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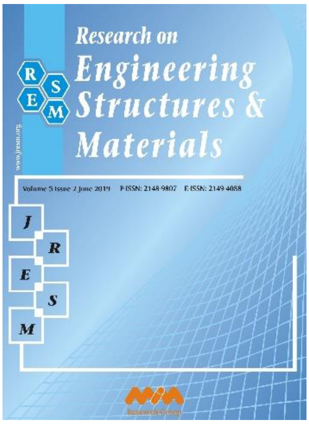

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Research Article

Damage progression in rubble-mound breakwaters scale model tests, under a climate change storm sequence

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Abstract

This paper describes the two-dimensional (2D) physical model tests of a rock armor breakwater, performed at LNEC´s experimental facilities, under the framework of the HYDRALAB+ project. The aim of the present work was to evaluate damage evolution under future climate change scenarios, by using different damage evaluation techniques. The tested wave conditions simulated a storm sequence where two water levels (low water and high water) were considered, as well as an increase of the wave height. The water levels and the wave heights were chosen to simulate extreme events forecasted on climate change scenarios. Damage evaluation was based on the traditional counting method and on stereo-photogrammetric techniques. Test results are presented in terms of the damage parameter S and in terms of the percentage of removed armor units. The analysis is focused on the damage progression during the scale model tests, for the imposed storm sequence. The damage presents an oscillating behavior with two main damage areas corresponding to the active zones for each level, due to the variation of the water level between low-water and high-water. This behavior differs significantly from that found for the common storm sequences usually tested, where the water level does not change. Both measuring techniques lead to an intermediate damage of the cross-section breakwater. However, the damage parameter assessment with the stereo-photogrammetric technique allows a more versatile evaluation, since it is possible to characterize damage in representative zones of the cross-section

1. Introduction

Most climate change scenarios predict, in addition to mean-sea-level rise, the increase of sea storminess, more frequent extreme events and changes of the dominant wave direction [1]. However, the actual failure probability of existing structures under such conditions is not known. To ensure an adequate performance of rubble-mound breakwaters in such scenarios, adaptive structures have to be designed, aiming at not increasing significantly the breakwaters' dimensions and the associated costs. This means that it is mandatory to characterize and measure further the response of these structures to climate change, in what concerns wave run-up, wave overtopping and hydraulic stability (damage), as well as how altered run-up/overtopping conditions impact the stability of both the main and the rear armors [1].

Project HYDRALAB+ (H2020-INFRAIA-2014-2015) gathers an advanced network of environmental hydraulic institutes in Europe, which provides access to a suite of

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environmental hydraulic facilities that through physical experiments plays a vital role in the development of climate change adaptation strategies, by allowing the direct testing of adaptation measures and by providing data for numerical model calibration and validation. The use of physical (scale) models allows the simulation of extreme events as they are now, and as they are projected to be, under different climate change scenarios.

Task 8.2 of RECIPE, one of the Joint Research Activities of the HYDRALAB+ project, entitled "Damage characterization under variable and unsteady test conditions", has as main objective to develop new innovative experimental techniques, methods and protocols to characterize damage evolution on structures under extreme events. Damage can be assessed using visual observation, profilers and/or photographic techniques. Digital overlay techniques are employed to assess rock and concrete unit movements. Photographs (taken before and after the test) and videos are also used to assess structural/toe stability. However, the success of each technique relies on the setting conditions (light conditions, camera characteristics, etc.), on the experience of the technician and on the need of emptying the flume to use the technique.

In this framework, LNEC's HYDRALAB+ team performed a set of physical experiments to simulate 2D damage and overtopping tests with a rock armor slope for extreme events (climate change). Overall, those tests aimed at developing and comparing different methodologies/techniques to measure and quantify the most important responses of hydraulic structures (wave run-up, wave overtopping and hydraulic stability) to the altered wave/water-level conditions due to climate change.

The main goals of the present work were to simulate a cumulative storm sequence, where the water levels (alternating low-water with high-water levels) varied with an increase of wave heights, and to study the damage evolution throughout the tests. To achieve these goals, two different measuring techniques were applied: displacement counting method and photogrammetric techniques.

