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CONCRETE ARMOUR UNIT BREAKWATER PHYSICAL MODEL MONITORING WITH 3D MODELING TOOLS

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ABSTRACT

SEABIM® is a patented scan to BIM process that can generate a reliable and complete 3D model of a rubble-mound breakwater precast protective layer (Xbloc®, Accropode™, Core-loc™ etc.). Using computer vision techniques, the known 3D shape of the Concrete Armour Units (CAU) is detected in a high-resolution point cloud, which allows to obtain the position and orientation of each unit relative to the cloud. By superimposing 3D models produced from different scans at different dates, the movement of each block can then be quantified and represented as a vector.

For natural riprap armours, a point cloud segmentation algorithm is applied. Each rock is identified, and then geometric characteristics of the armour can be computed (apparent rock diameters, placement density), and the movement between each scan can be monitored.

This tool has been applied to numerous real-scale projects since 2019, both in the monitoring of newly built infrastructures and in the asset management phase (Aberdeen South Harbour, Calais port 2015, Nouvelle Route du Littoral etc...). Breakwater physical models in laboratories, in wave flumes or basins, also require monitoring of the movement of reduced-scale blocks between each wave series. With SEABIM® this movement can be computed with accuracy for each CAU, allowing for a consistent evaluation of the armour layer response to wave loads.

The automatic block detection process can be launched on the point cloud from a survey of the initial physical model, obtained either by photogrammetry or LiDAR. Then a new survey is done after each wave series in order to create a sequence of 3D models. Those models can be compared by computing the displacement vectors of the centers of gravity of the units. The vectors can be visualized using color graded arrows within the 3D model. All the information can then be exported to a spreadsheet for further analysis. Using this technique, settlement, rocking and sliding effects can be identified.

In this paper we will discuss in detail the adaptation of the survey techniques from real scale to laboratory projects (difference in scanning technique, scale effect on point cloud density etc.). Then we will explain the 3D modeling process and the applications of the 3D models for engineering analysis purposes.

KEYWORDS: breakwater, 3D model, point cloud, monitoring

1 INTRODUCTION

1.1 Origin of SEABIM® on real scale projects

Single-layer concrete armour breakwaters (see Figure 1) need a very rigorous placement, according to the rules of the designer, to ensure a good structural and hydraulic stability. The goal is to allow the construction to resist extreme design waves with minimal damage during its whole lifetime. Even though this kind of structure can resist higher strains than rock breakwaters, concrete armour units cannot absorb the same degree of armour movement as can be accepted by rock armour. Thus, a regular inspection is necessary to check for damage and anomalies in the structure, as those can evolve quickly and lead to serious issues. That is why it is necessary to be reactive and exhaustive in the analysis of the structure and the planning of maintenance operations.

Figure 1. ACCROPODE™ I breakwater of Sainte-Rose harbour, La Réunion.

To make seawall inspections both faster and more reliable, the patented process SEABIM® has been developed by ID OCEAN in 2019. It allows for the automatic generation of a complete 3D model of the structure from a point cloud, obtained by bathymetry, photogrammetry, or LiDAR (see Figure 2).

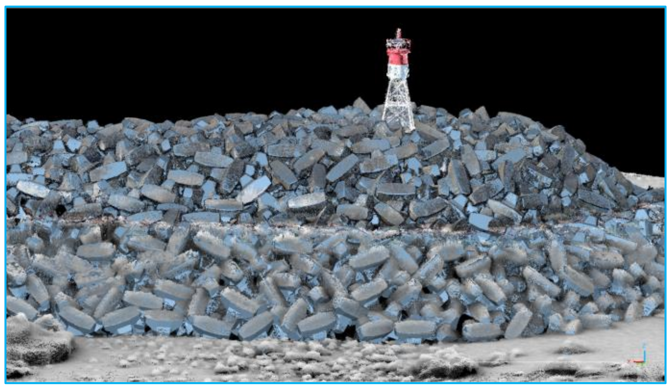

Figure 2. Survey point cloud and 3D model of Sainte-Rose breakwater roundhead.

