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EVALUATING BREAKWATER DAMAGE PROGRESSION: EXPERIMENTAL AND THEORETICAL INSIGHTS

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ABSTRACT

The ProCoast-3D project aims at the development, application and testing of methodologies for predicting the structural behavior of rubble-mound breakwaters (RMBs), as part of a decision support system for the planning and prioritization of maintenance/repair work developed at LNEC, to increase the safety, functionality, and resilience of RMBs in the face of climate change.

The study uses both experimental data (through 3D wave basin simulations) and theoretical models to analyze the progression and variability of damage for Ericeira's breakwater. This combination allows to create a more accurate representation of the breakwater's behavior under different wave conditions.

Melby and Kobayashi's damage evolution formulae to rubble-mound breakwaters are revisited to reflect the specific behaviour of tetrapod armour layers. The study proposes recalibrating the empirical coefficients to improve the prediction of damage evolution in breakwaters with tetrapod armor layers, through the application of 3D long-duration experimental tests and probabilistic and statistical methods offering deeper insights into their structural behavior under wave action.

Keywords: *3D physical experiments; tetrapod armour layer; Ericeira's breakwater; photogrammetry; probabilistic and statistical methods*

1. Introduction

Rubble mound breakwaters protect ports from wave action and are the most common type of breakwaters in Portugal suitable for regions with severe wave conditions. They have an approximately trapezoidal cross-section, consisting of a core of stones covered by larger rock armor or concrete blocks (Fig. 1). The progressive nature of their failure, mainly in the armour layer, is one of their characteristics, allowing for timely repairs.

Fig. 1. Breakwater armor layers composed of a) rock units (Vila Praia de Âncora); b) and c) concrete units (Viana do Castelo,Foz do Douro)

The random nature of waves impacting RMBs, the effects of climate change, the high capital investment in their construction and their importance for port protection justify regular monitoring of the behavior of RMBs to identify maintenance and repair needs, thereby avoiding greater risks/costs.

2. Damage Mechanisms and Progression

The study of damage progression in RMBs has evolved significantly over the years, reflecting advancements in theoretical models, empirical research, and experimental techniques.

The earliest studies on breakwater stability, including those by Hudson (1959), provided foundational insights into how waves impact coastal structures. The Hudson formula offered a simple, static relationship for calculating armor unit size based on wave height and structure slope. However, it lacked the ability to account for the progressive nature of damage and assumed a deterministic response from the structure. As a result, its application was limited when assessing long-term breakwater performance under wave attack.

A significant leap in understanding dynamic breakwater damage came with the work of Van der Meer (1988). His semi-empirical formula introduced the concept of gradual damage accumulation due to wave action, incorporating variables like wave height, wave period, and structure permeability. The Van der Meer formula used the damage parameter S to quantify the level of damage based on the displacement of armor units, marking a shift from static to dynamic models. This approach allowed engineers to predict damage progression more accurately over the course of a storm or series of wave events.

Building on Van der Meer's findings, Melby and Kobayashi (1999) developed a more detailed wave-by-wave damage accumulation model. Recognizing the cumulative and random nature of wave impacts, their model emphasized that each wave event incrementally contributes to the overall damage of the breakwater. The Melby-Kobayashi model is expressed as:

$$S_i = S_{i-1} + A_{Si} T_{m_i}^{-b} \left(t_i^b - t_{i-1}^b \right) \tag{1}$$

where S_{i-1} is the known damage level at $t = t_{i-1}$, T_{m_i} is the mean wave period during the period from $t = t_{i-1}$ to $t = t_i$. A_{S_i} is an empirical coefficient that includes wave height, armor size, and other parameters and b is an empirical coefficient related to the duration of wave attacks, typically *b=0.5*. $A_S = a_S \left[{H_S}/{(\Delta D_{n50})} \right]^5$ where a_S is the empirical coefficient resulting from the adjustment of the expression to the results of the scale-model tests, permeability P, and slope of the armour unit $\tan \theta$, and Hs the significant wave height, Δ the relative density and D_{n50} the nominal size of armor stones.

