Rubble-mound breakwater armour units displacement analysis by means of digital images processing methods in scale models

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ABSTRACT: Rubble-mound structures are commonly used for coastal and port protection and needs a properly design as well as inspection and maintenance during its lifetime. The design of such breakwaters usually requires a physical scale model to be tested under different irregular incident wave and tide conditions in order to evaluate its hydraulic and structural behaviour, namely the stability of the proposed design. Armour units displacement and fall analysis in physical models are then a key point in the design verification and usually requires a trained technician. In this work, an algorithm made in Matlab® is presented, consisting in digital images processing and analysis which allows automatic and precise displacement detection as well as its location in time and space. For a selected displacement, it is also possible to characterize it.

Keywords: Rubble-mound breakwaters, image-processing, armour units displacement, Matlab®.

1. INTRODUCTION

In Portugal, rubble-mound breakwaters are a very common harbour protection structure. However, their design is not a simple matter. Usually, breakwaters design is done preliminarily by semi-empirical formulas, namely the Hudson formula (1):

$$W_r = \frac{\gamma_r H^3}{K_D (\Delta)^3 cotg\theta} \qquad (1)$$

where Wr is the design armour unit weight, γ_r is the armour units specific weight, H is the design wave height at the toe of the structure, θ is the armour layer angle with the horizontal, K_D the stability coefficient (which depends on parameters such as the armour unit type and material) and Δ is the relative armour unit mass density.

This formula gives the armour unit weight for each layer of the rubble-mound breakwater but doesn't include certain aspects as the wave steepness, the relative depth, the wave period and bottom slope angle, type of wave breaking or temporal storm duration, which are not considered in the formula (Taveira Pinto & Neves, 2003).

It is thus common to perform physical model tests to confirm hydraulic and structural behaviour of the proposed design. In particular, stability physical model tests permit the selection of the size, armour units density and its placement within the whole rubble-mound breakwater as well as evaluate damage progression of the structure for a set of different incident wave conditions and tidal conditions.

During each physical model test (incident wave condition and tidal level) and for each stretch of the rubble-mound breakwater, a technician usually identifies and quantifies by visual observation the displacements of the armour layer units (rocks or artificial blocks). Based on this quantification, displacements are subsequently classified within classes from 0 to 6 defined by: hardly any displacement (0), slight displacement (1), little displacement (2), moderate displacement (3), important gaps (4), serious damage (5) and destruction (6) (Pita, 1984). The analysis of those results obtained in all the test series allows the evaluation of the damage progression at each of the breakwater stretches as well as of the breakwater as a whole. This procedure is very dependent on the experience of the technician. Moreover, tests performed by different technicians will always have differences in damage evaluation, since each person has his / her own sensibility/criteria.

Image processing tools belong to the class of non-intrusive methods. Non-intrusive methods can be quite effective in extracting new information because they do not disturb the flow or the set-up conditions of the experiment. Leandro et al (2012) developed an image processing procedure (IPP) to extract information about air-concentration in a hydraulic jump, following the pioneer work of Mossa and Tolve (1988). Later it was extended and successfully applied to stepped spillways in Leandro et al (2014).

In this paper, we use image processing tools in order to ease and automate those tasks and quantify the unit displacements of rubble-mound breakwater armour. An algorithm made in Matlab® is presented, consisting in digital images processing and analysis which allows automatic and precise displacement detection as well as its location in time and space. For a selected displacement, it is also possible to do its characterization.

In the following sections, a brief description of physical model tests performed is presented in section 2. Then, section 3 presents the technique based upon Matlab® scripts. Section 4 presents and discusses the results from the image analysis and section 5 concludes the work and presents possible upcoming works.

2. EXPERIMENTAL FACILITIES, EQUIPMENT AND SOFTWARE

The physical model tests were carried out in the Maritime Hydraulics Testing Hall of the Hydraulics and Environment Department (DHA) of the National Laboratory for Civil Engineering (LNEC), in one of LNEC´s irregular wave tanks (TOI1). LNEC owns a testing hall for hydraulic tests with an area of 6,500 square meters. This hall is mostly occupied with testing flumes and basins for hydraulic model studies. Basins are used for three-dimensional (3D) studies of structure stability and wave disturbance tests, as well as pressure tests and wave energy power plants scale model test. Flumes are used for stability and overtopping tests of maritime structures. (Lemos et al, 2013).

Two physical models were considered: 1) a rubble-mound breakwater cross-section, whose armour layer is composed of tetrapods; (Figure 1a); b) three-dimensional model of a breakwater, whose armour layer is composed of cubes (Figure 1b). In the physical models, several armour units were coloured using different and chosen colours that were placed in some arrangements to test several procedures of the displacement location.

Several tests were performed under different incident wave conditions (different wave heights ranging between 3.5 m and 4.5 m) remaining about 27 minutes. We filmed each test with a camcorder Canon LEGRIA HF M56 model, positioned in front of the structure with a stable support. Three previously calibrated wave gauges were also placed in front of the wave generator and in front of the breakwater in order to evaluate the incident wave height.

