MEASURING ARMOUR LAYER EROSION IN SCALE MODEL TESTS

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In Portugal, rubble-mound breakwaters are a very common harbour protection structure. Since this is a sort of structure where repair or maintenance works may have to be carried out during its lifetime, there has been some effort in the definition of suitable procedures to forecast the need for such works. One of these procedures involves the time evolution of the armour layer erosion and the definition of a dimensionless quantity called the damage of the structure. Melby (1999) presented a formula for predicting the damage evolution of rubble mound breakwaters, based on the incident wave characteristics. This paper presents the results of a study that aimed at assessing the applicability of those formulae for wave conditions different from the ones of the tests of Melby (1999), but using the same kind of long-term scale model tests. In such tests sequences of stationary sea states hit the armour layer and the eroded volume is measured at the end of every two sea states. This measurement of the eroded volume was carried out using a technique based upon the reconstruction of stereo pairs, in which, refraction due to the air-water interface, is corrected. This was the first time this survey technique was used intensively in such long-term scale models and it aimed at assessing the technique performance in scale model tests where intensive profile surveying is necessary.

Keywords: Rubble mound breakwaters, Prediction of armour layer damage progression, Scale model tests. Stereo reconstruction.

1. Introduction

Aiming to predict the rubble-mound deterioration with time, Melby (1999) conducted a set of experiments measuring the erosion of a stone-armour layer for varying wave and water-level conditions.

The structure profile was measured throughout the test and the measured profiles were used to obtain mean armour layer damage. Such damage was defined as a dimensionless index (S) using profile data (Broderick e Arens, 1982 and and Van der Meer, 1988).

$$S = \frac{Ae}{D_{n50}^2} \quad [1]$$

where,

A_e is the cross-sectional eroded area and Dn_{50} is the armour rock nominal diameter.

The empirical equation relating mean damage to spectral wave characteristics was given by Melby and Kobayashi (1998) as:

$$\bar{S}(t) = \bar{S}(t_n) + a_p (N_{m0})^5 (T_p)^{-b} (t^b - t_n^{b)}) \quad \text{for } t_n<t<t_{n+1} \quad [2]$$

where,

- N_{m0}= (H_{m0}/Dn_{50}) is the stability number based on the zeroth moment of the incident wave spectrum;
- Dn_{50} is the nominal armour stone diameter;
- $\bar{S}(t)$ and $\bar{S}(t_n)$ are the mean eroded areas at times t and t_n respectively;
- T_p is the spectral peak period;
- *a* and *b* are empirical coefficients function of the structure slope, wave period and beach slope.

This study aimed to assess the applicability of this formula for wave conditions different from the ones of the tests of Melby (1999), but using the same kind of long-term scale model tests.

In order to speed up the armour layer survey, it was carried out using a photogrammetric technique based upon the reconstruction of stereo pairs, in which, refraction due to the air-water interface, is corrected. This means that it is not necessary to empty the flume.

The main objectives of the present study are:

- To assess the applicability of that formula for wave conditions different from the ones of the tests of Melby, but using the same kind of long-term scale model tests;
- To assess a photogrammetric technique performance in scale model tests where intensive profile surveying is necessary.

2. Scale Model Tests

2.1. Model set-up

The scale model tests were conducted in one of the LNEC's irregular wave flumes, named COI1. The COI1 flume is approximately 50 m long and it has an operating width and an operating water depth of 80 cm. It is equipped with a piston-type wave-maker and an active wave absorption system, AWASYS, (Troch, 2005), which allows the dynamic absorption of reflected waves.

Figure 1. Irregular Wave Flume COI1

The flume profile consisted in a 11.3 m offshore beach, comprising a 1:20 slope that ended on a flat bottom where the structure was buit (Figure 2).

