The Contribution of Drones to the Monitoring of Rubble-Mound Breakwaters

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Abstract: Breakwaters are built to promote sheltered areas, for people, ships, and harbour activities. In the design of rubble-mound breakwaters, a common type of breakwater in many countries, including Portugal, it is assumed that damage may occur in certain stretches of the structures, and therefore maintenance and repair works will be quite certainly needed. To successfully carry out these interventions, in a timely and cost-effective manner, the structures must be observed and monitored systematically. This enables one to follow their structural behaviour and, through diagnosis analysis, to specify the most suitable timespan to undertake any necessary intervention. The severity of the sea on the Portuguese coasts justified the establishment, by the National Laboratory for Civil Engineering (LNEC), of a program of Systematic Observation of Maritime Works (OSOM) which, in 2018, was improved with the introduction of drones to monitor the structural present condition, evolution condition and risk condition of the structures, namely movements and falls of blocks in the armour layers. This communication presents some results of the application of OSOM+ program on breakwaters in Sines and Algarve (Faro-Olhão and Portimão) harbours, an activity that LNEC has developed for the APS – Ports of Sines and the Algarve Authority.

1 INTRODUCTION

In 1986, the National Laboratory for Civil Engineering (LNEC) started developing a programme for Systematic Observation of Maritime Works (OSOM) to monitor the behaviour of rubble-mound breakwaters along the Portuguese west and south coasts and recommend timely interventions for their maintenance and/or repair. This maintenance and/or repair works should be carried out at an early stage following the acknowledgment of problems, at the time these might likely affect a small area and therefore repairs are simpler and less expensive.

The OSOM methodology is based on a series of systematic visual observation campaigns that provide the necessary information to feed the ANOSOM database (Reis *et al.*, 1995; Lemos *et al.*, 2007), which is meant to characterize the Present Condition, the Evolution Condition, and the Risk Condition of the observed maritime structures.

Since the 2010's the OSOM programme has been improved and, in 2017, when drone monitoring started to be used in breakwaters, the programme changed its name to OSOM+ (Capitão *et al.*, 2018). The use of drones improved the monitoring because it provides detailed and more accurate information on the condition of the structures, and made it possible to quantify changes of settlements, volumes, etc..

This paper presents the expertise of LNEC in the monitoring of rubble-mound breakwaters using drones. Most of the situations presented here were obtained in the breakwaters of Sines (Figure 1 and Figure 2) and Algarve (Faro-Olhão inlet and Portimão, Figure 3 and Figure 4), in an activity that LNEC is providing for APS – Ports of Sines and the Algarve Authority – since 2018 (Capitão *et al.*, 2022).

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Figure 1: Breakwaters of the port of Sines.

Figure 2: Breakwater of the leisure port of Sines.

Figure 3: Breakwaters of Faro-Olhão inlet.

Figure 4: Breakwaters of the port of Portimão.

2 THE BREAKWATERS

The three ports managed by APS – Sines, Faro and Portimão – have several breakwaters, all rubble-mound breakwaters (Figure 5 and Figure 6, photos taken by one of LNEC's drones). Sines has a total of six breakwaters (one of these, the less exposed, is not monitored); Faro-Olhão inlet and Portimão harbour have two breakwaters each. All the breakwaters of Sines were constructed to protect several infrastructures that exist in the area: five terminals (liquid bulk, petrochemical, dry bulk, liquified natural gas and containers), a logistic activity zone, the fishing harbour, and the leisure port. In Algarve, on the Faro-Olhão area, the construction of the breakwaters in the 1930's created a channel that allowed the development of several ports, while in Portimão the breakwaters were built at the mouth of a river to ensure protection at its entrance.

These rubble-mound breakwaters consist of a core of finer material covered by large blocks forming the so-called armour layer. The blocks are of rock being that in areas more exposed the armour layer blocks are in made concrete in several shapes (tetrapod, Antifer, or parallelepiped). The superstructures of the breakwaters are also made in concrete. Some breakwaters have public access, while others are in (very) restricted non-public access areas.

Figure 5: The head of Sines west breakwater.

