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Numerical Modelling of Hydrodynamic Changes Induced by a Jetty Extension – the Case of Ria de Aveiro (Portugal)

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ABSTRACT

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Tidally induced currents in estuarine flows are usually modulated by the tidal regime and respond differently to changes imposed to its natural propagation due to geomorphologic alterations. Some of these changes are due to the implementation of heavy engineering works, most of the times imposed by navigation needs associated with harbours growth. The main purpose of this study is to evaluate the hydrodynamic response of Ria de Aveiro to an alteration on the present geometry of its inlet, which was artificially delimited in 1808 through the construction of two jetties. In order to provide access to deeper draft vessels to the Aveiro harbour, its Administration intends to create better conditions for navigation through the extension by 200 m of the north jetty. A bidimensional hydrodynamic model SIMSYS2D was used in this study to simulate two distinct situations: the actual Ria de Aveiro configuration (2009), which is used as reference, and other including the future inlet configuration with the jetty extension. Several simulations were performed, using both bathymetries and considering extreme tidal conditions as forcing on the model oceanic open boundary. The tidal prism at the lagoon mouth and at the main lagoon channels was determined. Values of sea surface elevation and horizontal current velocity were comparatively analyzed as well as harmonic analysis results. The results for the projected inlet increase comparatively to those for the present configuration, although the differences found are not significant for most of the cases analyzed. More studies should be performed in order to clarify the long term impact of these works on the lagoon hydrodynamics.

ADDITIONAL INDEX WORDS: *tidal prism, inlet changes, harmonic analysis.*

INTRODUCTION

The geomorphologic differences are important factors in establishing the structure of estuarine flows. Tidally induced currents in these environments are usually modulated by the tidal regime and respond differently to changes imposed to its natural propagation due to geomorphologic alterations. Some of these changes are due to the implementation of heavy engineering works in estuarine areas, most of the times imposed by navigation needs associated with harbours growth. These construction works will affect significantly the natural tidal wave propagation most of the times. Therefore, it is necessary to simulate, analyze and evaluate properly a construction of this nature, in order to identify the advantages and disadvantages of such implementation, and if possible to present better solutions, that assure the preservation of the natural estuarine environment.

The Ria de Aveiro lagoon inserted in the area of jurisdiction of the Administration of the Aveiro harbour has a long time development dependent on the human intervention. Its maintenance and evolution were due to distinguished professionals who have always been linked to maritime and hydraulic works. There is sufficient evidence to describe the periods of evolution of the lagoon in their overall and understand the scenarios in which the lagoon as been developed and transformed. The progression of the Geophysicist phenomenon in the lagoon matched the progression of historical and economic phenomenon, which reflected the successive changes of Ria de Aveiro.

The most important landmarks of Ria de Aveiro's evolutionary transformation occurred between 1318 and 2008. Early historical records of the Portuguese coast date from 1318, and according to the Viscount Portulano de Petrus, at that time Ria de Aveiro did not exist. By 1560 the lagoon was already forming, but its configuration was far different from today's, as the Mira channel did not exist.

From the beginning of its formation there were problems with inlet closure and migration. Over time several projects were made to improve access to the Ria de Aveiro. Among them was a 1687 project by two Dutch engineers to fix the inlet position. However, these works were not realized due to lack of funding.

The lagoon configuration subsequently forced temporary closure of the inlet, and consequent retention and putrefaction of accumulated waters inside. Finally, in 1808 works were concluded to fix the inlet's position, the realisation of a project by the military engineers Reinaldo Oudinot e Luís Gomes de Carvalho.

Subsequently, several dredging works in the inlet channel, as well as different configurations jetty constructions were undertaken to improve ship access to the inner lagoon harbour. Finally in 1986 the North jetty reached its present geometry (Figure 1).

