

# INSPECTION AND DIAGNOSIS OF SINES' WEST BREAKWATER

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A set of tools that is being developed for the automated inspection of rubble-mound breakwaters, as well as its application to the survey of Sines' west breakwater armour layer, are described. The results from the IRIS surveys are compared to those of the surveys carried out by the Portuguese Hydrographic Institute and first assessment of the structure evolution between 2000 and 2003 is made.

## 1. Introduction

In Portugal rubble-mound breakwaters are the most common harbour protection structure. In order to decide on the most adequate timing for the maintenance and repair works that are needed during the structure's life, a monitoring program should always be considered. Since it is not possible to monitor continuously this kind of structure, the most common procedure, so far, has consisted of a periodic inspection of these structures. In most cases, due to the high costs of the underwater inspection, this periodic inspection has been limited to the above water part of the breakwater.

In 1985, the National Civil Engineering Laboratory (LNEC) proposed the systematic periodic inspection of the harbour protection works in mainland Portugal under the jurisdiction of the Portuguese Port Directorate. Actually, this inspection work was tailor made to the requests of this government agency, in order to help them in the selection of the breakwaters that should be repaired first with the available resources.

LNEC, together with the Institute for Systems and Robotics (ISR) of the Engineering School of Lisbon's Technical University, the Sines Port Authority (APS) and the Avilés Port Authority (APA) are involved in a joint industry project, named MEDIRES, that aims at developing and testing a set of methodologies and tools for accurate and efficient inspection of rubble mound

breakwaters. One of the project key points is the development of IRIS - a measuring device for high accuracy surveys of both the submerged and emerged parts of those structures.

The Sines west breakwater, due to its history, it is one of the few Portuguese rubble mound structures whose submerged part is regularly surveyed, thus becoming a quite interesting case study to check the quality of the surveys produced by the IRIS pre-prototype that is already available.

The objective of this paper is to present the results already achieved within the scope of MEDIRES, namely, the results from the field campaigns carried out with IRIS and to assess the evolution of the Sines' west breakwater based upon the available surveys. After this introduction, there is a brief description of the visual inspection in Portugal carried out by LNEC, section 2, and then, in section 3, the IRIS surveying device and the procedures for geo-referencing and fusion of the data obtained by IRIS are described.

The description of the first field campaign with IRIS, as well as of the problems found thereon, is included in section 4, which deals with the evolution of the Sines' west breakwater, as it can be established from the available surveys. The paper ends with some conclusions on the information to be gathered from the surveys in order to produce a proper diagnosis.

## **2. Visual inspection in Portugal**

In the visual inspections carried out by LNEC there is one observer - i.e. the person that carries out the inspection - that walks along the crest of the rubble-mound breakwater and qualifies the status of the several stretches into which the structure was divided.

The qualifications given by the observer to the status of the profile components of a given stretch – armour layer, crown wall or inner slope – are written down on an inspection form that is later on fed to a database that stores the information from the several inspections. The most important feature of this data base is its ability to combine that information with adequate criteria in order to produce the diagnosis of each profile element for the several stretches into which the structure was divided.

This visual inspection work started in 1985 and it was tailor made by LNEC to the requests of the Portuguese Port Directorate. The objective of the work was to help this government agency in the selection of the breakwaters, among the 19 being inspected then, that should be repaired first with the available resources. Nowadays this work encompasses the periodic inspection of the above water part of 30 rubble mound structures protecting 17 ports and marinas.

In mainland Portugal the length of the breakwaters inspected by LNEC represents approximately 75 % to the total.

This visual inspection has a couple of limitations (Santos et al. 2003). Since one only looks at the emerged part of the structure, this means that for some events in the submerged part of the structure it may take too long for their effects to become visible above water. Moreover, the obtained diagnosis is based upon a subjective status evaluation. Although the criteria used in the diagnosis reflect the experience of the people who established it, they are not based on measurements of any physical quantities on the structure. Finally, there is no direct influence of the wave regime in the structure's diagnosis.