Melby (1999) further refined his understanding of damage progression on rubble mound breakwaters by conducting long-term experimental studies. His research confirmed that damage evolves in stages, with initial minor displacements of stones or armor units leading to more significant damage as exposure to wave action continues. Melby's findings emphasized the variability in structural response due to the random nature of wave conditions and how infrequent extreme waves contribute disproportionately to overall damage.

Recognizing the limitations of deterministic models, Castillo et al. (2012) introduced a stochastic approach to damage modeling. They treated the damage parameter S as a random variable, reflecting the inherent variability in wave conditions and the response of the breakwater. By incorporating probabilistic distributions for wave heights, periods, and armor displacement, Castillo's model allowed for more nuanced predictions of damage progression, especially under extreme storm conditions.

More recently, Lemos et al. (2023) investigated how to predict damage evolution of rubble-mound breakwaters with tetrapod armor layers, using the Ericeira Harbor breakwater as a case study. The study expands on Melby's formula, which traditionally applies to rock armor layers, by developing a similar predictive model for tetrapods. Long-duration 2D test series were conducted with a 1:50 scale model of the quay section of the Ericeira Harbour breakwater. These tests measured the eroded volume of the armor layer using a Kinect position sensor. The damage parameter values measured in the experiments were lower than those predicted by the formulation for rock armour layers since damage progression in tetrapod layers follows a smoother, slower evolution compared to rock armor layers. Tetrapods exhibit greater stability than rock armor units due to their interlocking nature and high porosity, which helps redistribute loads and fill voids left by previous displacements. New a_p and b coefficients for the Melby formula for the tested armour layer were established by Lemos et al. (2023) based on the minimum root mean square error between the measured and the predicted damage. The adjusted coefficients for the tetrapod armor layer were $a_p=0.030$ and $b=0.16$, offering a more accurate prediction of damage evolution.

3. Experimental and Theoretical Approach

3.1. Refining the empirical coefficients for tetrapod's

This study proposes recalibrating the empirical coefficients to improve the prediction of damage evolution in breakwaters with tetrapod armor layers, offering deeper insights into their structural behavior under wave action.

For Melby (1999), the existing empirical coefficients were developed for rock armor. This methodology will allow adjustments to the formula that more accurately represent how tetrapods resist progressive damage through their interlocking and energy-dissipating features. Moreover, the adjusted coefficients by Lemos et al. (2023) will be verified and refined through the application of 3D experimental tests.

The Melby and Kobayashi (1999) wave-by-wave damage model tracks incremental damage from each wave event. This study can provide more precise data on how individual wave impacts incrementally damage tetrapod layers, allowing for a more accurate calibration of wave-induced damage coefficients in the formula. This would enhance the prediction of damage progression in tetrapod-based breakwaters.

In addition, the incremental damage progression model can be enhanced by capturing how small-scale, localized damage in the tetrapod armor layer can lead to larger-scale structural weaknesses over time, especially under long-duration wave attacks.

3.2. Case study – Ericeira's breakwater

The Ericeira breakwater, built in the 1970s, is located on the western coast of Portugal, and is an important coastal protection structure designed to shield the town's harbor from Atlantic waves and storms (Fig. 2). Ericeira is a popular fishing village and surf destination, so the breakwater plays a key role in protecting both local infrastructure and maritime activities.

The Ericeira breakwater has been repaired multiple times, particularly after major storms in the 1990s, 2001, 2007, 2013, and 2018. Each of these events involved significant interventions to restore displaced armor units, replenish core material, and reinforce the overall structure to withstand future wave action. Regular maintenance continues to be an essential part of keeping the breakwater operational and effective in protecting the harbor.

