Universidade de Aveiro Departamento de Engenharia Civil
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Sofia Raquel Gonçalves dos Santos

Medições de sedimentos em suspensão em laboratório.

Suspended sediment measurements on laboratory experiments.

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Civil, realizado sob a orientação científica do Doutor Carlos Daniel Borges Coelho, Professor Auxiliar do Departamento de Engenharia Civil da Universidade de Aveiro e coorientação do Doutor Agustin Sánchez-Arcilla, Professor Catedrático e do Doutor Iván Cáceres Rabionet, Investigador, ambos do Departamento de Engenharia Hidráulica e Ambiental da Universidade Politécnica da Catalunha.

O júri / The jury

Presidente / President	**Professora Doutora Ana Luísa Pinheiro Lomelino Velosa** Professora Associada do Departamento de Engenharia Civil da Universidade de Aveiro.
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	Professor Doutor Carlos Daniel Borges Coelho Professor Auxiliar do Departamento de Engenharia Civil da Universidade de Aveiro.

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A todos, um sincero obrigado.

Palavras-chave

Concentração de sedimentos em suspensão, Optical Backscatter Sensor, Transverse Suction System, Matlab, calibração.

Resumo

Os processos de transporte sedimentar nos rios e zonas costeiras caracterizam-se por dois tipos de transporte: pelo fundo ou em suspensão. A quantificação deste transporte é importante, na avaliação da evolução da linha de costa e do leito dos rios, com vista a proteger zonas que possam estar em perigo de erosão na eminência de fenómenos meteorológicos extremos.

A medição da concentração de sedimentos em suspensão tem sido, ao longo dos últimos anos, objeto de estudo por vários investigadores. Existem vários métodos para estimar esta grandeza no entanto, ainda apresentam muitas incertezas nos resultados.

Esta dissertação, desenvolvida no Laboratório de Engenharia Marítima (LIM) da Universidade Politécnica da Catalunha (UPC), tem como objetivo a verificação do distanciamento dos resultados entre o *Optical Backscatter Sensor* (OBS) e o *Transverse Suction System* (TSS) no projeto SINBAD. Para isso, e após realizar 329 testes, foram descritos o procedimento experimental e de cálculo para obter a melhor reta de calibração de um OBS. Seguidamente, as concentrações obtidas com o OBS e com o TSS foram comparadas com as concentrações de sedimentos reais e no final foram verificados parâmetros relacionados com a funcionalidade dos equipamentos utilizados na calibração, a aplicabilidade do OBS e a eficiência do TSS.

Os resultados mostraram que, a curva de calibração mais exata de um OBS obtém-se quando os dados são divididos em secções em função da concentração de sedimentos, com diferentes comportamentos, e tratadas separadamente. Este equipamento foi considerado o mais exato, até concentrações em que o sensor não está saturado.

Keywords

Suspended sediment concentration, Optical Backscatter Sensor, Transverse Suction System, Matlab, calibration.

Abstract

The sediment transport processes in rivers and coastal zones are characterized by two types of transport: bed-load and suspension. The quantification of this transport is important, in the evaluation of the shoreline and rivers evolution in order to protect areas that could be in danger of erosion when extreme meteorological phenomenon’s happen.

How to measure the suspended sediment concentration has been subject of many discussions during the last years. There are several methods to quantify it numerically, although all of them exhibit uncertainties in the results.

This work, performed in the Laboratori d’Enginyeria Marítima (LIM) of the Universitat Politècnica de Catalunya (UPC), has as goal to understand why the results obtained from the Optical Backscatter Sensors (OBS) and the Transverse Suction System (TSS) in SINBAD project were distant. To do it, after perform three hundred and twenty nine tests, the experimental and calculation procedures to obtain the best OBS calibration curve were described. Then, the concentrations from OBS and TSS were compared with the real concentrations. In the end, the functionalities of the equipment’s involved in the calibration set-up, OBS applicability and trapping efficiency of TSS, were verified.

The results showed that, an accurate fit of OBS data is obtained when the curve is divided in sections depending on the suspended sediment concentration, with different behaviours and fitted differently. This equipment was considered the most accurate, up to concentrations bellow the saturation situation of the sensor.

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Acronyms

ABS - Acoustic Backscatter Sensor

ASTM - Acoustic Sand Transport Monitor

CIEM - Canal d'Investigació I Experimentació Marítima

LIM - Laboratori d'Enginyeria Marítima

OBS - Optical Backscatter Sensor

SSC - Suspended Sediment Concentration

TSS - Transverse Suction System

UPC - Universitat Politècnica de Catalunha

Chapter 1

Introduction

1. Introduction

In this section, firstly is presented an introduction to the subject under study on this work being followed by the aims and the organisation of this document.

1.1. Motivation

It is important to understand the sediment transport processes, because they are directly related with the coastal morphology dynamics and the shoreline evolution (Coelho, 2005). As an example, frequently, during the winter the social media refers many cases of floods or several damages in coastal structures due to sea wave actions and shoreline retreat. These are related with coastal erosion problems due to irregularities in sediment transport processes.

To intervene in coastal zones that suffer from high risk of erosion, the first step is to evaluate the type and the amount of sediments transported in the zone. According to White (1998), the sediment transport rates are probably the most important and unknown factors in design of any hydraulic structure (fluvial or coastal). To estimate the sediment transport rates there are several field methods that can be considered.

The sediments can be transported by suspension (suspended sediments transport) or by rolling and saltation (bed-load sediments transport). While in suspended transport the sediments are carried above the bottom by the turbulent eddies of the water, in bed-load the grains transported remain close to the bed. In field it is difficult to measure the type of transport separately. So, relatively to contribution of each to the total transport rate there are distinct options. Since it is more readily measured than bed-load transport, suspended-load transport has been subject of manifold studies (Dean *et al.*, 2008).

Besides the field methods that exist to estimate the suspended sediment concentration, this parameter can also be determined from mathematics and engineering judgement. However they are not the best choice due to inaccuracy and unreliability of the results (assumption related to sediment processes description, local characteristics and obtained results), being the field measurements the best option due the lack of choices. In spite of that, field methods have also limitations such as impossibility of obtaining data at all time and locations of interest and the cost of the measurements. Therefore, for engineering projects requiring accurate concentration estimates, mathematics and field measurements are combined (White, 1998). The selection of the measurement equipment's is highly dependent of the variables to be measured, the available facilities and the accuracy required. This is always difficult due to the wide range of equipment's developed in the last years (from simple mechanical samplers to sophisticated optical and acoustical samplers) (Van Rijn, 2005).

This thesis is in the frame of SINBAD project, as a complement to understand the suspended sediment measurements discrepancies obtained from different observational equipment's. Between 4th November of 2013 and 23rd January of 2014 the SINBAD experiments were performed in the CIEM (Canal d'Investigació i Experimentació Marítima) wave flume, with the participation of University of Aberdeen, University of Twente and University of Liverpool. These experiments were developed to improve the knowledge of the near-bed hydrodynamics and sand transport processes occurring under large-scale irregular non-breaking waves and regular breaking waves in the sheet flow, and also to understand how net suspended transport rates and total net transport rates can be related to overall flow and sediment parameters in a wide range of large-scale experiments under sheet flow regime (Van der Zanden *et al.*, 2014).

1.2. Aims

As referred previously there are several field methods to measure the suspended sediment concentration.

During the SINBAD project, developed at CIEM wave flume, several suspended sediments measurements using Optical Backscatter Sensors (OBS) and the Transverse Suction System (TSS) were performed. In these experiments, significant discrepancies between the OBS and TSS concentrations were obtained. Given this, it was admitted that the source of the problem were the concentrations obtained with OBS. To solve it, the OBS was recalibrated using a calibration method similar to Downing and Beach (1989) that consider a controlled concentration of sediments in water and two different methods to measure the SSC. This was different from the first SINBAD experiments in which the OBS was calibrated following the Butt *et al.* (2002) procedure (with glycerol instead of water). The work was developed in Maritime Engineering Laboratory (LIM), at Polytechnic University of Catalonia (UPC), during the academic year of 2014/2015.

In these new experiments, were performed 329 tests which, were also used to improve the calibration tank characteristics and the experimental procedure. Once this was done, the results were analysed, and compared to verify if the discrepancies between the concentrations of both equipment's remained.

1.3. Dissertation outline

The present document is divided in seven chapters. In the first chapter, is presented a brief introduction to the problematic and the goals of this work. In the second chapter, are presented seven different techniques used to measure the suspended sediment concentration (SSC), their main functioning processes and advantages/disadvantages. The third chapter presents the documented applicability conditions of the measuring equipment's used in this work (OBS and TSS). In the fourth chapter, are described the UPC laboratory conditions, the sediment characteristics, the experimental procedure and finally the tested scenarios and the tests presented in the sixth chapter. The fifth chapter presents the calculation procedure to obtain a proper OBS calibration. Then, this procedure is applied to OBS T8267 and an analysis to obtain the most adequate calibration curve to this OBS is performed. The calibration curves from the remainder OBS's used in this work are also presented. Finally, a comparison between the results from OBS, TSS and real SSC is performed.

The analysis of the tested scenarios is performed in the sixth chapter. In here, are presented and analysed the scenarios that could spoil the results. First, are described the two corrections applied to the real SSC, which is the most important parameter to control. Then the equipment's functionality is verified. To the OBS were verified the stability and repeability of its signal. To verify if the sediments were in suspension on high concentrations, were measured the concentrations correspondent to three different voltages applied to the engine. To end this group of verifications, was tested which was the proper intake velocity, to obtain samples with TSS. Then, were performed three OBS applicability verifications. First, was verified how the SSC obtained with all OBS's was related with the real SSC. Then it was tested if the incident laboratory light and a residual amount of bubbles within the calibration tank could influence significantly the concentrations. To end the chapter, was verified how the real SSC affected the trapping efficiency of TSS.

In the seventh, and last chapter of this work, are enumerated the main conclusions drawn from the work developed and future developments which may be considered to improve the OBS calibration and the OBS and TSS measurements.

Chapter 2

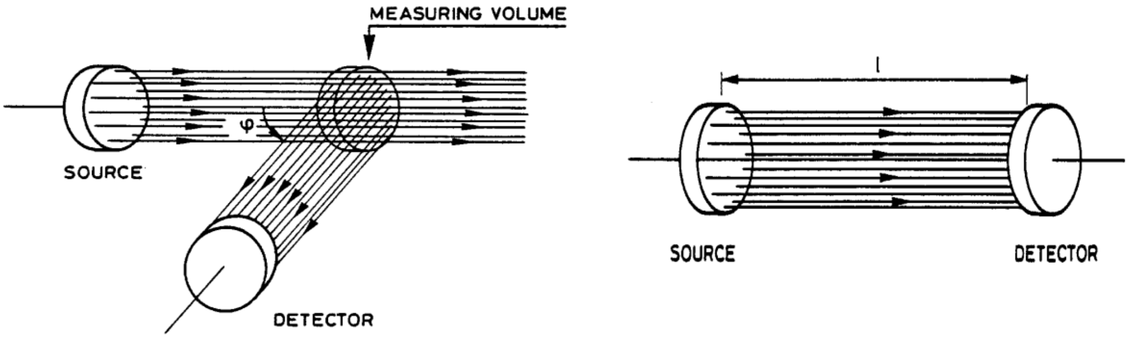
Methods to measure suspended sediment concentration

2. Methods to measure suspended sediment concentration

Briefly, seven different techniques are referred for measuring suspended sediment concentration (SSC) in a section of a river or in the shoreline. Only the first and the fourth technique (Optical and Pump sampling) were applied during the proffered work.

2.1. Optical method

There are two methods to measure the SSC with optical devices, scattering (Figure 2.1a) and transmission (Figure 2.1b). Both emit near-infrared (NIR) light and then measure the signal received by the detectors (White, 1998). These have photo-detectors that convert the measured light to a photocurrent (Downing, 2006).



a) Scattering method

b) Transmission method

Figure 2.1 - Methods to measure sediment concentration with optical devices (Van Rijn, 2005).

In contrast, the two methods also have several differences such as the position of the detector, the signal measurement and the relationship between the detected signal and the SSC. In scattering, the source and detector are placed at an angle relative to each other (Van Rijn, 2005). The detector, containing photo-detectors, receives the light scattered by the sediments particles and afterwards convert it to a photocurrent (Downing, 2006). The equipment used in the previous method is the Optical Backscatter Sensor (OBS). There are several models of this equipment in the market, though the used in this work was the OBS-3+ (Figure 2.2).

The OBS-3+ is a submersible (maximum depth between 500 and 1500 m, depending of the body material), turbidity sensor used to measure suspended solids and turbidity that can be used to quantify the water quality in rivers and streams, sediments transport and dredge monitoring. This sensor has a high intensity infrared emitting diode (IRED) which emits a light beam with a divergence angle of 42° (95% of the beam power is contained within a 42° cone) and a detector which reads the infrared scattered between 90° and 165° in clean water (Figure 2.3). The sensor can see to a distance of approximately 50 cm in very clean water. The maximum concentration range of OBS-3+ for mud is from 5 to 10 g/L and for sand 50 to 100 g/L and provides 6.67 records per second (Downing, 2008).

Figure 2.2 - Optical Backscatter Sensor 3+ (Downing, 2008).

According to Downing (2008), there are three basic ways to calibrate the OBS-3+: with dry sediments, wet sediments or *in situ*. Dry sediments calibration, is a calibration performed with sediments that have been dried, crushed and turned to power. This is considered the easiest calibration, because the amount of sediments can be determined accurately with an electronic scale and the volume of water with a volumetric glassware, and is also the method that causes the greatest physical and chemical alteration of the sediments. The reduction of the grain size can increase the OBS sensivity by a factor of two. Wet sediments calibration is performed with sediments obtained from water samples or from the bed of a river that has not been dried or pulverized, and it is introduced into a sediment suspender as it comes. This kind of calibration requires withdrawn from the suspender, of water samples after each addition of sediments for the determination of SSC by filtration and gravimetric analyses. *In situ* calibration is performed with water samples taken from the proximity of an OBS sensor in the field, over sufficient time to sample the full range of SSC to which a sensor will be exposed. It is considered the best calibration because the particles are in their natural form. However, is the most tedious, expensive and time consuming calibration. The concentrations obtained from sampling, related with the OBS sensor output establish the mathematical relation for future SSC. This is similar to the three approaches. In general the equations obtained were linear polynomials (Downing, 2008; Sousa, 2009; Carrilho, 2014; Domingues, 2014), though they can vary with the conditions of the measurement location (Kineke and Sternberg, 1992).

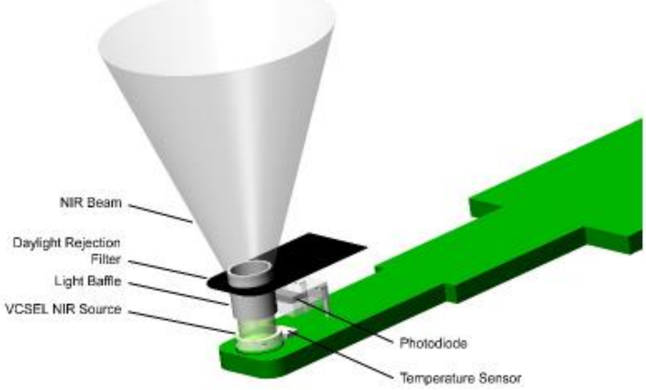


Figure 2.3 - OBS-3+ components (Downing, 2008).

In transmission, source and detector are placed on the opposite directions (at a certain distance) and the detector receives the light that has not been absorbed or scattered by the sediments present in the sample (Wren *et al.*, 2000).

The transmissometer (Figure 2.4) is the equipment used in this method. This device measures the intensity of a 660 nm laser at 25 cm distance (Venus Instruments, 2015). To obtain the SSC, is necessary to proceed first to a calibration of the device, similar to the scattering method. The calibration consists in study the variation of the beam attenuation with the sediment concentration (Holdaway *et al.*, 1999). The beam attenuation, defined as c, is calculated using the equation 2.1 (Holdaway *et al.*, 1999; Venus Instruments, 2015):

$$c=-\frac{\ln(T_r)}{r} \tag{2.1}$$

In which, Tr is the percent transmission of light and r is the path length.

The two types of optical instruments have almost the same advantages. Both have a linear response to varying concentrations of homogeneous sediments however, optical transmission sensors allow very good spatial and temporal resolution and are generally more sensitive to low particle concentrations than OBS instruments. Another advantage is that both equipment's are readily available from several manufacturers. Although the advantages referred previously, these equipment's have some limitations as well. Both exhibit a particle-size dependence (OBS presents more sensitivity to small particle sizes) and influence of the refractive index of the particles. At high concentrations OBS sensors can reach saturation, so they are not recommended for sand/mud mixtures. On the other hand, the transmissometer show a nonlinear response, with disproportionately small changes in output being produced by large changes in sediment concentration. In transmission, large variations in sediment concentration require multiple transmissometer or multiple path instruments (Wren *et al.*, 2000).

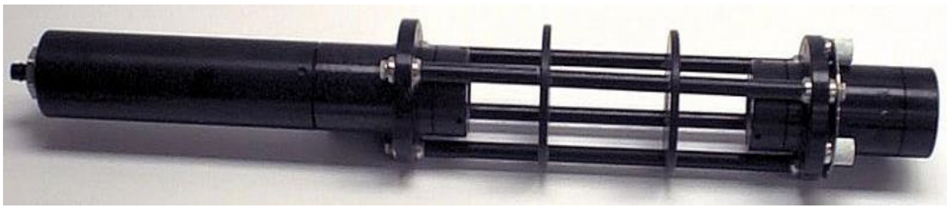


Figure 2.4 - Transmissometer (Venus Instruments, 2015).

2.2. Acoustic method

When using the acoustic method to measure the SSC, short sound waves, emitted by an acoustic transducer, are propagated through the sample. These sound waves are scattered and attenuated by the suspended sediment sample (Figure 2.5) (Wren *et al.*, 2000; Van Rijn, 2005; Deltares, 2012). The signal strength detected allows the estimative of the sediment concentration (Smerdon *et al.*, 2014). To use this method there are two types of equipment's: the Acoustic or Ultrasonic Sand Transport Monitor (ASTM or UTSM) and the Acoustic Backscatter Sensor (ABS).

The ASTM is only used to measure the concentration of sands (and also flow velocity in one or two horizontal dimensions although, only the first functionality interests to this work). This equipment uses the scattering and attenuation of ultrasound waves by the suspended sand particles in the sample. Using the amplitude and frequency shift of the scattered signal, the concentration is determined simultaneously and continuously. The ASTM consists in a sensor with a pre-amplifier unit mounted on a submersible carrier (Figure 2.6a) and a separated converter with panel instruments and switches (Figure 2.6b) (Van Rijn, 2005; Deltares, 2012).

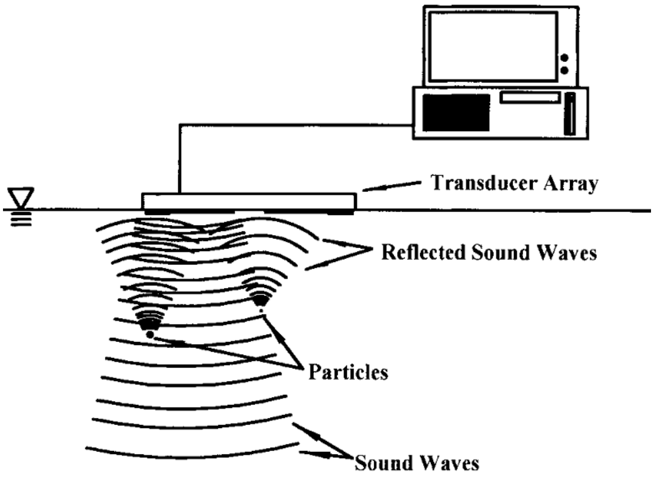


Figure 2.5 - Acoustic backscatter (Van Rijn, 2005).

The ASTM can be calibrated using pump sampling concentrations positioned close to the sensors. It is possible to analyse the response of the equipment by determining time-averaged (over about 15 minutes) sand concentrations. In former experiments performed in Deltaflume, was concluded that for concentrations larger than 0.05 g/L the ASTM output varies linearly with the sediments concentration and for concentrations smaller than 0.05 g/L the output is larger than may be expected for a linear relationship. The frequency emitted is 4.5 Hz. The calibration curve for concentrations between 0.1 g/L and 10 g/L and sand particles with sizes of d_{50} between 0.16 and 0.33 mm is presented in equation 2.2 (Van Rijn, 2005):

$$SSC=0.257\times Output_{ASTM} \tag{2.2}$$

The ABS (Figure 2.7) uses short pulses (10 µs) of acoustic energy, emitted by a sonar transducer (1 to 5 MHz), to estimate the SSC present in the local. The pulse emitted is scattered by the suspended material in the water column towards the sonar transducer, which also acts like a sound receptor. With the knowledge of the speed of sound in water, the scattering strength of the suspended material and the sound propagation characteristics, a relationship can be developed between the intensity of the received echoes and the characteristics of the suspended sediments (Van Rijn, 2005).

a) ASTM fivefold sensor (Van Rijn, 2006). **b) ASTM converter (Deltares, 2012).**

Figure 2.6 - ASTM components.