In relation to damage characterization, note that some of the most commonly used damage indicators are the percentage of damage for all armor, N_d, the number of displaced blocks per width of one block, N_{od} (both based on counting the number of individual units that have been dislodged) and the dimensionless erosion area, S (based on determining the volumetric change in areas where armor units have been displaced) [2], [3] and [4]. Critical values of N_d, N_{od} and S for varying materials (rock, concrete armor units) and varying armor thicknesses are presented in the Rock Manual [3] and in the Coastal Engineering Manual [2].

This paper begins with the description of damage assessment and stereo-photogrammetric techniques. Then the physical model tests are described, and their results and discussion presented. Some conclusions are drawn in the final section of the paper.

2. Materials and Methods

2.1. Damage assessment

Damage in physical scale models of rubble-mound breakwaters can be characterized by two methods: counting the number of displaced units and measuring the eroded area of the profile. In the last case, Broderick & Ahrens [5] and Van der Meer [6] defined a dimensionless damage parameter, $S=A_e/(D_n)2$, where A_e is the eroded cross-sectional area around the still water level (SWL) (Figure 1) and D_n is the nominal diameter of the armor units.

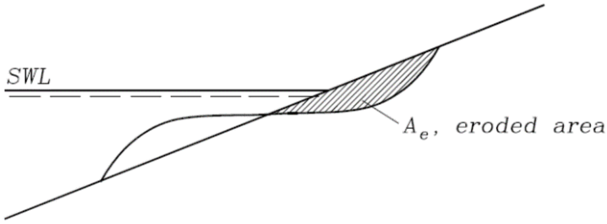

Fig. 1 Eroded cross-sectional area (A_e) [2]

Several measuring techniques can be used for the two damage assessment methods (number of displaced units or eroded area of the profile), such as, visual observation and stereo-photogrammetry. These techniques have the main advantage that they do not require emptying the flume/basin before measurements are taken. However, visual observation can only be applied to identify the unit displacements and movements, and it is very dependent on the technician experience. Stereo-photogrammetry can be applied to both damage progression methods since the counting method can be achieved by photos and the eroded area can be determined through comparison of cross-section profiles.

2.2 Stereo-photogrammetry

Stereo-photogrammetry consists of identifying depth from two different views of the same scene (stereo image pairs).

Stereopsis is the base of reconstructing a three-dimensional (3D) scene from a pair of images acquired from two slightly different locations. In the present study, the profile surveys were carried out with a fixed separation of 16 cm between the centers of the camera lenses.

The available software package allows a complete 3D reconstruction environment, using stereo image pairs as input. It consists of two distinct applications implemented in MATLAB™ [7], each with a specific objective:

- Camera calibration, which consists of identifying the parameters describing the projective cameras and their position and orientation within the observed world;
- Scene reconstruction, which consists of identifying depth from two different views of the same scene.

The output of the package consists of a (x, y, z) file describing the cloud of surveyed points. This is a standard file format that can be imported by various modelling tools. By using a MATLAB™ algorithm [8] and [9], it is possible to create regular grids, enabling to extract the breakwater surveyed surface, as well as profile definition, in order to quantify the eroded area (A_e) and, subsequently, the non-dimensional damage parameter S.

Since the used scene-reconstruction software rectifies the distortion introduced by the air-water interface, it is possible to reconstruct both the emerged and submerged scenes without emptying the flume/basin.

3. Physical Model Tests

3.1 Physical model setup and equipment

LNEC´s experiments were performed at the Ports and Maritime Structures Unit (NPE) of the Hydraulics and Environment Department (DHA), in a wave flume (COI 1) approximately 50 m long, with an operating width and an operating water depth of 80 cm (Figure 2). The flume is equipped with a piston-type wave-maker that combines both irregular wave generation and dynamic absorption of reflected waves.

Fig. 2 COI1 wave flume

The structure is a rubble-mound breakwater, with a 1:2 rock slope and a trapezoidal core covered by two rock layers with a porosity of ~37% and a rock nominal diameter, D_n, of 0.045 m (model scale).

The physical model was constructed and operated according to Froude's similarity law, with a geometrical scale of 1:30, to ensure reduced scale effects (with wave heights that lead to values of the Reynolds number, $Re = (\sqrt{gH_s}D_n)/\nu$, were higher than $3x10^4$, where g is the acceleration due to gravity (m/s^2) and ν is the kinematic viscosity of water (= 10^{-6} m^2/s).

