Lemos, Rute; Reis, Maria Teresa; Fortes, Conceição Juana; Peña, Enrique; Sande, Jose; Figuero, Andres; Alvarellos, Alberto; Laiño, Emilio; Santos, João; Kerpen, Nils

Measuring Armour Layer Damage in Rubble-Mound Breakwaters under Oblique Wave Incidence

Verfügbar unter/Available at: https://hdl.handle.net/20.500.11970/106641

Vorgeschlagene Zitierweise/Suggested citation:
Lemos, Rute; Reis, Maria Teresa; Fortes, Conceição Juana; Peña, Enrique; Sande, Jose; Figuero, Andres; Alvarellos, Alberto; Laiño, Emilio; Santos, João; Kerpen, Nils (2019): Measuring Armour Layer Damage in Rubble-Mound Breakwaters under Oblique Wave Incidence. In: Goseberg, Nils; Schlurmann, Torsten (Hg.): Coastal Structures 2019. Karlsruhe: Bundesanstalt für Wasserbau. S. 295-305. https://doi.org/10.18451/978-3-939230-64-9_030.

Standardnutzungsbedingungen/Terms of Use:
Die Dokumente in HENRY stehen unter der Creative Commons Lizenz CC BY 4.0, sofern keine abweichenden Nutzungsbedingungen getroffen wurden. Damit ist sowohl die kommerzielle Nutzung als auch das Teilen, die Weiterbearbeitung und Speicherung erlaubt. Das Verwenden und das Bearbeiten stehen unter der Bedingung der Namensnennung. Im Einzelfall kann eine restriktivere Lizenz gelten; dann gelten abweichend von den obigen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Documents in HENRY are made available under the Creative Commons License CC BY 4.0, if no other license is applicable. Under CC BY 4.0 commercial use and sharing, remixing, transforming, and building upon the material of the work is permitted. In some cases a different, more restrictive license may apply; if applicable the terms of the restrictive license will be binding.
Measuring Armour Layer Damage in Rubble-Mound Breakwaters under Oblique Wave Incidence

R. Lemos, M. T. Reis & C. J. Fortes
Laboratório Nacional de Engenharia Civil, Lisbon, Portugal

E. Peña, J. Sande, A. Figuero, A. Alvarellos & E. Laiño
Water and Environmental Engineering Research Group (GEAMA), University of A Coruña, A Coruña, Spain

J. A. Santos
Instituto Superior de Engenharia de Lisboa, Instituto Politécnico de Lisboa, Lisbon, Portugal
Centre for Marine Technology and Ocean Engineering, Universidade de Lisboa, Lisbon, Portugal

N. B. Kerpen
Leibniz University Hannover, Ludwig-Franzius-Institute, Hannover, Germany

Abstract: This paper presents a set of scale-model tests carried out to extend the range of wave steepness values analyzed in wave run-up, overtopping and armour layer stability studies, focusing on oblique extreme wave conditions and on their effects on a gently sloping breakwater trunk armour and roundhead. 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 Universität Hannover to assess, under extreme wave conditions (wave steepness of 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 layers, composed by rock and Antifer cubes. Non-intrusive methodologies were used for the assessment of armour layer damage evolution, including a laser scanning technique, stereo photogrammetry and a Kinect© motion sensor. The aim of the present work is 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 program.

Keywords: Coastal Structure, Stability, Surveying, Measuring Techniques, Large Scale Experiments

1 Introduction

Guidelines on how to consider the effects of oblique waves on the stability of armour layers have been proposed by several authors (e.g. Yu et al., 2002; Van Gent, 2014; Maciñeira and Burchartha, 2016). Especially for very oblique waves, for which the increase in stability is the largest, limited data are available. The existing data gaps triggered the present experimental work, whose main goal is to contribute to a new whole understanding of this phenomenon to mitigate future sea-level-rise impact in European coastal structures. It is expected that this work contributes also to check and extend the validity range of formulae developed for armour layer stability of rough and permeable slopes. The key point is to broaden the range of wave steepness values analysed in stability studies, focusing on extreme oblique wave conditions and on their effects on a breakwater’s trunk armour and roundhead, a subject not yet sufficiently covered in the literature. Also, in spite of the great progress achieved in model survey techniques, the survey of large models, composed of artificial armour layer units, is still a challenge.