A set of tools is implemented to check the respect of the design placement rules and to automatically detect recurrent singularities according to the designer's specifications, like:

- Out of profile units (see Figure 3a);
- Number of contact points between neighbouring blocks (see Figure 3b);
- Column placement (see Figure 3c);
- Nose perpendicular to the slope (see Figure 3d);
- Varied orientation between neighbours (see Figure 3e);
- Φ formula (US Army Corps of Engineers, 2004) density (see Figure 3f);
- Broken blocks (see Figure 3g);
- Holes with a risk of sublayer stone extraction (see Figure 3h).

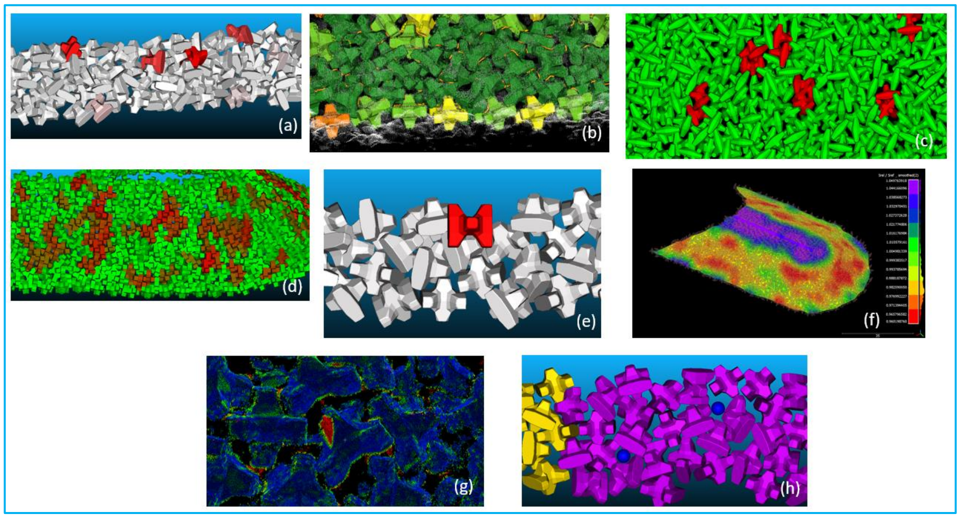

Figure 3. Automatic quality control filters on the breakwater.

This makes the analysis easier and more complete for the experts. This new method has already been adopted for the construction and diagnosis of several large-scale projects, with diverse types of armour units, such as ACCROPODE™ I and II, CORE-LOC™, Xbloc®, Tetrapod and Antifer blocks. The main iconic application projects of this methodology are:

- New Coastal Road (NRL), 21 000 ACCROPODE™ II and Xbloc®, Reunion (see Figure 4);
- Calais 2015 harbour extension, 16 000 Xbloc®, France;
- Khalifa fort, 60 000 ACCROPODE™ I, UAE;
- Aberdeen South Harbour, 3 000 ACCROPODE™ II, UK.

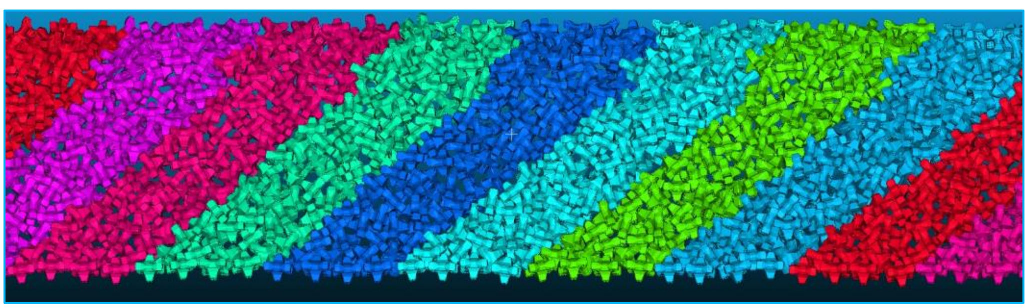

Figure 4. Panels color-coded 3D model of the NRL breakwater, La Réunion.

1.2 Breakwater armor layer physical model monitoring requirements

During the conception phase, small-scale physical models of the breakwater armour layer are built in laboratories, either 2D models in wave flumes or 3D models in basin. Various series of waves are applied to analyze how the breakwater withstands. These reduced models, which are as faithful as possible to the reality, allow to validate the general design parameters of the breakwater such as:

- the type and size of CAU;
- the slope angle;
- the toe stability and erosion;
- the wave overtopping parameters.

