The shore platforms are cut into heavily fractured granitic rocks and they have extensive boulder deposits. The hinterland is low in this area and, in the absence of any cliff erosion, the boulders must have been produced by wave quarrying on the shore platforms and other rocky outcrops, possibly facilitated by frost weathering when sea level was lower during MIS 2 and 3 and other glacial periods. The shore platforms along the southern coast, between Cabo Silleiro and A Guarda, are almost bare in some places and partly covered by extensive rounded or angular boulder deposits in others. The area has a high hinterland and material was derived largely from platform erosion and from the release of pre-formed rounded boulders from MIS 2 and 3 para-periglacial and fluvio-nival sediments in the cliff behind (Trenhaile et al., 1999; Pérez Alberti et al., 2002; Blanco Chao et al., 2007).

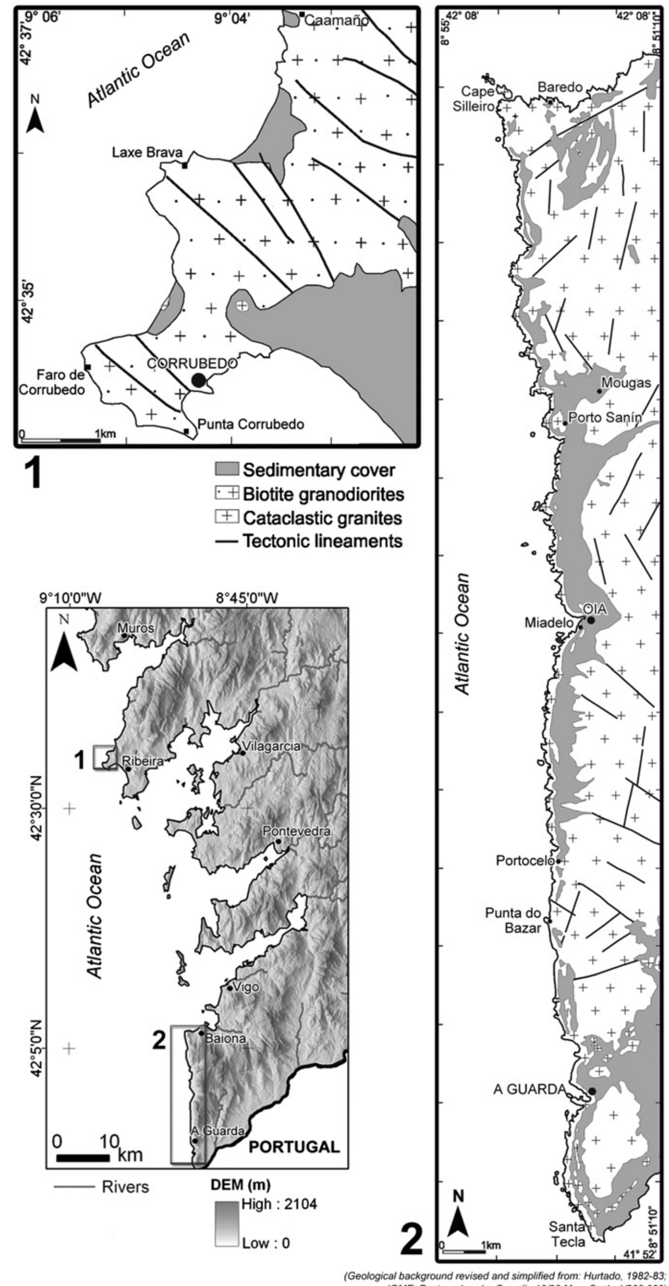


**Fig. 2.** General geology of the two study areas.

## 3. Materials and methods

The revised Udden-Wentworth scale was used to describe the size of boulders and other large rocks (Blair and McPherson, 1999). The grain size of fine, medium, coarse, and very coarse boulders range from 25.6 to 51.2 cm ($-8$ to $-9\varphi$), 51.2 to 102.4 cm ($-9$ to $-10\varphi$), 102.4 to 204.8 cm ($-10$ to $-11\varphi$), and 204.8 to 409.6 cm ($-11$ to $-12\varphi$), respectively. Larger rocks, or megaclasts, include fine (4.1 to 8.2 m, $-12$ to $-13\varphi$) and medium (8.2 to 16.4 m, $-13$ to $-14\varphi$) blocks.

The shore platforms and their associated boulder accumulations were surveyed and mapped using a GPS integrated system (Trimble GPS GeoExplorer XH) (Fig. 3), orthophotos of the two areas with a 25 cm pixel resolution and LiDAR images with a 10 cm pixel resolution for the Barbanza Peninsula, high resolution oblique aerial photographs provided by the autonomous community council (Xunta de Galicia, Dirección Xeral de Sostibilidade e Paisaxe), and ESRI ArcGis 10 software. The orthophotos were used to map joint patterns in the study areas and the Trimble reference station *SOPAC, A Coruña* was used to determine GPS measurement errors and corrections during post-processing. Approximately 30 cm accuracy was obtained in the horizontal plane with the internal GPS antenna and 10 cm accuracy with the Hurricane external antenna. The GPS provided vertical accuracy after post-processing in the order of < 25 cm.

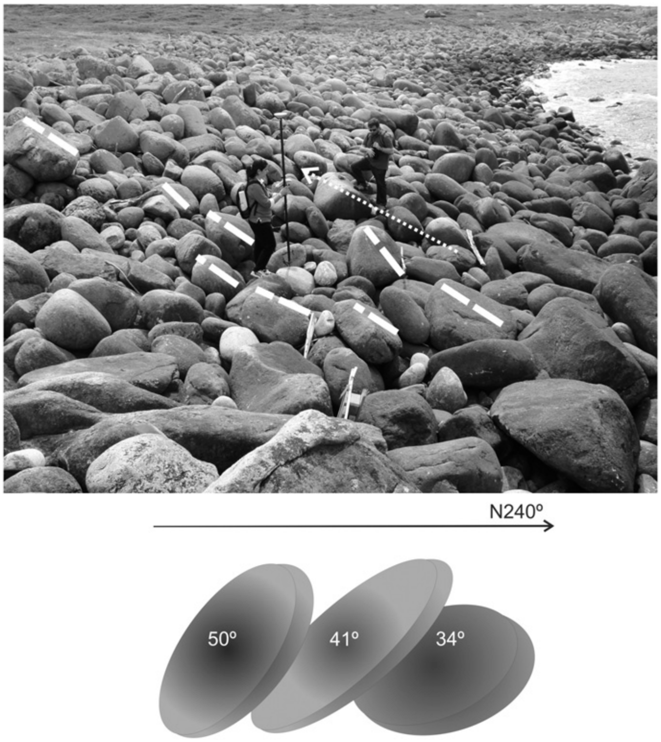


**Fig. 3.** GPS surveying of the boulder beach over a steeply sloping shore platform at Laxe Brava on the Barbanza Peninsula. The arrowed line shows the orientation of boulder imbrications and the thicker dashed lines individual boulder gradients. Although most large boulders are apparently immobile there are some smaller boulders with abraded, unweathered surfaces and impact scars on larger boulders in the foreground.

Measurements were made with a tape of the short, intermediate, and long axes of 340 boulders and, largely for comparative and representative purposes, of only the longest axes of another 460 boulders. A compass was also used to record the orientation and a clinometer to measure the slope of the 340 boulders (Fig. 3). The three axes were measured on 10 boulders at sites spaced at regular intervals along shore-normal profiles on boulder-covered platforms. Measurements were also made on more scattered deposits on shore platforms, and on a few very large boulders and megaclasts. Where 10 boulders were measured, the axes of the boulder at the centre of each measurement site were recorded, and then of all the rocks that were in contact with it. Measurements then continued in a clockwise manner with the boulders that were closest to the centre of the site although not in direct contact with the central boulder, until 10 boulders had been measured. Boulder selection also depended on the need to have access to the three primary axes. This sampling system ensured that all the rocks were fairly close to the centre of the site, thereby minimizing locational variations within each site, and it prevented over-representation by larger boulders which have a greater surface area and consequently a greater chance of random selection than smaller boulders. The Corey Shape Factor (CSF) was used to represent the degree to which the shape of a boulder diverged from a perfect sphere (CSF=1) (Corey, 1949; Komar, 1980):

$$\mathrm{CSF} = D_s/(D_i D_l)^{0.5}$$

where $D_s$, $D_i$, and $D_l$ are the length of the short, intermediate, and long axes of a boulder, respectively. Boulder volume was represented by the product of the three axes and boulder mass by the volume times the density of the rock (2691 kg m$^{-3}$ for solid granite).

The size, orientation, and slope of 180 boulders were measured at 10 m intervals along 6 shore-normal profiles at Laxe Brava (Fig. 4). The profiles were generally spaced at 15 m intervals, although this distance varied a little in the eastern part (profiles A and B) where there were outcrops of bare rock platform and some very large boulders from the adjacent, eroding headland. Similar measurements to those at Laxe Brava were made of 40 boulders at four sites, 10 m apart, along a single profile at Faro de Corrubedo (Fig. 5). The size (three axes), orientation, and slope of twenty more boulders were recorded at two sites on the boulder beach at Punta de Corrubedo, to compare those on an exposed headland at the edge of the bay with those in a shallow channel in a more sheltered location about 25 m to the south. The same variables were measured on 100 boulders in southern Galicia to characterize the size, shape, and possible organisation of the deposits.

A log transformation was used to provide more normalized distributions for some positively skewed boulder mass data. Visual comparison was then made between histograms of the transformed data and the normal probability curve. The Lilliefors (Kolmogorov–Smirnov) and Shapiro–Wilk tests and normal Q–Q plots suggested that boulder mass and shape (CSF) data for each shore-normal (A to F) (3 sampling sites and 30 data points each) and shore-parallel (6 sampling points and 60 data points each) profile at Laxe Brava did not deviate significantly from a normal distribution (Shapiro–Wilk significance values, S–W, $>0.05$), with the exception of boulder mass at the high tidal level (Fig. 6). Therefore, *t*-tests were used to compare mean boulder mass and shape between adjacent profiles at Laxe Brava. Normality tests are unlikely to detect non-normality in the small (10) data sets from each site, but as the population distributions (combined data for all the sites at each beach) were normally distributed, the parametric *t*-test was also used to compare boulder mass and shape between individual sites on the Barbanza Peninsula, at Laxe Brava, Faro de Corrubedo, and Punta de Corrubedo. Because of the possible effects of marked skewness and kurtosis (particularly when they were more than two times the standard error of the skewness or kurtosis), however, the results of comparisons between some individual sampling points should be treated with caution. The 95% confidence level was used for all the statistical analyses in this paper.

## 4. Results

Boulder accumulations only occur on granitic shore platforms and they are absent from those consisting of fissile slates or schists. Although the boulders on the platforms of southern Galicia were larger than those on the Barbanza Peninsula (Table 2), the difference would have been much greater if the very coarse boulders and megaclasts on the southern coast had been included in the calculations. The observed degree of rounding was generally greater on the Barbanza Peninsula than on the southern coast, although the three-dimensional shape (CSF value) of the boulders was essentially identical (means 0.50 and 0.51, respectively).

### 4.1. Boulder deposit characterististics

Medium to coarse boulders cover the shore platform at Laxe Brava on the Barbanza Peninsula (Fig. 3). They extend up to 4 to 5 m above the present high spring tidal level into grass-covered deposits that contain immobile boulders that are discoloured and covered in lichen. These backshore deposits are probably MIS 5 in age, although they include some recently deposited fine boulders with freshly abraded surfaces (Fig. 7). The gradients of the beach,

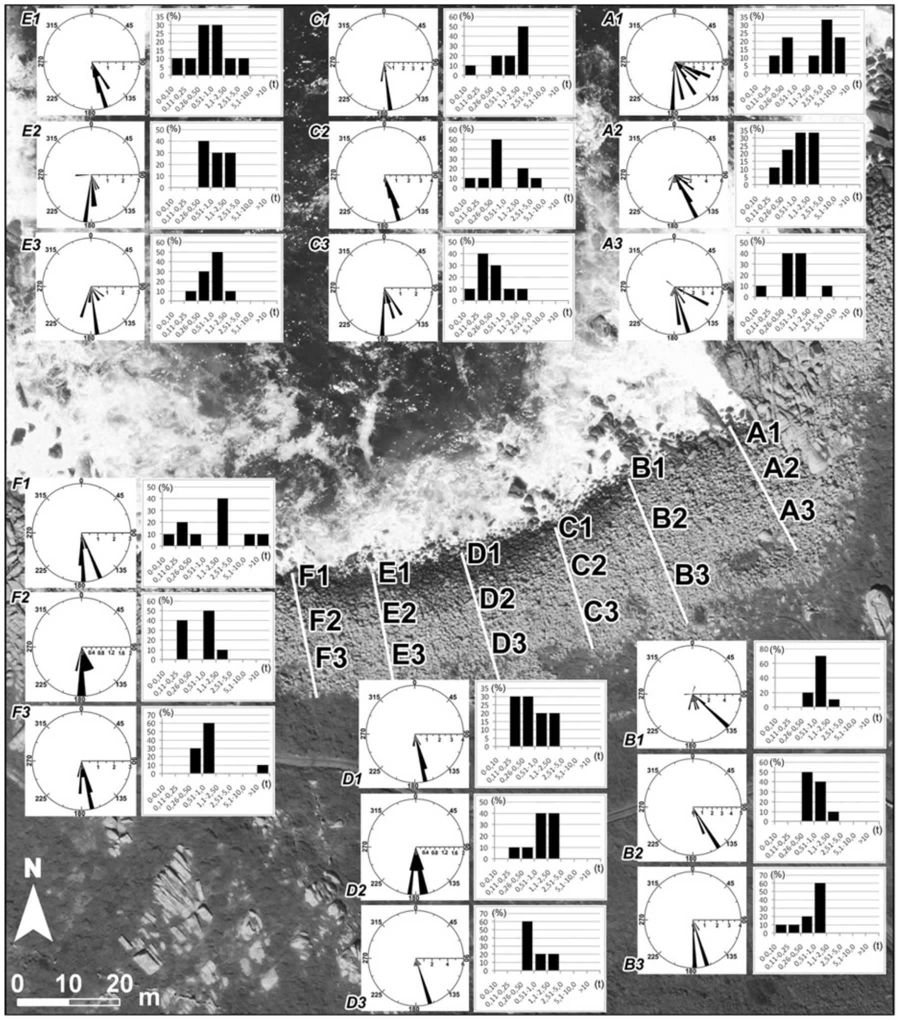


**Fig. 4.** Boulder mass and orientation along 6 profiles at Laxe Brava. The boulder sampling profiles A, B, C, D, E, and F correspond approximately to the topographic profiles P1, P4, P6, P8, P9 and P10, respectively, in fig. 7.

which were measured along the top of the boulders, and underlying shore platform were generally between about 7.5° and 8.7°, although they were less than 7° on profiles P3 and P4 and more than 11° on P8. On several profiles, the gradient of the lower portion of the beach was less than the upper, more landward portion. The mean mass of the boulders at Laxe Brava was 1.0 t. Boulder mass generally decreased landwards along each of the profiles, although the zone containing the boulders with the greatest mass migrated from the low tidal level at the eastern and western extremities of the bay, to the mid-tidal level in the more central portions of the bay (Table 3). Although this landward shift may reflect greater exposure to wave action in the centre of the bay, the mean mass for each profile was highest for the most sheltered profiles (A and B), possibly because of their proximity to, and the shelter afforded by, the eroding headlands, and correspondingly lower amounts of movement, breakage, and attrition. Thirty-four *t*-tests (two-tailed, two-sample tests assuming unequal variances) were run on log-transformed boulder mass data to compare individual sites (e.g., A1 with A2 and A1 with B1, etc) and profiles (e.g., A1 to F1 with A2 to F2, and A1 to A3 with B1 to B3) that were adjacent in the longshore or cross-shore directions. The only significant differences were between two sets of individual sites (C2/C3 and C3/D3) and the mean mass at the midtidal (A2 to F2) and high tidal (A3 to F3) levels (Tables 3 and 4), although two of these differences are questionable because of the lack of normality in the data at C2 and at the high tidal level (Fig. 6; Table 4). Furthermore, in contrast to the pronounced shape sorting that often characterizes the much smaller clasts on pebble beaches, there was marked uniformity in boulder shapes (CSF values) along and between the profiles at Laxe Brava (Table 3). A similar series of 34 *t*-tests showed that the only significant differences in shape were between the boulders at the low (A1 to F1) and midtidal (A2 to F2) levels. There were no significant differences in boulder shapes along each profile or between adjacent profiles, and the correlation between individual boulder mass and shape was not significant (Table 5).

There was some evidence of organisation in the boulder deposits covering the shore platforms at Faro de Corrubedo and Punta de Corrubedo (Fig. 2). The gradient of the fine to medium boulder beach and underlying shore platform at Faro de Corrubedo is more than 10° (Fig. 8), and the upper portion of the beach is relict, extending to more than 9 m above the spring high tidal level. Possibly because of smaller boulders (mean mass of 0.46 t), there was a stronger tendency for landward fining at Faro de Corrubedo than at Laxe Brava (Table 3), although the only significant difference was between boulders at sites A1 and A2 in the lower part of the beach (Table 4). Mean boulder shape was similar to that at Laxe Brava (mean CSF 0.48 compared with 0.52 at Laxe Brava), and the highest value was again located at the low to mid-tidal level (Table 3). The difference between boulder shapes was significant between sites A1 and A2 (Table 5) and

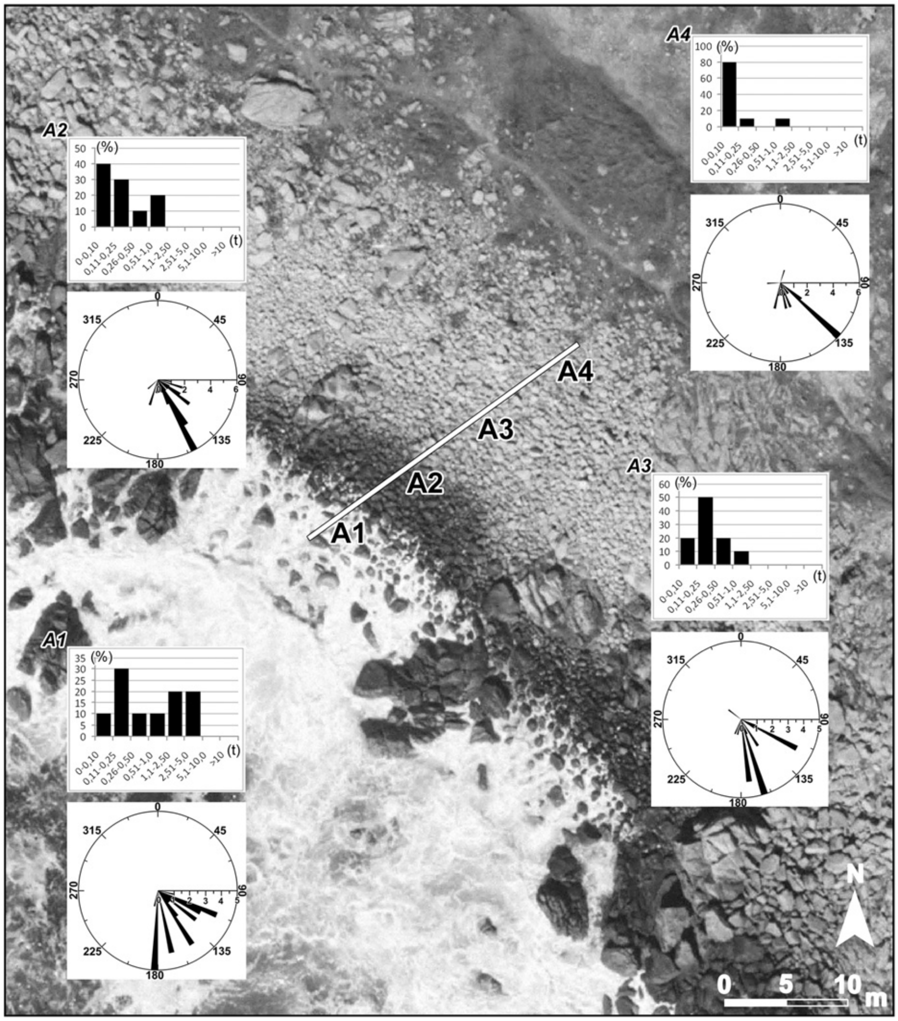


**Fig. 5.** Boulder mass and orientation along a single profile at Faro de Corrubedo.

there was a low ($r^2$=0.16; $p$: 0.05) but significant correlation between individual boulder mass and shape (CSF value) at Faro de Corrubedo. The boulders in the bay at Punta de Corrubedo were smaller than those on the headland (means 2.04 and 2.97 t, respectively), possibly reflecting breakage, abrasion, and selective transport from the eroding headland, although the difference was not significant (Table 4). There was essentially no difference in the degree of sphericity at the two sites (CSF 0.45 and 0.42 for the bay and headland, respectively) and no correlation between individual boulder mass and shape (CSF value).

In contrast to the Barbanza Peninsula, where boulder beaches may cover the shore platforms in some areas, extensive boulder deposits in southern Galicia are generally restricted to the back of the platforms and to topographic depressions, including shore-normal, valley-like channels eroded along prominent joints. There was no relationship between individual boulder mass and shape (CSF value) for the entire southern coast, but correlations were significant at Baredo ($r^2$=0.24; $p$: 0.05) and Mougas ($r^2$=0.39; $p$: 0.05), and for the smaller boulders at the lower level at Punta do Bazar ($r^2$=0.38; $p$: 0.05).

### 4.2. Clast mobility

Boulder orientation and imbrication provide strong evidence of the effect of exposure on the Galician coast, and of the ability of waves to move large boulders. On the Barbanza Peninsula, at Laxe Brava, Faro de Corrubedo, and Punta de Corrubedo, for example, there is a predominance of boulders oriented towards the south and southeast, corresponding to the direction of the storm waves, which come from the northwest (Figs. 4 and 5). Imbrication, with slopes typically between 30 and 70°, is evident in many places. At Laxe Brava, the steepest imbrications are at the high tidal level in the exposed, central portions of the bay (Fig. 4, profiles B to D), and at the low to midtidal level at the more sheltered extremities (Fig. 4, profiles A, E, and F). The effect of local platform gradient and topography is also important, however, particularly in the narrower and less exposed landward sections of the joint-controlled channels where boulder orientation is less variable and more strongly related to channel orientation than in the wave-dominated sections seawards (Fig. 5,A4).

There were no significant correlations between boulder orientation and boulder mass, the length of the longest axis, or boulder shape (CSF) on the Barbanza Peninsula or along the southern coast. There were also no significant correlations between the gradient of the imbricated boulders and boulder mass, the length of their longest axis, or boulder shape (CSF) in the two study areas.

There is still a thin coating of petroleum on rock surfaces from the Prestige oil spill in November 2002. The removal of this coating in places illustrates the effect of boulder abrasion and impact and provides a maximum time for its occurrence (Fig. 9). No abrasion data are available for the large boulders in this area, but abrasion

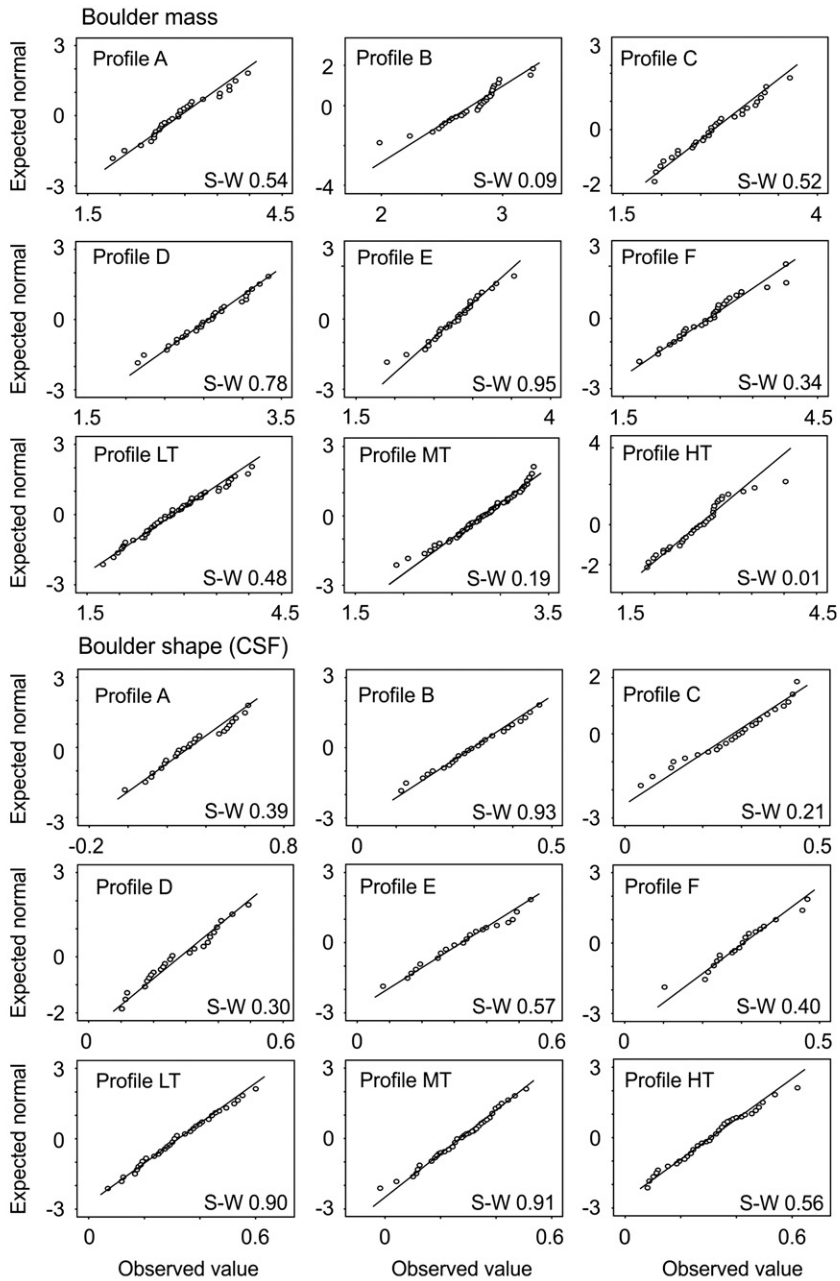


**Fig. 6.** Normal Q–Q plots and Shapiro–Wilk test significance values (S–W) to assess the normality of the log of boulder mass and shape (CSF value) along shore normal (A to F) and shore parallel (LT, MT, HT) profiles at Laxe Brava. LT, MT, and HT refer to the low tide, mid-tide, and high tidal levels, respectively. Shapiro–Wilk significance values $>0.05$ suggest that distributions, with the exception of boulder mass on profile HT, do not deviate significantly from a normal distribution.

**Table 2**
Descriptive statistics for mean boulder shape and mass for the two study areas.

| | | Short axis (m) | Intermediate axis (m) | Long axis (m) | Mass (t) |
|---|---|---|---|---|---|
| Barbanza Peninsula | Mean | 0.39 | 0.66 | 0.98 | 1.06 |
| | Median | 0.36 | 0.62 | 0.91 | 0.55 |
| | Standard Deviation | 0.18 | 0.30 | 0.43 | 1.61 |
| Southern Galicia* | Mean | 0.45 | 0.78 | 1.14 | 1.59 |
| | Median | 0.42 | 0.69 | 1.02 | 0.76 |
| | Standard deviation | 0.21 | 0.32 | 0.50 | 1.92 |

* Data for southern Galicia do not include boulders and megablocks of more than 10 t.

rates by smaller, more mobile pebbles to fine boulders have been recorded at Miadelo (Oia) on the southern Galician coast. The data, obtained from twelve micro-erosion meter stations, ranged from a low of 0.13 mm yr$^{-1}$ at a roughly horizontal station in a shallow groove to 1.8 mm yr$^{-1}$ at a near vertical station on the lower wall of a structural channel (Blanco Chao et al., 2007).

In addition to extensive boulder accumulations on the shore platforms in the two study areas, there were also some very coarse boulders and megaclasts, primarily on the southern coast, that have been eroded from the platform surface. At Punta do Bazar, for example, rocks ranging from coarse boulders to medium blocks with long axes generally oriented towards the east-northeast are perched on top of a gently curving structural dome. The largest of these blocks has a mass of over 57 t (Figs. 8 and

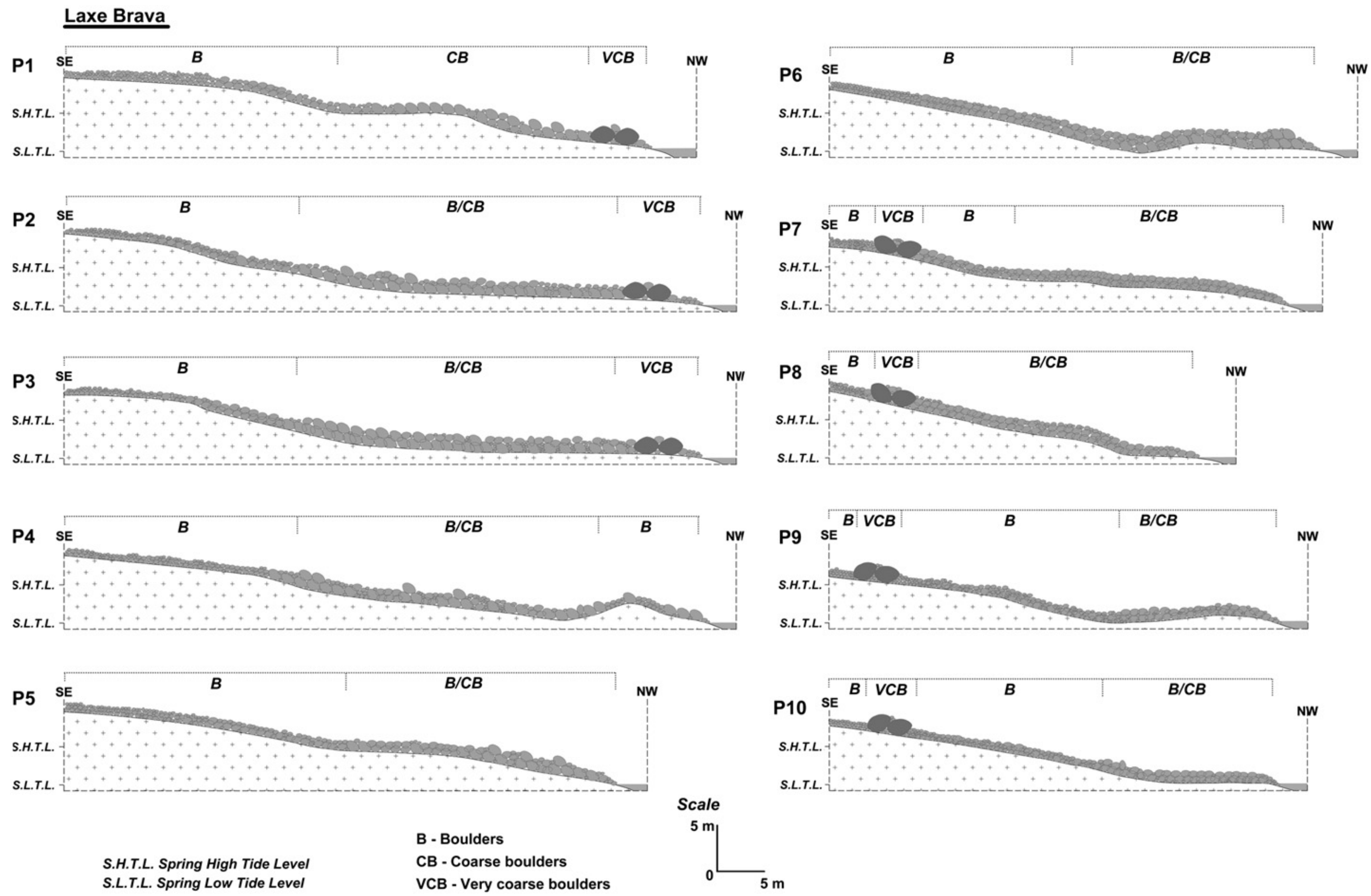


**Fig. 7.** Shore-normal profiles on the primarily medium to coarse boulder beach and shore platform at Laxe Brava on the Barbanza Peninsula. The profiles extend over an area of approximately 100 m alongshore, from P1 in the east to P10 in the west. The term 'boulder' (B) is used for imbricated and interlocking boulder accumulations. The boulders are shown approximately to scale.

**Table 3**
Boulder mass and sphericity (Corey Shape Factor, CSF) for the Barbanza Peninsula.

| | | Shore-normal Line | Profile | | | | | |
|---|---|---|---|---|---|---|---|---|
| Laxe Brava | | | | | | | | |
| | | | F | E | D | C | B | A |
| | Mass (t) | 3 (High tide) | 1.61 | 0.61 | 0.76 | 0.34 | 0.54 | 0.85 |
| | | 2 (Midtide) | 0.59 | 0.90 | 0.92 | 1.19 | 0.66 | 0.75 |
| | | 1 (Low tide) | 2.31 | 0.84 | 0.56 | 0.90 | 0.77 | 3.49 |
| | CSF | 3 (High tide) | 0.48 | 0.49 | 0.57 | 0.5 | 0.48 | 0.53 |
| | | 2 (Midtide) | 0.53 | 0.51 | 0.55 | 0.6 | 0.55 | 0.57 |
| | | 1 (Low tide) | 0.5 | 0.48 | 0.49 | 0.52 | 0.50 | 0.46 |
| Faro de Corrubedo | | | | | | | | |
| | Mass (t) | A4 (High tide) | 0.12 | | | | | |
| | | A3 | 0.25 | | | | | |
| | | A2 | 0.25 | | | | | |
| | | A1 (Low tide) | 1.26 | | | | | |
| | CSF | A4 (High tide) | 0.42 | | | | | |
| | | A3 | 0.51 | | | | | |
| | | A2 | 0.59 | | | | | |
| | | A1 (Low tide) | 0.39 | | | | | |

The profiles for Laxe Brava are listed in the table in the order in which they are found on the boulder beach, with F being the most westerly and A the most easterly. The only significant differences between mean rock mass (log-normalized) at the 95% probability level were A1 and A2, C2 and C3, D1 and D2, C3 and D3, and for mean rock mass for lines 2 and 3. Differences between A1 and B1, E2 and F2, and B3 and C3 were significant at the 90% but not at the 95% probability level. A1 refers to the low tidal sampling site on profile A, B3 to the high tidal site on profile B, etc. There was only one profile at Faro de Corrubedo.

10A,B). At Baredo, a coarse boulder with a mass of about 28 t has been detached from the platform surface and deposited on top of a high salient, more than 3.5 m above the height of the highest tides (Figs. 8 and 10C).

## 5. Discussion

Field observation and orthophoto and LiDar image mapping suggest that discontinuity patterns, and in particular density,

**Table 4**
*t*-test values for comparison of mean mass at adjacent sampling sites on the Barbanza Peninsula (t critical values ranged from 2 to 2.23).

Laxe Brava

| Site | A1 | A2 | A3* | B1 | B2 | B3 | C1 | C2* | C3 | D1 | D2 | D3 | E1 | E2 | E3 | F1 | F2* | F3! |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A1 | | 1.76 | | 1.70 | | | | | | | | | | | | | | |
| A2 | | | 0.61 | | 0.34 | | | | | | | | | | | | | |
| A3* | | | | | | 0.61 | | | | | | | | | | | | |
| B1 | | | | | 0.62 | | 0.31 | | | | | | | | | | | |
| B2 | | | | | | 0.91 | | 1.05 | | | | | | | | | | |
| B3 | | | | | | | | | 1.68 | | | | | | | | | |
| C1 | | | | | | | | 1.18 | | 0.77 | | | | | | | | |
| C2* | | | | | | | | | 2.94 | | 0.25 | | | | | | | |
| C3 | | | | | | | | | | | | 2.54 | | | | | | |
| D1 | | | | | | | | | | | 1.92 | | 0.82 | | | | | |
| D2 | | | | | | | | | | | | 0.88 | | 0.12 | | | | |
| D3 | | | | | | | | | | | | | | | 0.44 | | | |
| E1 | | | | | | | | | | | | | | 0.88 | | 1.33 | | |
| E2 | | | | | | | | | | | | | | | 1.29 | | 1.55 | |
| E3 | | | | | | | | | | | | | | | | | | 0.99 |
| F1 | | | | | | | | | | | | | | | | | 1.04 | |
| F2* | | | | | | | | | | | | | | | | | | 1.30 |
| F2 | | | | | | | | | | | | | | | | | | |
| A/B | 0.73 | | B/C | 0.37 | | C/D | 0.38 | | D/E | 0.10 | | E/F | 0.18 | | | | | |
| LT/MT | 0.14 | | MT/HT | 2.17 | | | | | | | | | | | | | | |

Faro de Corrubedo A1/A2 2.28 A2/A3 0.60 A3/A4 1.56

Punta de Corrubedo 1.69

LT, MT, and HT refer to profiles at the low, mid- and high tidal levels.
! and * refer to sites with data skewness and kurtosis greater than 2 times the standard error of the skewness and kurtosis, respectively.

**Table 5**
*t*-test values for comparison of mean CSF sphericity values at adjacent sampling sites on the Barbanza Peninsula (*t* critical values ranged from 2.1 to 2.2).