This paper aims at describing the experiments conducted under the Transnational Access Program, RODBREAK, which involved people from eight different institutions and lasted for six weeks, at the wave-current basin of the Leibnitz University Hannover (LUH). 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 arisen from the developed work. More details can be seen in Santos et al., 2019.
Three different techniques were used to measure armour layer damage, in addition to the visual identification of rocking and displaced armour units: (1) laser scan survey of the armour layer envelope; (2) stereo photogrammetry, in which two cameras were hung above the breakwater model so that two simultaneous pictures of almost the same area could be taken by the cameras; and (3) a Kinect© motion sensor that travelled over the study area. The results presented in this paper are based on surveys conducted with this last technique. In fact, unlike the photogrammetric surveys, the Kinect© sensor enabled to survey the whole roundhead. The survey conducted with a laser scan was used as ground truth.

2 Materials and methods

2.1 The physical scale model

A stretch of a rubble-mound breakwater (head and part of the adjoining trunk, with a slope of $1(\mathrm{V}):2(\mathrm{H})$) was built in the wave-current basin of the LUH to assess, under extreme wave conditions (wave steepness of $s = 0.055$) with different incidence 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 breakwater. The model was 9.0 m long, 0.82 m high and 3.0 m wide.

The reason for building such a large breakwater model was to reduce the scale effects associated to wave-induced flows across small models. The angle between the longitudinal axis of the breakwater and the tank wall was 70º. Figure 1 illustrates the physical scale model ready to be operated.

![Fig. 1. Physical scale model.](image)

2.2 Equipment

Four different categories can be identified in the equipment deployed in the experiment according to the variables measured: Sea waves; Run-up; Overtopping; Armour layer damage.

A plan view of the key instruments for those variables (apart from “armour layer damage”) is presented in Figure 2.

Three 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 one is a laser scan survey of the armour layer envelope. The second one is based in stereo photogrammetry, where a pair of cameras is hung above the breakwater model so that two simultaneous pictures of almost the same area can be taken by the two cameras.

The third technique is based on the use of the Kinect© motion sensor that was moved on a rail, above and around the head of the breakwater, enabling overlapping scans in order to gather a 3D model of the above-water part of the armour layer.

The Kinect sensor used (model: Kinect 2.0) is equipped with a depth sensor composed of an infrared projector and a monochrome CMOS (complimentary metal-oxide semiconductor) sensor which work together to "see" in 3-D regardless of the lighting. It is also equipped with a color VGA video camera, which acquires three color components: red, green and blue. It is called "RGB camera" referring to the color components it detects.
The acquisition of depth values by the Kinect© is determined by the Time of Flight (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 (Castaneda and Navab, 2011).

Additionally, as the Kinect sensor is also equipped with a RGB camera making possible “to see” below the water level, 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© motion sensor after the water is drained from the wave tank, Musumeci (2018) and Sande et al. (2018).

Just before the beginning of the test series of the second day of the test program and at the end of that test series, a laser scan survey of the armour layer envelope established the ground truth for the measurements made with the other techniques. The same happened with the test series of the last day of the test program. Figure 3 illustrates the equipment used to evaluate armour layer damage.
2.3 Test Plan

For each incident wave angle, at least 4 different wave conditions acted on the model (significant wave heights $H_s=0.100$ 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).

The influence of the directional spreading of short-crested waves was investigated for the lowest water depth (0.60 m) and the incident angles of $40^\circ$ and $65^\circ$, the directional spreading being $50^\circ$.

