An estimation of the damage of scale models of breakwaters using the time of flight method

Avaliação do dano no manto resistente de modelos de quebra-mares utilizando o método time of flight

Rute Lemos[1] | **Conceição Fortes**[1] | **Gabriel Silva**[1] | **Liliana Pinheiro**[1]

[1] LNEC – Laboratório Nacional de Engenharia Civil, Portuga rlemos@lnec.pt, jfortes@lnec.pt, lgsilva@lnec.pt, lpinheiro@lnec.pt

abstract

The assessment of damage evolution in scale model tests of rubble-mound breakwaters can be achieved by comparing eroded depths and volumes between consecutive surveys. Aiming to evaluate damage evolution on rubble-mound breakwater, scale model tests were recently conducted on the maritime hydraulic facilities of the National Laboratory for Civil Engineering. This paper focuses on the use of novel, non-intrusive survey methodologies such as the Time of Flight (ToF) principle technique. In this study, damage evaluation is based on the comparison of point clouds obtained before and after each test series, enabling the calculation of eroded depths and eroded volumes and the estimation of displaced units by using a non-dimensional damage parameter based on the eroded volume.

Keywords: Stability, Breakwater, 3D Surveying, Measuring Techniques

resumo

A avaliação da evolução do dano em ensaios em modelo físico reduzido de quebra-mares de talude pode ser alcançada comparando as profundidades erodidas e os volumes erodidos entre levantamentos consecutivos. Com o objetivo de avaliar a evolução do dano num quebra-mar de taludes, foram realizados ensaios em modelo físico reduzido no pavilhão de hidráulica marítima do Laboratório Nacional de Engenharia Civil. Este artigo foca-se no uso de novas metodologias de levantamentos tridimensionais não intrusivas, tais como a técnica baseada no princípio de *Time of Flight* (ToF). Neste estudo, a avaliação do dano é baseada na comparação entre nuvens de pontos antes e depois de cada série de testes, permitindo o cálculo de profundidades e volumes erodidos, bem como a estimativa de blocos removidos, usando um parâmetro adimensional de dano baseado no volume erodido.

Palavras-chave: Estabilidade, Quebra-mar, Levantamento 3D, Técnicas de Medição

1- INTRODUCTION

Due to its extensive coastal zone, Portugal owns a number of relevant maritime structures, being the most common ones breakwaters that protect artificial harbors. Breakwaters are thus protection structures built to create sheltered areas for safe mooring, loading operations, handling of ships, and also to protect harbor facilities, although they may also have other roles such as controlling the sedimentation, by guiding the currents, or protecting water intake structures in thermoelectric plants.

In order to optimize the hydraulic design of such structures, physical scale model tests are often necessary and overtopping and hydraulic stability tests are the most common ones.

The assessment of the damage evolution (in stability tests) during scale model tests of rubble-mound breakwaters is traditionally made by comparing erosion profiles, which are representative of the tested section, and by determining the eroded volume of the tested section between consecutive surveys.

Armour layer damage is then characterized by parameters based either on the number of displaced armour units, as is the Nod parameter (van der Meer, 1988) or in the dimensionless damage parameter, $S=Ae/D_{n50}^2$ defined by Broderick and Ahrens (1982), 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, $e = (z_{before} - z_{after}) \cos \alpha$, where z_{before} and z_{after} are the structure elevation before and after a test run, respectively, and α is the structure slope (erosion of the profile being positive). They also consider the dimensionless erosion depth, where $E_{2D}=\max(e)/Dn_{50}$, where e is averaged over a predefined width of mDn_{50}, 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 survey of rubble-mound breakwaters can be obtained with sub-millimetre 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, 2017).

Despite 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.

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 al.* (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. Musumeci *et al.* (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.

In the present work, damage evaluation was based on surveys with the Kinect© motion sensor, taking into account the eroded volume over the damaged areas of the model. Lemos *et al*. (2019) has previously tested this damage evaluation approach during a set of tests conducted on a stretch of a rubble-mound breakwater which armour layer was composed of regularly placed Antifer cubes.