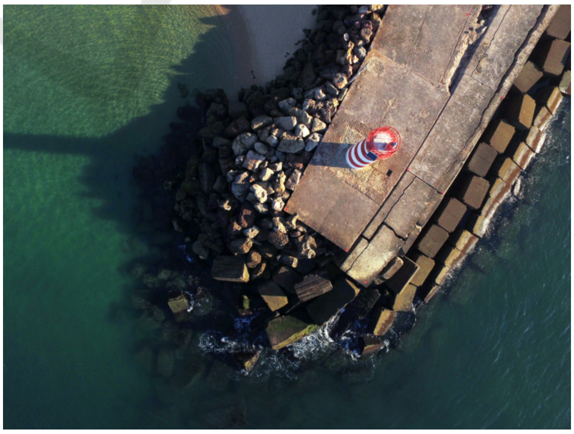

Figure 6: The head of Faro-Olhão inlet west breakwater.

3 OSOM✢ PROGRAMME

The OSOM✢ – Systematic Observation of Maritime Works – programme has been developed by LNEC to help the owners of breakwaters and other maritime structures.

The objective of this programme is to monitor the behaviour of these structures and recommend timely interventions for their maintenance and/or repair. The OSOM✢ methodology is based on a series of systematic visual observation campaigns complemented with data from drone photogrammetric surveys. All the data provide the necessary information to feed the ANOSOM database (Maia *et al*., 2017), which is meant to characterize the Present Condition, the Evolution Condition, and the Risk Condition of the structures. Based on this information, it is then possible to establish when, where and under what circumstances maintenance or repair works should be carried out.

More recently, ANOSOM-WEB interface app was developed, a web mapping platform accessible by any device (smartphone, tablet, or PC) equipped with web connection. During visual observation campaigns, this app allows the observer to carry out, on a mobile device, various operations such as, as examples, consultation of information from previous campaigns (Figure 7) and accessing, *in situ*, the current, evolution and risk conditions of the structure, and whether the structure needs immediate repair or maintenance works.

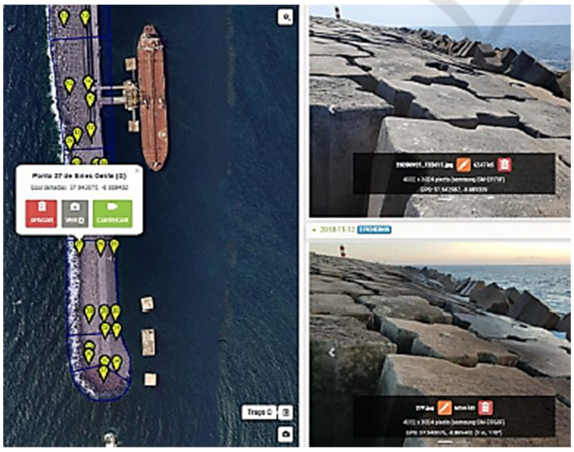

Figure 7: Interface ANOSOM-WEB – Breakwater Sines west.

4 THE DRONES AND THE FLIGHTS

The first surveys with the drone (2017), used a DJI Inspire V1 and a camera Zenmuse X3; since June 2022, it has been used a DJI Matrice 300 RTK and a camera Zenmuse H20 (Figure 8 and Figure 9). Due to the use of this drone with RTK, the security of the landing was improved, especially with mild to strong winds (up to 54 km/h). Both cameras have sensors CMOS, the first one with 12.4 MP, the second with 20 MP. At an altitude of 100 m, a pixel in a photograph taken by the X3 covers about 5 cm^2, with the H20 3.4 cm^2. H20 camera has zoom capabilities.

Before 2020, the breakwaters were fully surveyed, e.g., the flights covered an area comprising from the head to root of the breakwaters, always avoiding flight over pipes of gas or of liquid petrochemical products. After 2020, due to the European legislation, in some breakwaters the covered area was reduced to keep flights more than 150 m away from buildings. This rule led to some limitations on the image acquisitions, leading that the seaside armour layer of one of the breakwaters has been only covered with oblique photos, with the drone flying over the sea. Figure 10 presents the two flight plans made over this breakwater, where the area shaded in blue is the photographed area, and the green line represents the flight path. The left image in the Figure 10 shows the flight path over the head of the breakwater (nadir photos), while the right image shows the flight path over the sea (oblique photos).

Until now the RTK was used only with navigation proposes; in a near future the data collected will be integrated in the processing, to reduce the number of ground control points (GCP) needed. Concerning the information needed for processing the aerial images, it is mandatory to have GCP (Figure 11) marked on the surface of the breakwaters, and clearly visible in photographs. The points have been coordinated with GNSS (Henriques *et al.*, 2014).

