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A methodology for the evaluation of evolution and risk of breakwaters. Application to Portimão harbor and of Faro-Olhão inlet

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ABSTRACT: This paper describes a program under the responsibility of LNEC for the systematic observation and monitoring of maritime works that has successfully been applied to a number of maritime structures on the Portuguese mainland coast. The now-called OSOM+ program comprises the following four main components for each structure: i) periodic visual inspections by an experienced technician; ii) periodic aerial inspections with a UAV/drone; iii) a ANOSOM-WEB database, to store and/or query obtained information on the observation campaigns, as well as to diagnose present, evolution and risk conditions of the structure; iv) a mobile, portable, application, for real-time input and visualization of the database information. OSOM+ has recently been updated with a number of tools and functionalities that are illustrated in this paper with applications to two real case studies: the Portimão harbor breakwaters and Faro-Olhão inlet entrance breakwaters, both located in the south coast of Portugal.

Keywords: Breakwater, Inlet, Harbour, Risk assessment.

RESUMO:Este artigo descreve um programa, sob responsabilidade do LNEC, de observação e monitorização sistemática de obras marítimas, denominado OSOM+, que tem sido aplicado com sucesso a várias estruturas marítimas na costa continental portuguesa. O programa OSOM+ inclui as seguintes componentes principais, para cada estrutura: i) inspeções visuais periódicas, com um técnico experiente; ii) inspeções aéreas periódicas, com um VANT/drone; iii) uma base de dados ANOSOM-WEB, para armazenar e/ou consultar informações obtidas nas campanhas de observação, bem como para diagnosticar os estados atual, de evolução e de risco da estrutura; iv) uma aplicação informática móvel, portátil, para preenchimento em tempo real e visualização das informações da base de dados. Esta metodologia foi recentemente atualizada com uma série de ferramentas e funcionalidades que

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são ilustradas neste documento com aplicações a dois casos de estudo reais: os quebra-mares do porto de Portimão e os quebra-mares da embocadura da barra de Faro-Olhão, ambos na costa sul de Portugal.

Palavras-chave: Quebramar, Enseada, Porto, Avaliação de Risco.

1. INTRODUCTION

Since 1989, The National Laboratory for Civil Engineering (LNEC) has developed a program for Systematic Observation of Maritime Works (OSOM).

The objective of this program is to monitor the behaviour of maritime structures and recommend timely interventions for their maintenance and/or repair. Actually, in the design of this kind of maritime structures, in particular, rubble-mound breakwaters, it is assumed that during the lifetime of the structure damage may occur in some of its sections and therefore maintenance and repair works will be quite certainly needed. However, to successfully carry out these interventions, in a timely and cost-effective manner, it is imperative that the structures are observed and monitored in a systematic way throughout their lifetime. This enables one to follow up their structural behaviour and, through diagnosis analysis, to specify the most suitable (and preferably the less expensive) timespan to undertake any necessary intervention.

The OSOM program includes the ANOSOM database, which has been, since 1995, the main diagnostic tool for about 36 port protection and inlet structures located along 19 points of the coast. The ANOSOM database (Reis e Silva, 1995, Lemos and Santos, 2007) contains all the information from the visual inspections carried out to date, having been adapted to systematic observation programs in the autonomous region of the Azores (Silva, 2010), in Macau (Reis *et al.*, 2001) and in Moroccan ports (Lemos *et al.*, 2014).

This application has been used to prioritize interventions to be carried out in terms of maintenance or repair works. In this context, several tools have already been developed by other authors, both within the scope of the management of the life cycle of maritime works (Marujo *et al.*, 2013) and in the analysis of coastal dynamics (Pires *et al.*, 2009).

However, in order to make the use of the ANOSOM database more friendly and partially accessible to port entities, designers and research centers, it become evident the need to implement it in an geographical information system (GIS). This was the first step to upgrade the OSOM program.

In 2018, LNEC has developed a programme for Systematic Observation of Maritime Works (OSOM+) for a set of rubble-mound breakwaters along the Portuguese coastline (Capitão *et al.*, 2018).

The current OSOM+ programme comprises the four main components below (with features recently introduced <u>underlined</u>):

- Periodic visual inspections, supported by systematic photos and <u>video taking</u>, <u>all GPS-tagged</u>;
- <u>Periodic aerial inspections, through vertical-oriented photographs with an Unmanned Aerial Vehicle (UAV), or drone</u>;
- The ANOSOM-WEB database, to store and query all information obtained during the visual <u>and aerial inspections</u> and to perform a diagnosis analysis of each section of the structures, namely its Present, Evolution and Risk Conditions. With this information, it is then possible to establish when, where and under what circumstances maintenance or repair works should be carried out;
- <u>A mobile, portable, application, for real-time input and visualization of the database information obtained during visual and aerial inspections</u>.

The OSOM+ was recently applied to Portimão harbour and to Faro-Olhão's inlet entrance, both located on the south coast of Portugal, under the framework of a research contract between LNEC and the APS - Ports of Sines and the Algarve Authority, S.A.. Following the work of Capitão *et al.* (2018), the present paper describes the main features of the OSOM+ methodology and its application to the breakwaters of Portimão harbour and of the entrance of Faro-Olhão's inlet (Figure 1).

2.CASE STUDIES

2.1 Faro-Olhão's inlet entrance breakwaters

The port of Faro is an important port infrastructure serving the Algarve region (APS, 2018). It is located in the south coast of Portugal, between the Atlantic Ocean and the Mediterranean Sea. Its commercial quay, 200 m long, offers a sea bottom level of -8 m (CD), and a covered storage capacity of 3 500 m^2, and is equipped with three electric cranes, with capacity up to 12 tonnes (Figure 2).

The cement produced on the Cimpor plant, in Loulé, is the principal export cargo of this port, especially for Algeria and Cabo Verde. The port also handles rock, iron and tile, sent to Gibraltar, as well as the Algarve's carob, exported to England, the salt from Olhão, the rock-salt from Loulé and the tuna fish, exported to Japan.

The harbor is sheltered by the west and east breakwaters, of variable sections, whose heads are apart about 170 m and whose construction was completed in 1959 (Figure 3).

The so-called Faro-Olhão inlet was opened artificially between 1928 and 1931, due to the construction of two breakwaters that were to be extended for the current bar opening of about 170 m between 1947 and 1955 (Silva, 2014). The average sea bottom level at the section between the two breakwater heads has undergone a rapid evolution over the years, as there was a clear deepening of the bar from approximately -12.5 m (CD) to -28 m (CD), between 1972 and 1985.

The east breakwater is of the rubble-mound type, about 990 m long, and reaches maximum depths at the head. It consists of two straight alignments connected by a concordance curve with a reduced radius. The approximate characteristics of the straight and curved sections are: straight alignment of the breakwater root with a length of 260 m and direction S-77°-E; transition curve of 45 m and radius of curvature of 80 m; straight head alignment of 650 m long with S-20°-O direction. The armour layer

Figure 1. Location of Portimão harbour and Faro-Olhão inlet (Google Earth, 2018).

Figure 2. General view of Faro´s harbour (Google Earth, 2018).

consists of rock with weights ranging between 40 and 150 kN in almost all of its length, of tetrapods of 160 kN in the final zone of the trunk and Antifer cubes of 400 kN around the head of the breakwater.

The west breakwater is also of the rubble-mound type, is rooted in the east extremity of the Barreta Island, has a south orientation and a total length of 400 m, although its main section (the end of the breakwater, slightly curved) is only about 80 m long. The outer armour layer consists of rock, whereas the inner layer consists on parallelepiped artificial blocks.

Figure 3. The east and west breakwaters of Faro-Olhão inlet entrance, in the protected area of ria Formosa.

