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# 3D SURVEY MODELLING FOR DAMAGE ASSESSMENT IN RUBBLE-MOUND BREAKWATERS UNDER OBLIQUE WAVE INCIDENCE

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## EXTENDED ABSTRACT

La misura dell'evoluzione del danno sui modelli fisici in scala di una diga frangiflutti può essere ottenuta mediante i metodi tradizionali, attraverso il confronto tra i profili erosi, rappresentativi della sezione di testata, determinando l'area erosa come differenza tra rilievi consecutivi. Tuttavia, questo tipo di stima del danno è adatto solo per modelli 2D o per modelli 3D rappresentativi di un tratto della struttura.

Attualmente, le nuove tecniche di rilievo, mediante laser scanner o metodo del Time of Fly (ToF), consentono di effettuare rilievi tridimensionali, con l'obiettivo di ottenere modelli digitali del terreno, a partire dall'acquisizione di nuvole di punti. Le nuvole di punti possono essere elaborate attraverso un elevato numero di software, offrendo la possibilità di estrarre profili trasversali e, quindi, stimare l'erosione della struttura. Nonostante i grandi progressi, il rilievo di modelli digitali tridimensionali di tali tipi di strutture risulta essere ancora difficile, in quanto l'erosione è fortemente influenzata dagli spazi tra gli elementi artificiali costituenti la mantellata che potrebbero essere erroneamente considerati segno di una potenziale erosione della struttura. Pertanto, è necessario condurre ulteriori indagini al fine di ottimizzare i parametri di post - elaborazione delle informazioni raccolte durante i rilievi sui modelli in scala.

Una ulteriore difficoltà che si riscontra nella progettazione di tali tipi di strutture è rappresentata dalla necessità di dover considerare gli effetti indotti sulla stabilità degli elementi di mantellata dagli attacchi ondosi non perpendicolari, specialmente per onde incidenti inclinate rispetto la struttura di un angolo superiore a 45°, per i quali vi è un incremento di stabilità e sono disponibili pochi dati.

Al fine di superare i suddetti limiti, è stata condotta una campagna sperimentale su modello fisico in scala nell'ambito del progetto TA HYDRALAB+ "RODBreak". L'obiettivo principale del progetto è di approfindire lo studio del fenomeno, al fine di mitigare nel lungo periodo l'impatto dell'innalzamento del livello medio del mare sulle strutture di difesa costiera europee.

La campagna sperimentale è stata condotta su un modello fisico 3D presso il laboratorio di Marienwerder dell'Università di Leibnitz di Hannover (LUH). Durante i test sono state misurate le condizioni ondose, la risalita delle onde, la portata di tracimazione e il danno sugli elementi costituenti la mantellata di una diga frangiflutti soggetta ad attacco ondoso obliquo.

Il presente lavoro riporta l'evoluzione del danno subito dalla struttura nella sezione di testata indotta da onde estreme non perpendicolari alla struttura e le nuove metodologie non intrusive utilizzate per il rilievo degli elementi di mantellata, mediante l'utilizzo del sensore del movimento Kinect ©, utilizzando come riferimento per le misure un rilievo eseguito mediante laser scan (Faro Focus 3D). Gli obiettivi principali del presente lavoro sono: i) valutare l'evoluzione del danno dello strato di mantellata del modello fisico; nel presente lavoro si riportano i risultati di 4 set di test (su 11 test totali condotti durante la campagna sperimentale) al fine di confrontare l'evoluzione del danno della struttura in differenti condizioni d'onda, direzioni e directional spreading (onde lunghe e corte); ii) testare la metodologia ToF con il sensore Kinect ©, al fine di valutare l'evoluzione dei volumi erosi globali e locali, utilizzando rilievi intermedi condotti in presenza di acqua e iii) stimare il numero di elementi della mantellata spostati, usando un parametro di danno adimensionale basato sul volume eroso.

Il programma sperimentale è consistito in quattro serie di test rappresentative di quattro differenti combinazioni di direzione delle onde incidenti, $\beta$, e directional spreading. Per ciascuna direzione di onda incidente, sono state testate 4 diverse condizioni d'onda (caratterizzate da altezze d'onda significative $H_{m0}$ = 0.100 m, 0.150 m, 0.175 m e 0.200 m con periodi di picco corrispondenti $T_p$ = 1.19 s, 1.45 s, 1.57 s e 1.68 s). Prima e dopo ogni serie di test, è stato effettuato il rilievo della struttura mediante Kinect © in presenza e in assenza di acqua nella vasca. Al termine di ciascun test, è stato condotto il rilievo della struttura senza vuotare la vasca. Le nuvole di punti acquisite sono state elaborate mediante il software CloudCompare. Al fine di calcolare l'evoluzione del danno al termine delle prove intermedie (in presenza di acqua), le nuvole di punti acquisite sono state corrette, utilizzando la nuvola di punti di riferimento iniziale, ottenuta senza acqua.

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I principali risultati dello studio sono i seguenti: i) per quanto riguarda l'evoluzione del danno, per i test condotti con $\beta$ = 90 °, directional spreading e in presenza di onde lunghe e con β = 40 ° e onde corte si è osservato il danno localizzato più elevato sulla testata della struttura; ii) le potenzialità del sensore Kinect © nel rilevare le diverse fasi di danno sono promettenti, nonostante una sovrastima del danno durante la fase iniziale ed intermedia; iii) i lavori futuri dovrebbero comprendere più test con il sensore Kinect © per poter ricercare il numero più adatto delle scansioni, della densità delle nuvole di punti acquisite e il passo ottimale della griglia per il rilievo degli strati di mantellata caratterizzati da elevata porosità, soprattutto per la parte di struttura sommersa; iv) l'uso di tecniche innovative per il rilievo degli elementi di mantellata dei modelli fisici in scala può costituire una tecnica promettente e affidabile per la valutazione dell'evoluzione del danno su strutture di questo tipo.