Finally, for the incident angle of $40^\circ$, results were also obtained for the highest water depth (0.68 m) and short-crested waves with a directional spreading of $50^\circ$.

Table 1 summarizes the test parameters of the test series target of the present paper.

<table>
<thead>
<tr>
<th>Date</th>
<th>Test</th>
<th>$d$ (m)</th>
<th>$H_m$ (m)</th>
<th>$T_p$ (s)</th>
<th>Dir (°)</th>
<th>Spreading (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01-11-2017</td>
<td>T13</td>
<td>0.60</td>
<td>0.100</td>
<td>1.19</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>T14</td>
<td></td>
<td>0.150</td>
<td>1.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T15</td>
<td></td>
<td>0.175</td>
<td>1.57</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T16</td>
<td></td>
<td>0.200</td>
<td>1.68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>02-11-2017</td>
<td>T17</td>
<td>0.60</td>
<td>0.100</td>
<td>1.19</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T18</td>
<td></td>
<td>0.150</td>
<td>1.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T19</td>
<td></td>
<td>0.175</td>
<td>1.57</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T20</td>
<td></td>
<td>0.200</td>
<td>1.68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>03-11-2017</td>
<td>T21</td>
<td>0.60</td>
<td>0.100</td>
<td>1.19</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T22</td>
<td></td>
<td>0.150</td>
<td>1.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T23</td>
<td></td>
<td>0.150</td>
<td>1.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T24</td>
<td></td>
<td>0.175</td>
<td>1.57</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T25</td>
<td></td>
<td>0.200</td>
<td>1.68</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T26</td>
<td></td>
<td>0.250</td>
<td>1.88</td>
<td></td>
<td></td>
</tr>
<tr>
<td>08-11-2017</td>
<td>T35</td>
<td>0.60</td>
<td>0.100</td>
<td>1.19</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T36</td>
<td></td>
<td>0.150</td>
<td>1.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T37</td>
<td></td>
<td>0.175</td>
<td>1.57</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T38</td>
<td></td>
<td>0.200</td>
<td>1.68</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T39</td>
<td></td>
<td>0.250</td>
<td>1.88</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.4 Damage evaluation

Broderick and Ahrens (1982) and Van der Meer (1988) defined the dimensionless damage parameter,
\[ S = \frac{Ae}{D_{n50}^2}, \]
where \( Ae \) is the eroded cross-section area around the still water level (SWL) and \( D_{n50} \) is
the nominal diameter of the armour units. Melby and Kobayashi (1998) defined the local damage
depth, \( e = (z_{\text{before}} - z_{\text{after}}) \cos \alpha \), where \( z_{\text{before}} \) and \( z_{\text{after}} \) are the structure elevation before and after a
test run, respectively, and \( \alpha \) is the structure slope (erosion of the profile being positive). They also
consider the dimensionless erosion depth, where \( E_{2D} = \frac{\max(e)}{D_{n50}} \), where \( e \) is averaged over a
predefined width of \( mD_{n50} \), longshore direction. Nevertheless, this measure can only be applied for a
2D flume or in a breakwater trunk. Hofland et al. (2014) additionally propose the local damage depth
\( E_{3D,m} \), which includes the circular moving average of the erosion pattern, such that it is applicable to a
variety of non-standard two and three-dimensional rubble-mound structures.

With the new measurement techniques, the surface elevation of rubble-mound breakwaters can be
obtained with millimeter resolution and sub-millimeter accuracy. The most commonly used high-
resolution techniques are terrestrial laser scanning (Rigden and Steward, 2012; Molines et al., 2012;
Puente et al., 2014), and stereo photogrammetry (Hofland et al., 2011; Lemos and Santos, 2013).

In spite of the great progress achieved in this research area, the survey of large models, composed
of artificial armour layer units, remains a challenge, as eroded depth is strongly affected by the gaps
between armour units, which can be wrongly computed as erosion.

