

Application of the OSOM+ Systematic Observation Methodology to Maritime Structures at the Port of Sines

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ABSTRACT: LNEC's current OSOM+ methodology has been applied to the maritime and port infrastructure at the Port of Sines, aiming to monitor their performance and, when necessary, recommend timely maintenance interventions. During monitoring campaigns, systematic photographic records were captured at georeferenced locations along each structure, and observed anomalies were identified. Also, drone-based photogrammetric surveys were conducted, providing more detailed and accurate information on the condition of the structures. The embedded cloud-based GIS system enables intuitive and comprehensive online interface for visualization and a mobile interface to allow efficient on-site data input and real-time access to relevant information stored in the corresponding maritime structure database. This methodology has enabled evaluation of the current condition, evolution, and risk status of the port structures at Sines. Based on these assessments, it has been possible to plan maintenance and repairing actions on the structures in a timely and informed manner.

This paper compares results from inspections carried out in 2018, 2020, 2022, and 2023 at the west breakwater, based on visual and drone inspections, and supported by a critical analysis of georeferenced photographs, orthomosaics, point clouds, digital surface models, and profiles.

It was found that only minor displacements of armour units have been observed along the Sines west breakwater, which, up to now, were classified as non-significant anomalies.

KEYWORDS: Maritime structures, monitoring, visual inspection, drone survey, photogrammetry

1 INTRODUCTION

Since 1986, the National Laboratory for Civil Engineering (LNEC) has been developing the Systematic Observation of Maritime Works (OSOM) programme, aimed at monitoring the structural behaviour of rubble-mound breakwaters along the continental Portuguese coasts, namely west and south, but also on the island's coasts. The main objective was to identify structural anomalies on these maritime structures at an early stage, enabling timely maintenance and/or repair interventions when the affected areas are still limited and remediation is simpler and more cost-effective.

The OSOM methodology started being grounded in systematic visual inspection campaigns, which provided data for the former ANOSOM database (Reis *et al.*, 1995; Lemos *et al.*, 2007). This database supports the assessment of the present condition, evolution condition, and risk condition of the maritime structures under observation. Since the 2010s, the OSOM programme has undergone significant improvements. In 2017, with the integration of drone-based monitoring, the programme evolved into OSOM+ (Capitão *et al.*, 2018).

The use of drones has enhanced the accuracy and detail of structure's condition assessments, enabling more accurate quantification of settlements, volume losses, and other structural changes on the observed structures.

This paper presents LNEC's expertise in visual inspection and drone-assisted monitoring of rubble-mound breakwaters and demonstrates the application of the OSOM+ methodology to a specific case study: the port of Sines, where inspections started in 2018 (Fortes *et al.*, 2019) under a contract established with the Port of Sines Authority (APS). The present paper focuses especially on the main port protecting maritime structure, the west breakwater.

2 THE PORT OF SINES

The Port of Sines is the largest artificial harbour in Portugal, functioning as a deep-water port with natural bathymetries reaching depths of up to -28 metres CD (Chart Datum), see Fig. 1. Owing to its strategic geophysical characteristics, it serves as the country's main maritime gateway for energy supply of Portugal, handling the import and export of containers, liquefied natural gas, coal, crude oil, and petroleum derivatives.



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Figure 1. The port of Sines

The port is equipped with specialized terminals designed for the efficient handling of various cargo types, all of which are safeguarded by extensive rubble-mound breakwaters.

All Sines' breakwaters are monitored under the OSOM+ programme, including the west breakwater, the east breakwater, the marina breakwater, the fishing harbour breakwater, and the service port breakwater, see Fig.2.

Among these, the west breakwater is the case study presented in this paper (outlined in the figure in yellow, while the others are shown in red). This breakwater suffered severe storm damage during years 1978 and 1979, with progressive failure episodes that broke and displaced large dolos armour units and undermined the superstructure, culminating in extensive reconstruction works (Reis *et al.*, 2011). Subsequent repairs included the use of heavy Antifer-type cubes on widened sections and smaller slopes before final redesign to meet updated 100-year sea states, making it clear how unit mechanical strength limits, placement density, and storm climate underestimation are important. These lessons align with broader reviews of concrete armour integrity that emphasize size-effect fragility and the need for structural and hydraulic checks beyond notional stability numbers (Scaravaglione *et al.*, 2022 and Leone *et al.*, 2024), which motivates systematic monitoring as described here.