These models do not require to monitor the interlocking of the blocks like with real scale projects, because the units are placed by hand by an experienced technician (see Figure 5).

Figure 5. Construction of a breakwater 2D physical model in a wave flume, photo credit ARTELIA.

The main armour layer parameter which must be monitored after each wave series is the accurate displacement of the blocks. Until now, this movement analysis was done either qualitatively by comparing pictures of the breakwater before and after each wave series or quantitatively by overlapping the point clouds generated by LiDAR or photogrammetry, after partially emptying the tank to get the model dry (see Figure 6).

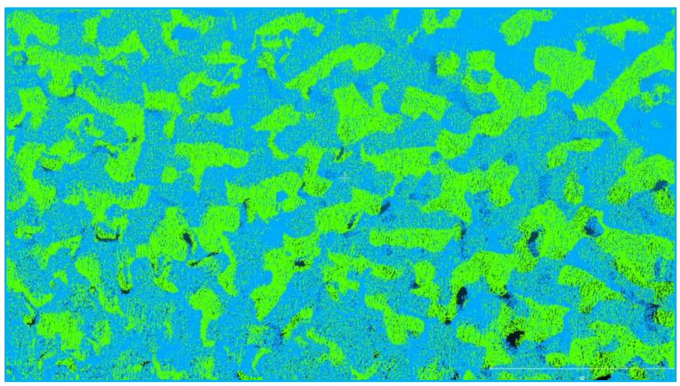

Figure 6. Point cloud comparison for a breakwater 2D physical model in a wave flume.

Nevertheless, neither methodology allows to automatically compute the accurate displacement, in direction and amplitude, of all the blocks in the model. Indeed, the photo comparison by eye only gives an estimation of the overall movement trend to identify areas with some settlement, sliding or rocking but the movement of each block cannot be computed for quantitative analysis. Likewise, the point cloud comparison is difficult to analyse, time consuming and not very accurate because one cannot precisely estimate the position of a block center of gravity from the scan. Therefore, there is a gap to bridge to extract rapidly and accurately the movement of each block between wave series so that better engineering analysis can be carried out. This is the reason why we looked at how our SEABIM® real scale process could be adapted to such physical models to automatically generate the movement vector of each block.

2 GENERAL 3D MODELLING PROCESS FOR REAL SCALE PROJECTS

2.1 Collection of data onsite

The first step of the process consists in carrying out an onsite point cloud survey of the breakwater. ID OCEAN has specialized in such breakwater surveys by developing a portable sonar and LiDAR survey kit that can be mobilized on any project abroad in-flight luggage and installed easily on a vessel available locally.

For the above water part of the structure, a photogrammetric survey can be carried out at low tide from a drone or from the survey vessel. Visible targets are placed regularly along the breakwater crest, alternatively some remarkable elements of the breakwater can be identified. The coordinates of these Ground Control Points (GCP) are then measured precisely with a GNSS RTK receiver. Several overlapping pictures of the breakwater are then taken. Finally, the 3D point cloud of the breakwater is reconstructed in a dedicated photogrammetry software (such as Pix4D or Metashape), and the GCP visible in the pictures are used to geolocate the point cloud. Alternatively, a LIDAR survey can also be realized.
Regarding the underwater part, an acoustic multibeam survey of the breakwater is realized at high tide using a high-resolution sonar coupled with a motion sensor, a positioning system, and a sound velocity profiler. The point cloud is then processed

and cleaned using dedicated processing software. This methodology ensures there will be no missing block in the digital twin. Both point clouds are saved as a set of point coordinates in a XYZ or LAS file to be processed (see Figure 7).