In the present work, damage evaluation was based on surveys with the Kinect© sensor, taking into
account the armour layer porosity changes, the non-dimensional eroded depth (\( E \)), as well as the
eroded volume over the most damaged areas of the model. The present work also approaches damage
evolution in roundheads by estimating the eroded volume. A ratio between the eroded volume of the
most damaged area and the volume of a single armour unit results on an estimate of the number of
displaced units.

For all the test series, a Kinect© survey was conducted before and after each test run, consisting on
several scans around the roundhead. The clouds of points resulting from the merging of those sub-
clouds have a density of around 0.50 points/mm\(^2\).

Their edition with the Cloud-compare software enabled to filter points which 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. Cloud to cloud distances and volume calculations (before and after test
series) were made in order to estimate global and localized damage.

3 Results

This section presents an overview of the model at the end of each test series, as well as of the scans
before and after the test series illustrating erosion and deposition in mm. An estimate of the maximum
eroded depths is also illustrated.

Figure 4 illustrates the comparison between the surveys conducted with the laser scan and the
Kinect© sensor before Test T17, for the leeward, front and seaward sections. The two methodologies
revealed a good agreement both in the leeward and the seaward sections. Only the front section
showed some anomalies for both methodologies, due to the influence of the run-up gauge in the armor
layer survey.
In the 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 armor unit extraction (Figure 5). Vertical distance between initial and final clouds of points are presented in Figure 6, showing global and local estimation of erosion and deposition for test series T13-T16, according to a normal distribution of the eroded depth in the analyzed zone.

Fig. 4. Roundhead scanned with a laser scan before Test T17, for leeward, front and seaward sections.

In the 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 armor unit extraction (Figure 5). Vertical distance between initial and final clouds of points are presented in Figure 6, showing global and local estimation of erosion and deposition for test series T13-T16, according to a normal distribution of the eroded depth in the analyzed zone.

Fig. 5. Roundhead scanned with Kinect©. Left: Before Test T13; Center: After Test T16; Right: Model after Test T16.
In the test series T17-T20, scans conducted before Test T17 and after Test T20 presented movements only between the armour units (increasing porosity).

Figure 7 illustrates an overview of the model at the end of Test T20, as well as the scan before and at the end of the test series. The analysis of the movements of the entire surface of the roundhead gave an estimated number of 19 pieces moved out of their initial position, without extraction of armour units.

For this set of tests, the scanning results enabled the detection of minor movements of the Antifer cubes through the porosity analysis.

Porosity was evaluated by comparing the number of pieces and the area they occupy, before and after the test series. Figure 8 illustrates the movements of armour layer elements in terms of depth differences.
Surveys before and after Tests T21-T26 were conducted with water. Despite the loss of the quality of survey of the submerged part of the structure, it was possible to estimate the important eroded volume at the end of this set of tests, mainly located at the center and outer sectors of the roundhead, around the still water level, exposing the inner layer of Antifer cubes (Figure 9). The graphical representation of the erosion that occurred between Tests T21 and T26 is presented in Figure 10.

Fig. 9. Roundhead scanned with Kinect©. Left: Before Test T21; Center: After Test T26; Right: Model after Test T26.

Fig. 10. Tests T21-T26. Armour layer eroded depth. Red (erosion), blue (deposition). Left: Global estimate; Right: Local estimate.

Surveys before Test T35 and after Test 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 armor layer of the outer sector of the roundhead presented several movements and rearrangements of the Antifer cubes (Figure 11).

These tests, conducted with the same wave conditions (d=0.60 m and Dir=40°) of Tests T13-T16, but with a directional spreading of 50° (for short-crested wave reproduction), presented a higher localized damage (Figure 12).

Fig. 11. Left: Roundhead scanned with Kinect© after Test T39; Center and Right: Model after Test T39.
Fig. 12. Tests T35-T39. Armour layer eroded depth. Red (erosion), blue (deposition). Left: Global estimate; Right: Local estimate.