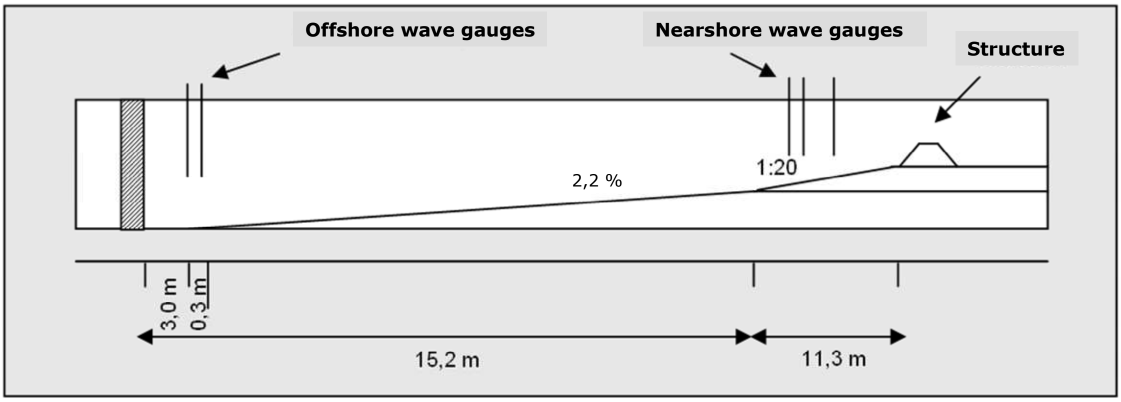


Figure 2. Flume Profile

The tested structure was a regular rubble-mound breakwater with a 1:2 slope, whose armour layer consisted of a double rock layer of 128 g. The underlayer consisted of a double rock layer of 32 g.

The structure crest height, h_c, was 31.5 cm and the toe depth, h_t, was 15.8 cm or 11.9 cm according to the two tested water levels.

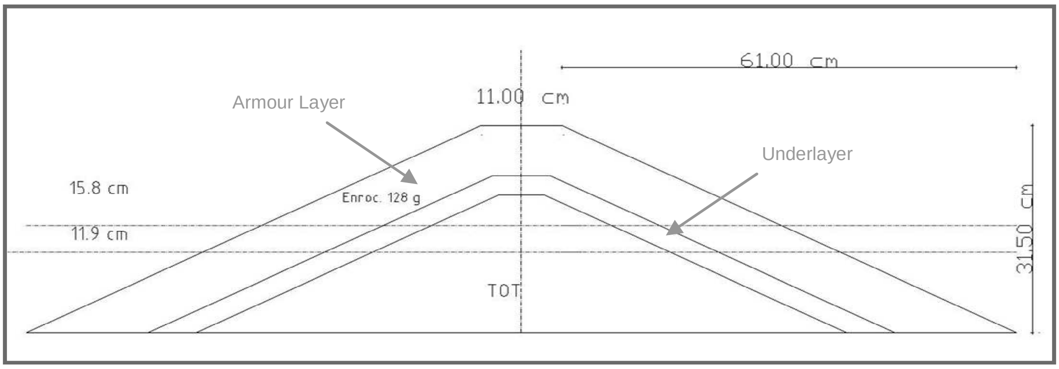


Figure 3. Structure cross-section

The armour layer consisted of stones with M_{50} = 128 g. Since the stone density was of 2.7 g/cm^3, the stone nominal diameter, $Dn_{50,}$ was of 3.64 cm. The tested structure is illustrated in Figure 4.

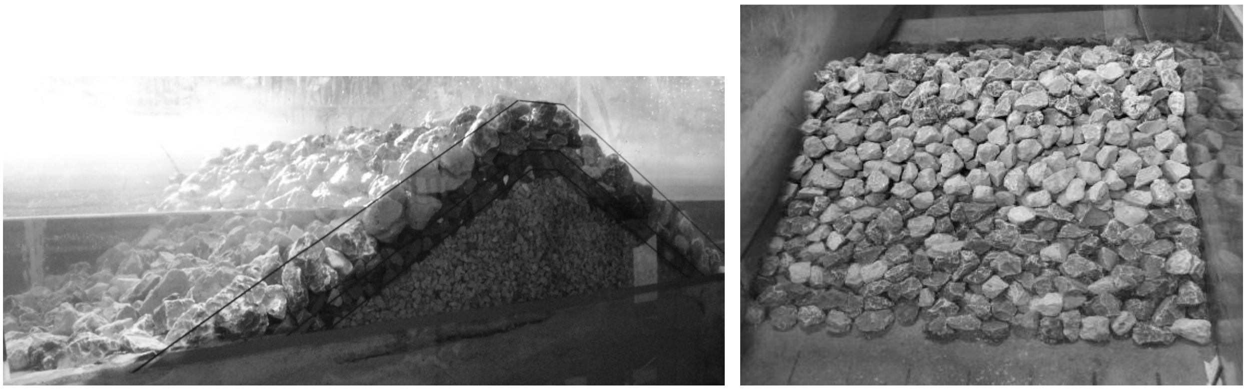


Figure 4. Tested structure

2.2. Wave Conditions

The tests were carried out with irregular waves, being reproduced 6 wave conditions, using 2 water levels; 2 peak periods and 6 significant wave heights. Table 3 summarizes the nearshore wave characteristics tested.

Table 1. Nearshore wave characteristics

Test	Water depth at toe (cm)	Water depth at wave paddle (cm)	Tp (s)	Hs (cm)
1	11.9	55.0	2.54	5.65
2	11.9	55.0	2.52	6.34
3	11.9	55.0	2.39	7.04
4	15.8	59.4	2.42	6.26
5	15.8	59.4	2.51	7.73
6	15.8	59.4	2.50	8.66

2.3. Test Series

Throughout the experiment, five test series were performed (test series A, B, C and repetitions of test series B and C). Nevertheless, only test series A results will be presented in this paper. Table 4 summarises the test series performed.