Figure 2.7 - ABS (AquaTec, 2015).

The acoustic backscatter intensity from a uniform field of particles with constant concentration is assumed to be an inverse function of the distance from the source, with corrections for attenuation due to water particles. Thus, calibration in uniform suspensions is required to find this relationship (Van Rijn, 2005). Acoustic suspended sediment measurements offer the ability to non-intrusively measure sediment parameters through a vertical range on the order of several meters, which is a unique specification among suspended sediment measurements. This technique is also well suited for deployment over long periods of time. On the other hand, the translation of acoustic backscatter data into sediments concentration and size is too difficult. Laboratory calibration has been used to determine the relationship between backscattered signal strength and sediment parameters. However, is difficult to create a calibration apparatus that can maintain a uniform sediment concentration suitable to use in calibrating instruments. Another limitation is the attenuation induced by high concentrations, because to convert the backscattered signal to sediment parameters this phenomenon has to be considered. This requires knowledge of the SSC, with the unknown value being sought. To overcome this problem, either a concentration at the range bin nearest the transducer (*e.g.*, zero concentration at the surface) must be assumed, or an independent measurement of concentration at some range bin must be made (Figure 2.8). Using the assumption method leads to errors that increase in magnitude as distance from the sensor increases (Wren *et al.*, 2000).

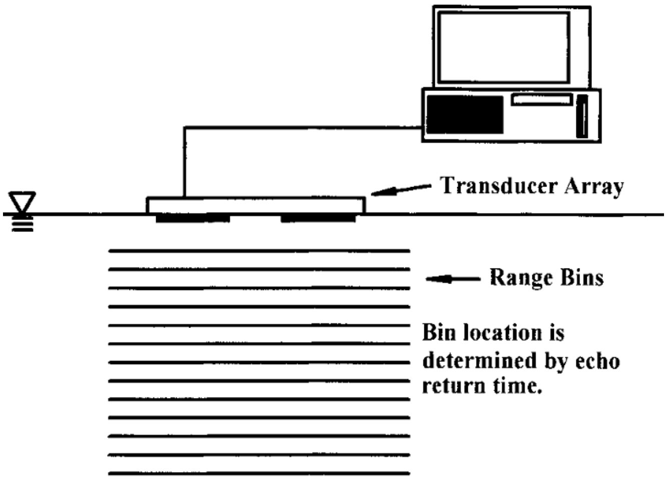


Figure 2.8 - Range gating (Wren *et al.*, 2000).

2.3. Bottle sampling

Bottle sampling method involves extracting a water sample by dipping a bottle into a stream to determine the concentration at a specific point in the flow (Figure 2.9). The bottle is placed upright in a container and lowered to the sampling point, staying opened from 20 to 400 seconds (varies with the bottle orientation). The velocity at the mouth of the bottle must be the same as the stream to avoid unviable results. In the end, the bottle is closed with a ball and the samples are taken to be analyzed in the laboratory (Wren *et al.*, 2000; Brisset *et al.*, 2005; Van Rijn, 2005). The samples can be treated in two different ways, by evaporation or by filtration.

The evaporation method consists in allowing the sediments to settle in the sample bottle bottom, decanting the supernatant liquid, washing the sediments into an evaporating dish and drying it in the oven. Comparatively with the filtration method, this method is easier due to the simplicity of the equipment and technique, although if the sediments studied does not settle readily in the bottom (samples with dispersed clay), other techniques have to be studied. The filtration method for the determination of SSC has many advantages over the evaporation method and should be used whenever it is practical to do so. This method usually uses a Gooch crucible (small porcelain cup with capacity of approximately 25 mL and a perforated base) along with various types of filter material. This one is easily adapted to an aspirator system and vacuum filtration. The filter material has proven being satisfactory for filtration of most types of sediment samples (Guy, 1965). After laboratory analysis the sediments concentration is determined by equation 2.3 (Van Rijn, 2005):

$$SSC=\frac{G_s}{V} \tag{2.3}$$

In which, G_s is the sediment dry mass (milligrams) and V the water sample volume (liters). Bottle sampling is a reliable, well-documented, and widely used technique. Depth and point integrating samplers allow nearly the entire depth of the stream to be sampled. Bottle samplers are generally considered the standard against other types of samplers that require calibration. When compared to techniques using instrumentation, bottle sampling has poor temporal resolution. Unlike automated methods such as pump sampling, personnel must be on hand to take samples which, often involves working late at night in storm conditions, consequently adding expenses. Due to their shape, the inlet nozzle of most bottle samplers is above the lowest point on the sampler and because of that, the bottle cannot sample lower than 0.1–0.15 m in the water column (Wren *et al.*, 2000).

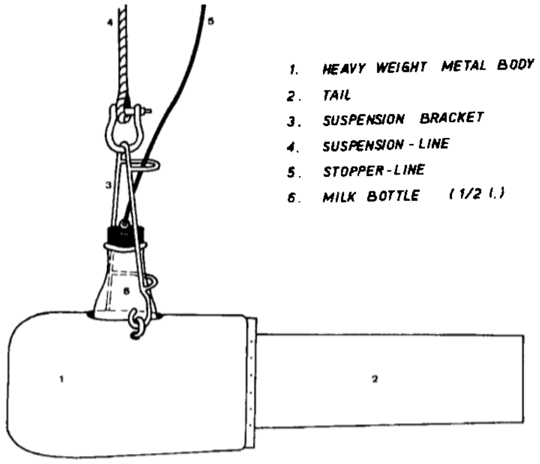


Figure 2.9 - Bottle and container (Van Rijn, 2005).

2.4. Pump sampling

In Pump sampling method the sample is collected by applying a vacuum to a line submerged in the channel. The sample is afterwards analysed in the laboratory to determine its SSC (Wren *et al.*, 2000; Brisset *et al.*, 2005).

This method allows the automatic collection of multiple samples, although sampling frequency is limited by the time taken to fill each bottle (in unidirectional flow, to obtain a reliable average sample the measuring period should be large, about 300 seconds) and by the number of bottles in the sampler. In unidirectional flow, the pump sampler (Figure 2.10) has the nozzle lines pointed upstream. For oscillatory flow, the sampling period should be long (15 minutes) under irregular wave conditions (at least 100 waves) (Van Rijn, 2005). In this type of flow, Bosman *et al.* (1987) says that the best nozzle direction is the normal to the ambient flow, suggesting an adaptation of this method: the Transverse suction system (Figure 2.11).

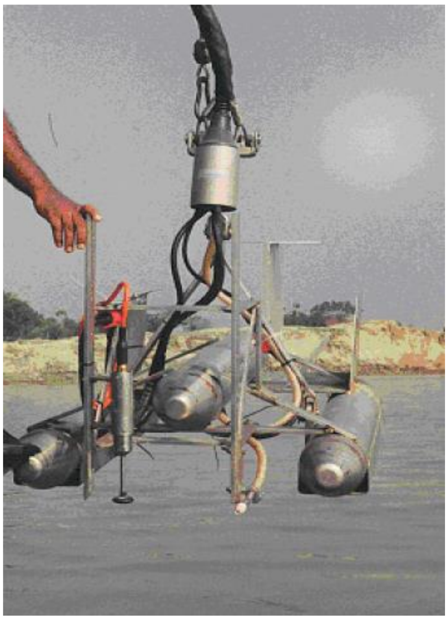


Figure 2.10 - Pump sampler (Van Rijn, 2005).

Peristaltic pumps or propeller type pumps can be used. The peristaltic pumps are very efficient for pump sampling in river and coastal conditions. The discharge is relatively small (1 l/min), yielding a relatively small water-sediments sample that can be easily handled. The hose diameter is extremely small (0.006 m), which reduces the fluid drag forces in it. The pump direction can be easily changed to remove small objects blocking the intake nozzle (shell fragments, organic materials, etc.). The propeller-type pumps produce a relatively large discharge (10 l/min) resulting in the handling of a large water-sediments volume. Its hose diameter is in the range of 0.01 to 0.016 m (Van Rijn, 2005).

To avoid sample biasing, the intake velocity must be matched to the local steam velocity. For reliable results the sediment samples collected from the equipment must be calibrated with samples collected from cross-section depth-integrated or point-integrated samples (Wren *et al.*, 2000; Brisset *et al.*, 2005).

The sample analysis in laboratory consists in separate the water from the sediments particles. A practical solution can be obtained by using the filtration or evaporation methods, being the remainder procedure equal to section 2.3 (Van Rijn, 2005).

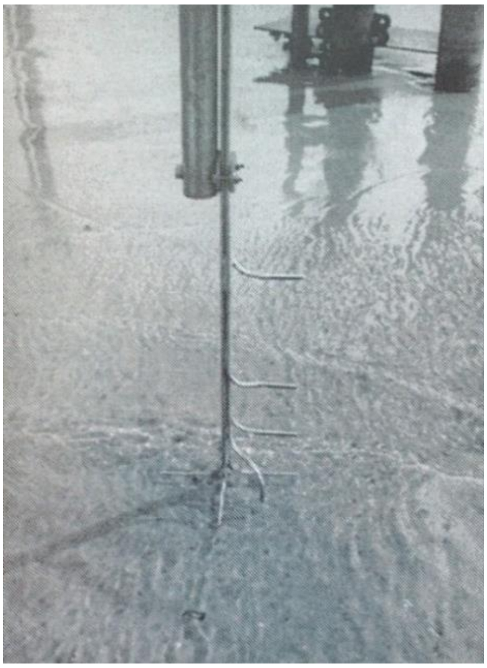


Figure 2.11 - Transverse Suction System (Bosman *et al.*, 1987).

Pump sampling provides a reliable method for collecting samples and works well for fine sediments (<0.062 mm). It can also be programmed to take samples at predetermined intervals or when coupled with appropriate sensors, eliminating the need of personnel to take samples. When compared to instrumented sampling techniques, this method has poor temporal resolution. An instrumented technique allows the user to take many readings and measure changes in concentration. The personnel and laboratory sampling add expenses to the technique. The amount and size of sediments sampled are dependent on the pump speed and nozzle's orientation with the respect to the flow (Wren *et al.*, 2000).

2.5. Laser diffraction

Laser diffraction consists in pointing a laser beam to a sample volume where particles in suspension will scatter, absorb, and reflect that beam (Figure 2.12). Thereafter the scattered light is received by a series of ring-shaped detectors that allow the measurement of the scattering angle of the beam (Wren *et al.*, 2000). These instruments usually measure the volume and the grain size of suspended particles, but it is also possible to estimate the sediment concentration through density conversion (Melis *et al.*, 2003).

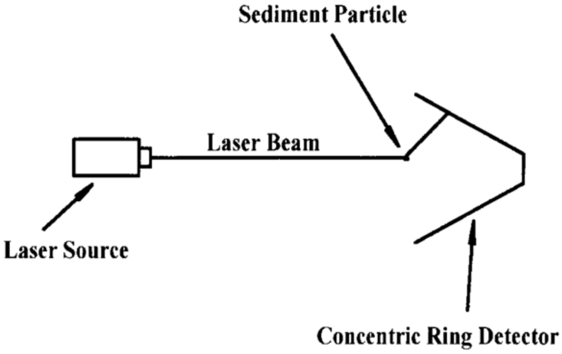


Figure 2.12 - Laser diffraction (Wren *et al.*, 2000).

A major technological advance for measuring suspended load transport is the *in-situ* Laser diffraction instrument (Figure 2.13). This instrument can measure the particle size distribution and sediments concentration simultaneously. However, has some limitations related to light penetration. The maximum concentration ranges are about 0.15 g/L for fines (mud/silt) and 0.50 g/L for sand particles. Hence, the instrument cannot be used in high concentration conditions (close to bed or upper flow regime) (Van Rijn, 2005).

Figure 2.13 - Laser diffraction instrument (Sequoia, 2015).

The particle composition and the particle-size does not affect the readings because, the last one is used to obtain the SSC value. The disadvantages of using this device are: the price of the equipment's, particle size limitation (up to 0.25 mm), low concentration range (up to 5 g/L) and requirement of specialized training for operation and data interpretation (the statistical algorithms used to translate the data do not obtain an unique concentration). This process works well when the sediments have a smooth distribution (Wren *et al.*, 2000).

2.6. Spectral reflectance

The determination of SSC in spectral reflectance is based on the relationship between the amounts of radiation (visible or infrared range) absorbed or scattered by the properties of water and its constituents (Figure 2.14). Thus, the sediment absorption and scattering also affect the water reflectance. This radiation is measured by a handheld, airborne, or satellite based spectrometer (Novo *et al.*, 1989a; Novo *et al.*, 1989b; Wren *et al.*, 2000).

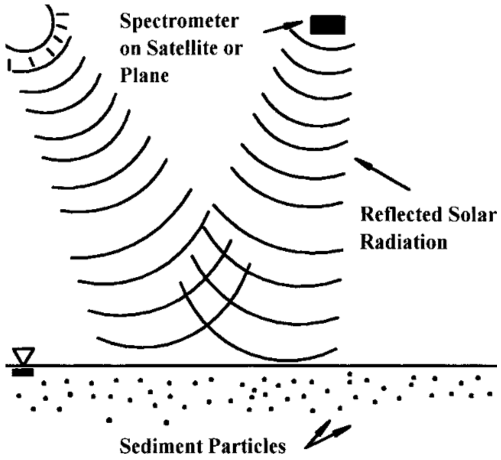


Figure 2.14 - Spectral reflectance (Wren *et al.*, 2000).

The ability to measure sediment concentrations over abroad areas and the ability to control areas with significant erosion problems (to "see" things through the air) are important advantages of this method. However, the range of sediments concentration related to reflectance values is small. The water rarely reflects more than 10% of its incident radiation, a concentration of 0.050 g/L only increase the reflectance value in 1%. In higher SSC, the measuring range is limited to approximately the top meter of the water column. It has also a significant particle-size dependence and due to a strong correlation between spectral readings and mineral composition of the sediments, larger errors in measured SSC readings may be introduced when the sediment type is unknown (Wren *et al.*, 2000).

2.7. Nuclear method

In the nuclear method is measured the attenuation or backscatter of radiation intensity, through a water-sediment mixture (White, 1998; Wren *et al.*, 2000; Van Rijn, 2005). There are three types of nuclear methods to measure the SSC: measure backscattered radiation from an artificial source; measure the transmission of radiation from an artificial source; or, measure radiation naturally emitted by the sediments. The first two methods have wider use (Wren *et al.*, 2000).

In the backscatter type, the radiation is directed to the sample by a radioactive emitter isolated from the sensor with lead. This sensor is placed in the same plan as the radiation emitter and measure the radiation backscattered from the sediments. In transmission (Figure 2.15), the emitter and the detector are on opposite sides. The detector measures the attenuation of the radiation caused by the sediments. These results are compared with the attenuation measured in clear water. The ratio between the last two measurements allows the calculation of the sediment concentration. This method also requires calibration due to dependency of the distance between the source and the detector, the radiation source and the absorption coefficient of the sediment particles (Van Rijn, 2005).

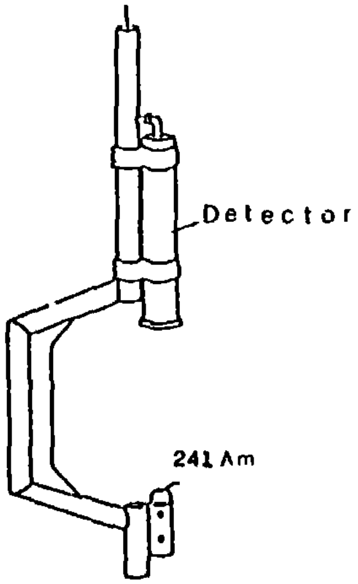


Figure 2.15 - Example of transmission gauge (Crickmore *et al.*, 1990).

In general, the advantages of using nuclear instruments are that they are well suited to installations where continuous monitoring is necessary due to inherently low power consumption of the instruments, they can be used over a wide range of sediments concentrations (from 0.5 to 12 g/L) and they are not affected by the colour of the water or by the suspended organic matter. On the other hand nuclear measurements also have limitations. Radioisotopes, by nature, suffer decays during the time, and the source must be eventually replaced. Due to the radiation incidence, the change in chemical composition of sediments can affect the readings. Licensing and training are required for the use of these devices. The geometry of the gamma backscatter instruments prevents their use in streams <1.5 m deep. These instruments are best suited to concentrations above 1 g/L. Field calibration is difficult, and laboratory calibration cannot be replaced by field calibration due to the different chemical characteristics exhibited by river water and tap or distilled water. This problem is multiplied because periodic recalibration of nuclear instruments is required. Most instruments require 3–5 min of observation time per measurement, to not capture any fluctuations in SSC shorter than the observation time (Wren *et al.*, 2000).

2.8. Resume

In Table 2.1 is presented a resume of the advantages and disadvantages of the application of each method referred along this chapter.

All the equipment's have advantages and disadvantages. In general, with equipment's that emit signals (optical and acoustic methods), the user has good temporal and spatial resolution and relatively low cost. However, they suffer from particle size and concentration influence and it is difficult to create an efficient calibration apparatus. Methods in which samples are collected (bottle and pump sampling) can cover the entire depth of a stream and allow sediments size distribution. As opposed, these methods provide poor temporal resolution, flow intrusion and require on-site personnel and laboratory analysis. Laser diffraction method does not present particle-size influence, but is an expensive, flow intrusive method and requires specialized training to operate. With spectral reflectance the user can "see" the change of the sediments concentration in time over abroad areas but the influence of the sediment characteristics is a problem. Finally, the nuclear method have low consumption, can be used in a wide range of concentrations and is not influenced by water color. In contrast, suffers from radioactive decay and requires personnel with specialized training.

It is not easy to choose the best method to quantify the SSC. This will always depend of the local measurement conditions and the available budget to proceed the experiments.

Table 2.1 - Advantages and disadvantages of each method (Wren *et al.*, 2000).

Method	Advantages	Disadvantages
Optical	Very good temporal and spacial resolution, sensitive to a wide range of concentrations, relatively inexpensive and allows real time output, remote deployment and data recording.	Particle size dependency, saturation of the sensor on high concentrations, flow intrusive instruments and sensor fouling,
Acoustic	Nonintrusive, measures through a vertical range on the order of several meters and high degree of temporal and spatial resolution.	Translation of the acoustic backscatter data is difficult, signal attenuation at high particle concentration and difficulty in creating a calibration apparatus.
Bottle sampling	Depth and point integrating samplers allow nearly the entire depth of the stream to be sampled and is a reliable, well documented and widely used technique.	Poor temporal resolution, flow intrusive, requires on-site personnel and laboratory analysis.
Pump sampling	Works well for fine sediments (<0.062 mm), the pumps can be often automated and allows the sediments size distribution determination.	Poor temporal resolution, flow intrusive, requires on-site personnel and laboratory analysis and dependency of the pump's speed and nozzle orientation to the flow direction.
Laser diffraction	No particle size dependency (sediments concentration obtained from the particles volume).	Expensive, flow intrusive, limited particle size range and require specialized training to operate and data interpretation.
Spectral reflectance	Able to measure and "see" changes in time of the sediments concentration over broad areas.	Particle-size and mineral composition dependency.
Nuclear	Low power consumption, no affection by the water color and can be used in a wide range of sediment concentrations.	Radioisotopes decay, low sensitivity and licensing and training required.

Chapter 3

Equipment applicability conditions

3. Equipment applicability conditions

In this chapter, previous studies related to the measurement equipment used to estimate suspended sediment concentration (SSC) on this work, will be presented. As was referred previously, the equipment's that were used on the experiments were the Optical Backscatter Sensor (OBS) and the Pump Sampling. The TSS is an adaptation of the Pump Sampling method, as will be explained further on.

3.1. Optical Backscatter Sensor

The OBS was created more than 30 years ago. Over the years, these sensors have been used in a number of different marine environments, including the surfzone (Sternberg *et al.*, 1984; Jaffe *et al.*, 1984; Beach and Sternberg, 1988; Russel, 1993; Yu *et al.*, 1993; Ogston and Sternberg, 1995), estuaries (Kineke *et al.*, 1989; Davies, 2013) and ocean (Guillen *et al.*, 2000). This is due to their low cost, durability and wide range of concentrations which comprises (Downing, 2006). Although the advantages referred, this equipment has shown to suffer interferences from the sediment characteristics and the surrounding environment where the sensors are placed. Given this, the OBS has been aim of many scientific studies.