## ABSTRACT

Several authors have proposed guidelines on how to consider the effects of oblique waves on the stability of armour layers of rubble-mound breakwaters. Especially for very oblique waves, for which the increase in stability is the largest, limited data are available. Under the scope of the HYDRALAB+ transnational access project "RODBreak", experiments were conducted in a tank at the Marienwerder facilities of the Leibniz University Hannover (LUH), comprising measurements of sea waves, run-up, overtopping and armour layer damage of a rubble-mound breakwater under oblique extreme wave conditions. This paper focuses on the analysis of damage evolution of the breakwater roundhead subject to these conditions, on the novelty of the non-intrusive survey methodologies and on the advance in knowledge on roundhead stability.


*Keywords: coastal structure, stability, surveying, measuring techniques. large scale experiments*

## INTRODUCTION

Breakwaters are structures built to create sufficiently calm waters for safe mooring and loading operations, handling ships, and protecting harbour facilities. They usually also help to control sedimentation by guiding currents or protecting coastlines against the action of abnormal wave activity, such as tsunamis. Rubble-mound breakwaters with an armour layer composed of rock or artificial armour units are the most common of these structures (Figure 1). Prior to their construction, the design of most of these structures requires a series of scale model tests in order to evaluate their hydraulic and structural behaviour and thereby characterize the structure's response to incident waves in terms of overtopping and damage in the armour layers.

A challenge for breakwater design is how to consider the effect of oblique waves on the stability of armour layers, despite the existence of guidelines proposed by several authors (e.g., Yu *et alii*, 2002; Van gent, 2014; Maciñeira & Burcharth, 2016). Especially for very oblique waves, for which the increase in stability is the largest, limited data are available.

The assessment of the evolution of damage shown by scale-model tests can be achieved by comparing the damage in profiles that are representative of the tested section and by determining the eroded area of the tested section between consecutive surveys. Damage to the armour layer is then characterized either by parameters based on the number of displaced armour units, such as the Nod parameter (Van Der Meer, 1988), or by dimensionless parameters based on the eroded area of a profile of the armour layer, such as S (Broderick & Ahrens, 1982; Van Der Meer, 1988) or the dimensionless eroded depth, E2D (Melby & Kobayashi, 1998). Nevertheless, this damage evaluation is only applicable in (2D) tests or in 3D tests of a breakwater trunk.

Recently, Hofland *et alii* (2014) developed the local damage depth E3D,m that includes the circular moving average of the erosion pattern in rock armour layers, being applicable to a variety of non-standard 2D and 3D rubble-mound structures.

Nowadays, 3D surveys of physical scale models are performed by using new measurement techniques, such as laser scanning (Rigden & Steward, 2012; Molines *et alii*, 2012; Puente *et alii*, 2014), photogrammetric methods with photographic cameras (Hofland *et alii*, 2011; Lemos *et alii*, 2017) or with the Time of Fly (ToF) method (Castaneda & Navab, 2011).

The goal of those surveys is to obtain surface models of rubble-mound breakwaters, based on point clouds, which can be edited by a wide range of software, enabling the extraction of profiles and the calculation of eroded depths and eroded volumes.

Despite the great progress achieved lately in this research

*Fig. 1 - Typical rubble-mound breakwaters with armour layers composed of: Left: rock units; Right: artificial units.*

area, the survey of large 3D models, composed of artificial armour layer units, remains a challenge, as eroded depth is strongly affected by gaps between armour units, which can be wrongly computed as erosion. Hence, further investigation should be made to optimize the post-processing parameters of the information collected during scale model surveys (as the grid step to use while computing volumes and distances). The Kinect© motion sensor is a helpful tool, since it enables real-time 3D modelling of the surveyed scenes without time consuming post-processing reconstruction.

The use of the Kinect© motion sensor for 3D surveys of breakwater scale models has been tested by different authors, in order to facilitate the surveys for damage evolution assessment. Soares *et alii* (2017) tested the use of this device to detect displacements of cubes and tetrapods in two different scale models, based on data acquired by a Kinect©V2. Sande *et alii* (2018) conducted a set of tests at the National Laboratory for Civil Engineering (LNEC), Portugal, and at University of La Coruña, Spain, in order to optimize the best distance of the Kinect© sensor to the surveyed scene. This investigation comprised scans of a 2D scale model of a breakwater with an armour layer composed of Antifer cubes. The distances from the sensor to the model, which ranged from 1 m to 5 m, enabled the conclusion that the best combination of practical distance and point density was obtained at 1.5 m with 6.2 points/cm$^2$ resolution.

Musumeci *et alii* (2018) conducted investigations on surveys of the submerged part of a breakwater model using a Kinect© sensor, during 2D scale model tests of accropode armour units, showing a promising progress on surveys without the time-consuming task of emptying the flume or basin to conduct a survey. The correction of the deformation caused by light refraction in the interface air-water was carried out by considering a rotation angle, α, and a scaling factor, f, of the submerged part of the section. In Musumeci's experiments, it was possible to reach measurement errors smaller than 0.003 m at a distance from the breakwater of about 1.0 m.

Within the scope of the HYDRALAB+ transnational access project "RODBreak", Santos *et alii* (2019) conducted 3D experiments at the Marienwerder facilities of the Leibnitz University Hannover (LUH), comprising measurements of sea waves, run-up, overtopping and armour layer damage of a rubble-mound breakwater under oblique extreme wave conditions. Those experiments lasted for six weeks and involved seventeen people from seven different institutions from four European countries. The existing data gaps triggered the experimental work, whose main goal was to contribute to a new whole understanding of the phenomena to mitigate future sea-level-rise impact in European coastal structures.

