Monitoring the Madeira airport protection breakwater using visual and Unmanned Aerial Vehicle observations

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Abstract. An aerial monitoring system was developed for the maritime structures protecting the foundation columns of the airport infrastructure of the Madeira Island Airport, in the scope of research project MEGE, to complement the already existing monitoring program of visual observations. For the aerial monitoring of the berm breakwater, with about 770 m in length, a fast data acquisition system was envisaged. Imaging techniques acquired through a high-resolution camera coupled to an unmanned aerial vehicle (UAV) were used, which allowed for a very fast and efficient automated procedure, compatible with the difficult accessibility to the structure on the seaside. Point clouds corresponding to the breakwater geometry were obtained from the set of aerial images from the camera on board of the UAV, using photogrammetric techniques. In this paper, the two complementary parts of the monitoring of this structure are described and corresponding results are shown.

Keywords: visual monitoring, UAV monitoring, berm breakwater.

1 Introduction

In order to protect the foundation and the base of the columns that support the runway extension of the Madeira airport from the sea wave action, a berm breakwater was built next to that airport structure, Figure 1, along with the "Posto de Socorros a Náufragos" breakwater, being both structures under the jurisdiction of ANA - Aeroportos de Portugal, S.A. The berm breakwater has a development of about 770 m in length and is aligned from SW to NE, parallel to the rows of pillars, with a slope base largely above the bathymetric of 13.6 m (ZH).

Figure 1. General view of the berm breakwater and the foundation columns of the airport runway extension, April 2021.

The berm breakwater is a dynamic behaviour structure, consisting of rock blocks, with weights between 5 kN and 40 kN and a profile of 4(H):3(V). As this structure has a deformable slope, in its design a safety line is defined located at a distance (30 m) from the axis of the alignment of the seaside row of the outer columns of the extension runway structure, a line that must not be exceeded. In this case, intervention is required so as not to compromise the stability of the structure.

Since it is a dynamic structure, it is quite important to know the evolution of this breakwater along its lifecycle, to identify the preliminary stages of damages and the need (or not) of repairing works in due time. This will avoid the progression of damages that could put the foundation in danger and the base of the columns that support the runway of the airport, as well it will avoid extra costs. In this framework and following the LNEC's OSOM+ program of visual observations [1], visual inspections were made in October 2009, June 2012 and December 2013, and a qualitative photo comparison of the different inspections has been performed. Although these visual campaigns give a general view of the evolution of the breakwater and identify the main damages problems, it does not characterize the whole breakwater in a more quantitative and detailed way (profiles, damage volumes, etc.).

In this context, a research project called "MEGE - Structural Monitoring of Large Structures" was proposed with the aim of developing, implement and operating a system to monitor the structural evolution of Madeira International Airport. The system revolved around two components: the support structure of the runway extension and the berm breakwater that protects the former structure. This paper is about the berm breakwater.

For the berm breakwater the implemented process will add up to do the existing program of visual observations, and can be divided into two main phases, one corresponding to image acquisition and another to post-processing. The first operation corresponds to flying the UAV and capturing the images. The second supports photogrammetric image processing for acquiring 3D point clouds. These point clouds are processed to detect possible changes in the breakwater shape that may have occurred in the time interval between the two flights.

Ideally, monitoring campaigns should be performed at least once a year and after any relevant storm, comparing the campaign results (photos, point clouds, DEM models) obtained in the different instances and identifying possible changes in the geometric configuration of the breakwater. In this way, it is possible to identify movements within the structure occurred between the two instances. With this detailed and accurate information, it is then possible to verify the condition of the structure and analyse in detail areas with stability problems, where blocks were either displaced from its resting positions or even broken. In addition, different surveys can be compared to examine the evolution of structural integrity and identify areas that require intervention to maintain structural function and stability throughout the expected lifespan.

Here the work developed for OSOM+ program and MEGE project for the berm breakwater is presented.

2 The berm breakwater

The purpose of the berm breakwater is to protect the foundation and base of the columns supporting the airport runway extension infrastructure in Santa Cruz (Madeira Island Airport) against sea wave action.

