Controlling the Damages of Physical Models of Rubble-Mound Breakwaters by Photogrammetric Products - Orthomosaics and Point Clouds

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Abstract. During the design process of a rubble-mound breakwater, in order to evaluate its effectiveness, scale model tests are required to study the hydraulic and structural behaviour of the proposed structure under predefined sea-wave conditions. The main goal of such tests is to study the structure overtopping and infer on damage progression by quantifying movements and displacements of the armour layer units. Scale model tests results can be also used to calibrate numerical models.

Scale models of rubble-mound breakwaters are built in wave flumes (two-dimensional models, 2D) or in wave basins (three-dimensional models, 3D), enabling to simulate sea-wave conditions to study wave-structure interaction. A wave characterization and simulation software package is used to reproduce the prototype wave conditions, namely the significant wave height as well as the associated wave period. This makes possible to generate different sea states and therefore to study the rubble-mound breakwater behaviour and to identify possible weak areas in the armour layer.

In order to characterize the armour layer envelope, recent applications of photogrammetric surveys were used, making it a promising technique. This method makes use of orthomosaics and clouds of points created from the photogrammetric survey. In this paper the first conclusions from the use of this technique are presented. The results of this analysis are extended to *in situ* breakwaters monitoring campaigns.

Keywords. point clouds, orthomosaic, breakwater, physical model, Micmac software, QGIS.

1 Introduction

There are five basic transport modalities: air, motor carrier, train, maritime, and pipeline. In Europe almost 90% of the EU external freight trade is seaborne (EU Transports, 2015).

Obviously, harbours have a key role in maritime transport and the maintenance of the trade routes depends on harbours in good conditions. Some harbours were constructed in shores with harsh wave regimes. Thus, protection structures, as breakwaters, are built, aiming to protect a coast or the activities along the coastline. Quite often, on the shore side of the breakwaters, quays are constructed to allow ships to dock so that cargo or passengers are load or unloaded, increasing the importance of the breakwaters.

Damages on breakwaters can influence the activity of a harbour and have huge economical impacts. So, it is important a correct design of the breakwater and, after construction, an implementation of a monitoring program, in order to early detect the areas where the armour layer has lost its ability of protection. This will help the authorities to decide which areas must be subject to repair works. This procedure, when done in advance, have always smaller costs.

Among the several types of breakwaters, rubble-mound breakwaters (RMB) are the most appropriate sheltering structures for port areas that are prone to the action of severe sea states. The main objective of the design of a RMB is to determine the size and layout of the components of the structure. After a preliminary design, the performance of the breakwater is verified with a physical model to evaluate the design effectiveness. The physical model is constructed, geometrically similar to the full size structure, inside a wave basin or a wave flume. The more frequent studies comprise: i) stability and overtopping tests of maritime structures; ii) wave

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disturbance tests to evaluate tranquillity conditions of the sheltered areas and iii) the mean sea level rise in harbour basins (Reis *et al.*, 2014).

The evaluation of the stability of a breakwater scale model can be studied by identifying the displacements of its armour layer units, i.e., changes in their positions. Usually, the identification of those displacements is made by visual observation, but this technique depends on the experience of the technician.

Photogrammetric surveying techniques can be a helpful tool to acquire information about the armour layer of the breakwater, both in scale model and *in situ* breakwaters monitoring campaigns. Those techniques have been studied to assess their suitability for stability scale model tests which are built on the experimental facilities of the Ports and Maritime Structures Division of the National Laboratory for Civil Engineering of Portugal (LNEC). The same techniques are also under study with the aim of applying them to *in situ* breakwaters survey during monitoring campaigns in the Portuguese coast.

In this paper, the recent tests of the use of photogrammetric survey techniques to evaluate the damage on the armour layer of RBM, both in scale models and *in situ*, are described. Advantages and limitations of this methodology will be presented.

2 The RMB's

RMB are the most common harbour protection structures in areas with severe wave regimes. During its design process, in order to evaluate the design effectiveness, scale model tests are many times required, in order to evaluate its hydraulic and structural behaviour (Fig. 2).

In general, the purpose of RMB is to provide shelter to harbour basins, harbour entrances, and water intakes against waves and currents. Its main function is to dissipate wave energy and/or to reflect wave energy back into the sea.

The conventional rubble-mound structures consist of a core of fine material covered by an armour layer, made with stone or concrete blocks. To prevent fine material being washed out through the armour layer, filter layers must be provided.