Table 2 presents the global and localized erosion volumes from the roundhead, obtained from a 3 mm grid. The estimated values of removed/displaced units, based on the ratio between eroded volume and the volume of a single armour unit (around 0.00013 m³) are also summarized. One can observe that values of counted and estimated armour units are of the same order. Nevertheless, a difference of around 22% and 9.5% was found for test series T21-T26 and T35-T39, respectively. Further investigation on the more suitable grid spacing may be necessary.

<table>
<thead>
<tr>
<th>Test series</th>
<th>Removed units (Counting method)</th>
<th>Eroded volume (m³)</th>
<th>Removed/displaced units (Estimated)</th>
<th>s_max (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Global</td>
<td>Local</td>
<td>Global</td>
<td>Local</td>
</tr>
<tr>
<td>T13-T16</td>
<td>0</td>
<td>0</td>
<td>0.0188</td>
<td>N/A</td>
</tr>
<tr>
<td>T17-T20</td>
<td>0</td>
<td>0</td>
<td>0.0079</td>
<td>N/A</td>
</tr>
<tr>
<td>T21-T26</td>
<td>48</td>
<td>48</td>
<td>0.0228</td>
<td>0.0080</td>
</tr>
<tr>
<td>T35-T39</td>
<td>42</td>
<td>42</td>
<td>0.0173</td>
<td>0.0081</td>
</tr>
</tbody>
</table>

Eroded depth values obtained using the survey of the global area seems to be overestimated. In fact, movements that lead to the display of the gaps between the armour units of the inner layer can contribute to an overestimation of the eroded depth.

Figure 4 illustrates the comparison between the surveys conducted with the laser scan and the Kinect© sensor before Test T17, for the leeward, front and seaward sections. The two methodologies revealed a good agreement both in the leeward and the seaward sections. Only the front section showed some anomalies for both methodologies, due to the influence of the run-up gauge in the armor layer survey.

4 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 Universität Hannover to assess, under extreme wave conditions (wave steepness of 0.055) with different incident wave angles (from 40° to 90°), the structure behaviour in what concerns wave run-up, overtopping and damage progression of the armour layers, composed by rock and Antifer cubes. Non-intrusive methodologies were used for the assessment of armour layer damage evolution, including a laser scanning technique, stereo photogrammetry and a Kinect© motion sensor. The aim of the present work is 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 program.
The results suggest that Kinect© can be used by laboratories and research groups to identify the different damage stages with a good resolution, not only in 2D cases, but also in 3D studies.

Tests conducted with Dir=90°, directional spreading of 0°, and with Dir=40°, directional spreading of 50° (short-crested waves) presented the highest localized damage at the roundhead.

Tests conducted with the same wave conditions (d=0.60 m and Dir=40°) presented a higher localized damage when conducted with a directional spreading of 50° (short-crested waves) than with a spreading of 0° (long-crested waves).

The values of the eroded depth obtained using the global area seem to be overestimated when compared to localized damaged area.

The Kinect© was able to determine porosity evolution without damage. Some of slight motions were clearly detected by the device. Such results are relevant to understand the first stages and behaviour of the roundhead evolution, and to develop maintenance strategies before damage reaches failure.

The results from the present work, using innovative survey techniques of the armour layer of a scale model breakwater, seem to lead to promising, powerful tools for evaluation of eroded volumes.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 654110, HYDRA LAB+.

All the other participants on the RODbreak project: Francisco Pedro, Mário Coimbra, Moritz Koerner, Julius Weimper, Antje Bornschein, Bastien Dost, Bas Hofland, Jeroen van den Bos, Rita Carvalho and Reinhard Pohl

The authors would also like to acknowledge the support from LUFI, namely from Dr.-Ing. Sven Liebisch and the people at the Laboratory “Hannover Marienwerder”: Björn, Mareike, Mario, Raoul and Tom.

References