The main objectives of the present paper are:

- To evaluate the damage evolution of the armor layer of a scale model of a rubble-mound breakwater. Results of 6 test series are presented in order to compare damage evolution between tests conducted with different wave conditions and with different wave directions.
- To test the ToF methodology with the Kinect© sensor, in order to evaluate the damage evolution based upon the differences of volume found between the initial and final surveys conducted without water in the basin;
- To estimate the number of displaced armor units by using a non-dimensional damage parameter based on the computed eroded volume.

2- MATERIALS AND METHODS

2.1. The physical scale model

A stretch of a rubble-mound breakwater was built in in one of the LNEC's irregular wave tanks, a basin with dimensions 44 m long, 23 m wide, with an operating height of 0.75 m, equipped with two 6.0 m-length irregular wave generators.

The section subject of the present study was a segment of a multi-layer rubble-mound breakwater, consisting of an armour layer composed of 0.141 kg, randomly placed, Antifer cubes with a nominal diameter (Dn) of 0.045 m, whose slope is approximately 2:1 and a Porosity around 0.54. Fig. 1 illustrates the tested section in the wave basin. Table 1 presents the test program and the wave conditions used on the experiments.

2.2. Damage evaluation

To measure the armor layer damage, two different techniques were used: The traditional counting method of rocking and displaced armor units and a methodology based on the use of the Kinect© motion sensor that was placed above the stretch of the breakwater, in order to gather a 3D model the armor layer by conducting three-dimensional surveys at the beginning and at the

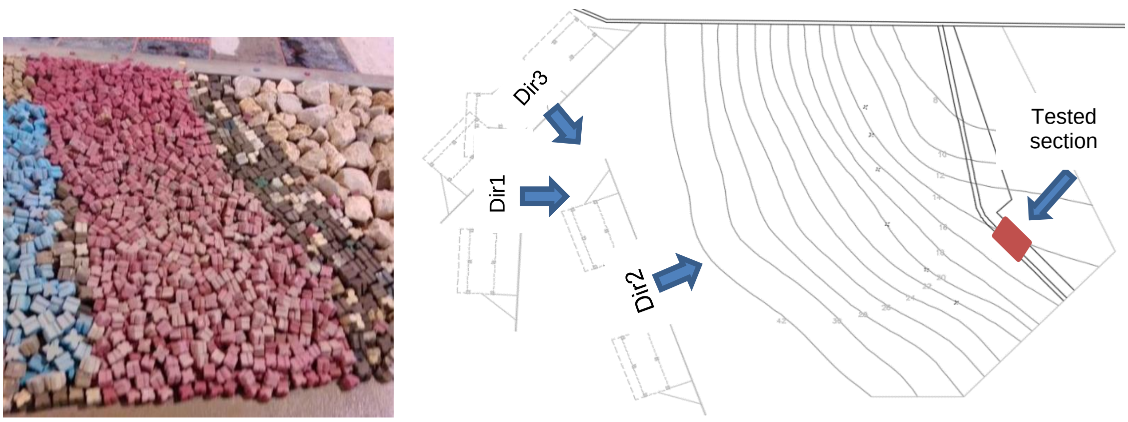


Fig. 1 | Tested section and wave directions

Table 1 | Test conditions (near the wavemaker)

Series	Water depth (m)	Test	Test duration (min)	Tp (s)	Hs (m)
1 (Dir1) 3 (Dir2) 5 (Dir3)	0.69	1	22	1.49	0.12
		2	22	1.74	0.14
		3	44	1.98	0.15
		4	44	2.23	0.17
		5	44	1.49	0.19
		6	44	1.98	0.19
		7	44	2.48	0.23
2 (Dir1) 4 (Dir2) 6 (Dir3)	0.73	1	22	1.49	0.12
		2	22	1.74	0.14
		3	44	1.98	0.15
		4	44	2.23	0.17
		5	44	1.49	0.19
		6	44	1.98	0.19
		7	44	2.48	0.23

at the end of each test series, without water in the tank. Intermediate surveys and counting of the displaced units were conducted with water at the end of each intermediate tests (Table 2), although they were not considered in the present work.

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). Fig. 2 illustrates the equipment used to evaluate armor layer damage.