Table 2. Summary of tests series

Test Series	Test sequence	Duration
A	1, 2, 3, 4, 5, 6	28.5 h
B	1, 2, 3, 5, 6	8.5 h
C	4, 5, 6, 2, 3	9.0 h

During all the test series, waves ran in 15 minutes bursts. Armour layer profiles were measured after each pair of these bursts. This means that one pair of stereo images had to be taken after every 30 minutes of waves.
For test series A, each wave condition was run until damage stabilization, beginning with the lower water level in an increasing intensity sequence. The structure was exposed to waves until failure.

For test series B and C, the test was intended to simulate damage from a sequence of individual storms implying that test series had a well defined duration. Test Series B e C were carried out with increasing and decreasing water levels respectively.

2.4. Wave Generation and Measurement

In order to measure the free-surface elevation, the flume was equipped with 5 resistive-type wave gauges. The first array of two wave gauges was located in front of the wave maker and the second array in front of the structure (Figure 5). The wave gauges in front of the structure were positioned so that incident wave characteristics could be determined according to the Mansard & Funke (1980) procedure. The SAM software (Capitão, 2002) was used on the data analysis.

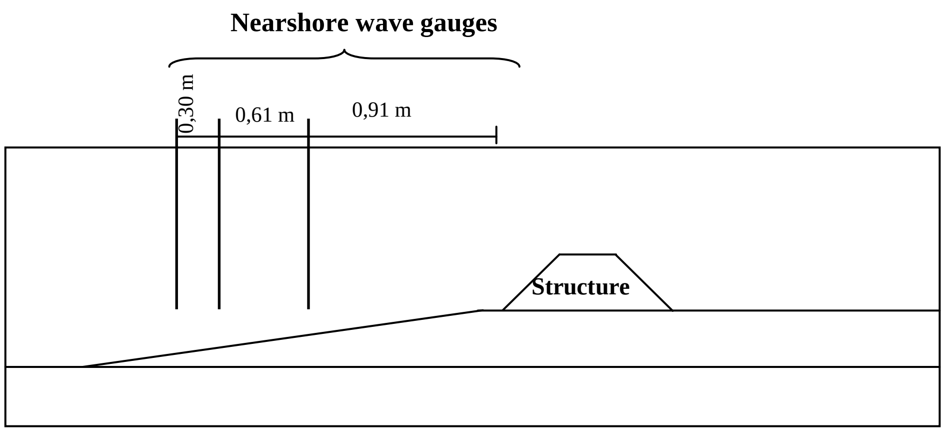


Figure 5. Location of the nearshore wave gauges

Figure 6 illustrates the spectral analysis for a 15 minutes test run.

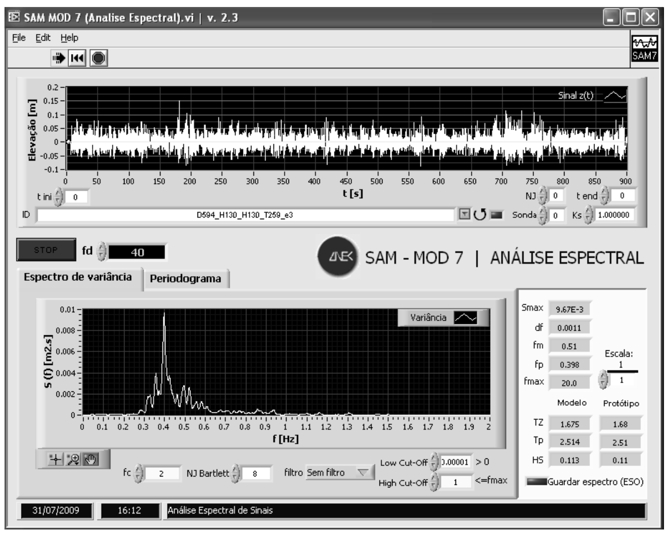


Figure 6. Spectral analysis using the SAM software

3. Damage Measurement - The Photogrammetric Technique

For a better damage characterization, the armour layer was divided in seven profiles, 10 cm apart (Figure 7).

For all the 5 test series, a survey of the undamaged profile was carried out (L0) and 18 surveys (L1 a L18) were performed for test series B e C and 57 surveys (L1 a L57) for test series A.