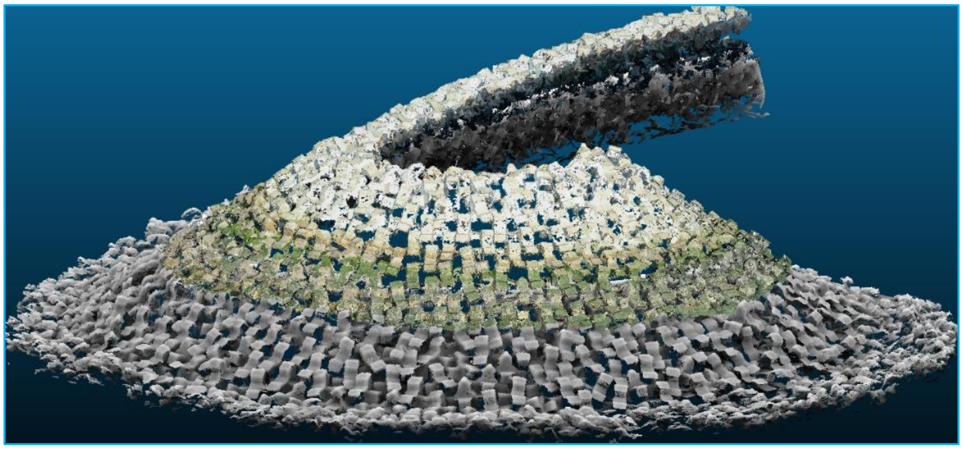

Figure 7. Overlapping multibeam survey (grey) and photogrammetry survey (natural colour) on a Xbloc® breakwater.

2.2 Automatic 3D modelling

Our in-house patented shape detection process based on machine learning techniques can automatically detect the position of a regular 3D object in a point cloud. Because the CAU have a known 3D shape that can be extracted from a CAD file, the algorithm will find all the instances of that shape in the processed point cloud (See Figure 8). Finally, the positions can be validated using geometric criteria combined with manual verification, and if needed it is possible to correct a position or add missing blocks. All of these functions are integrated in a dedicated on-premise software called SEABIM editor.

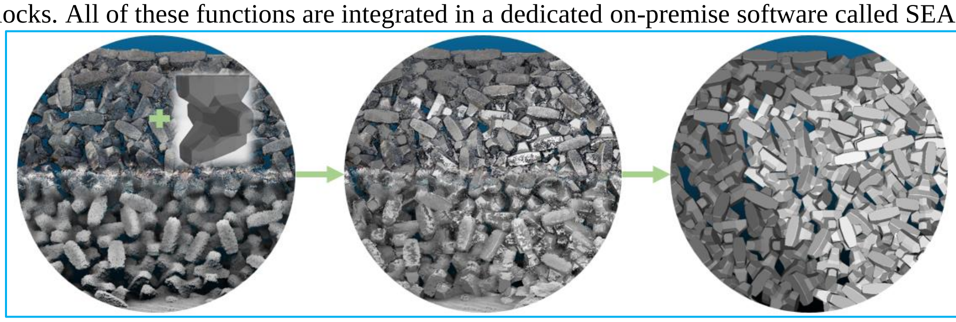

Figure 8. Process from point cloud to 3D model on ACCROPODE™ I.

The algorithm is fast and can detect more than 100 blocks per minute. This leads to a very reasonable computation time of a few hours for large scale projects with up to 30 000 blocks. The algorithm can either be ran on one of our dedicated computation servers via an internet connection or on a local computer if its specifications are sufficient. The reconstruction rate (the percentage of actual blocks that are found by the algorithm) is very dependent on the quality of the data but is usually above 90% and can reach rates as high as 99% on a dataset of sufficient quality.

Once the block positions have been found, a 3D model based on triangular meshes can be visualised in the open-source 3D viewer CloudCompare in which the SEABIM Editor tools are integrated (see Figure 9).

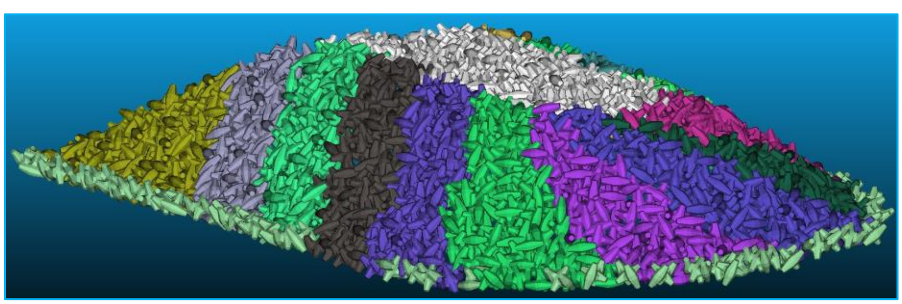

Figure 9. 3D model of a CORE-LOC™ breakwater in CloudCompare.