3.1.1. Sediment concentration

According to Downing (2006), the sediment concentration is the most important effect on OBS signal because it was the first order effect that OBS's were designed to measure and, also the most important response for the equipment users. On high sediment concentrations, especially in suspensions containing high concentrations of silt and clay, the infrared radiation from the emitter can be partially blocked and the backscatter decreases with increase sediment concentration above the peak level (Figure 3.1). This response can be problematic because the same OBS signal correspond to two SSC. On an explanation about

Figure 3.1, Downing (2006) says that in region A, the relationship between the OBS signal and SSC is nearly linear and the OBS gives excellent estimates of SSC. Then, light attenuation becomes the dominant process at about 6 g/L causing the signal to increase sharply and then decrease with increasing SSC (region B). In region C, the OBS behaves like a transmissometer, the ratio between the received and the emitted signal is less than one, so the received light measured decreases exponentially with increasing SSC.

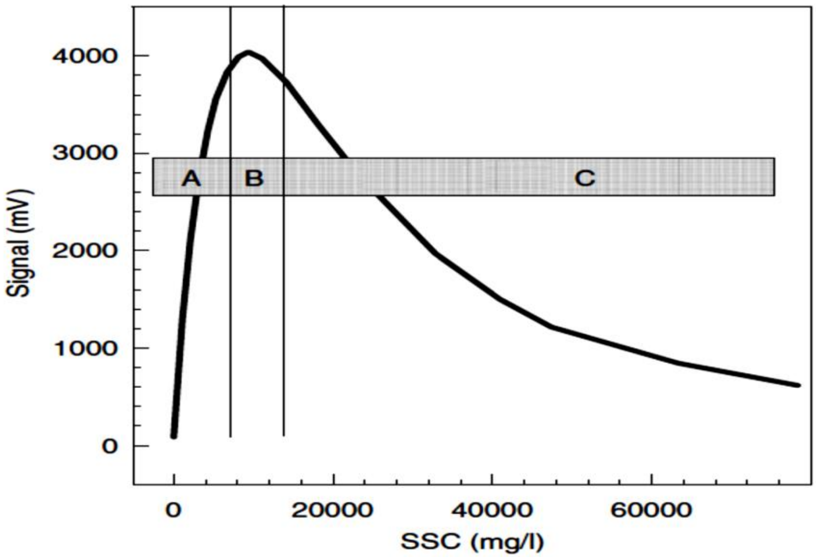


Figure 3.1 - Response of an OBS-3 to a wide range of SSC (Downing, 2006).

To estimate the high SSC near the mouth of Amazon River, Kineke and Sternberg (1992) developed a response curve similar to the one presented in Figure 3.1. With a profiling system, automatic suspended-sediment samplers and OBS's through the water column, the authors built a SSC profile. Knowing that the muddiest water was near the bottom and the OBS signal evolution along the height above the bottom, the calibration curves presented in Figure 3.2 were built. The data was divided into three ranges of concentrations (before peak, around peak, post-peak). The curves were fitted using least squares for various forms (linear, second and third order polynomials, exponential, logarithmic, and power laws). After some adjustments to build the curve continuous as possible, three curves were chosen as representative with each one an equation related.

Maa and Xu (1992) tested the performance of OBS for mineralogy (kaolinite, ilite and montmorillionite) differences on the sample, the operational range of an OBS for cohesive sediments and the effect of ambient light, water salinity, and water color variation. The maximum operational ranges obtained for each mineral were different. For kaolinite, the maximum is 0.5 g/L while the maximum operational range for illite and montmorillonite are between 0.8 and 1.2 g/L. The results of the other tests indicated that the salinity was important. Between fresh water and saltwater (with a fixed concentration of sediments) the results indicated a significant difference when the concentration is higher than 0.5 g/L (explained by the contribution of salt in the flocculation process). The flocculation occurs when the sediments particles or flocs collide. Therefore, higher SSC, greater is the chance of flocs colliding. On the other side, the color of the water and the ambient light where considered not important.

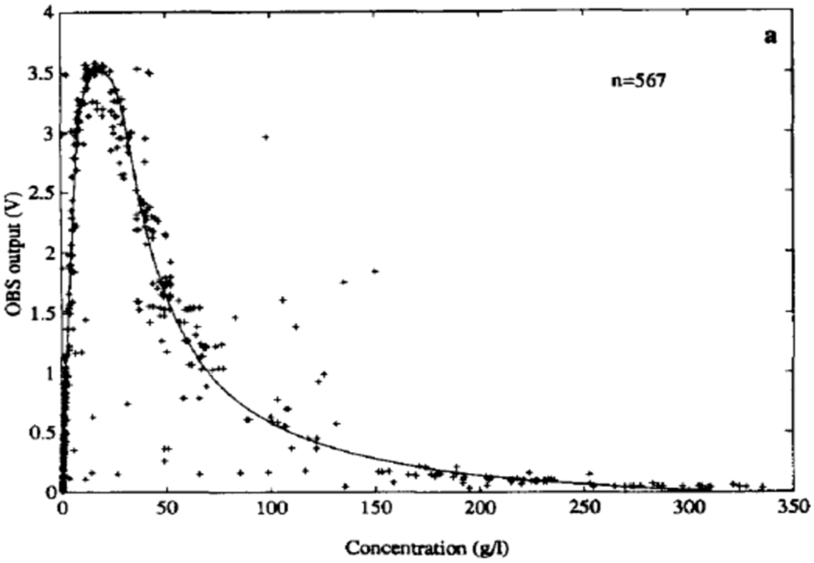


Figure 3.2 - OBS output versus concentration (Kineke and Sternberg, 1992).

3.1.2. Particle size

The second largest effect on OBS signal is the particle size. The suspended sediment transported in streams, rivers and oceans can have from 0.0001 to 1 mm (Downing, 2006). A number of studies have documented this effect. For example, Conner and De Visser (1992) made several calibrations for particles between 0.037 and 0.212 mm obtaining a regression which relates OBS gain with particle size. The final results obtained showed that OBS is well suited for collecting SSC data in environments with nearly constant particle size distribution. This equipment is minimally affected by particle size changes with particles between 0.2 and 0.4 mm. However, is not recommended for particles sizes of 0.1 mm or less. Ludwig and Hanes (1990) studied the OBS response to sand in the presence of suspended mud. The sediments collected on the field site used for the experiments were sieved, mixed and the results gave several sediment sand-mud mixtures with uniform and known concentration. The response to different grain sizes was examined by sieving the collected sand into size classes of 0.063, 0.090, 0.125, 0.180 and 0.250 mm and a mixture approximated to the natural distribution with mean grain size of 0.183 mm. For each size was measured the OBS signal varying the sample concentration. Then, with the addition of controlled mud concentrations, the response of each sensor was studied (attributed to each sand size class). The conclusions drawn from this experiment were that the OBS sensivity to suspended mud is higher than to sand. On high mud concentrations, a non-linear curve is required (see Kineke and Sternberg, 1992) and for sand-mud mixtures, the OBS responds linearly to the concentration of each component. According to Ludwig and Hanes (1990) is not recommended the use of these instruments to measure suspended sand in areas which experience suspended mud. This is to avoid sensor saturation with mud during high energy events and when the mud concentration varies, because it is unclear to evaluate which portion of the signal is the suspended sand or the suspended mud.

In addition to the size of individual sediments grains, disaggregation and flocculation can influence the size parameter of the suspended particles. Disaggregation of sediments groups make the small particles out of larger sediments groups, creating small sediment particles finer than it was in the environment and the treatment of this data can give an invalid representation of OBS response. Sediments susceptible to disaggregation effects include: (1) organic-rich estuarine mud, (2) cohesive (see Maa and Xu, 1992) and flocculated suspended matter (see Gibbs and Wolanski, 1992), and (3) clay-rich sediments (Downing, 2006).

3.1.3. Particle or flocs shape

Particle shape also affects OBS sensitivity. Gibbs and Wolanski (1992) studied the flocs concentration varying the flow conditions. Considering the same SSC, the results showed that an OBS measures a signal 50% higher in highly turbulent cohesive sediment suspensions than in a low turbulence environment. Thus, flocs size must be considered in OBS measurements and to obtain accurate results the authors counsel to have multiple calibration curves for high and low flow conditions and equally for the surface and bottom waters due to the difference in the floc size in these two areas.

3.1.4. Particle and water color

The near-infrared (NIR) reflectivity, sometimes also indicated as sediment color, was studied by Sutherland *et al.* (2000). The results of their experiments showed that the Munsell value (scale from 0 to 10, where 0 is black, meaning that the signal is absorbed and 10 is white, meaning that the signal is 100% reflected), artificially coloured sediments and various minerals induced a varied response by OBS. This is important because if the blackness level of the sample is high, the concentration and particles size become unimportant due to a 100% signal absorption. On the other hand, Downing and Asher (1997) studied the absorption of light by the materials dissolved in a water sample. It was expected that the SSC indicated by an OBS sensor got affected. The absorption reduces the incident light energy on scattered particles even as the intensity of scattered light detected by the sensor. The copper dye dissolved in the water sample during the experiments caused an 80% decrease in SSC when increased to 51 milimolar. To determine if this effect was significant to the environment, were made several reviews of water chemistry data to identify analogues of the dyes in the nature. Only in mine runoff was found a significant influence, but only if the copper^{+2} concentration exceed, at least 100 times, the lower level needed to produce a 10% reduction in OBS sensitivity (which happens in some situations).

3.1.5. Calibration apparatus

To improve the sediment concentration estimation several authors proposed many calibration apparatus to OBS. Sternberg *et al.* (1986, 1991) affirmed that the best way to calibrate the sensors was by taking water samples near the sensor location and develop a numerical relationship between the signals and SSC samples. Downing and Beach (1989) proposed an alternative procedure to calibrate OBS using dry and disaggregated material, which works for non-cohesive sediments because the water and the sediments can be accurately weighted and are easy to handle. They also proposed the laboratory apparatus presented in Figure 3.3. Another possible calibration is instead of water, use glycerol, reducing the particles settling velocity, thus simplifying the procedure to obtain the calibration slopes for non-cohesive sediments samples (Butt *et al.*, 2002).

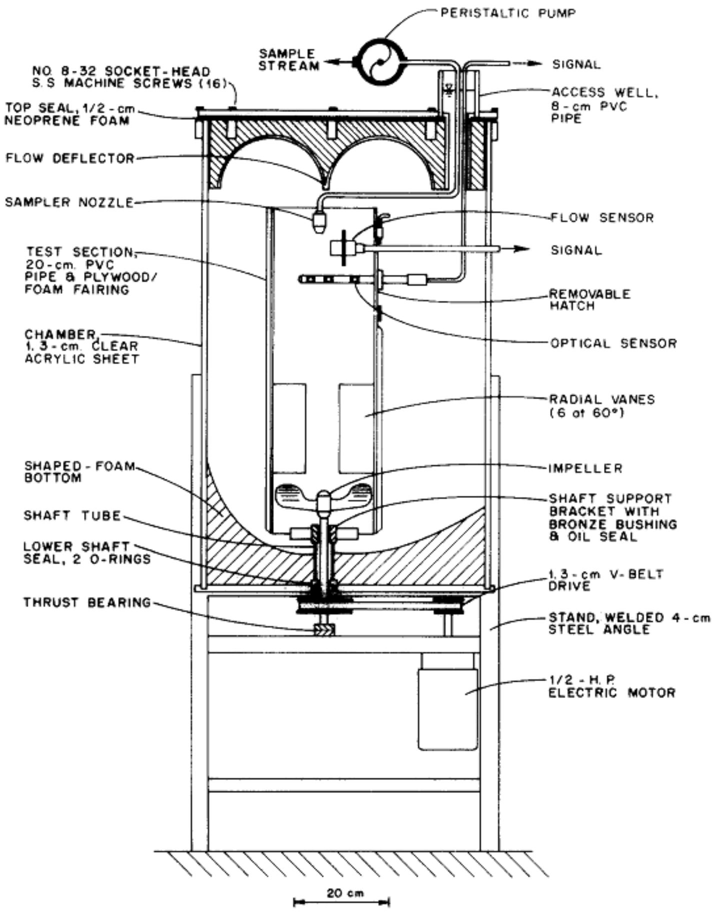


Figure 3.3 - Laboratory apparatus proposed by Downing and Beach (1989).

3.1.6. Bubbles

Other effect that has been studied is the bubbles effect. The concern about bubble interferences in OBS signal is justifiable. Bubbles and sand have refractive indices different from the water, being efficient backscatters, even though buoyancy forces the bubbles to be near the surface and the sand near the seabed (Downing, 2006). Black and Rosenberg, (1994) have reported bubble effects in calibration containers and Smith and Mocke (2002) in wave flumes. Puleo *et al.* (2006) performed experiments in which, in a water tank, were varied the bubbles and water types, the air flow rate and the sand or mud concentration. The results obtained showed that the persistence of air bubbles is bigger in salt water than in freshwater, and smaller the size of the air bubbles bigger the influence in the output signal on this type of water (the bubbles probably act more like solid particles). In order to correct the bubbles effects, these authors suggested a calibration factor, R (equation 3.1), to be applied in the final output, based in the influence of the bubbles.

$$R=\frac{s}{s_b} \tag{3.1}$$

In which s is the slope of the calibration curve obtained in natural conditions (with sediments and bubbles) and s_b the slope of the calibration curve obtained from the calibration with only bubbles.

According to Downing (2006) the surf-zone bubble plumes are an entirely different matter from whitecap plumes. The first presented concentrations 100 to more than 1000 times bigger than the second ones, in the size range from 0.40 to 1 mm of diameter. So, these plumes are very likely to produce bubble interference in the swash zone. In foamy streams, laboratory flumes and calibration tanks, and near propellers where the aeration can be more intense than under breaking waves, the potential of bubble interference cannot be ignored.

3.1.7. Chemical and biological fouling, fish and bugs

The last factors that can affect the OBS signal are the chemical and biological fouling, fish and bugs. Any material that accumulates in the window of an OBS sensor will interfere in signal detection because it changes the sensor way of "seeing" the water. Chemical films, biological growth and dirt can produce an apparent decline in SSC. On the other hand, fouling does not always produce an apparent decline of SSC. Organisms, algae and sediments can adhere and scatter directly into the detectors causing an apparent rise of the SSC. Another form of biological interference occurs when there are high concentrations of phytoplankton. The phytoplankton cells are not efficient scatterers, although when present they can interfere with OBS measurements (Downing, 2006). Schoellhamer (1993) studied this situation and determined that plankton signal could be equivalent to a 0.1 g/L signal produced by SSC. This should only be considered in situations when the SSC is low and phytoplankton blooms can occur.

3.2. Pump sampling

Although less used (and studied), pump sampling is a simple and inexpensive method to measure time-averaged sediment concentrations under dynamic environments (Bosman *et al.*, 1987). Nowadays, this equipment is often combined with others like OBS and/or ABS to get accurate results of SSC estimation (Poppe, 2014; Van Til, 2014). Previously Bosman

(1981) studied the bed behaviour and sand concentration under oscillatory water motion using a TSS.

In this section, are referred the experiments where Bosman *et al.* (1987) studied the trapping efficiency of pump sampling in unidirectional, steady flow conditions and non-unidirectional, unsteady flow conditions (waves): two-dimensional wave conditions and three-dimensional wave conditions.

According to Bosman *et al.* (1987) the trapping efficiency of the suction, α, is defined by equation 3.2.

$$\alpha = \frac{C_s}{C_c} \tag{3.2}$$

In which C_s is the sediment concentration of the pumped sample and C_c the concentration in the flow.

The trapping efficiency depends on many parameters such as the nozzle dimensions, its orientation relative to the flow, the velocities of the intake and ambient flow, the sediment particle characteristics (size and shape) and the relative density. For example, with the nozzle projecting upstream and identical intake velocities and ambient flow, the trapping efficiency is one. Under other conditions this parameter, in general, differs from unity (Bosman *et al.*, 1987). To evaluate its behaviour, in these experiments, Bosman *et al.* (1987) considered that the intake velocity direction was normal to the ambient flow (Transverse suction system) and exceeded it by a factor of three at least (the ambient flow was controlled).

3.2.1. Unidirectional, steady flow conditions

The trapping efficiency for unidirectional, steady flow conditions (using 3 mm diameter nozzle and sediments with d_{50} equals to 0.17 mm) was studied in relation to the velocity ratio (ratio of the intake velocity over ambient flow velocity: u_s/u_c) for five nozzle directions: 0° (suction and ambient flow in line), 80°, 90° (*i.e.* normal suction), 100° and 180° (suction and ambient flow opposite). The 0° direction was performed to verify if a systematic error occurred, because in this direction the trapping efficiency is meant to be equals to one. The normal direction (90°) was the most important in the experiments and the 80° and 100°

were used to study the directional sensitivity of the trapping efficiency around the normal direction. The results are represented in Figure 3.4 (Bosman *et al.*, 1987).

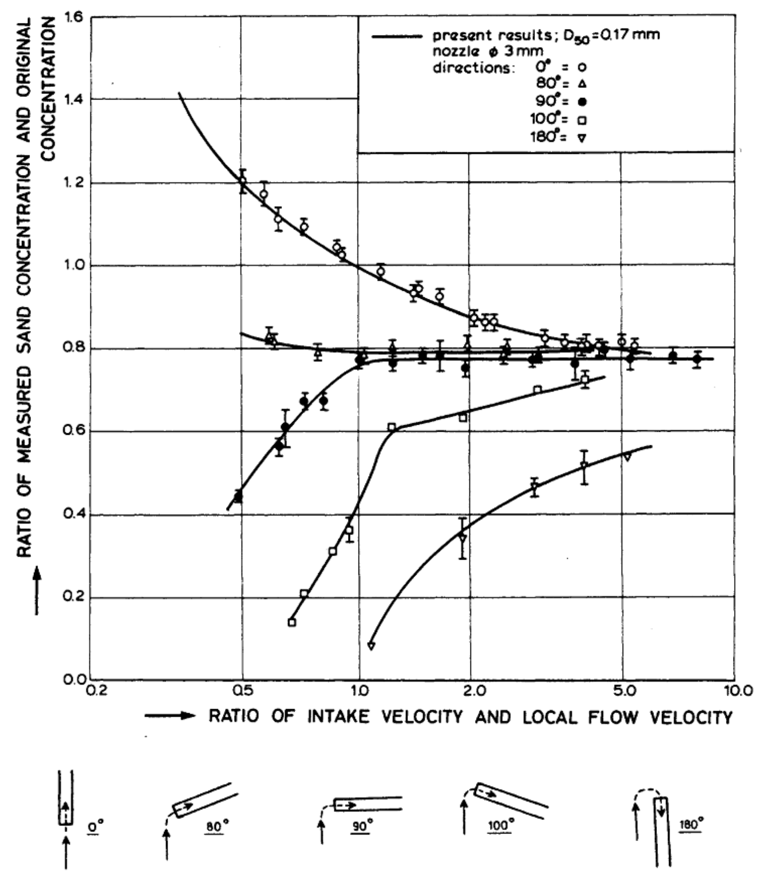


Figure 3.4 - Trapping efficiency, for 3 mm diameter suction nozzle related to the orientation and the velocity ratio (adapted from Bosman *et al.,* 1987).

The results indicated that the normal direction (90°) was the most attractive because the trapping efficiency was not very sensitive to the velocity ratio. The same happened for directions near the normal one. This was important to get an accurate value of the SSC in non-unidirectional, unsteady flows (Bosman *et al.*, 1987).

According to Bosman *et al.* (1987), the accuracy of the bent tube direction was ± 5°. To achieve an accuracy within 1° for the normal direction, the bent tube was replaced by a straight one. With this, was tested how the trapping efficiency varied with the velocity ratio for seven different sediments dimensions (d_{50}). The results are presented in Figure 3.5 and show that for all sediments, the trapping efficiency is independent of the velocity ratio when this is beyond three (Bosman *et al.*, 1987).