2.2 Portimão harbour breakwaters

The port of Portimão develops on both banks of the Arade estuary, and is protected by two breakwaters, whose heads are 250 m apart (Figure 4). Its construction was completed in 1959.

According to the few elements available on the works, its initial project dates from 1935, and in 1936 a second version was presented with some changes, namely as regards the size of the breakwaters. Under this project, the west breakwater begins on the cliffs of Santa Catarina Fortress, with a north-south orientation and about 805 m in length. The east breakwater begins in Ferragudo, with an orientation of 253º azimuth and a length of about 645 m. The breakwater profile of the rubble-mound breakwater consists on a rock core of 0.1 to 5 kN, covered by rock of 5 to 20 kN. On the seaside is covered by an armour layer consisting on rock of 20 to 60 kN. On the outer face of both breakwaters and on the inner face of the west breakwater, at sea bottom level of -5.0 m (ZH), the armour layer are enlarged at the base by a toe berm.

The slopes of the west breakwater and the outer slope of the east breakwater are covered with 220 kN-weight parallelepiped concrete blocks.

On both breakwaters crest, a concrete superstructure was built at a level of +1.50 m (ZH), which on the west breakwater, reaches a level of +5.50 m (ZH), with a crown-wall up to +6.50 m (ZH). The east breakwater, without crown-wall, has its crest level at +6.0 m (ZH).

Figure 4. The east and west breakwaters of Portimão harbour.

3. THE OSOM+ PROGRAM

3.1 Visual Inspection

The visual inspection allows, in a fast and intuitive way, to follow through the years the structural behaviour of the breakwaters. It also allows, through subsequent analysis and data diagnosis, to infer on the evolution of damages on the observed structure and on the likely need of interventions, thus preventing future structural problems. The visual inspection of the structure (Santos *et al.*, 2003) is usually conducted every year and whenever a strong storm/typhoon hits the structure. The main objective of each visual inspection is to better characterize the present condition of the structure.

For that purpose, the structure is firstly divided into several sections, according to their different physical and functional characteristics. In general, each section corresponds to a different cross-section along the breakwater, with the head of the breakwater always considered as a section.

For each section, a set of notable points is established where photos and videos are taken in every campaign, with the same photo view parameters (notably the same camera focal length and view angle and the same photo framing). These points are referenced in the GPS equipment used and inkmarked on the breakwater in order to be used in subsequent campaigns.

At the field, the following main tasks are performed:

a) visual observations are made by a technician who walks along the crest of the breakwater and looks at, at least, the following three main components of the breakwater: the outer armour layer, the superstructure and the inner armour (sometimes the filters may be seen). For each of these components, the observer is able to detect possible changes in the breakwater and its armour units, namely broken elements, changes in their placement, their relative location within the armour layers, etc.;

b) a simple characterization is made by the technician. This characterization involves observing the deterioration of the breakwater elements due to the natural physical and chemical processes that is likely to occur in the harsh sea environment where these structures are located. All this information is then filled into a paper or electronic (using a mobile app) form. Each form usually corresponds to a single section of the structure and enables characterization of all its main components;

c) a set of photos (and videos, if necessary) is taken at notable, predefined, points. These photos are taken systematically, at exactly the same predefined locations and with same photo pointing directions, through the use of GPS-tagging capabilities provided by smartphone or tablet equipment used to take the photos. For each photo the geographical location is found using the equipment´s internal GPS, and the pointing direction is given by using the equipment´s software that computes the True North on the basis of the distance between the equipment from the nearest base-station and a global map of declination angle (the angle between true north and magnetic north). Also, the observer compares, in situ, the current state of the section at that location/direction with previous photos taken in the last campaign, if available. In addition, 360° handheld videos may be made for selected points that, during the course of the campaign, are somewhat considered relevant to better illustrate and characterize the present condition of the observed component, section or even the whole structure.

In general, in order to have the maximum depth of the armour slope visible to the observer, the visual inspections should be carried out preferably during low tide. Also, it is important to guarantee the security of the observer, so that the inspections should be performed under good weather conditions and, preferably, also under calm sea wave conditions.

Faro-Olhão inlet breakwaters

Figure 5 illustrates the four sections of Faro-Olhão's breakwaters for the west breakwater (A, B, C and C1), and the five sections for the east breakwater (D, E, F, G and H).

Figure 6a) and Figure 6b) show photographs taken at a predefined point of Faro-Olhão's east breakwater (point 19, located in the inner part of section G), according to the southwest and northeast approximate directions, respectively.

The west breakwater shows a number of damaged areas, namely at sections C and C1 (near the breakwater head), at point 12 (Figure 7a), and point 15 (Figure 7b), where one can see several cracks and settlements on the breakwater's slabs and units.

For the east breakwater, three sections (F, G and H) clearly show problems, with a number of damaged areas clearly visible, although the most damaged sections are the latter two.

The more relevant damages are located in section F, at several locations (see example in Figure 8a) for point 10), in section G, mainly its last part, covered with tetrapods (see example in Figure 8b) for point 19 and Figure 8c for point 22) and in section H, namely at the inner part of the breakwater head (see example in Figure 8d) for point 24). It is clear from previous observations, when compared with the present one, that some units of these three sections have been removed in the recent years.

Portimão harbour breakwaters

Figure 9 illustrates the four sections of Portimão's west breakwater (A, B, C and D), and the three sections for the east breakwater (E, F and G).

Figure 10a) and Figure 10b) show photographs taken at a predefined point of Portimão's east breakwater (point 16, located in the exterior part of section G), according to the seaward and landward directions, respectively.