This paper is based on data analysis from the "RODBreak" project and it focuses on damage evolution of the breakwater roundhead subject to oblique extreme wave conditions, on the novelty of the non-intrusive survey methodologies and on the advance in knowledge on roundhead stability. More details on the project results from all the types of measurements may be found in Santos *et alii* (2019).

The main objectives of the present paper are:

• To evaluate the damage evolution of the armour layer of a scale model of a rubble-mound breakwater. Results of four test series are presented (out of 11 test series of the entire test program) in order to compare damage evolution between tests conducted with different wave conditions, including different directions and directional spreading (long and short-crested waves);

• To test the ToF methodology with the Kinect© sensor, in order to evaluate the evolution of global and local eroded volumes, using intermediate surveys conducted with water;

• To estimate the number of displaced armour units, using a non-dimensional damage parameter based on the eroded volume.

The paper includes a brief description of the model characteristics, the equipment used in the experiments, the test plan, the results on damage evolution assessment using the Kinect© sensor and the conclusions from the developed work.

## MATERIALS AND METHODS

### *The physical scale model*

A stretch of a rubble-mound breakwater (head and part of the adjoining trunk, with a slope of 1(V) : 2(H) was built in the wave-current basin of the LUH to assess, under extreme wave conditions (wave steepness $s$ = 0.055) with different incident wave angles (from 40º to 90º), the structure behaviour in what concerns wave run-up, wave overtopping and damage progression of the armour layer. The armour layer consisted on Antifer cubes of 0.350 kg with a nominal diameter ($D_n$) of 0.051 m and of rock units of 0.315 kg with a nominal diameter of 0.03 m. The trunk of the breakwater was 7.5 m long and the head had the same cross-section as the exposed part of the breakwater. The model was 9.0 m long, 0.82 m high and 3.0 m wide. Figure 2 shows the physical scale model ready to be operated.

### *Equipment*

Two different techniques were used to measure armour layer damage in the tests, in addition to the visual identification of rocking and displaced armour units. The first technique is based on the use of the Kinect© motion sensor, which was moved on a rail, above and around the breakwater head, enabling overlapping scans to produce a 3D model of the above-water part of the armour layer. The Kinect© scans were made at a vertical distance of 1.2 m of the breakwater.

The Kinect© is equipped with a depth sensor composed of an infrared projector and a monochrome CMOS (complementary

*Fig. 2 - Different views of the physical scale model.*

metal-oxide semiconductor) sensor, which work together to "see" in 3D, regardless of the lighting. It is also equipped with a RGB camera, which acquires 3-color components: red, green and blue.

The acquisition of depth values by the Kinect© is determined by the ToF method, where the distance between the points of a surface and the sensor is measured by the time of flight of the light signal reflected by the surface. In other words, ToF imaging refers to the process of measuring the depth of a scene by quantifying the changes that an emitted light signal encounters when it bounces back from objects in a scene.

As the Kinect© sensor is equipped with a RGB camera, it is possible to "see" below the water level and a first estimate of the armour layer's submerged region can also be made. Such rough estimate can be corrected with the information gathered with the Kinect© sensor after the water is drained from the wave tank.

The second technique is a laser scan survey (Faro Focus 3D) of the armour layer envelope, which established the reference for the measurements made with the Kinect© sensor. Figure 3 illustrates the equipment used to evaluate armour layer damage.

*Test plan*

Regarding the test conditions, tests were conducted with irregular waves, reproduced accordingly to a Jonswap spectrum with classical shape. Table 1 summarizes the test parameters of the four-test series analyzed in the present paper, where d is the water depth, $H_{m0}$ is the spectral significant wave height, $T_p$ is the spectral peak period, measured in front of the wave generator. According to the EurOtop manual (Van Der Meer *et alii*, 2018), the angle of wave attack, $\beta$, is defined at the toe of the structure, as the angle between the direction of the waves and the perpendicular to the long axis of the breakwater. The directional spreading is characterized by the directional spreading width ($\sigma$).

For each incident wave angle, at least 4 different wave conditions acted on the model: $H_{m0}$ = 0.100 m, 0.150 m, 0.175 m and 0.200 m and the corresponding peak periods $T_p$ = 1.19 s, 1.45 s, 1.57 s and 1.68 s.

*Damage evaluation methodology*

Before and after each test series, a Kinect© survey was conducted with and without water in the wave tank. After each test in the series, a survey was conducted with water, avoiding emptying the tank (Figure 4). All the obtained point clouds were post-processed using the tools and algorithms of the open source software CloudCompare (Girardeau - Montaut, 2006).

In order to compute damage evolution at the end of intermediate tests (with water), point clouds obtained from scans with water were aligned, using the initial (reference) cloud obtained without water.

For test series without localized damage (if only movements occur or if there are only isolated armour unit displacements) the proposed damage evaluation took into account the armour layer depth differences resulting from rearrangements of the armour units, where the erosion ratio was evaluated using CloudCompare by computing the ratio of elementary cells (resulting from the gridding process) corresponding to erosion over the total number of cells. Those depth differences were obtained using the