Figure 2. Rubble-mound breakwaters in the port of Sines

The breakwaters safeguard a wide array of critical infrastructures, including five specialized terminals (liquid bulk, petrochemical, dry bulk, liquefied natural gas, and containers), a logistics activity zone, the fishing harbour, and the leisure marina.

Structurally, each breakwater is composed of a core of finer material, overlaid by an armour layer of large blocks. In more exposed sections, the armour layer consists of concrete units in various geometries - such as tetrapods, Antifer cubes, or parallelepipeds - to enhance stability and wave dissipation. The superstructures of these breakwaters are constructed in reinforced concrete. Access to the breakwaters varies: while some are publicly accessible, others are located within restricted operational zones, subject to limited or prohibited public entry.

3 OSOM+ METHODOLOGY

3.1 Introduction

The OSOM+ methodology was designed to assist infrastructure owners in the systematic monitoring of breakwaters and other maritime structures, enabling the timely recommendation of maintenance and/or repair interventions. It integrates systematic visual inspection campaigns coupled with drone-based photogrammetric surveys, providing comprehensive and up-to-date information on structural behavior and evolution. All collected data are stored in the ANOSOM database (Maia *et al.*, 2017), which supports the characterization of each structure's Present Condition, Evolution Condition, and Risk Condition. This diagnostic framework enables informed decision-making regarding the timing, location, and urgency of required maintenance or repair works.

More recently, the development of the ANOSOM-WEB interface has introduced a web-based GIS platform accessible from any internet-connected device (smartphone, tablet, or computer). During field campaigns, inspectors can use this platform to review data from previous inspections, access real-time condition assessments, and determine whether immediate intervention is necessary (Fig. 3).

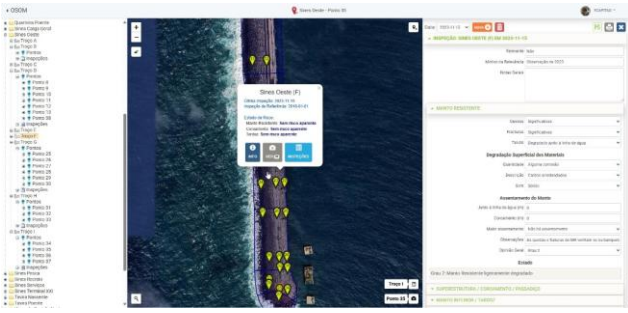


Figure 3. ANOSOM-WEB Interface showing the west breakwater, of port of Sines

Currently, OSOM+ comprises four main components:

- Periodic **visual inspections** by trained personnel, including systematic GPS-tagged photo and video documentation;
- Periodic **UAV-based aerial surveys**, using vertically oriented images;
- The **ANOSOM-WEB database**, storing all inspection data and supporting condition assessments and diagnostics;
- A **mobile application** for in situ data entry and real-time access to inspection results.

OSOM+ visual and UAV campaigns systematically observe the emerged parts of the breakwaters, with deliberate scheduling at low tide to maximize armour exposure and reduce surf-zone noise in geospatial products. Note that the absence of submerged monitoring can bias diagnostics by missing toe scour, filter exposure and settlement patterns, which have historically driven significant damages in concrete-armoured structures including Sines west breakwater, as referred to before. Also note that ANOSOM-WEB already supports feeding “surveys of emerged and submerged zones,” enabling integration of multibeam bathymetry, side-scan sonar, ROV/diver inspections, and subsea photogrammetry to close this gap in future campaigns (Reis *et al.*, 2011).

3.2 The visual inspection

Visual inspections provide rapid and intuitive means of monitoring the structural behaviour of rubble-mound breakwaters over time. These inspections, following the methodology outlined by Santos *et al.* (2003), are typically conducted on an annual basis, and additionally after the occurrence of severe storm events that may have impacted the structural integrity of the structures as a whole or some of its components.

To enhance the reliability and consistency of the observations, the breakwater is subdivided into distinct sections, each defined according to its

specific physical and functional characteristics. Generally, each section corresponds to a unique cross-section of the structure, with the breakwater head always delineated as an individual section. For each section, a set of observation points is defined and marked directly on the structure. At each campaign, photographs and/or videos are taken from these predefined points, using consistent photographic parameters—including camera focal length, direction and angle of view, and framing—to enable direct comparison over time. To ensure optimal visibility of the armour layers and filters (if existing), visual inspections are preferably carried out during low tide. Also, for safety reasons, inspections are conducted only under favourable weather conditions, ideally when sea state is calm, thereby reducing the risk accidents on the inspectors.

