An assessment of 3D scanning methods in physical models

R. Capitão[a,*], R. Lemos[a], C.J.E.M. Fortes[a] and R. Jónatas[a]
[a] *Hydraulics and Environmental Department, National Laboratory for Civil Engineering (LNEC), Lisboa, Portugal*

[*]*Corresponding author: Avenida do Brasil 101, 1700-066 Lisboa, Portugal, rcapitao@lnec.pt*

ABSTRACT: The evaluation of damage progression caused by wave action on physical models of rubble-mound breakwaters can be accomplished through two types of methods: quantifying the movements and falls of the resistant armor elements by visual inspection (the traditional, classical method) or determining the eroded volumes and depths between consecutive surveys of armor layers using sensors and photogrammetric methods (3D scanning methods). Of the latter, one may use techniques such as the so-called "Kinect", "Photogrammetry" and "LiDAR". The end-product of these techniques is, among others, point clouds, which allow obtaining three-dimensional surface models. In this paper, four of the latter techniques (3D scanning methods) are briefly described, and a comparison is made between them regarding their usability in current tests, their advantages and disadvantages, among themselves for a study case of the physical 3D model of the Ericeira breakwater. In evaluating survey quality across the four methods, RMSE (root mean square error) was employed to align obtained point clouds with ground control points (GCP). Notably, Photogrammetry, Kinect, and Azure techniques showed excellent RMSE values. Conversely, the LiDAR-derived-method cloud, using a smartphone with LiDAR sensor and 3dScanner app, fails to yield acceptable and accurate results for the research objectives of this paper.

KEYWORDS: *physical modelling, breakwater, damage progression, reconstruction techniques, 3D scans*.

1 INTRODUCTION

Physical model tests are often used as a fundamental tool in the design of rubble-mound breakwaters, which allows the hydraulic behavior of these structures to be easily studied under given conditions of wave action. The main purpose of these tests is to study the stability of the structure, and to infer on the possible progression of damage (if any) through the quantification of movements and falls of the resistant armor layer elements.

Normally, the identification of movements and falls of these elements is performed by visual inspection during the test period. However, this technique has some limitations, among which is that it is very dependent on the experience of the observer. Therefore, to better identify, and even measure those displacements, other methodologies have been used, such as photogrammetry and 3D scans with position sensors.

More recent methods of evaluation of damage progression caused by wave action on physical models involve non-intrusive surveys, utilizing photogrammetric techniques with RGB sensors, depth sensors based on the Time of Flight (ToF) methodology, and LiDAR (Light Detection And Ranging) laser scanning sensors. Depending on the survey conditions and the post-processing methodology of the acquired point clouds, these techniques enable the generation of three-dimensional surface models with varying degrees of accuracy.

One of the techniques to obtain three-dimensional surveys of breakwater models is using a Microsoft® Kinect position sensor, a depth sensor based on the Time of Flight (ToF) method. Soares *et al.* (2017) assessed the use of this sensor to detect movements of perfect cubes and tetrapods in two-dimensional (2D) physical models. Musumeci *et al.* (2018) conducted surveys of the submerged part of the slope of breakwaters using the Kinect sensor during 2D testing with Accropode® artificial blocks. Sande *et al.* (2018) conducted tests aiming at an approach to the validation of the surveys with the Kinect sensor, with determination of the variation of its accuracy depending on the parameters and distances to the sensor used in the surveys. Lemos *et al.* (2022) evaluated damage evolution of rubble-mound breakwaters based on aero photogrammetric surveys using both Kinect sensor and photogrammetric techniques.

The Microsoft Azure Kinect is an upgraded version of the previous, it also incorporates depth, IR and RGB sensors but of a more refined, more accurate kind. Utilizing the Azure Kinect SDK (software development kit), surveys with this low-cost equipment involve swift scanning as the user moves across the designated area.

Another technique is based on photogrammetry and has been successfully used in several works, in various areas, e.g., recently in the area of monitoring (Kwasi and Jayson-Quashigah, 2021). It uses the Structure-from-Motion (SfM) method to calculate camera positions and orientation with and without ground control points (GCP) (Pepe and Costantino, 2020).

Finally, one also deemed interesting to consider a third low-cost technique, consisting in the use of a smartphone with a built-in LiDAR sensor and the 3dScanner iOS app to perform 3D scanning of the model. At first sight, this methodology seems promising, since it presents portability, ease of use and cost as great advantages over the other techniques.

Any of these methods can produce point clouds, used to obtain surface models, profile extraction and eroded volume calculations. However, the accuracy of the results obtained and the ease of use in a laboratory environment depends on each technique. It is therefore especially important to evaluate the performance of the different techniques and to identify their main advantages and disadvantages.