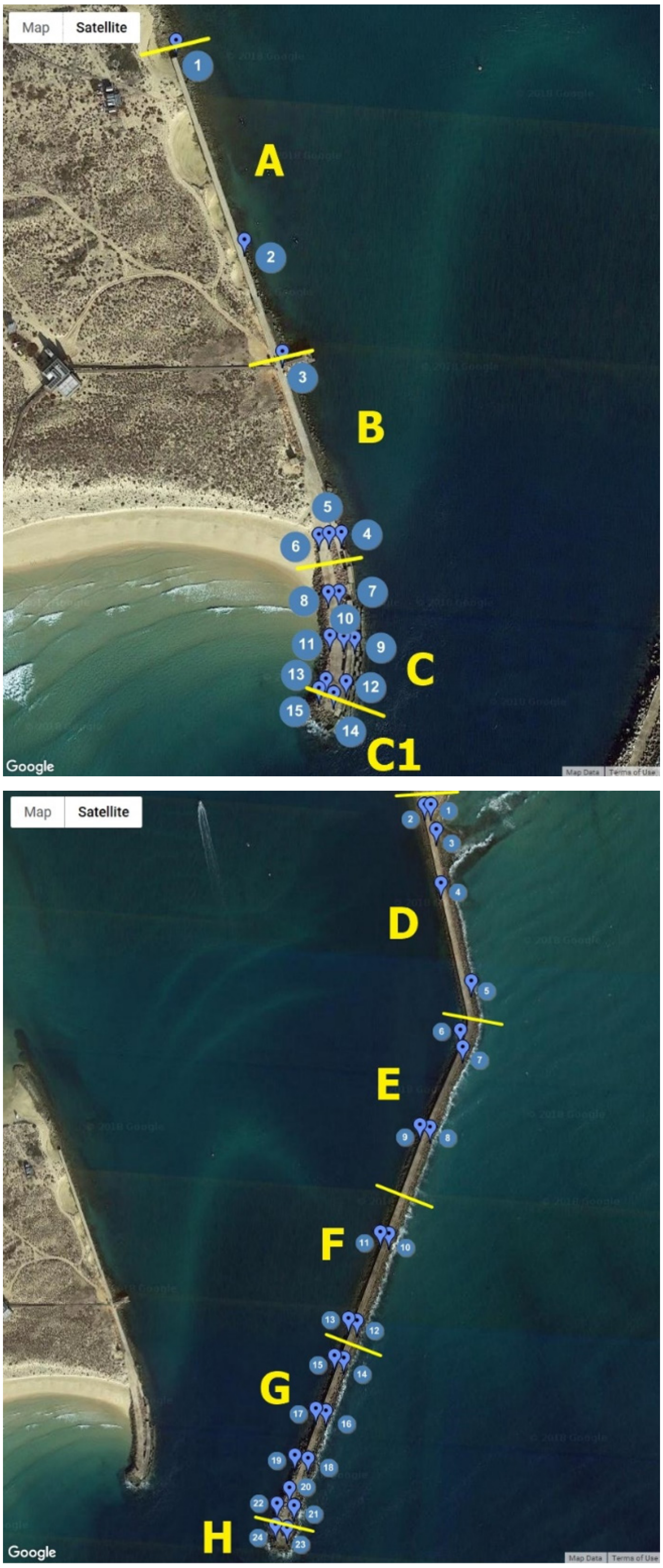

Figure 5. Faro-Olhão's breakwaters with division into sections and visual observational points: a) west breakwater, sections A to C1; b) east breakwater, sections D to H.

It was found that the east breakwater is somewhat damaged, especially in sections F and G (head). In particular, there are several degraded areas along the breakwater trunk, with visible block failures (resulting from falling / block movements).

The west breakwater is globally in good conditions despite some damages, mainly in the quay (end of section A). It should also be noted that there has been a slight worsening of the inner slope condition of all breakwater trunk sections as well as its head area, especially in its inner sector.

3.2 Aerial surveys

The use of a UAV/drone (Henriques *et al.*, 2014, 2016) besides providing a more detailed and accurate information on the condition of the structures, also allows a better assessment of the evolution of the structures' envelopes as it produces more relevant representative profiles of the most problematic zones of the structures.

LNEC uses a professional UAV, model DJI Inspire V1 Pro, sporting a 12Mpixel ZENMUSE X3 camera. This UAV performs aerial photographic surveys of the maritime structures, being the flight plan established a priori at office (Figure 13). Due to the proximity of the airport of Faro, the Portuguese Aviation Authority authorized flights of up to 30 m of altitude only.

The results of these observation campaigns are the individual aerial photographs, captured in a regular pattern and in the vertical direction (nadir), as well as the

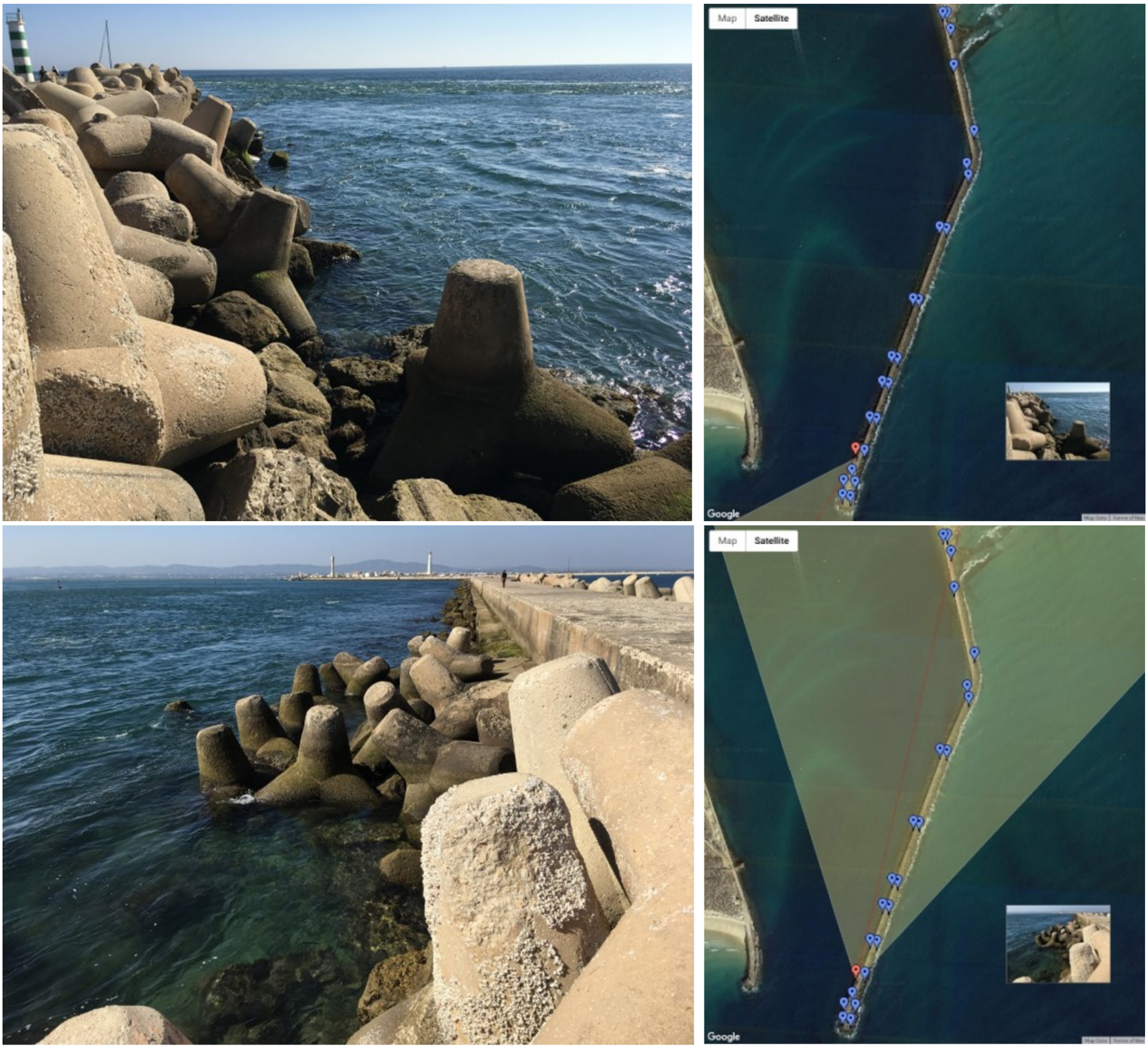

Figure 6. Systematic photographs taken at predefined points. Case of Faro-Olhão's east breakwater, point 19, according to two predefined directions: a) southwest; b) northeast.

Figure 7. Faro-Olhão’s west breakwater – Sections with problems: a) Point 12 (section C, inner layer); b) Point 15 (section C1, outer sector).