3.3 The aerial inspection

The use of Unmanned Aerial Vehicles (UAVs), or drones, as shown by Henriques *et al.* (2024), has significantly enhanced the accuracy and detail of structural condition assessments of rubble-mound breakwaters. UAV-based surveys enable the acquisition of comprehensive data on the evolution of structural envelopes, facilitating the extraction of representative profiles in critical areas. Each UAV campaign produces high-resolution nadir aerial images, captured in a regular flight pattern. These images are processed to generate point clouds, digital surface models (DSMs), and orthomosaics, which complement the ground-based visual inspections by offering additional perspectives, especially of areas not visible to an observer walking on the structure.

At LNEC, Initial surveys (2017) employed a DJI Inspire V1. Subsequent campaigns used a DJI Matrice 300 RTK, enhancing flight stability and safety, especially under moderate to strong wind conditions (up to 54 km/h). From 2020 onwards, the integration of RTK improved positional accuracy and operational safety.

Prior to 2020, UAV flights covered the full length of each breakwater, from head to root, while avoiding sensitive infrastructure (e.g., gas and petrochemical pipelines). Post-2020, compliance with European regulations required maintaining a minimum distance of 150 m from buildings, reducing coverage in some cases. To enable proper coverage in this case, oblique image acquisition from flight paths over the sea had to be taken.

Typical flight parameters include an altitude of 30–40 m and 80% longitudinal and transverse

overlap. Flights are autonomous (pre-programmed) and conducted during low tide to maximize exposure of the armour layer.

All necessary authorisations were secured in advance from relevant national entities, including the National Aeronautical Authority (ANA), local Port Authorities, aerodrome/heliport Authorities, and, where applicable, the Institute for Nature and Forest Conservation (ICNF).

Weather conditions were closely monitored five days prior to each flight using official meteorological forecasts, with particular attention to wind speed and gusts.

3.4 The ANOSOM-WEB database

The ANOSOM-WEB database, derived from the earlier ANOSOM system (Reis & Silva, 1995; Santos *et al.*, 2003; Lemos & Santos, 2007), has been significantly upgraded with a GIS-based interface to enhance the efficiency of querying information for each breakwater section. This is now a web-based geographic information system (GIS) platform enabling centralized management, access, and analysis of all observational data. The platform is accessible via any internet-connected device (smartphones, tablets, or personal computers) and was developed using modern web technologies including PHP/Laravel for backend development, JavaScript with Bootstrap/jQuery for frontend interactivity, and Leaflet for spatial data visualization and map integration (Maia *et al.*, 2017). The GIS capabilities are supported by MySQL's spatial features, which allow efficient storage, querying, and manipulation of georeferenced data.

The system allows the import and display of standard geospatial formats, such as shapefiles, and integrates cartographic layers from third-party services like ESRI/ArcGIS. This enables users to visualize inspection data directly overlaid on accurate basemaps and customized site plans. Key functionalities include interactive data mapping, attribute querying, and historical record retrieval, which collectively facilitate spatial-temporal analysis of the structural condition. Moreover, the system supports structured input forms for visual inspection and UAV survey data, which are geo-referenced and linked to individual structural components or segments. This enables a seamless workflow from field data collection to analytical diagnosis, ensuring that maintenance decisions are based on comprehensive, up-to-date information.

The ANOSOM-WEB platform provides the following functionalities:

- a) Storage and analysis of visual and drone survey data, as well as other structural inspection inputs (e.g., surveys of emerged and submerged zones);
- b) Diagnostic assessment of each section of the breakwater, including present, evolution, and risk conditions, based on predefined and calibrated evaluation criteria (Santos *et al.*, 2003);
- c) Historical data consultation, including design documents, past interventions, hydrographic and aerial surveys, and underwater inspections;
- d) Physical characterization of each section, detailing geometry, materials, and standard cross-sections.

The platform enables real-time diagnosis of the structural condition, allowing on-site users to determine whether immediate maintenance or repair actions are required. Fig. 4 illustrates the interface's ability to retrieve photographs linked to specific locations and inspection events. Initially populated with design-phase data, the database has since been updated with findings from systematic inspection campaigns and recorded structural modifications following significant interventions.