The concrete blocks, being more protecting but also more expensive than the stones rocks, are usually placed in the most exposed slope of the breakwater: the sea side and the head. Fig. 3 illustrates the different types of blocks used in the armour layer of the RMB of Ericeira.

During the construction of a 3D scale model, the bathymetry of the surrounding area of the breakwater, the breakwater itself and other structures nearby are reproduced. During the test series, different sea states are replicated. Each test run corresponds to an incident wave condition (i.e., a significant wave height associated with a spectral peak period, a mean wave direction, and a water level). Damage progression (displacements of blocks) is assessed by visual observation, and by video and photographic techniques. According to LNEC's Stability Criteria, a displacement is relevant when it is larger than the size of a unit (a block, for instance).

Fig. 1 Harbor protections under study and the same Spanish harbor after construction

Fig. 2 Physical model tests of the RMB of Ericeira

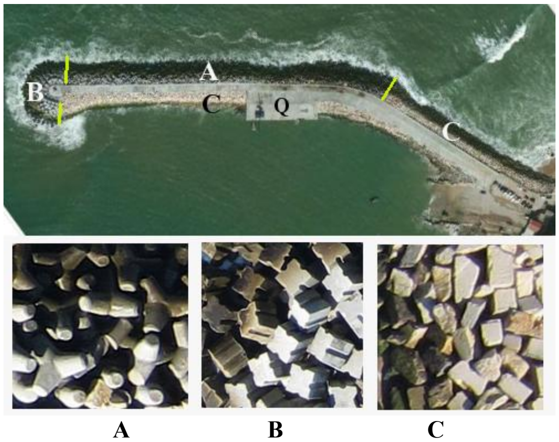

Fig. 3 Breakwater of Ericeira. A: stretch covered with tetrapods; B: stretch covered with grooved cubes; C: stretch covered with stones; Q (quay and crest): concrete

3 The Photogrammetric Survey of RBM Scale Models

Two 3D scale models of breakwaters, named A and B, Fig. 4 and Fig. 6, respectively, were used to evaluate the performance of the photogrammetric techniques. As at the moment of the evaluation of these techniques the RMB weren't under test, some artificial changes were applied: at breakwater A, some blocks on the armour layer were slightly moved; at breakwater B it was simulated a rise of the armour layer. A rise is a non-natural behaviour but is very easy to produce with an inflated bag. The images were collected with digital cameras, which were installed in a steady support or under a drone.

3.1 Breakwater A

Breakwater A, built at a geometrical scale of 1:43, was 2 m long, 1.3 m width and 0.3 m height (Fig.4). The breakwater armour layer consisted on cubic concrete blocks forming a single layer (Fig. 5). Each cube had an edge length of 3.3 cm.

Fig. 4 Breakwater A. General overview

Fig. 5 Concrete blocks of the armour layer.

Four different photogrammetric surveys were carried out, using a digital camera Nikon D200, at a distance varying from 2 to 3.5 m. The average pixel size was 0.3 mm. The first and the second surveys were terrestrial surveys, with the camera mounted on a tripod. The third and fourth surveys were aerial surveys: the camera was fixed on a horizontal rod that was attached to a support placed on the side of the model which was pushed during the surveys.

The aerial surveys were more difficult to set. Poor lighting at the experimental facilities and the need to use manual focus to prevent changes of the focal distance and aperture, led to a low shutter speed. For this and due to vibrations of the support of the camera, many photos were blurred.

Vertical photos from the aerial surveys proved to be effective on capturing images of submerged blocks. On the other hand, horizontal photographs, due to the phenomena of refraction, proved to be less effective on detecting those blocks.

3.2 Breakwater B

Breakwater B, built at a geometrical scale of 1:30, was 15 m long, 3.3 m width and 0.4 m height (Fig. 6). The breakwater armour layer consisted on Antifer cubes double layer.

In breakwater B, the colours of the blocks (Fig. 7) are of utmost importance on the detection of armour layer damages during the tests, when traditional monitoring techniques (visual or normal photographs) are used.

In this model, two different photogrammetric surveys were carried out. In the first one the breakwater was surveyed by a video camera during a few minutes. It was used a low quality camera of a small drone, a four rotors helicopter. During the survey it was noticed that the wind generated by the rotation of the propellers produced an agitation on the water surface, reducing the photos quality of the submerged areas of the breakwater.

Fig. 6 Breakwater B. General overview.

Fig. 7 Breakwater B. Different materials.