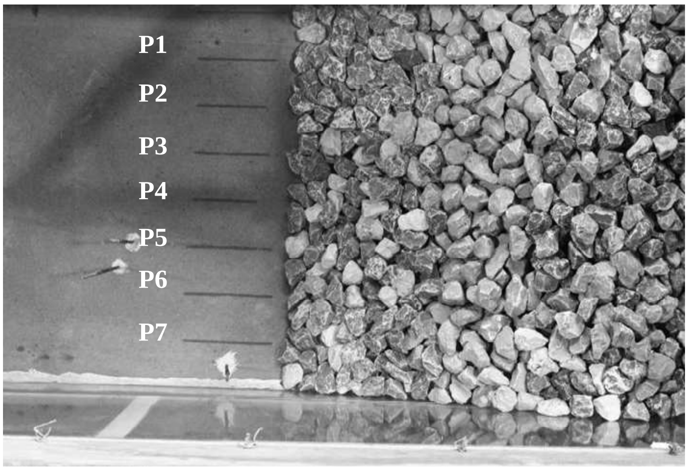


Figure 7. Location of the surveyed profiles

In order to speed up the long duration scale model tests, during which several damage measurements have to be done, underwater stereo reconstruction was used.

This technique consists of identifying depth from two different views of the same scene (stereo image pairs). Since the scene-reconstruction software used, rectifies the distortion introduced by the air water interface, it was possible to reconstruct both the emerged and submerged scenes thus avoiding the need of emptying the tank.

The photographic equipment consisted of two cameras mounted side by side in a support structure and able to photograph simultaneously the same scene (Figure 8).

Throughout the tests herein described, we used two digital SLR cameras (Canon EOS 350D) fitted with fixed focal length lenses (Canon EF 35mm $f/2$). This setup is capable of acquiring images with 3456 by 2304 pixels (8.0 megapixel), as well as images with 2496 by 1664 pixels (4.1 megapixel) and 1728 by 1152 pixels (2.0 megapixel).

Figure 8. Photographic equipment

Because the photographic equipment is made of two separate cameras, the separation between the lenses centre can be larger than before, and customizable.

Being stereopsis the base of reconstructing a three dimensional scene from a pair of images acquired from two slightly different locations, a larger separation between the two cameras lens centre should imply a better ability to reconstruct the three dimensional scene. However, the separation between the two cameras lens centre has to be kept within a acceptable size since too large separations may lead to photographing different faces of an object with each camera, which would render the scene reconstruction impossible.

In the present study, the profile surveys were carried out with a fixed separation of 16 cm between the camera lenses centre.

The software package available allows a complete 3D reconstruction environment, using stereo image pairs as input. It consists of two distinct applications implemented in MATLAB™ (Ferreira et al, 2005) with a particular objective:

- The camera calibration, which consists of identifying the parameters describing the projective cameras used and their position and orientation within the observed world;
- The reconstruction, which consists of identifying depth from two different views of the scenery.

Camera Calibration

As camera calibration is of utmost importance in any serious precision measurement system using stereo vision, before each test session, the camera setup was calibrated. It is recommended that each session of image acquisition has its own calibration step.

The calibration process defines the metric used to measure distances and angles, as well as absolute positions in the reconstructed 3D world. To accomplish this, several shots of a planar calibration chequered pattern were taken (Figure 9).

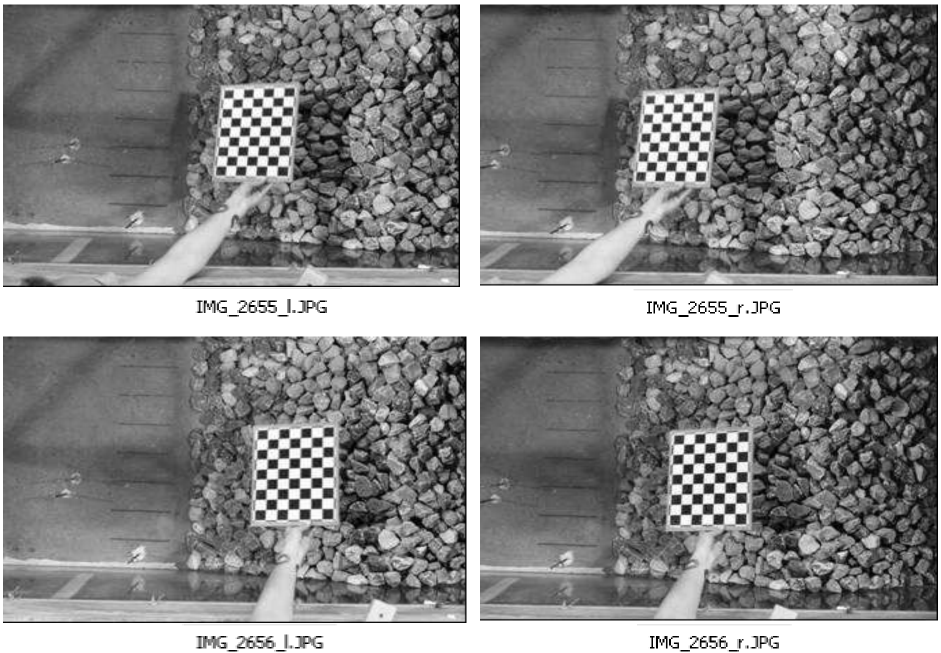


Figure 9. Set of stereo pairs used to calibrate the camera setup

The calibration procedure consists of clicking the inside 4 corners of the calibration pattern in a specific order (counter clockwise). The first clicked corner specifies the origin of the pattern and the second clicked corner the direction of the X axis (Figure 10).