In this sense, four techniques of envelope survey were evaluated on a 3D physical model of the Ericeira breakwater, Portugal, within the scope of the three-dimensional physical model tests of this structure currently being carried out at the National Laboratory for Civil Engineering (LNEC).

The four techniques are entitled “Kinect”, “Azure”, “Photogrammetry” and “LiDAR” and the study aims to evaluate the best technique to obtain three-dimensional surface models to ultimately identify changes in the physical model.

In the following sections, besides describing the physical model considered, the above four techniques, and the procedures for their use, are briefly described, as well as the respective results are obtained. A comparison is made between them regarding their usability in tests and their advantages and disadvantages, among themselves.

2 THE PHYSICAL MODEL

The 3D physical model of the Ericeira breakwater was built at the experimental facilities of the Department of Hydraulics and Environment (DHA) of LNEC, in the TOI1 wave tank of the Maritime Hydraulics Hall, with dimensions 46.6 m x 20.6 m. This tank is equipped with 2 mobile irregular wave makers of 6.0 m length each, for water depths up to 0.75 m (Fig. 1).

Figure 1. Model at LNEC’s experimental facilities.

The model was built and operated according to Froude's law of similarity with a geometrical scale of 1:75. The tested section is a rubble-mound breakwater, with a trapezoidal core covered by a filter composed of two rock layers. The armor layer at this cross-section is made of tetrapods weighing 300 kN, between +10.2 m (CD) and -4.5 m (CD), with a porosity of around 40%, developing in a 2:3 slope. The head contains 550 kN Antifer cubes, regularly placed, developing in a 1:2 slope.

Cross-sections of the trunk and head, at prototype scale, are shown in Fig. 2, respectively in the top and bottom parts of it.

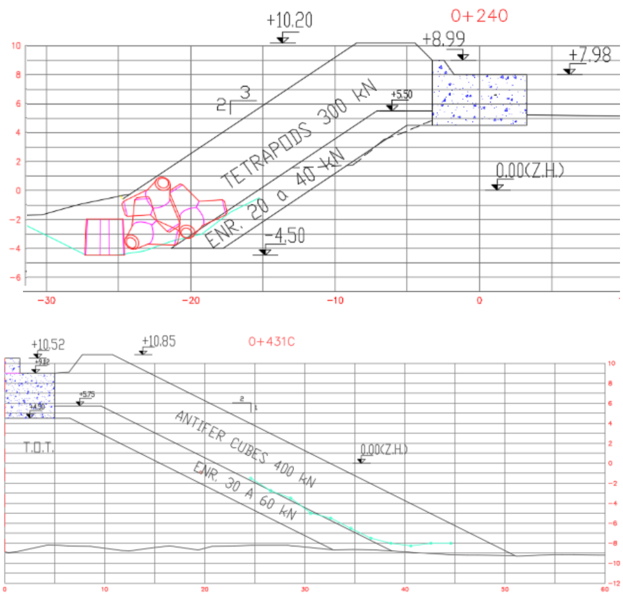

Figure 2. Cross-sections characteristics of breakwater’s trunk (top) and head (bottom).

3 TECHNIQUES USED

3.1 *Introduction*

For the characterization of undamaged model (before any tests) the following procedures were performed:

- Visual inspection, by accounting the number of displaced armor units;
- Three-dimensional survey of the breakwater model envelope using the Kinect position sensor and the Kinect Azure sensors.

Further, the other two techniques for surveying the model envelope, using photographs, were also used. For this, the camera of a smartphone (Apple iPhone 14 Pro), with 12-M-pixel resolution, was used. This capture allowed obtaining oblique photos around the physical model for different angles and positions.

For the 3D reconstruction from these photographs, two software packages were used: the commercial software Metashape (Agisoft, 2021) and the iOS mobile phone application 3dScanner (Laan Labs, 2021). Corresponding techniques used were close-range photogrammetry and 3D scanning, both used to generate point clouds.

The four techniques (“Kinect”, “Azure”, “Photogrammetry” and “LiDAR”) are described below with more detail. For all of them, the tank was emptied during the 3D scanning and photo acquisition periods.

3.2 *Kinect V2*

This technique uses Microsoft Kinect 2.0 depth, infrared (IR) and color (RGB) sensors and Microsoft Kinect Fusion SDK software. Kinect 2.0 sensors, developed for the Microsoft Xbox game console, are managed to survey the 3D model at a constant distance of 2.0 m. Post-processing is conducted using the Cloud Compare software.

The Kinect motion sensor (model 2.0) allows distance/depth determination through an infrared projector and a monochrome CMOS (complementary metal-oxide semiconductor) sensor, which work complementarily to "see" the scene in 3-D, regardless of the amount of light in the room. The device also contains an RGB camera, which acquires the three components of color (red, green and blue). The Kinect sensor uses 'Time of Flight' technology to estimate the position of a point relative to the sensor, by measuring the time it takes for an infrared beam to travel the distance between the sensor and the object and back, considering the speed of light.