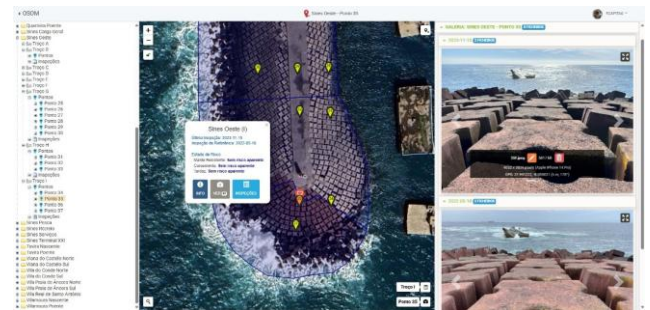


Figure 4. ANOSOM-WEB interface. Photos and other info at Sines west breakwater (point 35, section I, head)

4 APPLICATION TO SINES WEST BREAKWATER

4.1 Integrated visual and UAV monitoring

This chapter presents the application of the OSOM+ methodology to the monitoring of the west breakwater at the Port of Sines. The analysis integrates inspection data from four separate survey campaigns conducted in 2018, 2020, 2022, and 2023. These surveys include both traditional visual inspections and systematic drone-based observations.

The comparative assessment draws upon a diverse set of geospatial products, including georeferenced photographs, orthomosaics, dense point clouds, digital surface models (DSM), and longitudinal and transversal profiles. These outputs enable a detailed and multidimensional interpretation of the structure's evolution over time.

Through this integrated approach, it becomes possible to detect subtle morphological changes, quantify structural displacements, and evaluate the overall condition of the breakwater armour layer with greater accuracy. The combination of UAV-derived data and systematic visual inspections ensures a robust and cross-validated interpretation of physical changes, supporting more informed decision-making for maintenance planning and risk management at the Port of Sines.

4.2 Visual inspection

For the visual inspection, the west breakwater was divided into nine sections (A to I), according to the different physical and functional characteristics of the structure. In each section, several georeferenced points, varying according to the extent and clarity of the identified anomalies, are also established, see Fig. 5.

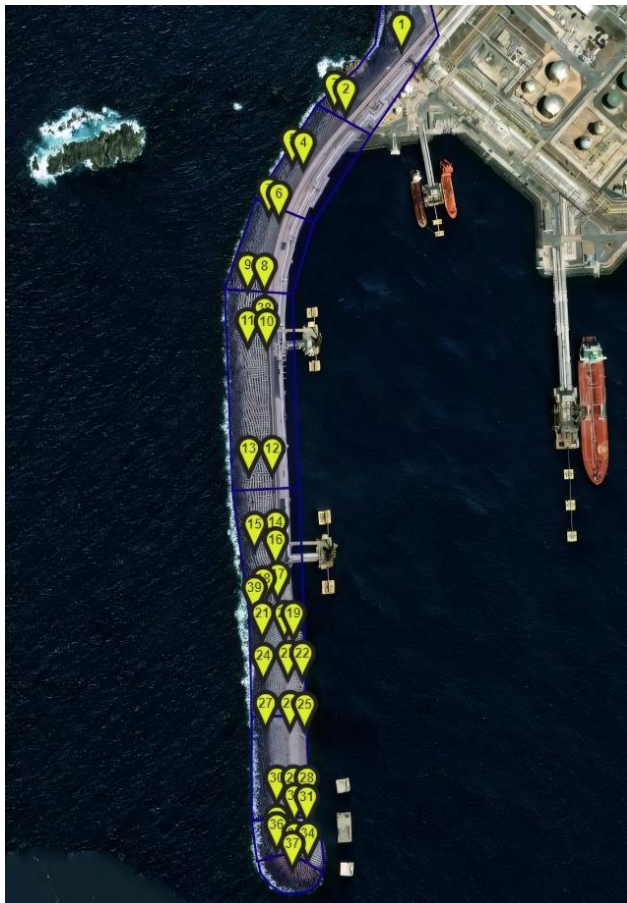


Figure 5. Sines west breakwater with division into sections (A to I) and visual reference points (1 to 37)

For each section, qualitative assessment of the structure's current condition, such as the state of the armour layer, superstructure, and inner filters will be noted. This involves aspects like unit displacements, fractures, and material degradations, often recorded using predefined qualitative scales (e.g., for unit displacement: none, few, some, many).

Figs. 6, 7 and 8 show, respectively, photographs taken on 2018, 2020 and 2022, at predefined points of Sines west breakwater (point 27, located in the seaward side of section G; point 28, in the inner ward side of section G and point 37 at the head of the breakwater, section I).