### **3. IRIS surveying device**

To overcome those limitations, there is the MEDIRES project that aims at getting tools for automated inspection of both the emerged and submerged parts of rubble-mound breakwaters and to establish the structures' diagnosis based upon the wave climate at the structure's location and on the surveys of the armour layer envelope.

The first tool being developed is a measuring device for high accuracy surveys, named IRIS. This device will be made of a laser range finder, to survey the emerged part of the structure and of a mechanically scanned sonar profiler to map the submerged part of the structure.

Although this device can work as standalone surveying instrument, in the end of this project it will be installed on the autonomous catamaran DELFIM property of the ISR. This IRIS-DELFIM ensemble will enable the autonomous surveying of the structure being carried out on a routine basis. The navigation and control systems of DELFIM ensure the maneuver repeatability, hence the quality of the collected data sets (Silva et al. 2003).

The structure's diagnosis is to be based on a probabilistic approach. Of paramount importance in this approach is the definition of the load / resistance relations for the armour layer that should take into account the structure's damage progression, as happens with the formula presented in (Melby and Kobayashi 1998).

In order to evaluate the armour layer failure probability one may use the so-called level III probabilistic approach: a set of series of independent sea states are randomly generated, according to their distributions in a selected time interval, and the armour layer damage after each of those series is estimated and the number of failures in the whole set is counted. The quotient of the number of failures over the number of series gives an estimate of the failure probability.

In what follows, a more detailed description of the IRIS components as well as of the procedures for both geo-referencing the data obtained with IRIS and the estimation of the platform heading are carried out.

### 3.1. *The IRIS components*

So far, the MEDIRES project produced a pre-prototype of the high-accuracy measuring device that is presented in Fig. 1. It surveys only the submerged part of rubble-mound breakwaters. The figure shows a detail of the mechanically scanned high aperture sonar and the IRIS pre-prototype mounted on the support vessel.

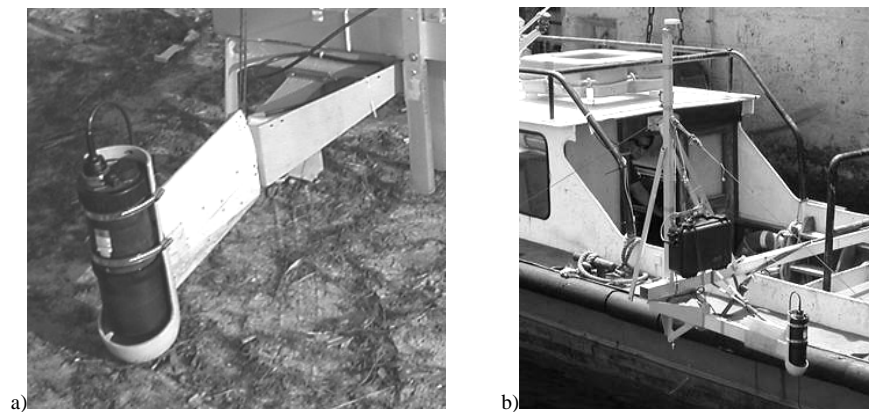


Figure 1. The IRIS high accuracy measuring device. a) Detail of the mechanically scanned high aperture sonar profiler; b) View of IRIS installed in the support vessel.

On top of Fig. 1 b) one can see the GPS aerial and the black box attached to it that contains the Inertial Measuring Unit. In that figure the sonar profiler is in its resting position. Only when the survey is about to start is the sonar profiler lowered to its working position. At this stage of the project the support structure was designed to be fitted in small vessels, and not in DELFIM. The IRIS-DELFIM ensemble will be dealt with later on in the project.