For the acquisition of the point clouds, the free-to-use software Kinect Fusion (Izadi *et al.*, 2011), belonging to the software package built with Microsoft SDK, was used.

Fig. 3 shows the equipment used to perform the three-dimensional survey of the model and the Kinect Fusion interface. The Kinect operated, mounted on a tripod, and the acquisition distance was about 2 m above the model, having been connected to a computer during the entire data acquisition phase.

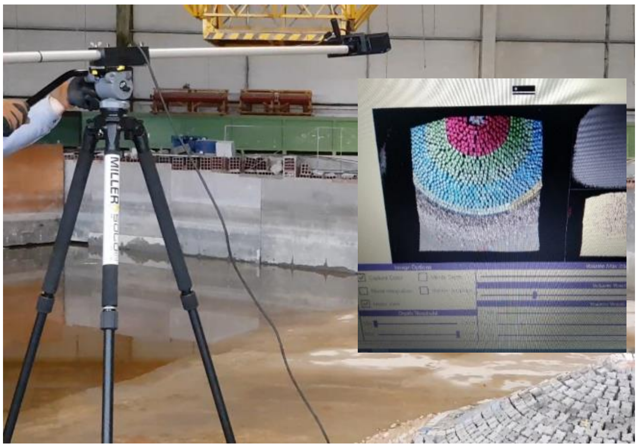

Figure 3. Kinect sensor and Kinect Fusion software interface.

Considering the large size of the model and to obtain the best compromise between the distance from the sensor to the model and the quality of the survey, as well as the optimization of the processing time of the point clouds, the scans were performed individually, section by section, keeping the parameters of the sensor used in the survey constant in all sections. Parameters used in the survey were: Voxel volume resolution in the three directions: 512 for the 3 axes; Voxel/m: 256; acquisition interval: between 0.5 m and 8 m.

Note that the voxel is a 3D unit of the image, just as for digital photographs, a pixel is a 2D unit of the image. i.e., it is a volume element that represents a specific grid value in 3D space. The obtained point clouds were subsequently merged, using the open-source free-to-use software CloudCompare (Girardeau-Montaut, 2006).

3.3 *Azure Kinect*

This uses Microsoft Azure Kinect depth, IR and RGB sensors and experimental software from GitHub platform. The Microsoft Azure Kinect is an upgraded version of the previous Kinect 2.0, as it also incorporates depth, IR and RGB sensors but of a more refined, more accurate kind.

Azure Kinect contains a depth sensor, spatial microphone array with a video camera, and orientation sensor as an all in-one small device with multiple modes, options, and software, Fig. 4.

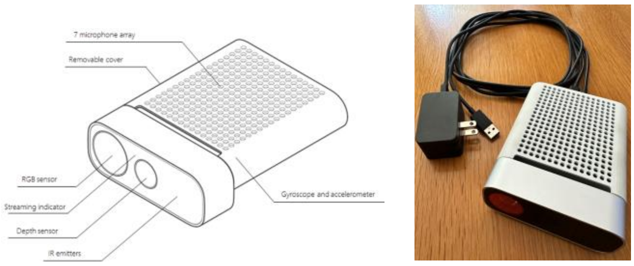

Figure 4. Azure Kinect sensor (Microsoft®).

Using the Azure Kinect SDK development kit (Microsoft, 2022), the survey with this low-cost equipment involved swift scanning of the model as the user moves across the designated area. Post-processing was done by employing a newly developed set of scripts being developed on the GitHub platform (Miranda *et al.*, 2022).

Below are some details of the implementation of this technique, namely: viewing the scene, recording the stream to a file, playing back the mkv (video) file, retrieving the point clouds from the mkv file, and finally loading and concatenating point clouds of all frames:

Azure Kinect Viewer is used to visualize the sensor stream (Depth camera, Color camera Infrared camera, IMU and Microphones), Fig. 5.

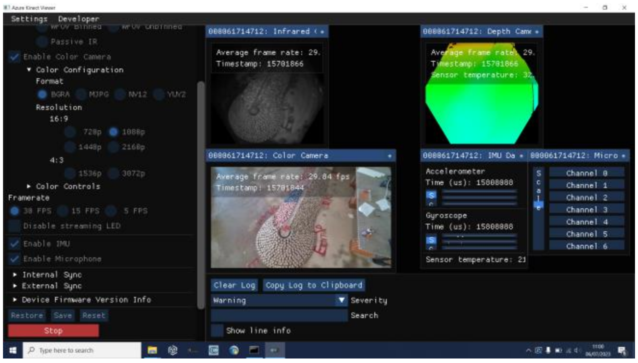

Figure 5. Azure Kinect Viewer interface when viewing the model.