*Fig. 3 - Left: Rail to support the Kinect© motion sensor; Center: Laser scanning; Right: Laser scan survey.*

| *Test* | *d (m)* | *$H_{m0}$ (m)* | *$T_p$ (s)* | *β (o)* | *σ (o)* |
|---|---|---|---|---|---|
| *T13* | *0.60* | *0.100* | *1.19* | *40* | *0* |
| *T14* | | *0.150* | *1.45* | | |
| *T15* | | *0.175* | *1.57* | | |
| *T16* | | *0.200* | *1.68* | | |
| *T17* | *0.60* | *0.100* | *1.19* | *65* | *0* |
| *T18* | | *0.150* | *1.45* | | |
| *T19* | | *0.175* | *1.57* | | |
| *T20* | | *0.200* | *1.68* | | |
| *T21* | *0.60* | *0.100* | *1.19* | *90* | |
| *T22* | | *0.150* | *1.45* | | |
| *T23* | | *0.175* | *1.57* | | |
| *T24* | | *0.200* | *1.68* | | |
| *T25* | | *0.250* | *1.88* | | |
| *T35* | *0.60* | *0.100* | *1.19* | *40* | *50* |
| *T36* | | *0.150* | *1.45* | | |
| *T37* | | *0.175* | *1.57* | | |
| *T38* | | *0.200* | *1.68* | | |
| *T39* | | *0.250* | *1.88* | | |

*Tab. 1 - Test conditions.*

Multiscale Model to Model Cloud Comparison (M3C2) algorithm (Lague *et alii*, 2013) provided by the CloudCompare software.

For test series with localized damage, the evaluation was based upon the local eroded volume computation. In this last case, the ratio between the computed eroded volume of the most damaged area (local damage) and the volume of a single armour unit enabled the determination of a non-dimensional 3D parameter, which reflects an approximate number of displaced units: *Estimated $n_o$. displaced units = (Eroded volume x (1-Porosity)) / Armour Unit Volume*.

The eroded volume computation was based upon the use of CloudCompare and relied on the gridding process of the cloud(s), by choosing a grid step. This step defines the size of the elementary cells used in the volume computation.

In the present work, after several experiences with grid steps ranging from 0.25 mm to 10 mm, the best combination of point density and depth estimation was obtained with a step of 1 mm. Smaller steps conducted to an overestimated depth, while grid steps higher than 1 mm led to an important loss of point density.

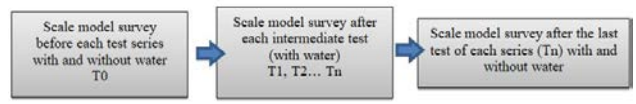


*Fig. 4 - Methodology for scale model survey.*

The number of estimated displaced units was compared with the number of displaced units, obtained after each test, with the traditional counting method.

All the surveys consisted on 40 scans around the roundhead with an overlap higher than 90%. The point clouds resulting from the merge of those sub-clouds had a density of around 0.50 points/mm$^2$. Figure 5 illustrates the methodology for a point cloud construction.

The edition of the final cloud with the CloudCompare software enabled to remove duplicate points, to discard points (segment) that are not part of the model area subject of study (e.g. instrumentation and stone at the toe of the structure), as well as to isolate the local erosion areas. In addition, to fasten data processing, clouds were subsampled with a minimum space of 1 mm between points. The density of the final cloud of points was around 0.25 points/mm$^2$.

*Comparison between surveys performed with a Kinect© and a laser scan*

As said in section 2.2, a laser scan survey (Faro Focus 3D) of the armour layer envelope established the reference for the measurements carried out with the Kinect© sensor. In order to compare the differences between both survey methodologies, a comparison was carried out between laser scan and Kinect© sensor surveys obtained without water before test T17 (Figure 6).

The average distance between both clouds of points was 0.008 m. The maximum distance was 0.081 m, corresponding to some anomalies occurred, for both methodologies, due to the placement of a run-up gauge along the armour layer slope.

Profiles extracted for the leeward, front and seaward sections

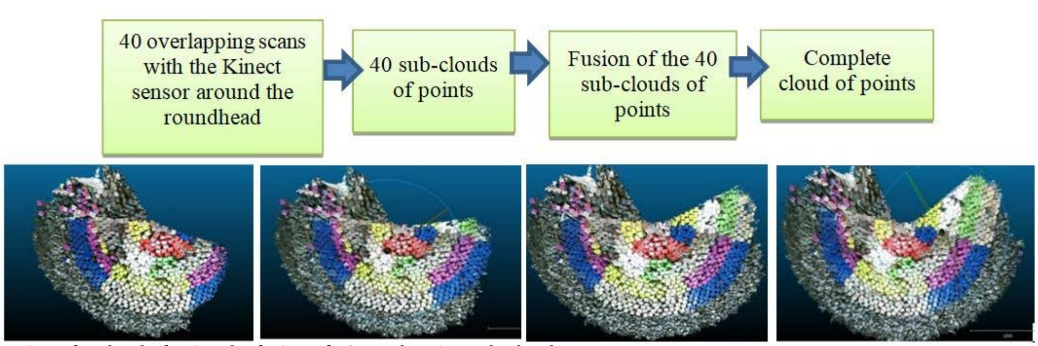


*Fig. 5 - Construction of a cloud of points by fusion of 40 overlapping sub-clouds.*


*Fig. 6 - Survey before test T17. Left: Laser scan survey; Center: Kinect© sensor survey; Right: Map of distances between both surveys.*

showed that both methodologies revealed a good agreement in the leeward and the seaward sections. The average error was of 0.015 m and the maximum error was of 0.053 m. On the other hand, the profile corresponding to the front section confirmed the interference of the run-up gauge in the armour layer surveys (Figure 7). In this last case, the average error was 0.028 m and the maximum error was 0.13 m.

Alignment of clouds of points obtained with water

As mentioned before, to compute damage evolution for intermediate tests (with water), point clouds obtained from scans conducted with the Kinect© sensor with water were aligned with the initial (reference) cloud obtained without water. This procedure required an initial rough alignment using points whose position did not change during tests, followed by a fine registration using the Iterative Closest Point (ICP) algorithm (Chen & Medioni, 1991) provided by CloudCompare.