2.3 Model accuracy validation

The accuracy of the computed block positions and orientations is always validated by checking the consistency with the input point cloud.

Indeed, the points from the survey associated with a block from the armour should all lie on the surface of the 3D model, with a tolerance corresponding to the uncertainty of the survey. That principle can be used to control the positioning accuracy of all the reconstructed blocks.

Specifically, one can compute the point to mesh distance from the cloud to the blocks of the 3D model, and check that the distances from most points to the surface of the blocks are small enough to be consistent with the survey uncertainty. This computation is done automatically for each block and is used for systematic inspection of the quality of the model as it allows for a reliable detection of inconsistencies (see Figure 10).

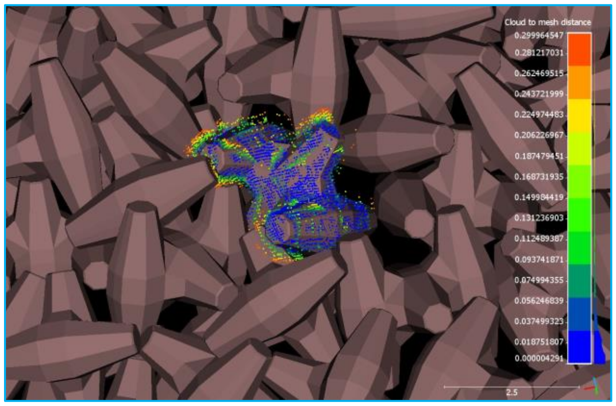

Figure 10. Consistency check between a block and the scan. Blue points correspond to a distance smaller than 2 cm.

2.4 3D model advantages

The blocks are also saved in a database where key information associated to each block is stored in the form of metadata, such as block type, position, volume, construction number, name, placement filters, displacement.

The main advantages of a 3D model are that:

- the hidden faces of the blocks missing in the point cloud appear in the 3D model, which makes it possible to check the interlocking of the blocks;
- each CAU in the armour layer is now individualized and represented by a light 3D mesh file;
- the accurate Center of Gravity (CoG) XYZ position and block Roll/Pitch/Yaw orientation can be exported in the desired format.

Once the 3D model of an armour layer has been generated using the automatic detection tool, if there is movement in the structure and a new survey is carried out, the blocks positions can be automatically updated in the software to be consistent with the new point cloud. Then it is possible to evaluate the block movements between the two surveys by calculating the displacement of each block's CoG . Each block is then color-coded depending on its displacement and a vector is automatically generated to show the direction and amplitude of the movement. The rotation of each block can also be evaluated the same way. This tool is very important for the asset management of such structures (see Figure 11).

Figure 11. Xbloc® movements between two surveys on Calais 2015 breakwater, France. Displacement scale in meters.

3 APPLICATION TO PHYSICAL MODELS

3.1 The scan challenges

On a real scale project, the CAU have a height between 1.5m and 4m. For the detection algorithm to work properly, the general rule of thumb in terms of point cloud density is that the distance between 2 points must be lower than the block's height divided by 100. For instance, with a 3m height block the distance between points must be lower than 3cm. This is easily achievable with drone-based photogrammetry or LiDAR, and it can also be done with a high-resolution 1°x1° beamwidth sonar underwater if the survey vessel sails close enough to the breakwater (approximately 10m distance).

On physical models the blocks can be as small as 5cm in height (see Figure 12). The challenge is thus to reduce the point cloud density to keep on respecting the previous rule of thumb because the distance between two points must ideally be lower than 5mm.

Figure 12. XblocPlus® placement in a wave flume, photo credit DMC.

Furthermore, it is no longer possible to scan the underwater part of the breakwater with an acoustic sonar in laboratory conditions because the basin depth is not sufficient to deploy such equipment. The model must thus be put in dry conditions before the survey. This can be done by emptying the whole water tank or by putting a watertight cofferdam to empty only the section of the tank where the model is. Once there is no longer water on the structure, there are 2 options to scan it with enough density.