Laxe Brava

| Site | A1 | A2 | A3* | B1 | B2 | B3!* | C1 | C2!* | C3 | D1 | D2 | D3 | E1 | E2 | E3 | F1 | F2 | F3!* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A1 | | 1.17 | | 0.97 | | | | | | | | | | | | | | |
| A2 | | | 0.48 | | 0.05 | | | | | | | | | | | | | |
| A3* | | | | | | 0.28 | | | | | | | | | | | | |
| B1 | | | | | 0.92 | | 0.18 | | | | | | | | | | | |
| B2 | | | | | | 1.47 | | 0.67 | | | | | | | | | | |
| B3!* | | | | | | | | | 0.32 | | | | | | | | | |
| C1 | | | | | | | | 1.09 | | 0.49 | | | | | | | | |
| C2!* | | | | | | | | | 1.76 | | 0.71 | | | | | | | |
| C3 | | | | | | | | | | | | 1.15 | | | | | | |
| D1 | | | | | | | | | | | 1.23 | | 0.26 | | | | | |
| D2 | | | | | | | | | | | | 0.38 | | 1.36 | | | | |
| D3 | | | | | | | | | | | | | | | 1.28 | | | |
| E1! | | | | | | | | | | | | | | 0.51 | | 0.59 | | |
| E2! | | | | | | | | | | | | | | | 0.32 | | 0.44 | |
| E3 | | | | | | | | | | | | | | | | | | 0.44 |
| F1 | | | | | | | | | | | | | | | | | 0.70 | |
| F2 | | | | | | | | | | | | | | | | | | |
| F2 | | | | | | | | | | | | | | | | | | 1.04 |
| A/B | 0.17 | | B/C | 0.83 | | C/D | 0.11 | | D/E | 1.36 | | E/F | 0.39 | | | | | |
| LT/MT | 2.28 | | MT/HT | 1.77 | | | | | | | | | | | | | | |

Faro de Corrubedo A1/A2 4.01 A2/A3 1.56 A3/A4 1.81

Punta de Corrubedo 0.45

LT, MT, and HT refer to profiles at the low, mid- and high tidal levels.
! and * refer to sites with data skewness and kurtosis greater than 2 times the standard error of the skewness and kurtosis, respectively.

probably account for differences in boulder size (Table 2) and in the number and extent of the accumulations in the two study areas. Joint density is much greater on the Barbanza Peninsula than in southern Galicia, and they are oriented in northern, northeastern, and northwestern directions which promote wave quarrying on the shore platforms from the northwest and west. Conversely, the fractures run parallel to the coast in southern Galicia and instead of extensive deposits of rounded boulders there are smaller deposits of angular or rounded boulders and isolated, very large boulders and megaclasts. The formation and movement of megaclasts is also facilitated in parts of southern Galicia by the occurrence of both vertical and horizontal

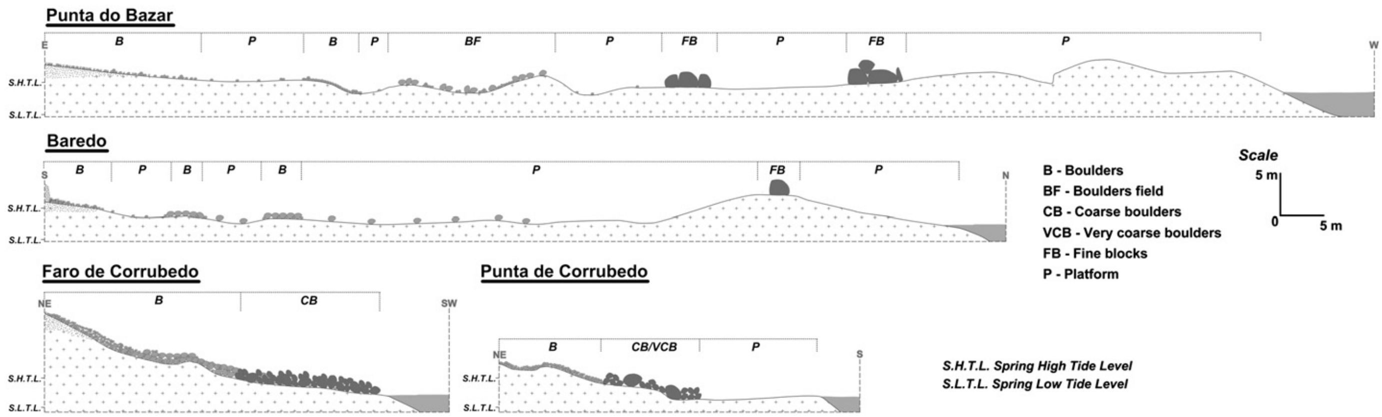


**Fig. 8.** Sample shore-normal profiles of shore platforms and boulder accumulations in southern Galicia and on the Barbanza Peninsula. The term 'boulder' (B) is used for imbricated and interlocking boulder accumulations, whereas 'boulder field' (BF) is used for a more chaotic, disorganized accumulation. The boulders and megaclasts are shown approximately to scale. The large, most seaward fine blocks (FB) at Punta do Bazar and the very coarse boulder at Baredo are also shown in Fig. 10. The high area at the seaward end of the Punta do Bazar profile occurs at the southern end of the headland. As shown in Fig. 10A, the platform is much lower (and slopes steeply seawards) in front of the megaclasts to the west and northwest.

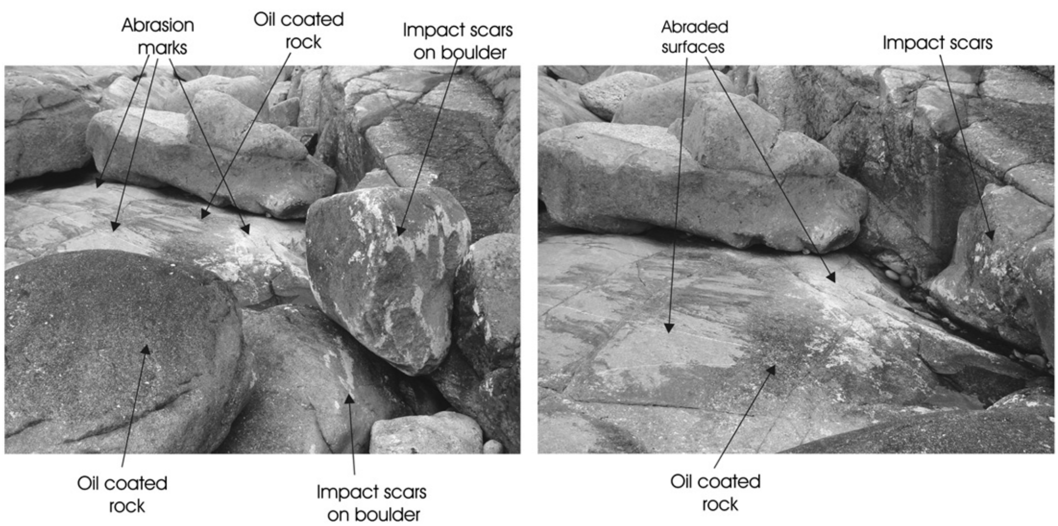


**Fig. 9.** Recently moved medium boulder (axes $>0.5$ m, mass $>1.4$ t) and abrasion scars at Miadelo (Fig. 2), southern coast of Galicia (photo looking landwards). The boulder, which is in the upper intertidal zone, on the southerly (right-hand) side of a channel ($<4$ m wide), exhibits impact scars and the platform surface has clean abraded surfaces interspersed with unabraded areas covered by oil from the 2002 Prestige oil spill.

(onion-skin) discontinuities which produce fairly even, gently-sloping sections of platform surfaces (Fig. 10A,B).

### 5.1. Boulder and megaclast movement

The movement of large boulders and megaclasts by storm waves has been well documented on the eastern Atlantic coast, often at elevations considerably above the present level of the sea (Williams and Hall, 2004; Hansom et al., 2008; Hall et al., 2008; Knight and Burningham, 2011; Fichaut and Suanez, 2011). In Galicia, there are ancient, presumably MIS 5, beach deposits cemented to the platforms and to the bottom of boulders in places (Blanco Chao et al., 2003). Furthermore, many grass-covered boulders do not appear to have moved for some time, and the deposits can extend up to several metres above today's extreme high tidal level. This suggests that boulder deposits in Galicia, in addition to the underlying shore platforms, were at least partly inherited from one or more interglacial stages. Nevertheless, some of the boulders are being moved today (Blanco Chao et al., 2006). The evidence includes boulders imbricated and oriented according to the direction of the strongest waves, the way that clast size and shape vary on boulder beaches with elevation, exposure, and distance of travel, and the presence of fresh abrasive striations and impact scars on the platforms and on the boulders (Figs. 4, 5, and 9). The evidence, including the presence of abraded surfaces on the seaward side of impact-scarred boulders, is consistent in demonstrating that boulder and block movement is in a landward direction (Figs.9 and 10). At Punta do Bazar, an encrusted dike of pegmatite in one of the megaclasts can be traced to an outcrop which is about 3 m seawards from the rock's present position (Figs. 8 and 10A,B). Very coarse boulders and blocks, with a mass up to 50 t or more, including those thrown onto and off narrow, rocky protrusions in the high tidal to supratidal zones, must have been moved during single large storm events (Fig. 10C,D), whereas the shoreward migration of blocks and smaller boulders over smooth, structural surfaces, was probably intermittent and the product of many storm events (Fig. 10A,B).

Although it does not appear that very large clasts (with the exception of the boulder shown in Fig. 10D) have been moved by recent storm wave action, they are unlikely to have resulted from ancient tsunami because of the lack of large, active subduction

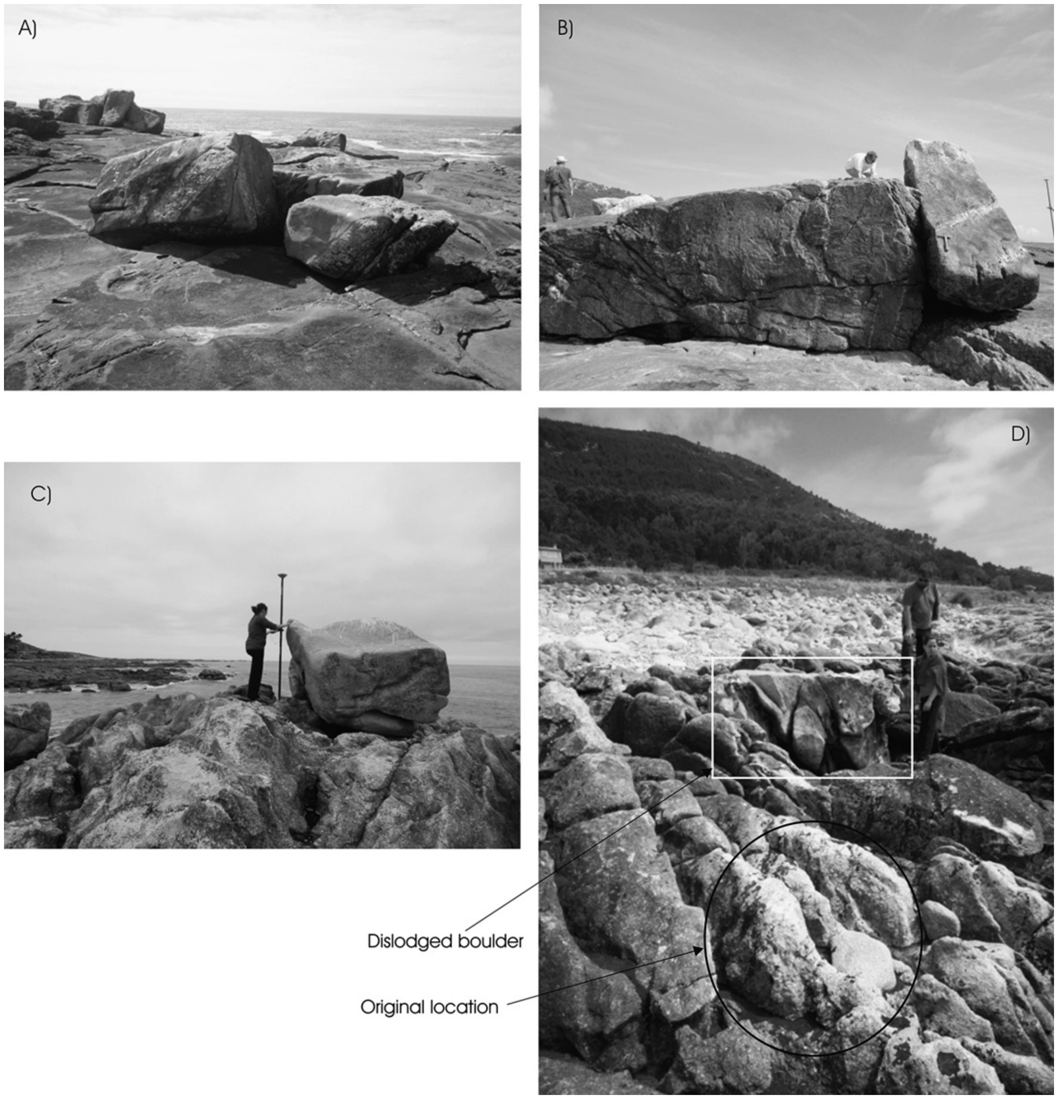


**Fig. 10.** Examples of angular, coarse to very coarse boulders in southern Galicia. (A) and (B) Two groups (centre and top left) of very large boulders to medium blocks that have migrated over a smooth platform surface to the high tidal level at Punta do Bazar (see Fig. 8); (C) Very coarse boulder thrown on to a high, supratidal salient at Baredo (see Fig. 8); and (D) Coarse boulder near the high tidal level at Miadelo. Fresh scars on the boulder and on the adjacent platform show that it has been detached recently and moved several metres landwards.

zones in the Atlantic Ocean. A notable exception to the lack of large tsunami in the Atlantic was generated by the 1755 Lisbon earthquake (8.5–9.0 on the moment magnitude scale). Although this tsunami was up to 6 m in height and formed boulder and other deposits west of Lisbon and in southern Portugal (Algarve coast) and southern Spain (Martínez and López, 2004; Scheffers and Kelletat, 2005; Whelan and Kelletat, 2005; Mendes-Victor et al., 2009), it generated only a slight swell in Galicia and caused no damage in this region. Nine or more flank failures in the volcanic Canary Islands may have generated tsunami during the Pleistocene, but none occurred in the Holocene (Pérez Torrado et al., 2006).

Several workers have developed equations and numerical models to relate boulder movement and deposition to wave energy and processes (Lorang, 2000, 2011; Nott, 2003; Noormets et al., 2004; Imamura et al., 2008; Goto et al., 2009). Given the evidence for recent movement of large to very large boulders in Galicia, the monthly maximum significant wave height ($H_s$) and peak period data for 2010 and for January and February 2011 (Table 1) were used to determine the stresses exerted on this coast by high storm waves. The breaker height ($H_b$) was calculated using Komar and Gaughan's (1972) expression:

$$H_b = 0.39g^{0.2}\left(\mathrm{TH_o}^2\right)^{0.4}$$

where $g$ is the acceleration due to gravity and $H_o$ is the deep-water wave height (in these calculations $H_o$ was represented by $H_s$, and the wave period $T$ by the peak period). The breaker depth ($h_b$), and consequently location on the platform for a given tidal level, was then determined from the relationship:

$$h_b = 1.28H_b$$

Sunamura's (1985) expression was used to calculate wave height in the surf zone ($H$):

$$H = H_b\exp\left[(-35.2D_b\tan\beta)/(T\sqrt{gh_b})\right]$$

where $\beta$ is the slope of the surf zone and $D_b$ is the distance shorewards from the breakers; calculations were made for surf zone slopes of 2 and 5°. The stress (Pa) exerted by a wave on rock structures at the breakers ($S_b$) was calculated using the USACE

(1984) expression:

$S_b = 0.5\gamma h_b$

where: $\gamma$ is the specific weight of water (about 1025 kg m$^{-3}$ for seawater). The stress generated by waves in the surf zone ($S_s$) was estimated by comparing their height with the height of the breakers:

$H/H_b = S_s/S_b$

The stress required to move a boulder up an inclined, frictional plane (gradient $\theta$) is given by:

$S_s > mg \sin\theta + \mu \, mg \cos\theta$

where $\mu$ is the coefficient of friction. The granite on granite friction coefficient at fairly low stresses can range between about 0.25 and 0.8, largely because of the effect of surface roughness (Byerlee, 1978; Lajtai and Gadi, 1989; Wyllie and Mah, 2004).

Plotting calculated wave-generated stresses against the distance shorewards from the breakpoint shows that the size of the boulders that can be moved by waves (for $\mu = 0.6$) increases with breaker height and period, and decreases with distance from the breakpoint, and for a given distance with the slope of the bottom (Fig. 11). The analysis suggests that very large storm waves, especially but not exclusively in autumn and winter, are able to move large to very large boulders in the shallow water near the shoreline, and especially where rocky salients project up from deeper water closer to the breakers. Although fine to medium boulders ($<0.5$ t) can usually be moved by the highest storm waves every month, and medium boulders ($<1$ t) during most months, larger boulders are most likely to be moved infrequently by large waves with long wavelengths (see Table 1, August 2010 and February 2011). The likelihood of large boulder and megaclast movement is even greater when one considers the maximum rather than the significant wave height. According to USACE (1984), the height of the highest 10% and 1% of the waves is, respectively, 1.27 and 1.67 times the significant wave height. To consider the effect of these waves, calculations were also made of the stresses generated by the highest (1%) wave in the January 2010—February 2011 series, one which was 19.4 m high ($1.67 \times 11.6$ m) in November 2010 (Fig. 11, see 11/10 max); the corresponding period for a fully arisen sea is 22 s. This maximum wave would be capable of moving boulders of about 3.5 t (equivalent to a granite sphere of diameter 1.4 m) at the shoreline on a gently sloping coast (2°) and of about 2 t (granite sphere diameter 1.1 m) on a more steeply sloping coast (5°). The movement of much larger boulders and blocks must occur very infrequently, under extreme wave conditions. Near Lisbon, Portugal, for example, two blocks of 8 and 14 t were moved short distances landwards on a narrow shore platform by translational bores generated by a single storm, which produced waves with a significant height of about 13 m (Oliveira et al., 2011). Because of the decline in bore height with distance from the breakers, even higher and more infrequent waves than those considered in the Galician analysis would have to break close to very large rocks in order to move them. It is significant therefore that the very coarse boulders and fine blocks at Baredo and Punta do Bazar, the largest in the study areas, lie on top of steeply sloping headland domes which are surrounded by fairly deep water during storm surges and high tides (Figs. 8 and 10). It is also significant that the megaclasts at Punta do Bazar (Fig. 10A,B) migrated landwards over a smooth structural surface, given that movement may not occur over surfaces with bed roughness elements with length scales in the order of ten percent of clast height (Weiss, 2012).

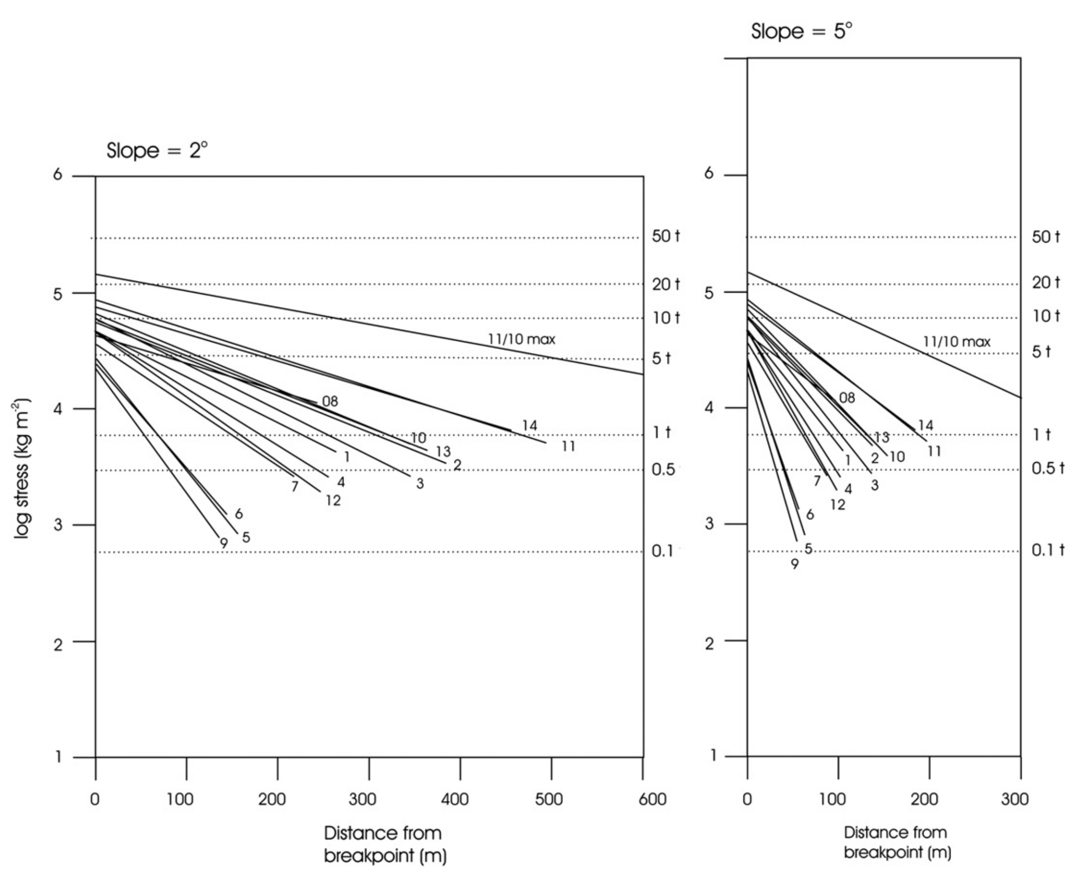


**Fig. 11.** Calculated wave stresses (monthly maximum) against distance shorewards from the breakpoint for January 2010 (line 1) to February 2011 (line 14) (based on significant wave height and peak period data from Puertos del Estado). Each line terminates at the shoreline. The horizontal lines show the stress required to move blocks of 0.1 to 50 t, with corresponding diameters (of a granite sphere of the same mass) of 0.4 to 3.3 m.

### 5.2. Boulders and shore platform evolution

There is an important two-way relationship between the boulders and the platforms. Whereas the boulders are produced by erosion of the platforms and para-periglacial and fluvio-nival deposits in the cliff, they can subsequently, depending on their quantity and mobility, promote or inhibit further erosion. Immobile or infrequently mobile boulders protect the underlying platform from mechanical wave erosion, and where they are in large numbers they inhibit drying of the underlying rock surface and consequently, weathering by wetting and drying and salt crystallization (Stephenson and Kirk, 2000; Porter et al., 2010a). Mobile blocks cause abrasion and impact lowering of the rock surface (Blanco Chao et al., 2006, 2007), although the abrasive efficacy of large boulders is limited by their spatially and temporarily limited mobility. Consequently, tightly packed boulders protect almost the entire platform surface at Laxe Brava and at a few other places on the Barbanza Peninsula (Fig. 3). In southern Galicia, where boulder deposits are less extensive, the distribution of recent surface striations and scars observed in this and previous studies suggests that boulder abrasion and impact is most effective in the mid- to lower high tidal zone, where the movement of isolated boulders promotes lowering and widening of channels and platform surfaces (Blanco Chao et al., 2006, 2007) (Fig. 9). Conversely, platform surfaces are protected by dense accumulations of largely immobile boulders in the upper high tidal and supratidal zones, and in the lower, seaward portions of many channels. The general absence of boulders on low-lying contemporary platform surfaces graded to present sea level, and on high, inter-channel areas of probable MIS 5 age, promotes wave quarrying and weathering on the more seaward portions of the intertidal zone (Fig. 8).

The gradient of fine sand to pebble and cobble beaches is determined by the relative strength of the uprush and downrush, and it increases with grain size and percolation efficacy (Doornkamp and King, 1971). The gradient of boulder deposits on shore platforms, however, is determined by such factors as the wave regime, gradient and regularity of the platform surface, mass, sphericity, and other determinants of boulder mobility, and inter-boulder interactions, including shielding, trapping, imbrication, packing, and other factors. Because of these mechanisms, the boulders on the Barbanza Peninsula (Laxe Brava, Faro de Corrubedo, Punta de Corrubedo) are largest in the lower, seaward portions of the profiles. In contrast to sand and gravel beaches, however, the largest boulders produce the most gently sloping beaches in this area, probably reflecting the low gradient of the seaward portions of the underlying shore platforms (Figs. 7 and 8).

The slope of a shore platform must be low enough or uneven enough to prevent quasi-spherical boulders from rolling seawards or into adjacent channels; flatter forms would be able to rest on much steeper slopes. Boulders role seawards when

$$mg \sin\theta > \mu \, mg \cos\theta$$

For a single, unobstructed boulder on a smooth granitic surface, seaward rolling would have occurred when platform gradient was equal or greater than about 38°, 30°, 21°, and 11° for $\mu$=0.8, 0.6, 0.4, and 0.2, respectively; these critical gradients would likely have been much higher because of bedrock scarps, previously deposited boulders, and other obstructions. Most seaward rolling would have taken place on steep slopes during the early stages of platform development, although it can still occur today down the sides of deep, joint-controlled corridors. Once platform gradients had become low enough, most boulders derived from cliffs would have been retained near the cliff foot, whereas those eroded from the platform would have been carried landwards by storm waves (Fig. 12, a and b). On the low lying Barbanza Peninsula, which has no cliffs, landward transport of material eroded from the platform accounts for the tendency for a corresponding decrease in the size of the boulders. The platform

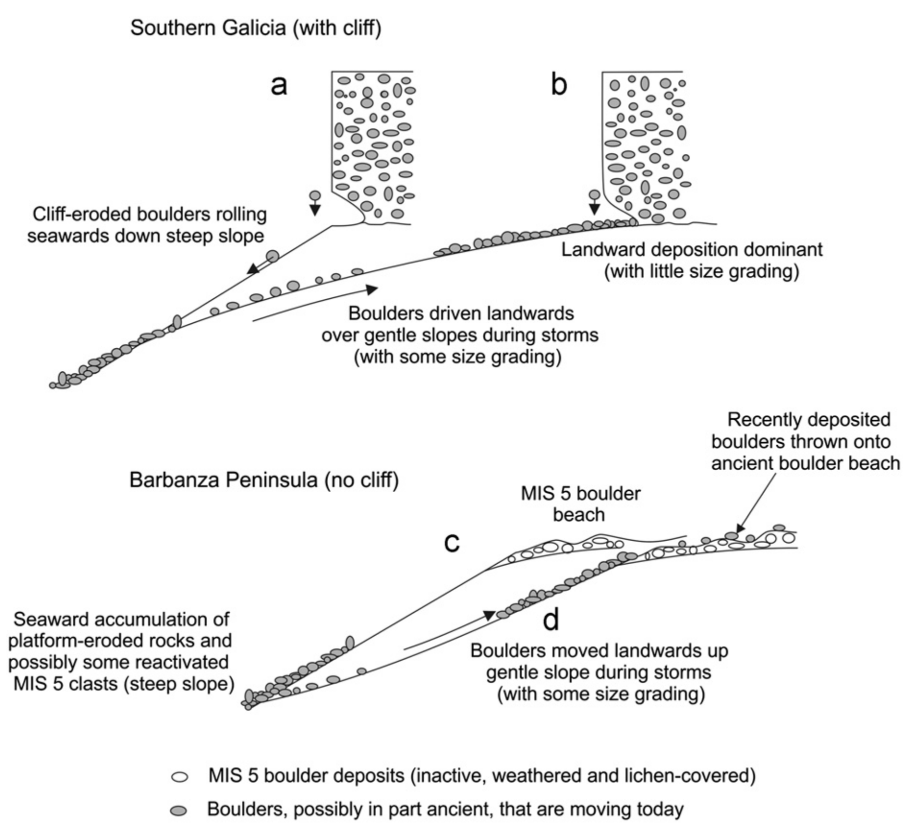


**Fig. 12.** Conceptual model of boulder transport and accumulation on the shore platforms of southern Galicia and the Barbanza Peninsula.

and boulder beaches in this area may be steeper in the upper than in the lower intertidal zone (Figs. 7 and 8) because of earlier burial and protection as the beaches extended seawards during the Holocene, or because the upper portion remained buried under MIS 5 boulder beach deposits and was never exposed to wave attack during the Holocene (Fig. 12c, d).

Platform gradients have been determined in this study and also during previous research in and near to the present study areas (Trenhaile et al., 1999; Blanco Chao et al., 2003, 2007). Trenhaile (1987, 1999) suggested that, in places with little sedimentary cover, mean regional platform gradient increases with the mean spring tidal range ($m$), although gradient also increases with the hardness of the rocks. The relationship between gradient and tidal range suggests that bare platforms in Galicia should have a slope of between about 1° and 2° (Fig. 13a). Low gradients of between 0.3 and 0.8° on the largely boulder-free platform at Caamaño, a few kilometres north of Laxe Brava (Fig. 2), are therefore fairly consistent with the tidal range, given the softness of the rocks at that site (Schmidt Rock Test Hammer rebound values of 10 to 21) (Trenhaile et al., 1999). Elsewhere on the Barbanza Peninsula and in southern Galicia, the overall gradient of shore platforms which have both bare and covered areas (partially covered) range from about 1.5 to 4.6°, which is generally higher than expected according to the tidal range, even when one includes the effect of the harder rocks in this area (Rock Hammer rebound values of 38 to 55)(Blanco Chao et al., 2007). At Laxa Brava and Punta de Corrubedo, where the platforms are almost completely covered by boulders, gradients range from less than 7° up to more than 11° (Fig. 13b).

The presence or absence of large, loose material also appears to affect the width of the shore platforms in this area, although this relationship is obscured in places by the occurrence of profile

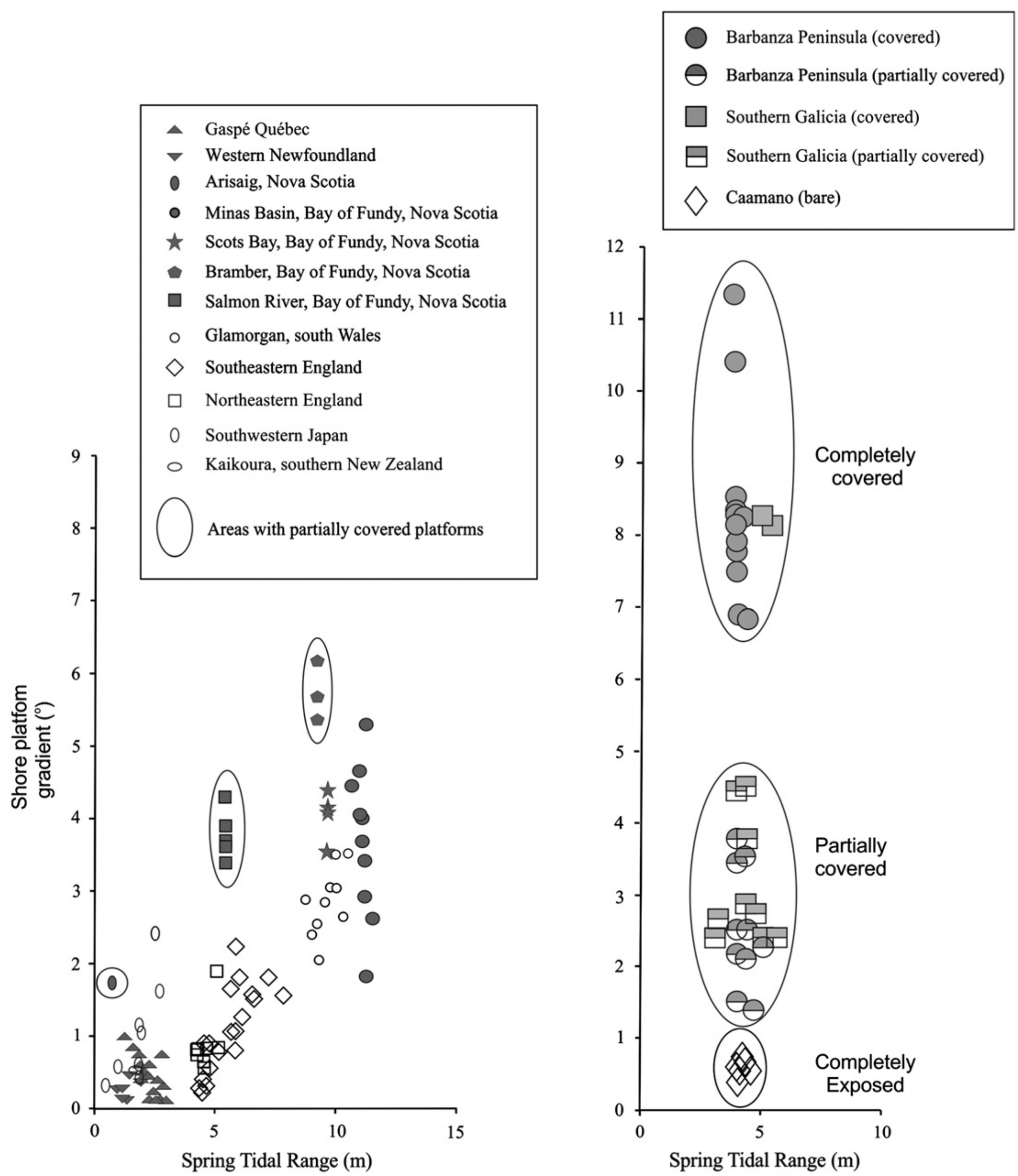


**Fig. 13.** (a) The relationship between mean regional shore platform gradient and tidal range in various parts of the world (each point represents the mean of a number of survey profiles). In contrast to the other areas plotted on this graph, the platforms at Salmon River, Bramber, and Arisaig in eastern Canada are partially covered by sediment and cliff debris. (b) The effect of boulder accumulation on platform gradient in southern Galicia and the Barbanza Peninsula.

elements that have been inherited from the last interglacial. The bare platforms at Caamaño (Trenhaile et al., 1999) range from about 70 to 120 m in width, compared with only 40 to 70 m for platforms that are completely buried under boulder beaches on the Barbanza Peninsula and in places on the southern Galician coast. Other largely bare platforms, with isolated boulders and boulder beaches at the rear, range from 50 m to more than 180 m in width in southern Galicia, although only portions of the wider platforms have adjusted to the present level of the sea (Fig. 8).

The results of this research suggest that there is a relationship between the gradient and to some degree the width and profile shape of shore platforms in Galicia and the occurrence and amount of loose, boulders (Fig. 13b). In supply-limited environments, erosion has reduced extensive areas of bare platform to gently sloping surfaces consistent with the tidal range and rock hardness. Conversely, in transport-limited environments, once platform gradients had become low enough for boulder deposition, rapid accumulation buried and subsequently protected platform surfaces, arresting their development and preserving their slope.

Although platform gradient in areas with little sediment is determined by tidal range, rock resistance, and possibly Holocene relative sea level history (Trenhaile 2010) (Fig. 13), the results presented in this paper suggest that, in areas with abundant coarse material, it may also be influenced by the amount and grain size of the sediment. In eastern Canada, for example, the effect of a partial sediment cover at Salmon River (fine boulders) and at Bramber and Arisaig (coarse to fine rocky debris) may provide an explanation for their anomalously high gradients, relative to the tidal range, in comparison with other areas with little or no sediment (Porter et al. 2010a,b) (Fig. 13a). Trenhaile (1974) proposed that the gradient of a shore platform is just sufficient to remove cliff and platform debris. Theory suggests that sand and small pebbles cannot accumulate on platforms that have gradients that are greater than the equilibrium gradient of the beachface (Trenhaile, 2004b). Conversely, large boulders can only accumulate on shore platforms that have attained critical gradients, for a given platform and boulder roughness, which are low enough to prevent their rolling seawards. The accumulation of a fairly thick and essentially immobile layer of sediment would tend to preserve the critical gradient of shore platforms, although the movement or removal of thin deposits during storms would allow some evolution to continue through abrasion and wave quarrying.

If, as suggested in this paper, there is a relationship between sediment grain size and shore platform gradient in sediment-abundant regions it would have important implications for the occurrence of sloping and sub-horizontal shore platforms. Although it remains to be determined whether there is a causal relationship, it is interesting to note that sub-horizontal platforms are particularly common in fine-grained argillaceous rocks that weather fairly easily, producing sediment that is transported seawards in suspension. The presence of low tide cliffs and other abrupt termini on sub-horizontal platforms also inhibits the landward return of coarser bed load sediments transported seawards during storms. Conversely, sloping shore platforms often develop in storm wave environments where coarse debris, eroded from the platform and cliff by mechanical wave erosion, accumulates on the platform surface.

Although the role of sediment on shore platforms has been largely ignored in the past, future work should be undertaken to examine the effect of fine to coarse sediments on weathering and erosional processes, and on short- and long-term platform development. This research is needed not only to better understand shore platform development in the past but also, with rising sea level and possibly increased storminess, in the future.

## 6. Conclusions

The main conclusions of this paper are:

(1) Large boulders to megaclasts are being moved across the shore platforms of Galicia by large storm waves, to elevations extending well above the present high tidal level.
(2) These boulders play an important erosional, and probably more importantly, protective role in the evolution of the shore platforms, especially where they are adjusting to the present level of the sea.
(3) Sediments in transport-limited environments play an important, albeit neglected, role in the development of shore platforms.
(4) Because of the effect of large amounts of sediment in arresting platform development, and the relationship between sediment grain size and equilibrium slope, the gradient of shore platforms tends to increase with the coarseness of the sediment that covers them.

## Acknowledgements

The participation of HIC and AP was under the framework of the PEst-C/CTE/UI4035/2011/2012 (GeoBioTec|UA), CARTGALICIA project (LABCARGA|ISEP – LTA|USC – Xunta de Galicia, 2010/11) and re-equipment program (LABCARGA-IPP-ISEP|PAD'2007/08). AP holds a doctoral scholarship from the Portuguese Foundation for Science and Technology (FCT|SFRH/BD/43175/2008), and AT was supported by a grant from the Natural Sciences and Engineering Research Council of Canada. The authors thank M. A. Freire Boado for his help in the graphical design, and two anonymous reviewers for their comments.

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# CHAPTER 8

# P7

## SYNOPSIS

*This publication is concerned with methodological approaches in mixed environments. A coastal geoengineering integrated system for rocky coast assessment was proposed and applied in two granitic key-sites in NW Iberia. The main stages of the study comprise six steps: (i) high-resolution aerial imagery surveys; (ii) visual inspection and systematic monitoring; (iii) applied field datasheet; (iv) in situ evaluation; (v) scanline survey; (vi) coastal geosciences engineering GIS based mapping. This work addresses a methodological approach to assess the rock strength – rebound values (R) and hardness values (HDL), in a fissured rocky coast context. There were selected two key-sites in NW Portugal (Lavadores, Gaia) and Galicia (Aguiño, Ribeira). The Schmidt Hammer (L type) and Equotip were applied to measure the rebound and hardness, respectively, in rocky platforms, geoforms and coastal boulders. Up to thirty measurements were taken along each scanline transect, in clusters of twenty five values around the site of each station. Additionally a detailed description of rock mass and a geologic-geotechnical evaluation in the rocky platforms was performed. The role of the durability on geomaterials for coastal geomorphology and rock engineering structures is the main issue to develop an integrated methodology related with rock characterisation. The current rock project is of great interest especially to coastal dynamic areas which have increasingly shown their weakness facing climate change and erosion problems. Due to impacts caused by the expansion of urban areas and unsatisfactory territorial planning, a correct approach to coastal geomorphology, geoengineering issues and geomechanical testing assessment to support coastal management and planning is required. These two studied areas have comparable geological characteristics but with very distinct coastal environments. In both cases it was possible to apply procedures and mythologies that couple geomorphological issues with coastal geoengineering aspects. The main conclusions of this paper are: (i) Aguiño studied site comprises a particular geomorphological setting, with a rocky platform which is used mainly as a foundation for the maritime work and narrow sandy areas along the shore; (ii) Lavadores shore platform and coastal boulders were characterised in terms of coastal dynamics and boulder (clast) mobility, as well as it was possible to define geotechnical zonings in terms of geological and geomorphological characteristics of the area and geomechanical parameters obtained in situ; (iii) in situ strength tests enabled the hardness/rebound assessment of the rock material, in rocky platforms, coastal boulders, geoforms (pot-holes) and in the armourstone placed along the groyne's armour layer; (iv) the thematic GIS maps displayed could be very useful in the future to determine zones of vulnerability to coastal erosion, hydraulic structure silting up, and for modelling, geohazard and regional/local assessment for coastal management.*

*Rock Engineering and Rock Mechanics: Structures in and on Rock Masses – Alejano, Perucho, Olalla & Jiménez (Eds)*


# Rock strength assessment and structural features analysis on rocky coasts

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ABSTRACT: This work addresses the rock matrix strength comparative analysis on rocky coasts. A coastal geoengineering integrated system for rocky coast assessment was proposed and applied in two fissured granitic key-sites in NW Iberia (NW Portugal, and Galicia). The main stages of the study comprise six steps: (i) high-resolution aerial imagery survey; (ii) visual inspection and systematic monitoring; (iii) applied field datasheet; (iv) in situ evaluation; (v) scanline survey; (vi) coastal geosciences engineering GIS based mapping. The Schmidt Hammer and Equotip tester were applied to measure the rebound and hardness, respectively, in rocky platforms, geoforms and coastal boulders. Moreover a detailed description of discontinuities and a geologic-geotechnical evaluation in the rocky platforms was performed. The current rock project is of great interest especially to highly dynamic coastal areas. This approach evolving geomorphic processes, geoengineering issues and geomechanical testing assessment contributes to support coastal management/planning.