The construction of the physical model began with the implementation at the flume of a foreshore slope of 2%. Then, the breakwater cross-section was built (Figure 3, top), with 0.80 m width. The slope of the breakwater was divided in three main parts, with the rocks painted with three different colors (red, yellow and blue). This procedure facilitates the identification of rock falls/movements and helped also the photogrammetric surveys. Finally, the experimental equipment was placed in the wave flume. The experimental setup is presented in Figure 3, bottom.

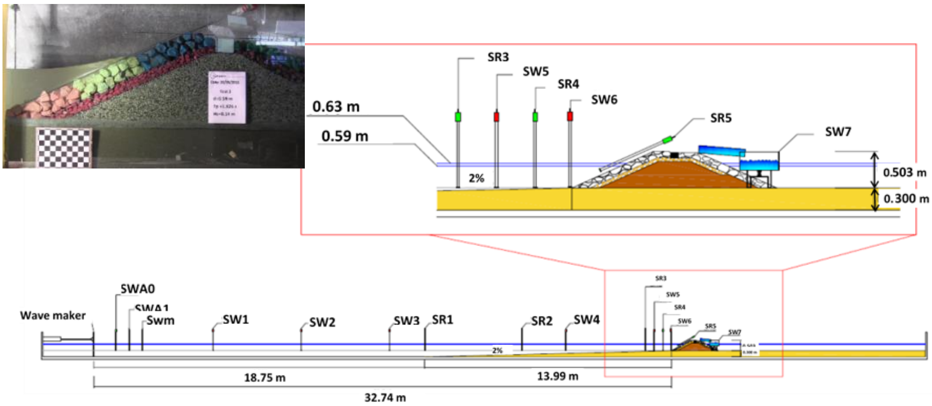

Fig. 3 COI1 wave flume

The flume was equipped with twelve resistive-type wave gauges deployed along the wave flume, to measure the free surface elevation (Figure 4, left). In order to measure run-up levels, an additional gauge was placed on the armor layer slope (Figure 4, right).

Fig. 4 . Measuring equipment. Left: wave gauges to measure free surface elevation; right: run-up wave gauge

As referred previously, for damage assessment, two methods were used. The counting of falls and movements of the armor units was performed by visual observation and by taking some photos of the breakwater cross-section with a common camera. The stereo-photogrammetric technique used two cameras mounted side by side in a support structure and able to photograph the same scene simultaneously (Figure 5, top). Throughout the tests herein described, two digital SLR cameras (Canon EOS 600D) were fitted with fixed focal length lenses (Canon EF 35mm *f*/2). This setup is capable of acquiring images ranging from 3.5 to 18 megapixel). All tests were filmed with 2 video cameras, one located above the model and the other placed next to the flume side wall (Figure 5, bottom). These cameras were used for run-up and damage measurements.

Fig. 5 Top: Photographic equipment. Bottom: Video camera for damage evaluation

3.2 Incident Wave Conditions

In the present work, a cumulative storm build-up was simulated. It represents a cumulative test series with constant wave period, alternating low-water and high-water levels, and increasing wave heights. The values of water levels and wave heights correspond to extreme events related with climate change scenarios.

In detail, the test conditions for Tests 10-17 are presented in Table 1, in which d represents the water depth at the toe of the structure, where low and high water levels correspond to d=8.1 m and d=11.1 m, respectively. Hs represents the significant wave height at the toe of the structure and T_p the peak period of the JONSWAP wave spectrum, with a peak enhancement factor of 3.3.

At the end of the test series 10-17, Test 16, was repeated three times, herein called Tests 16Rep1, 16Rep2 and 16Rep3. The test duration was 2400 s for the prototype peak period of 12 s (around 1000 waves).

Table 1. Test conditions at structure toe.

Test	Prototype			Model		
	d (m)	T_p (s)	H_s (m)	d (m)	T_p (s)	H_s (m)
10	11.1	12	3.2	0.37	2.191	0.107
11	8.1	12	3.2	0.27	2.191	0.107
12	11.1	12	3.7	0.37	2.191	0.123
13	8.1	12	3.7	0.27	2.191	0.123
14	11.1	12	4.2	0.37	2.191	0.140
15	8.1	12	4.2	0.27	2.191	0.140
16	11.1	12	4.7	0.37	2.191	0.157
17	8.1	12	4.7	0.27	2.191	0.157
16Rep1	11.1	12	4.7	0.37	2.191	0.157
16Rep2	11.1	12	4.7	0.37	2.191	0.157
16Rep3	11.1	12	4.7	0.37	2.191	0.157

4. Results and Discussions

4.1 Counting method

Figure 6 presents an overview of the cross-section before Test 10, after Test 16 and after Test 16Rep3, respectively.