This interface unfortunately does not enable recording of output stream into a file. That must be done separately, which is a problem when one must move the Azure along the model. Therefore, the recording was done by firstly opening a command prompt, providing the path to the Azure Kinect recorder, usually located in the installed tools directory as k4arecorder.exe and then recording it to an output.mkv file, Fig. 6.

Figure 6. Azure Kinect acquiring and recording 3D model's data.

Azure Kinect Viewer was also employed to play back the obtained recording (mkv file), by running k4aviewer.exe, unfolding the Open Recording tab and opening it, Fig. 7.

Figure 7. Playing back the Azure Kinect record (2D and 3D).

Two main packages were considered to obtain the point clouds, one Python coded (AK_FRAEX Azure Kinect Frame Extractor) and a C++ coded (KinectCloud). We used the latter by running "kinectcloud.exe" in windows terminal (or in the Microsoft Visual Studio Enterprise 2022 (64-bit) environment). As a result, one obtained point cloud files e_1.pts, e_2.pts…, etc, depending on the selected number of frames. For instance, kinectcloud.exe -e ericeira-All_10s.mkv created 51-point cloud files (e 1.pts.. e 51.pts) for a 10 sec acquisition with 5 fps, Fig. 8.

Loading and concatenating point clouds made use of CloudCompare software.

Figure 8. Point cloud obtained with Azure Kinect mkv.

Fig. 9 and Fig. 10 illustrate this process for the file ericeira-All_10s.mkv. Note that this file was obtained using the Azure Kinect about 2 meters from the head of the breakwater and over 3 meters from the beginning of the trunk, so one expected less details on the more distant elements.

Fig. 9 shows importing and creation of cloud points for all frames (at 5 fps) for 10 seconds (51 in total) of ericeira-Head_Ext_10s.mkv file using CloudCompare software.

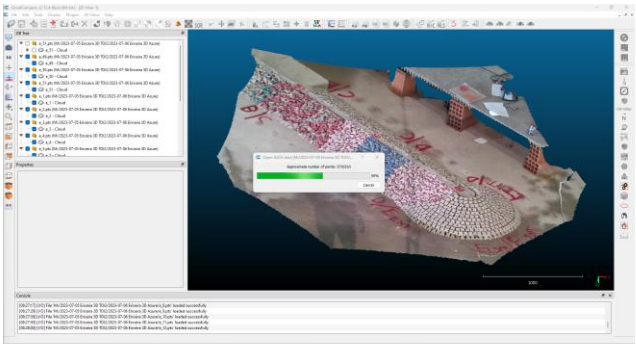

Figure 9. Point cloud import and creation for all frames (5 fps) for 10 seconds (52 in total) of ericeira-Head_Ext_10s.mkv file using *CloudCompare* software.

Fig. 10 shows the merging of all point clouds (each obtained for each frame). This was accomplished by firstly selecting all the clouds and the using command “Merge multiple clouds”.

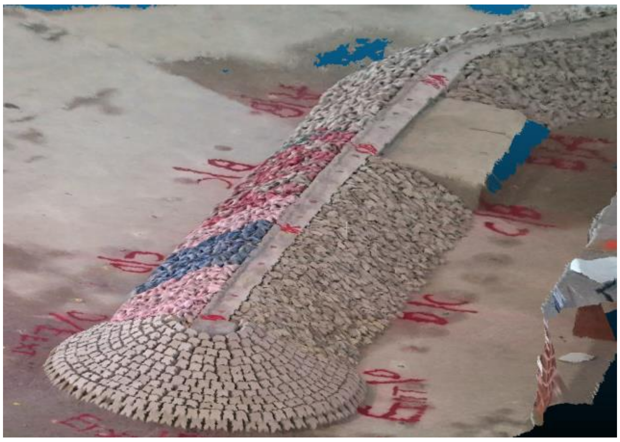

Figure 10. Point cloud for all frames summed up during 10 sec (at 5 fps).

The above process was done for the following clouds:

- ericeira-All_10s.mkv
- ericeira-Head_Ext_10s.mkv
- ericeira-Head_Int_10s.mkv
- ericeira-Trunk_Ext_10s.mkv
- ericeira-Trunk_Int_1_10s.mkv
- ericeira-Trunk_Int_2_10s.mkv

Corresponding summed clouds in CloudCompare format have the same name with .BIN extension. We found, however, that this concatenation is not necessary, as is time consuming and does not add much information to the obtained point cloud. Therefore, we used point clouds for the selected static locations, considering just one frame, corresponding to the frame before the last one of each acquisition, i.e., frame 50.