The breakwater is 440 m long, and the cross section (Fig. 2, Fig. 4) is composed of three layers: outer armor of 300 kN tetrapods, filter of 20–40 kN stone and a core of sand and gravel. On top of the breakwater, there is a concrete crown-wall

Fig. 2 .Breakwater of Port ofEriceira

3.3. Physical model and test conditions

The study is conducted at the Ports and Maritime Structures Unit (NPE) of the Hydraulics and Environment Department of the National Laboratory for Civil Engineering (LNEC), in Lisbon, Portugal. The wave basin used is 46.6 m long, 20.6 m wide and 1.5 m deep equiped with a piston-type wave generation system. The model represents the port basin up to the entrance (Fig. 4).

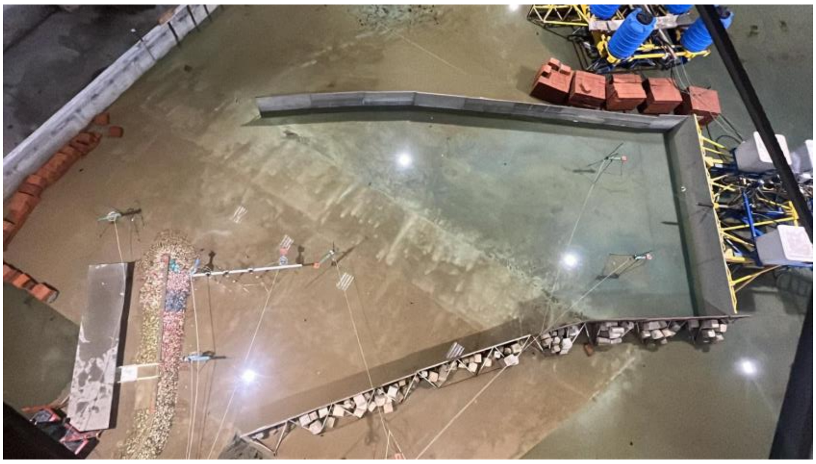

Fig. 3. Physical model of Ericeira breakwater. Scale 1:65

The tested breakwater has a 2:3 slope and a two-layer rock filter covering the core. The armour layer of the sections of the breakwater (Fig. 4) is composed of:

- Trunk: 300 kN tetrapod with a nominal diameter of 0.034 m and a porosity of 0.45;
- Head: 550 kN Antifer cubes with a nominal diameter of 0.042 m and a porosity of 0.30.

The geometrical scale of 1:65 was selected taking into account the experimental facility dimensions, size of the coastal area of interest, expected quality of results (i.e. scale effects) as well as operational and economic issues. Dissipative beaches were installed to minimize unwanted reflections from the wave basin side-walls.

The experimental equipment used consists of 8 resistive wave gauges to measure the water free surface elevation. A kinect position sensor was used for the breakwater survey, at beginning of the test series and at the end of each test.

The wave conditions tested are defined based on hindcast data and buoy measurements. These conditions cover the expected range of states for the breakwater, including extreme events and the effects of climate change on waves and water levels.

Three test series were conducted in the current experiments (**Table *1***): Test series A, lasting 28.5 h, was intended to provide an indication of the long-term deterioration of the structure. The model structure shown in Fig. 4 was exposed to waves 1-5 in sequence until stability. The water level was low for waves 1-3 and high for waves 4-5. The wave heights increased from wave 1 to wave 3, and from wave 4 to wave 5. The wave conditions were changed when the damaged profile became stabilized visually.

Table 1. Water levels and wave conditions for test series A, B and C

Series	Test	Hs S5 (m)	Tp S5 (m)	Depth (m)	Number of tests
A	1	5.0	14.0	37.05	Until stability
	2	6.0	14.0	37.05	Until stability
	3	7.0	14.0	37.05	Until stability
	4	6.0	16.0	39.0	Until stability
	5	7.0	16.0	39.0	Until stability
B	1	5.0	14.0	37.05	1
	2	6.0	14.0	37.05	4
	3	7.0	14.0	37.05	4
	4	6.0	16.0	39.0	4
	5	7.0	16.0	39.0	2
C	4	6.0	16.0	39.0	4
	5	7.0	16.0	39.0	2
	1	5.0	14.0	37.05	4
	2	6.0	14.0	37.05	4
	3	7.0	14.0	37.05	4

Test series B and C were intended to compare cumulative damages caused by different sequences of storms as listed in Table 1, where the B and C series lasted 7.65 h and 9.10 h,respectively. In series B, waves 1-3 at the low water level were run first, followed by waves 4 and 5 at the high water level. In series C, waves 4-5 at the high water level were followed by waves 1-3 at the lower water level.