The current operating conditions in the area of the inlet channel of Ria de Aveiro prevent and/or restrict the access of larger vessels to the inland harbour, with significant economic losses. In fact, the actual features of the inlet area restrict the passage inside the Aveiro arbour of ships over 140 m in length and 8 m submerged zone or draft. Furthermore, the most common sea conditions and currents that form in some tidal situations hinder the ships manoeuvrability at the inlet in terms of security, limiting the periods of operation of the of Aveiro harbour, in particular night navigation. In order to overcome these difficulties the Administration of the Aveiro harbour (APA) intends to performed heavy works in the inlet channel, including the 200 m extension of the North jetty (Figure 1) and dredging operations.

The main purpose of this study is to evaluate the hydrodynamic response of Ria de Aveiro to changes on the present inlet geometry due to the predicted works.

STUDY AREA

Ria de Aveiro (Figure 2) is a shallow lagoon with a very complex geometry, located on the northwest coast of Portugal (40º38'N, 8º45'W). It is 45 km long and 10 km wide and covers an area of 83 km^2 at high water (spring tide) which is reduced to 66 km^2 at low water (Dias and Lopes, 2006a).

It is characterized by narrow channels and by large areas of mud flats and salt marshes. Ria de Aveiro is a mesotidal lagoon with semidiurnal tides, which are the main forcing action. Tidal amplitude at the inlet ranges from a minimum value of 0.6 m in neap tide to a maximum of 3.2 m in spring tide with an average value of 2 m (Dias *et al.*, 2000). The lagoon receives freshwater from two main rivers, Antuã (5 m^3s^{-1}average flow) and Vouga (50 m^3s^{-1}) (Moreira *et al.*, 1993). The estimated maximum and minimum tidal prism of the lagoon is 136.7×10^6 m^3 and 34.9×10^6 m^3, respectively, for the maximum range spring tide and the minimum range neap tide. The total estimated freshwater input is very small (about 1.8×10^6 m^3 during a tidal cycle) when compared with the mean tidal prism at the mouth (about 70×10^6 m^3) (Dias and Lopes, 2006b). These values suggest a homogeneous vertical structure, as referred in a former hydrological lagoon classification (Dias *et al.*, 1999).

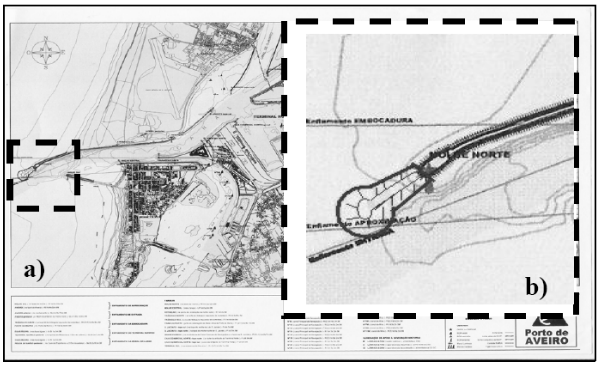

Figure 1. a) Area of jurisdiction of the administration of the Aveiro harbour with the 200 m North jetty extension; b) zoom of the projected works.

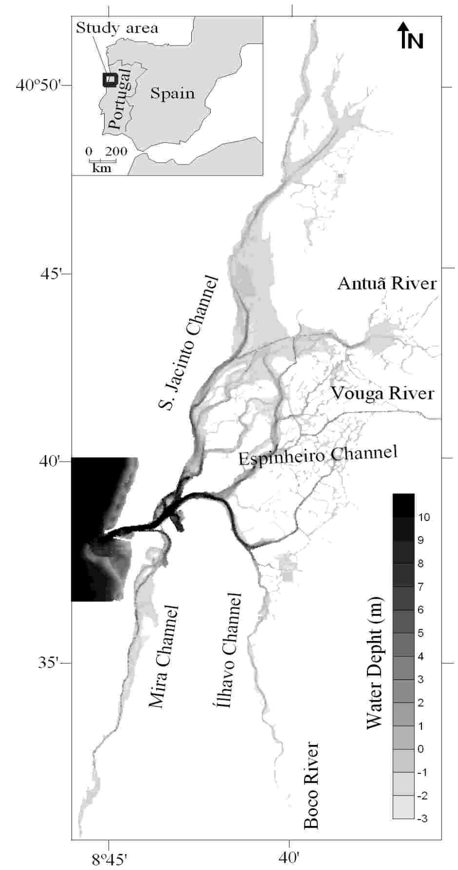

Figure 2. Map of the Ria de Aveiro lagoon bathymetry, and its location on the Portuguese coastline.