Observation between campaigns of 2028, 2020 and 2022, pointed out to some structural changes described in the following two figures (Figs. 9 and 10). These show photographs of the section where the most relevant changes were detected between 2020 and 2022, namely at section F, point 24 (Fig. 9) and also at section F, point 27 (Fig. 10).



Figure 6. 2018 visual observation at Point 27F (F – Front direction) of Sines west breakwater (outer armour layer)



Figure 7. 2020 visual observation at Point 28F of Sines west breakwater (inner armour layer)



Figure 8. 2022 visual observation at Point 37T (T – Back direction) of Sines west breakwater (head, section I)

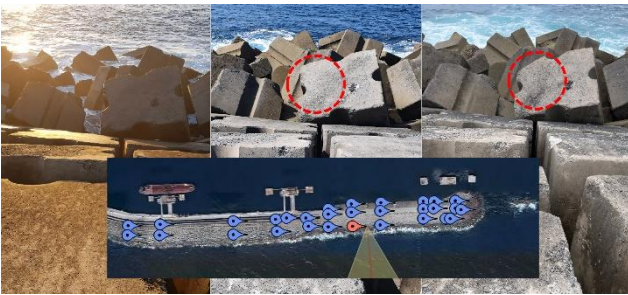


Figure 9. Visual observation at Point 24L (L – Lateral direction) of Sines west breakwater (2018-2020-2022). Broken Antifer between 2020 and 2022

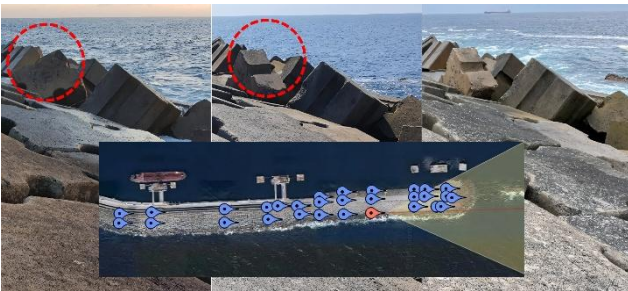


Figure 10. Visual observation at Point 27F of Sines west breakwater (2018-2020-2022). Broken Antifer between 2018 and 2020

Overall, based on the in situ visual inspection conducted in 2022, no significant changes in the general condition of the breakwater were observed when compared to 2018 and 2020. However, some localized alterations, such as broken blocks or minor displacements, were identified, though these do not compromise the structural integrity of the breakwater as a whole.

4.3 Aerial inspection

For the aerial inspection of the structure, required equipment consisted of a UAV system, operated in conjunction with dedicated control software. The initial survey campaign conducted in 2018 employed a DJI Inspire V1 platform equipped with a Zenmuse X3 camera (12 MPixel). In the subsequent surveys of 2020 and 2022, the system

was upgraded to a DJI Matrice 300 RTK with a Zenmuse H20 camera (wide-angle + zoom 20 MPixel cameras, with laser rangefinder), which significantly improved flight stability and operational safety, particularly under moderate to strong wind conditions (Fig. 11).



Figure 11. LNEC's DJI Matrice 300 RTK drone

To ensure accurate post-processing, Ground Control Points (GCP), coordinated using GNSS technology, were established and clearly marked for visibility in the UAV imagery. Also, some Check Points (CP) were established (Fig. 12).

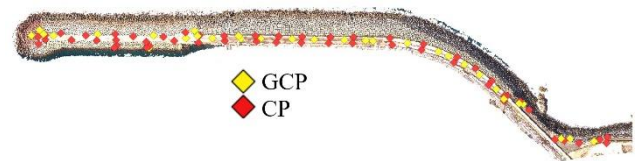


Figure 12. Location of GCP and CP on Sines west breakwater

Flight control was managed via the DJI Pilot app (DJI), primarily used for configuration, calibration tasks and mission planning, to ensure optimal image capture. It also controls the UAV during the flight, alerts the proximity of obstacles, and stops it to avoid collisions. (Figs. 13 and 14).