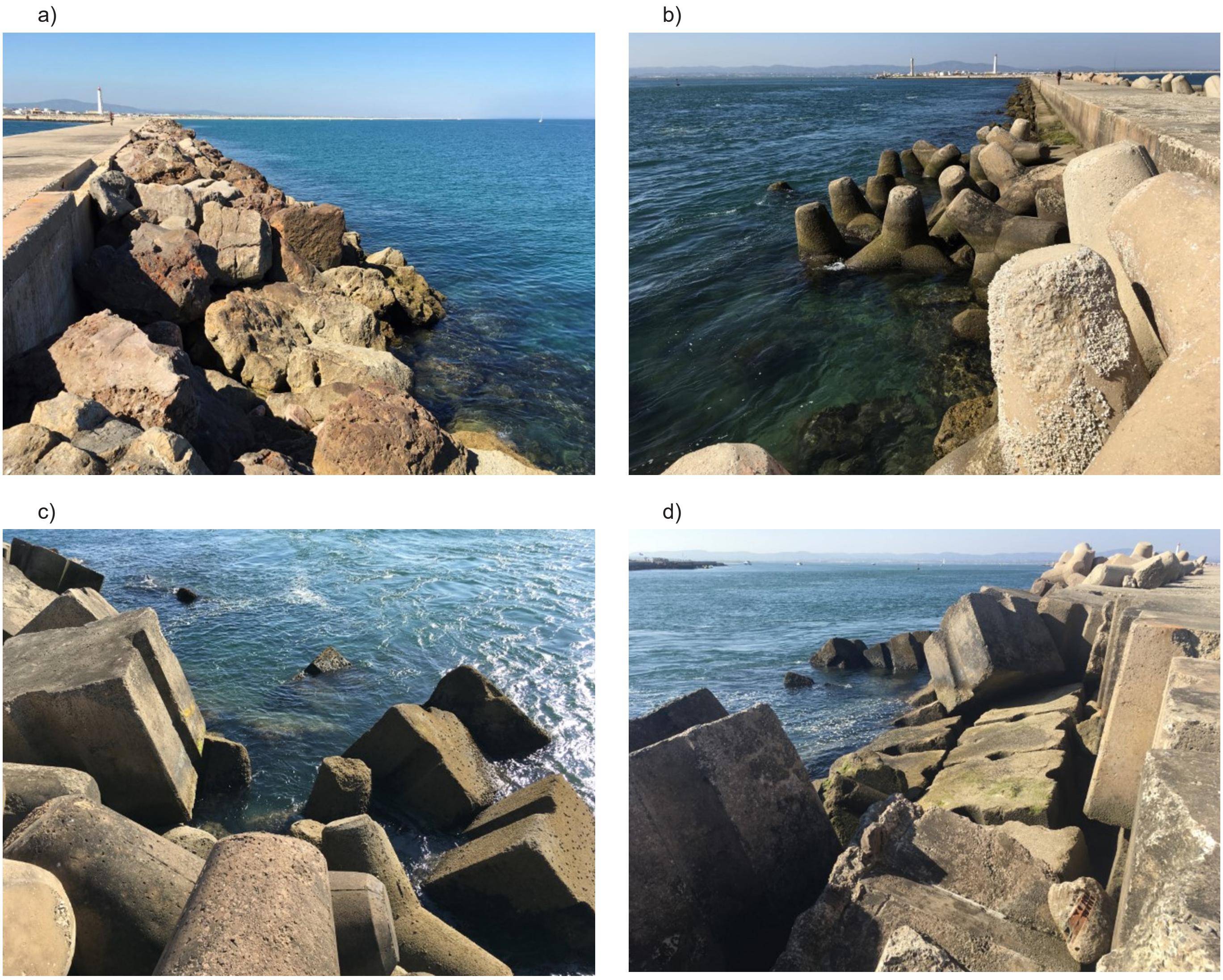

Figure 8. Faro-Olhão’s east breakwater – Sections with problems (see also Figure 5a): a) Point 10 (section F, exterior); b) Point 19 (section G, interior); c) Point 22 (section G, interior); d) Point 24 (section H, interior).

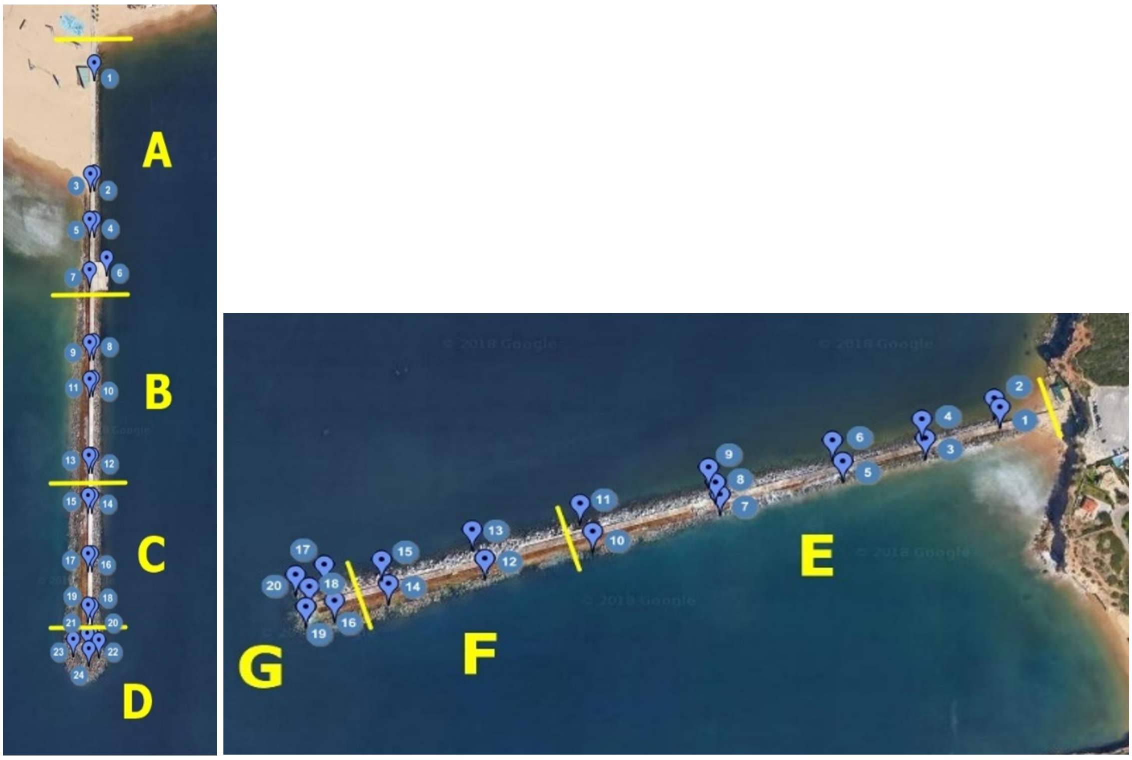

Figure 9. Portimão breakwaters with division into sections and visual observational points: west breakwater, sections A to D (left); east breakwater, sections E to G (right).

Figure 10. Systematic photographs taken at predefined points. Case of Portimão east breakwater, section G (head), point 16, according to two predefined directions: a) seaward direction; b) landward direction.

Figure 11. Portimão east breakwater – Sections with problems: a) Point 5 (section E, lee side) b) Point 14 (section F, seaward side); c) Point 20 (section G – head, inner sector).

Figure 12. Portimão west breakwater – Panoramic photo of section D (head).

respective orthomosaic (*i.e.*, each photo was corrected from geometric distortions and was orthorectified; then sections of these were stitched, forming the orthomosaic) and a point cloud from which the numerical surface model of the structure was derived. This complements the information obtained in visual observation campaigns and provides substantially more detailed information on the structure, since it covers hidden perspectives from a human observer walking on the structure.

In order to georeference the obtained models and to allow comparisons between surveys or models taken in different dates, it is always necessary to obtain data pertaining to specific positions on the structure called ground control points (GCP), by using high-resolution positioning equipment (a pair of GNSS receivers and/or a total station, with sub-centimetre accuracy). When the total station is used, which allows a higher internal accuracy, it is necessary to complement the observations with the coordination of two points by GNSS (static mode, more accurate than RTK) for transformation of the coordinates in the National reference frame. In this case, the GCP are located in the superstructure (the crown wall), and sometimes also on the units of the armour layers (Figure 14). Note that it is mandatory that all GCP must be recognizable in the photos.