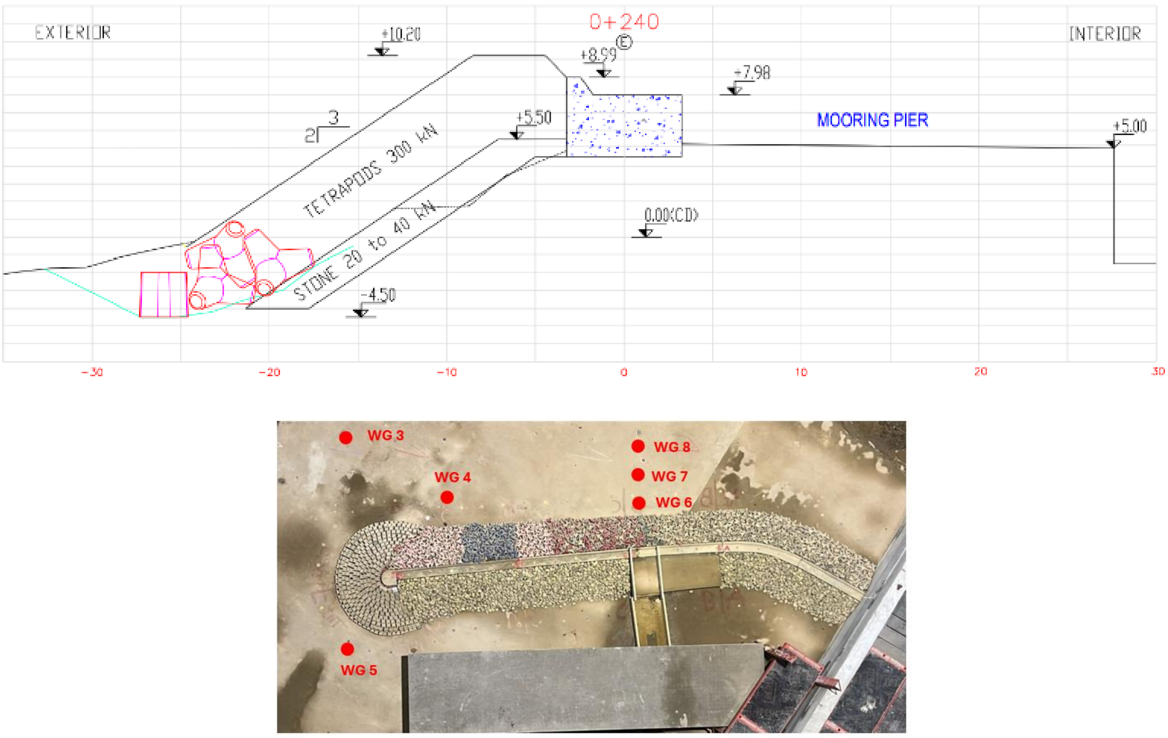

Fig. 4. Upper: Trunk cross-section; lower: Overview of the represented 3D scale model.

3.4. Methods

To validate and enhance the Melby (1999) and Melby and Kobayashi (1999) formulae, comprehensive three-dimensional (3D) long-duration experimental tests were conducted. These tests employed two armor layers of tetrapods with a 2:3 slope for Ericeira's breakwater, thereby extending the applicability of the Melby and Kobayashi (1999) model, which was originally developed for a 1:2 seaward slope subjected to depth-limited breaking waves on a 1:20 beach slope. The study aims to provide insights into the response of tetrapod breakwaters to repetitive wave impacts and storm events, capturing both short-term reactions and long-term degradation of the armor layer. This is particularly crucial for validating the wave-by-wave damage accumulation described by the Melby and Kobayashi (1999) formula, ensuring that it accurately represents the progressive deterioration characteristic of tetrapod structures.