The IRIS survey tool is composed by an Inertial Measurement Unit (Seatech MRU-6), two GPS receivers (Ashtech DG14), with the respective antennas carefully installed and calibrated at the bow and stern of the survey vessel, and a mechanical scanning sonar (Systems Technologies SeaKing). A GPS receiver (Ashtech DG14) is also installed inshore and calibrated to provide corrections in the post-processing phase. Communications between the support vessel and the fixed GPS station are not required thus the mission planning is simplified and the survey is not constrained by “line-of-sight” requirements between both stations.

### 3.2. IRIS hardware architecture

The Hardware architecture for the IRIS surveying tool is built around a modular network backbone. Two different networks with different specifications, capabilities and purposes are used in order to provide a reliable and versatile solution. One of those networks is the CAN bus (Robert Bosch GmbH 1991) which provides a highly reliable and real-time interface for synchronization and system messages, status report messages and light logging messages. Designed for small-scale environments, its multi-master architecture with CSMA/CR (carrier sense, multiple access with collision resolution) physical-medium access control, together with an extensive set of signalling and error detection schemes have made of CAN bus a very appealing solution on which to build distributed systems. A great example of its acceptance is its massive use in the automotive industry where it has been found to be the ideal solution to handle such harsh environments as cars.

On the other side of this dual network system there is a common Ethernet network that provides wider bandwidth for massive logging systems, such as a sonar and GPS raw data. The existence of this kind of universal interface also adds convenience to an end user when the time comes to download the collected data.

Fig. 2 presents a general diagram of the IRIS hardware architecture. The five major boxes represent the different containers or physical elements of the surveying tool. The system core is comprised of several microcontroller-based modules each of one with a specific task within the surveying tool. They interface commercial systems such as the GPS receivers, the Motion reference Unit and the sweep sonar and provide system-critical functionalities such as time synchronization and status checking.

There are two different GPS modules in the IRIS. One of them (the main GPS module) is responsible not only for interfacing the corresponding commercial system but also to disseminate the time base that will be the synchronization source for all modules.

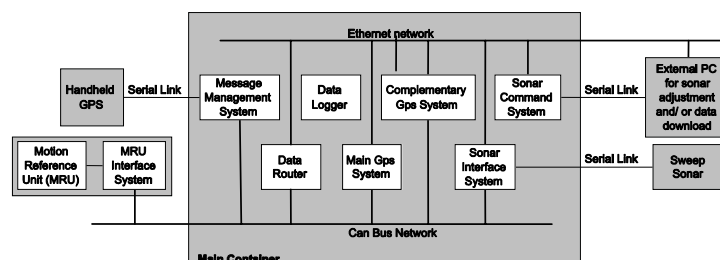


Figure 2. The IRIS Surveying Tool Architecture

The Sonar Command System provides a useful interface for a human operator to connect directly to the sonar via a PC and check real-time data or adjust sonar parameters. The data logger system is basically an Ethernet frame grabber. Collected data is stored in solid-state disk and can be accessed and downloaded by any external PC via a simple Ethernet interface. The data router system is responsible for bridging the two networks. In this specific case, its main task is to translate the logging messages generated in the Can Bus Network into Ethernet messages and forward them to the Data Logger using the UDP protocol. There is also a handheld GPS receiver with data input capabilities which works both as a system diagnosis tool/user console (since it receives the vital status from the message management system) and as a navigation tool for the vessel's helmsman where pre-programmed tracks can be used to conduct a survey.

### 3.3. Survey data geo-referencing

In what follows, let  $\mathbf{I}$  be a fixed reference frame located at the origin of the pre-specified survey area and  $\mathbf{S}$  a body-fixed coordinate frame that moves with the support vessel with the origin located in a pre-specified place on the IRIS tool. The following notation is required:

$\mathbf{p}_i = [x_i \ y_i \ z_i]^T, i = \{0,1,2\}$  – positions of frame  $\mathbf{S}$  and of the first and second GPS receivers installed onboard the survey vessel, relative to frame  $\mathbf{I}$ , respectively;