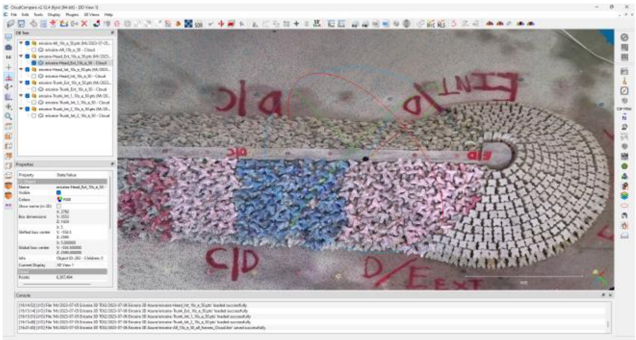

Figure 11. Point cloud creation for frame 50 of ericeira-Head_Ext_10s.mkv file using *CloudCompare* software.

3.4 *Photogrammetry*

This method uses a photo camera sensor (RGB sensor) and photogrammetric software. The iPhone 14 Pro smartphone incorporates a rather good RGB sensor and therefore it is used here to capture oblique photos from various angles and positions with significant overlap (+80%) around the physical model. The user moves across the model's area in both plan and altitude. The photogrammetric techniques were applied using the commercial (paid) package Agisoft® Metashape software. With this software, classical photogrammetry tools were applied to a set of images with large overlap and obtained from a photographic device that moves over the area covered by the model, both in plan and altimetry, which allowed obtaining orthorectified images, orthophoto maps, point clouds and digital terrain models (DTM).

Fig. 12 illustrates the use of this software, which has a very user-friendly interface and allows the necessary tasks to be carried out fluidly and efficiently.

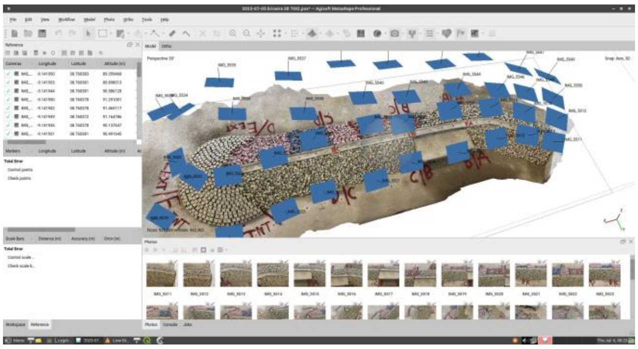

Figure 12. Metashape interface – Photo distribution along the model.

3.5 *LiDAR*

This method uses iPhone 14 Pro’ sensors (RGB, ToF and low-cost LiDAR) and the iOS app 3dScanner. This technique uses, through the iOS 3dScanner app, photogrammetric methods on the acquisition, with 3D scanning performed with LiDAR (Light Detection And Ranging) sensor, which is embedded on this simple non-professional smartphone, Fig. 13.

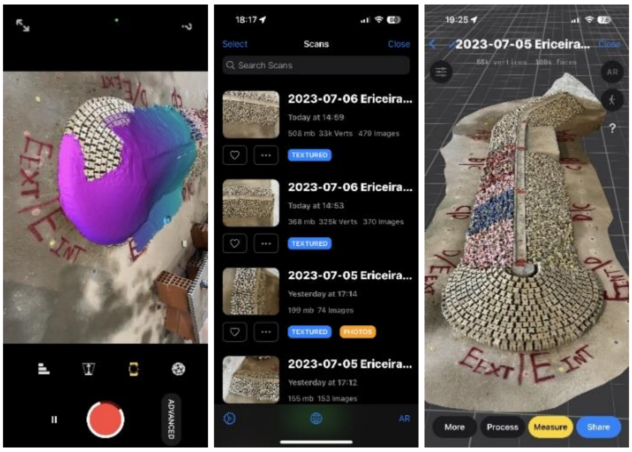

Figure 13. Views of the iOS 3dScanner app interface.

With this technique, the images of the model are obtained by measuring the speed of the light reflected by the elements of the model and consequently obtaining the corresponding distances and other valuable information from the same model. The determination of distances to objects is carried out using a pulsed laser that measures the time difference between the emission of the laser pulse and the detection of the reflected signal, in a similar way to radar technology, which uses radio waves.
Since LiDAR technology, in general, is extremely expensive, we thought it would be interesting to use this low-cost LiDAR version incorporated into a simple mobile device to find out about its usefulness in the context of experimentation with physical models. This technique allowed capturing data and create a 3D model while moving the phone across the designated area covered by the model. The process was eased by using 3dScanner, that also handled processing and exporting functions, although the last were limited since a free version of the app was used.

4 COMPARING THE TECHNIQUES

To allow comparison of the described four techniques, a topographic survey of some points of the model was conducted to obtain its coordinates to be used as ground control points (GCP), see Fig. 14.

Figure 14. Control points used for georeferencing the point clouds (in blue) and image capture around the model for Photogrammetry and LiDAR techniques.