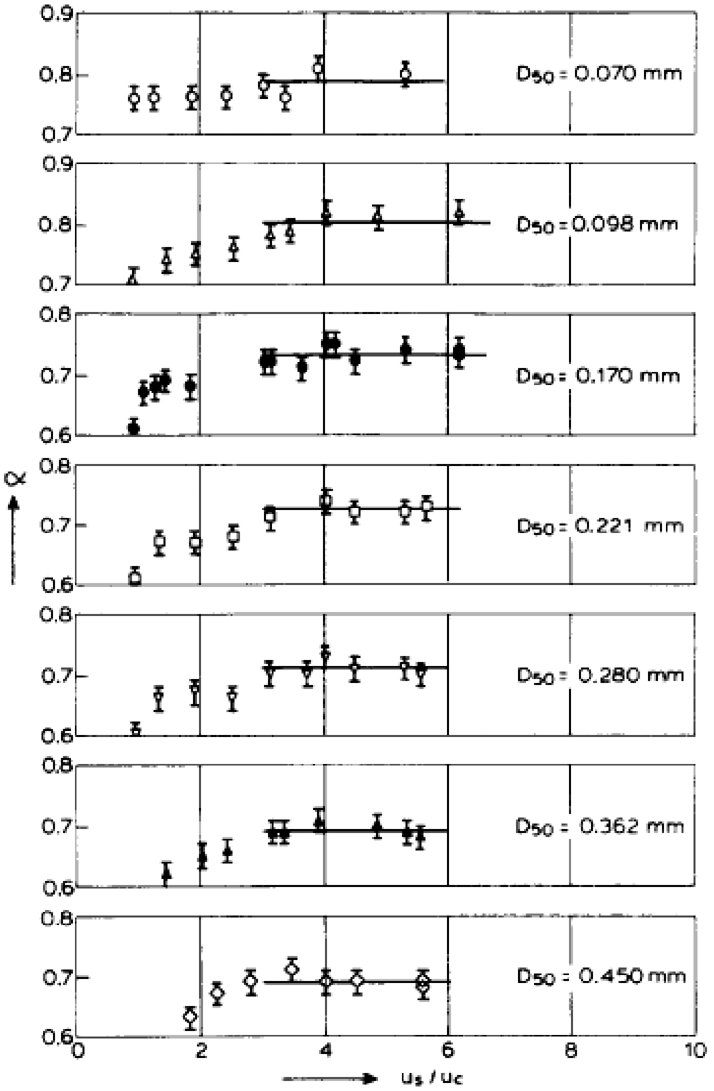


Figure 3.5 - Trapping efficiencies in transverse suction for seven different sediments sizes (Bosman *et al.*, 1987).

For applications of this method, the true concentration can be deducted from the product of the pumped concentration, C_s, with a calibration factor, β ($C_{true}=\beta\times C_s$), where $\beta=\frac{1}{\alpha}$. In Figure 3.6, Bosman *et al.* (1987) studied the relation between β and d_{50}, which showed minor influences of d_{50} in β. Both parameters can be related by equation 3.3, with an accuracy within 3%.

$$\beta=1+\frac{1}{3}\times\arctan\left(\frac{d_{50}}{0.090}\right) \tag{3.3}$$

In which, the arctan function is to be read in radians and d_{50} the sediment size (mm).

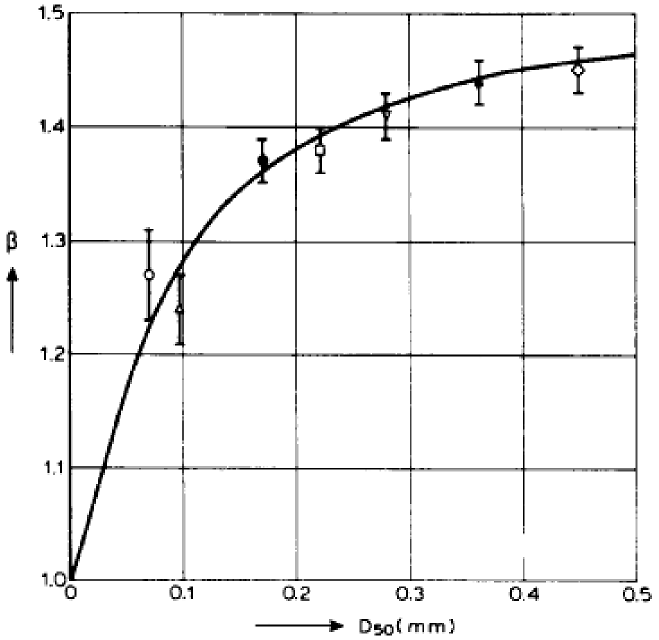


Figure 3.6 - Calibration factor, β related to the sediment size, d_{50} (Bosman *et al.*, 1987).

3.2.2. Non-unidirectional, unsteady flow conditions (waves)

As referred in previous section, the results presented in Figure 3.4 have importance when studying the SSC in non-unidirectional, unsteady flow conditions (waves) because under waves the water velocity can reaches peak values in opposite directions. For this type of flow, in laboratory wave flumes, the peak velocities usually are not much larger than 0.5 m/s. Thus with a peristaltic pump, the intake velocity can reach easily 1.5 m/s and consequently, the velocity ratio from three to infinity. However in large flumes, in wave tunnels and in the prototype much larger peak velocities may occur in the ambient flow. The peak velocity durations are short relative to the wave period. When this occurs, the suction velocity exceeds the ambient flow velocity maybe only by a factor of one, leading to a negligible small systematic error around 5% (Bosman *et al.*, 1987).

Bosman *et al.* (1987) tested the transverse suction method on two practical studies: two-dimensional laboratory wave conditions and three-dimensional prototype wave conditions. Two-dimensional wave conditions are defined by unidirectional waves with or without a net current along the same direction. To apply the transverse suction method under waves, the suction direction should be normal to the orbital motion plan. These conditions raised a few problems such as: requirement of an absolute reference to determine the true concentration and concentration dependence of the equipment position (horizontal and vertical) relatively to the bedforms.

To solve the first problem Bosman *et al.* (1987) added an optical device (no dependency from the velocities ratio and direction) to control the concentration obtained with TSS. To solve the problem referred secondly, many measurements were performed to average the horizontal reference and suction positions along the bed. The optical device and TSS were measuring side-by-side continuously along the wave directions at fixed height above the bed.

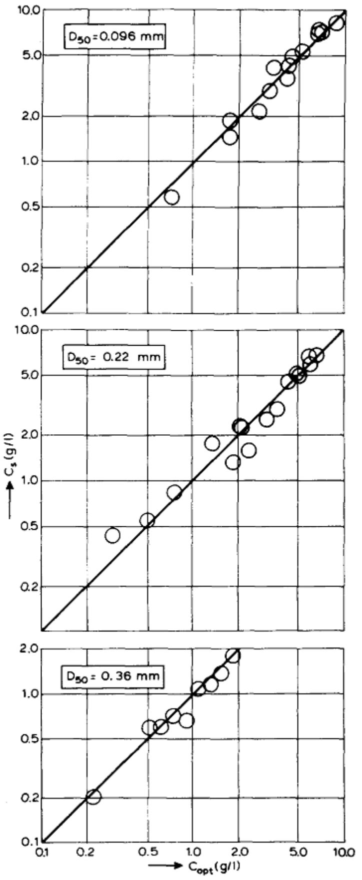


Figure 3.7 - Suction and optical concentrations for three sediments sizes (Bosman *et al.*, 1987).

Due to the large number of variables under waves (period, height, form and regular or irregular waves), and the size dependence of this method, this work did not cover all the verifications. The verifications covered three sediments sizes (d_{50}): 0.098 mm, 0.22 mm and 0.36 mm. The wave period varied between one and two seconds, the mean water depth between 19 and 28 cm and the wave height between 7 and 15 cm. The calibration factors from the previous section were applied in these experiments. The results of these experiments are presented in Figure 3.7. However limited to concentrations above 10 g/L, they show that the TSS calibration factors determined under steady flow conditions apply to the waves as well (Bosman *et al.*, 1987).

In three-dimensional wave conditions, the water velocity vector changes continuously in magnitude and direction. Without a system with directional feed-back applied, was not possible to define a suction direction to the ambient flow. Bosman *et al.* (1987) proposed a system with five spaced nozzles installed at the same height close to the bed (see Figure 2.11). Two nozzles were parallel to the longshore current, with entries in both directions, two other normal to the longshore current, also in both directions and the last oriented downward, normal to the ambient flow whatever its direction. For each nozzle were calculated the trapping efficiency factors, so that the concentrations in each flow direction could be compared. The last nozzle was the least sensitive for variations in the direction and the least sensitive to blockings. The average of the results of the four first nozzles were similar to the downward oriented one, this means that no matter what the suction direction is, the transverse suction calibration can be applied to all directions with an accuracy of approximately 10% (Bosman *et al.*, 1987).

Chapter 4

Experimental set-up

4. Experimental set-up

The calibration of the measurement equipment's is the first and one of the most important steps to evaluate the suspended sediment concentration (SSC) in any water flow. In this section, there is a brief description of the equipment's used in this work, the sediment characteristics, the experimental procedure and the tested scenarios.

4.1. Equipment's

Located in the Civil Engineering School of the Universitat Politècnica de Catalunya (UPC), the Laboratori d'Enginyeria Marítima (LIM) has a large-scale wave flume (CIEM - Canal d'Investigació i Experimentació Marítima), a small-scale flume (CIEMito) and a large number of tools and instruments of last generation. Only the CIEM flume characteristics are presented, because it was the flume where were performed the SINBAD experiments. Then is described the calibration set, explaining the sequence of equipment's settled to perform the optical backscatter sensor (OBS) and transverse suction system (TSS) experiments.

4.1.1. The flume

The Canal d'Investigació i Experimentació Marítima (CIEM) is an international research facility for controlled hydraulic experiments in coastal, harbour and oceanographic engineering and also other fields (aquaculture and the study of wave energy). The CIEM wave flume (Figure 4.1) is 100 m long, 3 m wide and 4.5 m deep for scaled tests (typically between 1:2 and 1:20) and studies under close-to-real conditions. The larger scale ratios reduces the scale experiments effects thus, reflecting real suspension sediment transport in certain generated conditions. However, this also requires advanced equipment and has more limitations on the equipment placement (UPC, 2014).

a) Sand-bed construction.

b) Measurement equipments during an experiment.

Figure 4.1 - CIEM wave flume (UPC, 2014).

4.1.2. The calibration set

The main element of the calibration set (Figure 4.2) is the water tank. This tank has a capacity of 85.72 liters, and is where are placed the OBS (Figure 4.3a) and the TSS nozzle (Figure 4.3b). To get a uniform and upwards flux passing by these equipment's in the inside of the tank, it is placed a plastic cylinder (open in the ends) which, in the bottom has inserted a propeller that maintain the liquid flowing and above it, a set of pipes to direct the flux and decrease the turbulence caused by the propeller (Figure 4.3c). Associated to the propeller, there is an engine (Figure 4.3d) where is possible to control the spinning direction and velocity (this is controlled by applying a voltage in the engine that makes the propeller spinning).

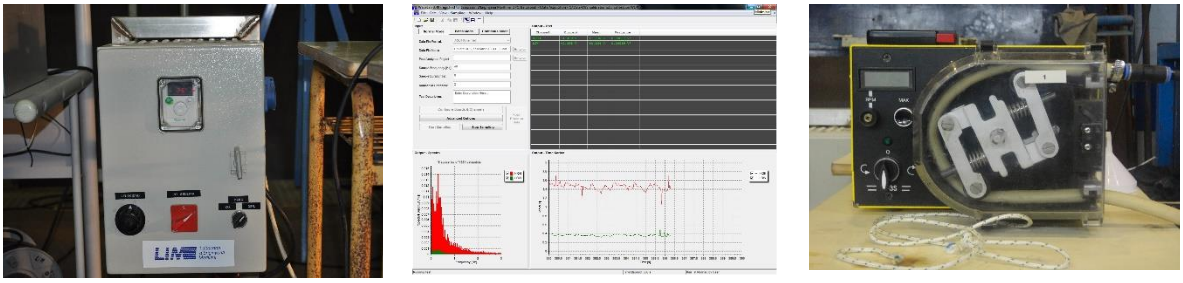
The OBS is connected to a computer with a specific program for data acquisition (Wavelab, Figure 4.3e) and a power supply. The TSS is connected to a Watson-Marlow 603S peristaltic pump (Figure 4.3f). In the pump is possible to control the rotations per minute (RPM) and the direction of the flux in the pump pipes. In the bottom of the tank there is a valve, used to drain the water with sand when the experiment is over.

Figure 4.2 - Calibration set.

a) OBS placed inside the tank.

b) TSS nozzle placed inside the tank.

c) View from the upper part of the tank.



d) Engine.

e) Wavelab display.

f) Peristaltic pump.

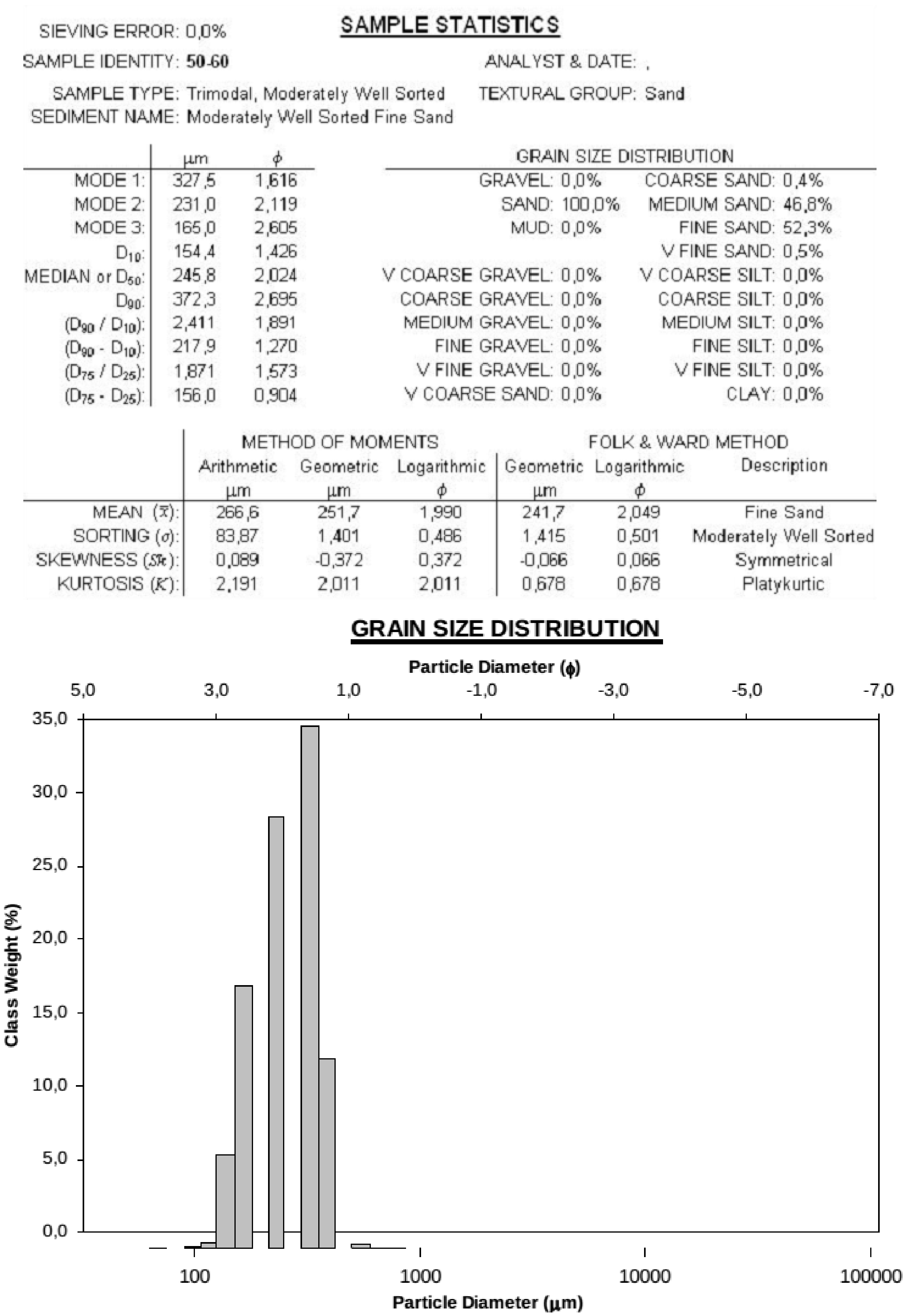
Figure 4.3 - Calibration set components.

4.2. Sediment characteristics

The sediment used consisted on a medium sand, provided by *Sibelco* and with commercial name of J5060S. The measured d_{50} of this sand is 0.25 mm and the settling velocity 3.4 cm/s. Table 4.1 shows the sediment mass collected in each sieve, for an initial sample with a total weight of 198.629 gr and the Figure 4.4 shows the sample statistics and grain size distribution.

Table 4.1 - Granulometry distribution for Sibelco J5060S (CIEM flume provided information).

Sieve (mm)	Weight (gr.)	%	Accumulated (%)
0.710	0.020	0.010%	0.010%
0.595	0.027	0.014%	0.024%
0.500	0.688	0.336%	0.360%
0.350	26.006	13.093%	13.453%
0.300	66.983	33.723%	47.175%
0.210	54.242	27.308%	74.484%
0.149	36.515	18.384%	92.867%
0.125	13.070	6.580%	99.447%
0.105	0.738	0.372%	99.819%
0.088	0.240	0.121%	99.940%
0.063	0.050	0.025%	99.965%
Remainder	0.070	0.035%	100.000%
Σ	198.629		



SAMPLE STATISTICS

SIEVING ERROR: 0,0%

SAMPLE IDENTITY: **50-60**

ANALYST & DATE: ,

SAMPLE TYPE: Trimodal, Moderately Well Sorted

TEXTURAL GROUP: Sand

SEDIMENT NAME: Moderately Well Sorted Fine Sand

	μm	φ
MODE 1:	327,5	1,616
MODE 2:	231,0	2,119
MODE 3:	165,0	2,605
D_{10}:	154,4	1,426
MEDIAN or D_{50}:	245,8	2,024
D_{90}:	372,3	2,695
(D_{90} / D_{10}):	2,411	1,891
(D_{90} - D_{10}):	217,9	1,270
(D_{75} / D_{25}):	1,871	1,573
(D_{75} - D_{25}):	156,0	0,904

GRAIN SIZE DISTRIBUTION

GRAVEL:	0,0%	COARSE SAND:	0,4%
SAND:	100,0%	MEDIUM SAND:	46,8%
MUD:	0,0%	FINE SAND:	52,3%
		V FINE SAND:	0,5%
V COARSE GRAVEL:	0,0%	V COARSE SILT:	0,0%
COARSE GRAVEL:	0,0%	COARSE SILT:	0,0%
MEDIUM GRAVEL:	0,0%	MEDIUM SILT:	0,0%
FINE GRAVEL:	0,0%	FINE SILT:	0,0%
V FINE GRAVEL:	0,0%	V FINE SILT:	0,0%
V COARSE SAND:	0,0%	CLAY:	0,0%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic μm	Geometric μm	Logarithmic φ	Geometric μm	Logarithmic φ	Description
MEAN ($\bar{x}$):	266,6	251,7	1,990	241,7	2,049	Fine Sand
SORTING (σ):	83,87	1,401	0,486	1,415	0,501	Moderately Well Sorted
SKEWNESS (Sk):	0,089	-0,372	0,372	-0,066	0,066	Symmetrical
KURTOSIS (K):	2,191	2,011	2,011	0,678	0,678	Platykurtic

Figure 4.4 - Sediment statistics and grain size distribution for Sibelco J5060S (CIEM flume provided information).

4.3. Experimental procedure

Before plug the TSS to the calibration tank, OBS tests were performed to check if there were any variations in the signal stability during time and repeated three runs of tests for the same OBS (repeatability). These tests were important to evaluate if the sediment concentration was stable in time, if the OBS was not measuring different voltages for the same concentration and to find the correct propeller velocity.

After checking if the OBS signal was stable and repeatable, the TSS was plugged and several samples were taken with different intake velocities to verify which was the most suitable and how long could take to obtain a sample that could fill a third of the bucket without compromise the sample. Once all verified, the experiments with both equipment's started.

To get accurate measurements, some aspects were considered in all tests:

1. The laboratory light. Some tests were performed with a spotlight on and directed to the tank (Figure 4.5a) and others with it off (Figure 4.5b);

a) Spotlight on **b) Spotlight off**

Figure 4.5 - Incident laboratory light tests.