## 1 INTRODUCTION

The coast comprises a complicated and dynamic transition between the marine environment and the terrestrial environment (Davis 2002). It also includes a wide range of areas, topographies, and geologic settings (Trenhaile 2002, Woodroffe 2003, Bird 2008). Along many coastal areas, this boundary is defined by the so-called rocky coasts (e.g. Sunamura 1992, Trenhaile 2002, Naylor et al. 2010, Trenhaile 2011, Pérez-Alberti et al. 2012, Stephenson et al. 2013). The designation "rocky coast" is currently used to refer to coasts that have fissured rocky substrates in the form of shore platforms with or without coastal boulders (i.e., rock blocks) (e.g., Trenhaile 2002, Nott 2003, Pérez-Alberti et al. 2012). This work is primarily concerned with the methodological approach to assess the rock strength – rebound values (R) and hardness values (HDL) – already applied by several authors in different approaches (e.g., Verwaal & Mulder 1993, Kahraman 2001, Kahraman et al. 2002, Aydin & Basu 2005, Aydin 2009, Pires et al. 2009a, Proceq 2012, Pires et al. 2013). Likewise essential in this study were the coastal processes operating on rocky coasts (dynamics and forcing conditions), as well as the geostructural features (e.g. geology, geomorphology, tectonics) and geomechanical evaluation that are mentioned and discussed. The main objective of this study is to propose an integrative coastal geoengineering approach for the geomechanical testing assessment in rocky coasts applied in different coastal environments with diverse perspectives.

## 2 STUDIED SITES

This paper presents the Aguiño, Ribeira (NW Galicia, Spain) and Lavadores, V.N. Gaia (NW Portugal) case studies (Fig. 1).

Aguiño site (Figs. 1a and 1a[1]) has a really distinctive and active coastline with different geological, geomorphological, topographical features and potential landslides associated with these features (Trenhaile et al. 1999, Blanco-Chao et al. 2007, Pérez-Alberti et al. 2013). Ribeira's area is mainly a rocky coast with a few mixed systems along the littoral such as sandy beaches, dunes and a hydraulic structure (groyne) founded in the rocky platform. The rocky coast in Aguiño site is mainly comprised by biotitic granodiorite (Pérez-Alberti et al. 2012, and references therein).

Lavadores site (Figs. 1b and 1b[1]) is also characterised by a mixed coastal system comprising rocky platform with boulders and mega boulders, sandy beaches, breakwaters and groynes. Immediately north of this site, a sand spit of about 0.7 km length exists, which narrows the mouth of an important Iberian river, the Douro River. The regional geology of Lavadores site is comprised mainly by medium to coarse grained

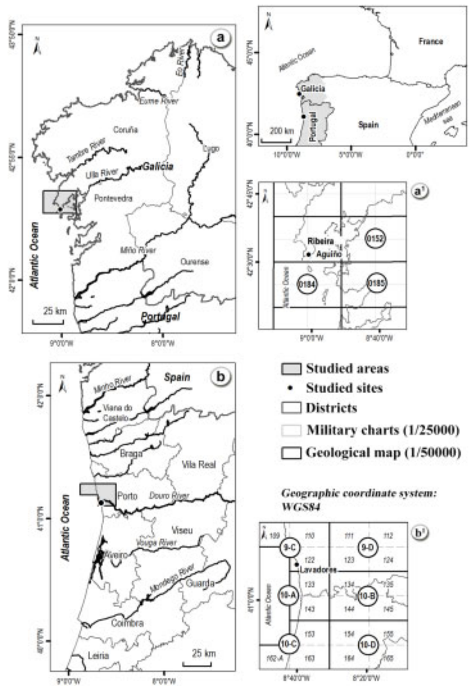


Figure 1. Cartographic framework of the research region and sites of Spain (Galicia) and Portugal.

granitic rocks and gneisses (e.g., Matos Alves 1966, Teixeira 1970, Canilho 1975, Vinha da Silva & Neiva 1999, Gomes et al. 2002, Chaminé et al. 2003).

These two sites are very distinct coastal environments but similar in terms of geological characteristics and significant stretches of rocky coastline.

## 3 METHODOLOGY

In this section it is presented the synthesis of procedures used and the workflow of the research for the coastal geoengineering integrated system in rocky coast assessment (Fig. 2). Definitely GIS mapping is intrinsic to this investigation, but there is an integrated system already tested on maritime environments (Pires & Chaminé 2007, 2009, Pires et al. 2009b, 2013). This approach is a step forward to the study of different coastal environments by using almost the same methodologies. The development of the applied cartography embraces six stages, which will allow the production of detailed maps of the maritime environment and the geomechanical assessment (Fig. 2). *Stage A* takes advantage of high resolution imagery by means of an airborne platform and photogrammetric techniques coupled with applied cartography in a georeferenced GIS database. *Stage B* concerns to visual inspection on the field, which are always made above-water, and allowing the observation of

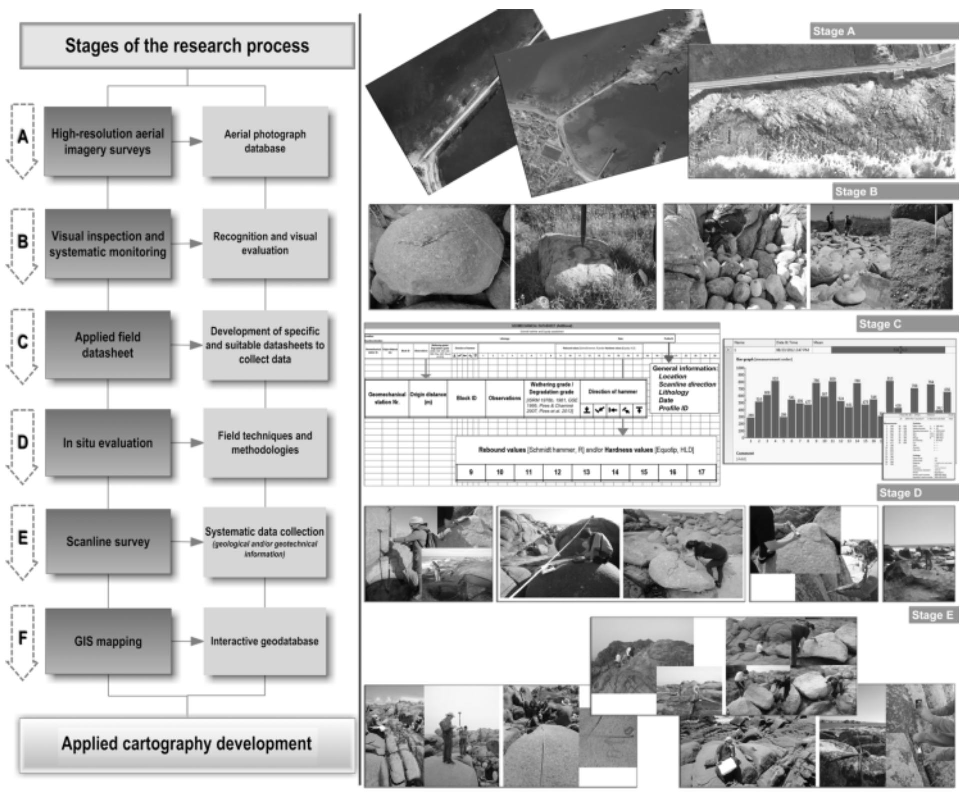


Figure 2. Flowchart with the main stages or procedures during the research process.


Figure 3. Example of mixed coast of Aguiño groyne with rocky platform: (a) and (b) general overview of the studied sector; (c) and (d) GIS mapping of all the geomaterials.

different aspects by using the comparative photography set. *Stage C* comprises the development of specific and suitable field datasheets to collect data and synthesise all the gathered data within a geodatabase of information. There were developed four types of datasheets for different evaluations: (i) maritime structure; (ii) boulder beach; (iii) geoform characterisation; and (iv) support datasheets (example in Fig. 2). *Stage D* comprises in situ evaluations which concerns to diverse field techniques and methodologies.

There was applied the high-accuracy GIS data collection system (Trimble® GPS technology) providing georeferencing information and integrated in the GIS plataform. The Original Schmidt hammer type L/LR (Proceq®) was applied to assess the rebound values. Over the years this equipment has been increasingly applied in the characterisation of rock materials (Aydin & Basu 2005, Aydin 2009). In general this evaluation is made on the basis of laboratory or field tests (e.g. ISRM 1978a, 1981, Katz et al. 2000, Kahraman 2001, ASTM 2001, Kahraman et al. 2002, ISRM 2007). The fields of action are broader and

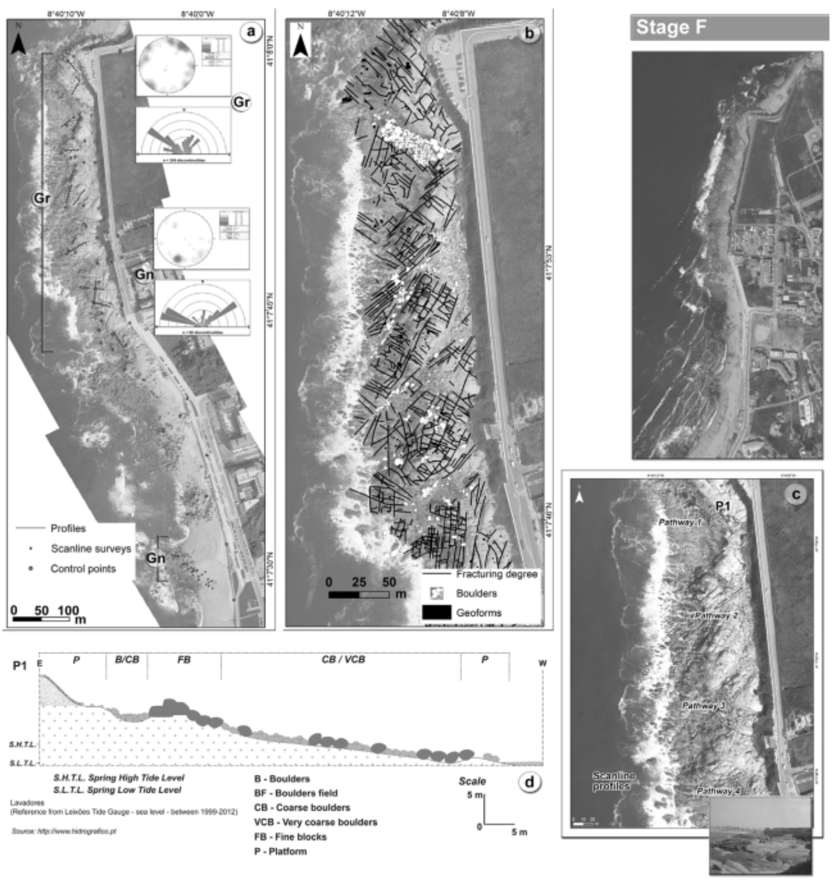


Figure 4. Lavadores site assessment: (a) scanline surveys, geomechanical evaluation and geologic characterisation with geostructural diagram plots examples for granite (Gr) and gneiss (Gn) areas; (b) coastal geomorphic mapping which includes boulders' mobility analysis and geoforms inventory (potholes mapping); (c) profiles location and boulder pathways; (d) beach profile P1 was based on the revised Udden-Wentworth scale to describe the size of boulders and other large rocks block size (Blair & Mcpherson 1999).

therefore this type of equipment is also applied in different maritime environments like rocky coasts, coastal boulders and shore platforms or in distinctive geomorphological contexts and using different approaches (e.g. Goudie 2006, Viles et al. 2011, Proceq 2012). In this study Equotip tester was employed to measure hardness in coastal boulders. The equipment allows data to be downloaded/uploaded from/to a PC using Equolink, the linking software for Proceq® (example of the software outputs in Fig. 2). *Stage E* displays the sampling collection along a scanline which is an accurate and fast method for representative data compilation (Pires & Chaminé 2009, Chaminé et al. 2013). In this particular work the scanline was applied with a different approach providing support for the characterisation of the blocks or discontinuities intersected by the fiberglass tape measure. This stage represents the systematic data collection in terms of geological and/or geotechnical information and show the scanline technique applied to rocky coasts or shore platforms (Fig. 2). Finally, *Stage F* is the result of the GIS-based mapping, applied cartography and final outputs it will be presented in the results section.

## 4 RESULTS AND DISCUSSION

The outcome of the *Stage F* combines coastal geosciences GIS mapping and high-resolution digital imagery. Two types of results are presented: (i) GIS mapping and structural features; and (ii) geomechanical testing assessment. Some of the results are displayed in Figures 3 and 4 and the proposed approach is summarised in Table 1.

The Aguiño site is comprised by a mixed environment with a rocky platform and a groyne (Fig. 3). There were performed 4 scanlines in the rocky platform and carried out a geological, geotechnical and geomechanical characterisation for discontinuities and rock mass features or properties including different elements, specifically: (i) general description of the outcrop; (ii) basic structural geology description; (iii) weathering grade (GSE 1995); (iv) basic geotechnical description of fissured rock mass (ISRM 1978b, 1981, Zhang & Einstein 2000, Naylor & Stephenson 2010, Feng et al. 2013); (v) in situ geomechanical evaluation.

The same procedure was then tested in the armour layer (superficial component) of the Aguiño groyne and more than 12000 blocks or polygons were vectorised in a GIS environment (Fig. 3). Aguiño maritime structure uses the rocky platform as a foundation, so this type of coastal protection solution offers numerous features to be analysed and characterised. There is an intrinsic relationship between the artificial maritime design/construction and the natural rocky coast. The detailed cartography allowed us to obtain interesting results and encompasses coastal geomorphology, rock engineering and coastal dynamic data. This holistic approach allowed the study of coastal geomorphology and geoengineering along the Aguiño site.

The same approach was made for Lavadores site along 19 scanlines in the rocky coast (Fig. 4a). Table 1

Table 1. Synthesis of results and measurements to assess the rebound and hardness values in the studied sites.

| Site | | Scanline (SL) | Length (m) | Nr. of stations | Rebound value (Schmidt, R) (Average) | |
|---|---|---|---|---|---|---|
| Aguiño, Ribeira (NW Galicia) | Rocky platform | 1 | 38.5 | 14 | 27.5 | |
| | | 2 | 27 | 10 | 29.3 | |
| | | 3 | 13.5 | 10 | 35.6 | |
| | | 4 | 18.5 | 10 | 28.9 | |
| | | **Profile (P)** | **Length (m)** | **Nr. of stations** | **Rebound value (Schmidt, R) (Average)** | |
| | Groyne (Geomaterials) | 1 | 50 | 11 | 40.5 | |
| | | 2 | 50 | 11 | 29.3 | |
| | | 3 | 50 | 11 | 36.1 | |
| | | 4 | 50 | 11 | 38.7 | |
| | | 5 | 50 | 11 | 31.1 | |
| | | 6 | 50 | 11 | 43.3 | |
| | | 7 | 50 | 11 | 34.9 | |
| **Site** | | **Pathway/Profile (Path/P)** | **Length (m)** | **Nr. of stations** | **Rebound value (Schmidt, R) (Average)** | **Hardness value (Equotip, HLD) (Average)** |
| Lavadores, V.N. Gaia (NW Portugal) | Boulders | 1/1 | 60 | 62 | 58.9 | 693.2 |
| | | 2/1 | 40 | 39 | 51.1 | 571.4 |
| | | 2/2 | 20 | 25 | 59.3 | 602.3 |
| | | 2/3 | 30 | 22 | 62.9 | 600.7 |
| | | 3/1 | 20 | 20 | 49.3 | 633 |
| | | 3/2 | 20 | 25 | 57.1 | 581.1 |
| | | 3/3 | 20 | 14 | 63.7 | 712.6 |
| | | 4/1 | 20 | 24 | 50.4 | 610.5 |
| | | 4/2 | 20 | 15 | 50.7 | 734.8 |
| | | **Scanline (SL)** | **Length (m)** | **Nr. of stations** | **Rebound value (Schmidt, R) (Average)** | |
| | Rocky platform | 1 | 33 | 8 | 50.2 | |
| | | 2 | 11 | 4 | 28.9 | |
| | | 3 | 25.8 | 7 | 36.5 | |
| | | 4 | 33.5 | 8 | 72.9 | |
| | | 5 | 42 | 10 | 56.4 | |
| | | 6 | 26.3 | 7 | 34.1 | |
| | | 7 | 27.5 | 7 | 46.7 | |
| | | 8 | 49 | 11 | 62.7 | |
| | | 9 | 35.4 | 9 | 51.3 | |
| | | 10 | 49 | 11 | 45.2 | |
| | | 11 | 31.2 | 8 | 56.2 | |
| | | 12 | 49.8 | 11 | 50.97 | |
| | | 13 | 50 | 11 | 48.6 | |
| | | 14 | 40 | 9 | 47.7 | |
| | | 15 | 35.3 | 9 | 46.4 | |
| | | 16 | 12.7 | 4 | 41.9 | |
| | | 17 | 7.3 | 3 | 64.2 | |
| | | 18 | 10 | 3 | 64.1 | |
| | | 19 | 16.1 | 5 | 64.9 | |
| | | **Nr. of stations** | **Rebound value (Schmidt, R) (Average)** | | | |
| | Geoforms (Potholes) | 47 | 44.8 | | | |

displays the scanlines length, number of stations (25 measurements/station) and the rebound value (average) for each scanline assess. It was also perfomed in Lavadores site and along the scanline surveys, a geomechanical evaluation and geologic characterisation with geostructural diagram plots examples for granite (Gr) and gneiss (Gn) areas (Fig. 4a).

The study of the geoforms involved the assessment of coastal potholes measured randomly and their vectorisation (Fig. 4b and Table 1). There were measured the rebound values for 47 potholes along the platform to interrelate with other parameters such as the altitude, the proximity of the sea water or the weathering grade. These data allowed the coastal geomorphic mapping for Lavadores site.

Lavadores site was also under a coastal boulder evaluation with 4 identified pathways of boulders' mobility and 9 profiles along these pathways (Fig. 4c and Table 1). Not only it was possible to characterise this studied area in terms of coastal dynamics and boulder (clast) mobility but also it was possible to define coastal geoscience zoning maps in terms of geological and geomorphological characteristics of the area and geomechanical parameters obtained in situ. Figure 4b shows the boulders vectorisation in the rocky platform and the fracturing degree. It is possible to observe in Figure 4c and 4d the location of profile P1 and the schematic sketch of the coastal boulders in pathway 1 describing the size of boulders and other large rocks block size based on the revised Udden-Wentworth scale (Blair & Mcpherson 1999).

Finally, for the evaluation of the boulders' rock strength it was also tested different equipment besides Schmidt hammer. Equotip was used to measure the hardness values (HLD) in more than 200 blocks and to perform a comparative analysis between the rebound and hardness data (Table 1).

It is important to draw the attention for the quality of the geospatial data and imagery acquisition which was an important step in this approach. All the images were a fundamental part of the GIS platform/project in raster format. The measurement parameters were also important information and took into account regarding the block characterisation before the strength evaluation.

## 5 CONCLUDING REMARKS

The main conclusions of this paper are:

- The methodological integrative procedure presented herein couples coastal geoscience mapping and high-resolution digital imagery suitable for maritime environments evaluation in general;
- Aguiño studied site comprises a particular geomorphological setting, with a rocky platform which is used mainly as a foundation for the maritime work and narrow sandy areas along the shore; and Lavadores shore platform and coastal boulders were characterised in terms of coastal dynamics and boulder (clast) mobility, as well as it was possible to define geotechnical zonings in terms of geological and geomorphological characteristics of the area and geomechanical parameters obtained in situ;
- In situ strength tests enabled the hardness/rebound assessment of the rock material, in rocky platforms, coastal boulders, geoforms (potholes) and in the armourstone placed along the groyne's armour layer;
- Two different equipment (Schmidt hammer and Equotip) were applied which allowed to determine the rock strength in a simple and effective way;
- This research is essential to understand the coastal processes operating on rocky coasts (dynamics and forcing conditions), as well as the geostructural features and geomechanical assessment that are mentioned and discussed;
- Finally, the thematic GIS maps displayed could be very useful in the future to determine zones of vulnerability to coastal erosion, hydraulic structure silting up, and for modelling, geohazard and regional/local assessment for coastal management.


## ACKNOWLEDGEMENTS

The study was partially financed by FEDER-EU COMPETE Funds and FCT (GeoBioTec|UA: PEst-OE/CTE/UI4035/2014) and Labcarga| ISEP re-equipment program: IPP-ISEP|PAD'2007/08. A. Pires holds a doctoral scholarship from Portuguese Foundation for Science and Technology (SFRH/BD/43175/ 2008). We gratefully acknowledge F. Piqueiro (FotoEngenho) that provided high resolution aerial imagery. Special thanks are due to L. Freitas, S. Rajcic, C. Rodrigues, R.S. Silva, and P. Moreira for all the support in some stages of the fieldwork.


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# Rock strength assessment and structural features analysis on rocky coasts

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ABSTRACT

In the last years there has been a growing interest in rocky coast research (e.g. Trenhaile 2011, Pérez-Alberti et al. 2012, and references therein). A coastal geoengineering integrated system for rocky coast assessment was proposed and applied in two granitic key-sites in NW Iberia. The main stages of the study comprise six steps (Fig. 1): (i) high-resolution aerial imagery surveys; (ii) visual inspection and systematic monitoring; (iii) applied field datasheet; (iv) in situ evaluation; (v) scanline survey; (vi) coastal geosciences engineering GIS based mapping. This work addresses a methodological approach to assess the rock matrix strength – rebound values (R) and hardness values (HDL), in a fissured rocky coast context (e.g. Pires & Chaminé 2009, Proceq 2012, Pires et al. 2013).

There were selected two key-sites in NW Portugal (Lavadores, Gaia) and Galicia (Aguiño, Ribeira).

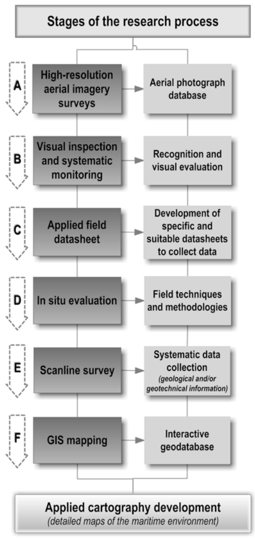


Figure 1. Flowchart with the main stages of the research process.

The Schmidt Hammer (L type) and Equotip were applied to measure the rebound and hardness, respectively, in rocky platforms, geoforms and coastal boulders. Up to thirty measurements were taken along each scanline transect, in clusters of twenty five values around the site of each station. Additionally a detailed description of rock mass and a geologic-geotechnical evaluation in the rocky platforms was performed. In addition, a geostructural study and geomechanical evaluation of the beach rocky platforms was made. The role of the durability on geomaterials for coastal geomorphology and rock engineering structures is the main issue to develop an integrated methodology related with rock characterisation. The current study is of great interest especially to dynamical coastal areas which have increasingly shown their weakness facing climate change and erosion problems. Due to impacts caused by the expansion of urban areas and unsatisfactory territorial planning, a correct approach to coastal geomorphology and geoengineering issues is required.

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# CHAPTER 9

# P8

## SYNOPSIS

*This publication emphasises the core of the thesis related to coastal geosciences GIS mapping and photogrammetric surveying. Digital photogrammetry and GIS-based mapping represent technologies that could be model based on GIS platforms in order to monitor and predict the evolution of coastal zones. This paper considers the interoperability framework from high-resolution imagery acquisition to the development of coastal geosciences maps. The layered system architecture of the cartographic methodology is also explained. Moreover, it highlights a new approach to assess heterogeneous geologic, geomorphological and maritime environments. In addition, coupling cartographic techniques and field surveying allows a tool chain interaction which will show the networking and clustering views from photogrammetric data and GIS-based mapping. This approach supports a methodological proposal to contribute to the monitoring of coastal zones and to evaluate the maritime forcing conditions. Furthermore, with accurate surveying techniques it is also suitable the assessment from rock shore basement to armourstone used in hydraulic structures. An integrated coastal geoengineering methodology was outlined in NW of Iberian Peninsula (South Galicia and North/Central Portugal regions). This approach will allow: (1) the acquisition of a large archive of high resolution imagery, (2) the development of a coastal database including all the field data and in situ assessments, (3) the study of coastal dynamics and shoreline evolution, (4) the rock platforms and hydraulic structures assessment, (5) the production of coastal geosciences maps. The architecture of this study is presented, coupling photogrammetric techniques with applied cartography, endorsing GIS software as a powering tool to encompass, not only several layers and inputs, but also thematic output maps. The aim is to present a new concept for the use of photogrammetric image acquisition to achieve modelling techniques, develop spatial analysis and coastal conceptual models. In addition, this study also highlights that applied cartography techniques, supported by Geographical Information Systems and Science (GIScience), are very suitable to obtain valuable information for the management of maritime environments, particularly when accuracy, cost and efficiency are considered. This research highlights digital photogrammetry and GIS-based mapping as powerful tools in littoral issues. This is more a methodological research linked to cartographic techniques, field surveys, research theory and practice, and management in littoral zone and coastal geoengineering surveying.*

Environ Earth Sci (2016)75:196
DOI 10.1007/s12665-015-4936-z

ORIGINAL ARTICLE

# Combining coastal geoscience mapping and photogrammetric surveying in maritime environments (Northwestern Iberian Peninsula): focus on methodology

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Received: 28 October 2014 / Accepted: 22 August 2015


**Abstract** Digital photogrammetry and GIS-based mapping are increasingly recognised as powerful tools in littoral issues. This paper considers the interoperability framework for high-resolution imagery acquisition and the development of coastal geoscience maps. The layered system architecture of the cartographic methodology is also explained. Moreover, it highlights a new approach to assessing heterogeneous geologic, geomorphological and maritime environments. The main goal of the present study was to test a new concept for photogrammetric images in order to assist modelling techniques, spatial analysis and coastal conceptual models. This approach proposes a methodological approach to coastal zone monitoring and to maritime forcing conditions evaluating. This approach will allow: (1) the acquisition of a large archive of high-resolution imagery; (2) the development of a coastal database including the entire data field and in situ assessments; (3) the study of coastal dynamics and shoreline evolution; (4) the assessment of the rock platforms and hydraulic structures; (5) the production of coastal geosciences maps. An integrated coastal geoscience and engineering methodology was outlined in NW of Iberian Peninsula (South Galicia and North/Central Portugal regions). This paper reports on the increased knowledge of the studied regions, providing essential data concerning coastal geo-morphodynamics. The overall assessment revealed additional evidence of erosion issues, which contributes to a better understanding of the hydraulic conditions. The main results are presented in regional coastal geoscience maps and local approach-outputs that could help government, local authorities and stakeholders to develop coastal management plans and to recommend strategies.

**Keywords** Maritime environments · Coastal geoscience mapping · Photogrammetry · NW Iberian Peninsula

**Electronic supplementary material** The online version of this article (doi:10.1007/s12665-015-4936-z) contains supplementary material, which is available to authorized users.

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## Introduction

Geographical information systems (GIS) represent an outstanding technology that is in constant development in mapping science. GIS applications are gradually becoming part of many scientific or technical studies, hence several open source software tools are available that are operational, fast and accessible (e.g., Goodchild 1992; Chacón et al. 2006; Liu and Mason 2009; Green 2010). According to Goodchild (2004, 2010) GIScience is an emerging concept dealing with the recognition and characterisation of the natural and/or social components to understand the mechanisms or processes toward an interaction level among geographic database systems. In fact, GIScience has an established history in coastal and marine applications (e.g., Wright and Bartlett 1999; Green and King 2003;

Bartlett and Smith 2004). In some studies the geoscientific context aims to summarise the techniques and principles that are useful in GIS applications within or connected with other fields (e.g., Liu and Mason 2009; Yu and Peuquet 2009; Green 2010; Reitsmaa 2013). Several studies have pointed out the value of merging various GIS techniques such as: image analysis and cartographic systems, geodatabase systems, photogrammetry and high-resolution imagery based mapping, global monitoring and 3D modelling techniques (e.g., Chandler 1999; Thumerer et al. 2000; Moore 2000; Lim et al. 2005; Genz et al. 2007; Addo et al. 2008; El-Hakim 2008; Addo 2013; Jordan 2015). There are a growing number of contributions on innovations and applications of GIScience in several scientific and technical branches (e.g., aerial surveying, urban geography, geosciences, water resources, engineering and military operations).

All these research fields connect with the real essence of this study, which is intrinsically related to engineering geoscience applications in maritime environments. The approach was closely followed by a transdisciplinary trend addressed by some authors such as Wickson et al. (2006); Kuhn (2012) and Wright (2012). A coastal GIS methodology needs to be an integrated coastal geoscience and engineering approach, with GIS and photogrammetric surveying of dynamic maritime environments. Such approaches should be established in a multidisciplinary and holistic context (e.g., Drummond et al. 1997; Buckley et al. 2002; Vallega 2005; CIRIA et al. 2007; Rogers et al. 2010; Pires et al. 2013, 2014a, b, 2015).

The conceptual framework described in Fig. 1 proposes the theoretical basis for a geoengineering approach in Integrated Coastal Zone Management (ICZM), which is related to this research. The coastal or maritime environment is one of the most dynamic and energetic interfaces between human society and environmental sustainability (e.g., Green and King 2002; Fröhle and Kohlhase 2004; Populus et al. 2004; Wang 2009; Addo 2013). In this GIS-based project all elements and processes considered are taken into account in the mapping framework. The proposed methodology is essential to anthropic intervention including hydraulic structures, and particularly the armour layer component (superficial and visible part of the structures), as described in Fig. 1. The relationship between all the processes, elements and forcing conditions allows the creation of several thematic geoengineering maps, as well as a better understanding of coastal morphodynamics. This holistic approach is inspired by the concepts, terminologies and methods proposed by Woodroffe (2003) and Pavlopoulos et al. (2009), associated with coasts and engineering geomorphology. In addition, GIS coastal mapping is also related to beach management and maritime engineering approaches presented in CIRIA et al. (2007) and Rogers et al. (2010). Likewise natural rock (armourstone) and artificial blocks (concrete) are important elements to take into account throughout the development methodology for geomaterials evaluation in hydraulic structures (Latham et al. 2006; Ciria et al. 2007; Pires and Chaminé 2009; Pires et al. 2009a).

The integrated coastal geoengineering methodology involves the quality of geospatial data and imagery acquisition. Recent evolution in such technologies has improved the assessment, monitoring and know-how in coastal studies. Mapping coastal features requires the combination of different techniques, such as photogrammetry, remote sensing and aerial imagery (Falkner and Morgan 2002; Pires et al. 2013). Digital photogrammetric techniques are frequently used to compare images and detect changes during a specific time period. There are various application fields: glacial movement, rock slide movement, long-term construction sites, advancing vegetation pathogens, wetlands evolution, urban growth charting, floods monitoring, erosion monitoring and natural hazards assessing (e.g., Chisholm 1990; Gillie 1992; Welch and Jordan 1996; Pérez-Alberti et al. 2013).

Historically, photogrammetric applications have relied upon aerial photographs as a basic tool. Their early development was mainly driven by military uses (e.g., Mikhail et al. 2001; Fleming et al. 2009; Jones and Reinke 2009). Later they became widely applied in civil use for applications including environmental issues, climatology, agriculture, engineering, cartography, water resources, coastal management, land planning and geohazards (e.g., Fleming et al. 2009; Wang 2009). The research procedure takes advantage of high-resolution imagery by means of an airborne platform. Although airplanes, helicopters, and lighter-than-air craft are employed as aerial photography vehicles, fixed-wing aircraft are the primary aerial photographic platform (Falkner and Morgan 2002; Cunha et al. 2006; Pires et al. 2009b) and also unmanned aerial vehicles the so-called micro drones (e.g., Jordan 2015; Pires et al. 2015).

The main goal of the paper is to propose a multidisciplinary framework approach that enables geo-professionals to pursue an innovative coastal geoscience and engineering methodology. Moreover, the integrated approach presented herein is important for proposing environmental strategies. The final target of this research would be to support regional authorities with reference to coastal or shoreline management concerns.

## Study area

The sites studied embrace a long stretch of coastline and involve a broad region of the north-west of the Iberian Peninsula (Spain and Portugal). The study comprises six main areas, two in Spain with eight specific sectors and

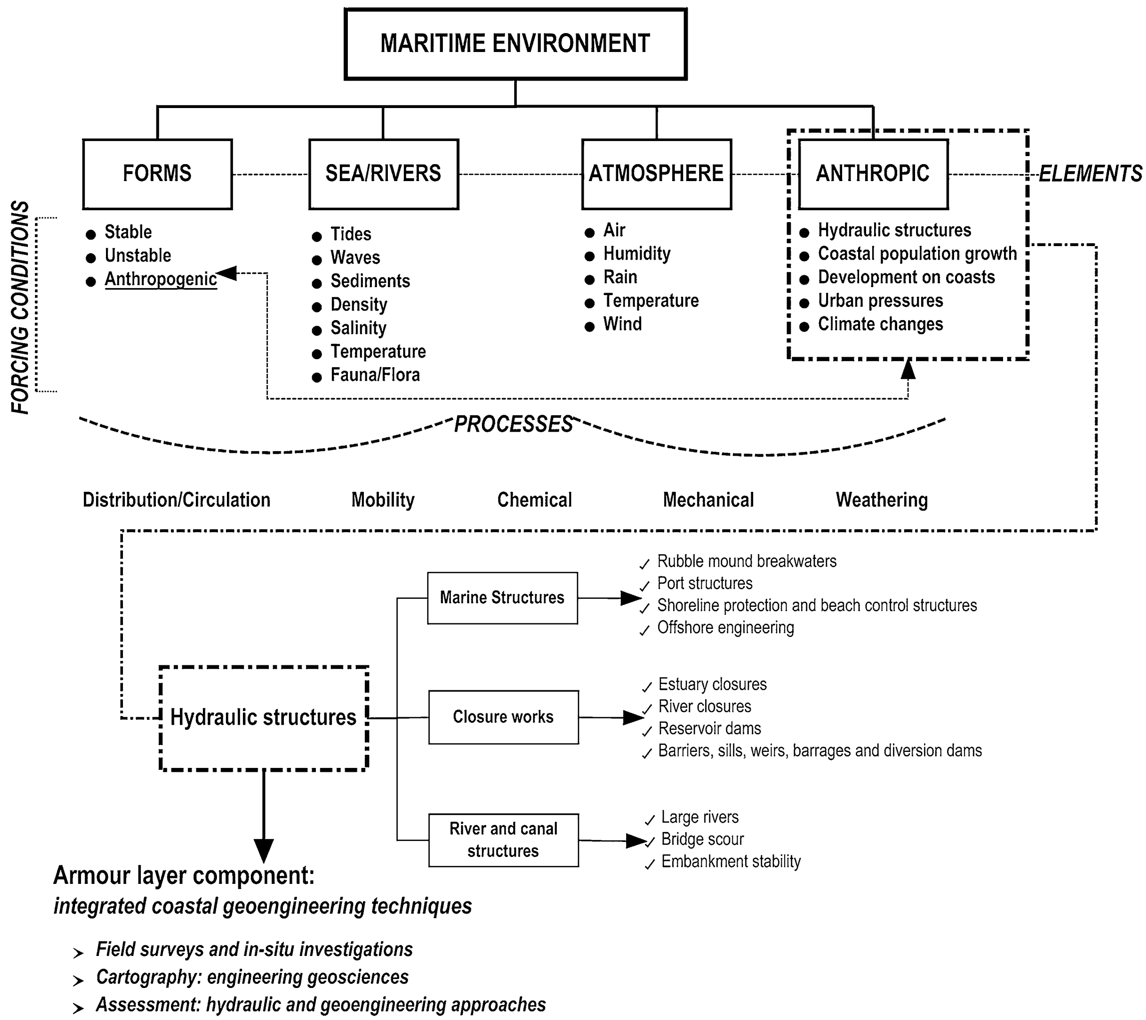



**Fig. 1** Conceptual framework and theoretical basis for coastal geoscience and engineering approach in integrated coastal zone management (ICZM)

four in Portugal with ten sectors (Fig. 2; see detailed description in Tables 1, 2). The Southern Galicia region (NW Spain) and the coastal stretch between Caminha and Figueira da Foz (north and central Portugal) extend more than 300 km. The region's coastline is very energetic, changeable and heterogeneous in terms of coastal dynamics. After the choice of the six studied areas (Fig. 2) the next stage of the research comprised the collection of aerial imagery for the GIS-based platform using digital photogrammetry. Three flight operations were made: (1) areas 1–3; (2) areas 4 and 5 and (3) area 6. Tables 1 and 2 display some examples of the high-resolution imagery acquired and also summarise the extent of the studied area, a description of each sector, as well as the ground control points used for image georeferencing. In this type of operation it is important to characterise the coastal region framework and the features of the site, such as physical behaviour, hydraulic constraints and forcing conditions. The results presented here are for two areas, Ribeira (Spain) and Espinho (Portugal), [1] and [5], respectively. Different GIS coastal applications were displayed for five sectors, including two rocky coasts (Laxe Brava and Corrubedo, in Spain) and three groynes (Aguiño, in Spain, and Carreira de Tiro and Casa Branca, in Portugal).

## Galicia and NW Portugal coastline: a general overview

The NW Iberian coastline is depressed by several rivers, inlets and bays. The shoreline has a very dynamic, heterogeneous and mixed coastal environment in terms of its coastal geology and geo-morphodynamics (e.g., Trenhaile et al. 1999; Dias et al. 2000; Pérez-Alberti et al. 2012). Ranging from a rocky shore or platforms to a diversified environment, the region also comprises sandy beaches and coastal protection works (Pires et al. 2013).