These control points were subsequently used to georeference point clouds resulting from each survey technique. The control points (encircled markers in Fig. 14) were located on the model's crown and on the tank floor in the area adjacent to the toe of the slope of the entire model. Their coordinates (x,y,z) were obtained by surveying it with a total station "Leica TCR307".
The point clouds alignment using the GPC was performed using the Iterative Closest Point, ICP algorithm (Chen and Medioni, 1991) available in the CloudCompare software.
For both the Photogrammetry and LiDAR techniques, photographs were captured using the smartphone camera. For the first technique, one took photographs manually trying to obtain oblique images covering the whole model with overlapping of at least 80%, which resulted in 65 photographs of 12 Mpixel.
For the second technique one performed a 3D scanning, which in the end also produced oblique photographs, but of lower resolution, although in an automatic way. According to the image capture algorithm of the application used in this technique (3dScanner App), 429 photographs of ~3 Mpixel were obtained.
Tab. 1 shows the characteristics of the equipment and software used and the products generated.

Table 1. Characteristics of equipment and software used.

	Kinect	Azure	Photogrammetry	LiDAR
Type	3D scan	3D scan	Photo	3D Scan
Direction	Nadiral	Oblique	Oblique	Oblique
Resolution	-	-	4032 × 3024	1920 × 1440 px2
Number of acquisitions	7 static scans	1 dynamic scan	65 photos	1 scan (429 photos)
Average distance to model	2.0 m	Variable 1-2.0 m	~1.5 m	~1.0 m
Software used for processing	Kinect Fusion	Kinect Cloud	Metashape	3dScanner
Obtained products	Point clouds + DTM + profiles, etc.			

The final product of the four techniques is point clouds, which allow obtaining three-dimensional surface models and, from these, the extraction of profiles and the calculation of eroded volumes.
The point clouds obtained with Kinect, Azure and Photogrammetry were referenced from the control points, using the Registration tool of CloudCompare software. Root mean square error (RMSE) found in the alignment of Kinect and Photogrammetry point clouds were 0.00971 and 0.01006, respectively.
RMSE translates the average differences found between the control points used in the cloud alignment and the same points after the alignment. Therefore, the error is similar in both techniques, of the order of 0.01 m, and therefore very small.
In the case of the LiDAR cloud, obtained with 3dScanner, due to the insufficient resolution of the cloud (i.e., due to the low density of points of exported cloud, consequence of using the free version of 3dScanner), it was not possible to distinguish the control points located at the base of the model, being only possible to distinguish some points of the crest. Therefore, the alignment was also performed with the Registration tool but, in that case, homologous points from the cloud obtained with the Metashape software were used. Markers at the slope's base and crest were used as homologous points.

5 RESULTS

To assess the quality of the surveys obtained with the four techniques, RMSE (root mean square error) was determined when aligning the clouds with the GCP (ground control points).
Unfortunately, LiDAR cloud could not be aligned, as GCP were not visible and therefore one could not calculate RMSE, which means that the low-cost LiDAR technique (smartphone with LiDAR sensor + 3dScanner application) does not produce acceptable and sufficiently accurate results for the objective of the present work. In that way, this technique was disregarded and omitted here. However, it is important to notice that this methodology can be used very usefully as a first indicator of the evolution of damage to the model during a series of tests. In fact, it is very quick to use, quite easy to operate and inexpensive.
On the other hand, the other three techniques (Kinect, Azure and Photogrammetry) have been shown to produce particularly good and comparable results. Tab. 2 shows the RMSE values obtained for three different clouds, aligned with the control points, carried out with a total station.

Table 2. Quality assessment of the surveys for three selected techniques (LiDAR was rejected).

	Kinect	Azure	Photogrammetry
RMSE	0.0048	0.0046	0.0048
Nº of points in cloud	3 000 000	2 465 586	5 884 065
Nº of GCP	18	13	19

For the comparative approach for each point cloud obtained with those selected techniques, a surface density analysis was made, by computing its geometric features with the CloudCompare software.
Fig. 15, Fig. 16 and Fig. 17 show the point clouds as well as their surface density maps obtained with the three techniques considered.

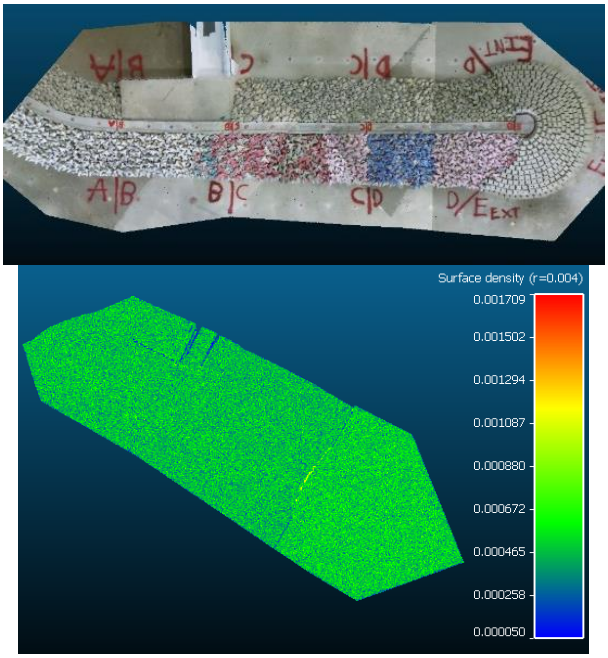

Figure 15. Kinect V2 point cloud and surface density map.