2. Before start adding any sediments to the tank, a “noise” test with OBS was performed (without any sediments and the propeller on) to evaluate if there was a significant amount of sediments from the previous experiments that was not eliminated and then correct the OBS concentrations;
3. In all tests, a visual inspection was performed to verify the amount of bubbles and to verify if all the sediments were in suspension.
4. Every time that bubbles were observed the propeller was stopped and the tank was “shacked” in order to drive the bubbles outside through the small pipes located in

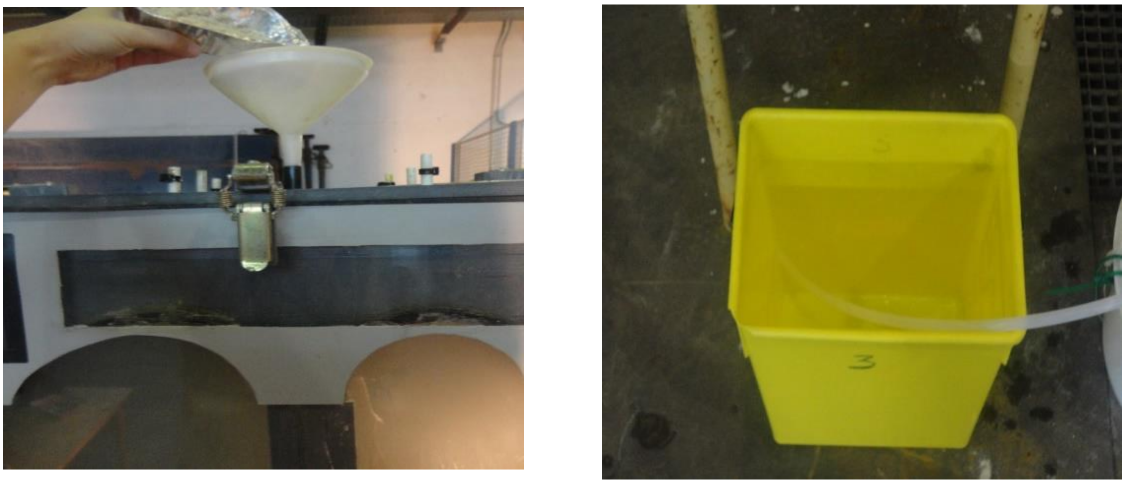
the upper part and the measurement with OBS was repeated in order to compare if they influenced significantly the results;

5. When the TSS was working, the OBS was not measuring (seems reasonable because when working, the TSS decreases the amount of water and sediments in the tank);
6. As referred in the previous point, while pumping there was a decrease of the water level. So, while pumping was necessary to add water to the tank to maintain the water level constant and prevent the appearance of bubbles;
7. If the nozzle was blocked, it was necessary to reverse the flux till the tube unblock, and continue pumping. If this did not work, the pump was stopped;
8. When draining the excess of water from the bucket and/or aluminium cup, it was necessary to be aware that there were any sediments left in the previous recipient and/or if there was sand being drained with the water.

The experimental procedure was the following:

1. The required amount of sediments (that were previously dried in the oven) was poured through the pipe located in the upper part of the tank (Figure 4.6a);
2. The OBS signal was measured during 5 minutes;
3. The signal acquisition with OBS was stopped;
4. The pump has worked during ± 10 seconds to insert water in the tubes;
5. The pump was started;
6. The pump was stopped when the bucket was a third full. The sample was settling in the bucket for one minute (Figure 4.6b);
7. The propeller was stopped to verify the amount of bubbles in the tank;
8. The propeller was reinitiated, more sediments were added to the tank and was started the data acquisition with OBS (the first three points of the procedure were repeated if the following test was just with OBS and the first seven if it was to perform also another TSS test);
9. The bucket was weighted with the sample on it;
10. The excess of water was drained and the sample moved to an aluminium cup (Figure 4.6c);
11. The excess water from the aluminium cup was drained;

12. The sample in the aluminium cup was dried in the oven at ± 80 degrees (Figure 4.6d);
13. The weight of the sand sample was notated when the sample was dry.



a) Sand poured to the tank. **b) Bucket to collect the sample from TSS.**

c) TSS sample in small recipient. **d) Oven with TSS samples.**

Figure 4.6 - Experimental procedure.

4.4. Tested scenarios

As referred before, 329 tests were performed in this work. In these tests different scenarios were considered by testing parameters that could spoil the results.

The main goal of this work was to calibrate properly an OBS. However, when the amount of tests with only one OBS was enough, it was realized that the number of TSS tests performed was not satisfactory. As there were other OBS's needing calibration, that were used in

SINBAD and other projects, and present the same way of functioning, tests with those OBS were also performed (Table 4.2).

Table 4.2 - Tests correspondent to each OBS.

OBS	Tests
T8267	From 1 to 160
T8285	From 161 to 183
T8276	From 184 to 205
T8282	From 206 to 229
T8287	From 230 to 251
T8284	From 252 to 274
T8277	From 275 to 296
T8286	From 297 to 318

In Table 4.3 are represented the tests related to the equipment's and the scenarios studied. Each parameter is associated to a group of tests performed with one or both of the equipment's.

Table 4.3 - Tests performed in the different scenarios.

<table>
<tr><th colspan="2">Scenario</th><th>OBS</th><th>TSS</th></tr>
<tr><td colspan="2">Stability</td><td>From 1 to 51</td><td>None</td></tr>
<tr><td colspan="2">Repeatability</td><td>From 1 to 51</td><td>None</td></tr>
<tr><td colspan="2">Propeller voltage</td><td>313, 325 and 326</td><td>None</td></tr>
<tr><td colspan="2">Pump conditions</td><td>None</td><td>56, 58, 65, 67, 70, 71, 73, 75, 77, 79, 84, 86, 88, 90, 92, 100, 106, 112, 119, 121, from 134 to 136, 139, 141, from 143 to 148, from 151 to 160, 167, 170, 174, 180, 189, 192, 196, 202, 211, 215, 219, 226, 235, 236, 238, 242, 248, 257, 260, 265, 271, 280, 283, 287, 293, 302, 305, 309, 315, from 319 to 326, 328 and 329</td></tr>
<tr><td colspan="2">Sediments concentration</td><td>From 62 to 318</td><td>67, 73, 90, 92, 97, 106, 112, 119, 121, 167, 170, 174, 180, 192, 196, 202, 211, 215, 219, 226, 236, 238, 242, 248, 257, 265, 271, 280, 283, 287, 293, 302, 305, 309 and 315</td></tr>
<tr><td rowspan="2">Incident laboratory light</td><td>On</td><td>From 62 to 93</td><td rowspan="2">None</td></tr>
<tr><td>Off</td><td>From 94 to 318</td></tr>
<tr><td colspan="2">Bubbles</td><td>5, 8, 17, 36, 48, 53, 55, 63 and 68</td><td>None</td></tr>
</table>

Given to the large amount of tests performed, in the analysis presented in chapter 6 was not possible to present all the results obtained. So, for each of the scenarios, only some of the tests considered representative were chosen to present in that chapter (Table 4.4).

Table 4.4 - Tests presented in chapter 6.

Scenario		OBS	TSS
Stability		7, 13 and 17	None
Repeatability		2, 7, 13, 17, 21, 25, 30, 33, 37, 41, 46 and 50	None
Propeller voltage		313, 325 and 326	None
Pump conditions		None	56, 58, 65, 67, 70, 71, 73, 75, 77, 79, 84, 86, 88, 90, 92, 100, 106, 112, 119, 121, from 134 to 136, 139, 141, 143 to 148, from 151 to 160, 167, 170, 174, 180, 189, 192, 196, 202, 211, 215, 219, 226, 235, 236, 238, 242, 248, 257, 260, 265, 271, 280, 283, 287, 293, 302, 305, 309, 315, from 319 to 326, 328 and 329
Sediments concentration		From 62 to 318	63, 73, 90, 92, 100, 106, 112, 119, 121, 167, 170, 174, 180, 192, 196, 202, 211, 215, 219, 226, 236, 238, 242, 248, 257, 260, 265, 271, 280, 283, 287, 293, 302, 305, 309 and 315
Incident laboratory light	**On**	64, 74 and 77	None
	Off	97, 105 and 109	
Bubbles	**Observed**	17, 63 and 68	None
	Residual	18, 64 and 69	

Chapter 5

OBS calibration curve

5. OBS calibration curve

In this section, first the calculation procedure to get to an OBS calibration curve is explained. This procedure is applied to the data obtained from the OBS T8267 tests. Then, are presented the calibration curves obtained for the remainder OBS's used in this work. Finally, the OBS concentrations are compared with the TSS concentrations.

5.1. Calculation procedure

The calculation procedure to get an accurate curve to fit the OBS results is explained in this section. The types of curves used to fit the data were the following:

Linear:
$$SSC=p_1\times OBS_{output}+p_2 \tag{5.1}$$

Quadratic:
$$SSC=p_1\times OBS_{output}^2+p_2\times OBS_{output}+p_3 \tag{5.2}$$

Cubic:
$$SSC=p_1\times OBS_{output}^3+p_2\times OBS_{output}^2+p_3\times OBS_{output}+p_4 \tag{5.3}$$

4thorder polynomial:
$$SSC=p_1 OBS_{output}^4+p_2\times OBS_{output}^3+p_3\times OBS_{output}^2+p_4\times OBS_{output}+p_5 \tag{5.4}$$

5thorder polynomial:
$$SSC=p_1\times OBS_{output}^5+p_2\times OBS_{output}^4+p_3\times OBS_{output}^3+p_4\times OBS_{output}^2+p_5\times OBS_{output}+p_6 \tag{5.5}$$

Exponential:
$$SSC=a\times e^{b\times OBS_{output}} \tag{5.6}$$

Twice exponential:
$$SSC=a\times e^{b\times OBS_{output}}+c\times e^{d\times OBS_{output}} \tag{5.7}$$

The parameters of these curves were obtained from the *fit* function of Matlab® (MathWorks, 2015a). This function also provides the goodness-of-fit statistics, described in Table 5.1 and used to evaluate the fit accuracy of each type of curve.

There are two options to fit the data obtained with OBS: fit with one type of curve, or divide the data in sections with different behaviours. The fit of each section is performed separately as was done by several authors (see section 3.1.1).

Table 5.1 - Goodness-of-fit statistics (MathWorks, 2015b).

Parameter	Value	Description
sse	Sum of squares due to error.	Measures the total deviation of the response values from the fit to the response values. It is also called the summed square of residuals. A value closer to 0 indicates that the model has a smaller random error component, and that the fit will be more useful for prediction.
r-square	R-squared (coefficient of determination).	Measures how successful the fit is in explaining the variation of the data. R-square can take on any value between 0 and 1. A value closer to 1 indicates that a greater proportion of variance is accounted for by the model.
dfe	Degrees of freedom in the error.	Number of independent ways by which a dynamic system can move, without violating any constraint imposed on it.
adjrsquare	Degree-of-freedom adjusted coefficient of determination.	Can take on any value less than or equal to 1. A value closer to 1 indicates a better fit.
rmse	Root mean squared error (standard error).	Also known as the fit standard error and the standard error of the regression. It is an estimate of the standard deviation of the random component in the data. A value closer to 0 indicates a fit that is more useful for prediction.

5.2. Fit the data of OBS T8267

Using the data from the sediment concentration scenario correspondent to OBS T8267 (from tests 62 to 122), first was verified the behaviour of its output when the real concentration increased.

In Figure 5.1 is presented the relationship between the OBS output and the real sediment concentration. Here was observed that this relationship was almost linear up to concentrations between 20-30 g/L and non-linear for higher concentrations.

The next step was to choose the best curve to fit the data with only one curve. To do this, on the first attempt, the polynomial curves were considered. In Table 5.2 are presented the goodness-of-fit statistics of four orders of polynomial curves (equations 5.2 to 5.5). Due to the non-linear behaviour of the data, the linear type (equation 5.1) was not used in this case.

The goodness-of-fit of each curve show that, to this type of curve, the best fit was with 5th order polynomial (equation 5.5). This order present the smallest sse, dfe and rmse and the biggest r-square and adjrsquare. However, the results above an output of 2.5 volts are not properly represented by this curve (Figure 5.2a). The second attempt to obtain the best fit was using exponential curves (equations 5.6 and 5.7).

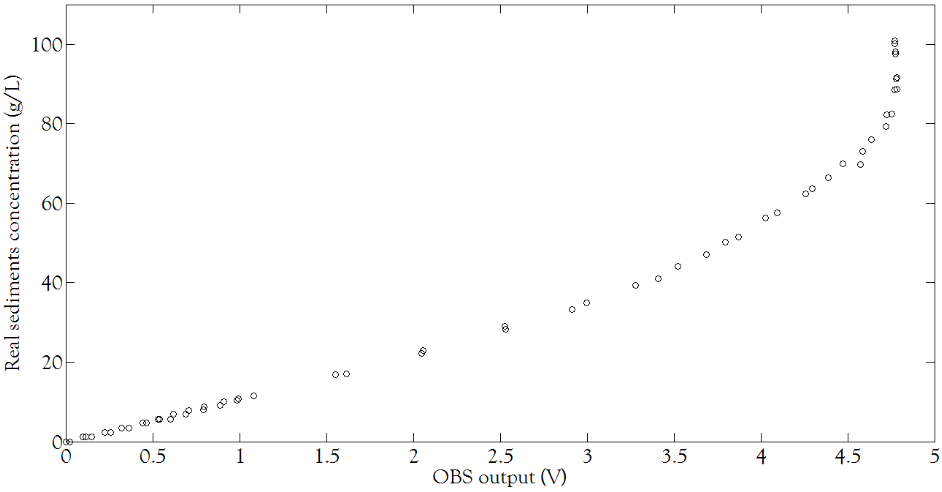


Figure 5.1 - Relationship between OBS T8267 output and the real concentration.

Table 5.2 - Goodness-of-fit statistics for four polynomial orders.

Type	sse	r-square	dfe	adjrsquare	rmse
Quadratic	1575.00	0.98	56	0.98	5.30
Cubic	832.71	0.99	55	0.99	3.89
4th order	628.51	0.99	54	0.99	3.41
5th order	537.18	0.99	53	0.99	3.18

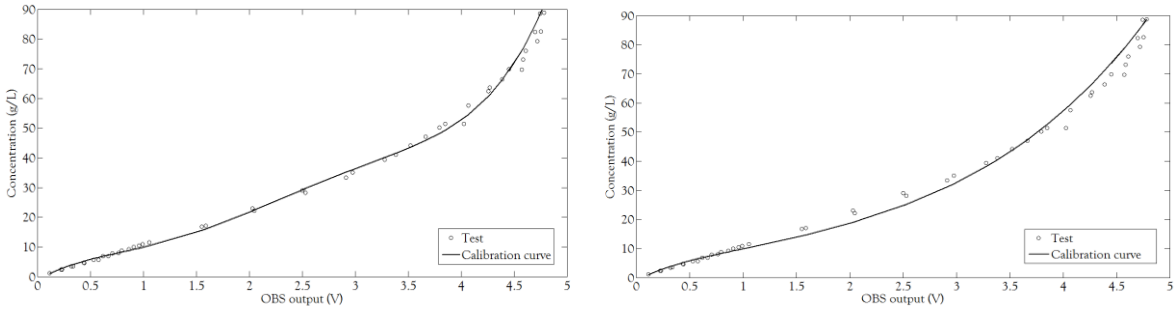
In Table 5.3 are presented the goodness-of-fit statistics of the exponential curves. The best fit was with the twice exponential curve (equation 5.7). This curve presents the smallest sse, dfe and rmse and the biggest r-square and adjrsquare. However, for voltages above 1 volt, the exponential curve deviates from the real concentrations (Figure 5.2b).

Table 5.3 - Goodness-of-fit statistics for exponential curves.

Number of exponents	sse	r-square	dfe	adjrsquare	rmse
1	1104	0.98	57	0.98	4.40
2	894.82	0.99	55	0.99	4.03

Comparing both types of curves, the best fit is obtained with 5th order polynomial. This curve present the smallest sse, dfe and rmse and fits better the data above 1 volt than the twice exponential. However, the 5th order polynomial still present an elevated sum of squares due to error (sse), that should be closer to zero, and deviations for concentrations above

20 g/L (Figure 5.2a). Thus, it was necessary study a second option to fit the data. Given that, the curve was divided in two sections. The first step was to choose the limits of the sections.



a) Polynomial **b) Exponential**

Figure 5.2 - Best fit with only one curve.

Looking again to the Figure 5.1, it seems that between 20 and 30 g/L the data change its behaviour. Given that, the limits of section assumed were 20, 25 and 30 g/L. To these concentrations, because there were no tests related, the Matlab® script was programmed to adopt as limit, the real sediment concentration of the closest test. The best curves below the limit concentration were the quadratic and cubic polynomial (Table 5.4) and above the limit concentration was the twice exponential (Table 5.5).

Table 5.4 - Best goodness-of-fit statistics for the first section (below the real concentration).

Real concentration (g/L)	sse	r-square	dfe	adjrsquare	rmse	Curve
20	2.12	1.00	25	1.00	0.29	Quadratic
25	2.45	1.00	26	1.00	0.31	Cubic
30	2.56	1.00	28	1.00	0.30	Cubic

Table 5.5 - Best goodness-of-fit statistics for the second section (above the real concentration).

Real concentration (g/L)	sse	r-square	dfe	adjrsquare	rmse	Curve
20	36.16	1.00	25	1.00	1.20	Twice exp.
25	31.89	1.00	23	1.00	1.18	Twice exp.
30	31.38	1.00	21	1.00	1.22	Twice exp.

For the limits considered, it was not possible to get the best goodness-of-statistics simultaneously for the curve below and above the same limit and so, it was not easy to choose the best limit to be considered. In the first section, 20 g/L presented the best sse, dfe and rmse while all limits have the same r-square and adjrsquare. On the other hand in the second section, all have the same r-square and adjrsquare, the 30 g/L presented the best sse and dfe and 25 g/L presented the best rmse. Given that, a residual analysis was performed to verify how the fit was influenced by the different limits (Figure 5.3).

The residuals are defined as the differences between the known data and the fit to the data at each predictor value. If the residuals appear randomly, they approximate random errors and so the curve obtained fit the data correctly. On the hand, if they present a systematic pattern, the data was fitted poorly (Mathworks, 2015c).

The residuals present a maximum relative variation of 1.82% for 28.20 g/L. The behaviour of this statistic parameter does not present a pattern. The biggest relative variations are between 28.20 and 33.34 g/L and the smallest 82.52 and 88.57 g/L.

In Figure 5.3 are presented graphically the residuals for each limit. The curves associated to each limit, from 0 to 20 g/L and from 50 to 88 g/L are closer (almost overlapped), and from 20 to 50 g/L, more separated. In general, the 20 g/L limit presents a residual average of 0.26 g/L, the 25 g/L of 0.24 g/L and the 30 g/L of 0.23 g/L. Since the curves are more distant between 20 and 50 g/L, it is possible to better observe their behaviour. These, whenever they are more distant from the reference line, the limit of 25 g/L is closer one. This limit was the adopted one.

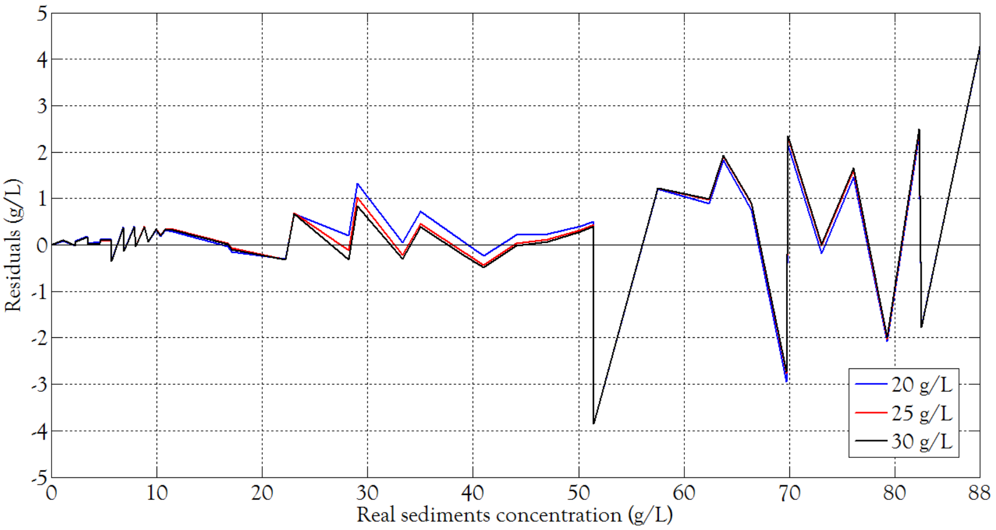


Figure 5.3 - Residuals differences, considering different curve limits.