For the necessary flight permissions, relevant national entities were contacted beforehand. These include the National Aeronautical Authority and Local Port Authorities (these are compulsory), relevant Aerodrome and Heliport Authorities, and the Institute for Nature and Forest Conservation, depending on the breakwater locations.

Five days before the survey, national weather forecast sources were checked (Henriques *et al.*, 2022). Rain, wind velocity and wind gust velocities were verified, although wind gust information was scarcely found.

Figure 8: DJI Matrice 300 RTK drone while taking off Sines east breakwater.

Figure 9: Preparing the flight on Sines west breakwater. Shown on top is the RTK GNSS antenna base.

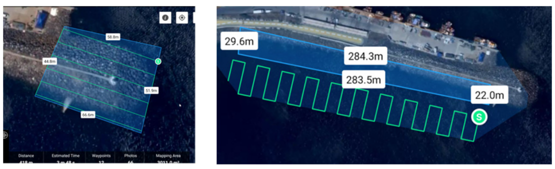

Figure 10: Flight plans over the fishing harbour breakwater at Sines. Left: head – vertical photos; Right: sea face – oblique photos.

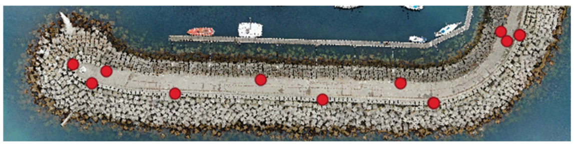

Figure 11: Location of GCP in the leisure port of Sines breakwater.

The flights have the following parameters: altitude of the flight: or 30 m or 40 m (depending on the length of the breakwater or local conditions); overlap 80% (both longitudinal and transversal). The flights are always autonomous (i.e. the missions are planned and upload to the drone before the flight) and made during low tides to maximize the area exposed. In Table 1 it is presented some data related to the flights in three breakwaters in Sines (the shortest, and the two longest). The pixel size of the orthomosaics produced is, in the three cases, 1.4 cm.

Table 1: Data concerning three drone surveys at Sines.

BW	Length Width	N.º flights	Duration flights	N.º photos
Leisure	250 m 30 m	1	12 min	178
East North Sec.	1000 m 55 m	2	56 min	982
West	1500 m 65 m	3	74 min	1092

5 DATA PROCESSING

Detection of changes in a rubble-mound breakwater armour layer is normally done by comparing the digital surface models (DSM) from two surveys performed at different dates.

To obtain it, following processing steps are used, in this order, and for each breakwater: point cloud computation, DSM creation (Figure 12). After the orthomosaic is generated (Figure 13).

It has been used Agisoft Metashape Pro software. Processing parameters used: i) Photo alignment quality: high; ii) Dense cloud quality: high; iii) Depth filtering intensity: mild.

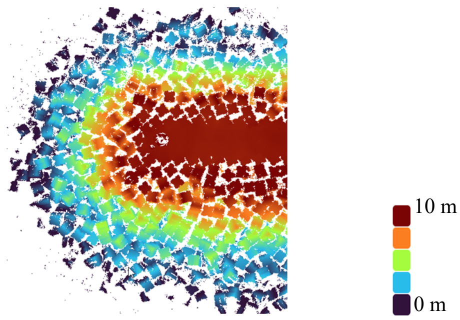

Figure 12: DSM (matrix form) of the head of Sines east breakwater.

Figure 13: Head of Ericeira breakwater. Two orthomosaic extracts with five years of difference are shown.

For presentation purposes, in reports, DSM are sometimes generated in the form of a mesh (Figure 14 and Figure 15).

Figure 14: Mesh of the head of Sines east breakwater.

Figure 15: Mesh of the head of Sines west breakwater.

It was determined the planimetric and altimetric RMSE (Root Mean Squared Error, see Table 2) for some breakwaters using the equations presented by FGDC (1998). Here it is presented the values obtained in Sines east north section breakwater, in 2020. The data used is the horizontal distance between a point coordinated and its image in the orthomosaic (Figure 16), and the vertical distance between this point and the point cloud. In the table are included the results obtained for the check points (points materialized like the GCP, used to assess the accuracy of procedures).