The point cloud obtained with the Kinect V2, Fig.15, is homogenous, with good quality, despite showing some discontinuity due to cloud merging.

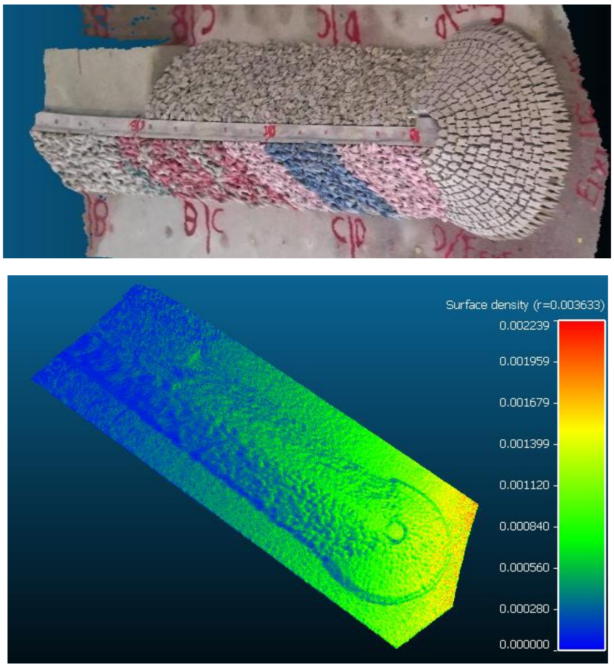

Figure 16. Azure point cloud and surface density map.

The point cloud obtained with the Azure Kinect, Fig. 16, is not a uniform point cloud but shows a good quality for a cloud obtained from a single frame.

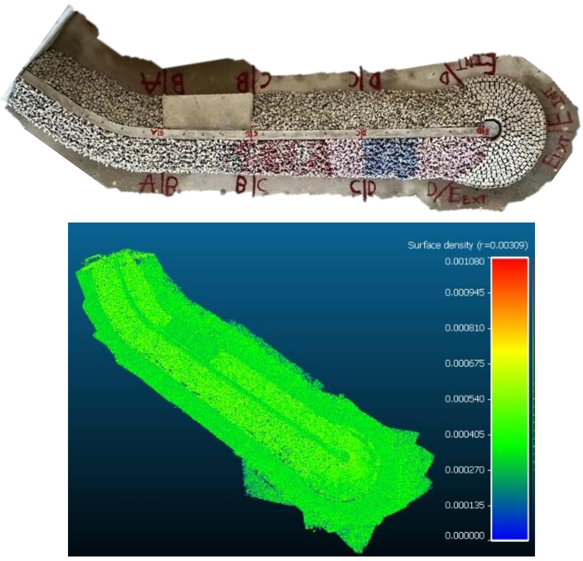

Figure 17. Photogrammetry point cloud and surface density map.

Point cloud obtained with the photogrammetry, Fig. 17, exhibits excellent quality, with good homogeneity.

Since this point cloud showed the best quality of all, it was considered as a reference to compute differences between the remaining clouds. Therefore, Fig. 18 and Fig. 19 show the difference maps of the trunk and head sections between the point cloud obtained by the Photogrammetry technique and the Azure Kinect, and between the Photogrammetry technique and Kinect V2 surveys, respectively.