The 3D tests enable the monitoring of tetrapod wear, erosion, and displacement across different sections of the breakwater, emphasizing the spatial variability of damage within rubble mound breakwaters as observed by Melby and Kobayashi. Such variability is influenced by wave height, wave period, and the structural characteristics of the breakwater, including the size and shape of the armor units. Damage assessment was conducted based on eroded area/depth and the number of displaced blocks, utilizing data acquired from Kinect V2 sensors. Each sensor was equipped with an RGB camera and a depth sensor, with data analyzed using CloudCompare software.

The characterization of damage in rubble mound breakwaters depends on factors such as structural typology, design specifications, and the type of armor units used. Damage is commonly defined by the extent of reshaping of the armor layer and is associated with the failure mode. It can be quantified by the eroded volume or the number of displaced units (Campos et al., 2020a). An appropriate damage descriptor must be employed to effectively assess breakwater stability. A frequently used approach is displacement counting, where damage (D) is correlated with various movement definitions, including rocking. The relative number of moving units can be further compared to the total number of units within a vertical strip of width equal to the nominal diameter (Dn), extending from the bottom to the top of the armor layer. Van der Meer (1988) introduced the parameters Nod for units displaced out of the armor layer and Nor for rocking units. However, a limitation of Nod and Nor is their dependence on slope (strip) length (CEM, 2011).

In the present study, the dimensionless damage parameter, $S = Ae/D_n^2$, as defined by Broderick (1983), was employed. Here, Ae represents the eroded area of the profile, while Dn denotes the nominal diameter of the tetrapod unit. The parameter S can be interpreted as the number of squares with a side length of Dn50 that fit into the eroded area. Recent advancements in 3D survey techniques, including LIDAR, photogrammetry, and artificial vision algorithms, have facilitated the combination of multiple damage descriptors. Given the complexity of defining a surface profile for tetrapods, the damage parameter S is less suitable. To address this, the mean eroded area was computed using the total eroded volume of the entire armor layer. Specifically, the section mean eroded area (Ae) was determined by dividing the eroded volume (Ev) at the end of a test run by the stretch to be analysed width (X = 0.64 m). Consequently, the dimensionless damage parameter was obtained as $S = Ae/Dn^2$.

The Kinect© position sensor was utilized for damage evolution assessment. Positioned 2.0 m above the breakwater crest within a fixed structure above the basin, the sensor generated a 3D model of the armor layer. Depth acquisition was based on the Time of Flight (ToF) method, wherein the distance between surface points and the sensor was calculated from the light signal's travel time upon reflection. The Kinect© sensor had the following survey parameters: voxel volume resolution for the three coordinate axes (x, y, z) set at 512, voxel density of 256 per meter, and an acquisition distance ranging from 0.5 m to 8 m. Surveys were conducted without water in the basin at the beginning and end of each test series, as well as with water following intermediate tests.

To reference the point clouds obtained from the surveys, 71 ground control points (GCPs) were established using colored markers placed at the channel bottom, near the toe of the armor layer, and on the superstructure. The coordinates of these GCPs were recorded using a total station prior to the initiation of the test series. Post-processing of submerged surveys involved aligning point clouds with those obtained from dry conditions to correct for submerged parts, as the infrared sensor's penetration capacity is limited to water depths of less than 0.05 m. This fine alignment was achieved using the Iterative Closest Point (ICP) algorithm (Chen & Medioni, 1991), implemented in the open-source software CloudCompare (Girardeau-Montaut, 2006).