The sensor parameters used in the surveys, were a Voxel volume resolution of 512 for the three coordinated axis x, y and z; 128 Voxel for meter and an acquisition distance between 0.5 m e 8 m.

A topographic survey of the model was conducted to obtain the coordinates of points to be used as ground control points (GCP) to geo-reference the clouds of points resulting from each model survey. Those points (Fig. 3), located on the model crest and also on the tank´s concrete floor, were obtained by using a total station.

The Kinect clouds of points were post-processed using the tools and algorithms of the open source software *CloudCompare* (Girardeau-Montaut, 2006). Those algorithms enabled to compute the eroded volume by comparing initial and final clouds of points and, based on that volume, estimate a non-dimensional damage parameter (S_{3D}) representative of the number of displaced armor units.

Fig. 2 | Kinect sensor

Fig. 3 | Ground Control Points used to georeference the clouds of points

The eroded volume computation 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.

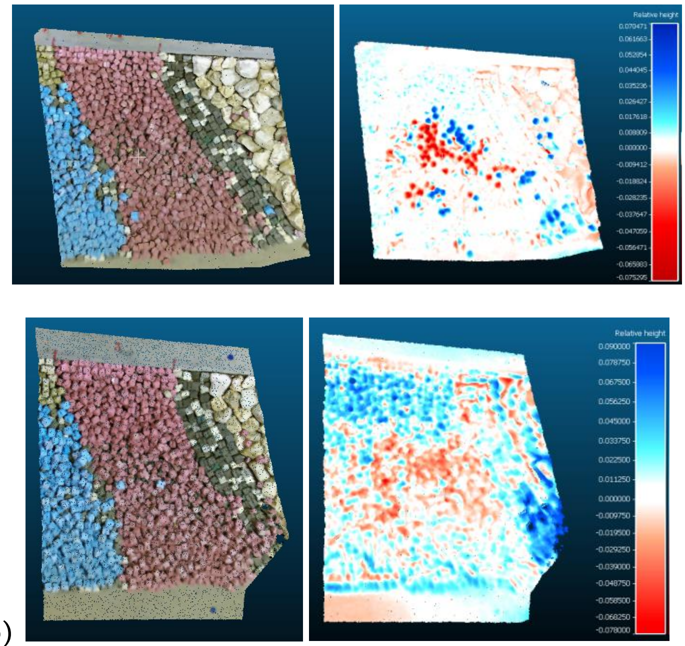
To compute the volume, *CloudCompare* sums the contribution of each cell. This contribution is the volume of the elementary parallelepiped corresponding to the elementary cell area, multiplied by the distance difference between clouds (*dV = grid step * grid step * distance*).

In the present work, after several experiences with grid steps ranging from 1 mm to 10 mm, the best combination of point density and depth estimation was obtained with a step of 6 mm. Smaller steps conducted to an overestimated depth, while grid steps higher than 6 mm led to an important loss of point density.

The ratio between the eroded volume of the damaged area and the volume of a single armour unit results on an estimate of the number of displaced units, $S_{3D} = (EV*(1-P))/(Dn^3)$ where EV is the total eroded volume, P is the armour layer porosity and Dn the nominal diameter of the armour unit. The number of estimated displaced units was then, compared with the number of displaced units obtained after each test, with the traditional counting method.