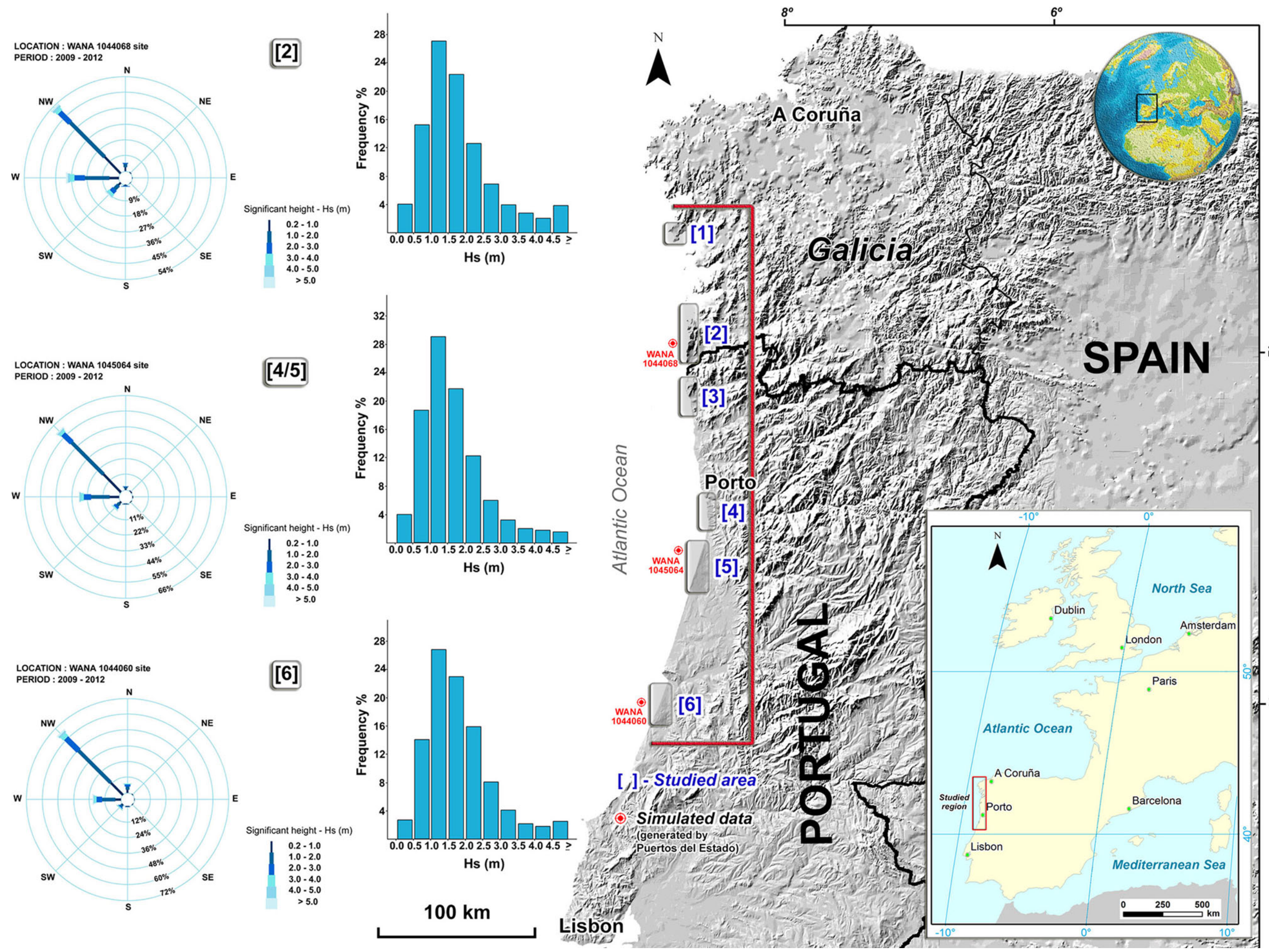



**Fig. 2** Studied sites—southern Galicia, Spain and north/central Portugal—and selected sectors for the photogrammetric assessment and GIS applications in NW Iberian Peninsula coastline (more details in Tables 1 and 2)

The wind factor is an important physical parameter in terms of wave direction or speed and must be taken into account when studying coastal dynamics and forcing conditions of the region. Generally dominant winds on the coast of Portugal are between N and NW, except in the winter, when the prevailing wind regime direction is from SW and is stronger than in the summer. Similarly, along the Galician coast the wind system in winter usually has a SW trend, while in spring and summer the wind has predominantly N and NW directions (NGA 2011; Puertos del Estado 2012). The forcing conditions, including mean wave height (Hs) and frequency (%), for the simulated data available along the study areas can be found in Fig. 2. Concerning the records, they were divided in two basic types: WANA and SIMAR 44 were both generated and distributed by *Puertos del Estado* (for more detail see Mendoza-Ponce and Quintana 2009, and references therein).

The maritime works that can be found along the coast between Portugal and Spain include a wide range of structures, such as harbours, breakwaters, groynes, jetties, seawalls or mixed solutions (Fig. 1). On rocky shores several geoforms were described along the coast and platforms, including boulders which in some places of Galicia have a very energetic and dynamic performance (e.g., Trenhaile et al. 1999; Blanco-Chao et al. 2007; Pérez-Alberti et al. 2012; Gómez-Pujol et al. 2014); the Laxe Brava site is an example of this (Area [1]). Vigo, Leixões, Aveiro and Figueira da Foz are the main commercial ports throughout the study area. There are other small ports for protection and fishing which are used by small craft and fishing vessels.

The Galician mainland adjacent to Area [1] is dominated by a mesotidal environment with a mean tide length of 2.5 m and a spring tidal range between 3.75 and 4 m (Pérez-Alberti et al. 2012, 2013). The Ribeira is mainly a rocky coast with a few mixed systems along the littoral such as sandy beaches and dunes. The Galician coast is about 2100 km long, including several islets and more than 380 hydraulic works along the coast (POLGalicia 2010).

**Table 1** Galicia (Spain) studied areas: description and characterisation with two examples of the high-resolution aerial imagery

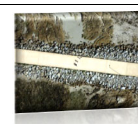
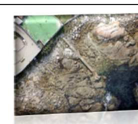
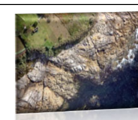
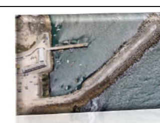
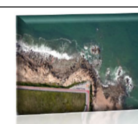
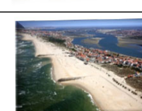
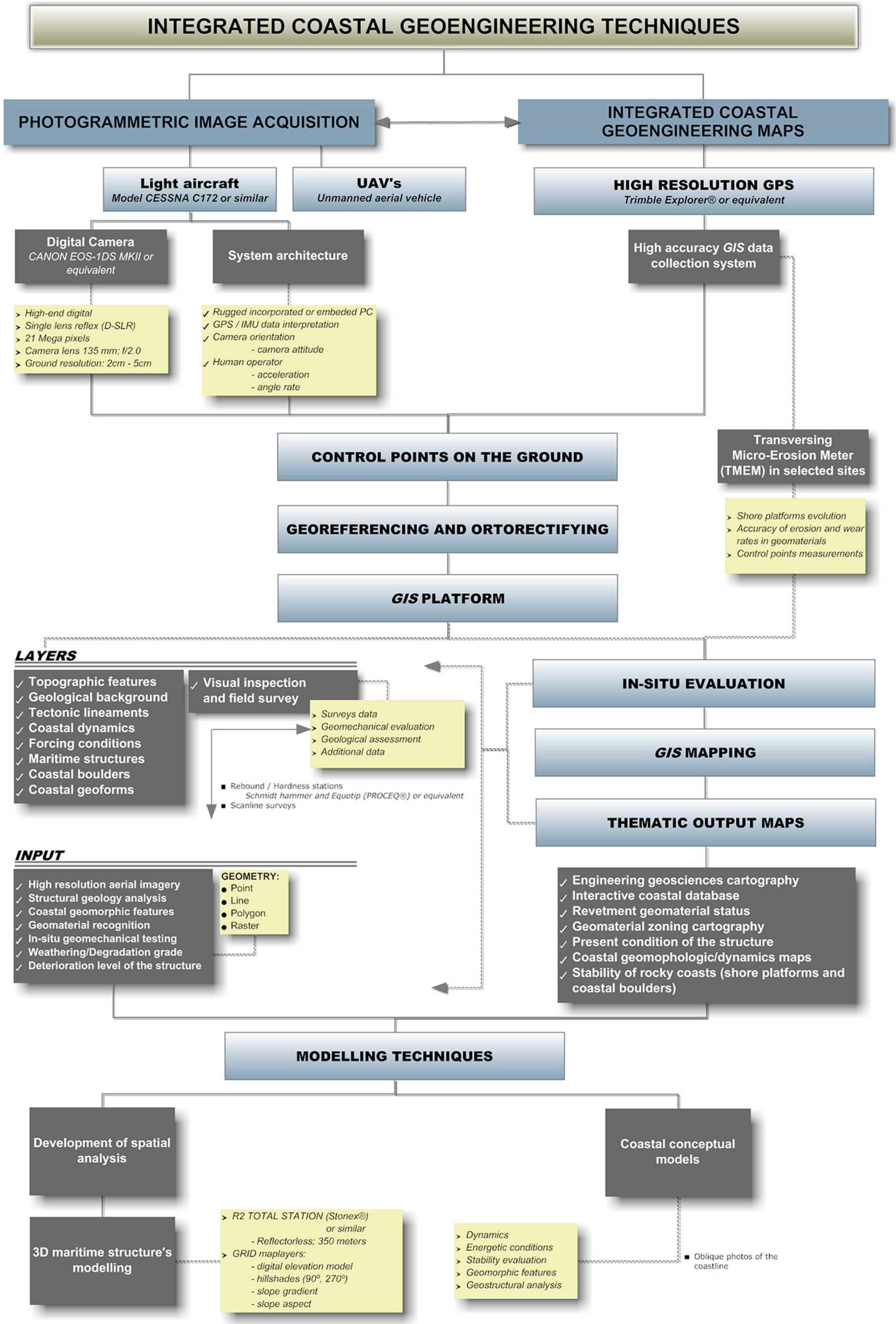
| Country | Studied sites [ID] | Type of coast | Studied sectors Nr. | Extension (km) | Maritime structures | Control points | Photo (example) |
|---|---|---|---|---|---|---|---|
| Spain | Laxe Brava, Ribeira **[1]** | Rocky coast and boulder beach | *1* boulder beach | 0,2 | - | 45 |   |
| | Corrubedo, Ribeira **[1]** | | *3* rocky platforms<br>I – Faro Corrubedo<br>II – Punta Corrubedo<br>III – Punta Couso/Corrubedo | 3 | - | 40 |   |
| | Aguiño, Ribeira **[1]** | Mixed coast | *1* groyne<br>*1* rocky platform<br>I – Aguiño groyne<br>II – Aguiño platform | 1 | 1 | 40 |   |
| | Baiona, Pontevedra **[2]** | Rocky coast with boulders | *1* rocky coast | 2 | - | 35 |   |
| | Oia, A Guarda **[2]** | | *1* rocky coast | 1,5 | - | 30 |   |

**Table 2** NW Portugal studied areas: description and characterisation with two examples of the high-resolution aerial imagery

| Country | Studied sites [ID] | Type of coast | Studied sectors Nr. | Extension (km) | Maritime structures | Control points | Photo (example) |
|---|---|---|---|---|---|---|---|
| Portugal | Vila Praia de Âncora **[3]** | Mixed coast | *1* breakwater<br>*1* rocky platform<br>I – V.P.Âncora groyne<br>II – Caminha rocky coast | 4 | 1 | 35 |   |
| | Lavadores, V.N. Gaia **[4]** | Rocky coast with boulders | *1* rocky platform | 1,5 | - | 45 |   |
| | Espinho, Aveiro **[5]** | Sandy coast | *4* groynes<br>*1* seawall<br>I – Marinha<br>II – Marinha seawall<br>III – Carreira de Tiro<br>IV – Casa Branca<br>V – Paramos ETAR | 5 | 5 | 200 |   |
| | Cova and Lavos, Figueira da Foz **[6]** | Sandy coast | *2* groynes<br>I – Lavos<br>II – Cova | 4 | 2 | 75 |   |


INTEGRATED COASTAL GEOENGINEERING TECHNIQUES
PHOTOGRAMMETRIC IMAGE ACQUISITION
INTEGRATED COASTAL GEOENGINEERING MAPS
Light aircraft
Model CESSNA C172 or similar
UAV's
Unmanned aerial vehicle
HIGH RESOLUTION GPS
Trimble Explorer® or equivalent
Digital Camera
CANON EOS-1DS MKII or equivalent
System architecture
High accuracy GIS data collection system
High-end digital
Single lens reflex (D-SLR)
21 Mega pixels
Camera lens 135 mm; f/2.0
Ground resolution: 2cm - 5cm
Rugged incorporated or embeded PC
GPS / IMU data interpretation
Camera orientation
- camera attitude
Human operator
- acceleration
- angle rate
CONTROL POINTS ON THE GROUND
Transversing Micro-Erosion Meter (TMEM) in selected sites
GEOREFERENCING AND ORTORECTIFYING
Shore platforms evolution
Accuracy of erosion and wear rates in geomaterials
Control points measurements
GIS PLATFORM
LAYERS
Topographic features
Geological background
Tectonic lineaments
Coastal dynamics
Forcing conditions
Maritime structures
Coastal boulders
Coastal geoforms
Visual inspection and field survey
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Geomechanical evaluation
Geological assessment
Additional data
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IN-SITU EVALUATION
GIS MAPPING
THEMATIC OUTPUT MAPS
INPUT
High resolution aerial imagery
Structural geology analysis
Coastal geomorphic features
Geomaterial recognition
In-situ geomechanical testing
Weathering/Degradation grade
Deterioration level of the structure
GEOMETRY:
Point
Line
Polygon
Raster
Engineering geosciences cartography
Interactive coastal database
Revetment geomaterial status
Geomaterial zoning cartography
Present condition of the structure
Coastal geomophologic/dynamics maps
Stability of rocky coasts (shore platforms and coastal boulders)
MODELLING TECHNIQUES
Development of spatial analysis
Coastal conceptual models
3D maritime structure's modelling
R2 TOTAL STATION (Stonex®) or similar
- Reflectorless; 350 meters
GRID maplayers:
- digital elevation model
- hillshades (90º, 270º)
- slope gradient
- slope aspect
Dynamics
Energetic conditions
Stability evaluation
Geomorphic features
Geostructural analysis
Oblique photos of the coastline

◀ **Fig. 3** Workflow implementation: relationship between different methodologies and outputs for achieving an integrated coastal geoengineering techniques approach

Forcing conditions along the Atlantic coast system in Portugal are characterised by semi-diurnal tides (with amplitudes of 2–4 m). In general, significant wave heights range from 2 to 3 m and maximum significant wave heights are greater than 8 m. The wave directions are dominated by W and NW, with some events from SW (Pires et al. 2009a, 2013). The total length of the Atlantic coast of mainland Portugal is more than 800 km. There are about 290 hydraulic works along the coast, 70 % of which are groynes and seawalls (Pires et al. 2009a). Area [5] is also characterised by a mixed coastal system comprising sandy beaches and groyne fields of approximately 5 km in length.

## Methodology

### Integrated coastal geosciences and engineering techniques

This paper deals with a holistic and systematic methodology that encompasses several layers of information obtained from different sources: field data (in situ evaluation) and existing maps, charts and documents. The thematic maps and outputs were developed by using all the layers and inputs. Afterwards all the information was embedded in GIS software and geodatabases. Finally, these outputs and the data analysis will support the framework of modelling applications.

This section presents the system architecture, the map design of the GIS and photogrammetric project. The workflow illustrated in Fig. 3 shows the structural design for the study implementation. It also presents the relationship between the different methodologies/techniques (e.g., light aircraft, unmanned aerial vehicles, high-resolution GPS, traversing micro-erosion meter technology, GIS-based platform) and the outputs (e.g., engineering geosciences mapping, geomaterial zoning mapping, stability of rocky coasts). The conceptual flowchart could be used as a general methodology using several modern techniques and equipment. As stated before the proposed sequence of techniques is intended to contribute to GIS in coastal environments. The workflow shows two important components of the system: (1) digital photogrammetric image acquisition and (2) coastal geoscience mapping, described below in "Geo-morphodynamic mapping: stability of rocky coasts" and "Geomaterial zoning map: marine structures assessment".

Firstly, it is important to effectively prepare the flight operation, which will translate into greater data accuracy and high-resolution aerial images. This system uses a light aircraft (in this case a Cessna C172, but any similar aircraft can be used) with the right door removed (more details can be found in Cunha et al. 2006; Pires et al. 2009b). This modification led to more accurate photos related to verticality, flexibility or even mobility of the camera operator (Teunissen 1995). Some of the main features of the flight are described in Fig. 3. Three flight operations were planned in order to obtain the aerial images. Several flights are required to obtain an adequate number of images of the coastal sites. Georeferencing information was provided by Trimble GPS GeoExplorer® XH technology, allowing more accurate collection of the control points (see Tables 1 and 2 with the number of control points registered for each sector).

Finally, the GIS platform was a necessary step toward the assessment and analysis of maritime environments to carry out coastal geoscience mapping. ArcGIS v10.1 software (ESRI®) and the available extensions were applied. The results of the photogrammetric mapping produced interesting outputs of the area. Figure 4 exemplifies the four different scenarios necessary to create and develop coastal geoscience GIS mapping from high-resolution aerial imagery acquisition and fieldwork surveys (Fig. 4a, b) to the integration, application and spatial conceptualisation in a GIS-based cartography framework (Fig. 4c, d).

This paper reports on the application of the approach in three types of coastal environment: (1) rocky coasts; (2) sandy coasts or mixed systems and (3) anthropic elements such as hydraulic structures or coastal protection works. The first and second types covered different layers and inputs from the third type, as will be shown in the results. Rocky and sandy coast assessment requires a thorough study of the platform and of mobile elements like boulders and geoforms, but also a good knowledge of the area's geology, tectonics, geomorphology, and coastal dynamics (Pérez-Alberti et al. 2012, 2013). Such background understanding has already been provided by previous works (e.g., Pérez-Alberti et al. 2012, 2013). The hydraulic structures evaluation incorporates several geoengineering methods allowing a new approach to the assessment and monitoring of coastal structures which has been updated from previous studies (e.g., Pires and Chaminé 2007; Pires et al. 2009a, 2009b, 2013 and references therein). GIS mapping, geomorphological features and geomaterials properties were incorporated into the coastal environments research to analyse these features in terms of the behaviour of the structure of different layers and rock/block movement (depending on the type of structure and the type of blocks placed in it, the performance of the different layers of the structure may vary in terms of coastal protection, and the movement of the blocks placed along the structures can differ). An interdisciplinary connection was also

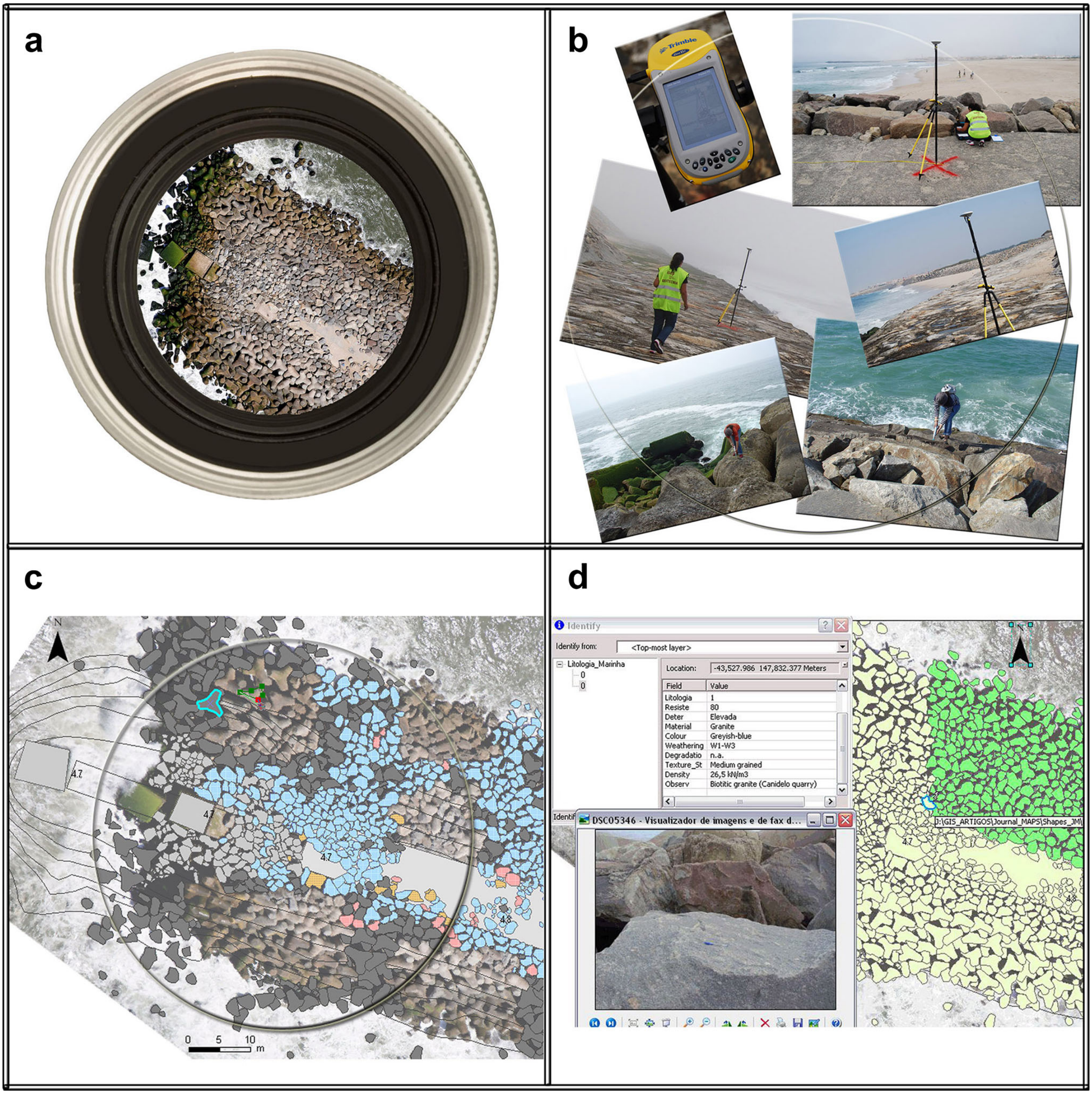


**Fig. 4** Applying different scenarios to create and develop coastal geoscience GIS mapping: **a** high-resolution aerial imagery acquisition; **b** field surveys and GPS measurements; **c** GIS integration, application and vectorisation platform or project; **d** spatial conceptualisation of layers, vectorial data, attributes, rasters and interactive geodatabases

established between geoengineering concepts and hydraulic behaviour in the planning process of maritime structures as recommended by Ciria et al. (2007).

The design of coastal conceptual models was an important aspect of the studied sites. To help conceptualise the 3D models of the hydraulic structures presented here, total station records (Stonex®) and a grid of points were used, with models based on the GIS project displaying the rock/blocks mobility of the maritime structures.

The outputs (thematic maps) are a good starting point to theorise and propose a conceptualisation of the coastal systems framework interaction. GIS mapping has been shown to be a good contribution for the integrated coastal geoscience and engineering approach. Scientific fields such as GIS cartography, engineering geosciences, applied geomorphology, rock engineering, and coastal engineering were applied to the studied areas as shown in the output maps displayed in this work. These maps involve diverse types of thematic layers and researched fields, previously applied with other perspectives or approaches by several authors (e.g., Fisher et al. 1993; Dykes et al. 2005; ISRM 2007; Ciria et al. 2007; Peterson 2009; Smith et al. 2011; Chaminé et al. 2013).

As a final remark, the study displays an integrative procedure for coupling coastal geoscience GIS mapping and high-resolution digital imagery for maritime environmental evaluation. A low-level aerial survey was conducted from a light aircraft in order to acquire the images in raster format, which were a fundamental part of the GIS platform/project. Finally, GIS mapping enabled 3D modelling and spatial analysis of the studied sites.

## Results and discussion

The research results are presented in three sub-sections: rocky coasts and boulder evaluation; marine structures assessment and conceptual model proposal and synthesis of results. Five practical examples will be displayed as an outcome of the GIS platform for data integration. The outputs of the GIS project correspond to different thematic maps according to the main purpose for each studied area. Hence, these final maps are associated with several factors: (1) coastal management issues; (2) type of coastal environment; (3) geologic, petrophysical and geomechanical characteristics of geomaterials; (4) geo-morphodynamics behaviour; (5) hydrographic and physical conditions and (6) data and information availability.

The examples shown here were selected to show the methodology presented. The key sites are located in Ribeira (Area [1], Spain) and Espinho (Area [5], Portugal) and comprise five sectors: Laxe Brava, Punta Couso and Aguiño (Ribeira) in Area [1]; Carreira de Tiro and Casa Branca (Espinho) in Area [5].

### Geo-morphodynamic mapping: stability of rocky coasts

Laxe Brava (Ribeira, Area [1]) is characterised by an open beach with boulders along a rocky granitic coast. Figure 5 exemplifies the geostructure vectorisation with a general overview of the drawn polylines and studied profiles for future monitoring, inspection and comparison. Laxe Brava embodies one of the most typical coastal environments found in Galicia (NW Spain). Along this coast, which is particularly unusual and energetic, it was very useful to use GIS tools to assess rocky coast stability. High-resolution imagery was used to vectorise all the geostructures and lithological heterogeneities to several scales, particularly megascale (tectonic lineaments and geological boundaries) and meso and macroscale (faults, fractures, joints, fissures and veins), Fig. 5a. The identification of dominant geostructure patterns can help correlate the orientations with the different rock clasts/boulders sizes along the beach. Moreover, the relationship between lineament directions and wave attack tendencies could also explain the boulders' shape as well as their differential positions along the rocky platform (Pérez-Alberti et al. 2012).

Perpendicular profiles to the beach were also carried out with the aid of high-resolution GPS equipment. The main goal was to determine the movement of boulders and to identify each of the clasts by performing a systematic inspection and survey of the area (Fig. 5b). This detailed task was carried out using aerial images at different periods of time to compare the mobility of the clasts. The profiles were also used to insert the entire data obtained during the fieldwork and to analyse the beach stability due to boulders movement.

Punta Couso/Corrubedo (Ribeira, Area [1]) is also characterised by a rocky platform with boulders and dispersed megaboulders. It is a very active and energetic coast which is sculpted on granitic rocks. In this example the main purpose was to carry out an integrated geologic, geomechanical and petrophysical study along scanline surveys to help systematise the collected data. Therefore, in situ geomechanical testing measures were obtained with a Schmidt Hammer and an Equotip (ISRM 2007, 2015; PROCEQ 2012; Pires et al. 2014a, b) as shown in Fig. 6. It was also possible to register and identify potential boulder pathways with the help of high-accuracy GPS (Fig. 6).

Another example of applied GIS mapping is displayed in Fig. 7. Using the GIS platform it was possible to define a criterion for vectorisation and categorisation of the rock platform joints along the Punta Couso/Corrubedo sector. The field calculator extension was used in order to evaluate the joint degree or density of each polyline: 1 for first-order joints; 2 for second-order joints and 3 for third-order joints (Fig. 7). The implemented hierarchy allows geomorphological corridors to be distinguished and sheds light on the dynamics of boulders along the platform. Using the high-resolution imagery it was possible to vectorise very accurately the tectonic lineaments and/or fracture network, as well as the geoforms (boulders and megaboulders).

The detailed maps suggest that: (1) assessing the degree of fracturing will benefit accurate coastal mapping (e.g., if the distances between joints are larger, this highlights potential boulder corridors); (2) analysing the existence or absence of displacements and the degree of mobility of boulders and megaboulders will allow the study of geoforms and coastal dynamics as well as leading to a better understanding of the consequences of the forcing conditions on the coast (Figs. 6, 7).

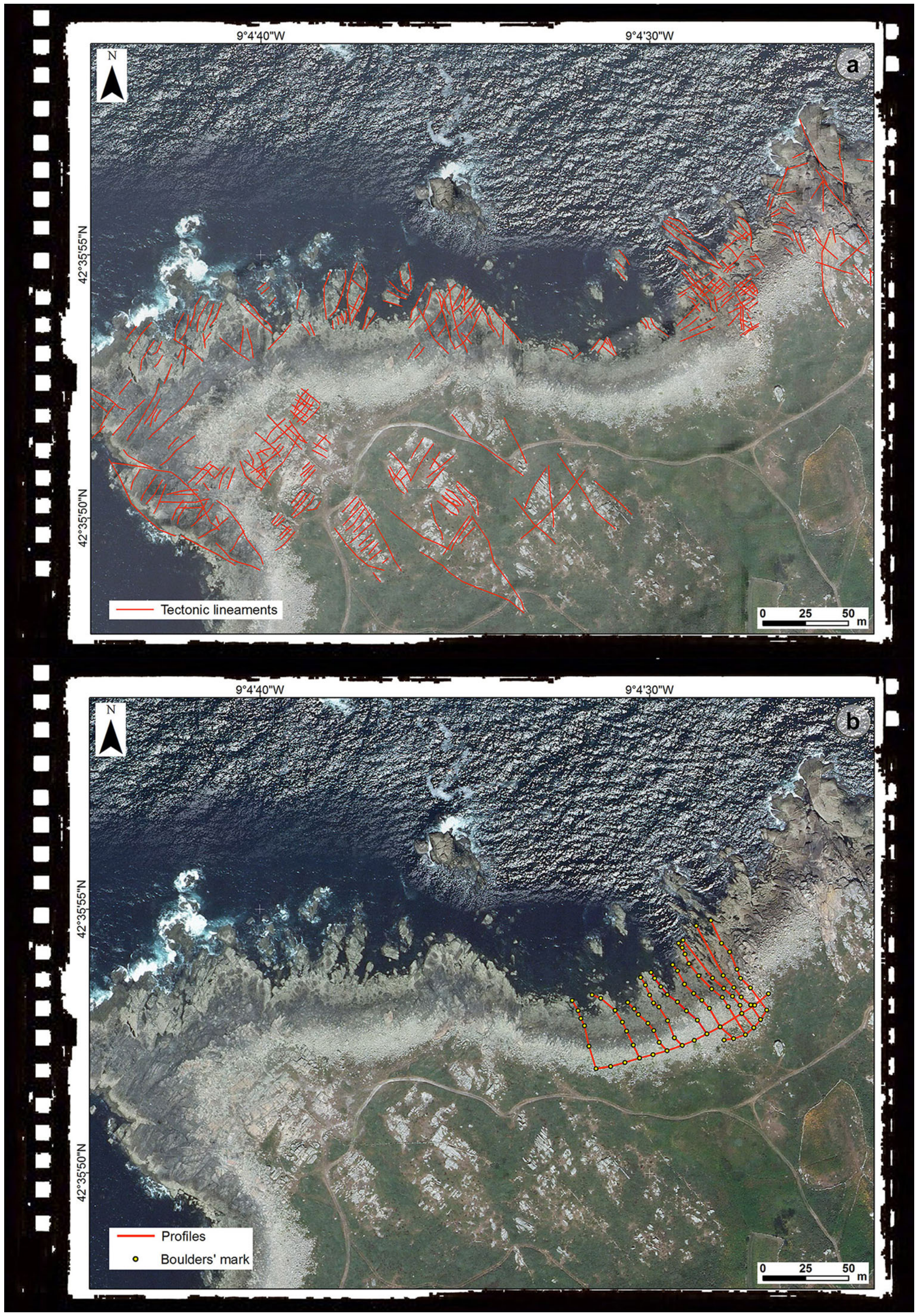


**Fig. 5** Example of the geostructures vectorisation of Laxe Brava sector (studied area [1]) and boulders stability analysis: **a** general overview of the drawn *polylines*; **b** studied profiles and boulders' marks for future monitoring, inspection and comparison

## Geomaterial zoning map: marine structures assessment

Aguiño groyne (Ribeira, Area [1]) is located in a mixed system. As shown in Fig. 8, it was possible to identify a groyne implemented or established on a rocky platform. The same approach to the rocky platform was made in this sector as described in the previous examples. However, Fig. 8 shows also the approach to hydraulic structures assumed in the methodology proposed here. A general overview of the studied sector is visible as well as the GIS mapping of the geomaterials surveyed (more than 12,000 vectorised blocks or polygons). Furthermore, this sector is a good example of the application of photogrammetric techniques to assess the armour layer (superficial part) of a groyne. It is also possible to visualise the sequence of high-

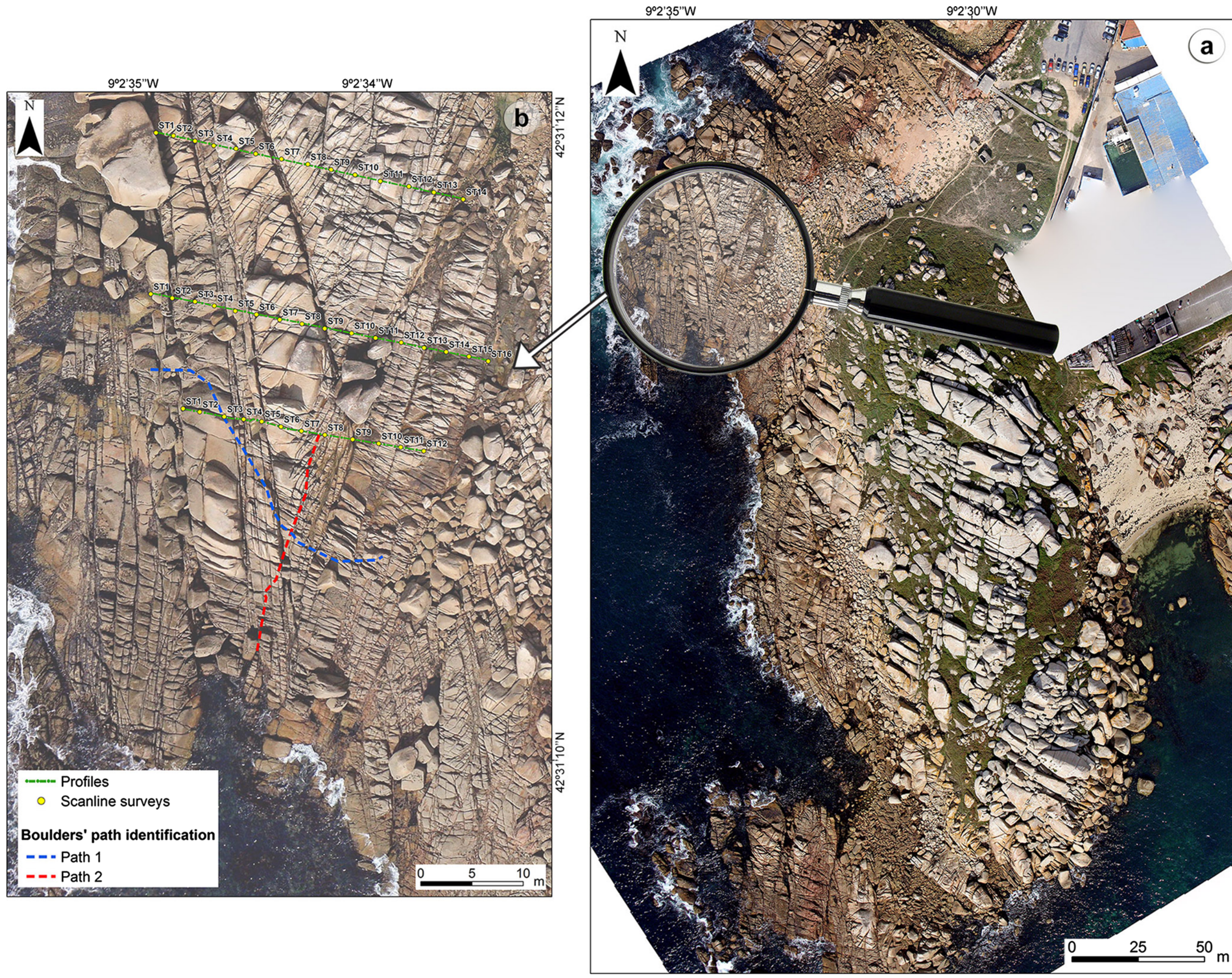


**Fig. 6** Punta Couso/Corrubedo sector (studied area [1]): **a** high-resolution aerial imagery of the boulder beach; **b** location of the scanline surveys and geomechanical stations (ST) obtained along the profiles, boulder's path identification and stability analysis

resolution imagery georeferenced along the coastal protection structure (Fig. 8c), which was the basis for the geomaterial delimitation.

Finally, the Espinho (Area [5]) is characterised by a sandy coast with a series of groynes. In the example shown in Fig. 9 it is possible to recognise the overlapping layers from high-resolution imagery to geomaterial recognition, durability and deterioration levels. Examples of the generated 3D models, GIS mapping projects and applied cartography are also displayed. Similarly to the previous example of Aguiño, this approach has been applied to Carreira de Tiro and Casa Branca hydraulic structures (groynes).

Figure 9a shows the first thematic map design concerning geomaterial recognition and characterisation. The second thematic map represents the Schmidt Hammer rebound values determined along the armour layer of the structure (Fig. 9b). The Schmidt Hammer was used to determine the hardness of the geomaterials. In addition, cross-checking all data and linking the two previous maps led to the last output displaying the structures' zoning, which comprises the deterioration level and current status (Fig. 9c). The deterioration level is based on the fieldwork surveys (data acquisition) and the applied geo-mapping. This evaluation allows a qualitative diagnostic of the actual condition of the superficial blocks forming the armour layer and presents the current status of the structure (for further information see previous works by Pires and Chaminé 2009; Pires et al. 2009b, 2013, 2014a, b and references therein). Espinho GIS mapping shows the layered architecture of the cartographical methodology approach for this type of environment. All the layers are interlocked, but it is possible to visualise features separately.