$\lambda(\phi, \theta, \psi)$  – vector of roll, pitch, and yaw angles that locally parameterize the orientation of  $\mathbf{S}$  relative to  $\mathbf{I}$ ;

${}^I\boldsymbol{\omega}_S$  – angular velocities of  $\mathbf{S}$ ;

${}^I\mathbf{R}_s(\lambda)$  – rotation matrix from  $\mathbf{S}$  to  $\mathbf{I}$ ;

The Inertial Measurement Unit (IMU) provides measurements of the attitude  $\lambda(\phi, \theta, \psi)$  and the angular velocities of reference frame  $\mathbf{S}$  relative to  $\mathbf{I}$ , expressed in the body frame  $\mathbf{S}$ , i.e.  ${}^S({}^I\boldsymbol{\omega}_S)$ . The sonar ranging sensor, with an instantaneous scan bearing angle  $\varepsilon$ , provides measurements of the breakwater, relative to  $\mathbf{S}$ . Assuming, without loss of generality, that the sonar is installed at the origin of the body-fixed frame  $\mathbf{S}$ , pointing downwards, and that the scanning angle lies on the transversal plane (defined by the  $(\mathbf{y}_S, \mathbf{z}_S)$  axes), the measurements  $d(i)$ , resulting from the scanning of the submerged part of the breakwater can be geo-referenced in the inertial reference frame  $\mathbf{I}$  by taking into account the instantaneous attitude and position of the surface vessel, as

$$z(i) = \mathbf{p}_0 + {}^I\mathbf{R}_s(\lambda)\mathbf{R}_X(\varepsilon)\begin{bmatrix} 0 & 0 & d(i) \end{bmatrix}^T \quad (1)$$

where  $\mathbf{R}_X(\varepsilon)$  is the rotation matrix from the instantaneous sonar bearing to the body-fixed frame  $\mathbf{S}$ .

Remark that the sensor suit installed onboard the survey vessel makes available estimates of all variables required for the computations in (1). However, the heading angle ( $\psi$ ) is estimated from measurements provided by magnetometers, installed inside the IMU. These measurements are corrupted by the hard and soft iron nonlinear magnetic field distortions caused by the surface vessel (Denne 1979) as well as by the special disturbances induced by the proximity to the breakwater, built with ferromagnetic materials. After some preliminary tests, errors of about 5 degrees of magnitude were identified on the yaw measurements, precluding its use in an accurate survey.

An alternative was pursued corresponding to the use of the measurements obtained from both GPS receivers installed onboard, after careful calibration. A GPS offline pos-processing technique was also used to combine the corrections obtained from a calibrated shore station with the measurements of the two GPS receivers installed onboard the survey vessel. This technique allows for the compensation of common disturbances, giving precise trajectory estimates of both GPS receivers installed onboard. From the geometry of the problem, a measurement of the yaw angle can be trivially computed using the relations

$$\psi_m = \tan^{-1}((y_1 - y_2)/(x_1 - x_2)) - \psi_{inst} \quad (2)$$

where  $\psi_{inst}$  is a constant that compensates for the relative onboard installation position of the GPS receivers. Note that no compensation for the local magnetic declination is required for the proposed method. The heading angle that results directly from the difference of the two GPS receivers position measurements is corrupted by high frequency noise. The fusion with data available from a rate gyro sensing the angular velocity about the  $\mathbf{z}$  axis, resorting to fixed-interval complementary filter smoothing techniques will be instrumental to obtain accurate estimates of the platform yaw angle.

### 3.4. *Optimal estimator and fixed-interval smoother designs*

The estimator and smoother were designed using the classical stochastic  $H_2$  framework, resulting for linear systems in an estimate with minimum expected covariance error, see (Gelb, 1975) and the references therein. Complementary Kalman filters arise naturally in the context of signal estimation, based on measurements provided by sensors over distinct, yet complementary regions of frequency (Brown and Hwang 1992) and will be selected to tackle the problem at hand.