Berm breakwaters are dynamically moving structures, consisting of rock-fill blocks that are significantly lighter than the weight of the protective armour elements of conventional breakwaters, and also being the thickness of the protective layer much greater than that of those conventional breakwaters. In this type of structure, the profile is expected to deform under the action of waves, resulting in an S-shaped equilibrium configuration, in which the less inclined section of the profile, with higher resistive capacity, is in the active zone of the breakwater [2]. Since this structure has a deformable slope, a safety line was defined in the project, from the axis of the alignment of the front row of the outer columns of the runway structure. According to the project designer [3], this distance should not be less than 30 m. The berm breakwater profile was designed for the 50-year return period design wave, with a significant wave height, Hs, of 5.5 m and consists of an all quarry run rockfill core with a 4(H):3(V) slope, protected by a selected rockfill mantle with weights between 5 kN and 40 kN and a thickness of 9 m. The design crest of the profile was 4.1 m (ML), ML being the mean level, corresponding to +1.4 m (CD), Figure 2.

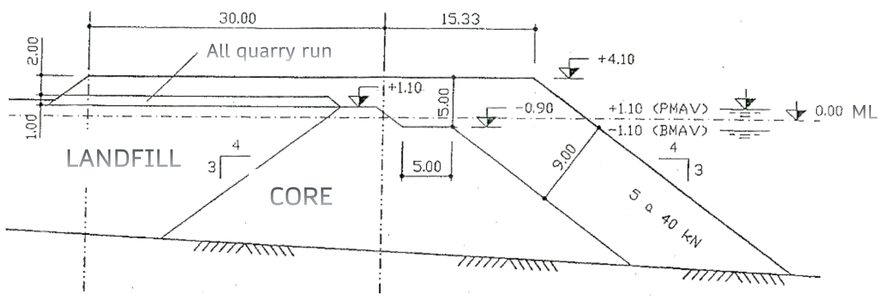

Figure 2. Cross-sectional profile of the berm breakwater (referred to ML).

3 Visual observation monitoring

Since 1986, LNEC has been systematically observing maritime structures based on structure monitoring campaigns (a program now-called OSOM+) to monitor and predict the behaviour of offshore structures along the Portuguese coast and recommend timely maintenance interventions on these structures as needed.

Regarding the evolution of the berm breakwater after construction, the information available at LNEC refers to visual inspections taken by LNEC technicians in October 2009, June 2012 and December 2013, and to information about surveys carried out in 2018, reported in [3]. Between the year of the first visual inspection (2009) and the year of the second (2012), this breakwater has undergone many of the expected changes in this type of structure (dynamic behaviour structure). The June 2012 campaign witnessed the worsening of the degradation foci identified in 2009, and the emergence of others. At that time, it turned out that the eastern half of the protection was much more affected than the western half [4]. The intense leakage of riprap blocks at the eastern end of the breakwater structure, in the NE zone, was the most worrisome situation at the time. It was thought to be caused by a presumed concentration of wave energy, possibly amplified by the effects risen by the proximity of a large rocky outcrop and by the near permanent maritime structures. However, the erosion line, even in the most eroded sections, was still beyond the safety line of the structure.

Visual observations in 2014 confirmed that two sections of the structure were severely damaged: one is between approximately the middle of the structure and the eastern edge of the structure, and the other is at the transition from the breakwater to the related infrastructure "Água de Pena" bathing area [4]. In these sections, the distance between the crest of the breakwater and the axis of the columns was less than 30 m, which is to say that, at some points, the safety line had already been exceeded by a few meters.

In Figure 3 one can observe the evolution of the berm breakwater profile at three instances in time: a) in December 2013; b) in October 2019 and c) in April 2021. Note, however, that tide level conditions are different (lower) in the last observation.

a) b) c)


Figure 3. Berm breakwater in: a) Dec. 2013; b) Oct 2019; c) Apr. 2021.

In August 2018 topographic and 3D Multibeam surveys were carried out, the results of which were presented in [3], together with the results of surveys conducted in February 2014 and June 1999. That report states that in two sections the crest setback exceeds the design safety line: from column 14 to 22 (central zone), with about 160 m and between columns 29 and 33, in the NE zone, with about 30 m (see Figure 4 for identification of referred columns). The setbacks at the height of the survey were generally less than 2 m, occasionally reaching 3.5 m in the central zone.

Figure 4. Reference points on the berm breakwater.

In October 2019, the slope continued to show signs of degradation along the breakwater, with the eastern half of the protection being significantly more affected than the western half. It was noted that the safety margin was exceeded in front of some columns (14 to 22, 30 and 32).