Fig. 6 Overview of the cross-section before Test 10 (left), after Test 16 (center) and after Test16Rep3 (right)

With the photos taken with the photogrammetric cameras it was much easier to count the number of rocks that fell down than by using visual observation. These values are presented in Table 2.

Table 2. Number of displaced blocks (N) and relative displacement (D) for Tests 10 to 17 and repetitions of Test 16.

Test	10	11	12	13	14	16	17	16 Rep1	16 Rep2	16 Rep3
N	5	6	8	8	9	11	13	14	14	15
D (%)	4.0	4.8	6.5	6.5	7.3	8.9	10.5	11.3	11.3	12.1

Figure 7 presents the cumulative damage curve in terms of percentage of displaced blocks (N) over the total number of blocks of the active zone, D (%).

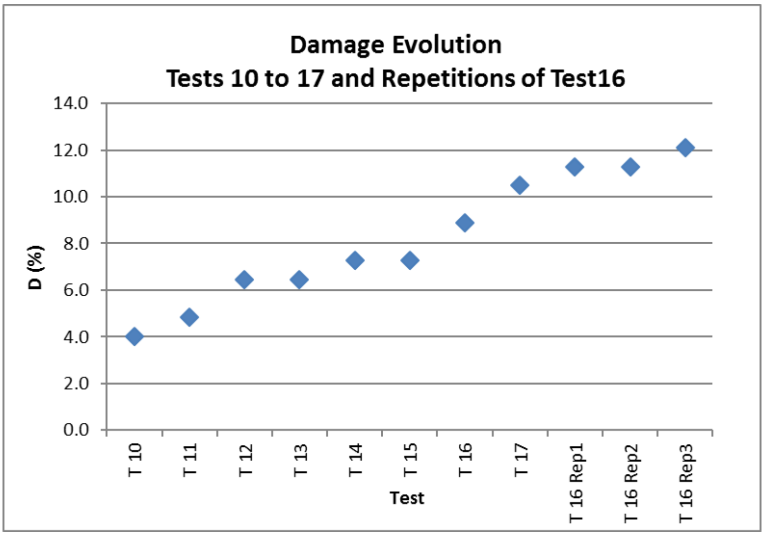

Fig. 7 Damage in terms of percentage of displaced blocks

According to the damage classification referred in the Coastal Engineering Manual [2], the cumulative damage at the end of Test 17 and Test 16Rep3 corresponds to an intermediate damage (units are displaced but without causing exposure of the under or filter layers to direct wave attack).

From the analysis of the damage curve one can infer that damage progression increases with the wave height, with some stabilization during tests with the low-water level. During the repetitions of Test 16, a damage stabilization is visible between Tests 16Rep1 and 16Rep2, and a slight increase with Test 16Rep3, mainly due to an additional displaced block near the active zone for the high-water level.

Figure 8 (left) illustrates image comparison, using an image analysis algorithm, between photos taken before Test 10 and after Test 16, with a modified area of 1327.1 cm^2 (9.6% of the photo total area). Figure 8 (right) depicts damage evolution between Tests 16 and 16Rep3, with a modified area of 1240.4 cm^2 (9.0% of the photo total area).

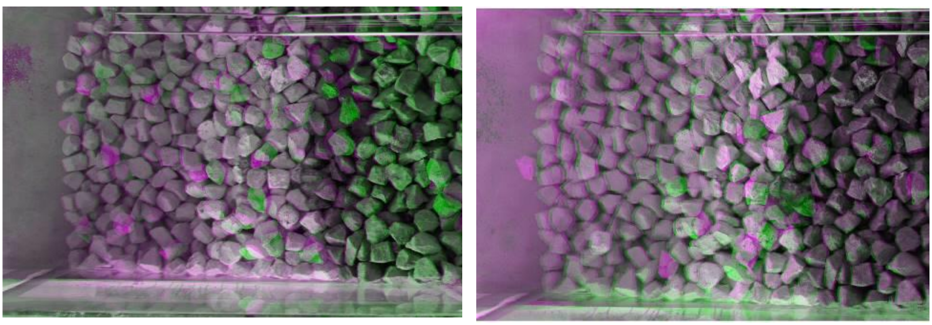

Fig. 8 Left: Differences between photos taken before Test 10 and after Test 16.
Right: photos taken after Tests 16 and 16Rep3

The algorithm overlaps final image (magenta) with initial image (green), calculating the area of the changed zones of the photos. This calculation is proceeded by calibration of the area of a square of a checkerboard.