Assume that there are measurements available, with a sampling period  $h$ , for the heading angle (based on the approach detailed on the previous subsection) and for the angular rate on the vertical axis. The key ideas in complementary filtering are very intuitive, and can be simply introduced by referring to the discretized version of the rigid body attitude kinematics, written in compact form as

$$\begin{aligned}\mathbf{x}(k+1) &= \mathbf{A}(k+1) \mathbf{x}(k) + \mathbf{B} \mathbf{u}(k) + \zeta(k) \\ \mathbf{y}(k) &= \mathbf{C} \mathbf{x}(k) + \nu(k)\end{aligned}\quad (3)$$

where  $\mathbf{x}(k) = [\psi^T(k) b^T(k)]^T$  is the vector of state variables,  $\mathbf{u}(k) = [0 \ 0 \ 1] \mathbf{Q}^T \mathbf{R}_s(\lambda)^S (\boldsymbol{\omega}_s)$  is the vertical component of the angular rate,  $b$  is a bias term associated with the rate gyro sensor, and  $\mathbf{Q}$  is a matrix relating the body fixed angular velocities with the Euler angle derivatives. The matrices

$$\mathbf{A} = \begin{bmatrix} 1 & h \\ 0 & 1 \end{bmatrix}, \quad \mathbf{B} = [h \ 0]^T \quad \text{and} \quad \mathbf{C} = [1 \ 0]$$

relate the underlying variables and  $k$  is a compact form to express the time instant  $t_k = hk$ . The state and measurements are corrupted by uncorrelated zero mean white noises  $\zeta$  and  $\nu$  with covariance  $\mathbf{Q}(k) = \mathbf{E}[\zeta(k)^T \zeta(k)]$  and  $\mathbf{R}(k) = \mathbf{E}[\nu(k)^T \nu(k)]$ , respectively, where  $\mathbf{E}[\cdot]$  is the expectation operator.

The estimator that presents the minimum expected error covariance is a Kalman filter (Gelb 1975), that in the case where the pair  $(\mathbf{A}, \mathbf{C})$  is observable and the pair  $(\mathbf{A}, \mathbf{Q}^{1/2})$  is controllable, exists and it is stable and unique. The structure of such filter is composed by a prediction stage based on the underlying model in (3), computed as

$$\begin{aligned}\hat{\mathbf{x}}^-(k) &= \mathbf{A} \hat{\mathbf{x}}^+(k) + \mathbf{B} \mathbf{u}(k) \\ \mathbf{P}^-(k) &= \mathbf{A} \mathbf{P}^+(k) \mathbf{A}^T + \mathbf{Q}(k)\end{aligned}\quad (4)$$

where  $\hat{\mathbf{x}}^-(k)$  and  $\mathbf{P}^-(k)$  are the predicted state and the prediction error covariance, respectively. Given a new measurement  $\mathbf{y}(k)$ , the estimates are updated according to

$$\begin{aligned}\hat{\mathbf{x}}^+(k+1) &= \hat{\mathbf{x}}^-(k) + \mathbf{K}(k) [\mathbf{y}(k) - \mathbf{C} \hat{\mathbf{x}}^-(k)] \\ \mathbf{P}^+(k+1) &= \mathbf{P}^-(k) - \mathbf{A} \mathbf{P}^-(k) \mathbf{C}^T (\mathbf{C} \mathbf{P}^-(k) \mathbf{C}^T + \mathbf{R}(k))^{-1} \mathbf{C} \mathbf{P}^-(k) \mathbf{A}^T\end{aligned}\quad (5)$$

where  $\hat{\mathbf{x}}^+(k)$  and  $\mathbf{P}^+(k)$  are the updated state and the updated error covariance, respectively, and  $\mathbf{K}(k) = \mathbf{P}^-(k) \mathbf{C}^T (\mathbf{C} \mathbf{P}^-(k) \mathbf{C}^T + \mathbf{R}(k))^{-1}$  is the Kalman filter gain. Notice that the filter relies on the heading information at low frequency, thus rejecting the high frequency disturbances present in the heading measurement, and blends it with the information provided by the rate gyro in the



complementary frequency region, compensating also for any bias present. Moreover, note that this filter, represented in Fig. 3, it is causal and can be running in real time during the mission to provide estimates off the heading and heading rate.