In April 2021 a visual observation was performed by LNEC for this breakwater, including the characterization of its current condition.

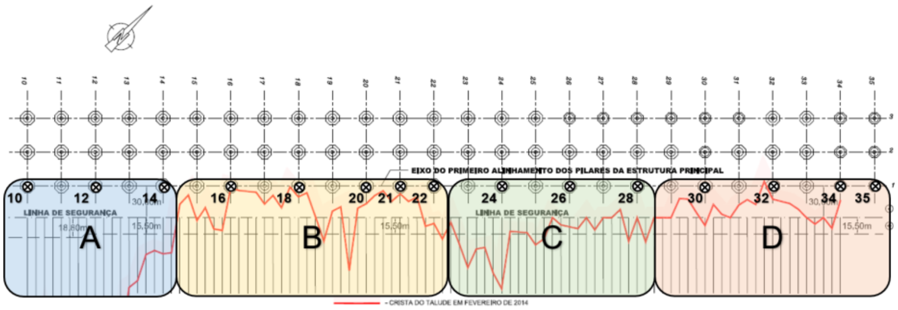

Figure 5. Identification of sections (A to D) and reference points (10, 12, 14, 16, 18, 20, 21, 22, 24, 26, 28, 30, 32, 34 and 35) - adapted from [3].

Also during the 2021 campaign, at certain points considered more relevant (see those in Figure 5), measurements were taken of the distance between the axis of the columns and the slope crest. The measurements are displayed in Figure 6, which shows the distances measured at each column and the 30 m line, considered in the project as the minimum safety value. The accuracy of the measurement is about ± 0.4 m. Measurement errors include uncertainty in defining points defined as vertices, uncertainty in orientation perpendicular to the column, and uncertainty due to the flexibility of the tape measure.

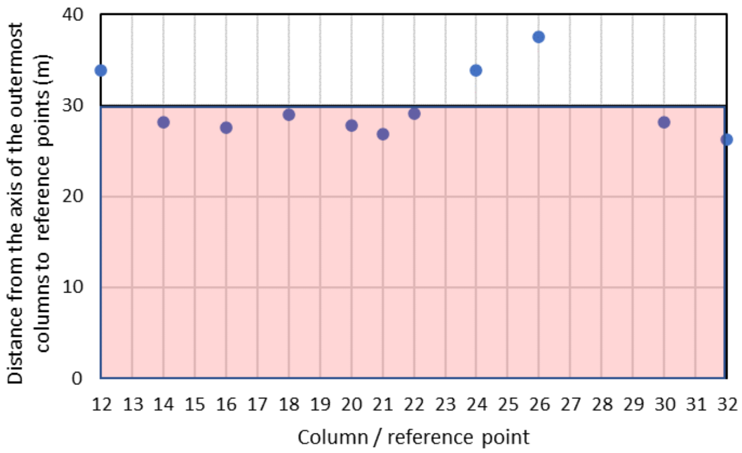

Figure 6. Distances (in m) from the axis of the outermost columns to homonymous reference points.

In general, and referring to both Figure 6 and a wide number of available photographs taken during the 2021 campaign, it can be seen that:

- The slope shows a considerable number of rockfill elements moved in the area in sections A to D revealing some foci of degradation. In particular, in front of columns 16 and 21, the slope deterioration is readily apparent;
- There is a lack of blocks in the area to the east of section A and sections B and C;
- The safety margin has clearly been exceeded in front of columns 14, 16, 18, 20, 21, 22, 30 and 32, with an approximate value varying between 3.7 m (column 32) and 0.9 m (column 22), below the safety line;
- In front of column 18, rockfill blocks from the slope are still there, but there was no evolution compared to 2019.
- In front of column 35, on the existing retaining wall, the same anomalies referred to in October 2019 were also observed, namely distances between blocks on the order of 7 cm, an area with the corner of a degraded block and a distance between blocks on the order of 7 cm and three deteriorated slabs. These distances did not change in the observation performed in April 2021.

According to the campaign of April 2021, the following classifications were assigned to the current condition of the berm breakwater in the year 2021, see Table 1. In this Table, level 1 means that the element/section is in good condition, although showing occasional signs of slight degradation; level 2 indicates that the element/section is slightly degraded; and level 3 suggests that the element/section is degraded.

Table 1. Levels assigned to the current condition of the berm breakwater in 2021.