In the present study, it was possible to successfully calibrate the system using as few as 18 stereo image pairs.

At the end of the calibration process, for each set of stereo pairs (left and right), it is obtained a file containing the camera parameters.

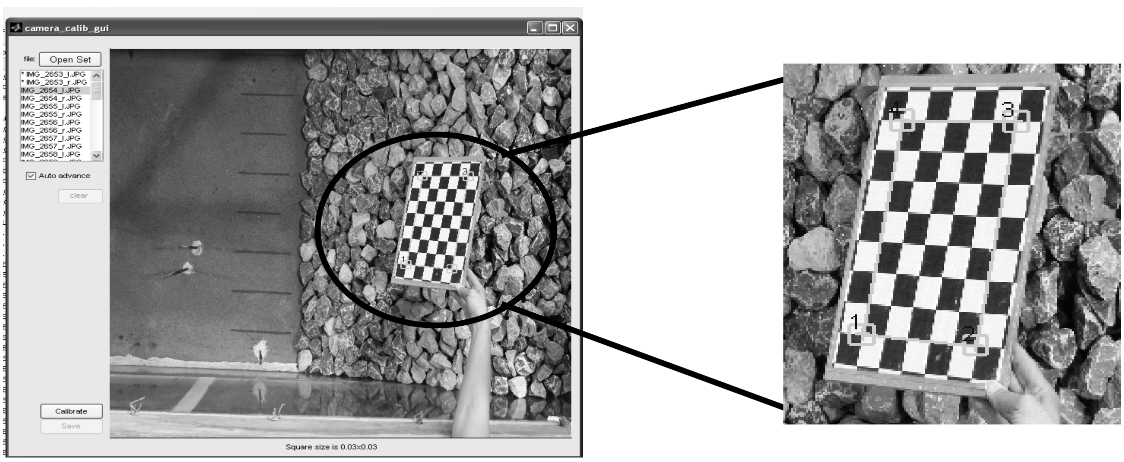


Figure 10. Clicking the inside corners of the calibration pattern

Reconstruction

Reconstruction consists of identifying depth from two different views of the scenery (Figure 11). It is possible to reconstruct both above water and/or submerged armour slope.

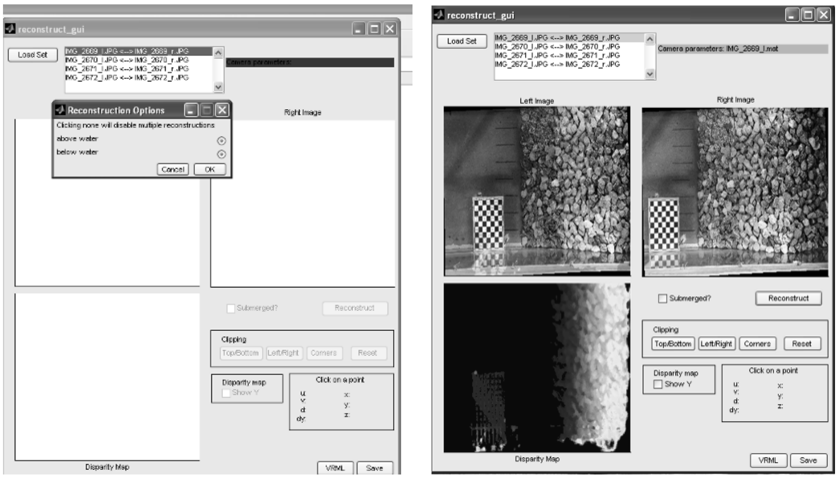


Figure 11. Reconstruction of a partially submerged scenery

The output of the package consists of a (x,y,z) file describing the cloud of reconstructed points. This is a standard file format which can be imported by various modelling tools. Using the Golden Software Surfer™, it was possible to create regular grids, enabling profile definition as well as the armour slope envelope (Figure 12).