The flights were automatic, programmed to be performed at an altitude of 30 m and with an overlapping area of 80%. They were made during low tide to maximize the visible area above water.

Faro-Olhão inlet breakwaters

During the flights, 176 photos, for the west breakwater, and 720 photos, for the east breakwater, were taken by the drone (see some examples of photos in Figure 15). For both breakwaters the photogrammetric software Micmac (Rupnik *et al.*, 2017) was used to produce the two orthomosaics (with pixel size of around 1.5 cm) shown in Figure 16 and Figure 17, respectively, and two point clouds.

Figure 18 shows the contour maps generated from the point clouds for the west and east breakwaters. Also, profiles at more vulnerable points of the structure may be produced: see Figure 19 for an example of two profiles comprising the current campaign (2018) as well as a previous campaign conducted in 2016. Profile 87 differences show an eroded depth of around 2 m (approximately the nominal diameter of an armour unit). To monitor the breakwater evolution, point clouds of different campaigns may be compared and areas and volumes of changed sections may be computed.

Portimão harbour breakwaters

Figure 20 depicts some examples of photos taken during the drone flights for Portimão breakwaters, 698 photos for the west breakwater and 822 photos for the east breakwater. Figure 21 illustrates the two orthomosaics obtained for the west and east breakwaters.

From the clouds of points it is possible to obtain a three-dimensional representation of the surveyed breakwaters, Figure 22.

3.3 The ANOSOM_WEB database

The ANOSOM_WEB database, associated with OSOM+ program, is based on the previous ANOSOM database (Reis and Silva, 1995; Santos *et al.*, 2003, Lemos and Santos, 2007), which was enhanced in 2016 with a GIS interface to query information on each section of the breakwater.

More recently, a new informatic solution was developed in order to allow the insertion of the systematic monitoring database in a cartographic platform (web

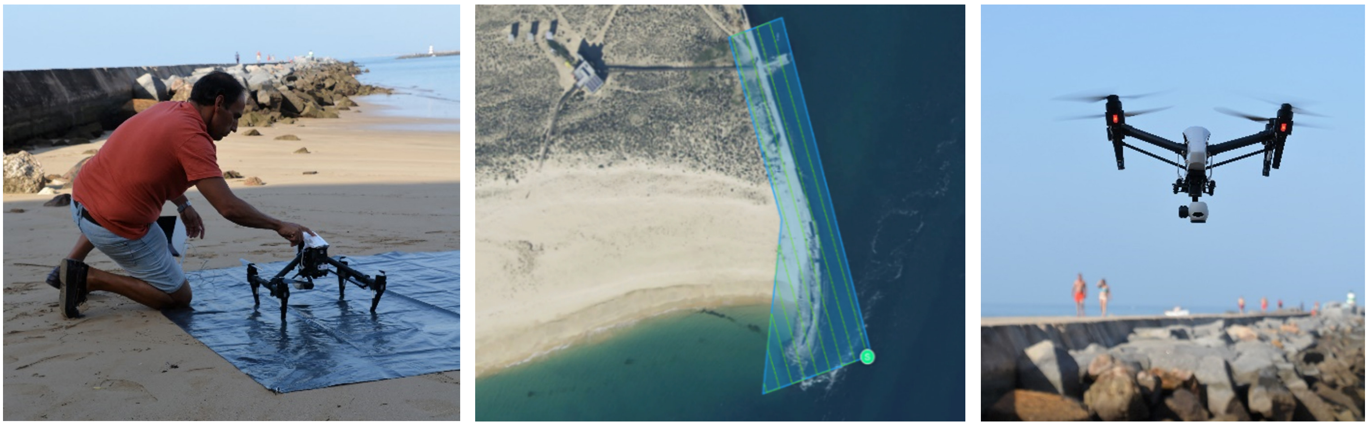

Figure 13. Preparing an UAV flight (left), with flight plan (middle), and beginning of the flight survey (right).

Figure 14. Survey of Ground Control Points on the superstructure and on one of the units of the armour layer.

mapping) accessible by any mobile device (smartphone, tablet) or PC equipped with web connection. This new ANOSOM_WEB platform is based on web technology (PHP/Laravel, Javascript, Bootstrap/jQuery e Leaflet) (Maia *et al.*, 2017) and GIS (Lemos *et al.*, 2016), which includes, among other assets, the data georeferencing (based on spatial features do SGBD MySQL), shapefiles import, cartography (ESRI/ArcGIS maps), mapping and information layers visualization.

The main features of the ANOSOM_WEB database are:

- The storage, query and analysis of the information collected on the already observed breakwaters, in particular the data from the visual and drone observation campaigns as well as design project data and materials;
- The diagnosis of the structure, by processing the present condition of the section of the breakwater, as well as the evolution condition (corresponding to the degree of evolution for a certain period of time) and the risk condition (associated to the lack of intervention) for each section. This process is based on the application of properly calibrated pre-specified criteria.

Figure 24, Figure 25 and Figure 26 illustrate the search and database populating operations regarding, respectively, visual inspections, geometry and construction materials and photos uploading for the breakwaters of Portimão's harbour.

The mobile application has been developed with a number of tools to provide easier and more intuitive navigation on the new platform, with side navigation tree, user profiles, logging and administration capabilities added. All navigation and interaction of this application with ANOSOM_WEB database has been thought in a mobile-first logic, to be usable on small devices with limited bandwidth. It is thus currently a tool for online information consultation, which allows, a) the storage, consultation and analysis of the information collected about the structures already observed, in particular the data of the visual observation campaigns and drone, or other information (*e.g.* surveys of submerged and submerged parts of structures); (b) the diagnosis of the structure, *i.e.* the present condition, the evolution condition (corresponding to the degree of evolution over a certain period of time) and the risk condition (associated with lack of intervention) for each section or component of the breakwater. This calculation is performed by applying pre-specified and calibrated criteria (Santos

Figure 15. Aerial photos of Faro-Olhão's breakwaters. West breakwater (left) and east breakwater (right). Drone campaigns of July 2018 25th and 26th.

Figure 16. Orthomosaic of the west breakwater of Faro-Olhão for drone campaign of July 25th 2018. Orthomosaic (with details) of the east breakwater of Faro-Olhão for drone campaign of July 26th 2018.

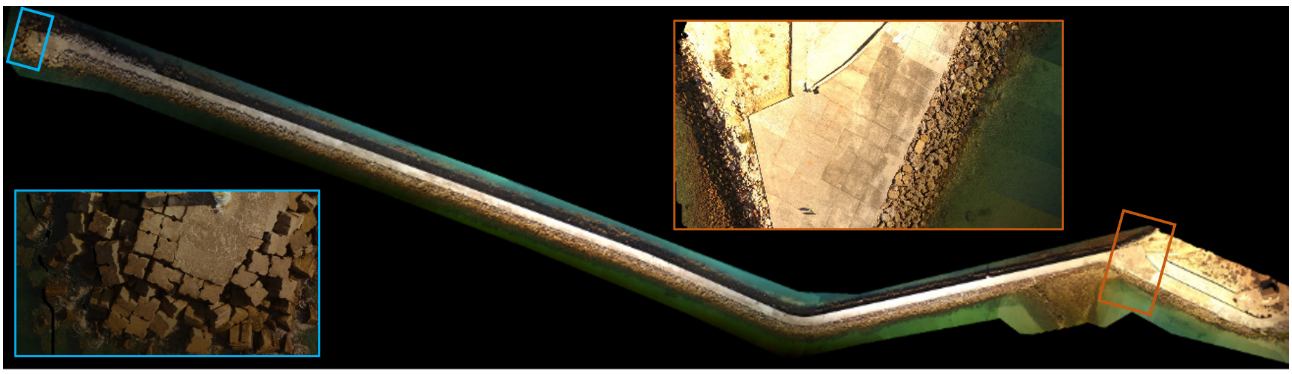

Figure 17. Orthomosaic (with details) of the east breakwater of Faro-Olhão for drone campaign of July 26th 2018.