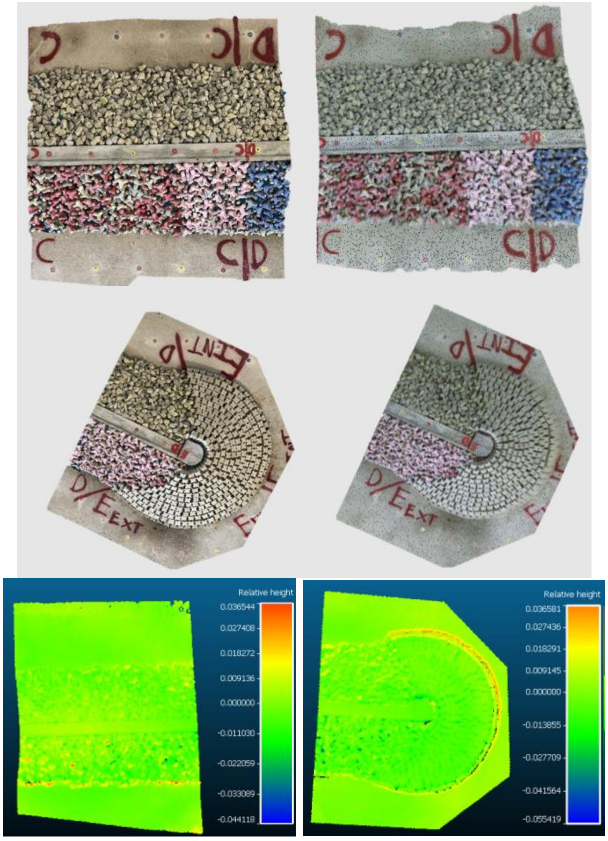

Figure 18. Difference maps between Photogrammetry (left) and Kinect V2 (right) point clouds.

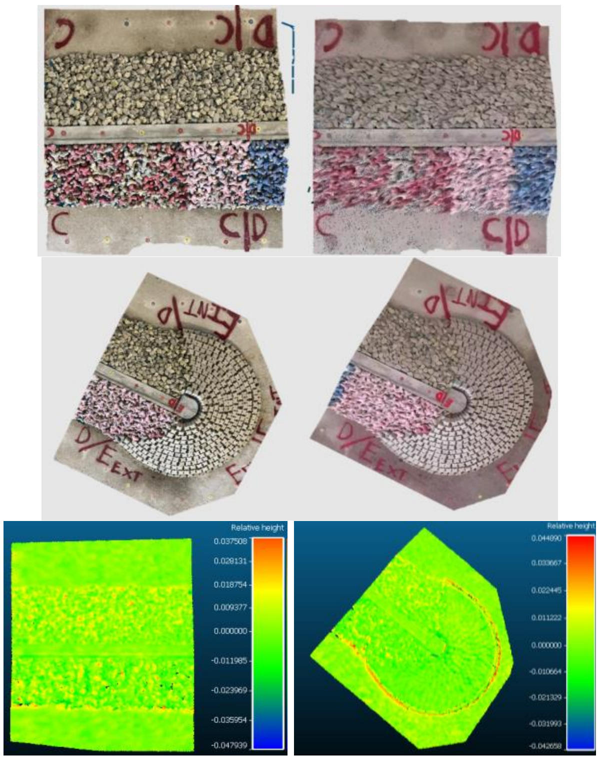

Figure 19. Difference maps between Photogrammetry (left) and Azure Kinect (right) point clouds.

The performance of Kinect v2 and Azure Kinect techniques were quite similar, when compared to the photogrammetric technique. The altimetric differences were millimetric, except at the toe of the structure, where the differences found to be around 0.044 m in the trunk and 0.055 m in the head zone. These differences are justified by the decreasing of the accuracy of the point cloud alignment with the distance to the sensor. Furthermore, the prismatic shape of the Antifer cubes at the toe of the head zone contributes to the error due to the occlusion phenomenon.

6 CONCLUSIONS

Photogrammetry, Kinect and Azure techniques were found to be quite suitable to evaluate evolution of damages based on corresponding point clouds, using RMSE. On the other hand, cost-effective LiDAR approach used here (a smartphone and 3Dscanner app) fails to yield results of acceptable and requisite accuracy for the current research objectives.

The Photogrammetry technique (photogrammetry with RGB images) was undoubtedly the one that led to a cloud with the highest number of points, although it required a lot of post-processing time, given that it is a photogrammetric method.

In the case of the Kinect and Azure techniques (with depth sensors), point clouds with the same order of magnitude in terms of number of points were obtained. The quality of the alignment with Azure was slightly better, given that a lower RMS was obtained, using fewer control points. However, the quality of the RGB obtained with Azure was much lower than any of the other three techniques, which made it difficult to select control points.

The Kinect V2 and Azure Kinect techniques thus produced high-quality results, comparable to those of the Photogrammetry technique. However, the latter has the disadvantage of using a commercial product (Agisoft Metashape), whose license requires a higher initial investment. Post-processing the point clouds obtained from Azure (with motion capture) requires a higher learning curve for the processing software, as it is fairly recent. As for the post-processing time of the clouds obtained with Kinect, this is done in real time using the Kinect Fusion software used in the acquisition.

However, all the techniques presented here (even LiDAR) have shown room for improvement within this work's scope, carrying out surveys where more time is spent in each zone of the model, in order to increase the quality of the point cloud.

ACKNOWLEDGEMENTS

This work was supported by the European Union-funded projects C2IMPRESS (Horizon Europe, GA no. 101074004) and LIFE Garachico (LIFE20 CCA / ES / 001641).

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