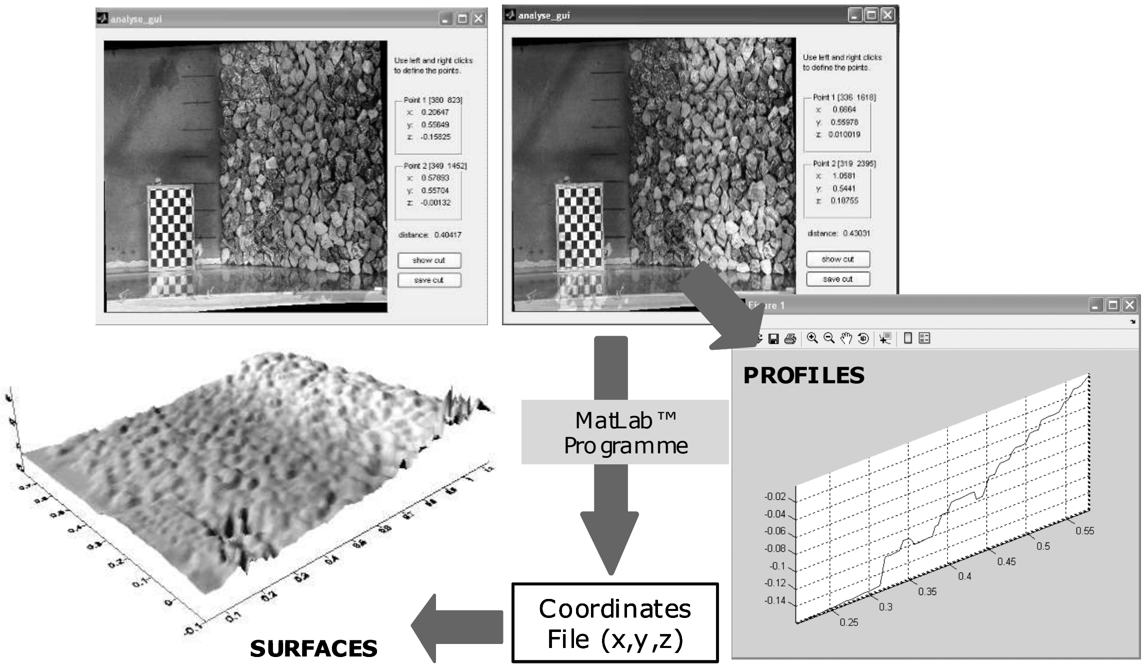
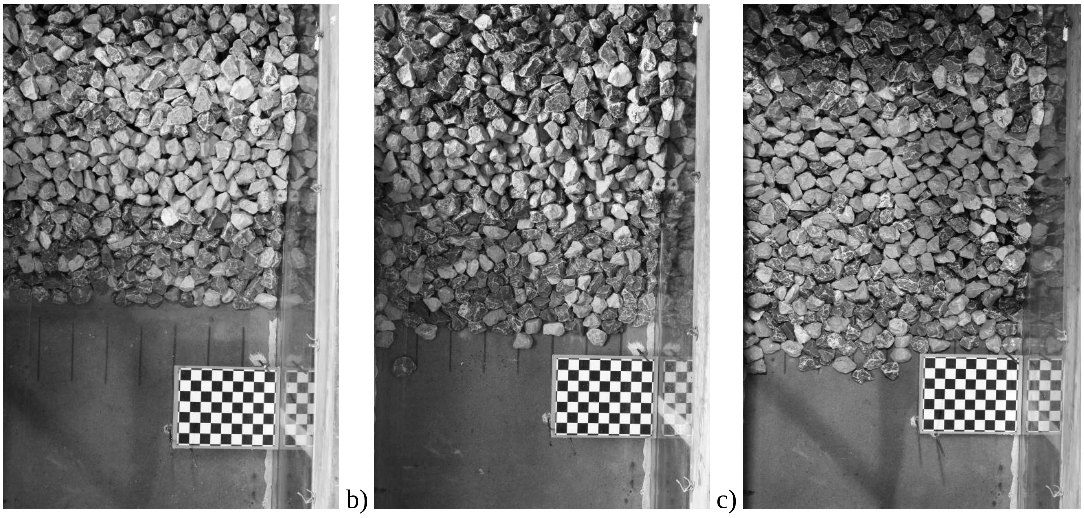


Figure 12. Profile and surface obtained from the stereo image pair reconstruction

4 Damage Estimation

Five long-term test series were carried out. Nevertheless, only the larger test series (Test series A) results will be presented in this paper.

Figure 13 illustrates the damage progression on the armour slope during the test series A. It can be seen in that figure that, as the test is being carried out, the armour stones do occupy a larger stretch of the channel length.



a) b) c)

Figure 13. Aspect of the armour slope a) At the beginning of the test series A b) At the middle of the test series A c) At the end of the test series A

Figure 14 illustrates the Profile P4 evolution during the 57 surveys performed.