Although this algorithm does not distinguish between erosion and accretion areas, it was a helpful tool for detecting stone displacements. Furthermore, the damage evolution trends calculated both with the photo modified area and with add up of displaced blocks are similar.

4.2 Calculation of the non-dimensional damage parameter (S)

For a better damage characterization, the armor layer was divided in five profiles, 10 cm apart (Figure 9). During the test series, a survey of the undamaged profile was carried out (T0) and 7 surveys (T10 to T17) were conducted to compare the eroded area between consecutive surveys. Furthermore, three repetitions of Test 16 were conducted, in order to infer on the reliability of the measurements (T16Rep1, T16Rep3 and T16Rep3). Due to problems with photo acquisition during Test 15, its results are not presented.

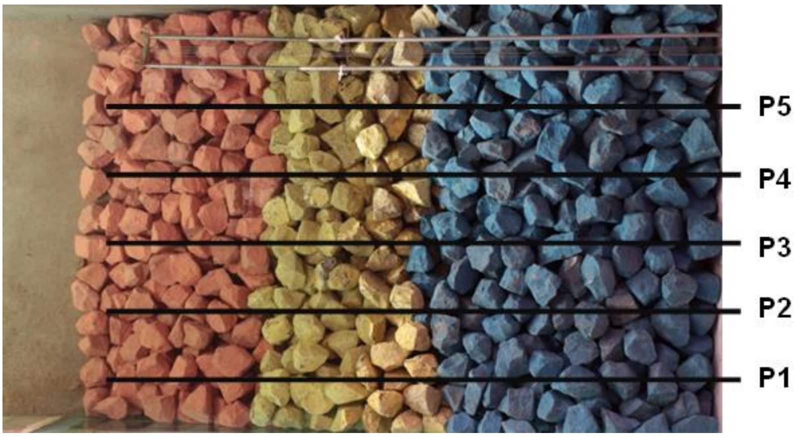

Fig. 9 Location of surveyed profiles

To obtain the eroded area for all the profiles, a MATLAB™ code [8], was used, having as input the point clouds resulting from the reconstruction files. It enables to extract the pre-defined profiles for all the surveys, including the initial survey (undamaged profile, T0). The second step of the code compares all the profiles with their initial surveys and measures the corresponding eroded areas. Finally, the last step of the code consists in the calculation of the S parameter.

The most relevant eroded area occurred around the SWL, between x=0.35 m and 0.7 m. Figure 10 (left) and Figure 10 (right) present the surveys at profiles P2 and P4, respectively, where x is the cross-shore distance and z the elevation of the profiles. These two profiles were the most representative profiles of damage since they do not suffer the influence of the flume side walls (friction conditions between units and glass are different than friction between units). Figure 11 illustrates the non-dimensional damage parameter (S) evolution for profiles P1 to P5 during the test sequence.

The main advantage of this technique is the fact that one can choose the number and the position of the profiles even after finishing the survey.

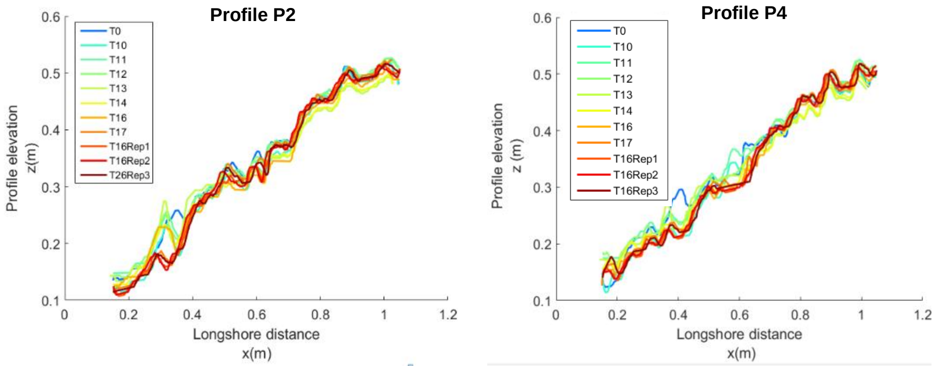

Fig. 10 Profile P4. Surveys for Tests 10 to 16Rep3 for Profile P2 (left) and for Tests 10 to 16Rep3 (right)