In the second survey, two Canon EOS 600D cameras were used. They were placed over the structure, at 2.3 m height, remaining in the same position during the test. Both cameras took the photos at the same time, every two seconds. The surveyed area was approximately 1.2 m × 1.0 m; the average pixel size was 0.9 mm. The test consisted on following the displacements of a set of blocks. Under the blocks it was placed a bag that was inflated to produce displacements of the blocks. The test took 38 seconds. There were made 19 pairs of photos, being that each pair must be processed independently.

4 Processing the Data

Orthomosaics and point clouds are generated upon the photographs, using the free open-source software Micmac (Multi-Image Correspondances, Méthodes Automatiques de Corrélation, Pierrot-Deseilligny et. al., 2011) from IGN (Institut National de l'Information Géographique et Forestière, France). The video frames captured by the drone had poor quality and couldn't be processed.

The main steps of the software processing are: i) identification of homologous points on photo pairs (one of the most time consuming phases); ii) computation of the calibration parameters of a camera (sensor parameters, lens parameters, camera-lens assembly parameters and extrinsic parameters, these related with the positions of the camera in a reference frame established by the software); iii) geo-reference of the data, by the use of coordinated ground control points, to transform the relative orientation (from step ii) in a absolute orientation; iv) correction of each photo; v) image matching and generation of an orthomosaic and a point cloud.

The estimation of the calibration parameters should not be made during this processing, but using photos specially taken for this purpose. The estimation of parameters can be done using Micmac or a software developed for this purpose. In the case of using Micmac, the "calibration photos", no less than five, must include an object with a strong 3D component – like a corner of a house or of a wall – and a surface with chromatic irregularities to have many homologous points in all the pairs of photographs. In a normal processing only a camera is used and the extrinsic parameters of each photo are determined, by the software, with the help of other photos.

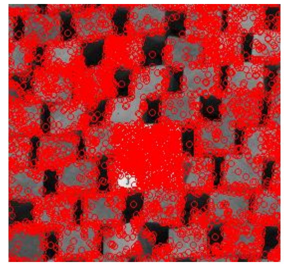

Fig. 8 Homologous points.

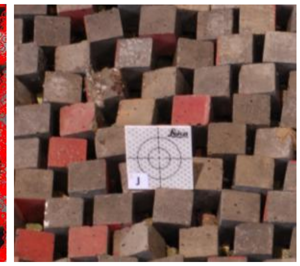

Fig. 9 Original surface.

In the special case of the test carried out with two cameras (see last paragraph), the processing is more difficult because there were only two photos, each photo taken by a different camera. In this case the only solution, provided by Micmac, is to include, during the processing, information on the location and orientation of both cameras as well as to provide some extra information about the characteristics of each camera.

The quality of the final products is influenced by the number of homologous points on pairs of photographs. A large number of points, homogeneously distributed, are very important for the computation of the calibration parameters and of the extrinsic parameters. To get some information on the identification of points on the model, it was run the first step of Micmac with two equal photos, followed by the analysis of the location of homologous points. Fig. 8 illustrates the results obtained. In the centre of each red circle is a point that was identified in both photos.

Comparing Figures 8 and 9, one can notice that, for the software, is difficult to find homologous points on the surfaces of the cubes, except if they have texture. White and black areas are also bad. The only good regions are the edges of the cubes and the target, this one due to the draw on its surface. Colours found in breakwater B had no influence on the number of points detected because the surfaces of these blocks have small radiometric variations. The software Micmac searches for homologous points using the monochromatic version of the image and the search is based in the luminosity.

5 Orthos and Point Clouds

The software Micmac generates orthomosaics (orthos) and point clouds. To produce the orthos, the software selects pixels in the different photos (after corrected) and gathers these pixels in one 2D image. This image has no depth information. Fig. 10 presents a detail of an ortho. The same area is presented in Fig. 11 where different colours represent different pixels sources (pixels with the same colour mean they were from the same photo). A close view of the Fig 11 shows that some small areas of the ortho have data from six different photos (Fig. 12).

In what concerns to point clouds, they can provide depth information since they include, per point, the three coordinates. It enables a general 3D view of the breakwater as well as the calculation of volumes and profile drawings. To access the damage evolution of the structure, new tools are currently being developed.

Point clouds can be difficult to manage because they have too many points. For instance, the point cloud for Breakwater A has about 20 million points. However, there is open source software, Cloud Compare, which can be used to identify alterations in a point cloud in a fast way. The drawback is that, sometimes, it doesn't detect small changes.