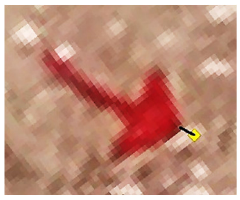

Figure 16: Point coordinated (in yellow), its image in the orthomosaic and vector between both (its length is the planimetric distance used).

Table 2: RMSE Sines east north section breakwater.

	Planimetric	Altimetric	N.ºPoints
Check Points	2.3 cm	2.5 cm	36
Ground Control Points	1.9 cm	2.0 cm	20

6 ANALYSES OF DATA

Since 2018, only few movements of blocks were detected and even those were non-significant. Some cases are presented here.

As stated before, geometric changes in the armour layer were detected through the analysis of the DSM: by computing the difference between two DSM outputs one can notice if there are changes. QGIS software is used for this task. In reports, the presentation of significant changes is accompanied by extracts from orthomosaics to present the evolution.

This is the case of Figure 17 to Figure 20, that show extracts of orthomosaics and DSM that illustrate some of the detected changes. Differences between DSM are illustrated in colour to clearly identify relevant evolution.

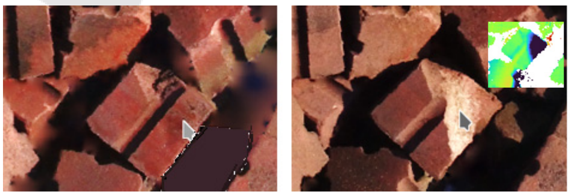

Figure 17: A block became more eroded in a period of two years.

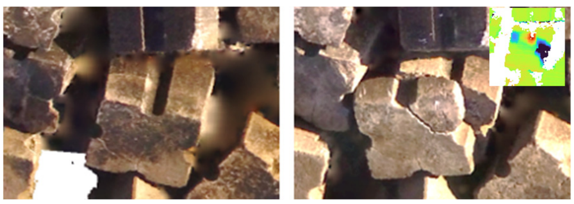

Figure 18: A block that broke.

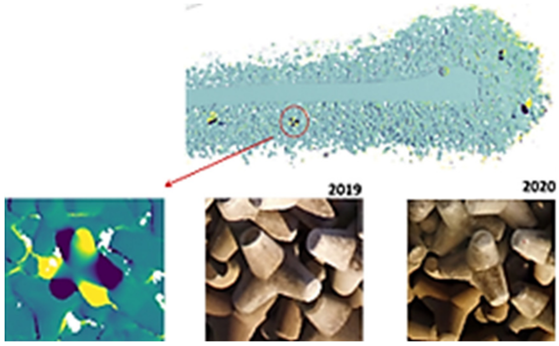

Figure 19: A tetrapod that rotated.

Figure 20: Displacements of blocks.

Figure 21 presents the comparison of DSM of the head of Faro-Olhão west breakwater (2023-2018) and Figure 22 presents the two meshes produced by Metashape where one can easily see the changes in the position of the blocks and verify that the concrete structure of the crest is less protected.

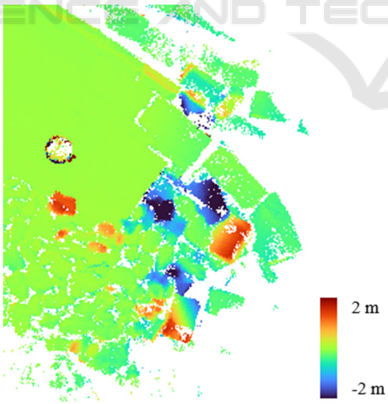

Figure 21: Block movements in the Faro-Olhão west breakwater between 2018 and 2023 detected by DSM comparison.

Figure 22: Meshes of Faro-Olhão west breakwater show the movements of the blocks.

Figure 23 shows the aerial photo and the orthomosaic at the Faro-Olhão inlet west breakwater. There, it can be seen the quite apparent (and, lately, quantified) erosion of sand in the northern area, on the land side, leaving the foundation of the breakwater exposed.

Figure 23: Faro-Olhão inlet west breakwater (aerial photo and orthomosaic). Indication of the area analysed situated on the north side. The red arrow shows the beginning and direction of the X axis of the graph of Figure 25.

Figure 24 shows DSM outputs from different dates. Figure 25 shows the profile drawn at the deepest location. The direction of the X axis is presented in Figure 23.