Section	Level
A	1
B	3
C	2
D	3

From the results presented, one should highlight the need to intervene on the structure, especially in sections B and D, to ensure compliance with the distance from the crest to the design safety line.

Presently, in June 2022, repair work is underway on this maritime structure to restore the originally intended project to ensure compliance with the distance from the crest to the design safety line. This work will likely be completed by November 2022, after which new inspections will be carried out both visual and aerial observations using the existing UAV System, described below.

4 The Unmanned Aerial Vehicle (UAV) System

4.1 Image acquisition

During the 2021 campaign, at the same time visual inspection was conducted, an aerial observation was also carried out. For this, a UAV system was used, complemented with the appropriate control software. As the main body, a “DJI Matrice 600 Pro” drone was selected with a payload consisting of a “DJI Ronin MX” gimbal and a “Phase One iXM-50” high-resolution camera. This camera offers a resolution of 50 MP (Megapixel) at a maximum acquisition rate of 2 fps (frames per second) and was specially manufactured for aerial photography applications.

Figure 7. UAV system in flight to acquire aerial images.

For control, it was necessary to use several applications, namely:

i) UgCS ground station software (SPH Engineering, Latvia), with which the flight mission plans were planned and executed;

ii) DJI Go flight controller application (DJI, China), which was used to configure the UAV flight parameters; and

iii) iX Capture image acquisition application (Phase One, Denmark), used to control the camera.

The images were acquired via programmed routes allowing the repeatability of acquisitions in both position and perspective. The route shown in Figure 8 is the path travelled by the drone followed in one of its missions. Two acquisitions were made with the same route, just varying the camera angle as to obtain more perspectives and thus minimize blind spots in the point cloud.

Figure 8. UAV system in flight to acquire aerial images.

Flights over the berm breakwater follow a planned path first in the north-east direction, until near the end of the structure, where it is necessary to do a small detour towards the ocean before continuing until the end. Then, the path is repeated in the opposite direction, and with a different camera orientation. Figure 9 shows images of two complementary flights with the same route but different perspectives.

Figure 9. Images of the first flight over the berm breakwater and the drone's direction of travel.

4.2 Photogrammetric image processing

After the flight, the acquired images were processed using the Pix4DMapper software (Pix4D SA, Switzerland) and the resulting point clouds were processed using the CloudCompare tool (GPL software, cloudcompare.org).

Due to the camera solution used, it was necessary to start the image acquisition before take-off. After each image acquisition, data from the camera's XQD memory card was transferred to the computer and images in transit were deleted. After that, the images, initially recorded by the camera in proprietary format IIQ (Intelligent Image Quality file format), were converted to TIF (Tag Image file Format). The EXIF (EXchangeable Image file Format) information from these images was also transferred, in order to secure the GNSS (Global Navigation Satellite System) information needed to use as input for processing with the Pix4DMapper photogrammetry software. Figure 10 shows the point cloud of the berm breakwater, for which a GSD (ground sampling distance) of 3.9 mm was obtained with an average reprojection error of 0.076 px (pixel) in the calibration.

To minimize point cloud matching errors, it was also necessary to manually define the correct GPS accuracy values to the ones guaranteed by the UAV. This procedure allows the software to position the camera on each image in a precision volume two hundred times smaller than the volume referring to the precision selected by default. This increase in accuracy of location is translated into faster processing and better correlation, thus minimizing error occurrence.

Figure 10. Resulting point clouds of the berm breakwater, April 2021.

Image processing with Pix4DMapper is to be performed at two moments in time, before and after any event that causes changes in the geometric configuration of the berm breakwater. A software tool was developed to read and process the PLY format exported by Pix4D to get a regular profile along the breakwater length. Previously it was planned to carry out this operation with CloudCompare, but added development time was compensated by the increased automation and control, as well as the high computational demand of the CloudCompare's graphical interface in a cloud with such a high number of points.

Processing starts by rotating the entire point cloud at a predefined fixed angle, corresponding to the orientation of the breakwater with respect to the North direction, resulting in the axis system shown in Figure 11.