HYDRODYNAMIC MODEL

A two-dimensional vertically integrated hydrodynamic model was applied in this study. This model was developed from the *SIMSYS2D* model (Leendertse and Gritton, 1971; Leendertse, 1987) and solves the shallow water equations:

$$\frac{\partial \varsigma}{\partial t}+\frac{\partial (HU)}{\partial x}+\frac{\partial (HV)}{\partial y}=0 \qquad (1)$$

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}=fV-g\frac{\partial \varsigma}{\partial x}-\frac{\tau_x^b}{H\rho}+A_h\nabla^2 U \qquad (2)$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}=-fU-g\frac{\partial \varsigma}{\partial y}-\frac{\tau_y^b}{H\rho}+A_h\nabla^2 V \qquad (3)$$

where U and V are the depth integrated velocity components in the x (eastward) and y (northward) directions, respectively, ζ is the surface water elevation, H is the water height, t is the time, f is the Coriolis parameter, g is the acceleration of gravity, ρ is the water density, A_h is the kinematical turbulent horizontal viscosity, τ^b is the magnitude of the bottom shear stress.

The bottom stress is assumed proportional to the square of the horizontal velocity (Dronkers, 1964; Leendertse and Gritton, 1971):

$$\tau_x^b = g\rho\frac{U(U^2+V^2)^{1/2}}{C^2} \qquad (4)$$

$$\tau_y^b = g\rho \frac{U(U^2+V^2)^{1/2}}{C^2} \tag{5}$$

where C is the Chézy coefficient. This coefficient depends on the bottom roughness and composition and on the height of the water column. In the present work the Chézy coefficient is determined from the Manning roughness coefficient, *n* (Chow, 1959):

$$C = \frac{H^{1/6}}{n} \tag{6}$$

The implementation and calibration of the model for Ria de Aveiro was made prior to this work, being described in detail in Sousa and Dias (2007).

The developed rectangular computational grid, that is used in this study, has the dimensions $\Delta x=\Delta y=40$ m, resulting in 409 cells in the *x* direction and 966 cells in the *y* direction. It were adopted values of 20 s and 20 $m^2s^{-1}$for the time step and for A_h, respectively.

The purpose of the model calibration was to adjust the bottom friction coefficient for the entire lagoon, in order to guarantee that the model predictions accurately reproduce the sea surface elevation (SSE) observations. In this procedure the results of model predicted SSE for seventeen different stations located along the main channels of lagoon were compared with SSE measurements at the same location.

The model predictions accuracy was quantified through the computation of the RMAE (relative mean absolute error), RMS (root-mean square) and the Skill. The best model results were obtained for the stations closer to the lagoon mouth (RMAE=0.00, RMS=0.02, Skill=1). For all the stations located at the lagoon central area the Skill values were very close of the unity, RMAE negligible and RMS lower than 10 cm. The worse results were for the stations located at channels head, although considered excellent by the RMAE classification, but with the Skill a little bit far from the unity and RMS values higher than 20 cm. Harmonic analysis of the predicted and observed SSE time series was also performed, and the amplitude and phases of the main constituents were compared. For the M_2 constituent, which amplitude is the largest, the mean difference between predicted and observed amplitudes is about 5 cm and the mean phase difference is 5º.

METHODS

The first step in this study was to update the Ria de Aveiro numerically grid developed by Sousa and Dias (2007) in the inlet are. A bathymetric survey campaign was performed from December 1st till 15th of 2009 at the APA jurisdiction area, and the results were included in the old bathymetry.

A second numerical bathymetry was build, integrating the projected works. The extension of the North jetty will have characteristics similar to current, consisting in a breakwater in the shape of a trapezoid, with a platform 10 m wide and slopes with inclinations similar to those current and have the same height as the current (10 meters above the average level of sea water). It will have an extension of 200 m and the jetty head will be circular with of 15 m width (Figure 1). At the head of the jetty, seaward the inlet a new navigation channel will be dredge with a depth of 12.5 m and a total width of 300 m height.