3- RESULTS

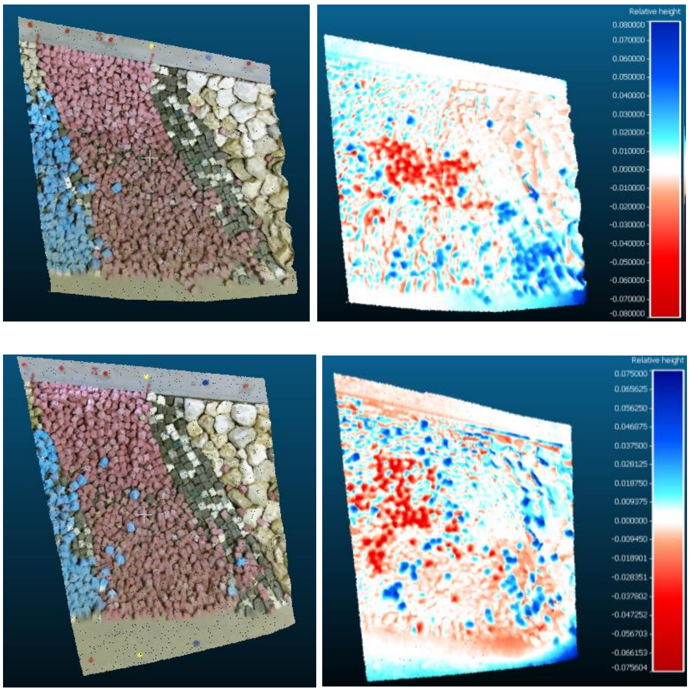
Fig. 4 to 6 present the three-dimensional surveys and the difference maps between surveys conducted at the beginning and at the end of each test series for the three wave directions associated with both water levels.



a)

b)

Fig. 4 | End of test series 1 (a) and 2 (b). Model survey and difference maps a)



b)

Fig. 5 | End of test series 3 (a) and 4 (b). Model survey and difference maps

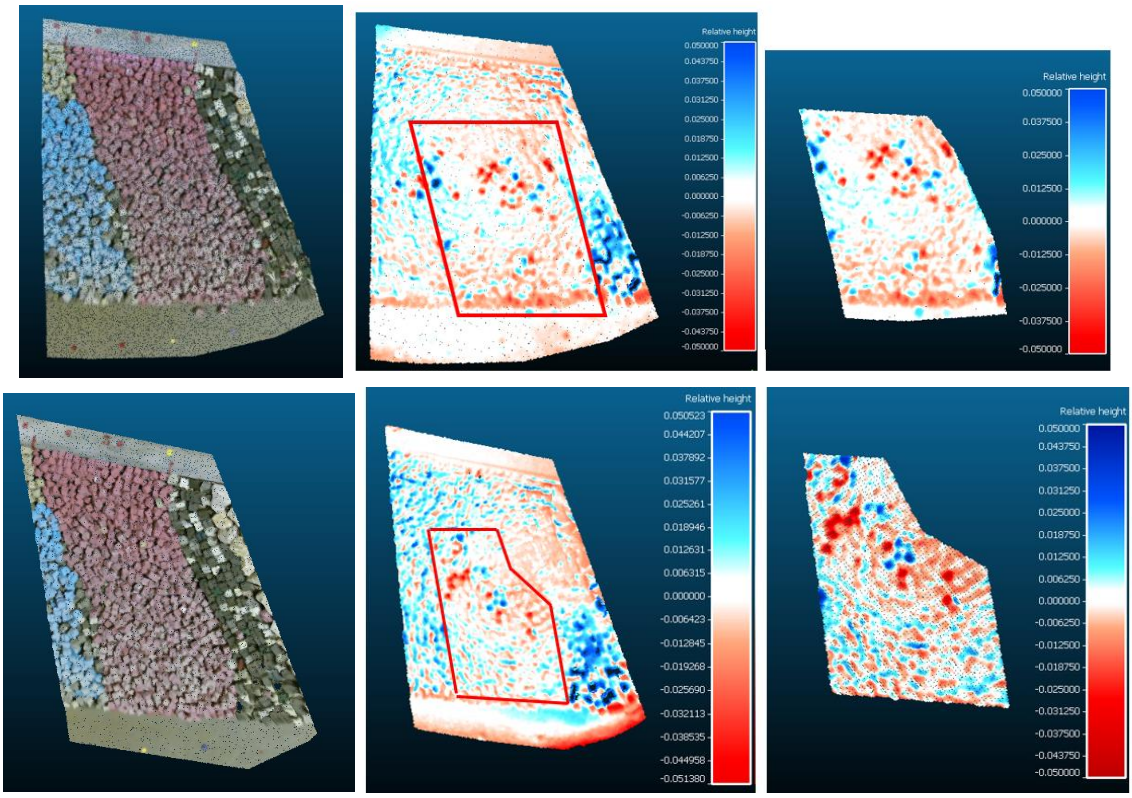


Fig. 6 | End of test series 5 (a) and 6 (b). Model survey and difference maps

For test series 1 to 4, the entire surveyed area was used in order to compute the eroded volume, since most of the movements correspond to displaced units (blocks with movements greater than their nominal diameter). On the other hand, for tests 5 and 6, with less removed units, but with many movements, a localized damage analysis was necessary, by cropping the most damaged area to be analyzed (Fig. 6).