The left panel of Figure 8 depicts a profile comparison between dry and wet surveys conducted before test T17, while the right panel depicts the same comparison after a fine alignment of the wet survey with the reference (dry) survey. The average of the absolute differences obtained without alignment and with alignment are 0.033 m and 0.009 m, respectively.

## RESULTS

For test series without localized damage (only with rearrangements of the Antifer cubes), the proposed analysis of

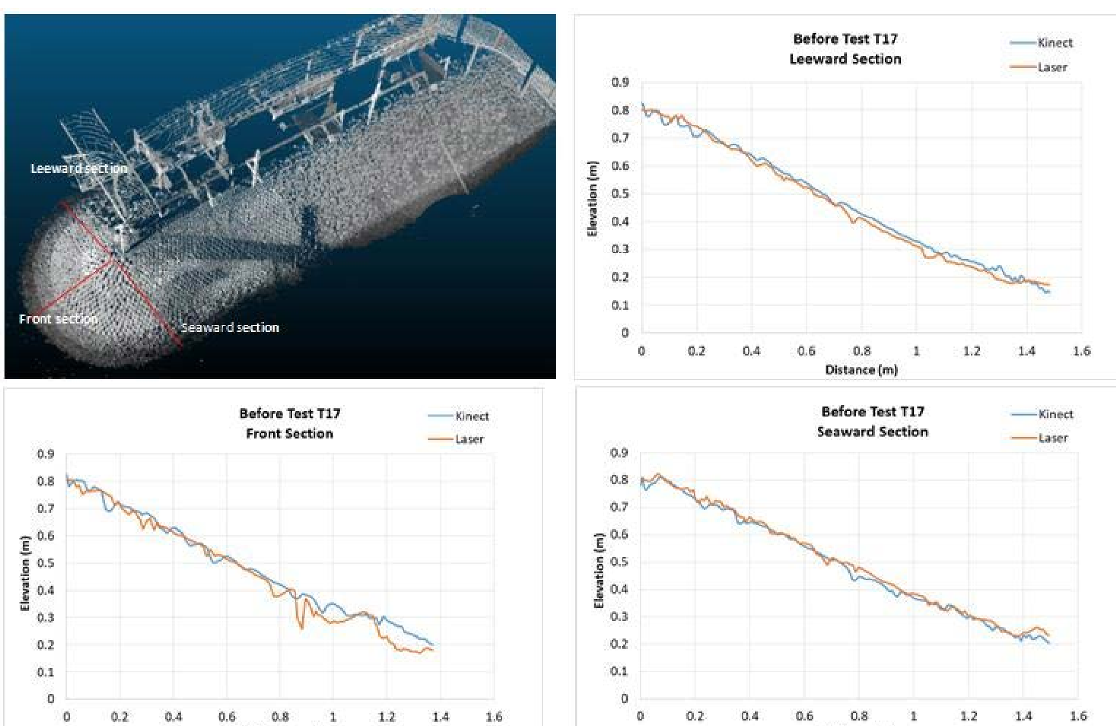


*Fig. 7 - Roundhead scanned with a laser scan before test T17 and profiles extracted for the leeward, front and seaward sections.*

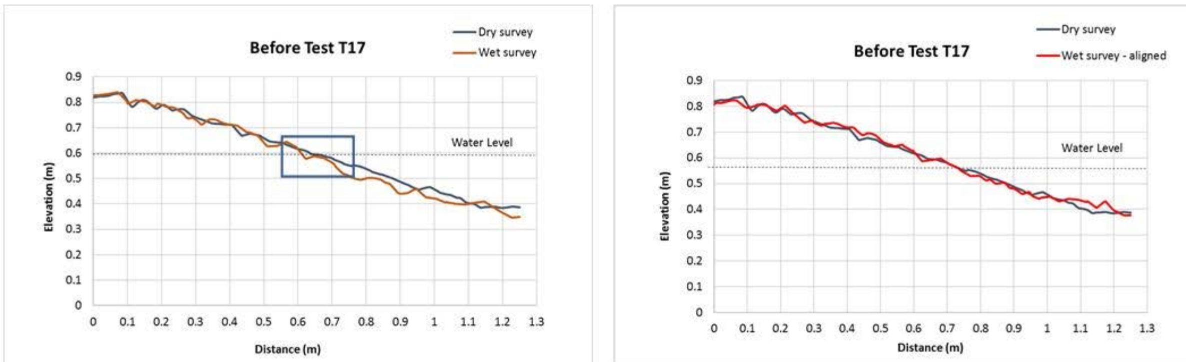


*Fig. 8 - Profile comparison for surveys conducted before test T17. Left: Between dry and wet surveys; Right: Between dry and aligned wet surveys.*

depth differences maps (in mm) considers positive and negative depth differences as erosion and deposition, respectively.

Regarding test series T13-T16, the most affected parts of the roundhead were the central and outer sectors, where an important number of movements were detected, without armour unit extraction (Figure 9). Figure 10 illustrates the depth changes map, caused by movements of the armour layer units during the test series.

During test series T17-T20, an important number of movements were also detected, as well as a small number of armour units removed from the inner section of the roundhead. Figure 11 illustrates an overview of the model at the end of test T20, as well as the scan of the model at the end of the test series. Figure 12 shows the depth maps at the end of tests T13 and T20.