In Figure 5.4 are presented graphically the curves of each section. These curves fit properly the data in the range concentrations of this work. Given that, the division of the data with different behaviours, is the correct approach to fit the data properly. These curves are represented in equation 5.8 for concentrations below 25 g/L and equation 5.9 for higher concentrations.

$$SSC_{\text{first section}}=0.19\times OBS_{\text{output}}^{3}-0.27\times OBS_{\text{output}}^{2}+10.85\times OBS_{\text{output}}-0.17 \quad \textbf{(5.8)}$$

$$SSC_{\text{second section}}=9.14\times e^{0.45\times OBS_{\text{output}}}+(4.65\times 10^{-15})\times e^{7.38\times OBS_{\text{output}}} \quad \textbf{(5.9)}$$

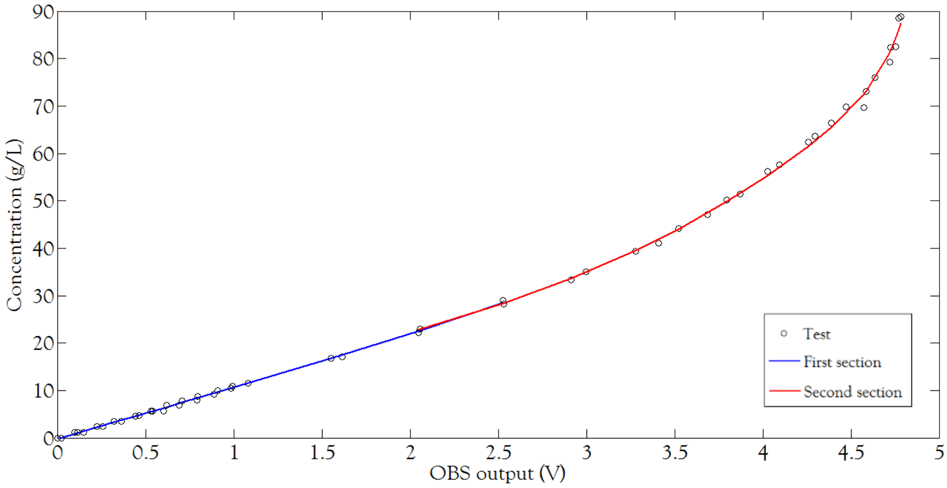


Figure 5.4 - The two sections of the calibration curve.

The last detail to evaluate is the connection between the curves, to guarantee continuity of the sections. To define the transition zone, Matlab® was programmed to look for the OBS output obtained in the two closest tests, below and above the limit. For this OBS, these tests correspond to an output of 2.05 and 2.53 volts and real concentrations of 22.33 and 28.31 g/L respectively. To the voltages in this zone, the correspondent concentrations are the average of the ones obtained in each curve.

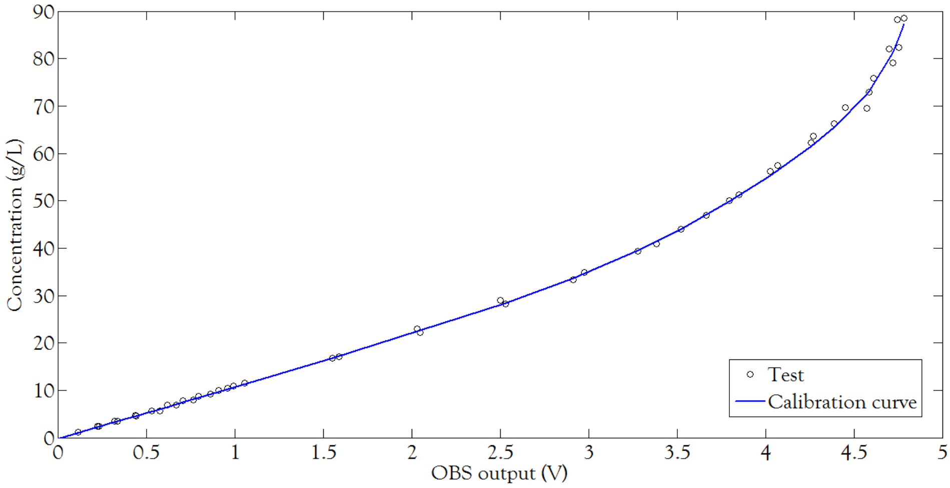


Figure 5.5 - OBS T8267 final calibration curve.

In conclusion, for the first section that goes from 0 to 2.05 volts the correspondent curve is presented in equation 5.8. For the transition zone, which goes from 2.05 to 2.53 volts, the concentrations obtained are the average of the concentrations obtained with each curve. Finally, the second section goes from 2.53 volts up to the maximum voltage (4.78 volts) and the correspondent curve is presented in equation 5.9. The behaviour of the final calibration curve is presented in Figure 5.5.

5.3. Calibration curves of the remainder OBS's

Following the calibration procedure of the OBS T8267 and the correspondent tests of each remainder OBS, the calibration curves and its respective limits (in volts) are:

	$SSC_{\text{first section}}=0.08\times OBS_{output}^{3}-0.03\times OBS_{output}^{2}+10.81\times OBS_{output}-0.05$	$0< v <2.15$	**(5.10)**
T8285	Average of both equations.	$2.15< v <2.53$	
	$SSC_{\text{second section}}=9.42\times e^{0.44\times OBS_{output}}+(1.70\times 10^{-15})\times e^{7.38\times OBS_{output}}$	$2.53< v <4.89$	**(5.11)**
	$SSC_{\text{first section}}=0.19\times OBS_{output}^{3}-0.45\times OBS_{output}^{2}+10.98\times OBS_{output}+0.39$	$0< v <2.16$	**(5.12)**
T8276	Average of both equations.	$2.16< v <2.57$	
	$SSC_{\text{second section}}=(1.90\times 10^{-15})\times e^{7.35\times OBS_{output}}+9.5\times e^{0.44\times OBS_{output}}$	$2.57< v <4.91$	**(5.13)**
	$SSC_{\text{first section}}=0.05\times OBS_{output}^{3}+0.41\times OBS_{output}^{2}+9.94\times OBS_{output}+0.01$	$0< v <2.13$	**(5.14)**
T8282	Average of both equations.	$2.13< v <2.55$	
	$SSC_{\text{second section}}=(1.89\times 10^{-15})\times e^{7.60\times OBS_{output}}+8.66\times e^{0.48\times OBS_{output}}$	$2.55< v <4.75$	**(5.15)**
	$SSC_{\text{first section}}=0.22\times OBS_{output}^{3}-0.15\times OBS_{output}^{2}+10.25\times OBS_{output}-0.04$	$0< v <2.17$	**(5.16)**
T8287	Average of both equations.	$2.17< v <2.56$	
	$SSC_{\text{second section}}=8.60\times e^{0.48\times OBS_{output}}+(1.67\times 10^{-15})\times e^{7.63\times OBS_{output}}$	$2.56< v <4.78$	**(5.17)**
	$SSC_{\text{first section}}=0.25\times OBS_{output}^{3}-0.35\times OBS_{output}^{2}+10.39\times OBS_{output}-0.03$	$0< v <2.21$	**(5.18)**
T8284	Average of both equations.	$2.21< v <2.61$	
	$SSC_{\text{second section}}=(1.52\times 10^{-15})\times e^{7.49\times OBS_{output}}+8.76\times e^{0.47\times OBS_{output}}$	$2.61< v <4.85$	**(5.19)**

	$SSC_{\text{first section}}=0.14\times OBS_{\text{output}}{}^{3}+0.18\times OBS_{\text{output}}{}^{2}+9.91\times OBS_{\text{output}}-0.05$	$0< v <2.16$	**(5.20)**
T8277	Average of both equations.	$2.16< v <2.56$	
	$SSC_{\text{second section}}=(2.75\times 10^{-15})\times e^{7.36\times OBS_{\text{output}}}+9.34\times e^{0.45\times OBS_{\text{output}}}$	$2.61< v <4.88$	**(5.21)**
	$SSC_{\text{first section}}=0.13\times OBS_{\text{output}}{}^{3}+0.21\times OBS_{\text{output}}{}^{2}+10.04\times OBS_{\text{output}}-0.03$	$0< v <2.15$	**(5.22)**
T8286	Average of both equations.	$2.15< v <2.53$	
	$SSC_{\text{second section}}=(2.2\times 10^{-15})\times e^{7.33\times OBS_{\text{output}}}+9.46\times e^{0.45\times OBS_{\text{output}}}$	$2.53< v <4.90$	**(5.23)**

The calibration curves present similar voltages in each limit. The limit of the first section varies between 2.13 and 2.21 volts, in the transition zone between 2.53 and 2.61 volts and the second section (and maximum voltage) between 4.75 and 4.91 volts.

5.4. Comparison between equipment and real concentrations

The goal of this work was to perform an OBS calibration similar to Downing and Beach (1989) in order to obtain closer concentrations between the OBS and the TSS. For the comparison between the equipment's it was used the OBS T8267 as an example. In Figure 5.6 are presented the concentrations obtained with this OBS (application of the calibration curve obtained in section 5.2) and with the TSS. The ideal was to obtain concentrations close or on the reference line, also drawn in Figure 5.6.

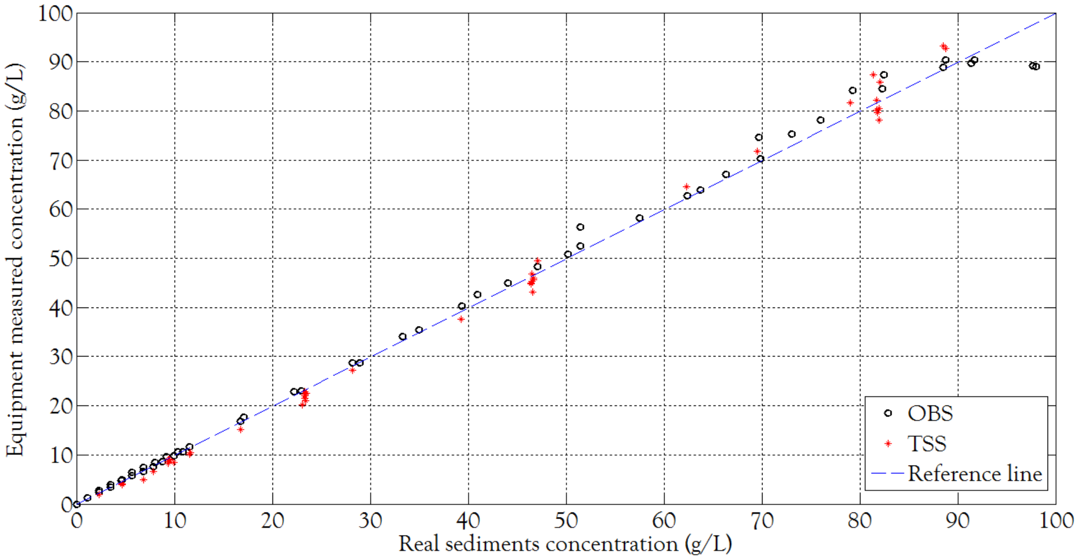


Figure 5.6 - Comparison between concentrations obtained with TSS, OBS T8267 and real sediment concentrations.

In general, up to concentrations of 50 g/L both equipment's are close from the reference line, while for concentrations above the results are more dispersed. However, OBS seems to be the equipment that present concentrations closer from the real, at least till 90 g/L, when reaches the saturation. To better analyse the data presented in Figure 5.6, was calculated the deviation of the concentration of each equipment, from the real sediment concentrations. In Figure 5.7 are presented the deviations of each equipment in percentage.

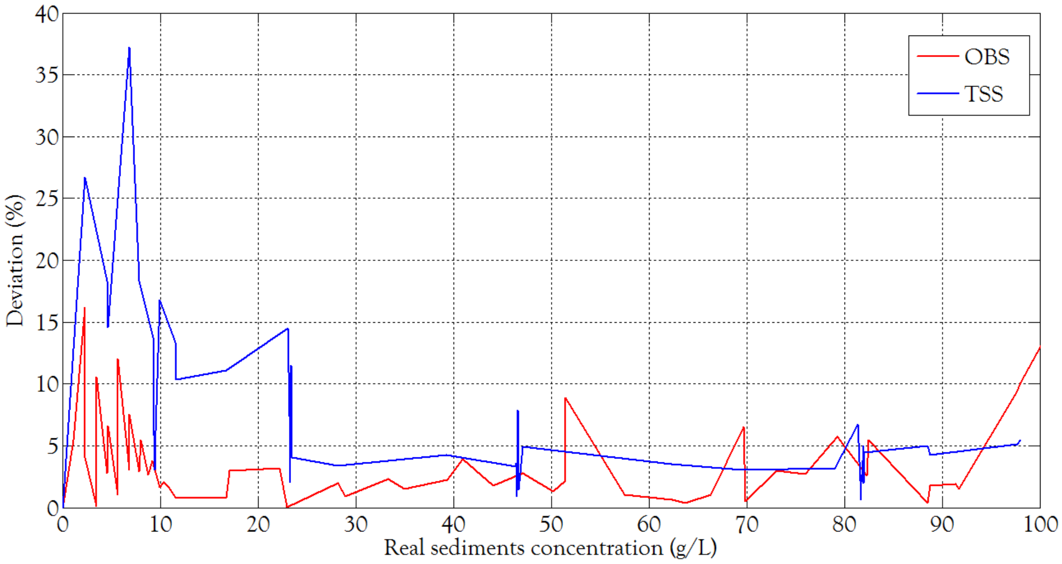


Figure 5.7 - Deviations related with the concentration measured by each equipment.

It is clear that the OBS is the most accurate equipment till 90 g/L, as said before, when reaches the saturation. This equipment, till reaching the saturation, present an average of deviations of 3.31% and maximum of 16.15%. On the other hand, the TSS has an average deviation of 7.59% and maximum of 37.22%. In both equipment's, the maximum deviations occur for concentrations between 0 and 10 g/L and between 10 and 30 g/L, they decrease considerably. Above 50 g/L, the concentrations of both equipment's got closer until the OBS saturation (around 90 g/L). In all range of concentrations, the TSS is the equipment that presents the biggest deviations, being only slightly exceeded by OBS four times (between 50 g/L and the OBS saturation). However being the OBS the most accurate equipment, it is recommendable the use of more than one type of equipment's to measure the sediment concentration, either in field or laboratory (including equipment's calibration).

Chapter 6

Tested experiments

6. Tested experiments

In this chapter, first were described two corrections applied to the real sediment concentration in the tank. In second, it was verified the functionality of the equipment's. In here it was analysed the stability and repeatability of the OBS output, the proper voltage to apply on the engine to be sure that the sediments were in suspension in high concentrations and finally the adequate intake velocity to pump the required sample.

Then the OBS applicability conditions and the TSS trapping efficiency were verified. In these last sections, it was analysed how the real sediment concentration and the concentration obtained with OBS were related and, if there was any influence of the incident laboratory light and the bubbles. Finally, it was verified how the suspended sediment concentration obtained with TSS and the real ones, prepared in the tank, are related. In this part of the chapter was applied to the OBS data presented graphically, a moving window Matlab® function in order to eliminate the majority of the outliers.

To simplify the presentation of the data, the calibration curves obtained in the previous chapter were applied to the correspondent OBS output measured in time, transformed in concentrations and presented as its time average value. Also, to obtain the most accurate OBS output, the concentrations presented on the tables of this section were corrected by subtracting the "noise", obtained from the OBS measurements without sediments (see section 4.3).

6.1. Corrections applied to the real sediments concentration

While performing the tests, TSS samples were taken from the tank and sand was added. Due to this, was necessary to correct twice the concentration in the tank. The first correction was applied to the weight of the sand inside the tank. This correction consisted in subtract the weight of the dry sand obtained from the TSS experiments, to the one added in the following OBS experiment. The second correction was applied to the water volume. The tank present a capacity for 85.72 liters of water. However, the addition of sand increase the water level being the tank capacity, for high concentrations, not enough. Due to the water volume importance in the control of the real concentration, it was necessary to verify how many millilitres were apparently added for each gram of sand.

In Table 6.1 is presented how the volume varies when an amount of sand is added to the water. The mean volume variation correspondent to the last results was 0.42 mL for each gram of sand added to the water. So, knowing the amount of sand in the tank, the correct volume of water is the 85.72 liters less the variation caused by the sand in the tank.

Table 6.1 - Volume variation in the experimental tank.

Sand (g)	Initial volume (mL)	Final volume (mL)	Volume variation per gram of sand (mL)
45.3	180 (only water)	198	0.40
101.6	198	220	0.39
145.7	220	240	0.45
207.8	240	267	0.43
259.2	267	288	0.41

6.2. Equipment's functionality verifications

As referred in section 4.3, before start the main experimental procedure, was necessary to perform, for each equipment, four verifications (two referred to the OBS, one to the propeller and another to the TSS) to verify if there is any problem with the equipment's, make the experiment accurate and performed in an acceptable period of time. In the OBS, the parameters verified were the stability and the repeability. In the propeller, the voltage applied in the engine and in the TSS, the adequate intake velocity was verified.

6.2.1. OBS output stability

The analysis of the OBS output signal stability was important to verify how long the OBS could be measuring without a relative variation in the sediments concentration of 1% maximum. So, if there was a variation equal or bigger than this value, the duration of the test should be adjusted.

As explained in section 4.3, before plug the TSS the duration of each OBS test was 10 minutes, and it was necessary to verify if the signal was stable in that period of time and if it was possible to decrease it to 300 seconds (5 minutes).

The relative variation between the results of the two test durations decreased with increase of the concentration. The maximum relative variation obtained was 0.71% when the real sediments concentration was 5 g/L. Thus, all tests presented in Table 6.2 verify the relative variation limit settled previously. In Figure 6.1 is observed that there are no important variations in the concentration between the beginning and the end of the tests, that could induce a lack of stability in OBS output. Given this, the OBS output was considered stable.

Table 6.2 - OBS output stability.

Real sed. concentration (g/L)	Test	Duration (s)	Average concentration (g/L)
5	7	300	5.35
		600	5.32
10	13	300	10.79
		600	10.73
25	17	300	27.07
		600	27.06

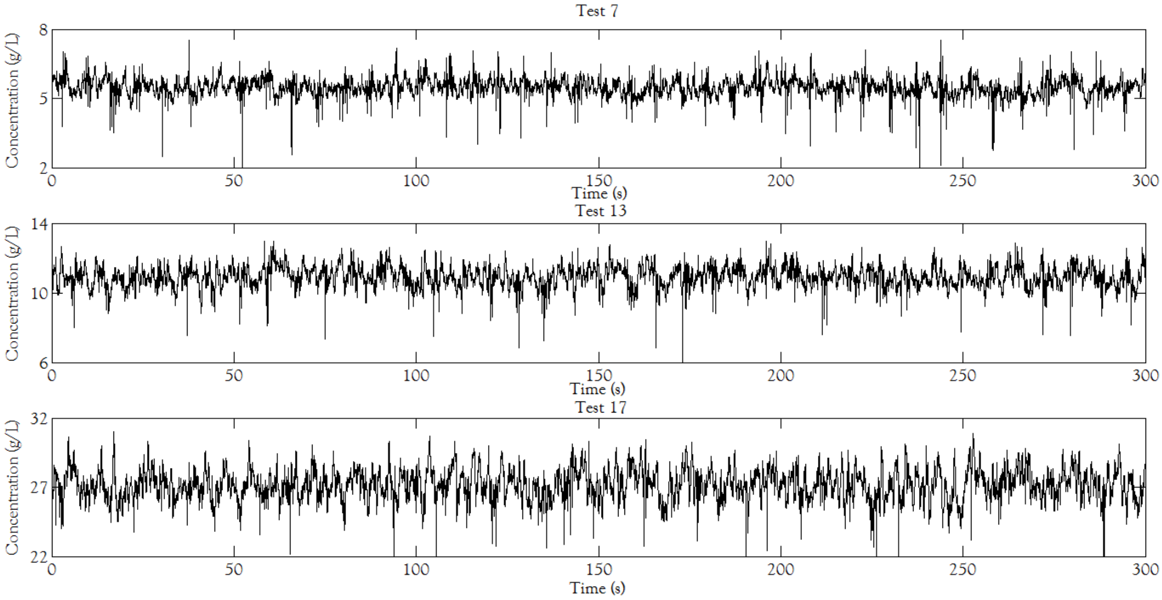


Figure 6.1 - Variation of the concentration in 300 seconds on tests 7, 13 and 17, corresponding respectively to 1 g/L, 10 g/L and 25 g/L in the tank.

6.2.2. OBS output repeatability

The repeatability was verified to confirm if the tank components were working properly and the concentrations measured in different runs of tests with similar conditions is the same (no leaks and similar sediments distribution for different tests). The analysis in section 6.2.1 verified that the OBS had a stable output, so the average concentrations presented in Table 6.3 were obtained considering tests performed in 300 seconds. The tests 2, 7, 13 and 17 are from the first run, the tests 21, 25, 30 and 33 are from the second run and the tests 37, 41, 46 and 50 are from the third.