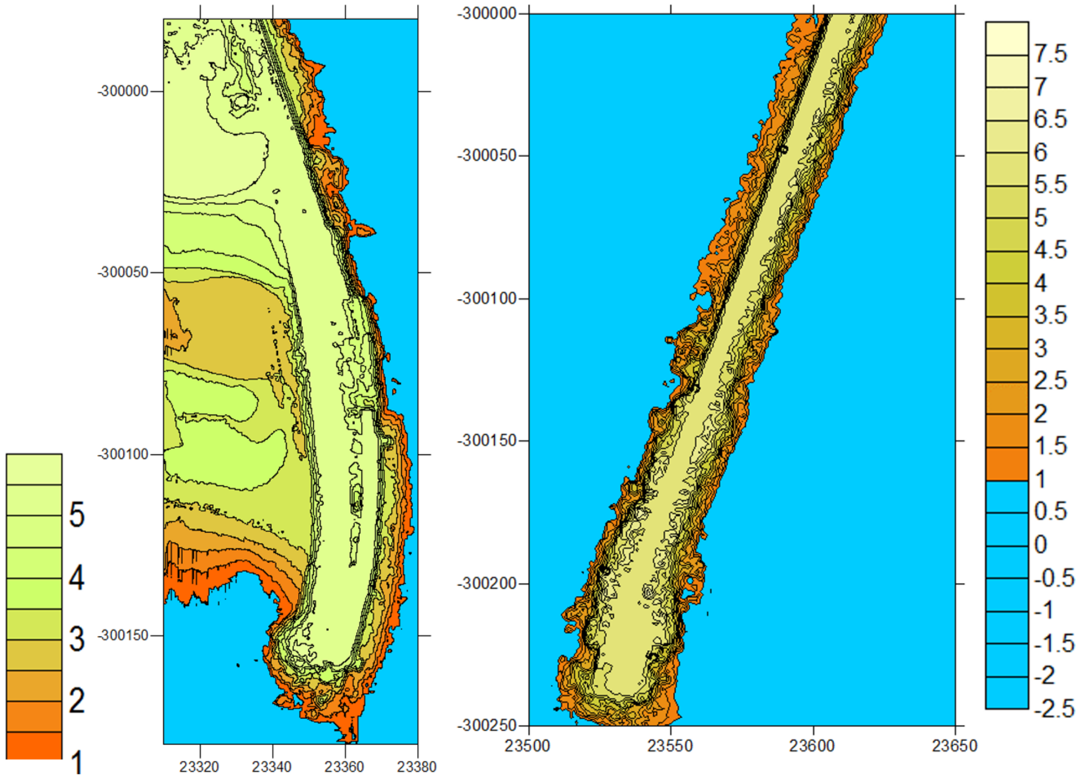

Figure 18. Contour maps for Faro-Olhão’s breakwaters. Detail of west breakwater (left) and east breakwater (right).

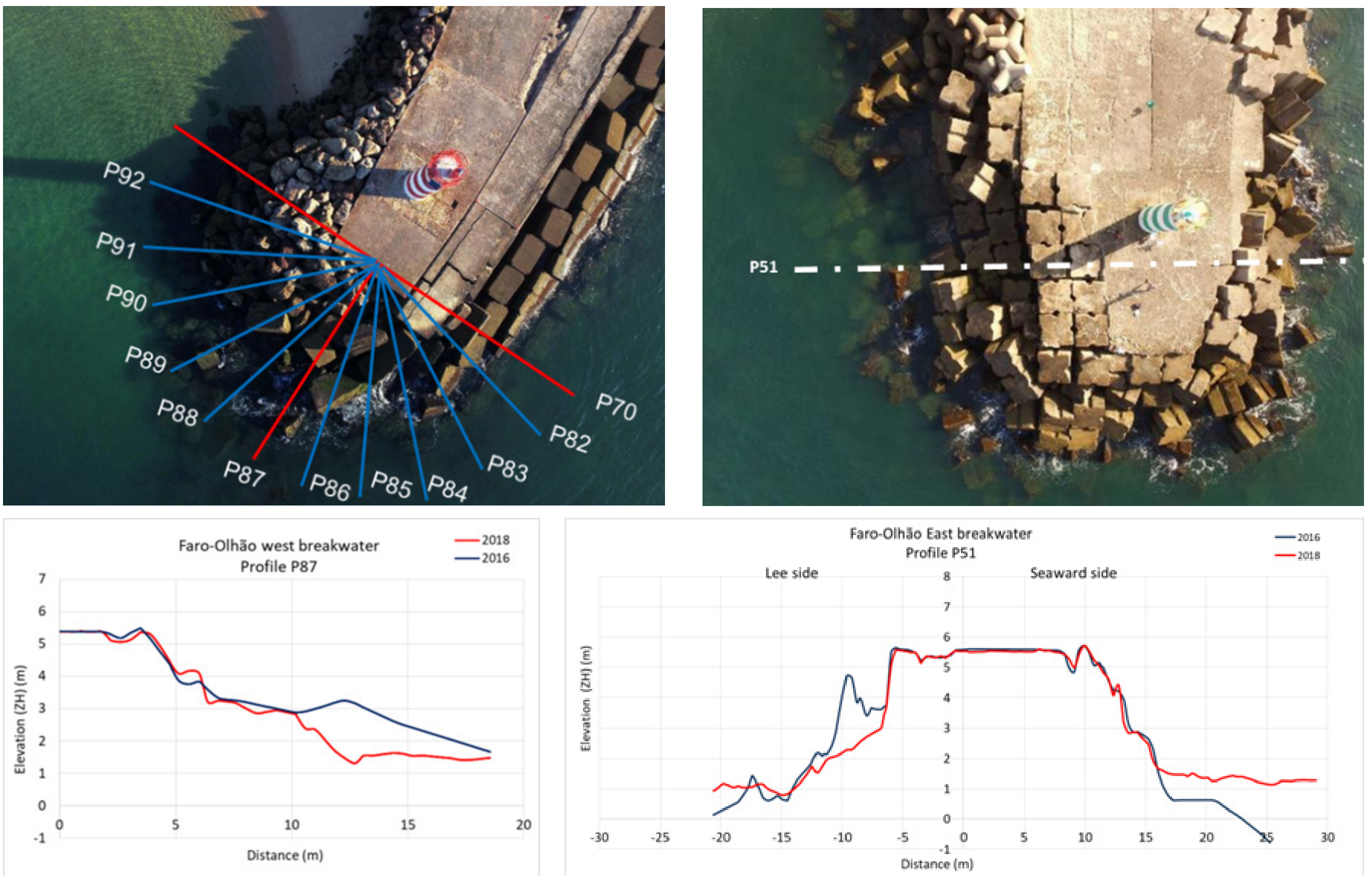

Figure 19. Profiles of vulnerable sections of Faro-Olhão’s breakwaters for campaigns of July 2018 25th and 26th. West breakwater (left) and east breakwater (right).

Figure 20. Aerial photos of Portimão breakwaters. West breakwater (left) and east breakwater (right).