## Conceptual model proposal

The examples presented above show the different approaches that can be used in an integrated coastal

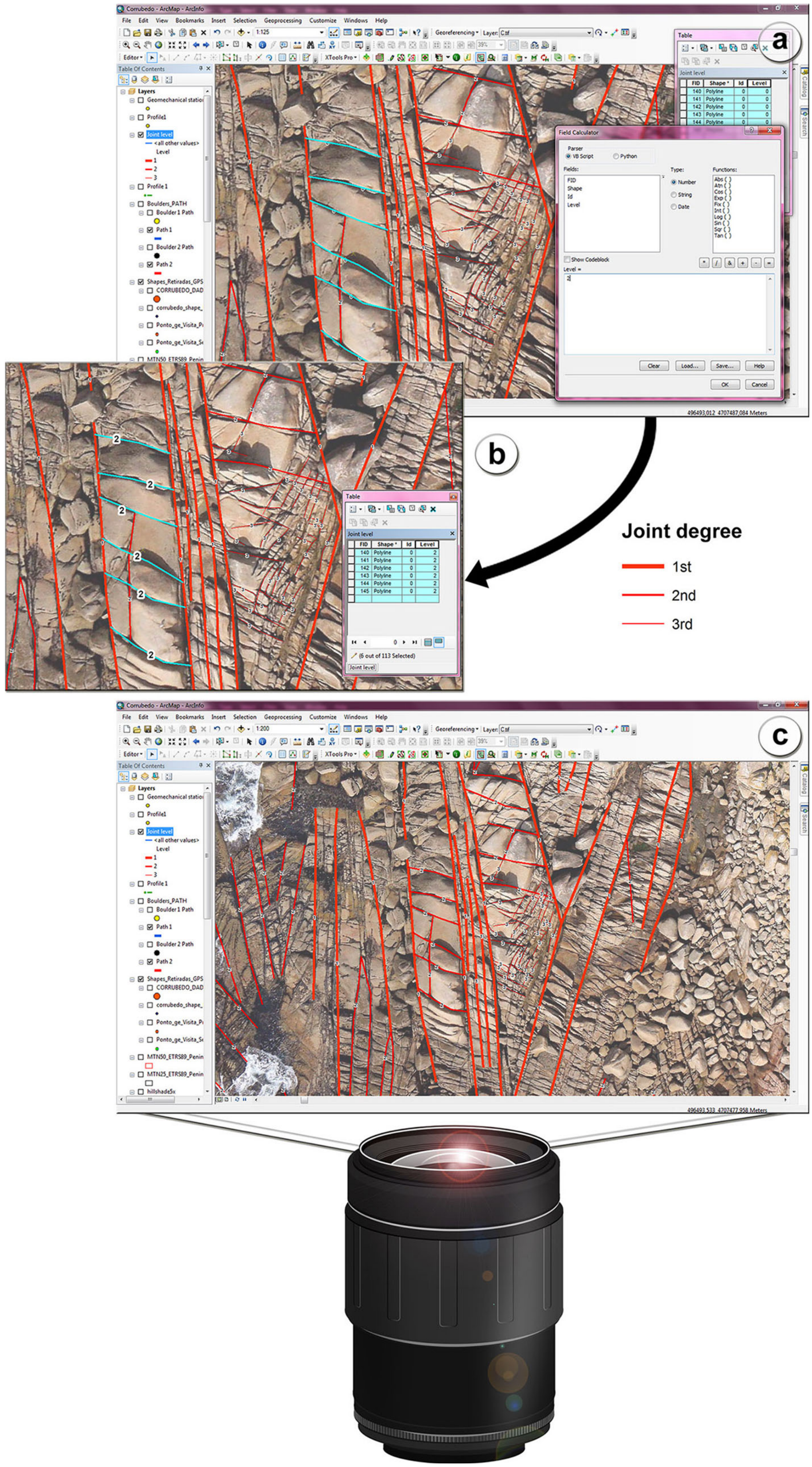


**Fig. 7** Illustration for Punta Cousa/Corrubedo sector: **a**, **b** criterion for vectorisation, categorisation and field calculator along the polylines in order to evaluate the joint degree in several scales; **c** final result with different line weights/density as well as different attributes or values

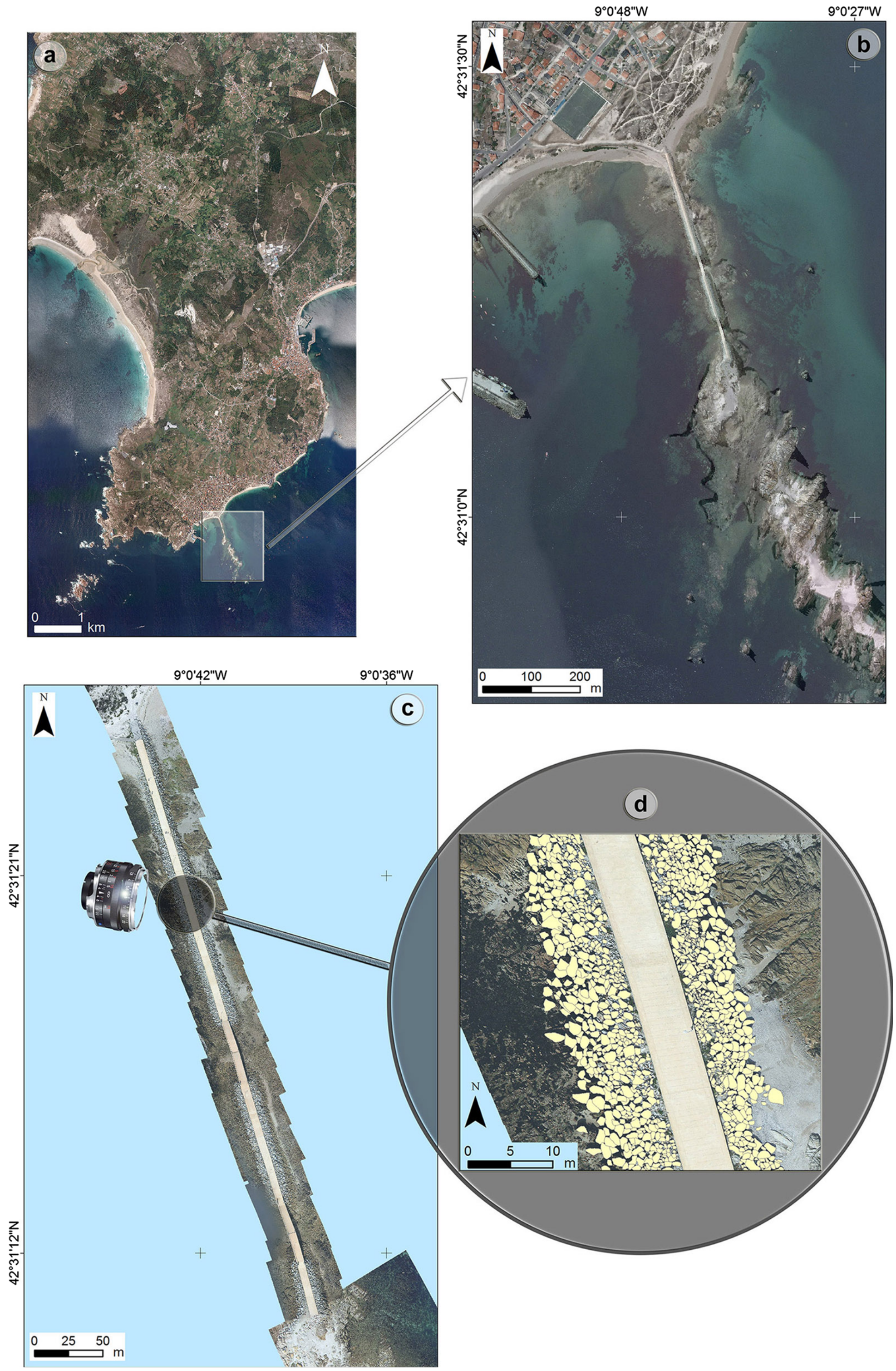


**Fig. 8** Example of the mixed coast of Aguiño groyne with rocky platform (studied area [1]): **a**, **b** general overview of the studied sector; **c**, **d** geomaterial zoning GIS mapping (more than 12,000 vectorised blocks)

geoengineering methodology. From data collection to GIS project implementation, there is a large variety of thematic maps and applied mapping available. These outputs are described in the workflow of Fig. 3, for instance: engineering geoscience cartography; revetment geomaterial status; present condition of the structure or stability of rocky coasts. The series of maps for the studied sites incorporates numerous geodatabases and vital information for future coastal studies along the NW Iberian region. Moreover, the maps contain a considerable number of mixed layers, from vectorial features to rasters. This will allow researchers to map coastal geoscience data and to

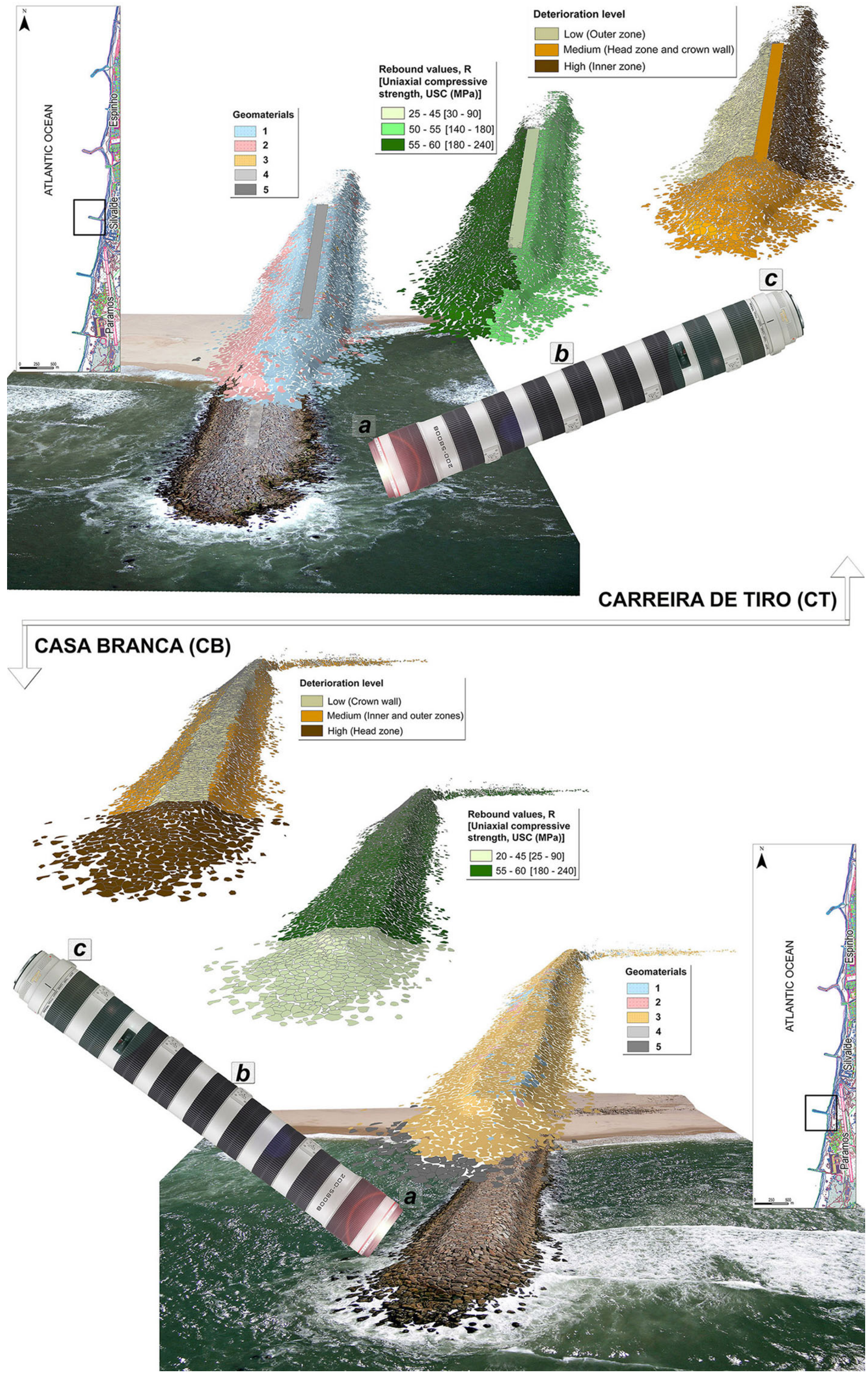


**Fig. 9** Armour layer assessment of hydraulic structures—Carreira de Tiro and Casa Branca groynes from Espinho (studied area [5]) and integrated coastal geoengineering techniques: **a**–**c** overlapping layers from high-resolution imagery to geomaterial recognition, durability and deterioration level; examples of the 3D models generated, GIS mapping projects and applied cartography. (Geomaterial explanation: *1* biotitic granite, *grayish-blue*, medium grained; *2* granite, *reddish-pink*, medium to fine grained; *3* biotitic gneiss, *yellowish-brown*, coarse to medium grained with quartz and large feldspar megacrystals; *4* concrete path along the structure crest or blocks with concrete and aggregates; *5* tetrapods)

develop conceptual models for each studied sector at different scales (regional and local approaches).

The developed methodology provides an interesting starting point for GIScience cartography in maritime environments. The conceptual model proposed in Fig. 10 not only represents the synthesis of this paper, but also the key elements and requirements for integrated coastal zone management and geoengineering. This model also illustrates the relationship between the acquisition of high-resolution imagery, photogrammetric techniques, high-resolution GPS measurements, basic fieldwork and the applied cartography production. This approach represents an integrated framework (interdisciplinary, multidisciplinary and transdisciplinary) of the studied regions.


**Fig. 10** An integrated coastal zone management: a coastal geosciences and engineering techniques approach

## Conclusions

The main concluding remarks are as follows:

1. The increased knowledge of the studied regions supplies essential data and inputs. The studied regions highlight some results concerning coastal morphodynamics. The assessment provided further evidence of erosion problems along the studied sectors that can contribute to a better understanding of the hydraulic conditions. The use of regional coastal geosciences maps and local approach-outputs could help the government, local authorities and stakeholders to develop coastal management plans and to recommend strategies;
2. The proposed integrated coastal geoengineering methodology is valid for any type of coast or maritime environment. GIS mapping was the key to promote the interdisciplinary framework that was employed in the NW Iberian region. This paper shows an innovative sequence of techniques and equipment and an efficient approach to easily assess maritime environments. The strength lies in coupling GIS applications with photogrammetric techniques to create applied cartography and thematic maps. The outputs can be represented by maps for rocky coasts or for hydraulic structures, ranging from the stability study of rocky platforms and coastal boulders to the geomaterial zoning mapping and revetment status;
3. GIS-based mapping assessment incorporates an interactive geodatabase that is being updated regularly. Such database merges several amounts of layers, inputs, information and data, as displayed in the output maps. Using GIS applications and extensions it is possible to create 3D models of the maritime structures as well as use spatial analyst extension for several interpretations (e.g., susceptibility or vulnerability maps and statistical studies);

The study provides the backbone for coastal management processes. The development of a general workflow shows the connection between all the stages along these processes. This paper also underlines the importance of the conceptual modelling from a geoengineering perspective which characterises the research framework.

4. The investigations in this region are continuing. This approach was the starting point for GIS platforms relating to coastal zones in the NW Iberian Peninsula. The platform has the potential to create coastal GIS mapping and analysis. The upcoming research involves land use planning strategies and recommending long/short-term actions to coastal management plans, suggesting more adaptive solutions to coastal communities (e.g., Moore 2012; Pontee and Parsons 2012; USACE et al. 2014), taking advantage of coastal geosciences mapping.

**Acknowledgments** We gratefully acknowledge Xunta de Galicia, which provided key information for the Galicia region (CartGalicia project, LABCARGA|ISEP–FEUGA|USC/2010-11). The study was partially financed by FEDER-EU COMPETE Funds and FCT (GeoBioTec|UA: PEst-C/CTE/UI4035/2014) and LABCARGA|ISEP re-equipment program: IPP-ISEP|PAD'2007/08. The research was also funded by a doctoral scholarship from the Portuguese Foundation for Science and Technology (FCT) to A. Pires (SFRH/BD/43175/2008). Special thanks are due to colleagues R. Nagano, I. Malta, M.J. Afonso, C. Rodrigues and L. Freitas for all of their support. We acknowledge the anonymous reviewers for the constructive comments that helped to improve the focus of the manuscript.

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# CHAPTER 10

# P9

## SYNOPSIS

*This paper is concerned with shoreline change mapping and coastal management strategies. Throughout this work the CartGalicia mapping project overview, data and results is displayed. CartGalicia is a joint project between the School of Engineering (ISEP) of the Polytechnic of Porto and the University of Santiago de Compostela. In addition, these results also contributed to the master coastal management plan (POLGalicia) carried out by the Local Authorities (Xunta de Galicia, Consellería de Medio Ambiente, Territorio e Infraestructuras). This study was concerned with shoreline change and cliff recession. The study focused on the analysis of the coastal dynamics and the spatio-temporal changes of coastal morphology for the years 1956, 2003, 2006 and 2008, using the digital shoreline analysis system (DSAS) extension. Estimation of the rates of erosion and accretion along the pilot site (Fisterra/Finisterre area) was performed. In addition, a continuous coastline along Galicia was integrated into a geographical information system project which comprises an interactive database with key information. A coastal susceptibility map (erosion/accretion) was created based on the DSAS results for the short-term approach and cross-checked with knowledge of the area in terms of geology, geomorphology and landslide occurrences. Aspects related to the engineering solutions, land-use planning or environmental management were considered in the recommended strategy, as well as the impact and disturbance severity analysis for each action used. This research was developed to provide useful information about the Galicia territory and to give reliable data for the coastal management plan supported by the council. Such plan addresses some changes to the coastal policy and encourages future issues. The main conclusions of this paper are: (i) the shoreline mapping and analysis is important for a wide range of coastal studies; (ii) it was possible to develop a methodology and also to design a GIS interactive database that can be updated throughout the time along the tested area (coastline of Galicia region); (iii) the study provides a solid base to easily forecast and model shoreline displacements throughout the years, and identify main areas of erosion/accretion; (iv) all the statistical data and analysis generated will help to assess the Galician region and will allow creating geo-cartography in terms of susceptibility maps; (v) the understanding of the erosion rates is also important and should have been taken into account when designing public works. In conclusion, specific challenges and recommendations were prepared for the coastal management plan. In addition, shoreline prediction is important for integrated coastal zone management/planning and strengthens the role of local administrative authorities.*

**Maritime Engineering**
Volume 166 Issue MA3
**Shoreline change mapping along the coast of Galicia, Spain**
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ice | proceedings

**Proceedings of the Institution of Civil Engineers**
Maritime Engineering 166 September 2013 Issue MA3
Pages 125–144 http://dx.doi.org/10.1680/maen.2012.23
**Paper 201223**
Received 29/07/2012 Accepted 10/10/2012
**Keywords:** dynamics/environment/management



ice
Institution of Civil Engineers
publishing

# Shoreline change mapping along the coast of Galicia, Spain

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**This study was concerned with shoreline change and cliff recession. Galicia (north-west Spain) comprises a very energetic and diversified coast. The study focused on the analysis of the coastal dynamics and the spatio-temporal changes of coastal morphology for the years 1956, 2003, 2006 and 2008, using the digital shoreline analysis system (DSAS) extension. Estimation of the rates of erosion and accretion along the pilot site (Fisterra/Finisterre area) was performed. In addition, a continuous coastline along Galicia was integrated into a geographical information system project which comprises an interactive database with key information. A coastal susceptibility map (erosion/accretion) was created based on the DSAS results for the short-term approach and cross-checked with knowledge of the area in terms of geology, geomorphology and landslide occurrences. Aspects related to the engineering solutions, land-use planning or environmental management were considered in the recommended strategy, as well as the impact and disturbance severity analysis for each action used. This research was developed to provide useful information about the Galicia territory and to give reliable data for the coastal management plan supported by the council. Such plan addresses some changes to the coastal policy and encourages future issues.**

## 1. Introduction

The assessment of cliffs and rocky coasts, beach dynamics and coastal processes is fundamental for a monitoring of littoral areas (Bird, 2008; Carter, 1988; Fookes *et al.*, 2007; Green and King, 2003; Trenhaile, 1987, 1997; Woodroffe, 2003). As coastal populations continue to grow and community infrastructures are threatened by erosion, there has been an increase in demand for accurate information regarding cliff retreat or shoreline movement. Thus, one of the more important aspects of coastal management and planning programmes that merits further investigation is shoreline dynamics (Crous *et al.*, 2004; Hapke and Reid, 2007; Hapke *et al.*, 2009; Morton and Miller, 2005; Morton *et al.*, 2004; Rogers *et al.*, 2008, 2010). The study of the hydraulic behaviour of maritime structures is also critical to the analysis of coastal morphological changes (Dupray *et al.*, 2004; Fookes and Poole, 1981; Latham, 1991; Pires *et al.*, 2009; Poole *et al.*, 1983; Sigurdarson *et al.*, 2004). These studies include not only the conditions of the progression and erosion of coastlines but also the role of hydraulic structures. The coastal cliff retreat, the landward migration of the cliff face, as well as beach erosion are chronic problems along Spain's coastline (Del Río and Gracia, 2009; Del Río *et al.*, 2009, 2012; Gomez-Gesteira *et al.*, 2011a; González de Vallejo *et al.*, 2012 and references therein). The Galician coastline (north-west Spain) is characterised by different types of coast, namely sandy beaches, shore platforms and cliffs. The cliff retreat processes involve a wide range of mass movements due to the variety of lithologies, internal cliff structures, rock mechanical properties and other influencing factors. Diverse types of mass movement processes and features occur at cliffs in the studied area, comprising different classical types (Huddart and Stot, 2010): slumps, rockfalls, slopes and collapses. The instability phenomenon in the Galicia region has been studied in previous work (Blanco-Chao *et al.*, 2007; Lopez-Bedoya and Pérez-Alberti, 2009; Pérez-Alberti *et al.*, 2002, 2009; Trenhaile *et al.*, 1999). The geographic information system (GIS) platform was used to develop a standard repeatable method for mapping and analysing shoreline movement so that periodic updates can be made regionally, regarding coastal erosion and land loss (Bailey and Gatrell, 1995; Burke *et al.*, 2001; Green and King, 2003).

This research was accomplished as part of the CARTGalicia project and the approach described here provides useful information about Galicia. In addition, it contributes to the master coastal management plan (POLGalicia, 2010) carried out by the local authorities (*Xunta de Galicia, Consellería de Medio Ambiente, Territorio e Infraestructuras*). Such a monitoring plan suggests some changes in coastal policy and encourages future trends in land-use and coastal engineering issues. CARTGalicia's main goals are: (*a*) to examine the original sources of shoreline data (historical maps, aerial photos, orthophotomaps, oblique images); (*b*) to evaluate both the utility of different shoreline proxies (geomorphic features, water mark, tidal datum, elevation) and the uncertainty associated with each method; (*c*) to develop and implement improved methods of assessing and monitoring shoreline movement; (*d*) to obtain a better understanding of the processes controlling shoreline movement; (*e*) to develop an interactive GIS database with the documented coastal information; and (*f*) to enter into strategic partnerships to facilitate data dissemination. This work reports on historical changes in the Galician shoreline, in terms of both accretion and erosion. The brief accounts of coastal land loss for each studied sector of the Fisterra (or Finisterre) pilot site provide a more comprehensive view of coastal processes and key references that can be used to learn more about coastal change in a broader context. In the Fisterra pilot site there were 11 studied sectors (five sandy, six rocky coasts). The method of analysis and interpretation of the results can also provide explanations regarding long-term/short-term rates.

## 2. Coast of Galicia (north-west Iberian Peninsula): general setting

Galicia has around 2100 km of coast extension, including several islets (POLGalicia, 2010). The Galician mainland comprises a very energetic and varied coast, dominated by a mesotidal environment with a mean tidal of 2·5 m and a spring tidal range between 3·75 and 4 m (Figure 1(a)). Therefore, shoreline changes and cliff recession are a matter of serious concern in the Galicia region. Hence, this study presents the first results for an assessment of shoreline dynamical processes by calculating average rates of shoreline movement (accretion/erosion) in a GIS environment. The method was tested on the pilot site (Fisterra area) locally known as the *Costa da Morte* ('Death Coast') which is a distinctive and active coastline. Different features were considered for this study: (*a*) the cliff top or the upper limit of the rocky coast; (*b*) the vegetation line of sandy beaches; and (*c*) coastal protection structures (Figure 1(b)).

The influence of physical conditions such as currents and wind are important to characterise the region. Regarding the currents, the main trend is from the south, with velocities of less than 30 cm/s (Figure 1(c)). However, with strong winds from the south or south-west, currents can come from the north, reaching a mean velocity of 40 cm/s (NGA, 2011; Puertos del Estado, 2012).

The wind regime over the Galician coast may present different directions and values depending on two different situations: winter and summer (NGA, 2011; Puertos del Estado, 2012). In winter the predisposition induces south-west winds on the coast. However, in spring and summer the wind blows predominantly from the north and north-west directions (McClain *et al.*, 1986; Penabad *et al.*, 2008) (Figure 1(d)). Sousa *et al.* (2011) registered a more variable wind regime during the winter, reaching a maximum of 14 m/s (meteorological stations) and 18 m/s (oceanic stations, for the year of 2001). During the summer the highest speeds in 2001 were 7 m/s (meteorological stations) and 13 m/s (all points) (for further information see Sousa *et al.* (2011)).

The north-western part of the Iberian Peninsula is characterised by diversified features along the coast in terms of marine hydrodynamic processes, geology, geomorphology, mode of evolution or geographic occurrence, namely cliffed and rocky coasts or sandy beaches (e.g. Del Río and Gracia, 2009; Del Rio *et al.*, 2012; González de Vallejo *et al.*, 2012; Malvárez *et al.*, 2000; Nonn, 1966; Pérez-Alberti *et al.*, 2002, 2012; Trenhaile *et al.*, 1999 and references therein). The coast of Galicia is an ancient bedrock in the Atlantic margin of the Iberian Peninsula and has a strong geostructural control. The geometry of the coast is controlled by a pre-mesozoic substratum joint network, oriented north-west–south-east and north-east–south-west, and by those developed during the Alpine orogeny, which trend mainly north–south (Pérez-Alberti *et al.*, 2002, 2012). Other factors are also important, including lithological heterogeneity and variations in the degree of weathering, as well as the role played by frost processes during the Pleistocene. The actual dynamics are dominated by periods of stability and instability strongly conditioned by local factors much by high intensity and low frequency (Pérez-Alberti *et al.*, 1998, 2002, 2012). Figure 2 presents the regional geological setting from the Fisterra/Finisterre area (updated from Urroz *et al.* (1981) and Llana-Fúnez (2001)). The beach areas are described by sand dunes, and all the rocky coastline mainly consists of cataclastic two-mica granites. Between Punta Cabanas and Cabo Finisterre

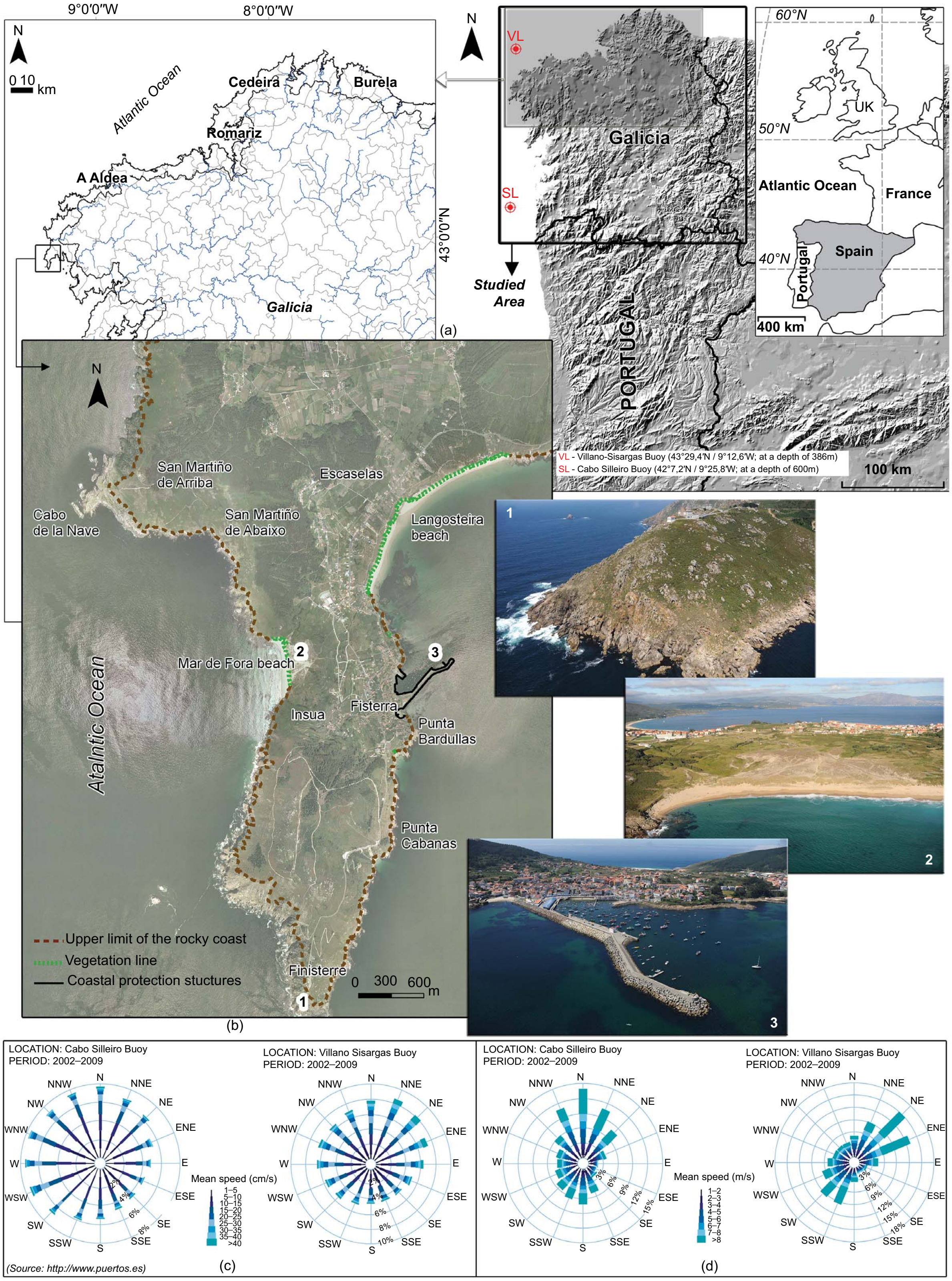


Figure 1. The studied region (north-west Spain): (a) the Galician coast; (b) representation method applied to the pilot site (Fisterra/Finisterre area), data vectorisation and coastaline survey; (c) and (d) physical site conditions including currents (c) and wind (d) for the two buoys available (SL and VL), located at the north and south of the studied area

there are several outcrops of micashists and paragneisses. The hydraulic forces characterisation comprising mean wave height and frequency for the two buoys (Cabo Silleiro – SL and Villano-Sisargas – VL) along the study area in Galicia can also be found in Figure 2. Regarding this point, deepwater waves of 1 to 2·5 m in height account for approximately 65% of the yearly total (2003 and 2008), and over 5 m for 5% of the total for the two buoys (Puertos del Estado, 2012). The largest waves occur during autumn and winter when low-pressure systems generate storms with westerly, north-westerly, and south-westerly winds; significant wave heights of 10·3, 10·4, 10·9 and 11·0 m were recorded in October 2003, February 2007, March 2008 and January 2009, respectively, for Cabo Silleiro buoy; significant wave heights of 10·2, 10·9, 12·6 and 13·5 m were recorded in October 2003, December 2006, March 2008 and January 2009, respectively, for Villano-Sisargas buoy (Puertos del Estado, 2012).

The present study is focused mainly on shoreline changes (rates and movement) that occurred in Galicia. Galician coasts have gone through a sea level rise of 2–3 mm/year over the second half of the twentieth century (EEA Report, 2004; Gomez-Gesteira *et al.*, 2011b; IPCC, 2007; Rosón *et al.*, 2009). This means that during the past century it has risen 10–20 cm, and by 2100 a rise of 9–88 cm is considered as a possible scenario. According to Eurosion (2004), the Galician region has a medium exposure to coastal erosion and relative sea level rise (best estimate for the next 100 years) was rated with two points which means a value of > 40 cm in 100 years. According to several authors (Dickson *et al.*, 2007; Engelhart *et al.*, 2009; Hall *et al.*, 2006; Leorri *et al.*, 2012), sea level rise acceleration is growing and is starting to stress coastal ecosystem environments. Consequently, it is important to understand ecosystems' responses to global climate changes along different timescales to predict future trends in the region. This study aimed also to bring out some information that is relevant to future coastal issues.

## 3. Site investigation procedures

Pérez-Alberti *et al.* (2011) have described the methodological approach to the study of the shoreline management in the Galicia region. Other authors have been using the same methodology with different approaches along the Spanish coast (Aguilar *et al.*, 2010; Del Río and Gracia, 2009; Del Río *et al.*, 2009, 2012; Gomez-Gesteira *et al.*, 2011a; González de Vallejo *et al.*, 2012; Jabaloy-Sánchez *et al.*, 2010) but this method is also being used in other contexts throughout the world (Moran, 2003; Morton and Miller, 2005; Morton *et al.*, 2004, 2005; Rogers *et al.*, 2008).

An important target was the identification of the major areas with erosion problems and the design of a susceptibility assessment mapping programme for the Galician coastline. To achieve these goals a coding system to report shore dynamics (accretion/erosion) was created. Finally, some policy recommendations were suggested for the coastal management trends to ensure their long-term sustainability. It was also important to take into consideration previous studies, mainly developed in the UK (Cooper and Dolan, 2012; Drake and Phipps, 2007; Frew, 2012; HGL, 2007a, 2007b, 2011; Lee, 2005; McInnes and Moore, 2011; Moore, 2012; Moore *et al.*, 2003; Pontee and Parsons, 2010, 2012 and references therein). Figure 3 illustrates the conceptual flowchart for the CARTGalicia project study.

The assessment of shoreline change and coastal cliff retreat is usually carried out by field and aerial surveys and is important for integrated coastal zone management. However, photogrammetry could also be used as the primary acquisition method for shoreline mapping due to its reasonable cost and high level of accuracy. Aerial photographs provide an important data source for coastal monitoring and a GIS is an appropriate tool for analysing these data (Aguilar *et al.*, 2010; Burke *et al.*, 2001). Therefore, coastal monitoring with aerial photographs and GIS is a common technique carried out in different environments (Hapke and Reid, 2007; Morton and Miller, 2005). The methodology presented here is an approach to GIS mapping and shoreline monitoring for a regional-scale analysis (Galicia, north-west Spain) and tested along a local scale (Fisterra area). By coupling the data layers and attributes along the shoreline, this investigation aims to develop a GIS platform-based methodology for a monitoring project. This would be a crucial part of any successful coastal maintenance programme.

The shoreline change focused on the analysis of the coastal dynamics and the spatio-temporal changes of coastal morphology for the years 1956, 2003 and 2008 by using the digital shoreline analysis system (DSAS) extension version 3.2 (Jiménez *et al.*, 1997; Moran, 2003; Thieler *et al.*, 2005). The conceptual flowchart represented in Figure 4 highlights the stages of the analysis of the shoreline change, since the data collection, to the DSAS application, until the statistic results. Figure 5 shows some aspects of the DSAS extension, the steps that must be followed and the user-friendly interface for assessing the shoreline movement. The first stage of the study was the integration of a continuous coastline (about 900 km of cliffs and rocky coasts) along the Galicia region into a GIS project. The programme comprises an interactive database with information about the stability of cliffs, categorisation/type of coast, photos and occurrences. In addition, for the coastline vectorisation three criteria were used: the upper limit of rocky coasts, the vegetation line for sandy coasts and the definition of hydraulic structures. The potential data sources for shoreline investigation included the comparison of oblique photographs and aerial photography (orthophotomaps). Estimation of the rates of erosion and accretion along the pilot site (Fisterra sector) was performed for the studied periods. Hence, two approaches were applied with different

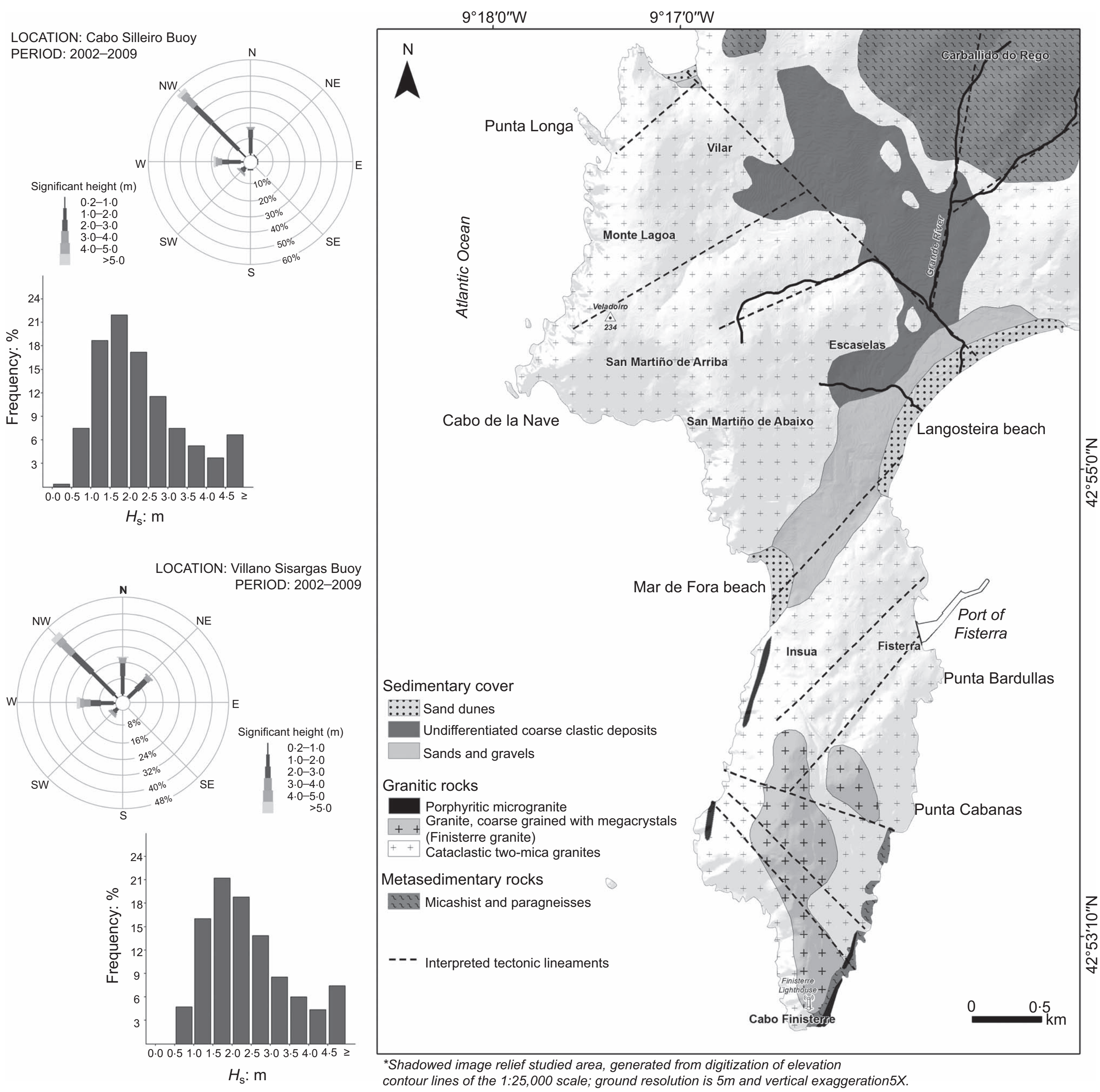


**Figure 2.** Regional geological setting from Fisterra/Finisterre area (updated from Urroz et al., 1981 and Llana-Fúnez, 2001); hydraulic forces characterisation comprising mean wave height ($H_s$: m) and frequency (%) for the two buoys (Cabo Silleiro – SL and Villano-Sisargas – VL) along the study area in Galicia, north-western Spain (Source: http://www.puertos.es)

timescales: a long-term analysis using three shorelines (1956, 2003 and 2008) and a short-term analysis using two recent shorelines (2003 and 2008). A comparison of three statistical methods was used to check the output rates (linear regression rate (LRR), weighted linear regression (WLR) and end point rate (EPR)). In terms of distances reported, there was the net shoreline movement (NSM) which represents the total distance between the oldest and youngest shorelines (Crowell *et al.*, 1991; Douglas and Crowell, 2000; Thieler and Danforth, 1994).