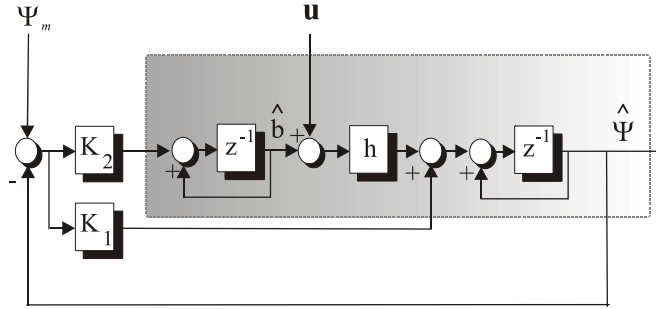


Figure 3: Complementary Kalman Filter

Finally, to complete the pos-processing task, a non-causal fixed-interval smoother was designed for the system introduced in (3), using the prediction covariance  $\mathbf{P}^-(k)$  and the updated estimation covariance  $\mathbf{P}^+(k)$ , as computed in (4) and (5), respectively. The classical solution (Gelb 1975) provides optimal *a posteriori* state estimate  $\hat{\mathbf{x}}(k)$  and *a posteriori* error covariance  $\mathbf{P}(k)$  using the backward recursions

$$\begin{aligned} \mathbf{G}(k) &= \mathbf{P}^-(k) \mathbf{A}^T \mathbf{P}^+(k)^{-1} \\ \hat{\mathbf{x}}(k) &= \hat{\mathbf{x}}^-(k) + \mathbf{G}(k) [\hat{\mathbf{x}}(k+1) - \hat{\mathbf{x}}^+(k+1)] \\ \mathbf{P}(k) &= \mathbf{P}^-(k) + \mathbf{G}(k) [\mathbf{P}(k+1) - \mathbf{P}^+(k)] \end{aligned} \quad (6)$$

where  $\mathbf{G}(k)$  is the smoother gain. This non-causal filter, is used to post-process survey data in order to obtain a yaw angle estimate with a minimum *a posteriori* estimation error.

#### 4. Sines' West Breakwater evolution

After the storms of February 1978 and of February 1979 that almost destroyed it, the breakwater was rebuilt from 1990 to 1992 using 90 metric ton Antifer cubes, on the trunk, and 110 metric ton Antifer cubes on the breakwater head. Due to importance of this structure, and to its past, the Sines Port Authority decided to have the breakwater surveyed almost every year. These surveys include both the emerged part and the submerged part, thus making this breakwater the natural structure to assess the performance of IRIS.

#### 4.1. The Portuguese Hydrographic Institute Surveys

The surveys of the submerged part of Sines west breakwater were carried out by the Portuguese Hydrographic Institute (IH). There is a set of sections that are surveyed almost every year with an acoustic sonar profiler. The survey lines are