The comparison of different two orthos (the first before displacement, the second after displacement) looked more reliable. In Fig 13, it is presented a comparison made with the software QGIS, a free and open-source application that includes modules for the analysis of images. First, it was calculated, for each ortho, the average of the three colour bands (red, green, blue) followed by the calculation of the negative of the modulus of the differences between the two images created. The black areas in Fig. 13 show the areas with differences.

Fig. 10 Detail of a ortho

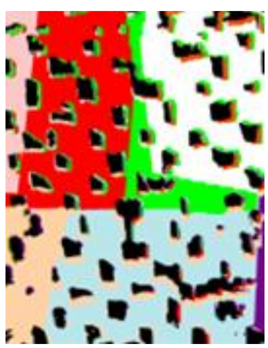

Fig. 11 The source of each pixel

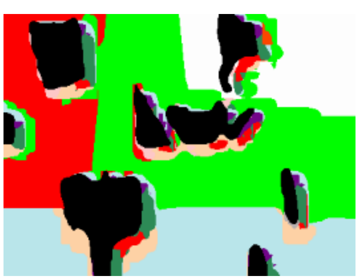

Fig. 12 Detail of Fig. 11

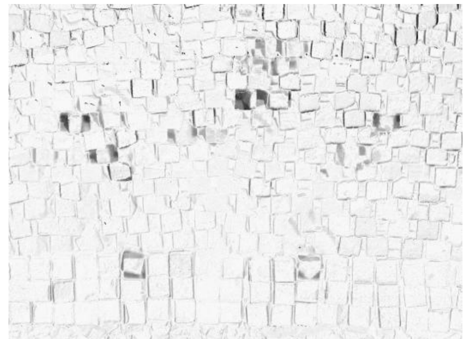

Fig. 13 Difference between two orthos created from photogrammetric surveys made at the end of two consecutive tests

Nevertheless, changes detected by QGIS can also have an origin in differences of colours of the model. Those differences are related with changes of the ambient light or with changes of the colour of the blocks as a result of changing from dry to wet or vice versa. These changes are more evident in non painted surfaces.

To see the influence of the dry/wet colour change, it was made a test with a concrete block partially wet (Fig. 14). Four rectangular areas in the photograph were selected – "light dry"; "shadow dry"; "light wet"; "shadow wet" – and converted to greyscale. The frequency of the 256 intensity levels of each area was calculated using Scilab (Toolbox SIVP). The relative frequency chart combining the four areas is present in Fig. 15.

One can conclude that the detection of changes of the armour layer by comparing two orthos of the model, despite being a fast and easy technique, may prove to be difficult to implement because it is influenced by chromatic variations not related with displacements.

Fig. 14 Block used to demonstrate the influence of light/shadow/dry/wet surface.

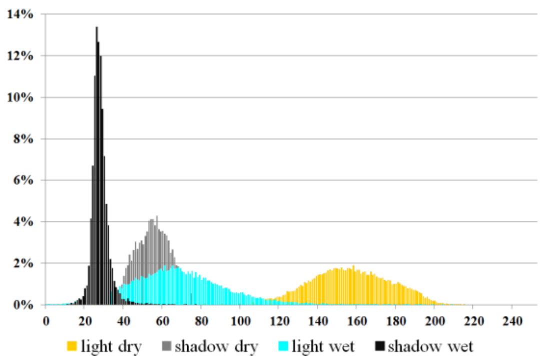

Fig. 15 Relative frequency chart of intensity levels.

In what concerns point clouds, besides its large number of points, it was, quite often, impossible to detect the location of some blocks. Fig. 16 presents a section of a point cloud of breakwater A, converted to a triangular mesh (conversion made by Cloudcompare; mesh seen in Meshlab). An analysis of an area delimiting four cubes revealed that it was impossible to detect each individual cube. But analysing the ortho, one can see colour changes in the area related with the spaces between the blocks. This can help to locate each cube and determine its 3D position, if it is established a link between the information of the ortho and the information of the cloud.

6 In Situ Monitoring Surveys

The use of photogrammetric techniques for breakwater surveys becomes more difficult *in situ* campaigns. This section refers to problems faced when processing the photos obtained during a drone flight over the Ericeira breakwater, Fig. 3, in the west coast of Portugal. The flight and the post processing were offered by the survey company Sinfic.