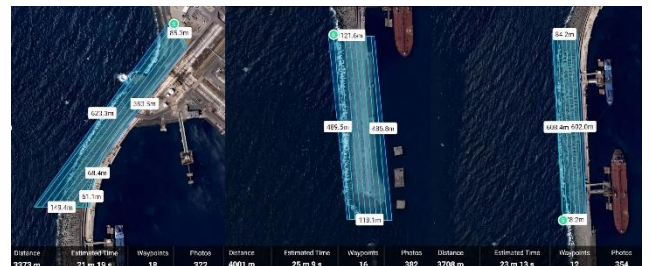


Figure 13. Flight plans over the Sines west breakwater



Figure 14. Drone operator preparing the flight on Sines west breakwater. Shown on top of this image is the RTK GNSS antenna base

Post-flight, the collected imagery was processed using Agisoft Metashape (Agisoft LLC), a photogrammetric software suite used to generate dense point clouds and digital surface models (DSM). These DSM were subsequently handled in QGIS (QGIS, GPL license), which provided the tools necessary for comparative spatial analysis.

To identify localised structural changes between the 2018, 2020, and 2022 campaigns, a sequence of DSM comparisons was performed. Differential DSM (d-DSM) were generated. These revealed structural changes. To enhance these changes the colour scheme of the d-DSM was edited to highlight the areas with important changes.

Dense point clouds, DSM, and orthomosaics were referenced in the ETRS89/PT-TM06 coordinate system to ensure spatial congruency between temporal survey datasets. An example output is presented in Fig. 15, showing the results of the DSM comparison after outlier removal performed in the point cloud. Most excluded data points corresponded to inconsistencies along the waterline, where noise and reflection effects were more prevalent.

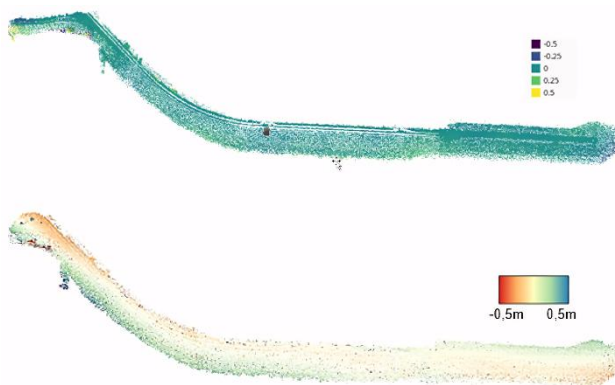


Figure 15. Result of the difference computation between the point clouds of 2018 and 2020 and between 2020 and 2022 after outlier filtering

The procedure follows a sequential workflow, applied individually to each breakwater and

survey: first, the point cloud is generated; next, the DSM is computed and stored in matrix form (see Fig. 16); finally, the orthomosaic is produced (see Fig. 17 for a detail of it).

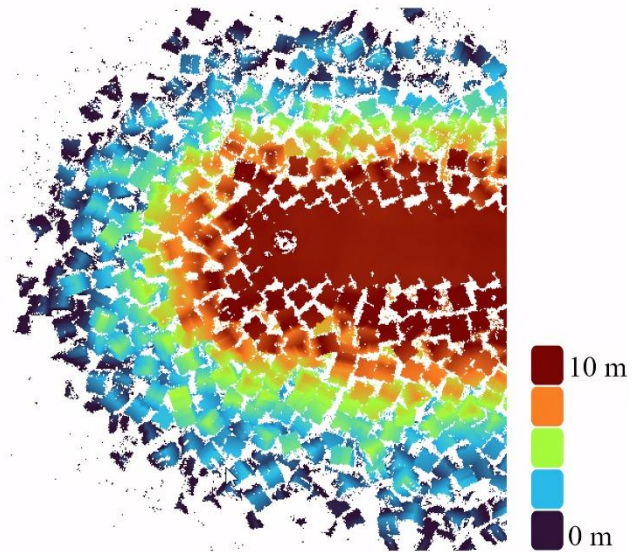


Figure 16. DSM (matrix form) of the head section of Sines west breakwater (head section)



Figure 17. Detail of the orthomosaic of Sines west breakwater (head section)

For reporting purposes and to improve visual interpretation, point clouds were converted into meshes (see Fig. 18).