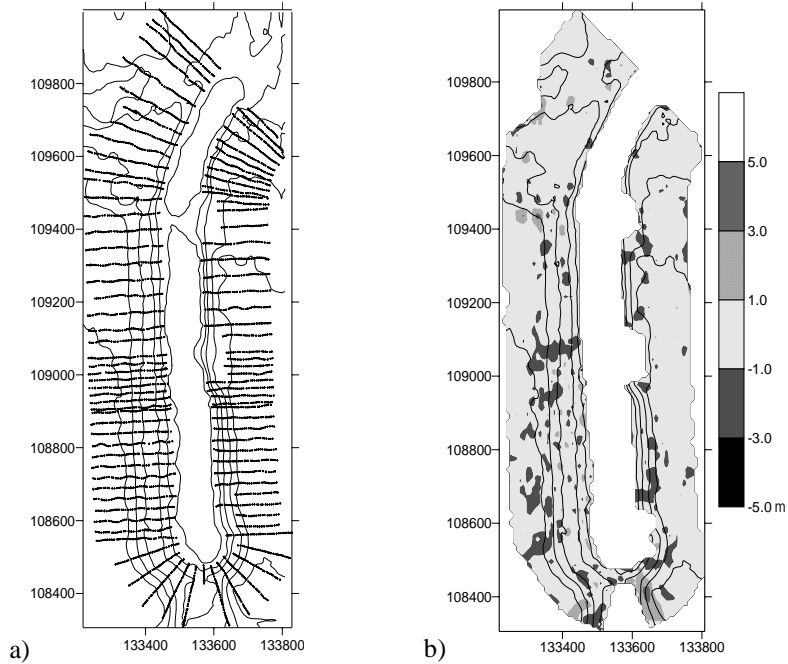


Figure 4. a) Plot of the lines surveyed by IH in 2003 b) Differences between the 2003 and 2000 IH surveys.

approximately 50 m apart in the first 1000 m of the breakwater extension and 25 m apart in the remainder of the breakwater up to its head, Fig. 4 a).

Although these surveys had been carried out regularly since 1993, only the data of the surveys of 2000, 2001 and 2003 were stored in an electronic format that made their processing easier. The number of surveyed points each year were approximately 4000, the only exception being 2001 when 6000 points were surveyed.

Both Fig. 4 a) and Fig. 4 b) present the contour lines of the surface that can be defined based on the sections surveyed by IH in 2000. Fig. 4 b) presents superimposed on those contour lines a map with the difference to the same surface of the surface that can be defined from the IH survey of 2003. The figure shows that in those three years, in the majority of the breakwater those differences are smaller than 1 m and only at some small regions those differences lie between 1 and 3 m. It must be pointed out that those surfaces

were obtained from surveyed sections that in some cases were 50 m apart and the Antifer cubes equivalent diameter is 3.27 m, so the results obtained for the regions between those sections must be interpreted carefully.

#### **4.2. The IRIS surveys**

So far, two surveys of the armour layer of Sines west breakwater were carried out with IRIS. The first one took place on June 2003, while the second took place in June 2004.

In the 2003 survey, the first time ever IRIS was used, it became obvious that at least two not so small details had been overlooked that far.

The first one was related to the measurement of the Earth magnetic field that was fundamental to find the IRIS' heading. In order to get heavier Antifer cubes at the head of the breakwater, hematite, an iron ore, was included in the concrete aggregates. That is the cause for the darkish area at the breakwater head in the pictures of Sines west breakwater. This means that the heading measurements from the electronic compass were disturbed by the structure. This problem led to the development of the procedure to estimate the IRIS heading that is now implemented: two GPS receivers, one at the fore and another at the aft of the support vessel give the vessel's heading and IRIS heading.

The second detail was the wave heights close to the breakwater. In a midsummer day, there were several waves whose spray passed over the boat cabin. These waves are certainly too much for the DELFIM catamaran. The evaluation of the general observed wave regime at a point in front of the west breakwater showed that, (Coli et al. 2004), waves with a wave height below half meter do occur only in less than 1% of the time.

This means that one should be very careful in the selection of the dates for surveying the armour layer of this breakwater with IRIS mounted on the DELFIM catamaran. Alternatively, one may use the IRIS surveying device installed on another vessel. What may be lost then is the maneuver repeatability ensured by the Vehicle Mission and Control Systems of DELFIM.