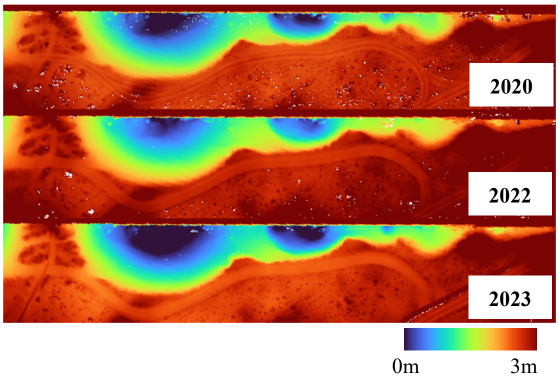

Figure 24: DSM of the area analysed in three years and colour scale.

Examination of the historical images available on Google Earth revealed that, in 2006, this problem already existed, although in a much smaller extent. As only planimetric information exists, the only values that can be obtained are distances. It was found that in 2006 the largest depression had an opening of 6 m. This area increased until it was clear, from the 2013 image, that, the depression stabilized. In 2023, the opening was 22 m, according to the DSM, as can be seen in Figure 25.

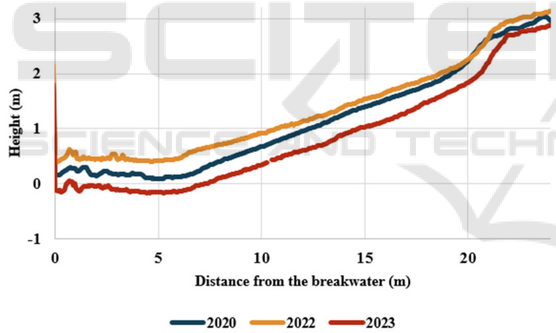

Figure 25: Profiles, starting from de breakwater, in the direction of land calculated in the lowest area.

The analyses presented in this paper were based on products fully generated by LNEC. There is other information, collected in previous years, which exists in the archives of APS or in the National Geographic Information System (orthophotos and DSM) whose analysis has been included in reports present to APS.

7 CONCLUSIONS

The paper presents the contribution of the aerial photogrammetric surveys made with the help of drones to the monitoring of rubble-mound breakwaters. The information generated from the photographs, especially DSM and orthomosaics, contribute to better quantify evolution of observed structures under OSOM⁺ - Systematic Observation of Maritime Works programme.

OSOM⁺, which initially was primarily based on qualitative analyses, can now also include additional quantitative analysis, and detect very small changes, in the order of a few centimetres, in the structures, considering the currently attainable quality of the surveys and, consequently, of the generated products.

This paper focused on the use of surveys to monitor already existing maritime structures, but the photo surveys can also have other uses. For example, by evaluating whether the geometry of the structure matches its design (Henriques, 2016 and Henriques *et al.*, 2017), which is especially useful during construction or repairs of the structure.

Between 2018 and 2023, the changes in the breakwaters of APS were small. The need to quantify these changes in the form of volumes, something simple to do when there are point clouds, was not considered important. For this reason, this data has not been included in the reports prepared for the APS although it was computed to be included in papers (Henriques, 2016 and Henriques *et al.*, 2016).

In the processing phase, to include drone coordinates obtained by RTK will reduce the number of GCP needed. This is an important step to be taken very soon. Regarding the improvement in the quality of results that would result from using more complex flight plans, such as those in the form of grids, or complementary flights with a camera in an oblique direction, it is necessary to point out that the time available for carrying out flights is reduced because these must be done during low tides. The improvement in quality of the results is not so relevant as to justify these procedures.

Concerning the detection of the movements of the blocks, there are interesting approaches. More complex analysis of the data produced (like the ones presented by Soares *et al.*, 2017 and 2022, or Arza-García *et al.*, 2024) are still academic advances which should evolve into procedures to be applied in production work (such as the one presented in this paper). As pointed out, there were no damages in APS breakwaters during the period 2018-2023 so there was not the need to more complete analysis of the breakwaters, as the one presented by Florio *et all.* (2024). There is an area in which research is really needed which is the detection of the movements of submerged blocks. This research may need to include the development of equipment. For instance, Sakamoto *et al.* (2024) present the results and limitations of the use of a green laser scanner in shallow waters.

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