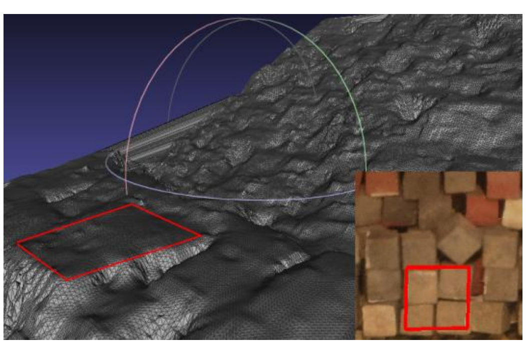

Fig. 16 Mesh of a section of breakwater B and a section ortho in the same area.

Fig. 17 Detail of the ortho.

The drone flight over Ericeira breakwater (Henriques *et al.*, 2014) took place in 2013 February, on a very windy day. The photos were taken by a camera Canon IXUS 220 HS mounted on the platform SenseFly Swinglet CAM. The flight was made at an altitude of 185 m. To produce the ortho and the point cloud it was used the processing software PostFlight Terra 3D from Sensefly.

Due to the altitude of the flight and the use of a less quality camera, the point cloud of the breakwater has, “only”, 280000 points (approximately). The ortho presents some anomalies which are common in areas that don’t have breaklines, i.e., lines that represent a distinct interruption in the slope of a surface. Cubes and other parallelograms like buildings, have breaklines. As a consequence, in those areas it is common to see a characteristic pixel pattern that looks like melted cheese (Fig.17). This phenomenon is caused by the lack of breaklines on the digital surface model generated by the software (this doesn’t create breaklines).

The variations of luminosity in the ortho are very large. Dry surfaces can become almost white. On the other hand, wet surfaces become very dark, even when exposed to direct sun light. In Figs. 18 to 21 it is presented a similar analysis to the one showed in the end of last section. Three different areas of the armour layer with the three different types of blocks were selected: one covered with Antifer cubes (Fig. 18); other with limestones (Fig. 19) and the last one with tetrapods (Fig.20). Fig. 21 presents the relative frequency chart of intensity levels for those three types of blocks in wet and dry conditions. The comparison of point clouds presented also some difficulties. In Fig. 22, a rectangular area of the head of the breakwater (ortho + point cloud) is presented. The distribution of points is very homogeneous.

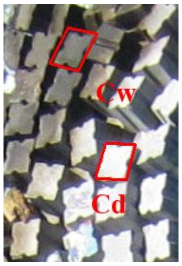

Fig. 18 Area with cubes.

Fig. 19 Area with stones

Fig. 20 Area with tetrapods.

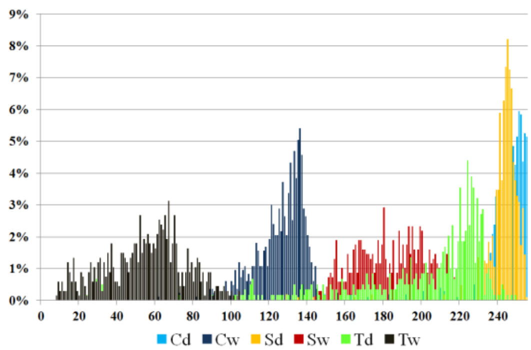

Fig. 21 Relative frequency chart of intensity levels.

Fig. 22 Ortho and point cloud (top view) of the head of the breakwater.

A triangular mesh was generated from the point cloud (Fig. 23). Analysing the mesh, one can notice some anomalies, like needles which are due to points that are surrounded by other points with lower height. The "needle" on the left of Fig. 24 has differences of height between 1 m and 3.7 m to its nearest points. Taking in account that the height of a tetrapod is approximately 2 m there are, clearly, significant errors.

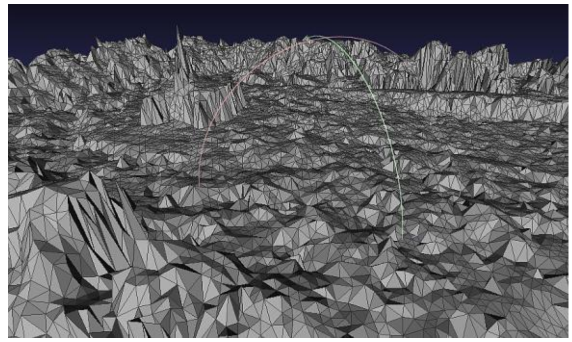

Fig. 23 Perspective view of the mesh.