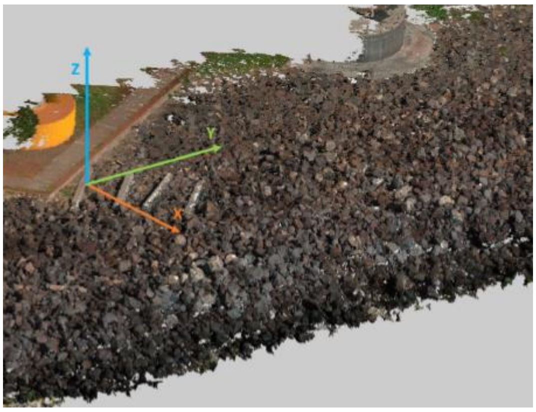

Figure 11. Coordinate system used in the processing of clouds of points**.**

A spacing between profiles and the thickness of the profiles is then defined. For each profile, points within a range of Y coordinates are selected according to the location and thickness of profile. Inside of this selection, bins were defined, evenly spaced in the X direction, and each one is matched by the mean altitude (Z coordinate) of its points, thus defining the profile.

Another program was also developed that, after rotating this point cloud, allows exporting sections as new point clouds between two Y values. This facilitates further processing in CloudCompare due to the decrease in the total number of points to view and process at once. As an example, 1250 images were acquired in two distinct flights, which generated a cloud of approximately 370 million points. The cloud in its full extent is represented in Figure 10 and an approximate view can be seen in Figure 12.

Figure 12. Detail of the berm breakwater point cloud.

Due to the large dimensions of the breakwater and its horizontal parallel orientation, the drone's camera’s field of view actually covers only the breakwater. Therefore, the point cloud contains few unwanted points, and as such, it is not necessary to delete cloud sections to continue processing.

Based on the acquired information it is also possible to extract profiles along the breakwater. Figure 13 shows example profiles, as well as their representation in the point cloud, using a 0.2 m thick profiles and 0.1 m thick bins. By visually inspecting the obtained point clouds and profiles, it can be concluded that these are a good representation of the local geometry of the structure.

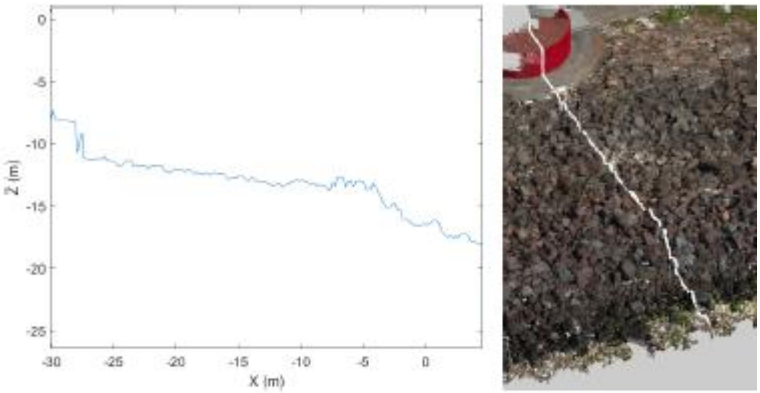

Figure 13. Example of berm breakwater profile and their approximate location (in white) in the point cloud.

5 Conclusions

This work presents two different, but complementary parts of the monitoring system developed for the berm breakwater that protects the foundation columns of the airport infrastructure in Santa Cruz (Madeira Island Airport). This is a special maritime structure about 770 m in length, that, due to its dynamic profile functioning, needs to be regularly inspected to verify its structural stability.

Based on the OSOM+ program of visual observations, the first methodology was applied to verify its current condition and evolution and, if possible, to predict its future behaviour and enable recommendation of timely maintenance interventions. This made it possible to observe that many expected changes in this type of structure (with dynamic behaviour) have occurred at this breakwater.

Under the MEGE project, a UAV system comprising an unmanned aerial vehicle carrying a camera, was also used for 3D model and profile acquisitions. Aerial images were acquired through pre-programmed routes, which allowed an increased repeatability of acquisition regarding both positioning and perspective. After the flights, acquired images were processed using Pix4DMapper and the resulting point clouds were processed. A custom software tool was prepared to read the point cloud and generate regular profiles along the breakwater length, with a predefined spacing between profiles and with the same reference axis. This system enabled a fast and efficient automated procedure to obtain 3D profiles of the whole breakwater.

Results of the two different (but complementary) methodologies allows one to more soundly verify the evolution of this breakwater and establish a tentative repairing schedule in advance.

In fact, repair work is currently underway on this marine structure to restore the originally intended project. This work will likely to be finished by November 2022, after which a new inspection will be performed both by carrying out visual observation and aerial observation, using the existing UAV.

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