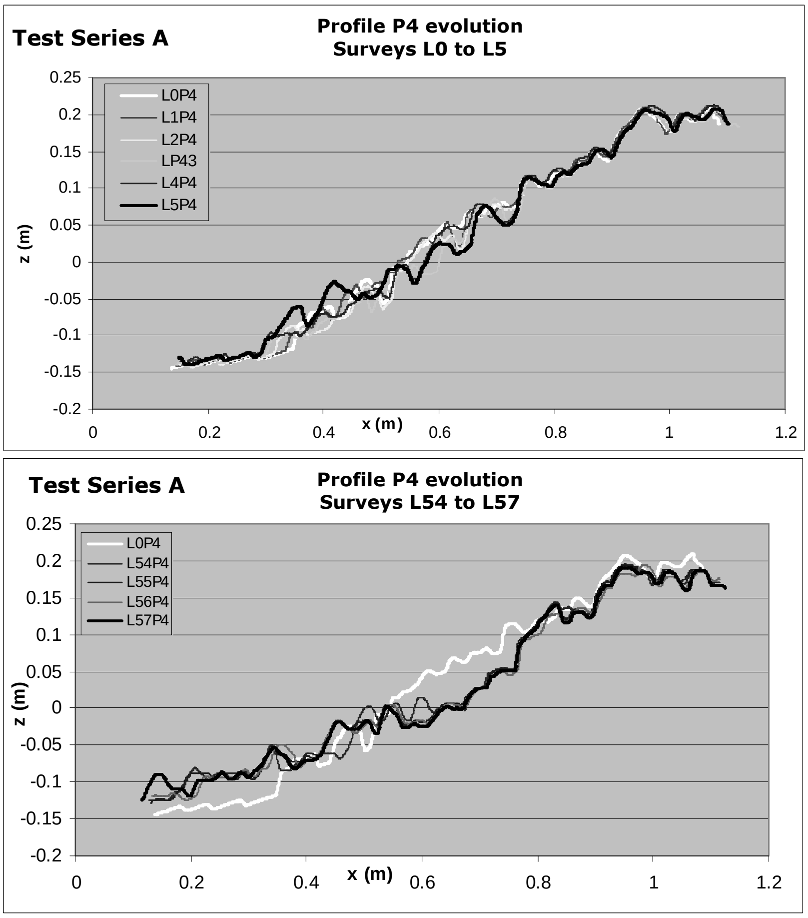


Figure 14. Profile P4 evolution during Test series A surveys

Between consecutive surveys, it does not seem to occur important damage, but at the end of the test series, an important eroded area was observed.

In order to test the software refraction correction, several surveys with and without water in the flume, were performed. It was observed that the highest difference estimated was of 1.9 cm at the toe (Figure 15). Considering that the stone nominal diameter was about 3.64 cm, it can be assumed that the refraction correction for the submerged part of the armour layer was reliable.

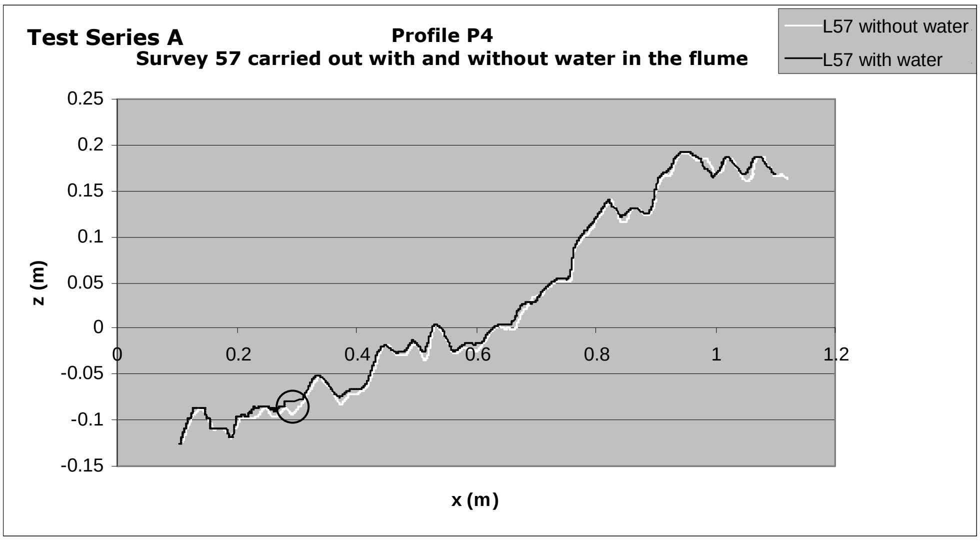


Figure 15. Testing the refraction correction. Survey 57 carried out with and without water

For each survey, it was possible to measure the eroded area, Ae, using a Visual Fortran™ code, which enables to compare each surveyed profile with the undamaged profile.