Numerical simulations were performed, considering two distinct situations. One corresponding to the actual Ria de Aveiro configuration (2009), which is used as reference, and other corresponding to the future inlet configuration, including the engineer work previously described.

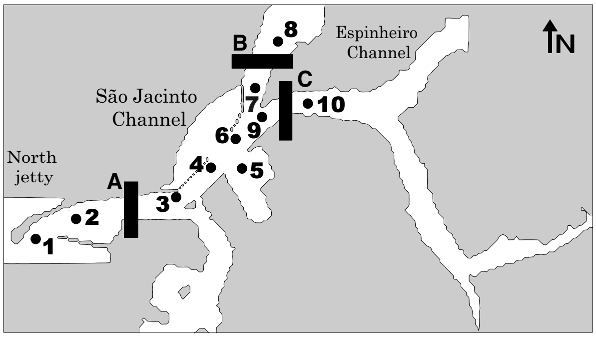

Figure 3. Cross-sections (A, B and C) and location of the stations along the study area (1 to 10).

Several simulations were performed, using both bathymetries and considering extreme tidal conditions as open oceanic boundary forcing (February 2009 - extreme spring tides and March 2009 - extreme neap tides). Ten stations and three cross-sections (Figure 3) were selected to analyze model results, located according to the interests of this research. Time series of SSE and horizontal current velocity were comparatively analyzed for extreme neap-spring tides. Harmonic analysis was also performed for selected stations and the results analyzed. The chosen cross-sections were used to calculate the tidal prism at the lagoon mouth, and at the main lagoon channels (São Jacinto and Espinheiro). Horizontal synoptic maps of SSE and horizontal current velocity were also drawn.

RESULTS

In a first analysis the sea surface average values obtained for the projected inlet configuration for the stations under analysis increase comparatively to the present configuration (Figure 4). At extreme spring tides the increase shows an average value of 0.05 m, and the highest value occurs for station 2, reaching 0.2 m. This highest amplitude is easily justified by the station location, which corresponds to the local of the jetty extension. At extreme neap tides, the amplitude increase is not significant. Concerning the current velocity, the results show that the stations closest to the lagoon inlet (1, 2 and 3) are those with more significant changes (Figure 4). At extreme spring tides the largest increase in velocity occurs for the lagoon mouth. The zonal component increases 0.4 m/s while the meridional increases 0.2 m/s. At extreme neap tides there is an increase in the zonal component of 0.2 m/s and in the meridional component of 0.1 m/s. Therefore the current velocity increase at extreme spring tides is twice the one determined at extreme neap tides. For the remaining stations the modifications in velocity are not significant.

The tidal currents patterns also change in response to the inlet modifications (Figure 5), revealing an intensification of the tidal currents. The ebb and flood tidal flows change their main directions, in accordance with the new inlet configuration.

The tidal prism in either extreme spring or neap tides has decreased with the 200 m jetty extension for all the sections analysed (Table 1). The differences found are more significant in spring tide, and almost negligible in neap tide.

The difference between the harmonic constants determined for each situation show that the amplitude or phase changes for the stations analysed (Table 2) are unimportant.