In the test series presented above, the erosion ratio resulting from armour unit rearrangements was evaluated, using the depth

*Fig. 9 - Left: Model after test T16; Right: Roundhead scanned with Kinect© after test T16.*

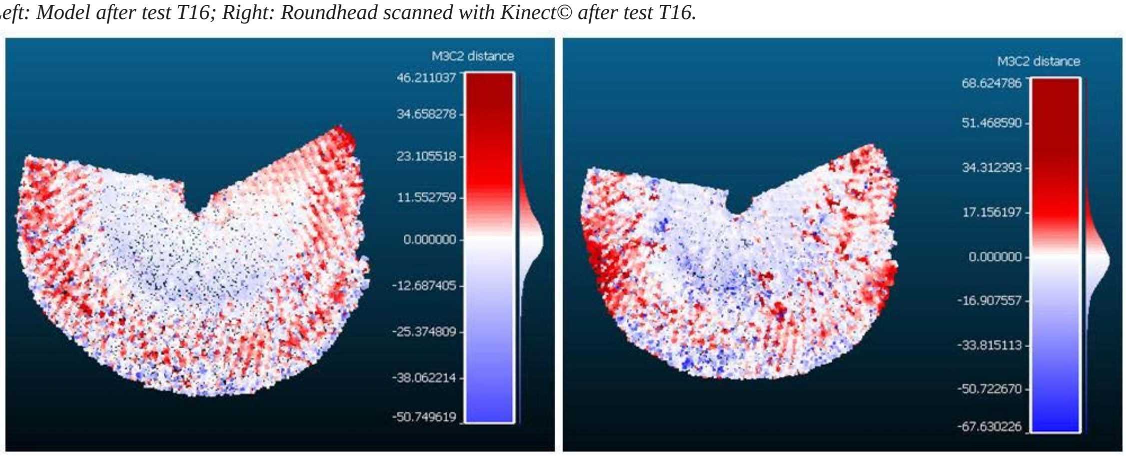


*Fig. 10 - Depth changes map, in mm (Red - erosion; Blue - deposition). Left: After test T13; Right: After test T16.*

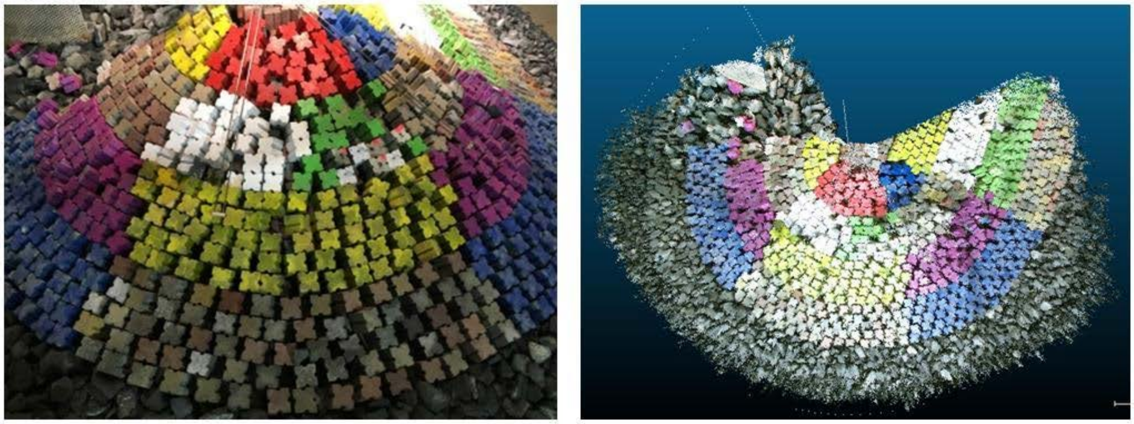

*Fig. 11 - Left: Model after test T20; Right: Roundhead scanned with Kinect© after test T20.*

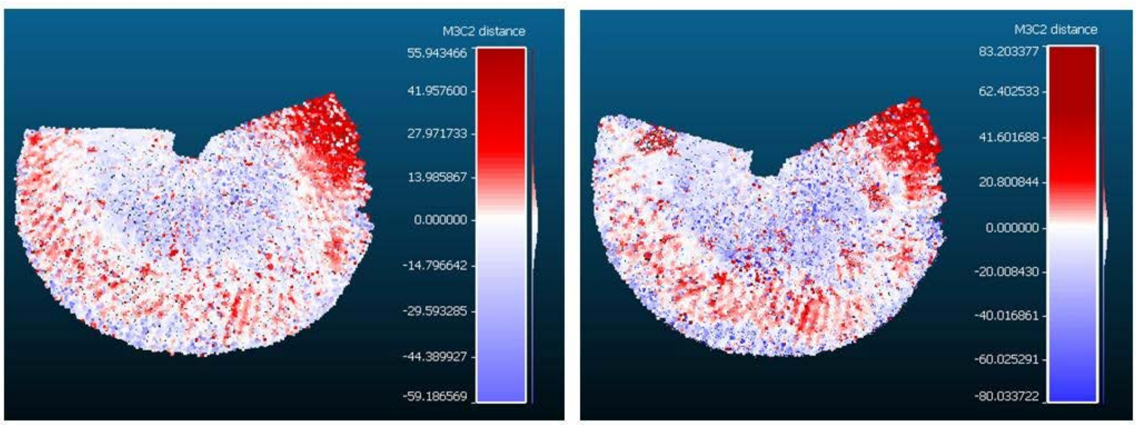


*Fig. 12 - Tests T17-T20. Armour layer eroded depth, in mm (Red - erosion; Blue - deposition). Left: After test T17; Right: After test T20.*

map histogram¸ by computing the ratio of points corresponding to erosion (red areas) over the total number of points.

For both test series, after an initial increase in erosion, it was possible to identify a decrease in erosion during the intermediate tests, probably due to rearrangements of the armour units. During the last test, with $H_{m0}$ = 0.20 m, the erosion ratio was 0.24 for test series T13-T16 and of 0.09 for series T17-T20. Table 2 and Figure 13 present the erosion ratio evolution for test series T13-T16 and T17-T20.