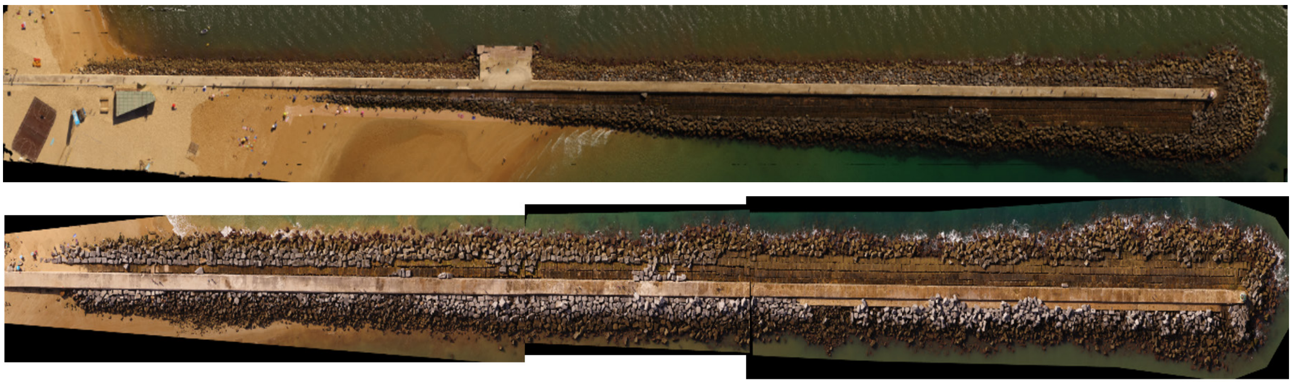

Figure 21. Orthomosaic of the west (top) and east (bottom) breakwaters of Portimão.

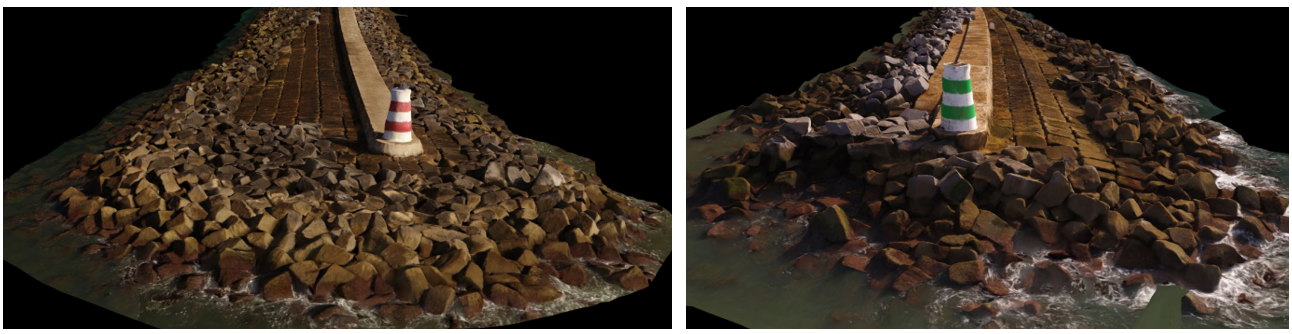

Figure 22. Three-dimensional representation of west (left) and the east (right) breakwaters of Portimão.

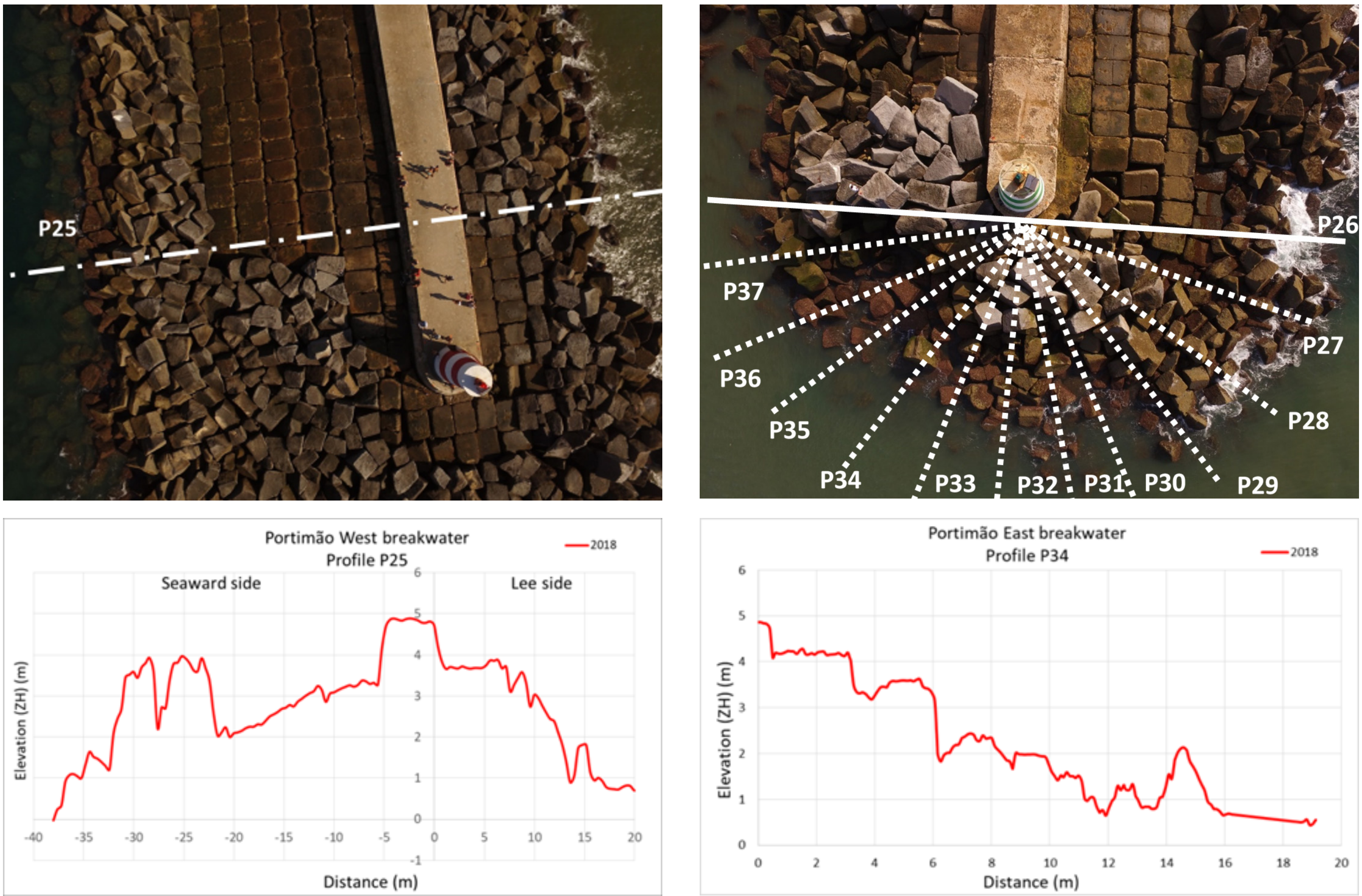

Figure 23. Profiles of vulnerable sections of Portimão breakwaters for campaigns of July 2018 25th and 26th. West breakwater (left) and east breakwater (right).

et al., 2003); c) consultation of structure history, based on the information on the structure made available to LNEC (year of construction, interventions carried out, project drawings, existing hydrographic surveys, underwater inspections, aerial photographs, historical data, etc.); d) the physical characterization of the sections, geometry, materials used, etc.

This multiplatform application, which runs on any mobile device or PC, calculates the present condition of the structure in real time with the available data. The user can thus access, in situ, whether the structure needs repair or immediate maintenance work.

4. CONCLUSIONS

In this paper, the OSOM+ methodology was applied to the Portimão harbor breakwaters and the Faro-Olhão inlet entrance breakwaters, by describing some of the main new features of the methodology and showing some relevant results for those real cases.