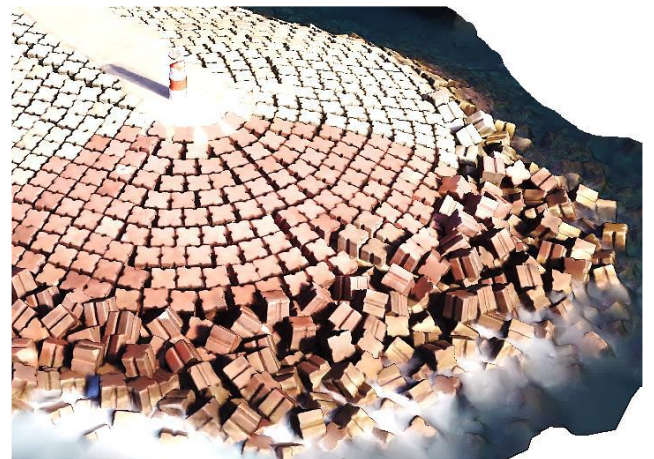


Figure 18. Mesh of the head of Sines west breakwater

In the following Figs. 19 and 20, the map of differences and the respective orthomosaics for 2020 and 2022 are shown, as an example, for the sections where changes were detected. The color scale used in the comparisons is as follows: in red when, between 2020 and 2022, there was material removed; blue when there was material deposition. This comparison was carried out using QGIS, which is also the software used to visualize the orthomosaics, as it offers superior capabilities for displaying georeferenced information (DSM and orthomosaics). It also allows for chromatic manipulation of DSM's, which enhances the visualization of topography and surface changes.

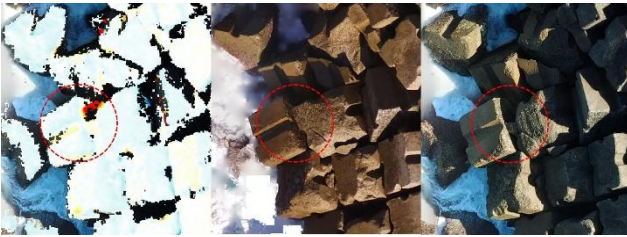


Figure 19. West breakwater. Changes found between 2020 and 2022 – Occurrence 2 – Section E



Figure 20. West breakwater. Changes found between 2020 and 2022 – Occurrence 3 – Section G

As previously noted, changes in the armour layer geometry are identified by analysing DSM's: subtracting one DSM from another reveals spatial differences, allowing both qualitative and quantitative assessments. This analysis is conducted using QGIS software.

Figs. 21 to 23 display selected orthomosaic excerpts highlighting areas where changes were detected. The differences between DSM's are represented through colour maps, facilitating a clear visualisation of localised morphological evolution.

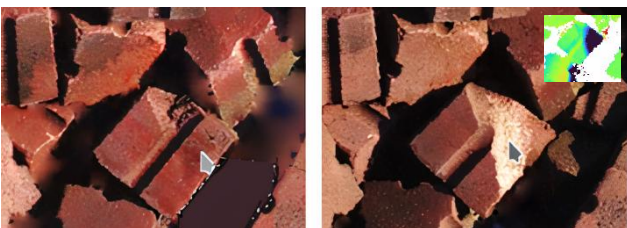


Figure 21. An armour unit exhibited increased erosion between 2020 and 2022

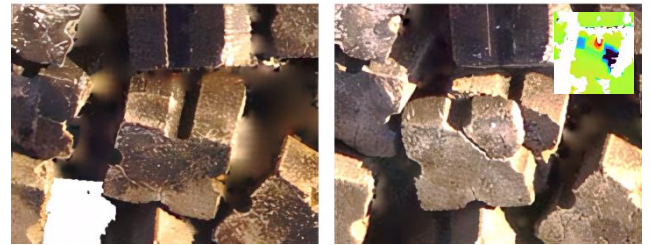


Figure 22. An armour unit broke between 2020 and 2022

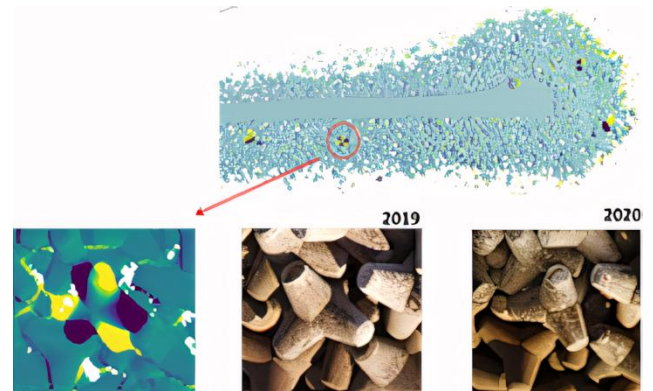


Figure 23. A tetrapod rotated between 2019 and 2020

4.4 Profiles

Point clouds, supported by use of orthomosaics, are used to provide accurate cross-sectional profiles. Transversal profiles were then extracted along predefined cross-shore sections, oriented perpendicular to the longitudinal axis of the breakwater.