The first option is to have a photogrammetry setup with pictures that can be taken either by an operator or by a drone depending on the size and access conditions of the model. Checked patterns can be installed on the edges of the model to be used as Ground Control points and scaling items, so that the successive point clouds are consistent with each other and are not distorted. The generated point cloud on 5cm high blocks can be dense enough if the pictures are taken close enough from the model with a high-resolution optical sensor. A recent test realized by Artelia laboratory in Grenoble, France, provided a point cloud with a distance between points of 2mm which is largely sufficient to identify the block shapes (see Figure 13).

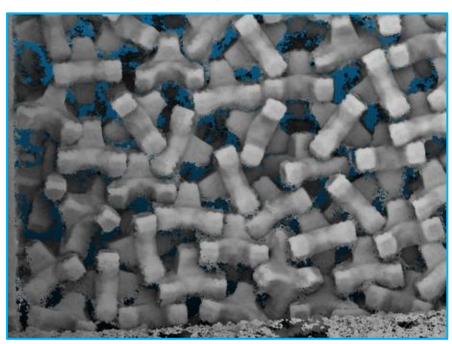

Figure 13. Photogrammetry point cloud with greyscale shading on an ACCROPODE™ II physical model.

The second option is to use a fixed laser scanner mounted on a tripod from different pre-defined station points along the model that will scan the surroundings at 360°. The advantage of this option is that albeit the operator must compile the scan from the different station points, it does not require any post-processing to obtain the point cloud like with photogrammetry. The drawback is that the point cloud density is reduced compared to photogrammetry: 5 to 10mm distance between points is achievable (see Figure 14). This density is acceptable for the 3D modelling of the units because our machine learning algorithm has been specifically trained for such situations.

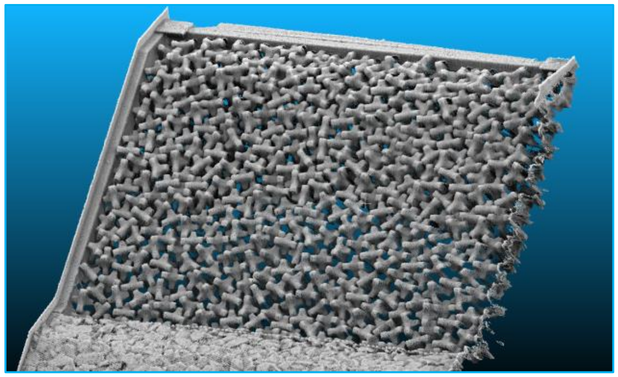

Figure 14. Laser scanner point cloud with greyscale on an ACCROPODE™ II physical model in wave flume.

Nevertheless, to overcome this issue one could also use a mobile LiDAR system to scan the breakwater as close as possible and use some reference points at the edges of the structure for the georeferencing.

3.2 The 3D modelling process

After the initial physical model block placement is realized, a first scan is carried out before the water tank is filled. The initial 3D model is generated from that scan with the software (see Figure 15).

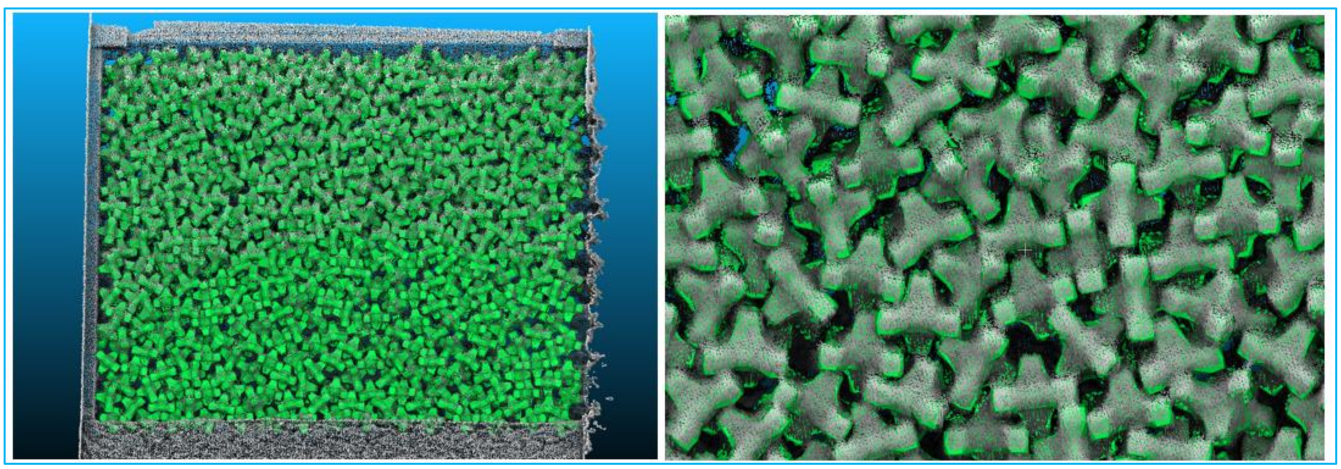

Figure 15. Initial 3D model of an ACCROPODE™ II breakwater in the wave flume.