Table 2 presents erosion volumes, obtained from a 6 mm grid. The estimated values of removed/displaced units, based on the ratio between the eroded volume and the volume of a single armor unit (around 0.09 dm^3), are also summarized. Volumes are presented in cubic decimeters to have a better understanding of the damage, according to the model dimensions.

Fig. 7 illustrates the counted and estimated number of armor units based upon the eroded volume.

In a general way, damage estimation using the global eroded volume slightly overestimated the number of displaced units, as small movements between armour units can be wrongly computed as erosion.

Estimated and counted displaced armor units were quite convergent, except for test series 4, where the differences between counted and estimated displaced units was of 18 units. This difference was probably caused by movements at the toe of the structure which were accounted as displacements.

Table 2 | Eroded volume, estimated and counted displacements at the end of Series 1 to 6

	Eroded volume (dm^3)	Displaced units	
		Estimated (S_{3D})	Counted
Serie1	4.37	48	42
Serie2	7.63	84	80
Serie3	6.67	73	76
Serie4	7.78	85	67
Serie5	2.26	25	21
Serie6	1.68	18	16

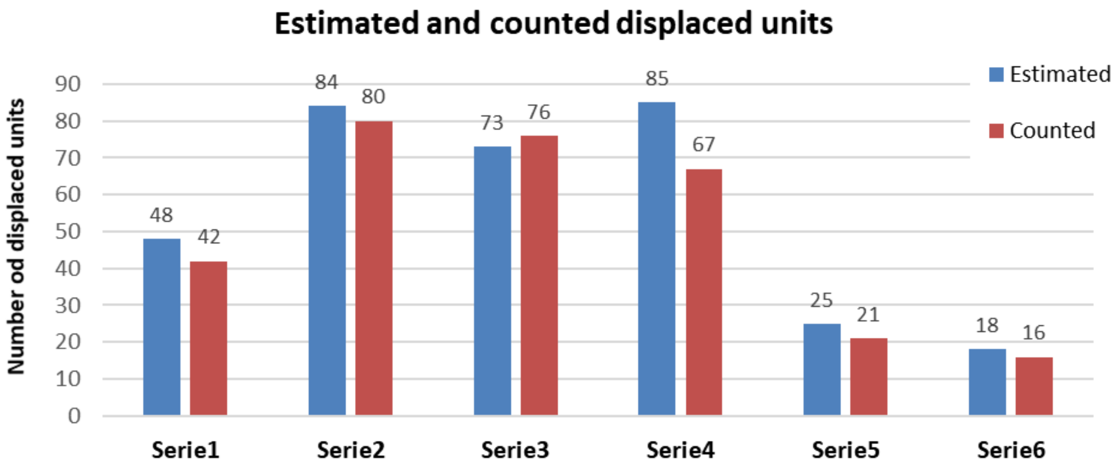


Fig. 7 | Estimated and counted displaced units at the end of test series 1 to 6

4- CONCLUSIONS

This paper presented the use of a non-intrusive 3D survey methodology based on the *Time of Flight* (ToF) technique. The damage evaluation of a stretch of a rubble-mound breakwater was carried out, for six test series, based on the comparison between point clouds obtained before and after those test series, enabling the calculation of eroded volumes as well as the estimation of the displaced units by using a non-dimensional damage parameter based on the eroded volume.

In what concerns the use of the Kinect© sensor, the survey technique seems to be powerful tools for damage evolution assessment of the armour layer of a scale model breakwater.

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.

Regarding the estimation of the displaced armour units based on a non-dimensional damage parameter computed upon the eroded volume, in a general way, estimated and counted displaced armor units were quite convergent, except for test series, with smaller levels of damage, where differences between the clouds of points due to movements of the armor units can be accounted as displacements.