The historical (1940s) and the topographic maps (1980s) were basic cartography for observing differences addressing the

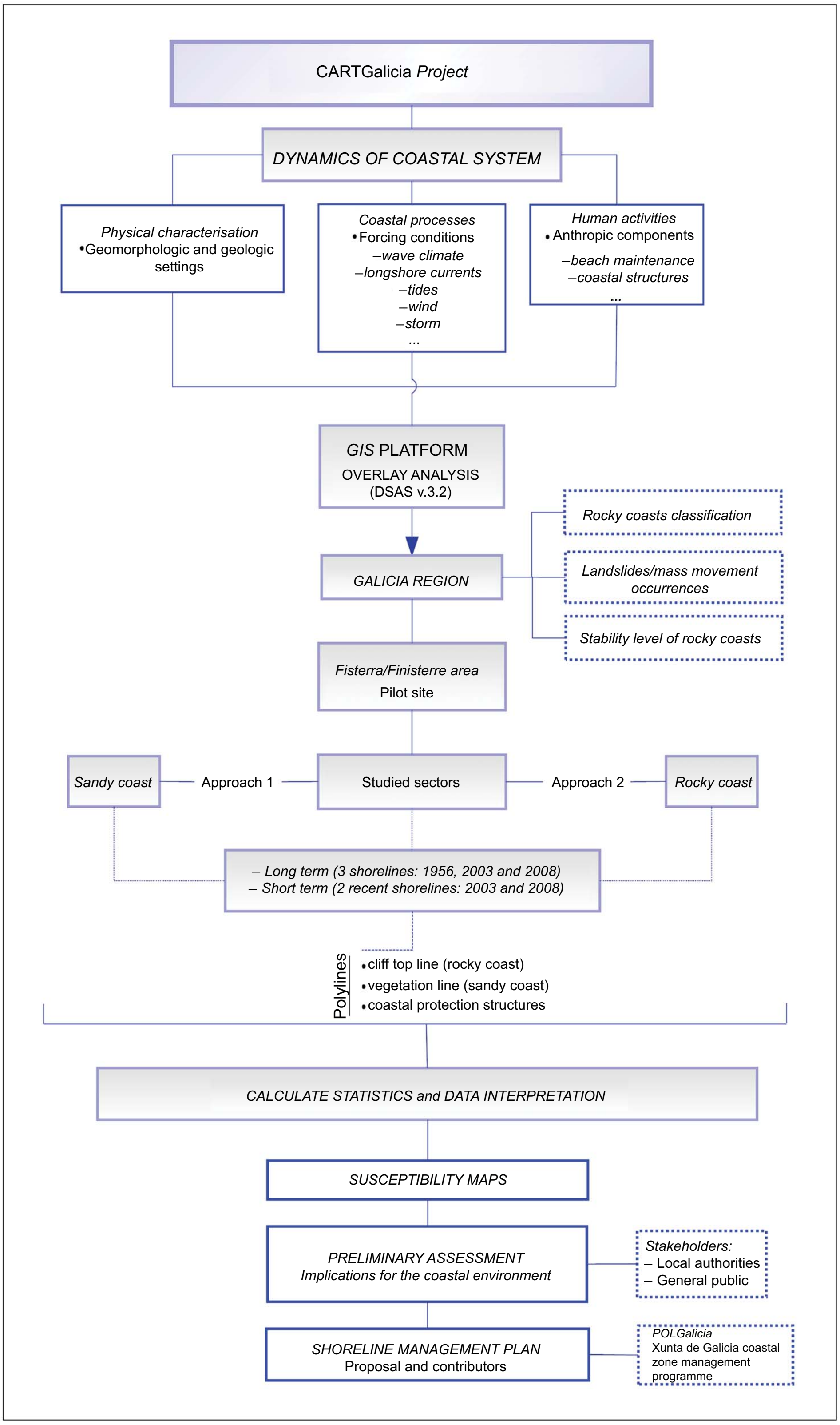


**Figure 3.** Conceptual flowchart for the study of the dynamics of coastal system: CARTGalicia project overview

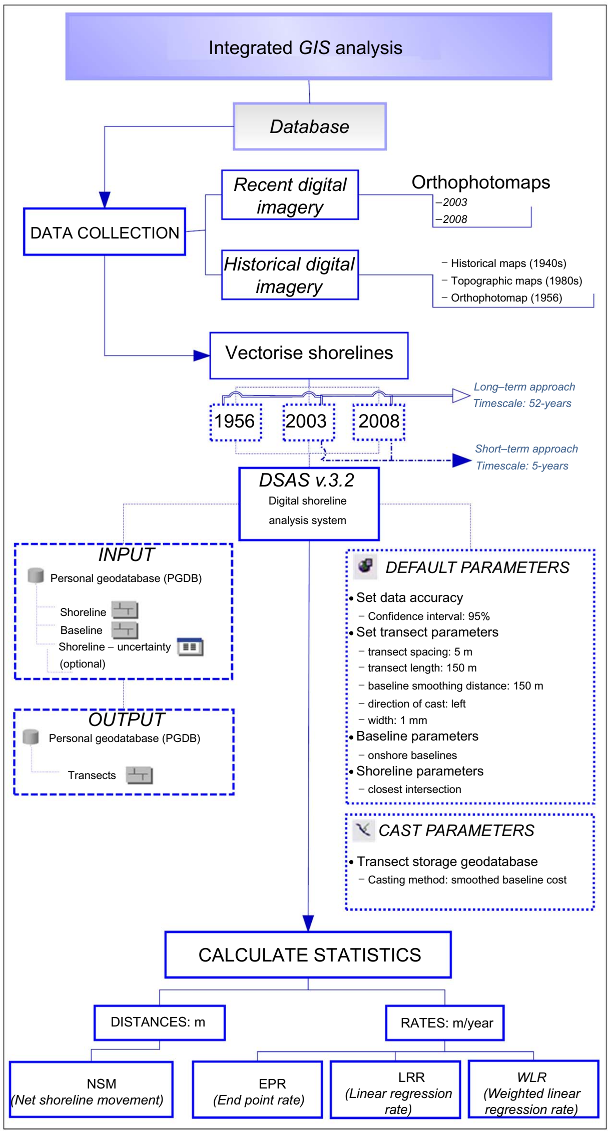


**Figure 4.** Conceptual flowchart for the integrated GIS analysis and the shoreline change

maritime structures built through the years and the main variations among the coast morphology and dynamics. Apart from this information, the shoreline vectorisation was determined by the orthophotomaps available. The 1956 and 2003 sheets were georeferenced using ArcGIS v9·3 software (LABCARGA|ISEP licence) by placing at least 20 well-spaced ground-control points on the selected images. The orthos assigned a cartographic reference system (WGS84 coordinate system, UTM Zone 29N) related to the 2008 orthophotomap. Digital shorelines for each selected period were compiled as a shapefile in a PGDB (personal geodatabase) and merged to produce a single shoreline for each of the three time periods.

Long-term rates of shoreline change were calculated at each transect using linear regression applied to all three shoreline positions from the earliest (1956) to the most recent (2008). LRR and WLR were selected because they have been the most statistically robust quantitative methods when a limited number of shorelines are available (Crowell *et al.*, 1991). They are also the most commonly applied statistical techniques for expressing shoreline movement and estimating rates of change (Thieler and Danforth, 1994). Moreover they minimise potential random error and short-term variability (cyclical changes) through the use of a statistical approach (Douglas and Crowell, 2000).

Short-term rates of shoreline change were calculated using the end point method comparing the most recent shoreline positions (2003 and 2008). With the support of aerial photographs and through comparison the rate of change of shoreline position and tracing were determined. As regards the reliability of the results for the documented trends and calculated rates of shoreline change an uncertainty field was determined. This field represents the measurement errors associated with mapping methods for historical shorelines, registration of shoreline position relative to geographic coordinates, and shoreline digitising. In this study the errors correspond to measurements taken to determine the accuracy of each shoreline position which influence the WSE (standard error of the estimate) when calculating WLR. Consequently, the main items proposed for uncertainty calculation were: (*a*) inherent errors of georeferencing; (*b*) flight circumstances; (*c*) verticality; (*d*) vectorisation technique and (*e*) orthophotomap conditions. The accuracy of the results depends on the uncertainty values considered. For each studied year, namely 1956, 2003 and 2008, these were considered to be 20·5, 7·5 and 4·5 (m), respectively. This conservative approach to measure the rates has been shown to be more reliable because these values will affect the final statistical analysis (Moore, 2000; Morton and Miller, 2005; Morton *et al.*, 2004). The rates of cliff retreat presented in this study represent the conditions from the 1950s to 2008 and are not intended for predicting future cliff-edge positions. In the case of this analysis, the coastal change being assessed is the upper edge of the coastal cliff (i.e. cliff top), a commonly used indicator of coastal cliff retreat (Del Río and Gracia, 2009; Del Río *et al.*, 2009).

## 4. Results and discussion

### 4.1 Regional assessment

Concerning the regional overview it was important to obtain an inventory of occurrences in terms of the mass movement along the cliffs. The GIS interactive database allowed incorporation of all the gathered data, from the basic cartography (historical and topographic maps, orthophotomaps) to the shapes and features vectorised. Figure 6 illustrates the regional

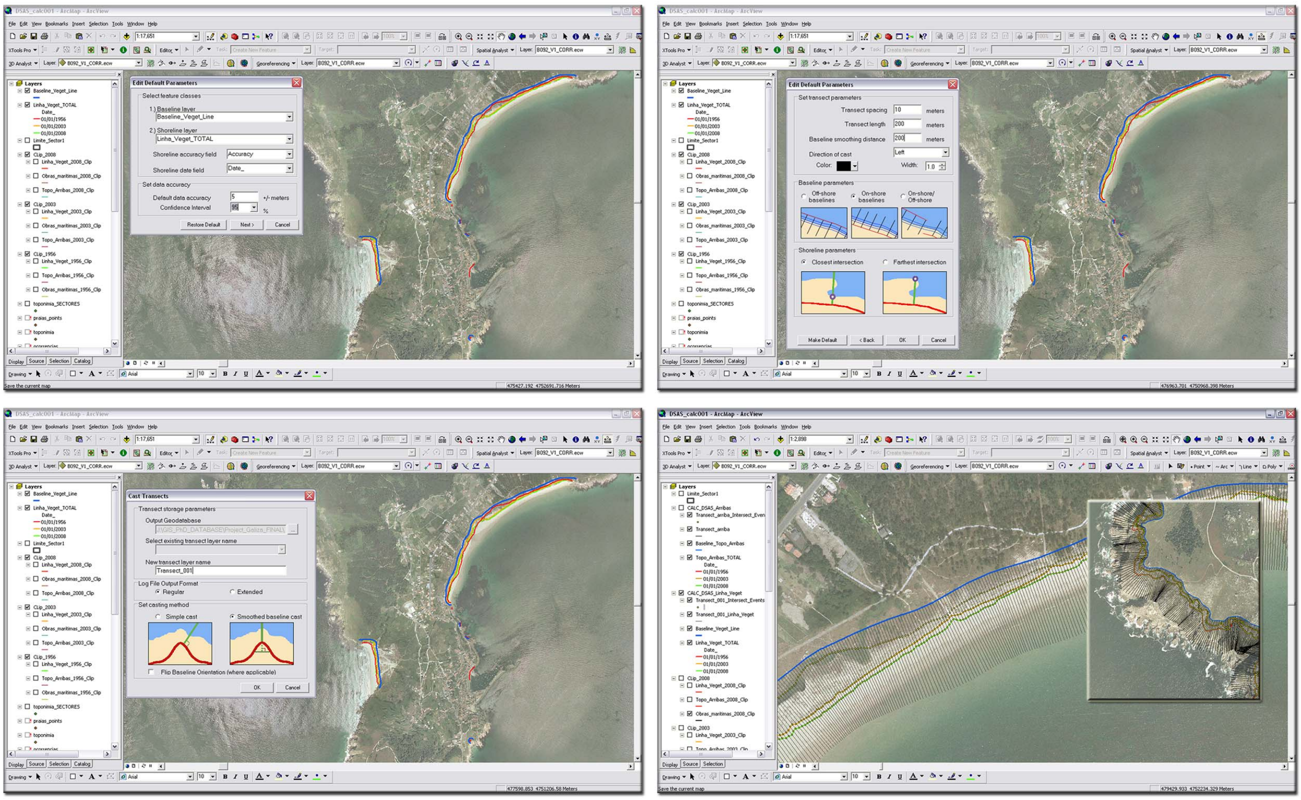

**Figure 5.** Examples of the DSAS extension (digital shoreline analysis system): different procedures of the program interface

project comprising an interactive database with different features: points, polylines and polygons. The location of the mass movements was hyperlinked to photos/images and basic information in relation to these occurrences (Figure 7). From the qualitative evaluation of the rocky coast a stability level based on the number of occurrences and visual inspections was defined. This evaluation was conducted by assuming qualitative attributes for each mass movement, ranging from stable to unstable and very unstable occurrences. The general assessment took into account the rock parameters that could influence the cliff stability such as the rock fracturing degree; weathering grade; forcing conditions (wave climate, longshore currents, tides, wind, storm, etc.); integrated lithologic, geomorphologic and geo-structural features.

### 4.2 Local approach: shoreline change analysis

More than 2500 transects were used to calculate the rates/distances along the Fisterra area using two approaches (long and short terms). Additionally, the rocky and sandy coasts were individualised as shown in Figure 8. Only the short-term results will be discussed in this paper because it was the most reliable approach. Short-term rates of shoreline change were determined at each transect by taking the EPR using the two recent shoreline positions also reported in units of m/year. Tables 1 and 2 along with Figure 8 present the synthesis of those results displayed by the DSAS application.

Long-term rates of shoreline change were also determined at each transect by taking the slope of the regression line (LRR) applied to all three shoreline positions (1956, 2003 and 2008). A long-term approach was not used in the development of map codification and susceptibility. Nonetheless, it is important to discuss the long-term method. The WLR range of values is perhaps more reliable because it takes into account the uncertainty field imposed in the beginning and associated with errors. The resulting rate is reported in units of m/year. Uncertainties for the long-term rates ($\pm$ values) are also reported in units of m/year. The reported uncertainties represent the standard error of the estimate for regression measures (LSE and WSE) which represents the amount of variability in the points around the regression line.

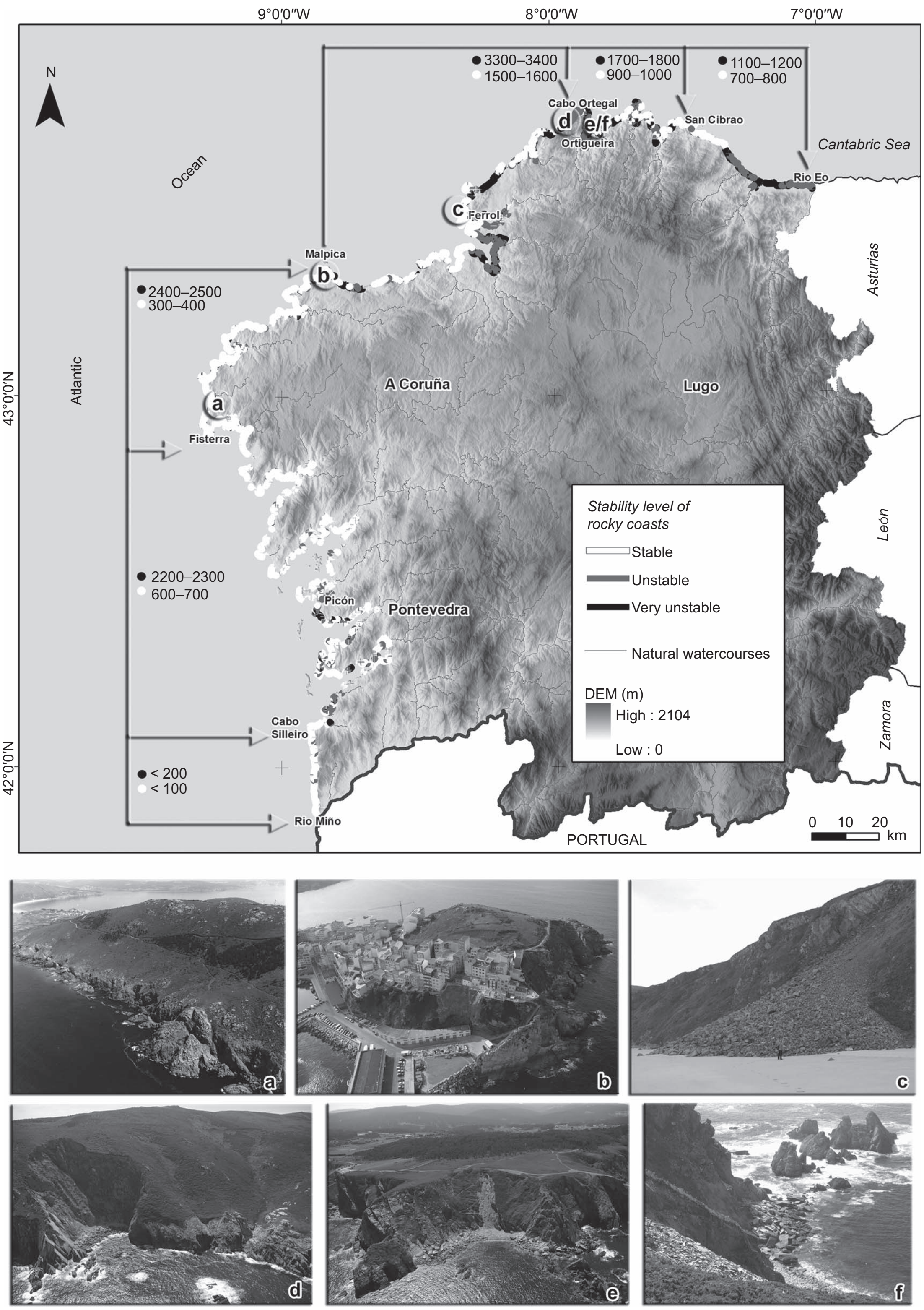


Figure 6. Stability level along the rocky coast and some examples of mass movement ((a) Fisterra; (b) Malpica; (c) Ferrol; (d) Cabo Ortegal; (e) Ortigueira, general view: (f) Ortigueira, detail). Black dot represents the occurrences before 2002; white dot represents the occurrences after 2002

### 4.2.1 Net shoreline movement

The average of net shoreline movement was a strong indicator of the distance reported between the oldest and the youngest shoreline by transect. In the case of the rocky coast, sector 1 presented the highest distances opposing sector 5, for the two approaches. For that sector, the average amount of cliff retreat was −22·03 m over the ~50-year time period of long-term analysis and −5·91 m over 5 years of short-term analysis. This happens because of the strong forcing conditions in the western area of the Cape due to the exposure of the coastline. Sandy coast sectors 1, 2 and 3 showed negative erosion rates and shoreline movements perhaps due to the existence of a breakwater and its influence on the area, also these sectors have very small beaches (about 100 m of length along the shore). Sector 5 presents the greatest amount of erosion in the long-term approach (about −16 m of net shoreline movement) in contrast to sector 4 which has a positive value indicating accretion in that zone (about 12 m of net shoreline movement). It is also possible to observe that for the short-term approach the values for sectors 4 and 5 are different because the timescale is smaller and the quality of the orthophotomaps, vectorisation and georeferencing influenced the results. However, despite the different results (short and long term) it is clear that the western area influences the results (Tables 1 and 2 and Figure 8). This could happen because the beach is not as exposed as sector 5 to the forcing conditions (Mar de Fora beach).

### 4.2.2 Rocky coast analysis

Sector 1 and 2 registered the highest values of retreat, −1·18 m/year and −0·38 m/year, respectively, in contrast to sector 5 which presented the lowest values, −0·09 m/year. These values were based on rates averaged from more than 2000 individual transects measured throughout all the areas of the pilot site rocky coastline (Table 1 and Figure 8(b)). For the two applied approaches (long and short terms) the tendency is the same and the western area is more susceptible than the eastern area. The long-term approach showed LRR retreat values (m/year) of −0·39 ± 3·45 and −0·38 ± 1·62 for sectors 1 and 2, respectively. On the other hand WLR values (m/year) for sectors 1 and 2 were −0·44 ± 0·53 and −0·39 ± 0·25. Once again the previous data are opposed to sector 5 values which presented a LRR of −0·15 ± 1·39 m/year and a WLR of −0·16 ± 0·21 m/year (all data with 95% confidence interval).

### 4.2.3 Sandy coast analysis

Sector 5 registered the highest amounts of erosion in contrast to sector 4 which presented accretion values regarding long-term approach and for the net shoreline movement (distances). These values were based on rates averaged from more than 500 individual transects measured throughout all areas of the pilot site sandy coastline (Table 2 and Figure 8(c)). Retreat rates were generally lowest in the east area where a coastal protection work exists and could have greatly altered the natural coastal system. Therefore, the Langosteira beach (sector 4) presents accretion rates and in contrast Mar de Fora beach (sector 5) has high values of erosion. From the short-term approach derived from end point rate and using only two recent shorelines (2003 and 2008), there are some rates of accretion in sectors 1, 3 and 5. In this short period (5 years) and for the studied area there is no report of any beach nourishment project. However, along the contiguous coastlines close to the pilot site there is information about beach nourishment projects that are completed and could be influencing the final results. Similar to the short-term approach in sector 5, for a period between 1956 and 2008 (long term) the mean shoreline change (m/year) for LRR and WLR, respectively was −0·37 ± 5·88 and −0·26 ± 0·91. Sector 4 also experienced accretion at rates of 0·15 ± 7·40 and 0·29 ± 1·14 (m/year) for LRR and WLR (all data with 95% confidence interval).

### 4.2.4 General overview

Comparing long-term and short-term summary values for each sector and the type of coast, it reveals a systematic decrease in the rates of eroding shore in the eastern area of the study site. The decrease of erosion rates and complementary increase of accretion rates may partly be related to the existence of maritime structures or even the surrounding cliffs that could act as a maritime defence. The adverse weather conditions of the problematic year of 2001 could cause erosional effects on the area. How those adjacent events will affect long-term/short-time shoreline position and rates of change is uncertain.

All the information available was cross-checked with the DSAS data calculation. Then it was possible to examine important considerations about the coastal area. First of all the geomorphology and configuration of the coast are essential to understand the coastal processes, especially along the rocky coasts which experience landslides. The geology, tectonic history and weathering processes and efficacy are other important factors that must be considered. For example, in this case there are differences between the granites and the metasedimentary rocks, mainly between very jointed and less fractured areas. Dynamics are more intense, progressive and fast on sandy than on rock coasts and, depending on exposure, these areas may be subjected to extreme hydrographical conditions.

A DSAS procedure requires fields that will have to be estimated for the final calculation to take place. One of the fields is the uncertainty value which was assumed by the user. This can influence all of the results. Perhaps it would be better to try different scenarios, proposing various uncertainty values. Furthermore, advanced statistical methods such as LRR and WLR require three or more lines, the more the better, to decrease the error/uncertainty and increase the accuracy of the

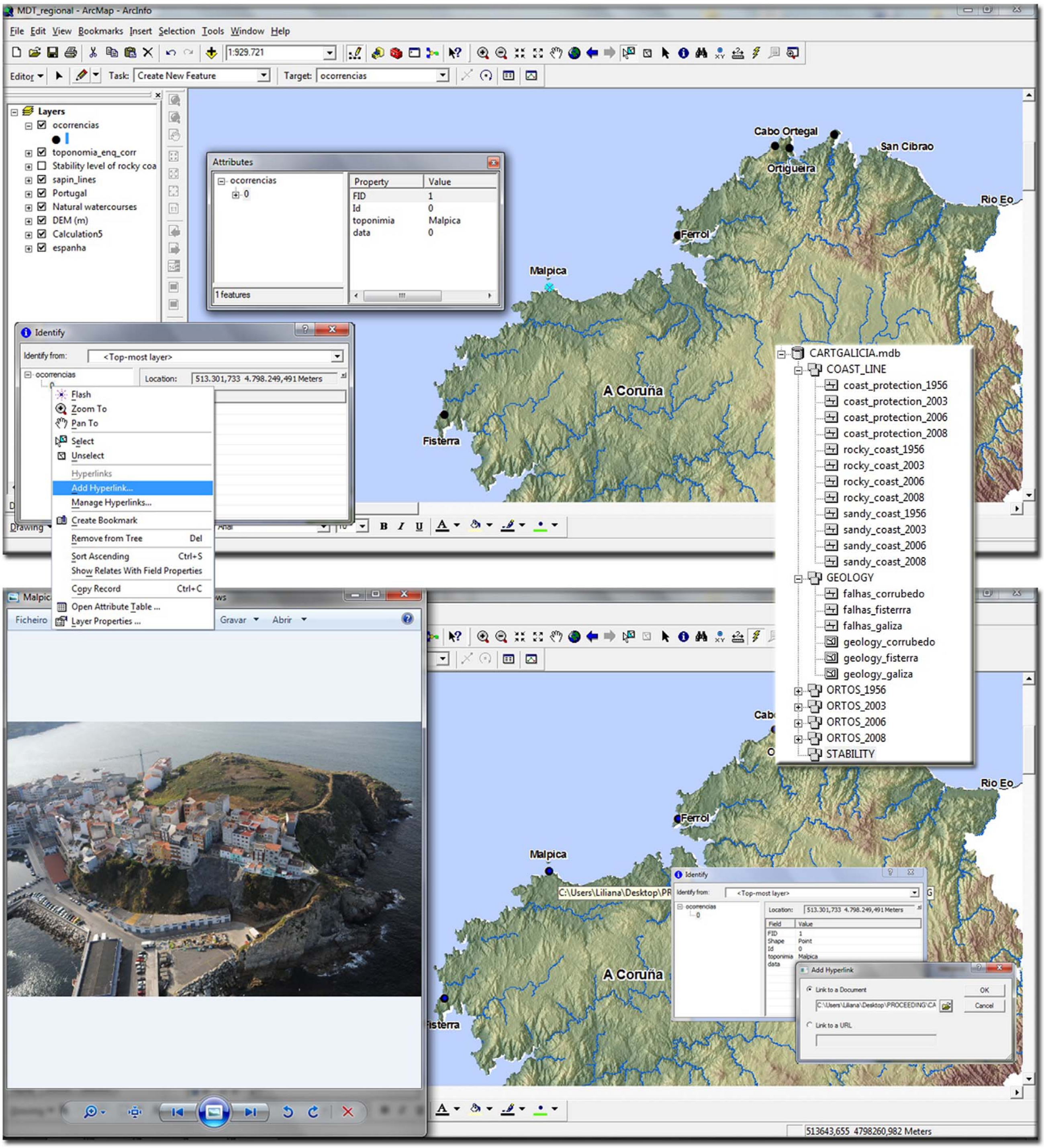


**Figure 7.** General overview of the geodatabase application with the main features implemented on a GIS platform

results. By using two shorelines it will be possible to calculate only the EPR value, which is a simple and efficient method to evaluate the net shoreline movement and erosion/accretion rates. Additionally, EPR works very well for two shorelines; however, the uncertainty field does not enter in the equation, so this could indicate less accurate values.

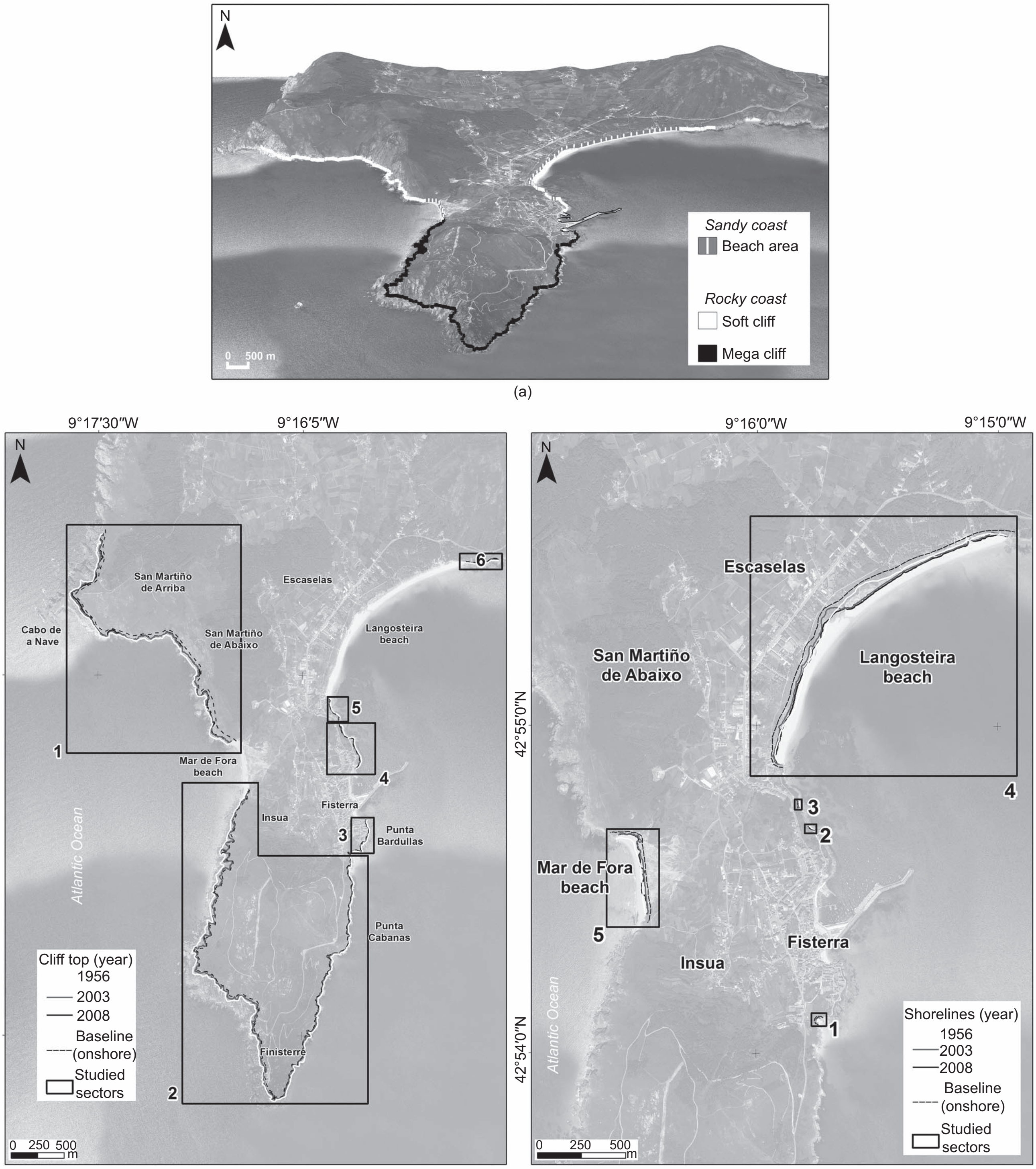


**Figure 8.** (a) Typology of the coast in the studied area and 3D model (×2·5 of vertical exaggeration); (b) studied sectors for the rocky coast; and (c) studied sectors for the sandy beaches

| Rocky coast | Number of transects | Mean net shoreline movement: m | Susceptibility map code system | Mean shoreline change: m/year | Maximum | Minimum |
|---|---|---|---|---|---|---|
| Sector 1 | 620 | −5·91 | 2 | −1·18 | −7·82 | −0·01 |
| Sector 1 | 1398 | −1·92 | 3 | −0·38 | −7·34 | −0·01 |
| Sector 1 | 90 | −1·03 | 4 | −0·21 | −1·42 | −0·02 |
| Sector 1 | 101 | −1·91 | 3 | −0·38 | −1·90 | −0·03 |
| Sector 1 | 51 | −0·45 | 4 | −0·09 | −0·75 | −0·01 |
| Sector 1 | 67 | −1·82 | 3 | −0·36 | −2·90 | −0·01 |
| Total | 2327 | −2·91 | – | −0·58 | −7·82 | −0·01 |

Table 1. Short-term shoreline change trends, derived from end point rates using two recent shorelines: rock coast, first results

### 4.3 Local approach: coastal susceptibility mapping

#### 4.3.1 Map codification

The coastal susceptibility assessment is a qualitative value that was achieved in the study so that it would be possible to identify areas with more or less predisposition to erosion and accretion phenomena. Susceptibility evaluation allowed the identification of areas needing strategic measures and alternatives to minimise the damages that erosion could have on rocky or sandy beaches and surroundings to be proposed.

The susceptibility map codification was based on the data of the net shoreline movement (NSM) for the short term. It combined the net shoreline values (NSM) with the area recognition in terms of physical characterisation (geomorphology and geology), coastal processes (forcing conditions) and instability events (landslide mechanisms and rock collapses). Table 3 presents the coastal susceptibility codification (erosion/accretion) for each type of coast (rocky/sandy) with regard to the expectable NSM data. The range of values displayed in the codification are values of reference and accessed along the shoreline movement calculation for different areas along the Galician coast. For the rocky coast there is punctual erosion which varies between high and very low. Regarding the sandy coast, there is a range of values which depends on the type of leading process, namely erosion, accretion, both or stable shore. A coastal susceptibility map with the codification (Figure 9) was then created where it is possible to identify not only the sectors with more or less susceptibility in terms of erosion but also sectors with some accretion.

#### 4.3.2 Shoreline management plan: challenges and recommendations

This coastal planning scheme allowed assessment and provided recommendations for the studied area. The recommended strategies for the Fisterra/Finisterre site are synthesised in Table 4. From the analysis of DSAS results for the rocky coast, sector 1 presented the highest value of retreat (mean net shoreline movement), therefore in the codification it was considered an area with moderate coastal susceptibility to erosion. The remaining sectors contrast with the previous one and presented

| Sandy coast | Number of transects | Mean net shoreline movement: m | Susceptibility map code system | Mean shoreline change: m/year | Erosion rates: m/year | | | Accretion rates: m/year | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Max. | Min. | Mean | Max. | Min. | Mean |
| Sector 1 | 5 | −1·83 | 5 | −0·37 | −0·71 | −0·05 | −0·48 | 0·07 | – | 0·07 |
| Sector 2 | 9 | −1·16 | 5 | −0·23 | −0·48 | −0·11 | −0·23 | – | – | – |
| Sector 3 | 8 | 0·41 | 8 | 0·08 | −0·28 | −0·07 | −0·18 | 0·50 | 0·03 | 0·17 |
| Sector 4 | 426 | 11·06 | 8 | 2·21 | −0·69 | −0·02 | −0·35 | 8·99 | 0·08 | 2·31 |
| Sector 5 | 118 | 6·19 | 8 | 1·24 | −0·97 | −0·01 | −0·44 | 5·16 | 0·01 | 1·55 |
| Total | 566 | 9·58 | – | 1·92 | −0·97 | −0·01 | −0·36 | 8·99 | 0·01 | 2·14 |

Table 2. Short-term shoreline change trends, derived from end point rates using two recent shorelines: sandy coast, first results

| Coastal susceptibility (erosion/accretion) | | | | Code | Colour |
|---|---|---|---|---|---|
| Type of coast | Erosion vs accretion | | Expectable NSM: m | | |
| Rocky coast | Punctual erosion | High | > −10 | 1 | |
| | | Moderate | −5 to −10 | 2 | |
| | | Low | −1 to −5 | 3 | |
| | | Very low | 0 to −1 | 4 | |
| Sandy coast | Predominant erosion processes | | < 0 | 5 | |
| | Predominant erosion and low accretion | | −10/0 to 0/1 | 6 | |
| | Moderate erosion and accretion | | −5 to +5 | 7 | |
| | Predominant accretion and low erosion | | 0/10 to −1/0 | 8 | |
| | Predominant accretion and/or stable shore | | > 0 | 9 | |

**Table 3.** Coastal susceptibility codification/keys

values which vary between low and very low coastal susceptibility to erosion. The rocky coastline comprises essentially jointed crystalline bedrock with different weathering grade. The 'do nothing' option in this case will allow that the cliffs continue to erode naturally and the coastal processes continue to develop along with a few recommendations regarding planning and land-use management as well as environmental issues. Results from the core calculations provided with the DSAS software for the sandy coasts (mean net shoreline movement) indicated that sectors 1 and 2 have predominant erosion processes and sectors 3, 4 and 5 have predominant accretion and low erosion. This once again allowed strategies in terms of planning and land-use management to be recommended, as well as environmental issues. Because of the proximity of the breakwater for sectors 1, 2 and 3 the 'hold the line' option was considered in order to maintain and improve/raise the existing defence (breakwater), including investigations and improvements to the beach control and recharge. Sector 4 (Langosteira Beach) presented accretion values and it is very well protected and not so exposed to severe forcing conditions, therefore the 'do nothing' option was selected. For sector 5 (Mar de Fora Beach), despite the punctual values of accretion, the 'acting' strategy could include new defences, beach control and recharge and it seems to be the right one because the beach is more exposed and in an open area. This way it could prevent the increase of erosion processes.