Test series T21-T25 and T35-T39 presented more severe damage levels than the other series. At the end of series T21-T25, an important eroded volume was observed, mainly at the center and outer sectors of the roundhead, around the still water level, exposing the inner layer of Antifer cubes (Figure 14). The global and local erosion maps (in mm) for damage occurred between tests T21 and T25 are presented in Figure 15.

Surveys during test series T35-T39 also revealed important damage at the leeward section of the roundhead, around the still water level, with exposure of the Antifer cubes of the inner layer. The armour layer of the outer sector of the roundhead presented several movements and rearrangements of the Antifer cubes (Figure 16). These tests, conducted with the same wave conditions ($d$ = 0.60 m and $\beta$ = 40°) as tests T13-T16, but with a directional

| *Test series* | *T13-T16* | | | | *T17-T20* | | | |
|---|---|---|---|---|---|---|---|---|
| *Test* | *T13* | *T14* | *T15* | *T16* | *T17* | *T18* | *T19* | *T20* |
| *Erosion ratio* | *0.22* | *0.18* | *0.15* | *0.24* | *0.08* | *0.07* | *0.06* | *0.09* |

*Tab. 2 - Erosion ratio evolution for test series T13-T16 and T17-T20*

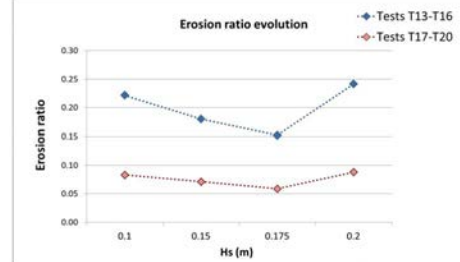


*Fig. 13 - Erosion ratio evolution during test series T13-T16 and T17-T20.*

| *Test* | *Global eroded volume (dm³)* | *Displaced units* | | *Local eroded volume (dm³)* | *Displaced units* | |
|---|---|---|---|---|---|---|
| | | *Estimated* | *Counted* | | *Estimated* | *Counted* |
| *T21* | *13.03* | *58* | *1* | *3.32* | *15* | *1* |
| *T22* | *14.02* | *63* | *4* | *3.49* | *16* | *4* |
| *T23* | *14.29* | *64* | *10* | *3.73* | *17* | *6* |
| *T24* | *15.33* | *69* | *16* | *3.85* | *17* | *10* |
| *T25* | *21.43* | *96* | *60* | *8.88* | *40* | *40* |
| *T35* | *13.29* | *60* | *0* | *1.44* | *6* | *0* |
| *T36* | *13.07* | *59* | *2* | *1.59* | *7* | *0* |
| *T37* | *13.14* | *59* | *6* | *1.61* | *7* | *0* |
| *T38* | *13.84* | *62* | *10* | *1.64* | *7* | *0* |
| *T39* | *14.72* | *66* | *42* | *7.91* | *35* | *37* |

*Tab. 3 - Global and local eroded volumes for test series T21-T25 and T35-T39*

spreading of 50° (for short-crested wave reproduction), presented a higher localized damage (Figure 17).

Table 3 presents the global and localized erosion volumes from the roundhead, obtained from a 1 mm grid. The estimated values of removed/displaced units, based on the ratio between the eroded volume and the volume of a single armour unit (around 0.13 dm³), are also summarized.

Figure 18 illustrates the counted and estimated number of armour units based upon the localized erosion volume. Volumes are presented in cubic decimeters to have a better understanding of the damage, according to the model dimensions. For both test series, the number of displaced units based on the global eroded volume is largely overestimated, with percentage errors higher than 58.3%. In fact, movements that lead to the display of the gaps

*Fig. 14 - Left and center: Model after test T25; Right: Roundhead scanned with Kinect© after test T25.*

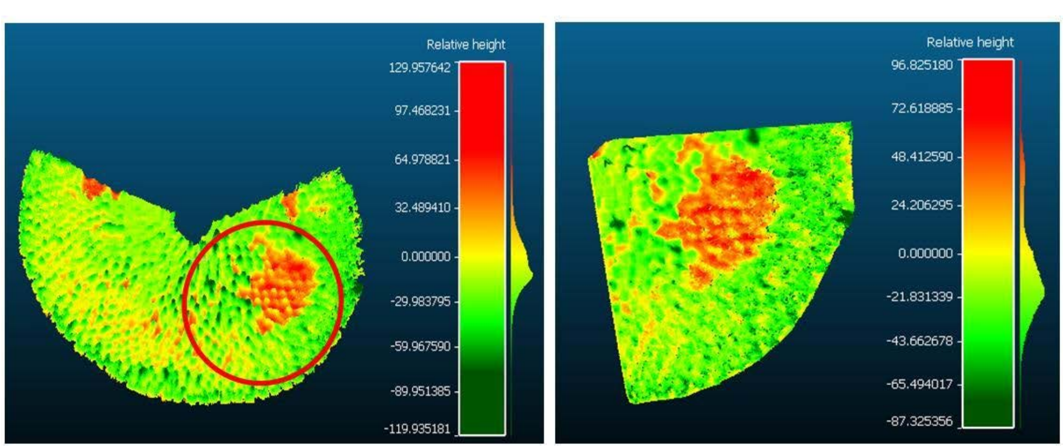


*Fig. 15 - Tests T21-T25. Armour layer eroded depth, in mm (Red - erosion; Green - deposition). Left: Global estimate; Right: Local estimate*

*Fig. 16 - Left and center: Model after test T39. Right: Roundhead scanned with Kinect© after test T39.*