The computation of eroded volume relied on a gridding process, where an optimal grid step was determined for accurate volume estimation. The contribution of each cell to the total volume was calculated as dV = grid step × grid step × distance difference between clouds. Various grid steps (ranging from 1 mm to 10 mm) were tested, with 2 mm found to provide the best balance between point density and depth accuracy. Smaller grid steps led to an overestimation of depth, whereas larger steps resulted in significant point loss. This methodology ensured precise measurement of erosion patterns and damage accumulation in the tetrapod armor layer.

4. Data Analysis

The damage characterization obtained from the survey of the armor layer across the entire usable section of the breakwater allowed for the computation of the total eroded volume. The average eroded area was then determined by dividing this eroded volume by the section width (0.72 m). It is important to note that this value represents an average; individual eroded areas within different profiles may vary due to the spatial heterogeneity of damage distribution.
Fig. 5 presents the point clouds obtained from Kinect© sensor surveys conducted at the beginning and end of test series A (T4, T8, T12 and T15), along with a map depicting the distance variations between the two point clouds. The results summarized in Table 3 provide the measured damage values (S) recorded at the end of each test run, each consisting of 1000 waves, for test series B. The damage level remains within the "start of damage" classification, with minor variations influenced by water level and peak period, while increasing with significant wave height (Fig. 6).

For test series B (Figure 8, Table 4), damage progression is observed to increase with rising water levels and peak periods. At the conclusion of the low water level (LWL) tests, the damage level remains in the "start of damage" phase. However, at the onset of high water level (HWL) tests, the damage level escalates to the "Intermediate Damage" category (Figure 9).