The proposal guidelines were based on previous works (HGL, 2007a, 2007b, 2011; Pope, 1997; Rogers *et al.*, 2008) and present three types of explanation: engineering; planning and land-use management; and environmental. Three important categories were studied for a short-term period (from 2011 till 2030). Concerning the engineering explanation, this was supported by the sequence of policy options presented in the past by Eurosion (2004) and then refined by the shoreline management plans (SMP) that have been developed in the UK (Cooper and Dolan, 2012; HGL, 2011; Pontee and Parsons, 2012). Also in Table 4 an impact key was created which assesses the disturbance severity analysis of the strategy proposed. The key ranges from positive impact, neutral impact or negative impact (going from high-severity to low-severity disturbances). The table synthesises (inspired from the proposed impact key presented by HGL (2011); Pontee and Parsons (2012)) the disturbance analysis concerning the assets and population, land use, infrastructures and material assets, facility and recreational use, landscape character and visual quality. The management options have been selected as part of the proposed coastal plan that has been developed by local authorities and the research team working together. The plan needs to be in agreement after having engaged with interested organisations and local communities. Some of the results have already been published (www.xunta.es/litoral). This website is always being updated by Galicia Council with improvements about the research and development issues, which are connected with the ongoing scientific projects, namely CARTGalicia. The proposed strategies intend to contribute to the first shoreline management master plan in Galicia region. The recommendations made in Table 4 are suggestions to shape the future of local planning policy in coastal areas, with reference to environmental strategies. Costa da Morte (Death Coast) is considered a protected area (in Spain LIC, equivalent to LNRs, in England, Local Nature Reserves), (Lopez-Bedoya and Pérez-Alberti, 2009). This approach must remain flexible to adapt to changes in legislation, politics and social attitudes. Therefore, the project aims to provide guidance for the government and tries to make some proposals to the SMP which is currently in research and discussion by the local authorities. Furthermore it would be imperative to involve local communities in determining the best way to manage the changing coast (as described by Frew (2012), McInnes and Moore (2011) and Moore (2012)), because local

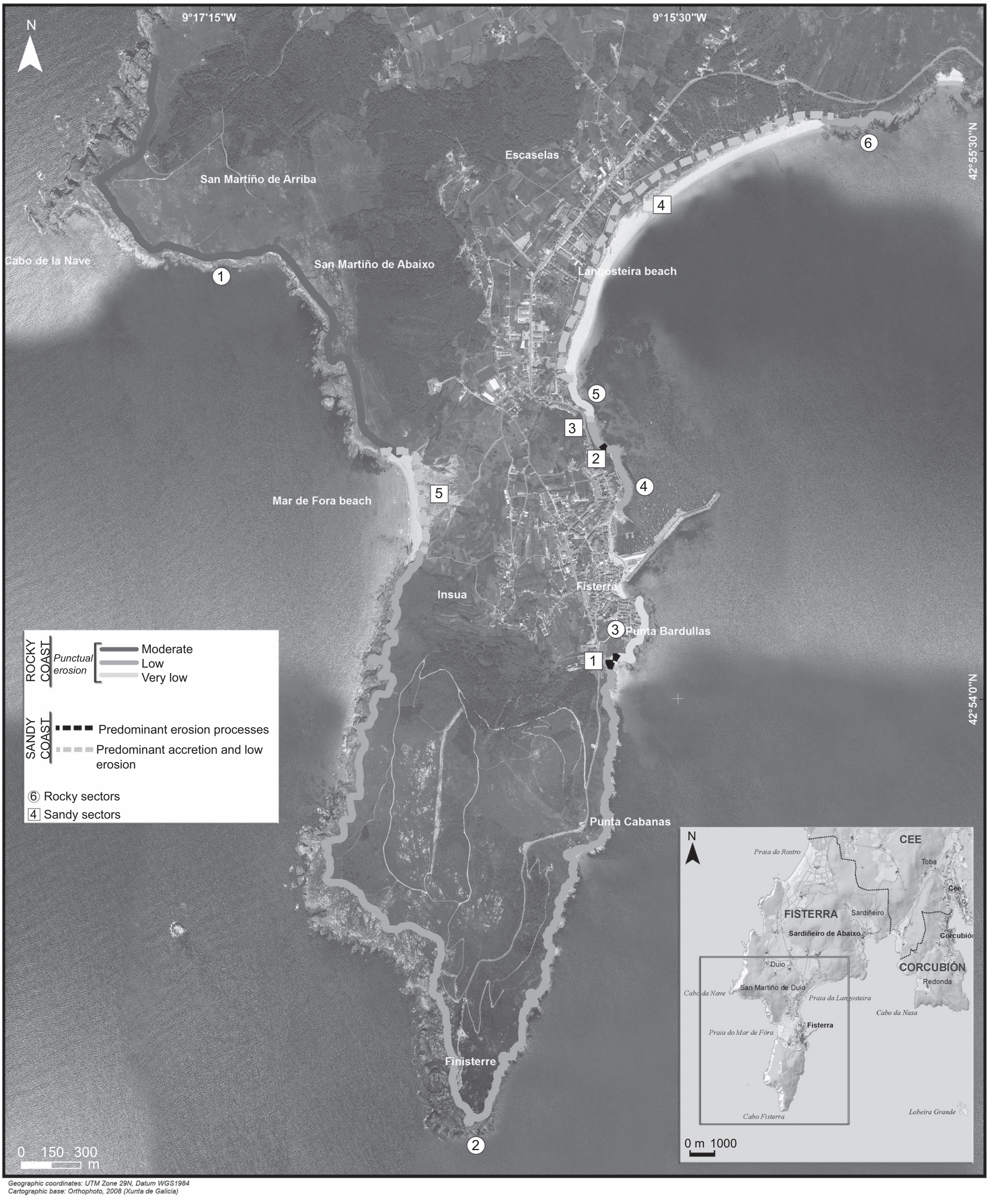


**Figure 9.** Susceptibility map of the Fisterra/Finisterre area

| Studied area Fisterra/Finisterre | | Recommended strategy (from 2011 to 2030) (short-term period) | | |
|---|---|---|---|---|
| | | Justification | | |
| | | Engineering | Planning and land-use management | Environmental |
| Rocky coast | Sector 1<br>Sector 2<br>Sector 3<br>Sector 4<br>Sector 5<br>Sector 6 | **Do nothing**: Allows designated cliffs to continue to erode naturally; allows natural processes to continue | No loss of infrastructure or material assets; avoid the construction of more houses or other type of structures along the coastal area because of the unstable cliffs; it is recommended a best practice policy to reduce the vulnerability of houses that are already built | Allows natural processes to continue; some erosion will be experienced |
| Sandy coast | Sector 1<br>Sector 2<br>Sector 3 | **Hold the line**: By maintaining and improving/raising the existed defence (breakwater), including investigating and improving the beach control and recharge | No loss of infrastructure or material assets; avoid the construction of more houses or other type of structures along the coastal area; it is recommended a best practice policy to reduce the vulnerability of houses that are already built; specially in sectors 1 to 4, with large urban areas, the construction of coastal restoration features is recommended | No special protection area present, except sectors 1 and 5 which are considered areas of nature reserve habitat (*Rede Natura 2000*) and should be maintained; local opportunities for environmental improvements and the layout and size of the predicted hydraulic structures, should be considered in a more detailed local study in the future; also future policy implementation should take this point into consideration |
| | Sector 4 | **Do nothing** | | |
| | Sector 5 | **Acting (advance the line)**: New defences, beach control and recharge | | |

| Studied area Fisterra/Finisterre | | Impact and disturbance severity analysis of the strategy proposed | | | |
|---|---|---|---|---|---|
| | | Assets and population | Land use, infrastructures and material assets | Facility and recreational use | Landscape character and visual quality |
| Rocky coast | Sector 1 | + | + | + | • |
| | Sector 2 | + | + | + | • |
| | Sector 3 | + | + | + | • |
| | Sector 4 | + | + | + | • |
| | Sector 5 | + | + | + | • |
| | Sector 6 | + | + | + | • |
| Sandy coast | Sector 1 | + | + | − | − |
| | Sector 2 | + | + | − | − |
| | Sector 3 | + | + | − | − |
| | Sector 4 | • | • | • | • |
| | Sector 5 | + | + | − − | − − |

Impact key: +, positive; •, neutral; −, negative (going from high-severity to low-severity disturbances: − − −, high; − −, moderate; −, low).

**Table 4.** Recommended strategies (from 2011 to 2030, short-term period) to the Fisterra/Finisterre area

liaison is fundamental. For example, start to create workshops along the villages and communities or other type of awareness campaigns/activities.

## 5. Conclusions

The main conclusions of this paper are listed here.

(*a*) The shoreline mapping and analysis is important for a wide range of coastal studies such as development of setback planning, geo-hazard zoning, erosion–accretion studies and conceptual or predictive modelling of coastal morphodynamics.
(*b*) It was possible to develop a methodology and also to design a GIS interactive database that can be updated throughout the time along the tested area (coastline of Galicia region).
(*c*) The approach adopted in this work contributes to improve the knowledge of the dynamics of Fisterra/Finisterre shoreline and has also provided new data about rates and distances (erosion/accretion) with the help of DSAS extension.
(*d*) The study provides a solid base to easily forecast and model shoreline displacements throughout the years, and identify main areas of erosion/accretion. Coastal cliff retreat rates are directly related to the geomorphology, geology, tectonic and weathering driving the retreat of the coast. Sandy beaches are also influenced by the exposure of the sector to extreme forcing conditions (protected areas or open beaches).
(*e*) All the statistical data and analysis generated will help to assess the Galician region and will allow creating geo-cartography in terms of susceptibility maps. The study emphasises the coastal susceptibility cartography that is new for the study site and will certainly help propose strategies based not only on the DSAS results but also on the coastal zoning crated.
(*f*) The understanding of the erosion rates is also important and should have been taken into account when designing public works. This type of study should also keep in mind problems and errors such as the shoreline vectorisation, the georeferenced orthos or the statistical method applied.
(*g*) These results are very important to incorporate in the coastal management master plan supported by the Galician local authority (*Xunta de Galicia*). This research aims to reach some of the goals included in the UK's National Coastal Erosion Risk Mapping project and provide better clarity of risk of erosion for both the public and institutions involved in coastal erosion risk management (McInnes and Moore, 2011; Pontee and Parsons, 2010; Rogers *et al.*, 2008).

As coastal communities expand along the shores of Galicia region, potential conflicts may arise between preservation of privately owned upland property and conservation of the publicly owned beach. Hence, adapting to coastal change is a difficult and an ongoing process. It is imperative that this adaptation can be built on existing coastal programmes and on risk management actions (Brown *et al.*, 2011; Pontee and Parsons, 2012). Basically there will always be a conflict between people and coastal processes. Thus, good communication and adaptive measures are important to promote public responsibility and coastal education (Pontee and Parsons, 2012).

Distinguishing between natural rates of shoreline movement and those influenced directly by human activities is crucial when historical rates of change are used for planning and to project future shoreline positions. This could probably be the case mentioned in section 4.2.3, along sectors 1 and 3 that displayed rates of accretion and even though the studied area does not report any beach nourishment project, there is information about beach nourishment projects completed along the contiguous coastlines close to the pilot site which could influence the final results. Improved methods of analysing shoreline movement will be needed to document the natural rates of shoreline change. Furthermore, shoreline prediction is important for integrated coastal zone management/planning and strengthens the role of local administrative authorities; therefore this research is still in progress to provide more detailed information.

## Acknowledgements

The authors are grateful to the Xunta de Galicia (Consellería de Medio Ambiente, Territorio e Infraestructuras) that provided key information and funded this study in the scope of the POLGalicia. The CARTGalicia project is cooperation between the School of Engineering of Polytechnic of Porto and the University of Santiago de Compostela (LABCARGA|ISEP–USC/2010-11). The participation of HIC and AP was under the framework of the PEst-C/CTE/UI4035/2011-2012 (GeoBioTec|UA), and re-equipment programme (LABCARGA|IPP-ISEP|PAD'2007-08). AP holds a doctoral scholarship from the Portuguese Foundation for Science and Technology (FCT|SFRH/BD/43175/2008). The preliminary results of the CARTGalicia Project were presented at the 7th Conference on Coastal Management, Innovative Coastal Zone Management in Belfast and were awarded the best poster communication. Special acknowledgements are due to A. S. Trenhaile (Univ. Windsor), M. Escarameia (HR Wallingford), C. Rodrigues (Polyt. Porto) and T. Oswald (Univ. Aveiro) for all the support.

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# PART III – CONCLUSIONS AND FUTURE TRENDS

*Illustration by M. Yardin (Laboratoire régional de Saint-Brieuc, in LCPC 1989)*

Shameless Sea / Mar descarado
Aimlessly so Blue / Sem rumo e tão Azul
Midnight moon shines for you / A lua da meia-noite brilha por ti

Still marooned / Ainda assim, ilhado
Silence drifting through / O silêncio paira
Nowhere to choose / Nenhum lugar para escolher
Just Blue / Apenas o Azul

Ceaselessly / Incessantemente
Star-crossed you and me / Tu eu eu estamos condenados
Save our souls / Salva nossas almas
We'll be forever Blue / Seremos sempre Azul

Waves roll / As ondas rolam
Lift us in Blue / Nos elevam no Azul
Drift us / Derivam-nos
Seep right through / Inflitram-se por todo
Color us Blue / Pintam-nos de Azul

Wait for me / Aguarda por mim
Shameless you the Sea / Descarado és tu, Mar
Soon the Blue / Em breve o Azul
So soon / Tão breve
Soon the Blue / Em breve o Azul
So soon / Tão breve

*DAVID GILMOUR*
*"The Blue", On an Island (2006)*

# 11. SYNTHESIS OF RESULTS

## 11.1. General discussion

The scientific fields of research initially proposed in this thesis were fulfilled. The research in its essence, covered coastal GIS mapping domain but also involved several methodologies and techniques related to: (i) coastal geosciences mapping and photogrammetry; (ii) DSAS (*Digital Shoreline Analysis System*) applications; (iii) study of rock-armourstone deterioration and durability; (iv) monitoring and inspections of hydraulic structures; (v) geomechanics studies on rock shore platforms; and finally (vi) integrated studies on coastal/shoreline management and territory planning.

These fields were the main research focus throughout the thesis framework. The sequence of procedures and methodologies applied remained a common denominator and it was tested on different maritime environments and geological contexts.

As stated in the thesis architecture, the dissertation presented herein is displayed as a series of original papers published or in press. However, the mixed version or style of the thesis allowed for an expanded introduction and background. Therefore *Part I* (Introduction and background) was comprised by three chapters that gave the overall perception of the thesis inherently associated with the PhD research; context, scope and objectives, characterisation of studied areas, methodologies and state of the art. The state of the art section (*Chapter 3*) reflected about general concepts regarding coastal systems and processes. As explained before, *Part II* of the thesis included a comprehensive coverage of relevant literature. Nevertheless, the contents of *Part I* displayed the reasons that led us to consider such an investigation and introduced a critical review of selected literature. This chapter also included the thesis aims, identification of knowledge gaps and the relationship of the bibliography to the research program. Finally, to help to understand coastal dynamics the concepts of coastal geoengineering and strategy were introduced.

The global working strategy involved the development and improvement of an applied methodology comprising the assessment and management of hydraulic structure durability, and included the characterisation of geomaterial at the rock quarry sources. At that moment the development of this integrated approach was the starting point to be extended in order to apply it globally to different maritime environments. In the beginning we undertook to answer specific questions/aims. The answers to these questions were obtained by accomplishing several tasks interconnected with visualisation and data information: (i) collection of information and selection of study areas; (ii) geoengineering GIS databases; (iii) creation of general datasheets; (iv) GIS and spatial analysis tools; (v) field techniques and geoscientific measurement methods; (vi) other cartographic features and processes and statistical analysis; (vii) an integrated analysis of the results: an original methodology proposal for coastal geoengineering assessment.

These aims were pursued by combining different techniques and tools, including aerial high-resolution imagery, field surveys and relational databases, evaluation of deterioration levels, geomechanical assessment of geomaterials, accuracy analysis of erosion and wear rates in geomaterials, and GIS modelling techniques.

After the long period of research that has taken place we must be able to answer the questions posed earlier. The questions are listed below with some observations:

1. *What is the present condition of the hydraulic structures under study?*
    a. Chapters 4, 6 and 8 give particular results about the current status of maritime structures and their geotechnical condition.
2. *Which types of geomaterials are involved in the failure of or damage to structures, and in what proportion?*
    b. Again Chapters 4, 6 and 8 display the alterations between different lithologies, rebound values (Uniaxial Compressive Strength – USC) and altered geotechnical zonings induced by deterioration levels.
3. *Which are the more suitable areas/quarries for the potential extraction of durable armour stones?*
    c. Chapter 5 emphasises the coastal geoengineering issues for the suitable selection and geomaterial characterisation of quarries.
4. *Which factors influence geomaterials behaviour and, thus, the performance and lifetime of the study structures?*
    d. Chapters 4, 6 and 8 address the geomaterials characteristics and geological and/or geotechnical information which could affect the structural parts or components of the hydraulic structure.
5. *How can different coastal environments influence the durability of armourstone layers and vice versa?*
    e. Again Chapters 4, 6 and 8 discuss the physical characterisation and evaluation of forcing conditions to understand the coastal dynamics of the studied area.
6. *How can shoreline evolution and cliff retreat be measured?*
    f. Chapters 6 and 10 address the methodologies to assess shoreline change and cliff retreat, focusing on the analysis of coastal dynamics and spatio-temporal changes of coastal morphology for a particular period of time.
7. *What are the consequences of erosion/accretion phenomena in the area in terms of coastal management and territory planning?*
    g. Chapters 6 and 10 relate the statistical rate analysis of the results (erosion and accretion values) with the coastal susceptibility evaluated from the results, providing useful information about the studied area and proposing recommendations for coastal management plans and policies.

8. *How can GIS mapping and cartography help to assess these coastal environments?*
    h. All chapters used GIS mapping and cartographic techniques combined with additional methodologies, equipment and tools.
9. *In what way can the integrated coastal geoengineering approach be related?*
    i. All chapters merged the specific topic with the coastal geoengineering concept as the main core of the research, featuring the integrated approach in diverse maritime environments and in different geological contexts.

One of the advantages of a multi-paper thesis is that all the chapters can stand alone and can support themselves. Hence each chapter of the thesis could be comprised by more than one section which corresponds to the papers written. The discussion in terms of results that will be done below is associated with the research fields associated with each chapter: applied cartography and coastal dynamics; georesources assessment; coastal geoengineering applications and monitoring; rocky coast evaluation; mixed environments; coastal geosciences GIS mapping and photogrammetric surveying; shoreline change mapping and coastal management strategies.

This section aims to summarise and highlight some of the aspects considered of greatest relevance in the development of the various chapters of the dissertation. After the initial part, seven chapters were presented. These are the chapters that were the target of analysis in this section.

### Applied cartography and coastal dynamics – *Chapter 4*

*Art historical analysis / coastal geomorphic mapping: general description and cartography*

❖ This chapter is all about the significance of art and cartography in coastal research. The work – presented as a catalogue – addresses art as a tool in coastal evolution. Also a brief history of Portuguese coastal art is supplied with some insights through science. Many historical elements and data were compiled in this catalogue about "art as a tool". Also a detailed analysis was given of some aspects of several Portuguese paintings or other associated media by different authors related with coast, sea, shoreline or coastal features and elements (e.g. paintings, old stamps, images related to coastal issues). Art in coastline evolution shows general aspects about the topic of coastal changes but from a different perspective. These paintings could "tell us a story", working as an instrument in support of the understanding of coastal change.

The timeline highlighted in this exhaustive research describes the analysis of old paintings in terms of coastal features, relating them to the most innovative techniques and systems to evaluate the shoreline: high resolution aerial imagery. The past and the present are confronted and challenged to show how images and cartography have defined their role in coastal evolution analysis and assessment.

❖ In general terms the coastal geomorphic mapping could be accessible in different framework levels or scales: from regional to local. We can have general sketch and particular sketch maps. GIS mapping and applied cartography supported the creation of regional maps showing the coastal dynamics background in a wide approach of the system. This chapter draws the attention that is also possible to generate detailed maps of the studied areas which can support important decisions in terms of coastal strategies. These maps could be established by basic cartography with intrinsic and basic elements. The applied cartography rises from derivative GIS mapping. These maps can be characterised by geomorphic features which includes standard and particular (specific) features: maritime works (hydraulic structures) or natural coast (rocky and sandy coasts). Furthermore these features categories can also be considered: static (e.g. coastal works, cliffs) or dynamic (e.g. related with processes and flows; beach nourishment; erosion/accretion data; historical records and evidence). The studied sites were the groynes along the Figueira da Foz coastal area (Central Portugal). This type of research proposes coastal geoengineering cartography by relating several levels of representation: (i) topographic features (physical characteristics); (ii) land use features; (iii) geological and geomorphological features; (iv) tectonic features; (v) coastal geoengineering features; (vi) coastal protection works; and (vii) main coastal landforms.

## Georesources assessment – *Chapter 5*

*The role of cartography in georesource zoning, assessment and armourstone durability*

❖ This work presented a methodology for the assessment and management of coastal hydraulic structures, focused on the quality, durability of protective rock-based materials and including the characterisation of geomaterials at the quarrying sources. The research involved different techniques and tools including aerial high-resolution imagery, field surveys and relational databases, evaluation of deterioration levels, geomechanical assessment of geomaterials, and GIS mapping and modelling techniques. The development of the research had two main phases: (i) the field survey, applied cartography and inspection of maritime structures and (ii) the geological and geotechnical quarry assessment. The research reported the results from the second phase, which comprises the evaluation of quarries and the identification of potential areas for the extraction of armourstone with the quality and availability to supply maritime structures.

A zoning of the NW Portugal region was proposed that takes into account some features like land use and management, urban and settlement plans, geological setting, and geotechnical and geomechanical description/typification of the rock masses. We identified 459 rock quarries, georeferenced and distributed in a total area of 14,010 $km^2$. More than 200 sites were selected, characterised and included in the GIS database project with interactive support (e.g. hyperlinks for the datasheets, photos or essential information). A total area of 4.1% was calculated, including relevant geological conditions and comprising existing quarries (active/inactive) or new places (suitable or potential areas). The main results were presented for two different approaches: (i) the applied cartography and inspection of maritime works; and (ii) quarry characterisation and recognition of potential areas for the extraction of armourstone.

For the first approach different geomaterials were recognised, such as natural rocks (granite and gneiss) and artificial materials (concrete or a mixed material, i.e., concrete + aggregates or tetrapods). This applied cartography provided an evaluation of the current condition of the structure and the revetment material status. A detailed mapping of the rock blocks was prepared with the support of the aerial photographic database. Afterwards, for the five studied sectors, more than 20,000 block materials on the structure's superficial section (armour layer) were vectorised in a GIS base. This approach allowed us to obtain thematic maps of the structures to be used in evaluating different geomechanical and geotechnical parameters. From the results obtained, there are substantial indicators of the need for repair/maintenance works in some components of the studied structures (5 sectors).

For the second approach two distinct databases were built: a relational and a georeferenced GIS database. The first database was compiled in Microsoft Office Access, enabling queries to explore all the information, which was organised by districts and counties. The georeferenced database, with the locations of all the quarries identified, is connected to the GIS project and comprises not only general information but also the datasheets for the quarry evaluation and the hyperlinks to the sites, cartographic bases, images, orthophotos, and other features. Therefore, the geographic database is functional, interactive and constantly updated. The GIS platform allowed the determination of potential areas for the extraction of armourstone, as a result of all the related data of the inventoried quarries and other layers previously described that were incorporated in the final project.

In the end the research looks forward into the future based on network analysis for the choice of the best route from the quarry to the coastal work. Thus, this study showed that a geo-engineering GIS project can provide critical information for analysis and decision-making about each structure. A multidisciplinary perspective must be adopted, providing a cost-effective method useful to the incorporation of important concepts (durability and integrity) in geo-monitoring coastal plans and highlighting GIS coastal projects.

## Coastal geoengineering applications and monitoring – *Chapter 6*

*Experimental field – Espinho site (NW Portugal)*

The Espinho pilot site is a well-developed study case comprising three sections: (1) the relation of coastal dynamics, shoreline evolution and the geotechnical characterisation of the hydraulic structure; (2) the methodological stages for cartography and assessment of hydraulic structures from the Espinho coastal area using high-resolution aerial imagery surveys and a GIS interactive database; and (3) the problem of assessing armourstone structures focusing on strengthening the combination of geo-marine techniques and geotechnical properties as well as the importance of quarry evaluation in order to improve armourstone quality and durability.

❖ The first section takes advantage of GIS tools to contribute to the knowledge of the geologic and geomorphological dynamics of Espinho shoreline. A GIS-based monitoring project was compiled, which gathers information on all coastal works located along Espinho shoreline, focusing especially on construction, monitoring, and repairing aspects. The shoreline change was analysed using the ArcGIS extension entitled Digital Shoreline Analysis System (DSAS) in order to understand this important aspect of coastal management that needs to be further investigated.

The main results indicate a general trend of erosion in the South and an accretion trend in the North of the Espinho coastal area. Geoengineering characterisation of the Paramos groyne allowed to define three main zones for the armor block materials, i.e., Zones I, II/III, and IV, which show, respectively, very low, medium to high, and low deterioration levels.

❖ The second section developed and presented a systematic methodology for the analysis of coastal protection structures in a GIS database project. Low-level aerial surveys were conducted from a light aircraft, providing high-resolution digital images suitable for armour layer integrity analysis. Combining photogrammetric and field techniques, this study aimed to define an applied cartography for geomaterials characterisation in hydraulic works. The research was comprised of different phases: i) visual inspection; ii) field techniques to study geologic-geotechnical features; iii) in situ measurement of geomechanical parameters; and iv) development of GIS mapping and assessment of the block materials. The GIS project incorporated high-resolution aerial imagery surveys and the results of the field techniques were applied for the structures' cartography. The interactive base included the pilot case presented in this work, from the Espinho coastal area (NW Portugal), which comprises five sectors. Based on the described methodology, different geomaterials were identified, providing an evaluation of the current condition of the structure and the revetment material status. Form the results obtained it was possible to define a geomaterial zoning for the structures' armour layer, according to the type of rock source, weathering/degradation grade and in situ geomechanical tests, as also accomplished by the first section.

❖ Finally the last section confirmed the relevance of a holistic approach to coastal design issues. The suggested approach couples GIS-based mapping with geo-engineering techniques assessment along five sectors of the Espinho coastal system. Once again this investigation allowed us to propose zoning a coastal structure according to its degree of deterioration, geomechanical properties and geomaterial status. Replacement of the primary armour layer in only selected sections or components of the structure will reduce the cost of maintenance, repair and reinforcement work. All of the data gathered about the preservation status of the armour layer and the quarry inventory have been compiled into a powerful GIS geo-database. The paper argues for the wider use of a combination of coastal geo-engineering and GIS analysis in planning the monitoring and/or maintenance of marine works using armourstone.

## Rocky coasts evaluation – *Chapter 7*

*Rocky coast and shore platforms studies*

❖ The results of the research and analysis reported in Pérez-Alberti *et al.* (2012) are presented in this chapter. This section comprises the study of boulder deposit characteristics, clast/megaclast mobility and shore platform evolution. Boulder accumulations are common on the granitic shore platforms of Galicia, northwestern Spain. Boulders are produced by erosion of the shore platforms and of cliffs consisting of Weichselian, cold-climate deposits. Measurements were made of the long axis length of more than 800 boulders, and additionally of the short and intermediate axes of 340 of these boulders, as well as their orientation and gradient. There were two study areas. Because of greater joint density, the boulders on the Barbanza Peninsula are generally a little smaller than those in southern Galicia with, respectively, mean long axis lengths of 0.98 and 1.14 m, and masses of 1.06 and 1.59 t. Joint density and orientation also account for the occurrence of very coarse boulders and megaclasts in southern Galicia. The distribution and extent of the deposits and boulder imbrication and orientation testify to the high levels of wave energy produced by north-westerly and westerly storms in this region. Although the boulders, as well as the underlying shore platforms, were inherited, in part, from previous interglacial stages, some boulder detachment and movement occurs today during storms, when significant deep water wave heights exceed 8 to 10 m. Despite some abrasion of the shore platforms, the primary role of large boulder accumulations is protective. The effect of sediment on shore platforms has been neglected in other studies, but this one suggests that, because of arrested development under thick accumulations, platform gradient in areas with abundant sediment increases with the grain size of the material. The occurrence and type of sediment on shore platforms may therefore help to explain the distribution of sloping and sub-horizontal platforms under different morphogenic and geological conditions.

## Mixed Environments Approaches – *Chapter 8*

*Sandy or mixed coasts*

❖ This chapter is concerned with methodological approaches in mixed environments. It presents the Aguiño study site, located in the Ribeira coastal area (NW Galicia), which comprises a very particular geomorphological setting. The studied site presented a rocky platform which is used mainly as a foundation for the maritime work and narrow sandy areas along the shore. The mixture of environments and the severity of hydraulic conditions in the Aguiño area made a unique research site. Several interdisciplinary studies were carried out to assess the coastal system considering the geomorphology, geotectonics, morphodynamic processes, forcing conditions, geomechanics of materials, geoengineering methodologies and GIS mapping. The Aguiño maritime structure uses the rocky platform as a foundation, so this type of coastal protection solution offers numerous features to be analysed and characterised. There is an intrinsic relationship between the artificial maritime design/construction and the natural rocky coast. The detailed cartography allowed us to obtain interesting results and encompasses geomorphologic, geoengineering and coastal dynamic data. In addition, in situ strength tests were performed to determine the hardness/rebound and durability of the rock material, not only on the rocky platform and boulders, but also on the armourstone placed along the groyne's armour layer. This holistic approach allowed the study of coastal geomorphology and geoengineering along the Aguiño site. The thematic maps displayed could be very useful in the future to determine zones of vulnerability to coastal erosion, hydraulic structure silting up, and for 3D modelling, geohazard and regional/local assessment for coastal management.

❖ The next section is about the Lavadores (NW Portugal) shore platform and coastal boulders. The research employed the same approach as the previous study, but with a wider development in terms of applied cartography and GIS mapping. However, the studied zone is presented on a smaller scale, to a lesser extent than that in Galicia in terms of boulders. It was possible to characterise the studied area in terms of coastal dynamics and boulder (clast) mobility but also it was possible to define geotechnical zonings in terms of geological and geomorphological characteristics of the area and geomechanical parameters obtained in situ. This research was thoroughly developed along the MSc thesis intitled "*Geotechnical mapping of boulders in coastal platforms (Gaia,NW Portugal)*", published by ISEP|IPP in Portuguese (further details in Costa 2014).

These two sections have comparable geological characteristics but with very distinct coastal environments. However, in both of the cases it was possible to apply procedures and methodologies that couple geomorphological issues with coastal geoengineering aspects.

❖ This chapter also embraces the research still in progress, about a comparative study and statistical analysis of concrete blocks along maritime structures. This research was conducted on the geomaterials and deterioration of concrete blocks in the maritime works of Espinho and V. Praia de Âncora (NW Portugal). This study is focused on the combination of geotechnical evaluation of the materials used in armour structures (based mainly on degradation level, geomechanics properties and hardness of the geomaterials) in order to consider how material properties might influence the design of coastal protection structures. Basically three types of devices or equipment were used for two locations/site investigations and on two types of concrete armour units (tetrapods in the Espinho site investigation and antifers in the V. Praia de Âncora study site). The main goal was to analyse the Equotip 3 and Schmidt hammer hardness correlation data. Equotip was used to measure surface strength concrete blocks, combined with other conventional methods such as Schmidt Hammer (type N) and DigiSchmidt (type ND). Up to thirty measurements were taken along each scanline transect, in clusters of 25 values around the site of each block (see preliminary results and some details in Appendix 3). Means and standard deviations are compared to assess differences between the different types of concrete blocks (e.g. tetrapods, antifers). In addition, a comparison between the rebound values estimated by the Equotip, Schmidt Hammer and DigiSchmidt was performed. The data from the armour layer condition evaluation are used to produce recommendations for maintenance or additional inspection. Therefore, this study was concerned with the identification and assessment of factors that could extend the life of coastal protection structures. It was possible not only to establish a correlation between the values of hardness and rebound, but also between types of block, degradation level, distance to the sea and location (site investigation).

## Coastal geosciences GIS mapping and photogrammetric surveying – *Chapter 9*

*Coastal geosciences and geoengineering mapping*

❖ This chapter highlights digital photogrammetry and GIS-based mapping as powerful tools in littoral issues. These technologies could be model-based on GIS platforms in order to monitor and predict the evolution of coastal zones. This research considers the interoperability framework from high-resolution imagery acquisition to the development of coastal geosciences maps. The layered system architecture of the cartographic methodology is also explained. Moreover, it highlights a new approach to assessing heterogeneous geologic, geomorphological and maritime environments. In addition, coupling cartographic techniques and field surveying allows a tool–chain interaction which will show the networking and clustering views from photogrammetric data and GIS-based mapping. This approach supports a methodological proposal to contribute to the monitoring of coastal zones and to evaluate the maritime forcing conditions. Furthermore, with accurate surveying techniques it is also suitable for assessment from the rock shore basement to armourstone used in hydraulic structures.

An integrated coastal geoengineering methodology was outlined in the NW Iberian Peninsula (South Galicia and North/Central Portugal regions). This approach will allow: (1) the acquisition of a large archive of high resolution imagery, (2) the development of a coastal database including all the field data and in situ assessments, (3) the study of coastal dynamics and shoreline evolution, (4) the assessment of rock platforms and hydraulic structures, and (5) the production of coastal geosciences maps. The architecture of this study is presented, coupling photogrammetric techniques with applied cartography, endorsing GIS software as a powering tool to encompass, not only several layers and inputs, but also thematic output maps. The aim is to present a new concept for the use of photogrammetric image acquisition to assist modelling techniques, and to develop spatial analysis and coastal conceptual models. In addition, this study also highlights the fact that applied cartography techniques, supported by Geographical Information Systems and Science (GIScience), are very suitable to obtain valuable information for the management of maritime environments, particularly when accuracy, cost and efficiency are considered.

This is a more methodological chapter linked to cartographic techniques, field surveys, research theory and practice, and management in littoral zone and coastal geoengineering surveying.

## Shoreline change mapping and coastal management strategies – *Chapter 10*

*CartGalicia mapping project overview: coastal management*

This section brings out data and results from the CARTGalicia project. This is a joint project between the School of Engineering (ISEP) of the Polytechnic of Porto and the University of Santiago de Compostela (LABCARGA|ISEP–USC/2010-11). In addition, these results also contributed to the master coastal management plan (POLGalicia) carried out by the Local Authorities (Xunta de Galicia, Consellería de Medio Ambiente, Territorio e Infraestructuras).

❖ This research was concerned with shoreline change and cliff recession in Galicia (NW Spain). The study focused on the analysis of the coastal dynamics and the spatio-temporal changes of coastal morphology for the period of 1956, 2003, 2006 and 2008, using the Digital Shoreline Analysis System (DSAS) extension. Estimation of the rates of erosion and accretion along the pilot site (the Fisterra/Finisterre area) was performed. In addition, a continuous coastline along Galicia was integrated into a GIS project which comprises an interactive database with key information. A coastal susceptibility map (erosion/accretion) was created based on the DSAS results for the short-term approach and cross-checked with knowledge of the area in terms of geology, geomorphology and landslide occurrences. Aspects related to the engineering solutions, land use planning or environmental management were considered in the recommended strategy, as well as an impact and disturbance severity analysis for each action used. The methodological phases of the research went through processes which encompass a regional assessment of the entire Galician coastline and a local approach concerning shoreline change analysis (short- and long-term data). Nonetheless only the short-term results were discussed because it was the most reliable approach. A comparison of three statistical methods was used to check the output rates (Linear Regression [LRR], Weighted Linear Regression [WLR] and End Point Rate [EPR]). In terms of distances the Net Shoreline Movement (NSM) was reported, which represents the total distance between the oldest and youngest shorelines. In summary the shoreline change assessment included an analysis of net shoreline movement, rocky coast, sandy coast and a general overview. From the general overview analysis, by comparing long-term and short-term summary values for each sector and type of coast, it was possible to recognise a systematic decrease in the rates of eroding shore in the eastern area of the study site. The decrease in erosion rates and complementary increase in accretion rates may partly be related to the existence of maritime structures or even the surrounding cliffs, which could act as a maritime defence. All of the information available was cross-checked with the DSAS data calculation. Then it was possible to formulate important considerations about the coastal area. First of all the geomorphology and configuration of the coast are essential to understand the coastal processes, especially along the rocky coasts which experience landslides.

The geology, morphotectonic and weathering processes and efficacy are other important factors that must be considered. For example, in this case there are differences between the granites and the metasedimentary rocks, mainly between very jointed and less fractured areas. Dynamics are more intense, progressive and rapid on sandy than on rocky coasts and, depending on exposure, these areas may be subjected to extreme hydrographical conditions. At the end of the study it was conceivable to create a map codification for coastal susceptibility mapping on a local scale. The susceptibility map codification was based on the data of the net shoreline movement (NSM) for the short term. It combined the net shoreline values (NSM) with the area recognition in terms of physical characterisation (geomorphology and geology), coastal processes (forcing conditions) and instability events (landslide mechanisms and rock collapses).

The coastal susceptibility assessment is a qualitative value that was achieved in the study so that it would be possible to identify areas with higher or lower predisposition to erosion and accretion phenomena. Susceptibility evaluation allows us to spot areas needing strategic measures and proposes alternatives to minimise the damage that erosion could cause to rocky or sandy beaches and their surroundings. To conclude, specific challenges and recommendations were prepared for the shoreline management plan. These proposal guidelines were based on previous works and offered three types of justification: engineering, planning and land use management, and environmental.

❖ This chapter also includes the research still in progress about coastal cliff retreat and morphodynamics in Galicia (N Spain) in order to show evidence of differential mass movements. As Lagoas and Estaca de Bares were the studied areas and once again DSAS (Digital Shoreline Analysis System extension) was applied to analyse the cliff retreats for the period of 2003, 2008 and 2010. The same statistical parameters were used to measure rates of erosion (EPR, LRR and WLR). This research implies a GIS mapping and cartographic analysis for coastal erosion assessment. These cartographic techniques and representations allowed us to create geological and geomorphological maps that will help to understand the coastal dynamics and the type of slope instability. From the cliff retreat survey output maps were created for the integrated geohazards ultimate analysis. The preliminary analysis and discussion will show the implications of shoreline and cliff changes on coastal management and planning.

This chapter draws attention to improved methods of analysing shoreline movement that will be necessary to document the natural rates of shoreline change. In addition, shoreline prediction is important for integrated coastal zone management/planning and strengthens the role of local administrative authorities.

In conclusion it is also crucial to highlight the importance of making science with engineering concepts and several technologies during the research period. As mentioned before, the results and discussion sections consist of sets of research papers. Thus the investigation development is an important part of the thesis and allowed to "*live*" the making of the thesis with other perspective. Perhaps with a more mature perspective because all the methodological approach is intrinsically related to the investigation and science work flow-line. By focusing on an academic career, it is expected for the candidate to develop a kind of work that comprises several goals, different methodologies and leads to find the solutions for scientific questions. Regarding the scientific approach it is important to emphasise the engineering perception included in this research. As stated before we addressed such research to both academia and industry. The creation process in science and experimental research are likewise important and necessary for the thesis development. This type of approach was the starting point to publish and to communicate our results. Moreover allowed to develop skills to design the final conceptual models presented herein this thesis.