Then after each wave series or at the end of the tests, the model is put to dry, and a new scan is carried out. The 3D model is then updated with this new point cloud in the software in a couple of minutes. Some manual adjustments might be necessary in some areas of the model, if there are blocks that have moved too much from their initial position and thus cannot be adjusted automatically by the program. This means that the block must be manually placed close to its new position by the operator, and then a local convergence algorithm is applied to align the unit into the point cloud accurately. After the model is successfully updated, the laboratory engineer ends up with 2 3D models that he can overlay in the 3D viewer to analyze the evolution of the breakwater against the wave series. This analysis is a lot easier with a 3D model than with a point cloud (see Figure 16).

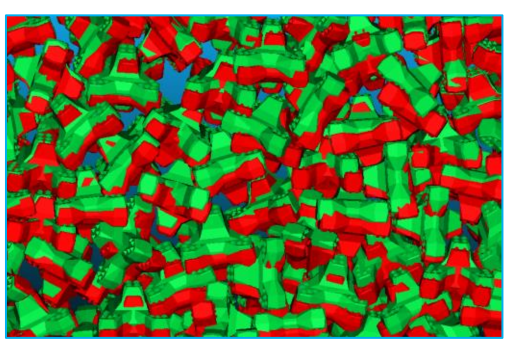

Figure 16. Overlay of the initial 3D model (green) and the updated 3D model (red).

To finish the process, the displacement of each unit is computed and displayed using vectors and a color scale. The color thresholds are customizable by the user because it highly depends on what must be highlighted (small settlement of all the units, bigger local sliding, or rocking).

Figure 17. Color-coded display of the block's movements with vectors.

Finally, all the displacements details for each block can be exported in a CSV file for a detailed engineering analysis. It is possible to decompose the movement vector in a local reference frame relative to the slope.

3.3 Stones monitoring

The same shape-matching tools cannot be applied for natural rock layers because the shape of the stones is not regular (see Figure 18). Nevertheless, we have developed a segmentation algorithm that enables to isolate each rock in the point cloud (see Figure 19). Each stone is a new entity in the 3D model with a randomly attributed color for an easier visualization.

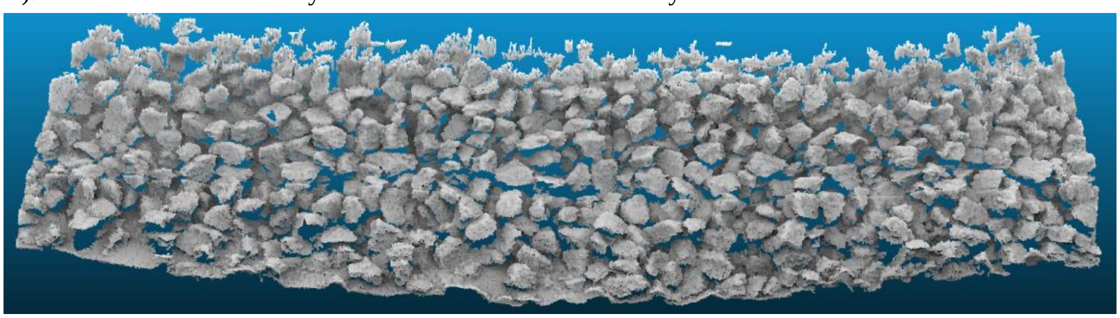

Figure 18. Original gray-scale rock layer point cloud.