Damage level (S) for each one of the seven profiles was estimated using Eq. [1], enabling to determine the mean damage level ($\bar{S}$) for each survey.

5 Comparing Predicted Damage With Measured Damage

Making use of the formulation proposed by Melby (Eq. [2]), the predicted mean damage values were estimated.

It was observed that the reproduced wave conditions in the present study were lower, in what concerns to wave height, than those used in the test that led to the formulation, as well as the wave breaking location, which, in the present study, occurred on the breakwater´s slope.

The mean damage predicted values, estimated upon those wave conditions, did not converged to the mean damage values measured during the model tests.

Figure 16 compares the damage measured during the test series with the predicted damages using Melby´s formulation.

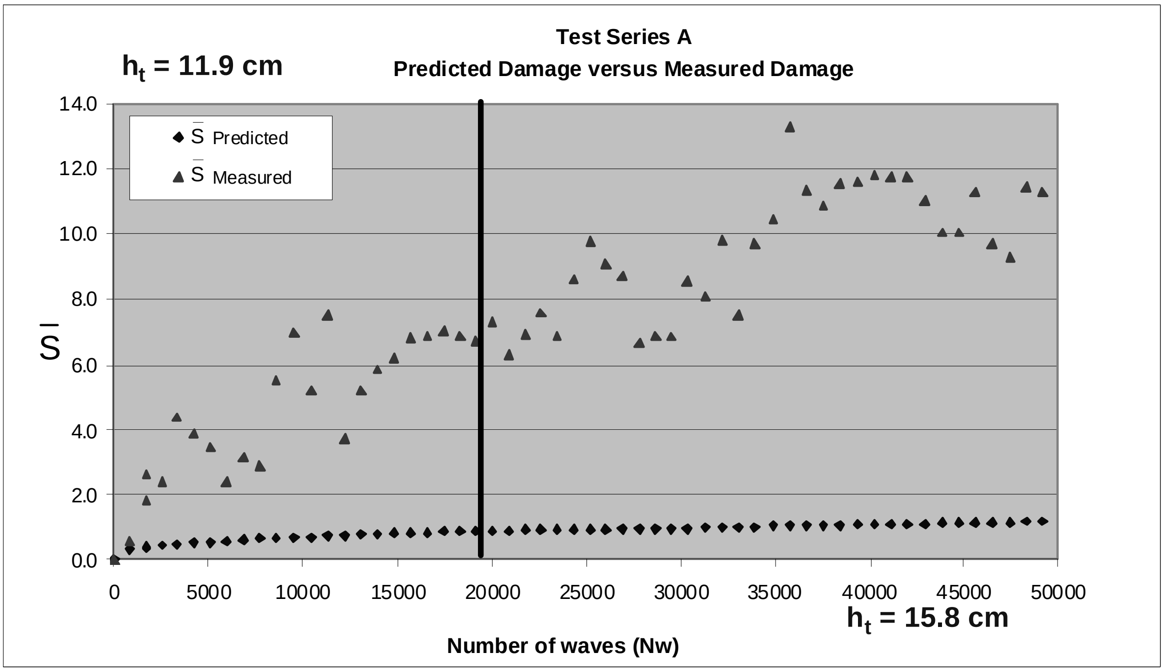


Figure 16. Test Series A. Predicted damage versus measured damage

6 Conclusions

In what concerns the applicability of the predicting formula for wave conditions different from the ones of the tests which led to the formulation, the main conclusion arisen from the study were:

- Although the structure geometrical characteristics were similar to that used in the tests which lead to the formulation, the wave propagation in the flume was different;
- The reproduced wave conditions in the present study were lower, in what concerns to wave height, than those used by Melby;
- The mean damage predicted values, estimated upon those wave heights, did not converged to the mean damage values measured during the model tests, due to a different wave breaking location;
- There is the need to adjust the formulation empirical coefficients to different types of wave breaking and also validate them with new scale model tests.

In what concerns the performance of the photogrammetric technique:

- It is of simple use. Nevertheless, the camera calibration procedure should be improved, since all the following procedures depend on it;
- It requires quite cheap equipment - only two photographic cameras;
- The survey data processing is not totally automatic, which can be a very time-consuming process, depending on the number of profiles to survey;
- There is the need to develop an additional software package, in order to speed up the survey data post processing;

The present work is part of an on-going study at LNEC. The continuity of the study comprises:

- To carry out more experiments in order to extend the use of similar formulae to different wave climate, as well as measuring the breakwater armour layer erosion in which artificial units are used;
- To create additional software, aiming to speed up the calibration and photogrammetric reconstruction data post-processing.

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