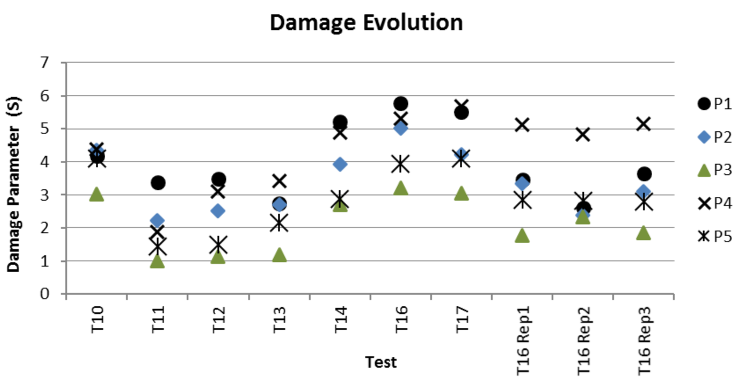

Fig. 11 Non-dimensional damage parameter, S, for Profiles P1 to P5

The analysis of Figures 10 and 11 shows a clear influence of the water-level variation between tests with low-water and high-water levels. There are two main eroded areas corresponding to low and high tides (Figure 10). There are significant damage differences between the profiles during the test series, since the central area of the cross-section (profiles P2 to P4) is the zone where there is more damage (although P3 presents lower damage than the other profiles) and it does not suffer the influence of the flume side walls, as P1 and P5 do.

Table 3 summarizes the non-dimensional damage parameter S obtained for each profile at the end of Test 16Rep3.

Table 3. Damage obtained at the end of Test 16Rep3.

Profile	P1	P2	P3	P4	P5
S	3.65	3.10	1.85	5.15	2.80

The average of the damage parameter for the five profiles at the end of Test 16Rep3 is 3.3, which, according to the damage classification proposed by Van der Meer [6] (Table 4), for a 1:2 rock slope, corresponds to initial/ intermediate damage. Nevertheless, P4 (S=5.15) is in intermediate damage.

Table 4. Damage level by S for a two-layer rock armor [6].

Armor Slope	Initial Damage	Intermediate Damage	Failure
1:1.5	2	3-5	8
1:2	2	4-6	8
1:3	2	6-9	12
1:4-1:6	3	8-12	17

The average damage only for profiles whose damage may represent the whole section damage (P2, P3 and P4, because they do not suffer the influence of the flume walls) is 3.36, which is quite similar to the one obtained with the five profiles.

5. Conclusions

This paper describes two-dimensional physical model tests of a rock-armor breakwater to characterize the damage evolution under future climate change scenarios, by using different damage evaluation techniques, such as counting the number of armor blocks that fall/move and the damage parameter S, which is the ratio between the eroded cross-sectional area around the still water level and the square of the nominal diameter of the armor units, $S=A_e/(D_n)^2$.

Cumulative test series with a constant wave peak period, varying between high-water and low-water levels, and increasing wave heights were simulated. Two different measuring techniques were applied to calculate the number of falling blocks and the damage parameter S. In the last case, five profiles were considered.

One noticed that due to the fact that the water level alternates between low-water and high-water, the damage also presents an oscillating behavior, with two main damage areas corresponding to the active zones for each level. This behavior differs significantly from that found for the common storm sequences usually tested, where the water level does not change.

Both measuring techniques lead to an intermediate damage of the cross-section breakwater. However, the damage parameter assessment with the stereo-photogrammetric technique allows a more versatile evaluation, since it is possible to characterize damage in representative zones of the cross-section.

Although in the present work only five profiles were considered for the average damage, one can assume that this can lead to some errors in the evaluation of the eroded area. So, it is recommended to use a higher number of profiles or, alternatively, one can measure the eroded volume and divide it by the length of the section [10]. This still needs further research, since it may not be applicable in cases where the damage is much localized.

6 Acknowledgements

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