In spite of all those troubles, Fig. 5 shows that the survey produced by IRIS is quite comprehensive. Instead of an ensemble of surveys from sections along the breakwater, one has a very good scan of the armour layer (in this part of the structure alone 63969 points were surveyed). This large number of surveyed points implies a finer detail in the description of the armour slope, as can be seen in the same figure, which presents the perspectives of the surfaces that can be defined based on the IH 2003 survey - Fig. 5 b) - and on the 2004 IRIS survey - Fig. 5 c).

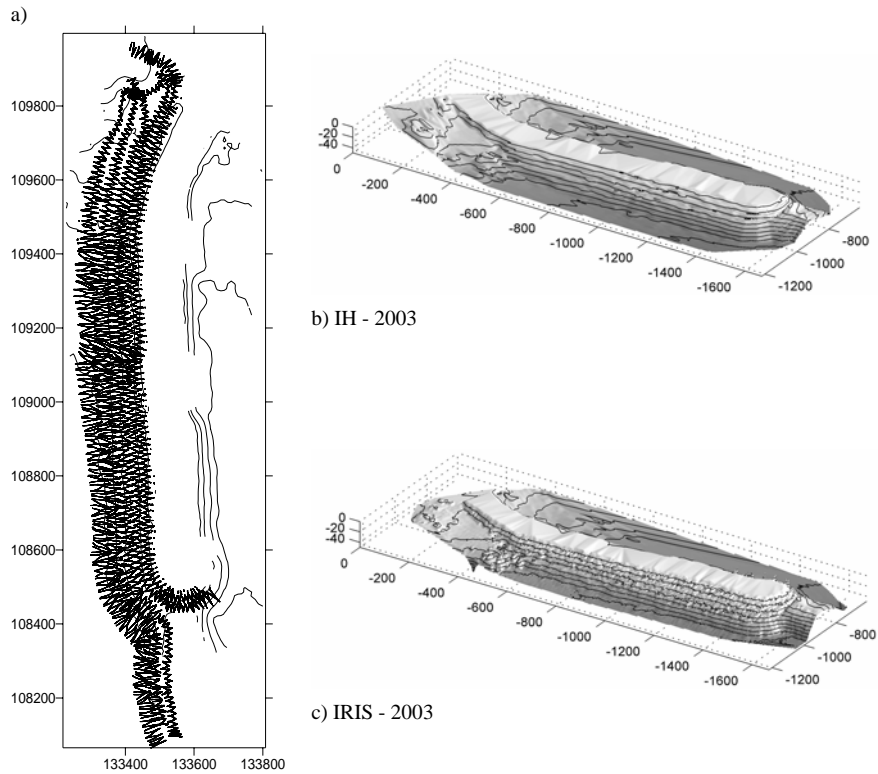


Figure 5. a) Points surveyed with IRIS in 2003; b) Perspective of the surface obtained with the points surveyed by IH in 2003; c) Perspective of the surface obtained with points surveyed by IRIS in 2003.

## 5. Conclusions

The advances in the MEDIRES project, which aims at developing and testing a set of methodologies and tools for accurate and efficient inspection of rubble mound breakwaters, were described.

A key point in that project is the development of IRIS - a measuring device for high accuracy surveys of both the submerged and emerged parts of those structures. The surveys obtained with the pre-prototype of IRIS, which is only able to survey the submerged part of the armour layer showed that a good scan of this part of the structure can be obtained.

The difference between the surfaces that can be defined from the sections surveyed by IH in 2000 and 2003 showed that in those three years no major changes occurred in the armour layer, apart from some small regions where that difference lies between 1 and 3 m. It must be pointed out that those surfaces

were obtained from surveyed sections that in some cases were 50 m apart and so the results obtained for the regions between those sections must be interpreted carefully. Actually, for these data the sensible procedure would be to evaluate the differences between the two surveys of the same section.

Anyway, this application confirms that these tools and methodology are quite promising, since the diagnosis methodology will improve and, consequently, the decision making process relative to the maintenance or repair works in this type of structure will improve as well.

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