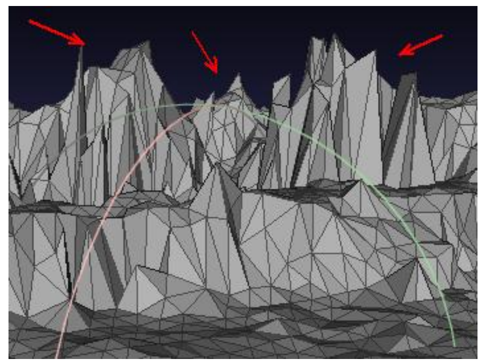

Fig. 24 A detail of the mesh: some "needles" in an area with three tetrapods.

7 The Special Case of Wave Flumes

3D scale models studies of RMB are conducted in wave basins, where luminosity problems are difficult to solve.

In 2D scale model tests, the scope of the study is a specific cross-section of the breakwater (Fig. 25). These studies are conducted in wave flumes (Fig. 26), where a permanent, steady camera support structure can easily be placed above the breakwater model and is easy to set good lighting. In 2D scale models, photogrammetric methodologies have already been tested intensively by LNEC, Fig. 27, in long-term scale model tests made for research studies (Lemos *et al.*, 2013). The photographic equipment consists of two cameras mounted side by side in a support structure over the model and able to photograph simultaneously the same scene.

This technique was used, recently, during stability scale model tests of the breakwater of Praia da Vitória harbour (Pedro *et al.*, 2015), proving to be an effective tool for surface and profile extraction in order to evaluate damage evolution during stability scale model tests of RMB.

Fig. 25 A RMB cross-section

Fig. 26 A wave flume

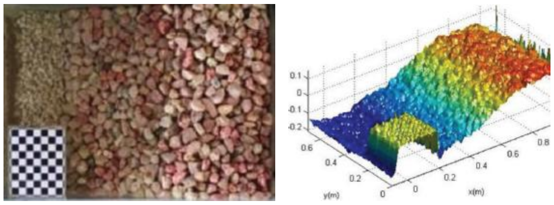

Fig. 27 Photogrammetric survey, with envelope surface representation

8 Conclusions

In the evaluation of the stability of RMB, both in the physical model testing and *in situ* monitoring campaigns, it is fundamental to know the position of the elements of the armour layer to be able to monitor displacements of the blocks, including settlements of this layer. Changes of the position of the blocks can lead to the weakness of the armour layer, leading to the exposition of the filters and core and possibly to ruin the structure. Usual visual observation or comparisons of photos are used to analyse the evolution of the damages of armour layers.

During monitoring campaigns, a more quantitative technique should be applied to provide information on the damage evolution of the armour layer. Photography is an easy and cheep technique that can provide data of the entire surface of a RMB. A careful photo acquisition, following some easy rules, can be processed using photogrammetric techniques that enables the generation of orthomosaics and point clouds and, subsequently to extract surfaces, profiles and elements location.

Several experiences using photogrammetry technique were performed on 2D and 3D scale models of different RMB's, as well as on the Ericeira breakwater where photos were captured during an UAV flight.

In what concerns the use of photogrammetric techniques in scale model tests, they provided valuable and reliable information about the armour layer. Nevertheless, there are still areas where more research is necessary: i) on the acquisition of vertical photos above a structure that is several meters long and is surrounded by water; ii) on the determination of the position of the blocks during the tests of sea-wave action that the models are subject to; iii) on the development of analysis techniques, taking in account colour changes and the variation of light. Identifying the blocks on the ortho and, after, their 3D location with the information of the point cloud seams the best methodology.

In what concerns the use of photogrammetric techniques in *in situ* monitoring campaigns, the main problems identified in the test performed on Ericeira breakwater, were: i) windy conditions, usual in coastal regions, during the flight ; ii) lack of good places to land near the RMB. Fixed wing UAVs have more stable flights and can be used with strong winds. Drones can land in very small areas but usually can't fly in strong wind. So is difficult to set a general rule: each RMB and flight conditions must be evaluated.

Accuracy tests performed with coordinates extracted from the point cloud of Ericeira RMB has showed that, after excluding the anomalous points (the needles) the errors are on the order of 10% of the size of a tetrapod. An equivalent test made with data from the breakwater A presents errors of 6% of the size of the blocks. As these values are much smaller than the size of the tetrapods or the cubes, photogrammetric methods can be applied to evaluate the damage on the armour layer.

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