More investigation should be made, including the analysis of all the intermediate surveys conducted with water, in order to validate this methodology for damage progression analysis using the 3D damage parameter.

Additionally, it would be interesting to apply this damage progression analysis to consecutive *in situ* photogrammetric aerial surveys of breakwaters made under systematic observation programs of breakwaters.

ACKNOWLEDGEMENTS

This work has received funding from the projects: To-SEAlert, Ref. PTDC / EAM-OCE/31207/2017 and BSafe4sea, Ref. PTDC/ECI-EGC/31090/2017. The authors also like to acknowledge the support of César Costa, Rosa Emília Soares and Jan Hilário for their help in this study.

REFERENCES

Broderick L. & Ahrens J.P. (1982) - Rip-rap stability scale effects. Technical Paper 82-3, U.S. Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg, MS.

Castaneda, V. and Navab, N. (2011). Time-of-Flight and Kinect Imaging, lecture online, Munich Technical University.

http://campar.in.tum.de/twiki/pub/Chair/TeachingSs11Kinect/2011-DSensors_LabCourse_Kinect.pdf

Girardeau-Montaut D. (2006) - Détection de changement sur des données géométriques tridimensionnelles. PhD thesis (French).

Hofland B., Disco M. & Van Gent M.R.A. (2014) - Damage characterization of rubble mound roundheads. Proc. of CoastLab 2014, Varna, Bulgaria.

Hofland B., Van Gent M.R.A., Raaijmakers T. & Liefhebber F. (2011) - Damage evaluation using the damage depth. Proc

Lemos R., Santos J.A. & Fortes C.J. (2017) - Rubble mound breakwater damage assessment through stereo photogrammetry in physical scale laboratory tests. RIBAGUA - Revista Iberoamericana del Agua, Taylor and Francis (Published online: 25 Oct 2017).

Lemos, R, Peña, E, Santos, J. A., Sande, J., Figuero, A., Alvarellos, A., Laiño, E., Reis, M.T., Fortes, C.J., Kerpen, N. (2019). "Measuring Armour Layer Damage in Rubble-mound Breakwaters under Oblique Wave Incidence". Coastal Structures 2019, Hannover, Germany.

https://doi.org/10.18451/978-3-939230-64-9_030

Maciñeira E. & Burcharth H.F. (2016) - Stability of cube armoured roundheads exposed to long crested and short crested waves. Coastal Engineering, 112, 99-112. http://dx.doi.org/10.1016/j.coastaleng.2016. 03.002

Melby J.A. & Kobayashi N. (1998) - Progression and variability of damage on rubble mound breakwaters. Journal of Waterway, Port, Coastal, and Ocean Engineering, 124(6), 286–294

Molines J., Herrera M.P., Perez T.J., Pardo V. & Medina J.R. (2012) - Laser scanning technique to quantify randomness in cube and cubipod armour layers. Proc. of CoastLab 2012, Ghent, Belgium.

Musumeci R., Moltisanti D, Foti E. & Battiato S. (2018). 3-D monitoring of rubble-mound breakwater damages. Measurement, 117 (March 2018), 347-364.

http://www.tandfonline.com/doi/full/10.1080/23863781.2017.1381455

Puente I., Sande J., González-Jorge H., Peña E., Maciñeira E., Martínez-Sánchez J. & Arias P. (2014) - Novel image analysis approach to the terrestrial LiDAR monitoring of damage in rubble mound breakwaters. Ocean Engineering, 91, 273-280.

Rigden T. & Steward T. (2012) - Use of 3D laser scanning in determining breakwater damage parameters. Proc. of CoastLab 2012, Ghent, Belgium.

Soares F., Henriques M. & Rocha C. (2017) - Concrete block tracking in breakwater models. Proc. of FIG Working Week 2017, June, Helsinki, Finland.

Van der Meer J.W. (1988) - Rock slopes and gravel beaches under wave attack. Ph.D. thesis, Delft University of Technology, The Netherlands; also Delft Hydraulics Publ. 396.