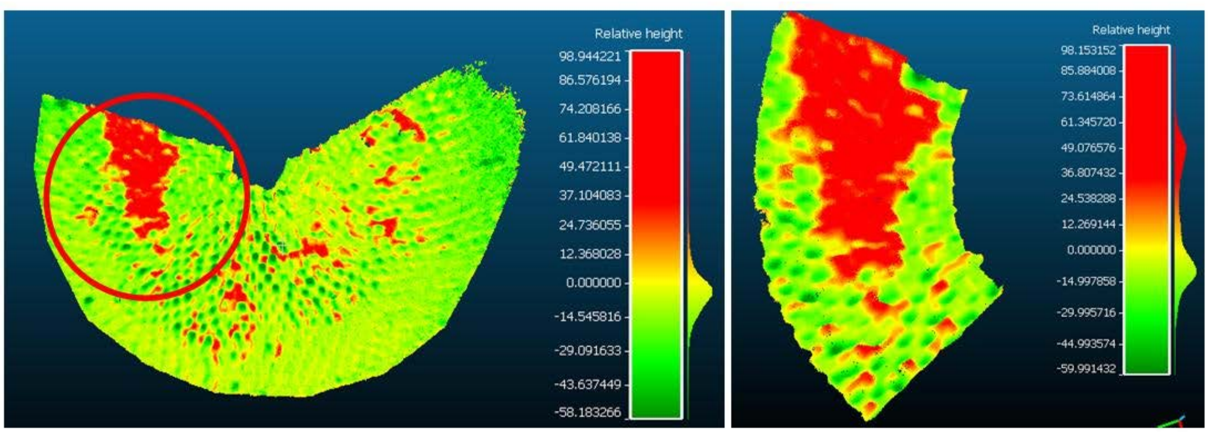


*Fig. 17 - Tests T35-T39. Armour layer eroded depth (in mm) (Red - erosion; Green - deposition). Left: Global estimate; Right: Local estimate.*

between the armour units of the inner layer may have contributed to an overestimation of the eroded depth, as well as slight differences on the cloud alignment between clouds to compare. Since matching cells percentage between compared clouds was around 98%, it may be concluded that the overestimation is mainly caused by the gaps between the armour units.

For the same reason, for both test series, the number of displaced units based on the local eroded volume is also overestimated for initial and intermediate damage stages, with percentage errors higher than 42%. Nevertheless, for the highest damage stages, both counted and estimated numbers of displaced units converge, with percentage errors of 0.5% and 4.3% for test series T21-T25 and T35-T39, respectively. This fact points out to the need of further investigation on more suitable grid spacing for estimation of intermediate damage levels.

## CONCLUSIONS

A stretch of a rubble-mound breakwater (head and part of the adjoining trunk, with a slope of 1(V) : 2(H) was built in a wave basin at the Leibnitz University Hannover to assess, under extreme wave conditions (wave steepness of 0.055) with different incident wave angles (from 40º to 90º), the structure behavior in what concerns wave run-up, overtopping and damage progression of the armour layers, composed by rock and Antifer cubes.

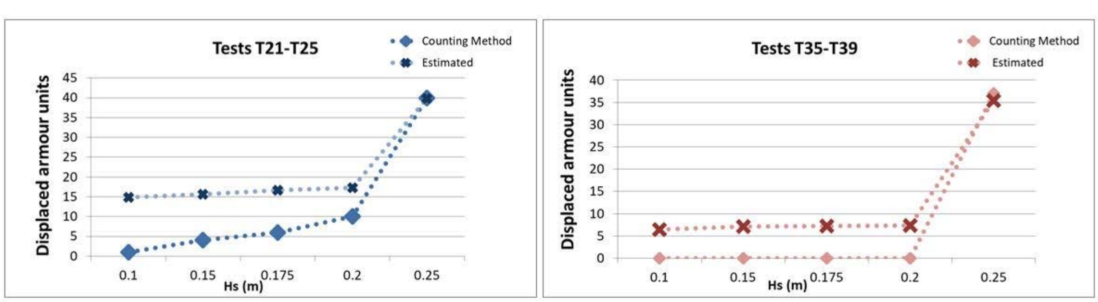


*Fig. 18 - Test series T21-T25 and T35-T39. Counted and estimated displaced armour units based on the local eroded volume.*

Non-intrusive methodologies were used for the assessment of the armour layer damage evolution, including a laser scanning technique and a Kinect© motion sensor.

The aim of the present work was to characterize damage evolution, based upon surveys carried out with the Kinect© motion sensor, for 4 of the 11-test series conducted during the test programme.

Regarding damage evolution during the test series, tests conducted with an angle of attack of 90°, directional spreading of 0° (long-crested waves), and with an angle of attack of 40°, directional spreading of 50° (short-crested waves), presented the highest localized damage at the roundhead.

Tests conducted with similar wave conditions (depth of 0.60 m and an angle of attack of 40°) presented a higher localized damage when conducted with a directional spreading of 50° than with a spreading of 0°.

In what concerns the use of the Kinect© sensor, damage estimation using the global eroded volume overestimated the number of displaced units. On the other hand, damage estimation using the local eroded volume converged with the counted displaced armour units, when applied to high damage stages. Nevertheless, it also overestimated initial and intermediate damage stages, as increasing gaps between armour units were wrongly computed as removed units. Small errors on the alignment between clouds to be compared, may also have contributed to this overestimation. This fact points out to the need of performing more experiments with the Kinect© sensor to achieve the most suitable number of overlapping scans, density of point clouds and grid step for high porosity armour layers, especially for surveys of submerged sceneries.

Once this goal is achieved, the presented innovative survey techniques of the armour layer of a scale model breakwater seem to be powerful tools for damage evolution assessment.

Results suggest that the sensor can be used by laboratories and research groups to identify different damage stages. Such results are relevant to understand first stages of damage.

The use of a non-dimensional damage parameter based on the eroded volume to estimate the number of armour layer displaced units seems to be easily applicable. Future works will comprise the application of this non-dimensional damage parameter to consecutive photogrammetric aerial surveys of breakwaters.

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