The location and spacing of these sections were selected to cover representative areas of the structure and were maintained consistently across survey campaigns for temporal comparison. Profile planes were defined by first considering a baseline polyline drawn along the crest of the breakwater, using the orthomosaic as a spatial reference and then defining a set of normal vectors at regular intervals along this baseline, indicating the direction of each transversal cut (see Fig. 24). An example of such profiles is given on Fig. 25.

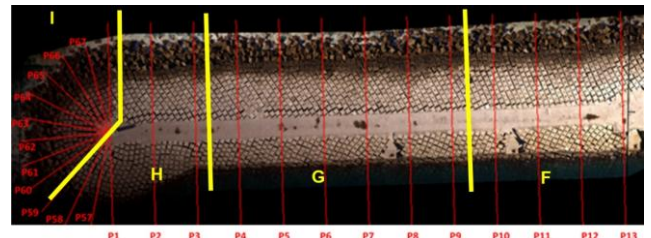


Figure 24. Sines west breakwater. Location and details of the profiles obtained, sections F to I (head)

Profile comparison allows the detection of changes in the most vulnerable sections across consecutive survey campaigns. For Sines west breakwater, only negligible to no changes were observed between consecutive profiles.

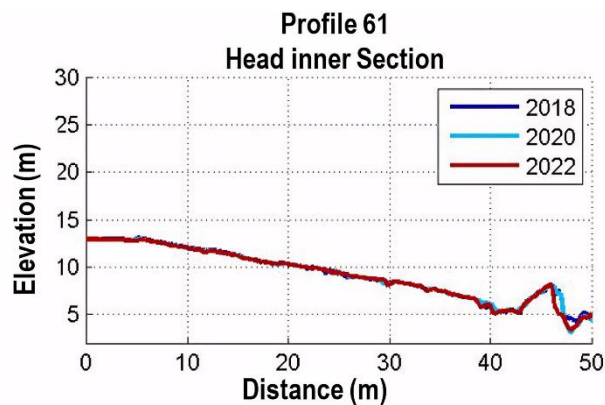


Figure 25. Example of obtained profiles (Profile 61 at the head of the breakwater)

When analysing the profiles, particular attention should be given to the following factors, as they may contribute to discrepancies between surveys:

- a better quality of surveys and point cloud was obtained in 2020 and 2022 compared to 2018;
- tide levels are not exactly identical in the three inspections;
- possible misalignment of point clouds may occur due to the inherent uncertainties of photogrammetric techniques;
- uncertainties relating to surf areas may exist in partially or fully submerged areas;
- certain areas of the breakwater are subject to image acquisition constraints due to the presence of vessels, pipelines, moorings, and other obstructions.

Concluding, since 2018, only minor, non-significant displacements of armour units have been observed along the Sines west breakwater. As with all maritime structures of this nature, it is essential to monitor these minor anomalies and, whenever feasible, restore the structure to its original as-built condition.

5 CONCLUSIONS

In general, the OSOM+ framework, with the integration of drone-based survey capabilities and the development of new tools, notably improves the operational efficiency and analytical depth of systematic coastal monitoring. Periodic visual inspections, when combined with UAV-acquired datasets, provide a more robust assessment of present conditions, structural evolution, and risk indicators. Furthermore, the deployment of a mobile, field-ready application during survey campaigns accelerates data collection and improves workflow integration.

For the Sines port, the present work highlights the significant contribution of visual and aerial photogrammetric surveys, to the monitoring of rubble mound breakwaters. The images captured

through visual inspections procedures and the data products derived from drone imagery, particularly digital surface models (DSM), point clouds and orthomosaics, enhance the ability to quantify structural evolution within the scope of the OSOM+ programme.

Originally based on qualitative assessments, the methodology has now evolved to incorporate higher-resolution, and better quantitative results. With the current level of precision achievable in drone-based surveys, structural changes on the order of a few centimeters can now be detected with confidence. This marks a critical step forward in the early identification of potential risks and a more trustful long-term management of the coastal infrastructure.

Although this study concentrated on the monitoring of existing maritime structures, the applicability of the survey methodology is broader. Such data can also support the verification of as-built geometry during construction or repair phases, an essential aspect for quality control and contractual validation.

This enhanced methodology benefits both the data provider (LNEC) and the primary end-users, including Port Authority Administrations, in this case the Port of Sines Authority (APS). The transition toward a predominantly quantitative monitoring approach yields more precise, objective, and actionable insights into the condition and performance of this type of maritime structure.

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