Table 6.3 - OBS output repeatability.

Real sed. concentration (g/L)	Test	Average concentration (g/L)
1	2	0.89
	21	1.16
	37	1.35
5	7	5.35
	25	5.37
	41	5.98
10	13	10.79
	30	11.25
	46	11.71
25	17	27.07
	33	27.83
	50	28.36

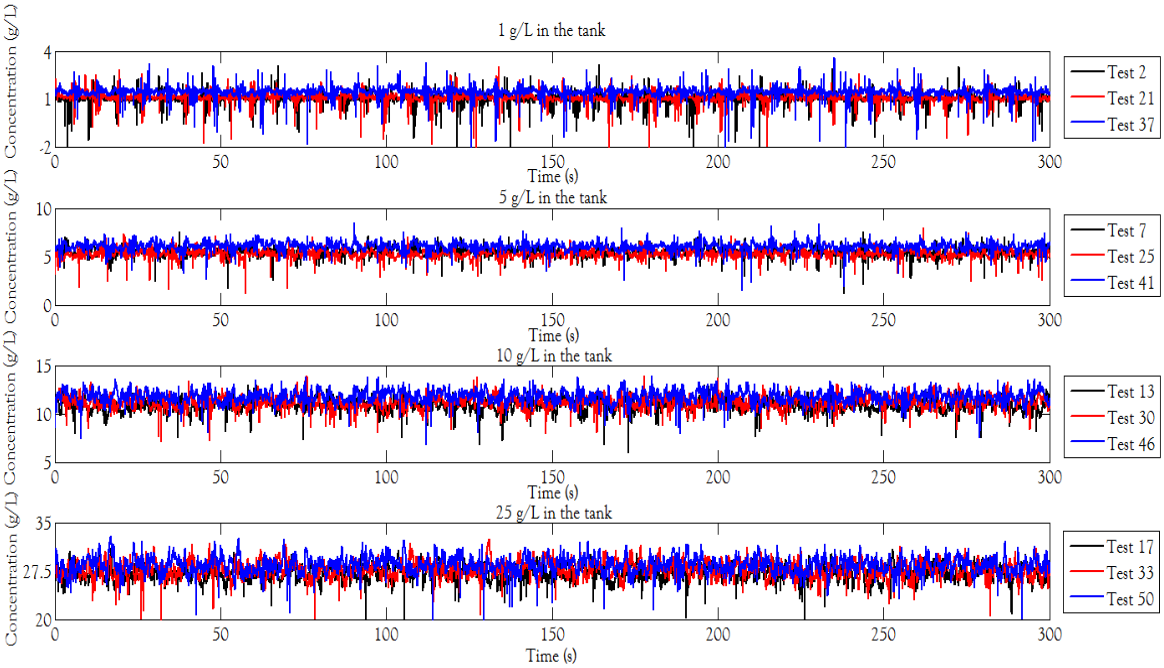


Figure 6.2 - Concentration measured with the OBS for 3 different tests to each one of the real concentration considered (1 g/L, 5 g/L, 10 g/L and 25 g/L).

The biggest deviation related to the average concentration was 26.08%, correspondent to test 37. The group with tests 37, 41, 46 and 50 present the biggest deviations that decrease with the real sediment concentration increase. On the contrary, the group with 2, 7, 13 and 17 present the smallest deviations, which decrease from 1 to 5 g/L and increase again for real sediment concentrations above 5 g/L. On the group with 21, 25, 30 and 33, the deviations increase and decrease several times with the concentration increase. The biggest relative variation was 46.42%, correspondent to a real sediment concentration of 1 g/L.

This value decreases when the real sediment concentration increase (the deviations get closer). In the group of tests with the biggest deviations, the concentrations were probably influenced (*e.g.* bubbles). However this error decreases and at 25 g/L is almost equal to the correspondent tests on that concentration.

In Figure 6.2 is represented the variation of the concentration during the time. To each real concentration, the tests present equal concentration limits although the outliers do not occur at the same time (possibility of different tank conditions occur for the same concentration).

6.2.3. Engine voltage

At high concentrations it becomes impossible to observe if the sediments were all in suspension. Figure 6.3 illustrates the visibility in the tank when the concentration was 56 g/L. To verify if the voltage applied in the engine used to control the propeller spinning that keeps the sediments suspended (as explained in section 4.1.2) was the correct, for a concentration of 70 g/L inside the tank, were performed tests applying three different voltages. In Table 6.4 are presented the average concentrations obtained for this scenario.

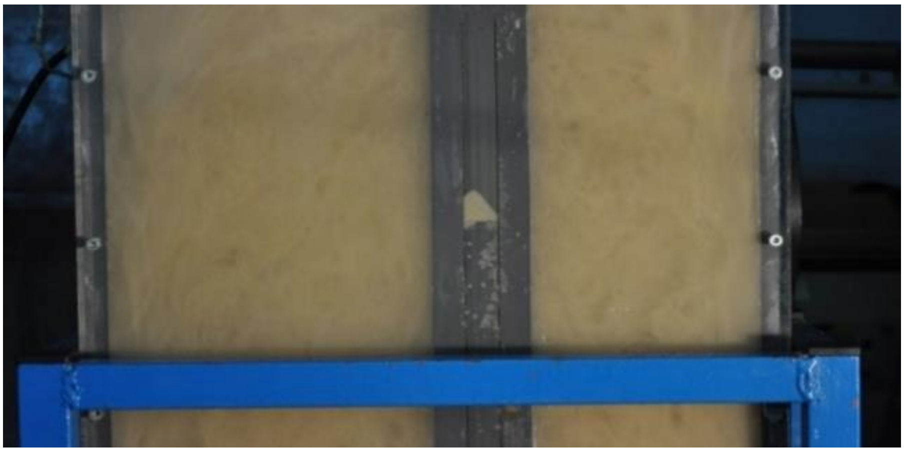


Figure 6.3 - View from the outside when the concentration inside the tank was 56 g/L.

The smallest deviation related to the average measured concentration obtained was 1.62%, correspondent to when 30 volts are applied on the engine. It was observed that bigger the voltage, bigger the deviation and also bigger the turbulence in the tank (not let the sediments get in suspension properly and bigger production of bubbles).

Between the three voltages there was a relative variation of 3.22%. The variation of the concentrations in time is presented in Figure 6.4 and show that, with 30 volts, the average concentration is the closest from the real concentration.

Apply 30 volts in the engine is the accurate option due to present a smaller deviation than the relative variation, less turbulence than the others voltages and in time the closer results to the real sediments concentration in the tank.

Table 6.4 - Analysis of the influence when varying the voltage applied on the engine with a real concentration of 70 g/L in the tank.

Real sed. concentration (g/L)	Test	Voltage applied in the engine (V)	Average concentration (g/L)
70	313	30	68.89
	325	40	66.63
	326	50	66.98

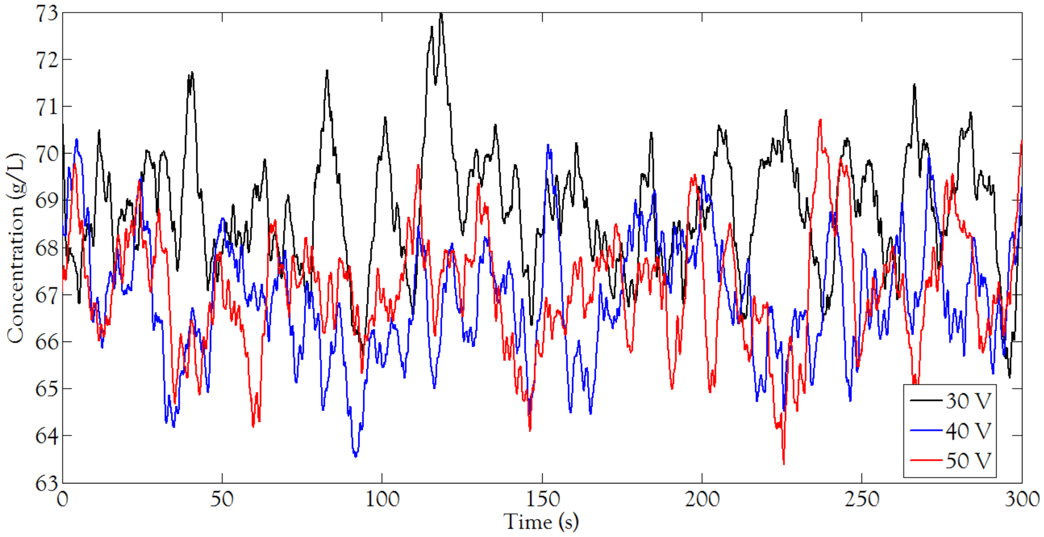


Figure 6.4 - Influence of the voltage applied in the engine.

6.2.4. TSS intake velocity

To start the TSS tests (see section 4.3), was studied which was the proper number of rotations per minute (RPM) to apply in the pump to get a sample around 3000 g (correspondent to a third of the bucket capacity), without compromising the tests. This parameter is dependent from the intake velocity which is obtained by applying the equation 6.1.

$$\text{Intake velocity} = \frac{\left[\frac{\text{Weight}_{\text{sample}}}{\text{time}}\right]}{\pi \times (\emptyset_{\text{nozzle}} \times 0.5)^2} \quad (\text{m/s}) \qquad \textbf{(6.1)}$$

According to Bosman *et al.* (1987), to get properly a sample with TSS, the intake velocity should be at least three times higher than the ambient flow. The ambient flow velocity was unknown in the present work.

Firstly, was analysed how much time would take to obtain the required sample and the correspondent intake velocity. For these tests, there was no correlation with the real sediments concentration. In Table 6.5 it is presented the relation between the intake velocity and the sample weight. The correspondent tests duration to pump water and sediments is between 96 and 109 seconds. Heavy samples were obtained with bigger intake velocities, meaning bigger RPM. For high RPM it was observed that the nozzle got blocked several times. So the better option was to adopt smaller intake velocities.

In Figure 6.5 are presented all tests performed with TSS. Now, there is a relation between the TSS concentrations and with the real ones and also the correspondent intake velocity.

Table 6.5 - Correlation between intake velocity and the sample obtained.

Sample (g)	Intake velocity (m/s)	Duration (s)	RPM
2594.00	3.82	96	81
2990.50	3.88	109	90
3029.00	4.01	107	100
2951.00	4.05	103	110
2970.00	4.20	100	130
3161.00	4.30	105	150

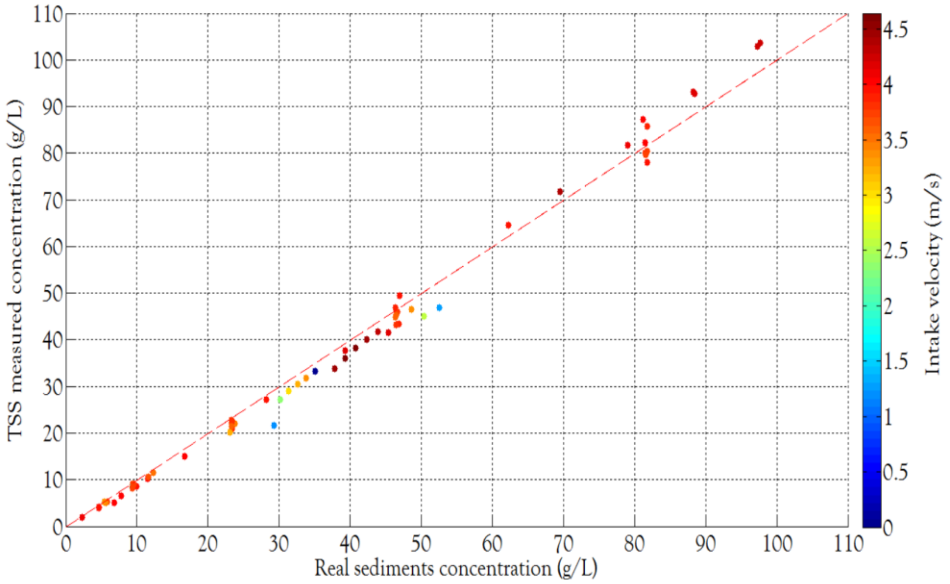


Figure 6.5 - Relationship between TSS concentration and real concentration in the tank, depending on the intake velocity variation.

Intake velocities below 3.5 m/s have always produced samples with smaller concentrations than the real ones. On the contrary, intake velocities above 4 m/s can produce samples with smaller concentrations up to concentrations around 50 g/L and bigger above this concentration. The intake velocities that produced samples with concentrations closer from the real ones were the velocities between 3.5 m/s and 4 m/s. As well as in the first tests with TSS (see Table 6.5), with bigger intake velocities the samples were obtained faster, but it also increased the probability of the nozzle get blocked, which spoiled the samples and the test had to be repeated. With low intake velocities the sampling was always inefficient and the pump duration was elevated. Given that, the ideal intake velocity was placed between 3.5 and 4 m/s. These velocities provided samples with the weight required, in almost two minutes and without compromise the sample. Looking again to results of Table 6.5, the RPM that verified all the parameters referred previously was 90, being the adopted one.

6.3. OBS applicability verifications

As referred in section 3.1, the OBS shown to have several behaviours depending on the sample characteristics and the surrounding environment. Given that, it was necessary to perform three verifications to be sure that the results were not spoiled. So, the verifications were the sediments concentration, the incident light and the bubbles.

6.3.1. Sediments concentration

Sediments concentration is the most important effect on OBS output and from where is obtained the calibration curve. In section 3.1.1 were referred several authors that studied the behaviour of the OBS output for different types of sediments. In all the sediments types it was observed that the concentration increased almost linearly up to a certain concentration (depending of the type of sediments) and then decreased, due to the saturation of the OBS sensor.

In Table 6.6 are presented some of the concentrations measured with each OBS related to the real concentrations in the tank. Note that, was not possible to group the concentrations measured with all OBS's, and relate them with the same real sediment concentrations (the TSS samples did not have exactly the same weight). Thus, each real sediment concentration presented in this table is the average of the real sediment concentrations of all OBS's.

The maximum deviation related to the average measured concentration was 66.67%, correspondent to OBS T8276 and real sediment concentration of 2.35 g/L. The following deviation was much smaller (9.56%) and correspondent to OBS T8267 and real sediment concentration of 97.61 g/L, in which, the OBS had already shown signs of saturation.

Table 6.6 - Average concentrations obtained in each calibrated OBS.

Real sed. concentration (g/L)	Average concentration (g/L)							
	OBS T8267	OBS T8285	OBS T8276	OBS T8282	OBS T8287	OBS T8284	OBS T8277	OBS T8286
2.35	2.45	2.42	1.41	2.38	2.43	2.40	2.26	2.37
9.49	9.80	9.44	9.12	9.54	9.47	9.75	9.57	9.48
23.16	22.91	24.01	23.66	23.51	23.60	23.82	23.98	24.13
34.35	34.14	34.54	33.95	34.14	34.75	35.26	34.69	35.24
40.36	40.25	40.62	40.73	40.67	40.61	40.58	40.93	41.03
69.42	74.60	69.39	69.85	70.35	70.50	70.46	69.29	68.79
91.28	90.33	90.14	90.66	93.06	94.44	92.73	95.16	94.34
97.61	89.09	90.11	90.31	92.56	94.42	91.98	95.69	95.24

In general, the smallest deviations were correspondent to real sediment concentrations between 34.35 and 69.42 g/L. The OBS that present, in general, the biggest deviations is the T8267 and the smallest the T8282.

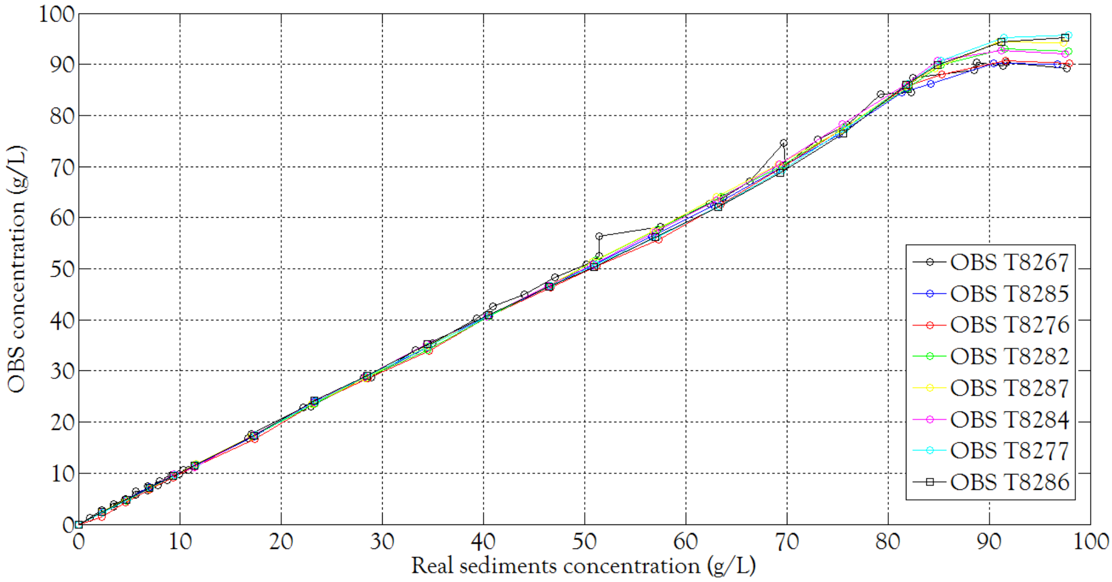


Figure 6.6 - Concentrations for all tests performed with the OBS's used in the experiments.

The maximum relative variation between OBS's was 44.26%, correspondent to the real sediment concentration of 2.35 g/L. This value decreases until 1.93%, when the real sediment concentration was 40.36 g/L, increases to 8.37% (correspondent to 69.42 g/L) and decreases to 5.5%, when the sensors start showing signs of saturation. With the exceptions of the real sediment concentrations of 2,35 g/L to OBS T8276 and 69.42 g/L to OBS T8267, the remainder biggest deviations (above 5%) are correspondent to

97.61 g/L, when the majority of the tested OBS's are saturated. The OBS saturation corresponds to the maximum sediments concentration followed by the signal decrease. The saturation was observed at real concentrations of 97.61 g/L in OBS's T8277 and T8286 and the remainder OBS's at 91.28 g/L.

In general, the calibration curves suit well the results obtained in each OBS (Figure 6.6). Deviations were observed while the concentration increases in OBS T8267, probably also a result of the bigger amount of tests performed with this OBS (appearance of deviated tests). The separation between the marks increases from 50 g/L up to the saturation probably due to the exponential behaviour of the signal. So, closer is the OBS from the saturation, worst its lecture is and higher the error chance.

6.3.2. Incident laboratory light

The OBS detects the near-infrared light (NIR) scattered from a sample (see section 2.1). If the exterior conditions produce an incident light with strong near-infrared rays (*e.g.*, the sun), the OBS output can be affected. So, it was verified if the laboratory light conditions could affect significantly the OBS output in this work. To verify this, tests with a spotlight on and directed to the tank and others with the spotlight off were performed (see section 4.3).

Table 6.7 - Incident light influence.

Real sed. concentration (g/L)	Test	Light	Average concentration (g/L)
1	64	On	1.11
	97	Off	1.37
10	74	On	10.69
	105	Off	10.42
28	77	On	28.77
	109	Off	28.24

The results presented in Table 6.7 show that, there is no significant influence of the laboratory light in the concentrations obtained with OBS. In these concentrations the maximum relative variation was 26.18%, correspondent to 1 g/L, decreasing considerably in the following real sediment concentration (to 2.68%) and continuing decreasing to 1.88%, when the real sediment concentration was 28 g/L. In consequence, the biggest deviation is associated to the biggest relative variation (deviation of 27.19%, test 97). This test was performed with the spotlight off. The remainder tests from this scenario present deviations below 10.05%, and until the real sediment concentration of 10 g/L these tests, presented bigger deviations than spotlight on tests. Above this value, the situation inverted and were obtained bigger deviations with the spotlight on.

In Figure 6.7 are represented the variation of the concentrations to the tests presented in Table 6.7. With the exception of the tests related to a real sediment concentration of 1 g/L, that presented the biggest relative variation, the remainder concentrations presented, in time, imperceptible differences between the correspondent tests.