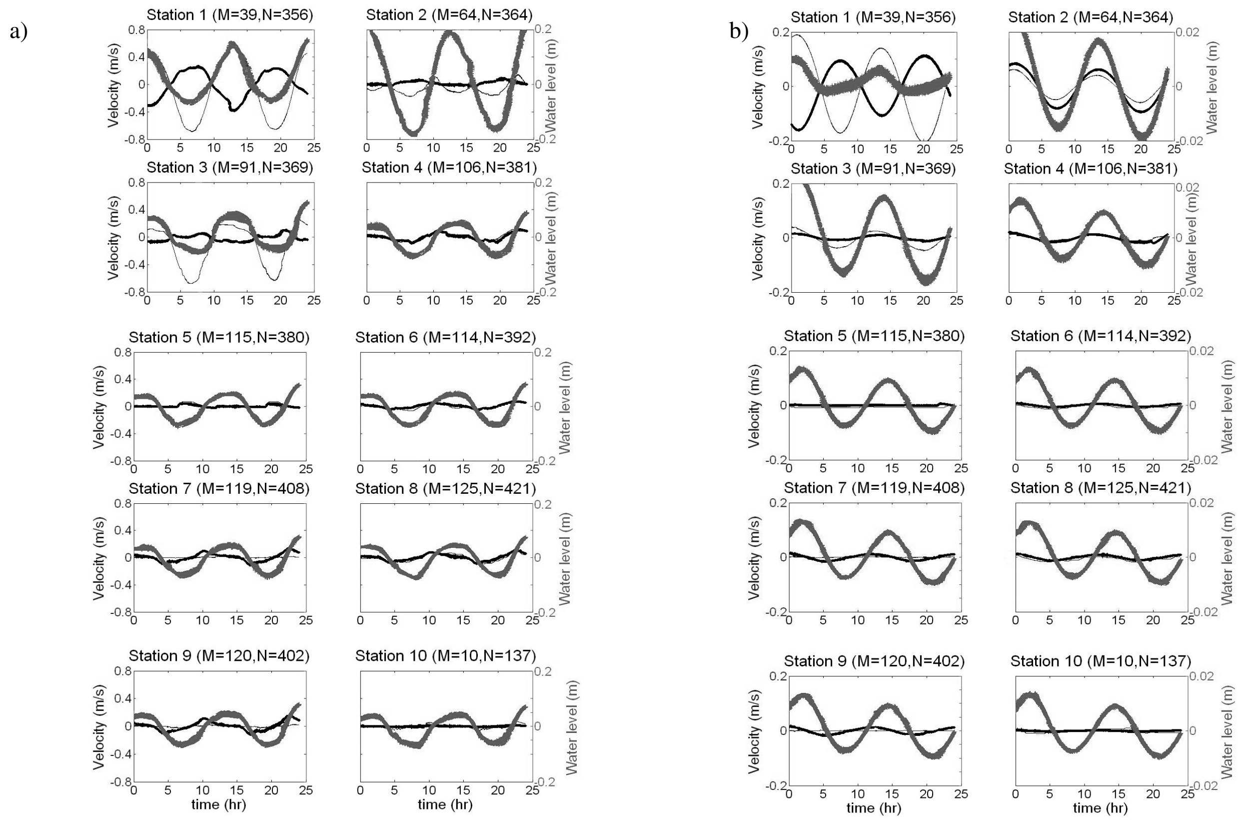

Figure 4. a) and b) Differences between sea surface elevation (▬ line), zonal velocity (— line) and meridional velocity component (━ line) components at extreme spring and neap tides, respectively, for the reference and 200 m north jetty extension configurations.

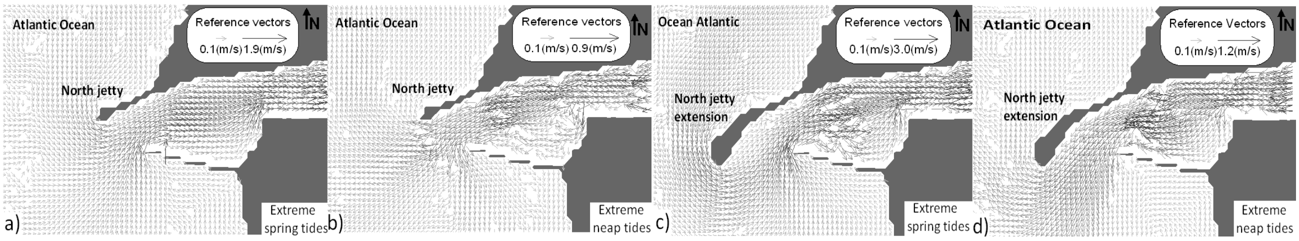

Figure 5. Current intensity near the lagoon mouth for the reference simulation (a) and b)) and for the 200 m north jetty extension configuration (c) and d)), at extreme spring and neap tides, respectively.