## 11.2. Conceptual models for coastal geosciences and geoengineering GIS mapping

Even though we have achieved particular and interesting results throughout the thesis by using GIS mapping and geo-cartography, it is also important to conceptualise ideas and theories and to structure the methodologies of the research. As already described in the methodology chapter, there are certain and specific procedures that were applied. The set of procedures and techniques combined in a certain way and with a multidisciplinary approach were able to support the research.

This section is the culmination of all the assembled knowledge, data, information, results and conclusions from all of the research conducted. Consequently, the conceptual models proposal displayed herein focus on the research logic: the georesource assessment – geomaterial evaluation – maritime environments characterisation – coastal management plan. The story will be told from the beginning, however this research does not have an end…it is almost like a "never-ending" story… Since this is an open and dynamic research topic we can encourage this evolution to do better, to improve, to transcend ourselves. Even the conceptual models are continuously updating their theories, methodologies and technologies, since we live in an innovative, evolutionary and mutative world.

Georesource assessment obviously includes the overall evaluation of the armourstone quality. The first conceptual model (Figure 124) proposes the stages or operations to take into account in maritime constructions, from proper selection of the quarry to armourstone durability tests and certification. The operations could be associated with the rock quarry or with the building site, from the rock exploration to the construction of the hydraulic structure. To improve the blasting methods some recommendations related to rock mass surveying and quarry evaluation are made. On the other hand rock quality and durability is essentially linked to the durability characteristics as well as to quality assessment and control.

The costs and a good rock specification are also factors that could indirectly influence the rock quality. Essentially the model highlights the challenge of assessing the georesources properly.

Over the period of the study it became clear that the methodology developed was an interesting starting point in GIScience cartography for maritime environments. The conceptual model proposed in Figure 125 not only represents the synthesis of integrated coastal zone management but also shows the key elements and requirements for geoengineering techniques. The relationship between the acquisition of high resolution imagery, photogrammetric techniques, high resolution GPS measurements, basic fieldwork and the applied cartography production is illustrated. Altogether this approach represents an integrated framework – interdisciplinary, multidisciplinary and transdisciplinary – of the studied region or site. This model is inherently coupled with the previous one, as from the very beginning of the research the genuine principle was to articulate the assessment and management of hydraulic structure durability, with the characterisation of geomaterial at the quarry sources. We have mentioned this link so many times for the reason that good production of rock armour and proper handling, transport, delivery, placement and construction will increase the service life-prediction and stability of the hydraulic structure. These are important aspects that should be taken into consideration by engineers, contractors, companies, etc.

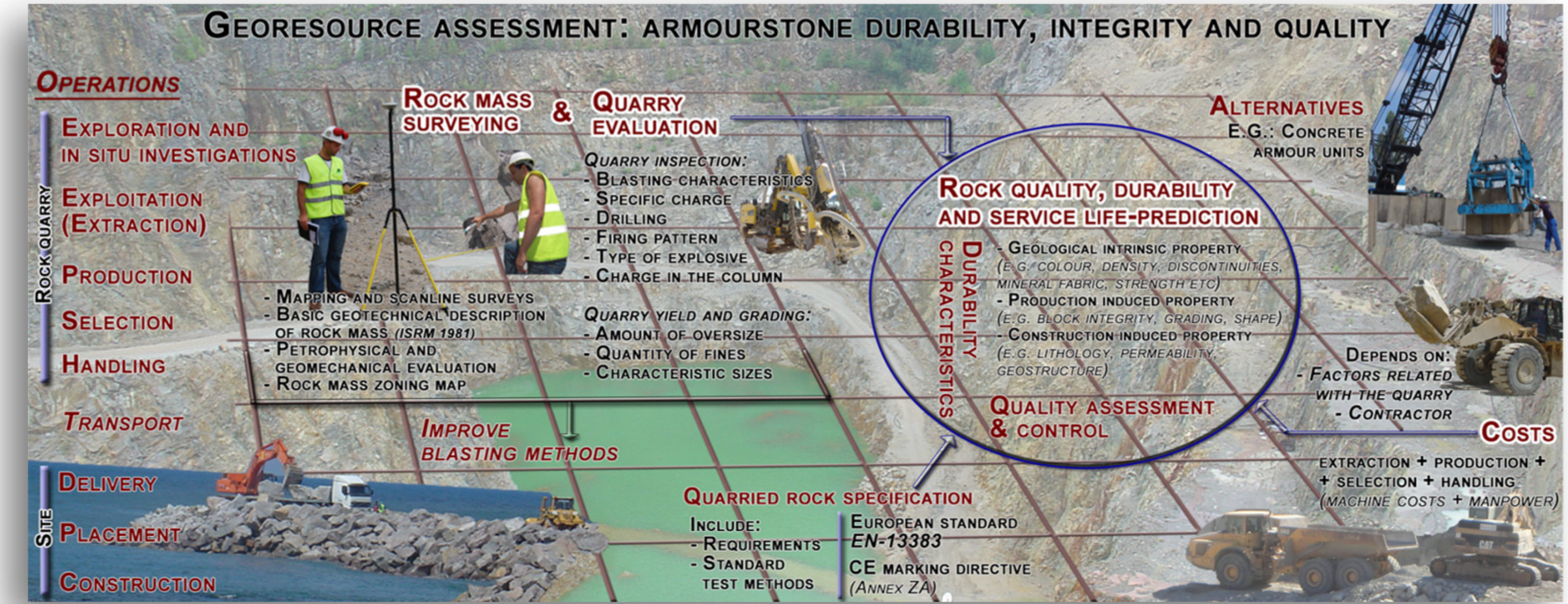


**Figure 124.** Georessource model: quarry assessment and armourstone quality.


**Figure 125.** Model for the integrated coastal zone management: coastal geoengineering approach.

Afterwards, from the conjugation of both models previously presented, the design displayed in Figures 126a and 126b it was then outlined. The schemes show that both conceptual models presented in Figures 126a and 126b complement each other: firstly, it is presented the methodological approach and the necessary inputs that need to be taken into account, which will lead to the integrated geohazard analysis using GIS applications (Figure 126a); finally, it is presented the global conceptual model for coastal management projects including shoreline and cliff assessment (Figure 126b).

Coastal management and territory planning should include both approaches, since the outputs resulting from well developed coastal projects combine several analysis elements (R&D and technical studies, anthropic factors, environment, socio-economic factors and policies). Always with the management goal in mind, the conceptual model put forward some features related to shoreline and cliff changes. The model makes use of maps, GIS, cartography, and several tools and methodologies illustrated in the schema. Also forms, processes, dynamics, evolution and data modelling were taken into account for the development of the conceptual model and system mapping. In summary, coastal management encompasses the outputs/results of the different approaches (quarry assessment, coastal geoengineering, shoreline and cliff evolution) taking into consideration the national policies, regional governments, local authorities, stakeholders and communities.

The last model will work as a prequel, whose story or in this case whose work takes place before that of a pre-existing work. Why show the beginning in the end? Because it is imperative to emphasise this conceptual schema (Figure 127). It is necessary to know the past and to understand the present in order to be able to project the future. Primarily we have elaborated on the previous three models, but we decided that if we want to visualise the global system we had to add another level (the beginning). The model is entitled the invisible "inception" within the inception. The reason in fact is because there is an origin before the beginning. Firstly, the main triggers already mentioned throughout the thesis are considered to be the problems (e.g. anthropic influence, coastal ecosystem, coastal erosion, climate change). Secondly, these same triggers caused the kickoff or start-up of the research. These triggers will somehow motivate the engineers and researchers to come up with innovative and diverse solutions to solve the problems in terms of coastal management. We can observe in Figure 127 that the background corresponds to the Espinho pilot site (NW Portugal) and its coastline evolution during the years from 1958 to 1988, until the construction of the field of groynes in the 1980s.

It is important to highlight this fact because it is needed to understand the past. The starting point of the research coupled rock quarrying source with ICZM (Integrated Coastal Zone Management) in a geoengineering perspective. Linking science, engineering and management to recognise the implications for coastal governance is the primary purpose of the inception.

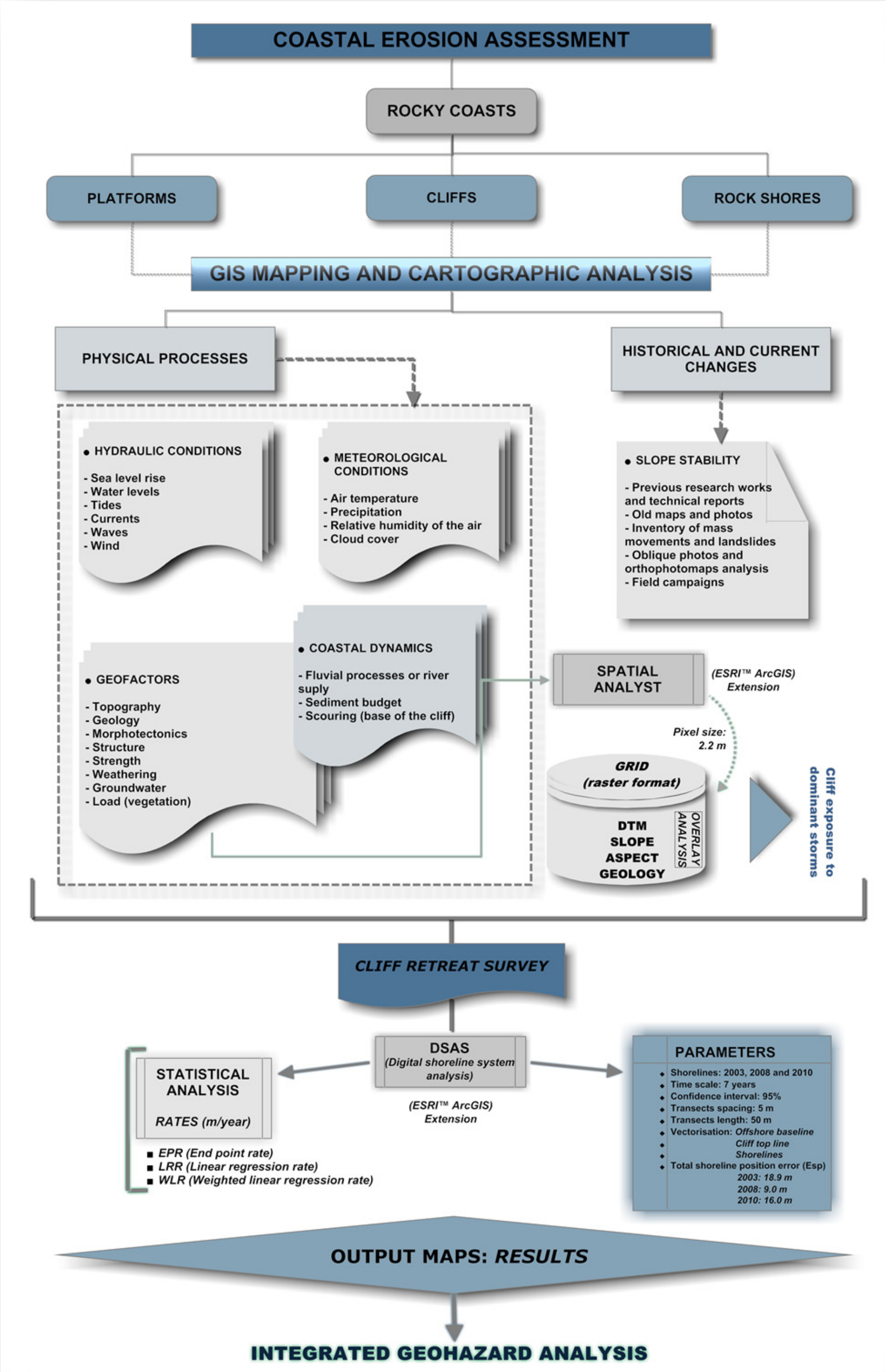


**Figure 126a.** Methodological approach and model for the integrated geohazard analysis: GIS data-based platform, from the inputs to the output maps.

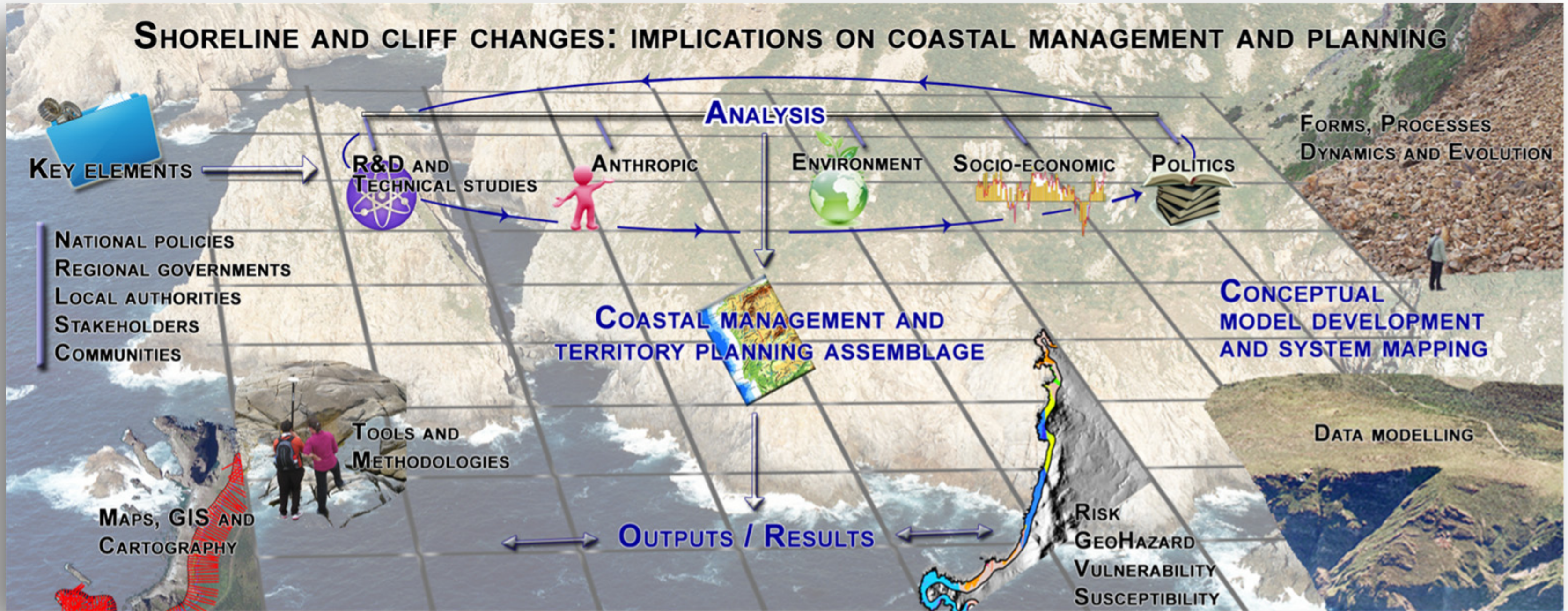


**Figure 126b.** Conceptual model for coastal management projects: shoreline and cliff evaluation.

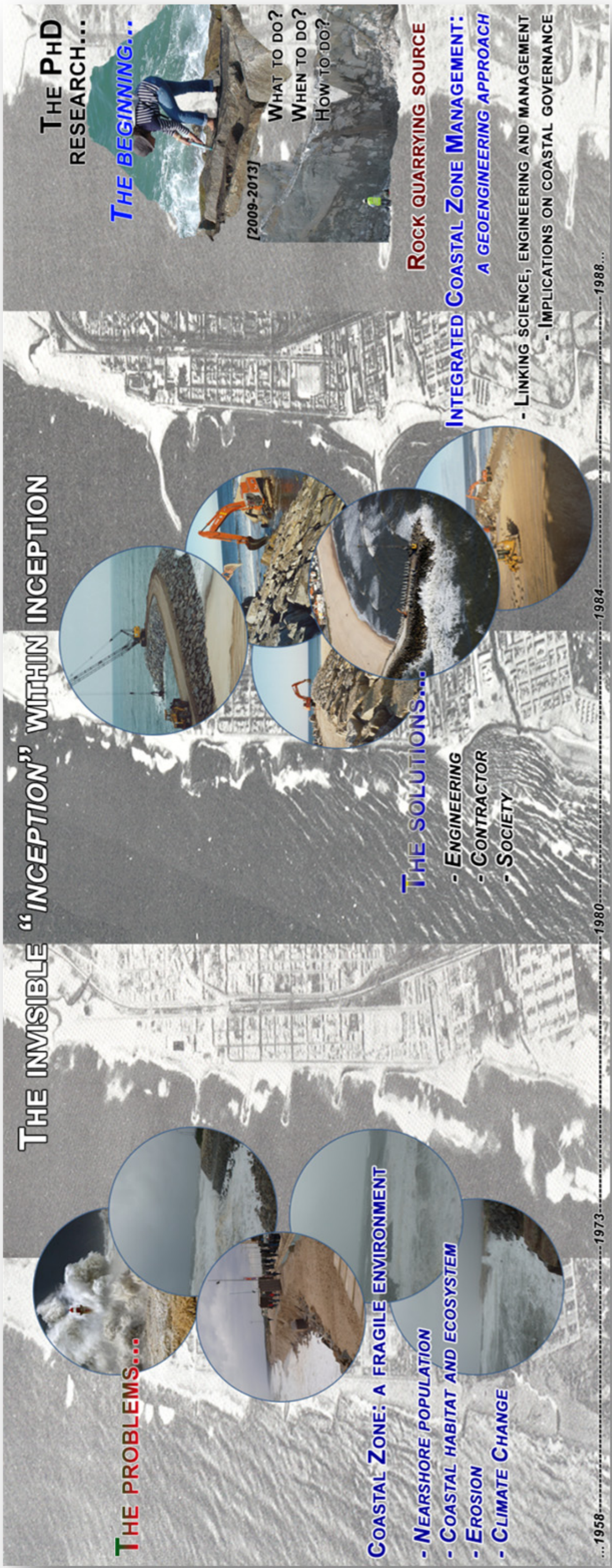


**Figure 127.** The inception model and the beginning of the research.

### *The coastal geoengineering overview*

Now we are able to see the coastal geoengineering cluster. The outlook showed in Figure 128 represents the coastal geoengineering system and the global outlook of the conceptual model. It is interesting to see how it makes sense to view all the models and how they work together, almost like a specific research cycle. Once again it is also essential to say that this global model is an open system and dynamic, basically these operate as evolving models. The model analysis based on geoengineering processes enhances the rock quarrying source, in situ investigations and the integrated coastal zone management. The global model is then wrapped up in a back-analysis integrated system which brings in the coastal features, coming up with a preliminary schema.

The first level consists of the inception of the research, covering the central triggers for the beginning of the study. Then we have at the same level integrated coastal zone management (coastal geoengineering approach) and georesource assessment (rock quarry). Finally the last level corresponds to the coastal management plan and territory planning. This level of research comprises all the previous features, processes, elements, data and outputs, as well as GIScience and cartographic analysis to the conceptual model development and overall system mapping.

### *Coastal geoengineering features: implications in maritime environments*

The last image (Figure 129) shows the shoreline system and the littoral zone in an extremely simplified form. This is the ultimate and idealised model exposing different types of coastal contexts. The strategic intention of this illustration is to make the reader aware of some coastal features, management aspects and territory planning. This theoretical model embraces various factors, parameters, forcing conditions, several contexts and different areas of research. We would like to draw attention to the point that this image is more than a repetition of the previous models. Instead, this hypothetical conception complements all the others since it shows the relationships between all the physical settings with the several maritime backgrounds.

The shoreline system approaches all sorts of environments and forcing conditions, factors and even the constraints. It is possible to visualise rocky and sandy coasts, cliffs, shore platforms, coastal boulders and hydraulic structures (mixed environments). Moreover the rock quarrying source is represented, as well as the networking route (transport operation) from the extraction location to the construction site. Therefore we almost have the complete elements in one model. Likewise it is possible to see the social perspective such as the fishing communities and activities. Being the shoreline, a dynamic system of moving sediment is involved, most of which is supplied by rivers; the river processes are also characterised here, bringing erosional debris from the continent and erosion of sea cliffs by wave action.

In a perfect coastal system it would be ideal that all this elements work together and would be perfectly interconnected, knowing that each one has its own function in the system. In reality this would be very difficult to achieve. Water in oceans and rivers is in constant motion and is an issue to be considered. The shoreline systems are complex open systems with several types of sources of energy and coastal dynamics.

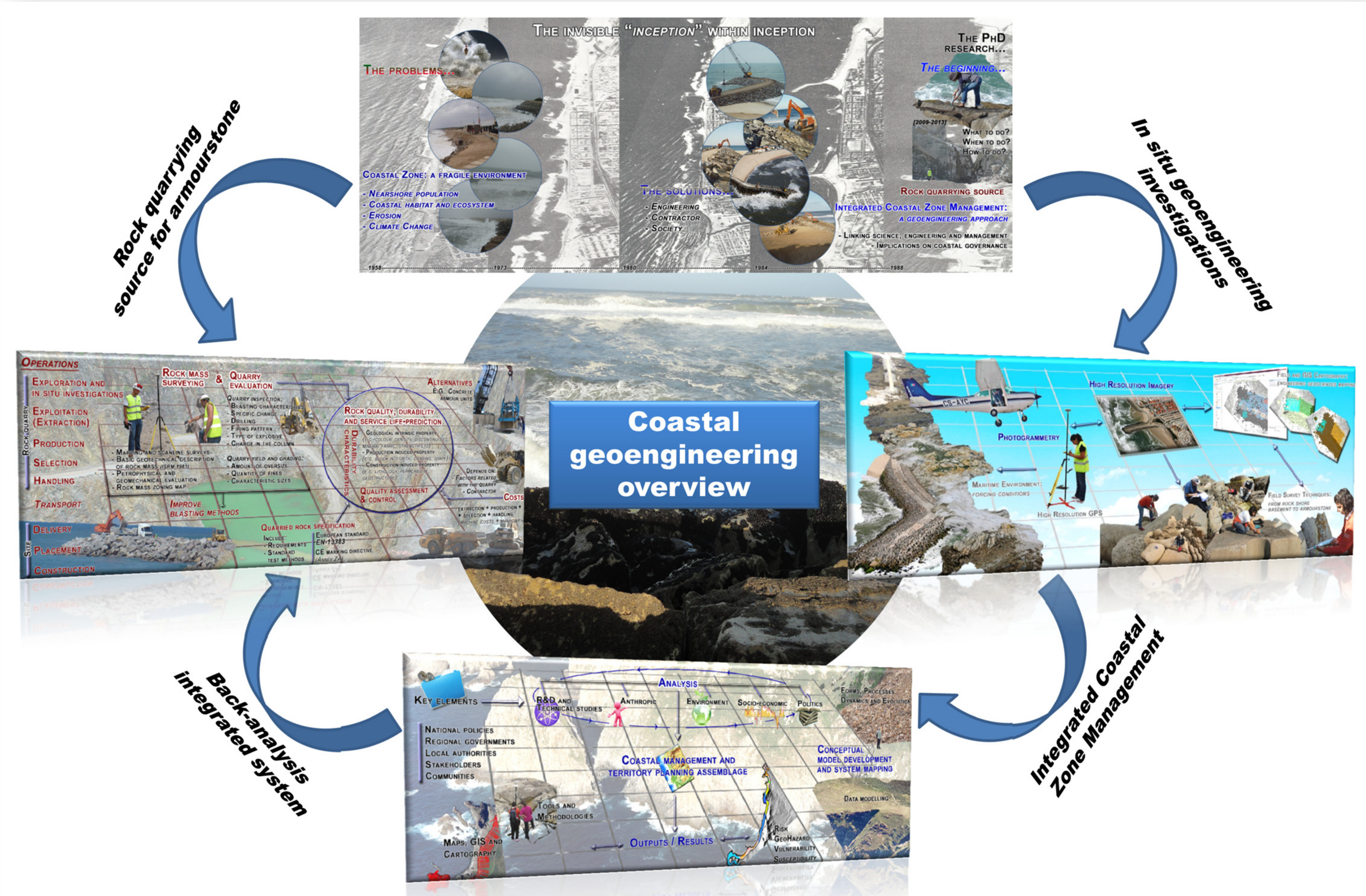


Figure 128. The coastal geoengineering system: a global conceptual model overview.

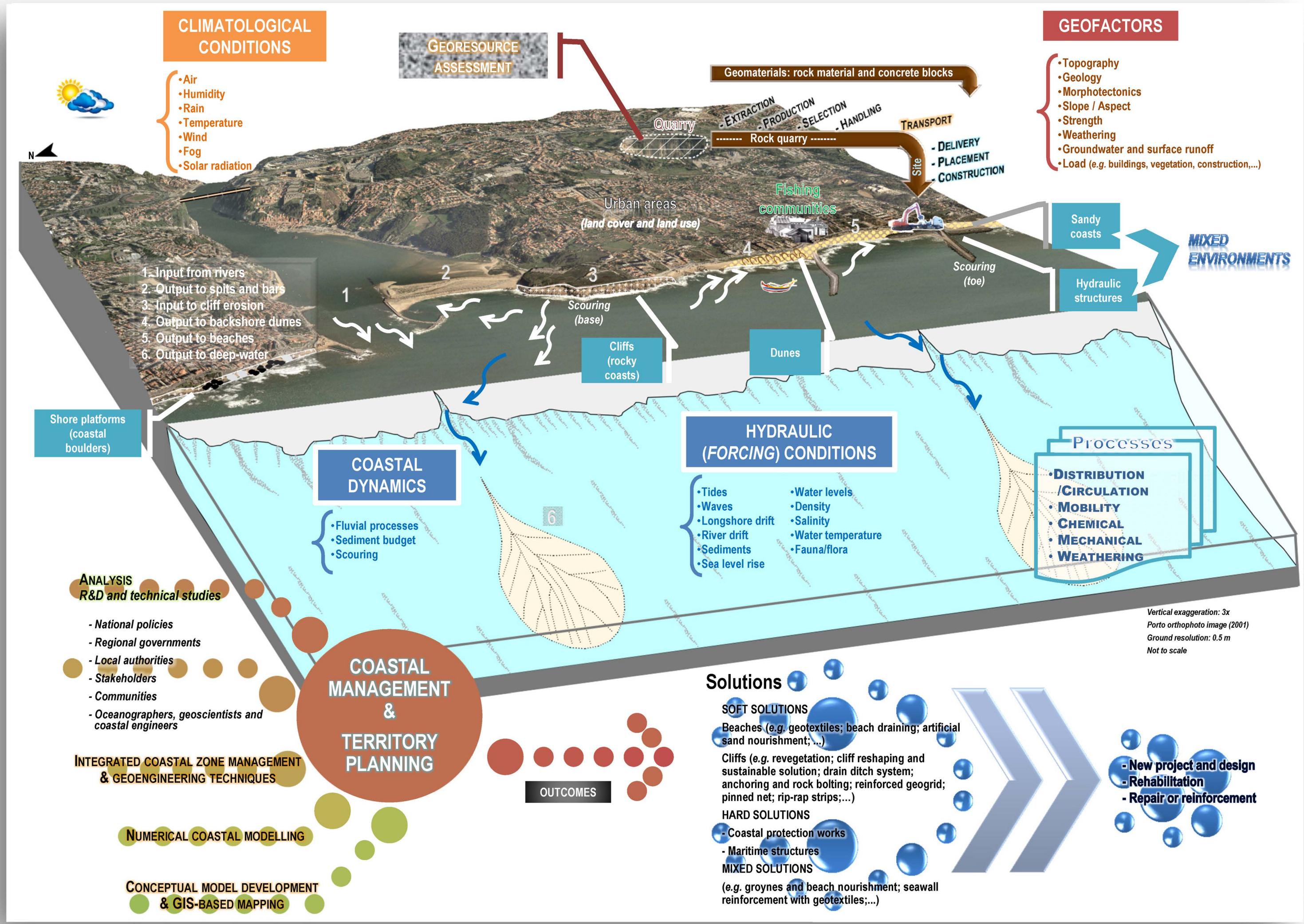


**Figure 129.** Conceptual model proposal and the coastal geoengineering outlook.

## 12. CONCLUSIONS AND FUTURE PERSPECTIVES

The overall research showed that through integrated coastal geoengineering approaches for maritime environments it is be possible to prepare a multidisciplinary methodology in applied geo-cartography GIS-based, geoengineering investigations and coastal zone management.

The coastal integrated system linked six stages allowing the production of detailed maps of the maritime environment: (i) high-resolution aerial imagery surveys; (ii) visual inspection and systematic monitoring; (iii) applied field datasheets; (iv) in situ evaluation; (v) scanline surveying; and (vi) GIS mapping.

The approach is a step forward to the study of different coastal environments by using almost the same methodologies. This was an actual contribution throughout the thesis. The use of simple and easy methods allowed the characterising, monitoring and assessing of coastal protection works, rocky coasts, and shoring platforms. The methodology can be utilised to propose or recommend strategies for coastal and shoreline management based on several justifications with social, economic and environmental issues or even a GIS-based planning support system reinforced by geo-cartographic decisions.

GIS mapping and modelling techniques reinforce geo-monitoring coastal plans. Moreover, the integrated approach applies different concepts to assess quality indicators for material armour layer and structure types or shoreline evolution and cliff retreat. The knowledge that was brought forth by this approach provided insights into how the variables studied could be used in risk assessment and coastal management programmes.

In addition the coast (or the coastal zone) is a dynamic environment with a history of change and which will continue to change in the future. Consequently it was important to understand the importance of coastal systems and processes involved. In fact, the relationship between all the processes, elements and forcing conditions allowed the production of several thematic geoengineering maps, as well as a better understanding of the coastal morphodynamics.

The main conclusions are as follows:

- ✓ Art in coastline evolution explores a new type of research developed to thoroughly consider art and history in coastal evaluation:
    - Several historical elements were used and helped to study the variances in coastline evolution and identify coastal components with relevance to landscape assessments, environmental change and the history of coastal development.

- ✓ Georesource assessment was an exploratory approach applied to the GIS mapping project which aims to contribute to the inventory of exploitation areas for minerals and industrial rocks, with different status (active/inactive) and different purposes (ornamental stone, aggregate or armourstone):
    - Furthermore, the created database for the quarry assessment can be very useful as well, as can all the information incorporated in the GIS tool;
    - The system potential features included georeferenced databases, applied cartography, interactive data, different levels of interrelated information and even statistical, spatial or network analysis;
    - Besides, it allowed us to define potential areas for the extraction of armourstone, which comprise either existing quarries or new places (suitable or promising areas).

- ✓ The Espinho site displayed a complete study of the coastal geoengineering approach applied:
    - The approach adopted in this work contributes to improving our knowledge on the dynamics of the Espinho shoreline. It provides a solid base to easily forecast and model shoreline displacements over the years, and to identify main areas of erosion/accretion;
    - GIS tools provided an easy and very useful way of handling large datasets and, most importantly, of visualising the results in a way that facilitates the rapid perception of the status of the structures, and thus the decision-making processes;
    - For the five groins studied it was clear that the head zone has the highest level of deterioration and is the most susceptible component of the hydraulic structures;

- In this area, the illegal occupation/use of the maritime public domain is common, and there is no cartographic record of the areas of the public shoreline domain, which makes the management of these areas very complicated. To achieve results for the proposed actions or measures, it is essential to study and adequately program the interventions on the littoral region;
- The methodology that was developed proved to be a fairly easy, fast, and economical way to evaluate the status of maritime works;
- Structural zoning, based on the analysis of geological, geotechnical and geomechanical properties (e.g. lithological and petrophysical features, weathering grade / degradation grade, rock strength, etc.) and GIS mapping allows repair programmes to be directed to selected parts of groynes and other structures, at a reduced cost;
- GIS databases and geomaterial assessment of coastal structures, as well as quarry characterisation and inventory, are important inputs to strategic decision making with reference to selection of quarries sources in the future and also with reference to determining the optimum timing of repair. On a local scale it is important to identify the availability of armourstone and active quarry locations.

✓ The application of regional coastal geosciences maps and local approaches outputs could help the government, local authorities and stakeholders to develop coastal management plans and to recommend strategies;

- ✓ The proposed integrated coastal geoengineering methodology is valid for any type of coast or maritime environment:
  - GIS mapping encouraged an interdisciplinary framework and showed an innovative sequence of techniques, equipment and efficient approach to easily assessing maritime environments;
  - The strength lies in coupling GIS applications with photogrammetric techniques in order to create applied cartography and thematic maps. The output maps are used in rocky coasts or in hydraulic structures. These range from stability studies of rocky platforms and coastal boulders to geomaterial zoning maps and revetment status.

- ✓ The rocky coast evaluation implies:
  - An effective assessment of shore platform, boulders and large boulders or megaclasts as well as the analysis of the mobility of clasts;
  - These boulders play an important erosional, and probably most importantly, protectional role in the evolution of the shore platforms, especially where they are adjusting to the present level of the sea;
  - Sediments in transport-limited environments play an important, albeit neglected, role in the development of shore platforms;
  - Because of the effect of large amounts of sediment on arresting platform development, and the relationship between sediment grain size and equilibrium slope, shore platform gradient tends to increase with the coarseness of the sediment;
  - Geologic and geotechnical characterisation, geomechanical testing and geotechnical zoning;
  - The development of GIS mapping can help us to understand the coastal dynamics of the study site, as well as categorisation of the coastal geomorphic features.

- ✓ The shoreline change mapping and analysis is important for a wide range of coastal studies such as development of setback planning, geohazard zoning, erosion-accretion studies and conceptual or predictive modelling of coastal morphodynamics:
  - It was possible to develop a methodology and also to design a GIS interactive database that can be updated over time, comprising shorelines (different periods) with thousands of kilometres vectorised;
  - The approach adopted contributes to improving our knowledge on the dynamics of the studied area and has also provided new data about rates and distances (erosion/accretion) with the help of the DSAS extension;
  - The study provides a solid base to easily forecast and model shoreline displacements throughout the years, and to identify main areas of erosion/accretion. Coastal cliff retreat rates are directly related to the geomorphology, geology, tectonic and weathering driving the retreat of the coast. Sandy beaches are also influenced by the exposure of the sector to extreme forcing conditions (protected areas or open beaches);
  - All of the statistical data and analysis generated can help to assess any region and will allow the creation of geo-cartography in terms of susceptibility maps. This coastal susceptibility cartography will certainly help to propose strategies based not only on the DSAS results but also on the coastal zoning created;
  - The understanding of the erosion rates is also important and should be taken into account when designing public works. This type of study should also keep in mind problems and errors such as the shoreline vectorisation, the georeferenced orthophotos or the statistical method applied;
  - Improved methods of analysing shoreline movement will be needed to document the natural rates of shoreline change. Besides, shoreline prediction is important for integrated coastal zone management/planning and strengthens the role of local administrative authorities; therefore, this research is still in progress to provide more detailed information.

There is always the feeling that a PhD thesis is an unfinished work and that we can improve some aspects of the research. However a dissertation has a deadline, similarly to a scientific journal paper and proceeding conference. And at a certain point the document has to reach its final version.

The following topics are essential because they launch a list of research clues to be developed and take into account in future works:

- The GIS project is an open and dynamic system that should be updated at all times.
- There are numerous innovative techniques to improve the quality of the high-resolution aerial imagery and to develop geo-cartographic maps.
- Highly accurate GPS equipment is constantly refining its methodologies; therefore it would be important to apply and experiment several tools.
- There are countless types of equipment for the measurement of hardness and rebound values of rock material and concrete blocks. With several degrees of accuracy the equipment can allow the correlation of data and even use digital applications.
- Nowadays with apps (mobile applications) and the use of tablets, perhaps the next step could be the development of digital datasheets and to take these apps to the fieldwork surveys. We were able to experiment with different kinds of modelling (e.g. basic, numerical) but it would very important to accomplish experimental modeling.
- Finally, multidisciplinary and interdisciplinary studies have many advantages. especially in developing holistic methodologies in broad coastal projects.

The next generation of researchers will have many challenges ahead regarding technology evolution and modelling techniques. We have to be prepared for this "*big wave*" of geotechnologies that will "*flood*" into novel research fields.

*****

***o esforço é grande e o homem é pequeno.***
***eu, Diogo Cão, navegador, deixei***
***este padrão ao pé do areal moreno***
***e para diante naveguei.***

***a alma é divina e a obra é imperfeita.***
***este padrão sinala ao vento e aos céus***
***que, da obra ousada, é minha a parte feita:***
***o por-fazer é só com deus.***

***e ao imenso e possível oceano***
***ensinam estas quinas, que aqui vês,***
***que o mar com fim será grego ou romano:***
***o mar sem fim é português.***

***e a cruz ao alto diz que o que me há na alma***
***e faz a febre em mim de navegar***
***só encontrará de deus na eterna calma***
***o porto sempre por achar.***

***the task is great and man is small.***
***I, Diogo Cão, navigator, have left***
***this padrao by the sandy shore***
***and onwards set my course.***

***the soul is divine and the work is imperfect.***
***to the wind and the skies this stone signals***
***that, of the daring deed, mine is what is done:***
***that is left to do, is God's will.***

***and to the vast and possible ocean***
***tell these escutcheons you see***
***that the bounded sea may be Greek or Roman:***
***the sea without bounds is Portuguese.***

***and the Cross on high says that what goes in my soul,***
***and causes in me the urge to sail forth,***
***will only find in God's eternal calmness***
***that port forever unfound.***

*****

**Padrão, Mensagem**
Segunda Parte/Mar Portuguez (1934)
*Fernando Pessoa [1888-1935]*

*Ancora et Catena – Scapha (in Sonnenschein 1908);*
*Segundo "Ora maritima de Festus Avienus" (pormenores em Martins Sarmento 1880).*

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# APPENDICES

## (*on CD-ROM*)

***Appendix 1-A.*** *Full paper from "11th International Congress" ISRM Proceedings, 2007 (Balkema / Taylor & Francis group)*

***Appendix 1-B.*** *Short paper: "Tecnologia & Vida" ANET Magazine, 2008 [in Portuguese]*

***Appendix 1-C.*** *Full paper: "Revista Luso-Brasileira de Geotecnia" Geotecnia Journal, 2010 [in Portuguese]*

***Appendix 2-A.*** *Leaflet: Sea Engineering (ISEP)*

***Appendix 2-B.*** *CD-ROM Guide of the "Geologia no Verão / Ciência Viva" ISEP Activity [in Portuguese]*

***Appendix 3.*** *PROCEQ – Application Note: rock and concrete strength (Proceq UK website)*

***Appendix 4.*** *Full paper from ISRM Volcanic Rocks and Soils Proceedings, 2015 (Balkema / Taylor & Francis group)*

***Appendix 5.*** *Datasheet examples (quarries [5-A], coastal structures [5-B], boulders [5-C], geoforms [5-D])*

***Appendix 6.*** *Catalogue – Art as a Tool in Coastal Evolution*
*Brief history of Portuguese coastal art: insights through science*