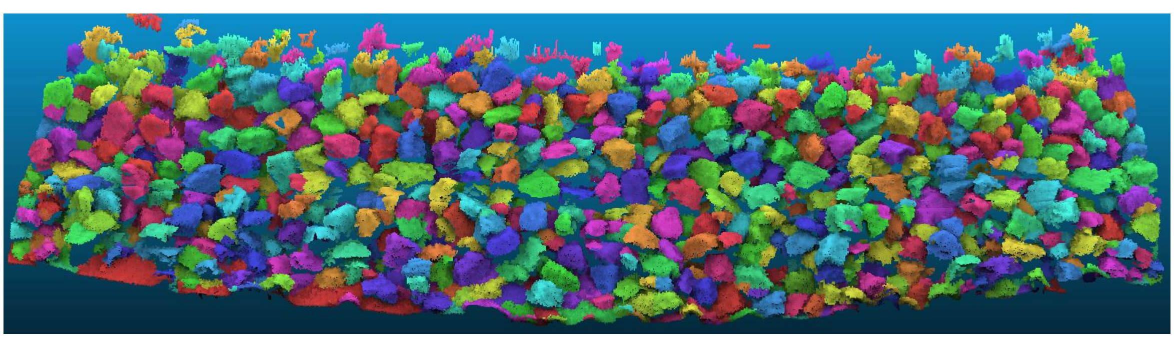

Figure 19. Processed point cloud where each rock is segmented.

From this segmented cloud, it is possible to calculate metrics obtained from the Rock Manual (CIRIA, 2007), like the stone density, the apparent diameter (see Figure 20) or even the displacement of a stone between 2 scans. The main limitation of this methodology is that the scan only provides information on the apparent surface of the rocks. The metrics calculations are thus prone to uncertainty because the shape of the invisible rock part cannot be predicted.

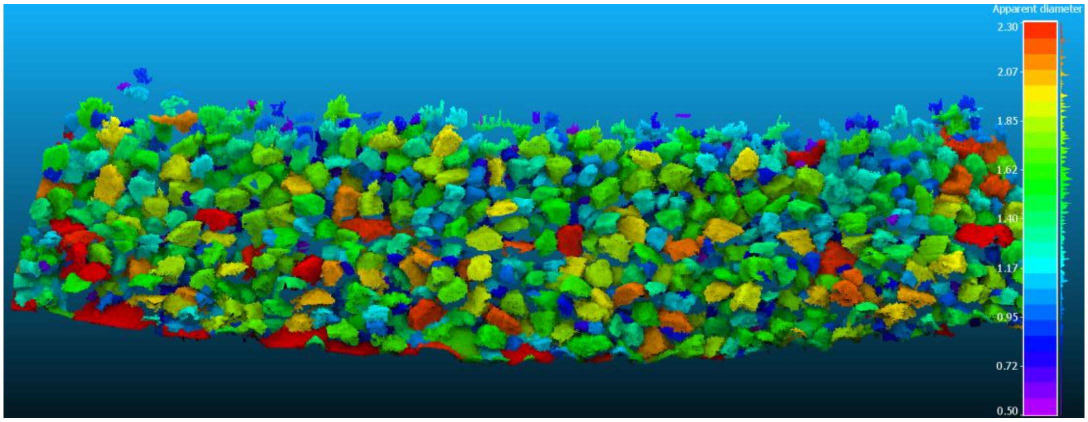

Figure 20. Point cloud in which each rock is color coded depending on its apparent diameter from purple to red.

Even though it has some limitations, this complementary tool can also be used on physical models to better evaluate the damage on a natural rock breakwater armor layer or on an anti-scouring stone mattress, for instance after a wave series.

4 CONCLUSIONS

Until now, doing a detailed quantitative displacement analysis of breakwater Concrete Armour Units in a physical model was a time-consuming and difficult process. The 3D modelling methodology integrated in the SEABIM Editor software makes this process easier and more accurate. Consequently, the engineering analysis based on physical models can be improved. Hence this new tool enables to have a better reliability of the real scale breakwaters by reinforcing the design process.

ACKNOWLEDGEMENT

We would like to acknowledge all our clients who trust in this innovative technology and push forward this disruptive methodology in the coastal inspection sector. A special thanks to the teams of ARTELIA and CLI for the assistance provided in developing this tool and the first trials on laboratory models carried out with them in 2023. ARTELIA laboratory in Grenoble, France, is currently the first and only laboratory in the world that has a SEABIM Editor licence to apply this tool on their physical model projects.

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