The continued application of the OSOM+ methodology to other breakwaters considered in the programme will allow one to calibrate the evaluation criteria for interventions nation-wide. Those criteria are now being developed based on the quantitative information provided by the drones. This information will feed the also improved ANOSOM_WEB database and associated mobile application. During field campaigns, the use of this mobile application also streamlines the programme processes and will increase productivity and efficiency of the inspections.

In the end, both the provider of this information (LNEC) and the end-users (*e.g.*, port and harbour administrations) will benefit from a more accurate information on the structural conditions in a predominantly quantitative nature, which complements the already existing detailed qualitative information obtained during the visual observation campaigns.

The OSOM+ is now able to evaluate the structures' risk condition during its lifetime and, based on it, to enable adequate planning of the maintenance and/or repair works to be done. This is extremely important from the management and planning standpoints. In fact, the timely identification of an anomalous behaviour of a maritime structure (*e.g.*, an excessive movement of the armour layer) may allow for immediate or planned actions, which, in turn, avoid further degradation of the structure.

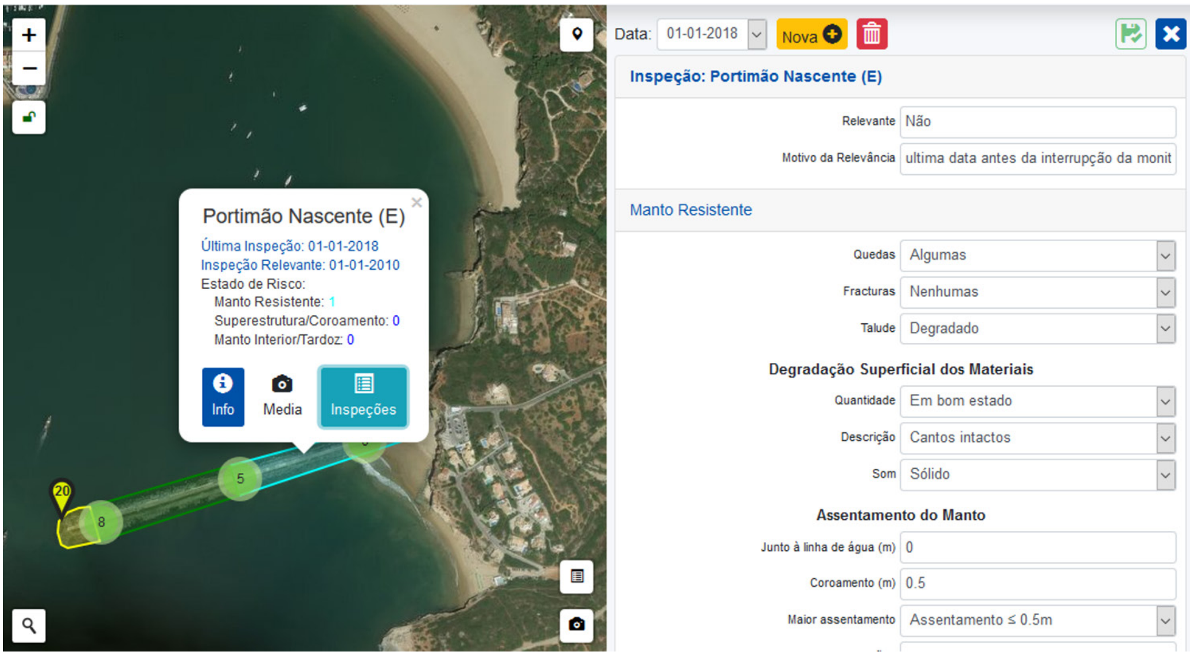

Figure 24. ANOSOM_WEB interface used for populating the visual inspection database.

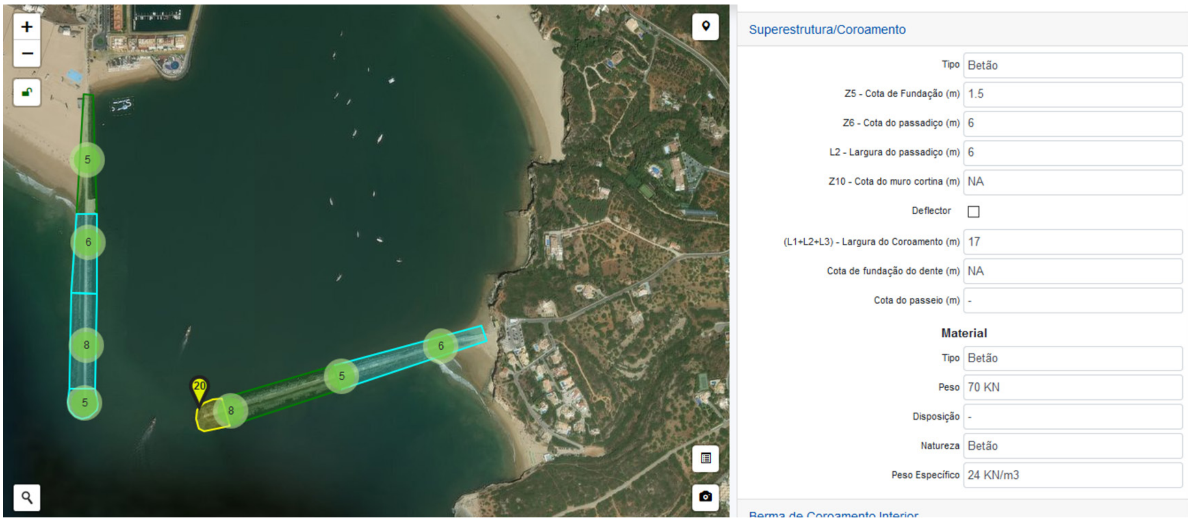

Figure 25. Searching in ANOSOM_WEB interface for geometrical characteristics and materials.

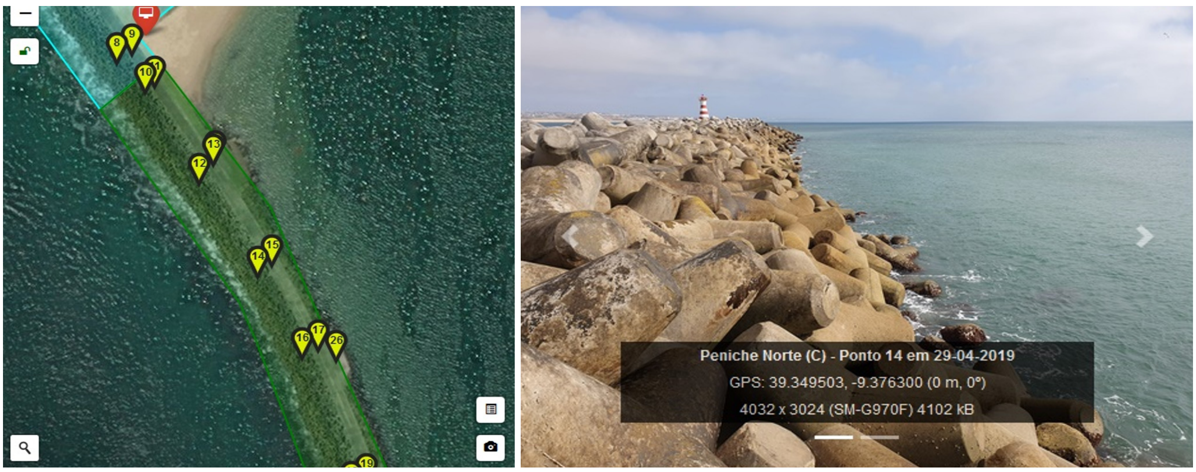

Figure 26. ANOSOM_WEB interface for searching and uploading photos in real-time.

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