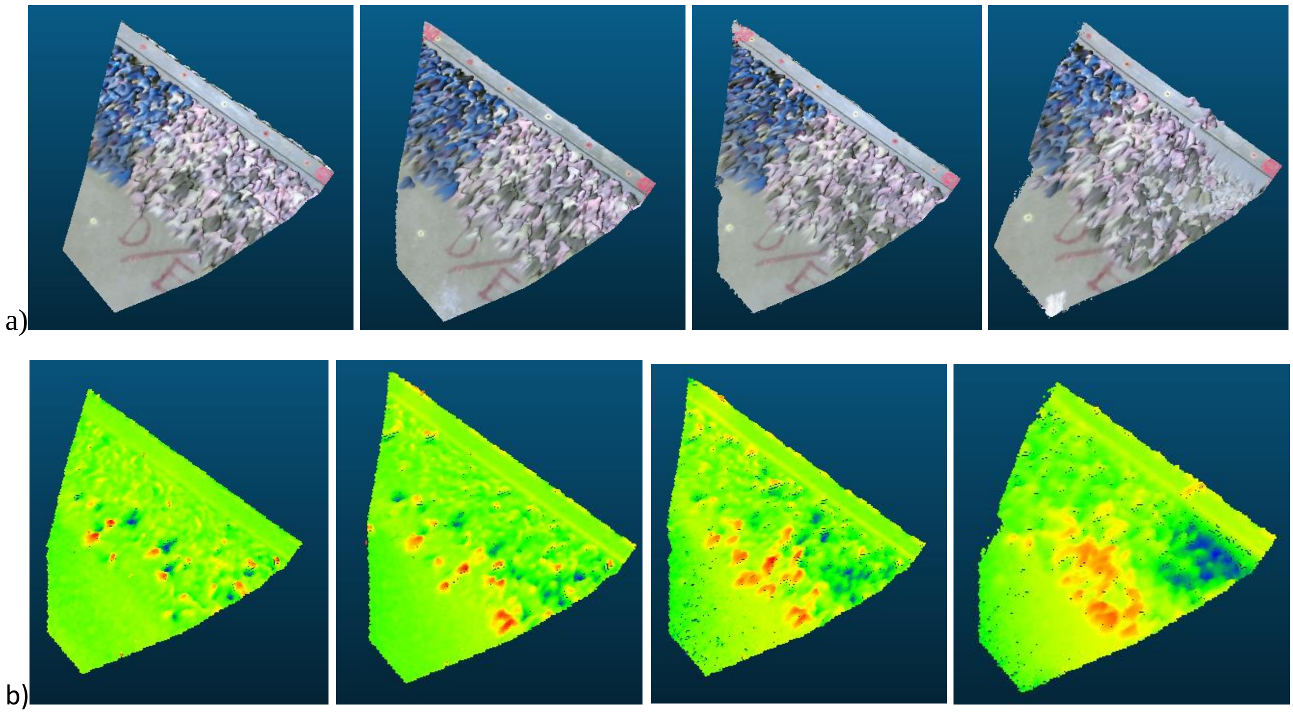

Fig. 5. Survey conducted for Test T4, T8; T12 and T15 of test series B. a) Clouds of points of the surveys b) Distance map (blue: erosion; red: deposition)

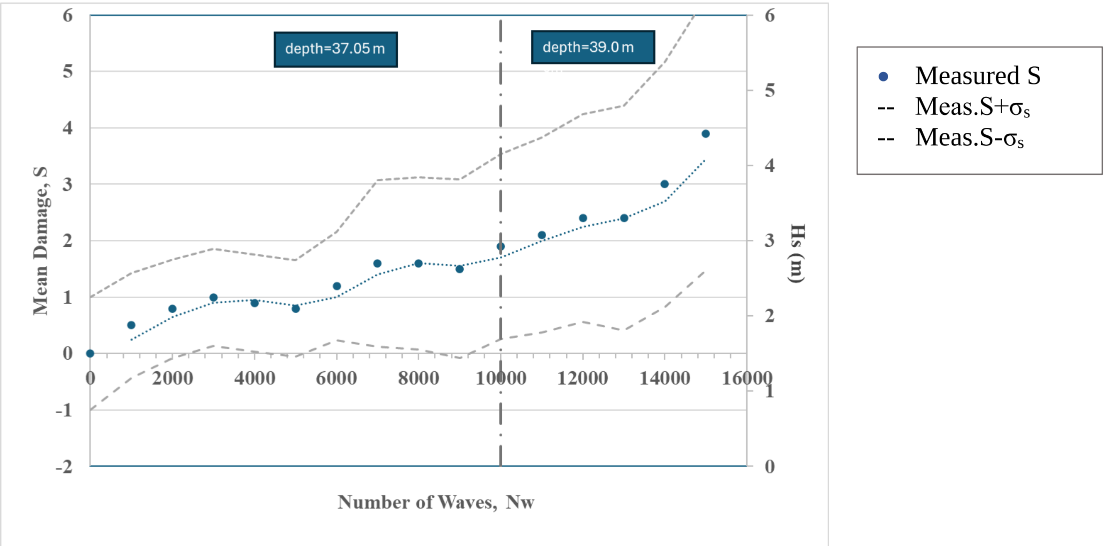

Fig. 6. Mean damage and damage variation as function of storm duration and wave height for Series B.

5. Conclusions

This paper described the three scale model test series (A, B and C) with different test sequences and durations, whose objective was to evaluate damage evolution of a stretch of the Ericeira harbour west breakwater. Damage measurement was made using the Kinect© position sensor, which proved to be quite effective in obtaining three-dimensional surface models of the armour layers (tetrapods) of the breakwater model. It was possible to obtain damage measurements, such as volume and eroded area. The comparison between initial and final clouds of points resulting from the model survey, enabled to compute the eroded volumes. The damage descriptor S computation was based upon the eroded volume and evolved with different trends for the three-test series.

Probabilistic and statistical methods will be applied to account for the random nature of wave impacts, which directly influence the cumulative damage on breakwater structures. As noted by Melby and Kobayashi's

(1999), it may be necessary to introduce the critical stability number, as a large number of small waves between storms could otherwise artificially increase damage. The empirical coefficients As, ap and b are derived from statistical fitting of the experimental data.

The probability of exceeding critical damage will be evaluated using the simulated cumulative damage distributions. As damage progresses, the structure approaches a point where it may become unrepairable or fail catastrophically.

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