DISCUSSION

The tidal wave propagation pattern found for the simulation considering the 200 m north jetty extension is very similar to that found for the reference configuration. In both cases the tidal wave amplitude reduces and the phase delay increases with the distance to the inlet. When introducing the 200 m north jetty extension the surface elevation remains identical to the reference configuration. The stations analyzed were distributed by the main channel, São Jacinto and Espinheiro channels, in the deepest zones of the lagoon. As result the changes in the inlet configuration don't modify significantly the local bottom friction effect in the tidal propagation and therefore the local tidal patterns.

The velocity patterns only change close to the inlet, with intensity rise and main flow direction changes, what is easily justified considering the proximity to the works to be performed and the implemented changes in the inlet channel configuration. The main flow tends to align according to the

Table 1: Tidal prism for sections A, B and C for the reference and 200 m jetty north extension configurations and respective differences.

Section	Tide	Reference Configuration ($\times10^6$ m^3)	200 m jetty extension ($\times10^6$ m^3)	Differences ($\times10^6$ m^3)
A	Spring	137.30	131.50	5.80
	Neap	23.20	23.00	0.20
B	Spring	54.10	51.10	3.00
	Neap	9.14	8.90	0.24
C	Spring	42.20	41.20	1.00
	Neap	7.30	7.20	0.10

Table 2: Difference between harmonic constants for the reference and 200 m north jetty extension configurations, at all stations.

Station		1	2	3	4	5	6	7	8	9	10
M_2	Amplitude (m)	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
	Phase (º)	-1.72	-7.34	-2.47	-2.21	-2.22	-2.20	-2.15	-2.13	-2.17	-2.21
S_2	Amplitude (m)	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	Phase (º)	-2.03	-3.08	-2.88	-2.62	-2.62	-2.57	-2.52	-2.49	-2.54	-2.60
N_2	Amplitude (m)	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	Phase (º)	-1.93	-3.93	-3.52	-3.84	-3.82	-3.79	-3.76	-3.75	-3.76	-3.84
K_1	Amplitude (m)	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Phase (º)	-1.67	-4.93	-1.19	-0.68	-0.59	-0.65	-0.58	-0.27	-0.55	-0.61
O_1	Amplitude (m)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00
	Phase (º)	1.01	0.77	0.22	0.56	0.36	0.43	0.42	0.50	0.48	0.34
M_4	Amplitude (m)	0.00	0.05	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01
	Phase (º)	-0.47	20.10	-11.43	-54.30	-64.25	-58.86	-58.06	-35.89	-48.41	-47.04
M_{S4}	Amplitude (m)	0.00	0.04	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Phase (º)	-20.79	-24.09	-13.30	-57.95	-94.33	-77.07	-77.20	-38.38	-53.15	-90.45

inlet channel axis centre, with maximum intensity at the deepest locations.

The hydrodynamic of each channel is governed by different tidal prisms, which were found to decrease with the distance to the inlet (in accordance with previous studies for Ria de Aveiro; e.g. Dias (2001)). For each section the tidal prism decreases for the projected scenario, and therefore changes in the overall lagoon hydrodynamics may be expected. Previous studies show that the tidal prism in Ria de Aveiro rise with the inlet channel deepening (Araújo *et al.*, 2008; Picado *et al.*, 2010), therefore these results are unexpected, although the simulations considered the deepening of a channel seaward of the inlet.

CONCLUSIONS

The actual configuration of Ria de Aveiro is the result of a long term evolution resulting from frequent engineer construction works and from its natural evolution.

In summary, this study shows that the works related to the 200 m north jetty extension in Ria de Aveiro inlet slightly change the local hydrodynamic patterns, and that may induce changes in the overall lagoon circulation related with the tidal prism decrease found for the main channels. Although this works serve the main navigation purposes and therefore have significant impact in the local economy.

More studies should be performed in order to clarify the long term impacts of these works in the lagoon hydrodynamics.

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