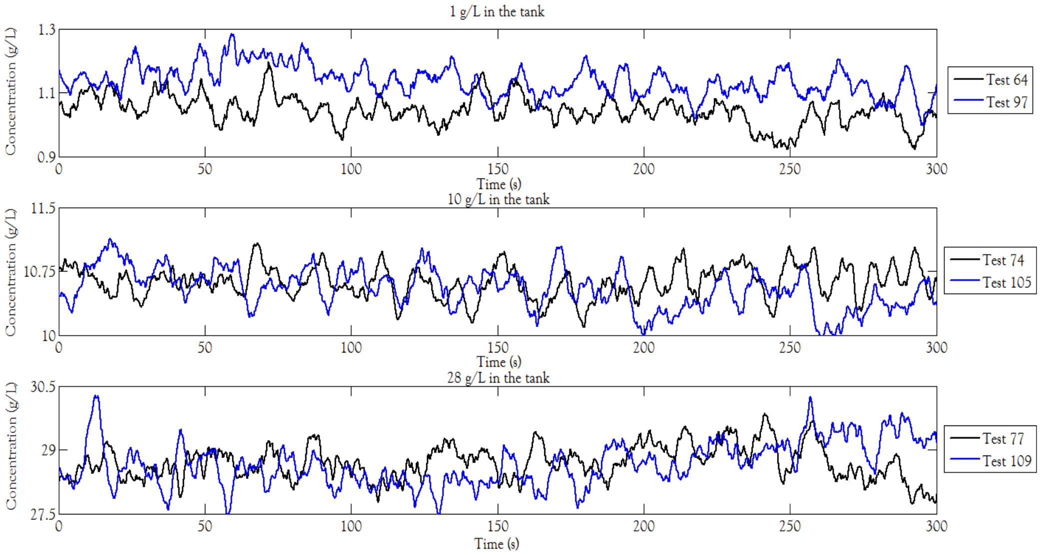


Figure 6.7 - Influence of the incident light for real sediments concentrations of 1, 10 and 28 g/L.

6.3.3. Bubbles

Many authors have documented interferences in OBS output produced by bubbles (see section 3.1.6). In this work, it was not possible to eliminate completely the bubbles from the experiments. Given this, it was necessary to verify if the residual amount of bubbles was not changing importantly the OBS output.

It was only possible to observe clearly the bubbles in the tank up to concentrations of 25 g/L. For concentrations above, its control was done by stopping the propeller and verifying the amount of bubbles ascending. There was no control of the bubbles characteristics produced in the tank and consequently, it was not possible to evaluate which type could produce errors in these results.

In Table 6.8 are presented the concentrations of the chosen tests to analyse the influence of the presence of bubbles. The maximum deviation was 25.04%, correspondent to a real sediment concentration of 1 g/L. This deviation decreased with the increase of the concentration in tests where bubbles were observed. Tests that presented the residual amount, the biggest deviation was correspondent to 5 g/L (14.61%). Tests where bubbles were observed, always presented bigger deviations than the ones that only presented the residual amount. The maximum relative variation was 22.24%, when the real sediments concentration was 1 g/L and decreased considerably (to 5 g/L was only 0.28%) with the increase of the real sediment concentration.

Table 6.8 - Presence of bubbles influence.

Real sed. concentration (g/L)	Test	Presence of bubbles	Average concentration (g/L)
1	63	Observed	1.33
	64	Residual	1.11
5	68	Observed	5.87
	69	Residual	5.86
25	17	Observed	27.05
	18	Residual	26.87

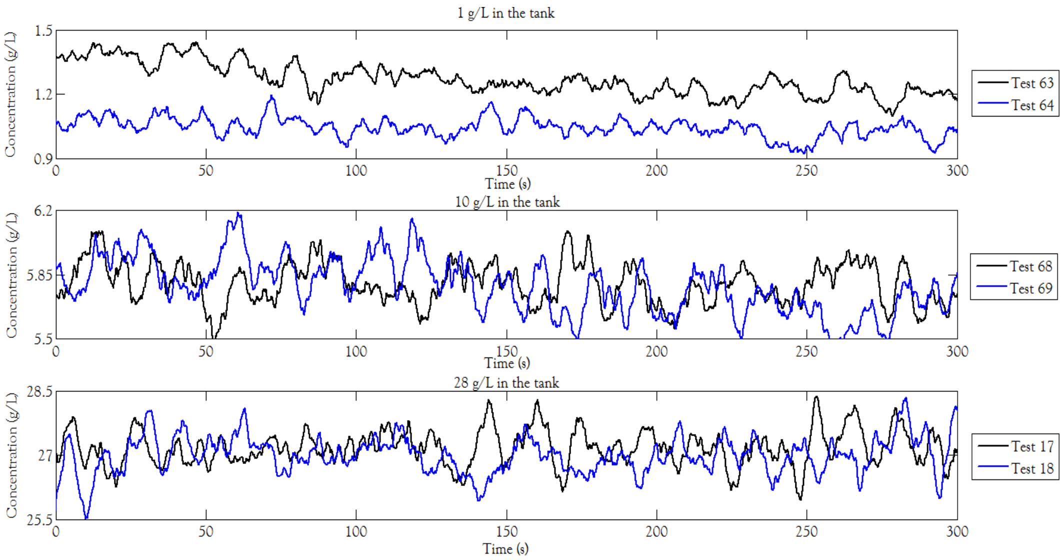


Figure 6.8 - Bubbles influence for real sediment concentrations of 1, 10 and 28 g/L.

In Figure 6.8 is presented the variation of the concentration in time. The difference between the concentrations was clear to observe for the real sediments concentration of 1 g/L, but for concentrations above 5 g/L the differences, are imperceptible in time.

6.4. TSS trapping efficiency verification

Bosman *et al.* (1987), in their experiments, performed an analysis in which studied the variation of the trapping efficiency of the TSS (see equation 3.2) with the ratio of the intake velocity and local flow velocity for sediments with different d_{50} (see Figure 3.5). The sediments used in the present work have d_{50} of 0.25 mm (see section 4.2) while Bosman *et al.* (1987) present results for d_{50} of 0.22 and 0.28 mm. For these characteristics, the trapping efficiencies obtained by Bosman *et al.* (1987) were maximum 0.7. For sediments with d_{50} between 0.07 and 0.45 mm, these authors, with the TSS, did not reach a trapping efficiency equal to one (see Figure 3.5). This parameter varied between 0.6 and 0.8, whatever its ratio between the velocities.

Table 6.9 - Real sediment concentration vs. TSS concentration.

Real sed. concentration (g/L)	TSS concentration (g/L)	Trapping efficiency	Standard deviation (g/L)	Number of samples
4.65	3.99	0.86	0.11	2
9.52	8.75	0.92	0.33	6
11.59	10.36	0.89	0.26	2
23.31	21.79	0.94	0.12	7
46.61	45.79	0.98	1.84	8
81.81	81.96	1.00	3.41	7
88.67	92.97	1.05	0.34	2
97.85	103.34	1.06	0.55	2

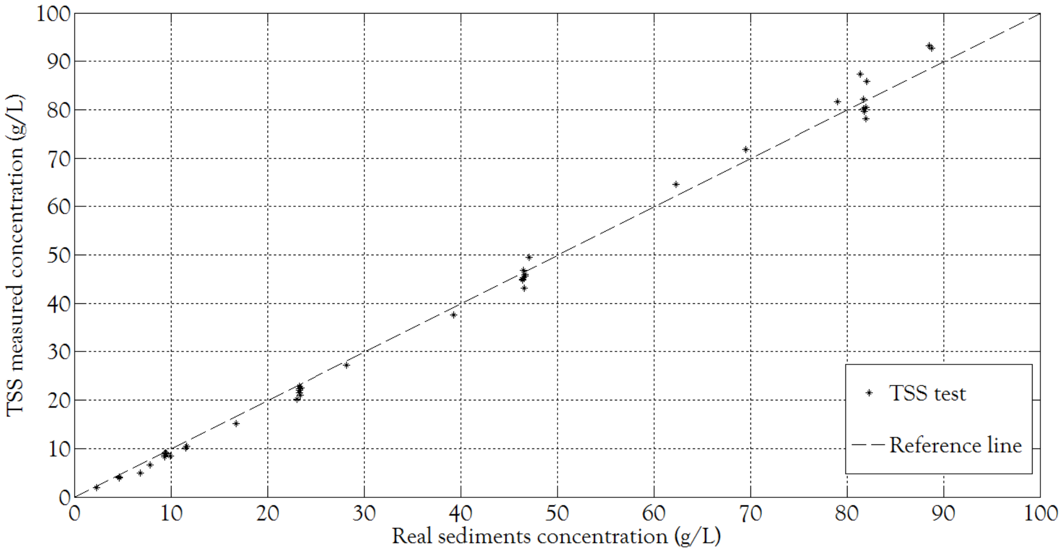


Figure 6.9 - TSS concentration vs. real sediment concentration.

In Table 6.9 are presented groups of TSS concentrations in which, for similar real concentrations, there were performed two or more tests. The average of the trapping efficiencies obtained in this work was 0.96, which is higher than the ones obtained by Bosman *et al.* (1987), but there are some concerns on this conclusion. In Bosman *et al.* (1987) there was a control of the flux velocity while in the present work, there is not. The standard deviation is bigger for the concentrations of 46.61 and 81.81 g/L (maximum).

The relative variation reaches its maximum in 46.61 g/L (13.53%) and minimum to 88.67 g/L (0.54%). The biggest values of the standard deviation are associated to real sediment concentrations where more than two tests were performed.

The tests performed with 90 RPM (see section 6.2.4) are presented in Figure 6.9. In general, for concentrations below 40 g/L were pumped samples with smaller concentrations than the real. Above this concentration the samples presented bigger concentrations than the real with the exception of some samples around 46 and 82 g/L. As was already referred, for these concentrations there were obtained bigger standard deviations and relative variations.

There is not an exact explanation to the variation of the trapping efficiency on TSS. This parameter can vary with the intake velocity, with the sediment concentration, with another unknown parameter or even with the combination of all. To take more conclusions, more tests with this equipment should be performed.

Chapter 7

Final remarks

7. Final remarks

In this section are presented the main conclusions and suggestions to give continuity to this work.

7.1. Conclusions

The study of the suspended sediments transport is highly important to understand the coast and rivers morphodynamics. For instance, if an intervention is required, this knowledge allows the designer to make a decision of which zone to protect. This is not easy to realize and the uncertainty associated to this type of studies is elevated.

This work was proposed given the discrepancies between OBS and TSS results obtained in SINBAD project. SINBAD project was developed between 4th November of 2013 and 23rd January of 2014 in the CIEM (Canal d'Investigació i Experimentació Marítima) wave flume with the main goal of improve the knowledge of the near-bed hydrodynamics and sand transport processes that occur under large-scale irregular non-breaking waves and regular breaking waves in the sheet flow, and also to understand how net suspended transport rates and total net transport rates were related to overall flow and sediment parameters in a wide range of large-scale experiments under sheet flow regime. The discrepancies in the concentrations were assumed as being originated by errors in the OBS. Given this, the goal was to test a calibration procedure, similar to the one proposed by Downing (1989) and verify if these discrepancies remained.

Bibliographic research allowed to know which methods exist to measure the suspended sediment concentration and, to understand how the equipment's associated to each method work. From this research were presented the seven most used methods according to Wren *et al.* (2000). All the equipment's present advantages and disadvantages. The decision on which equipment use is dependent of the conditions of the local where they will be placed and the available budget.

To the equipment's used in this work, an extra research was done in order to know which the parameters that could influence the results were. The number of eventual influences is bigger in OBS, being the sediment concentration the most important effect. However the results are also depend on the sediment characteristics (type of sediment, dimension, shape and mineral composition) and the surrounding environment (light, bubbles, water color, chemical and biological fouling and fishes and bugs). On the other hand, TSS presents influence on the nozzle direction and diameter, ratio between the intake velocity and ambient water flow velocity and sediments dimension. According to Bosman *et al.* (1987) the nozzle should be directed normal to the ambient water flow and the intake velocity three times higher than the previous one. This equipment is moderately sensitive to the sediments dimension. Note that, these experiments were the performed with 3 mm diameter nozzles (the same as this work), so the results can be slightly different for others diameters.

The calibration procedure on this work was similar to the one performed by Downing and Beach (1989). During the experiments were tested eight scenarios (five for OBS, one for the engine and two for TSS). The first four scenarios (OBS output stability, OBS repeability, engine voltage and TSS intake velocity) were used to verify if the equipment's were properly working and to improve the calibration procedure (decrease the duration, number of tests, voltage applied on the engine and intake velocity in TSS). The remainder scenarios were used to verify the equipment's applicability. In OBS the influence of the sediment concentration, the incident light and the bubbles were verified while in TSS, was the trapping efficiency.

The OBS T8267 sediment concentrations were used to get to an accurate calibration curve. These results presented different behaviours when the concentration increased and given that, were tested two different options to fit the data: to consider one type of curve or divide the data in sections with different behaviours and fit them separately. The curves applied were the polynomial and the exponential with different degrees.

The OBS output showed to be affected differently by the sediment concentration up to concentrations between 20 and 30 g/L and up to the saturation, at 88 g/L. With one curve, the best fit was obtained with the 5th order polynomial. However, graphically was observed that this curve did not fit properly the data above 2.5 volts. With two sections, the best fit was obtained with cubic polynomial till voltages of 2.03 volts, a transition zone between 2.03 and 2.53 volts and twice exponential curve from 2.53 till 4.78 volts (saturation of the sensor). Comparing the two types of fitting, the last one is the best, due to the possibility of divide the data with different behaviours and fit each section with the appropriated curve. This type of fit was applied in all OBS's used in this work.

As referred before, the main goal of this work was to obtain closer concentrations between the OBS and the TSS. The concentrations obtained verified that for concentrations bellow 90 g/L, in general, the OBS deviations from the real sediment concentrations were smaller than the TSS (only exceed four times, for concentrations above 50 g/L). The maximum deviation of OBS (up to saturation) was 16.15% and of TSS was 37.22%. These maximum deviations occurred in both equipment's when the real sediment concentration was between 0 and 10 g/L. The mean deviation of OBS (up to saturation) was 3.31% and of TSS, 7.59%. Between 50 and 90 g/L, the deviations of both equipment's presented closer percentages. After saturation, the deviation with OBS increased with the real sediment concentration while the TSS did not suffer from saturation problems (at least with the range considered on this work). It was clear that the OBS was the most accurate equipment. However, to avoid errors, it is recommendable to use more than one type of equipment to measure the suspended sediment concentration.

The tank considered in the experimental test has a capacity of 85.72 L of water. The addition of sand to the tank, rise the water level (not capable, to big concentrations, store the 85.72 liters of water). The volume of water had to be controlled, to get accurate real concentrations. For this situation, was studied the relation of the water level rise and the addition of sand. Each gram of sand in the tank, causes an increase of 0.00042 L in the total volume. This value, subtracted to the 85.72 L of water, gave the real volume of water. Additionally, the weight of sand was also corrected when a TSS test was performed. In this case, the dry sand weight (obtained from the TSS test), was subtracted to the sand added in the following test.

To verify the OBS functionality, it was tested if its output was stable and repeatable for the same concentration. To the stability, was settled that the average concentration to 300 seconds (desired test duration) and the average concentration to 600 seconds could not present a relative variation bigger than 1%. The maximum relative variation was 0.71% when the real sediment concentration was 5 g/L. All tests verified the stability condition settled previously and, the concentrations did not present significant variations in time that could induce lack of stability in the signal. To verify the repeability was studied the variation of the deviation related to the measured average concentration for each run of tests and for tests correspondent to the same real sediment concentration. The biggest deviation was 26.08% and the relative variation was 46.42%, both for a real concentration of 1 g/L. The relative variation decreased with the concentration increase. The group of tests 37, 41, 46 and 50, had bigger deviations than the remainders and decreased when the concentration increased. On the contrary, the group of tests 2, 7, 13 and 17 presented the smallest deviations that decreased from 1 to 5 g/L and increased for concentrations above the previous one. The group of tests 21, 25, 30 and 33, presented deviations that decreased and increased with the concentration, not presenting an important pattern.

It was important to guarantee that the propeller produced a flux capable of maintain the sediments in suspension without produce a significant amount of bubbles, and the only way to verify was varying the voltage applied in the engine that was used to control the propeller spinning. Three voltages (30, 40 and 50) were tested. The smallest deviation from the real sediment concentration was 1.62%, correspondent to 30 volts. The relative variation between the three voltages was 3.22%. The voltage applied in the experiments was 30.

For the TSS tests, a sample that could fill a third of the bucket, seemed to be the most reasonable and the one that, for small concentrations, did not occur the risk of being spoiled. This sample correspond to 3000 g of weight. From this, it was necessary to define the duration and the number of rotations per minute of the pump. Obtain the sample with the weight required, could take around 100 seconds. Varying the number of rotations per minute of the pump, were obtained intake velocities between 2 and 4.5 m/s. Comparing the concentrations obtained with TSS and the real one in the tank, with intake velocities bellow 3.5 m/s were obtained smaller concentrations, with intake velocities above 4 m/s were obtained concentrations smaller till 50 g/L and bigger above and was also observed that the nozzle could get easily blocked. The ideal intake velocity was placed between 3.5 and 4 m/s. With the conditions settled previously (weight and pump duration), the number of rotations per minute correspondent to this range of intake velocities was 90.

There were verified three applicability conditions with OBS and one with TSS. With OBS were verified the sediments concentration, the bubbles formation and the light incidence. With TSS was only verified the trapping efficiency.

The concentrations obtained with all OBS's are linearly related with the real sediment concentrations up to 70 g/L. Then, the curves lose their linear behaviour and at 97.61 g/L for OBS's T8277 and T8286, and at 91.28 g/L to the remainder OBS's, the sensors are saturated. The biggest deviation was 66.67%, correspondent to a real sediment concentration of 2.35 g/L and OBS T8276. On the contrary, the smallest deviations were between 34.35 and 69.42 g/L. On average, the OBS T8267 was the one presenting the biggest deviation, and OBS T8282, the smallest. The maximum relative variation was 44.26% when the real sediments concentration was 2.35 g/L, this value decreases and reaches the minimum at 40.36 g/L (1.93%), then increases again to 8.37% (correspondent to 69.42 g/L) and decreases to 5.5%, when the OBS's start to be saturated.

The incident light did not cause any significant influence in the concentrations obtained with the OBS. The biggest deviation obtained was 27.19%, and the biggest relative variation, 26.18 %, both correspondent to a real concentration of 1 g/L and a test with the spotlight off. As these values decrease considerably with the concentration increase (2.66% on 10 g/L and 1.88% on 28 g/L), was admitted that this deviation was caused by other conditions. On the other hand, the bubbles were impossible to eliminate completely from the experiments. Due to this, it was necessary to verify if they could influence significantly the results. The deviation obtained was bigger (25.04%) when the real sediment concentration was 1 g/L and bubbles were observed and decreased with the concentration increase. To tests that presented the residual amount of bubbles the maximum deviation was 14.61%, correspondent to 5 g/L. Tests where bubbles were observed always presented bigger deviations. The biggest relative variation was obtained when the real sediment concentration was 1 g/L (22.24%) and decreased considerably with the real sediment concentration increase. Note that, it is unknown the amount and the size of the bubbles that caused such discrepancies.

With the TSS, the trapping efficiency increased with the concentration. Till 50 g/L were pumped samples with concentrations bellow the real ones, while for concentrations above, the opposite happened. With the exceptions of 46.61 and 81.81 g/L, where were obtained samples with both behaviours, corresponding also to the biggest standard deviations. Bigger relative variations were obtained on concentrations where the amount of pumped samples was also bigger (13.53% to 46.61 g/L). The average trapping efficiency was 0.96, which was bigger than the ones obtained by Bosman *et al.* (1987). However in this work the flux velocity was not controlled.

7.2. Future developments

Given the uncertainty that the subject of this work implies it is suggested that, more experiments should be performed in order to understand more closely what can influence the output of each equipment. With OBS, more experiments should be performed to evaluate its behaviour to the variation of the sediment concentration, particle size, color and particle shape, various sizes and concentrations of bubbles and others parameters depending on the localization of the measurements. More OBS calibrations apparatus should also be tested or the ones that exist evaluated, so that an accurate way to calibrate the OBS can be found.

Due to the lack of studies more TSS experiments should be performed varying the nozzle diameter, the intake velocity, the ambient flow intensity and direction, the sediment characteristics and its concentration and bubbles. The last parameter is suggestion due to the influence of the air entrance in the nozzle.

The goal of this work was to compare the results between the OBS and the TSS. However others equipment's can be used and also need to be studied in the same way so that can be possible to obtain accurate quantifications of the suspended sediment concentrations.

With the results of the laboratory experiments, field experiments must be done in order to compare if the laboratory conditions could represent what really happens in field.

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