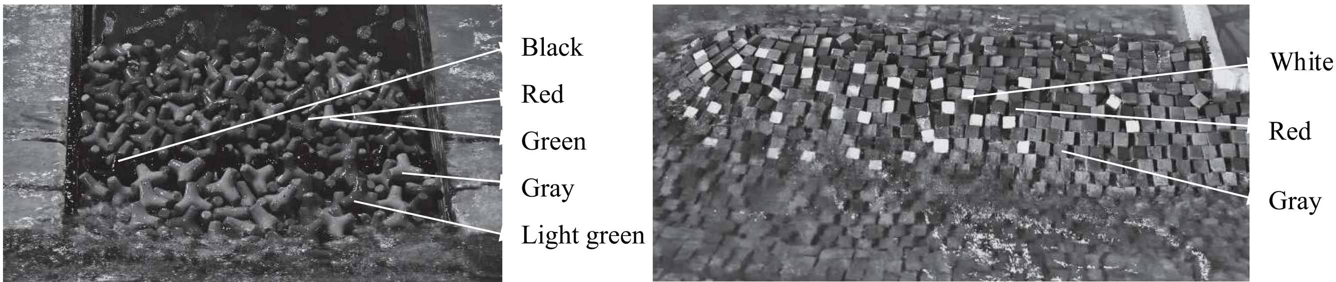


Figure 1. Captured frames: a) Breakwater cross-section with tetrapods; b) Three-dimensional model of a breakwater with cubes

Video analysis was carried out using the "Free Video to JPG Converter" enabling the creation of sequential capture frames to be subsequently analysed by the algorithm developed in Matlab® aiming to evaluate automatically if any displacements occurs or in that case its location and characterization.

3. METHODOLOGY

3.1 *Utility generalities*

The methodology of digital images processing and analysis for an automatic and precise identification of displacement and falls of breakwater armour units is based on the application of several functions already used in Ferraz et al. (2015) which were extended and tested for different conditions. The main methodology is now as following:

- Analyse the first and last image or a set of images over time, and locate eventual displacements in time for successive images using the intensity difference between pixels;
- Define, through relevant differences, consecutive images that corresponds to any armour unit displacement;
- Process images by separating them into groups equal to the number of the presented colours in the image – Analysis by groups of colours;
- Calculate the difference between images for each colour and the images obtained by dividing colours - Analysis by pixel intensity difference;
- Divide images into zones and sign those ones corresponding to a larger displacement by difference between pictures, using pixels intensity – Location of displacements;
- Perform edge detection in the images by selecting a particular block and identify and quantify its movement- Edge detection and Displacement characterization.

A set of Matlab® scripts were additionally developed to automate the process. For example, several dialog boxes were created to allow the inclusion of user options and to connect the different functions, thus facilitating the use of the utility to locate displacements in space and time or characterize it, doing the procedure sequentially or choosing individual analysis.

The developed utility presents a main menu with options for image reading and image analysis. Image reading includes image correction to reduce noise as proposed by Ferraz et al. (2015). The user can choose only two images or a set of images. Concerning to image processing and analysis, it presents four options, which can be performed individually or sequentially which are: a) Analysis by groups of colours; b) Analysis by pixel intensity difference; c) Location analysis; d) Edge detection and displacement characterization.

3.2 *Analysis by groups of colours*

This type of analysis consists on dividing the image into colours, using the command “k-means” which groups the pixels according to their intensity in k classes and segments the image into k regions. We must then give the required number of colours in which we want to split the image. RGB image is transformed into k L-type images defined by L * a * b *, where L * corresponds to the lightness, a * the colour index in the red-green axis and b * the colour index in the blue-yellow axis. This type of image ignores the variation in brightness in an image.

Figure 2 presents the procedure for the first physical model, breakwater cross-section, whose armour layer is composed of tetrapods with three main colours arrangement by strips: red, green and black. Figure 2a shows the original image and 2b to 2d illustrate the image separation using a three colours division.

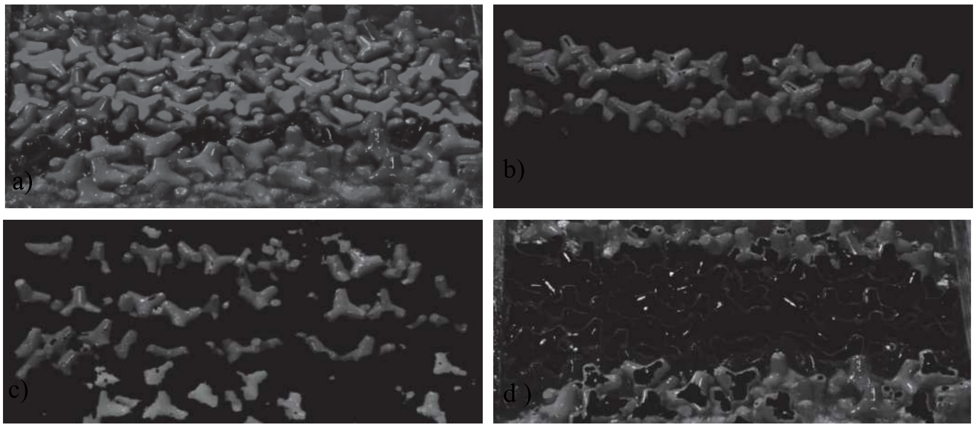


Figure 2. Image separation of three colours; a) initial image; b) cluster 1; c) cluster 2; d) cluster 3

3.3 *Analysis by pixel intensity difference*

Difference between pixel intensity of two images allows the detection of any difference between images. Thus when applied to sequential images of rubble-mound breakwater taken with a fixed camera detects any displacement occurred in any armour unit. In this work, this procedure is applied to binary images, in which pixels are 0 (black) or 1 (white), obtained from previous separation of the original by colours.

The pixel intensity difference menu is divided into 4 options allowing as first option the choice of new images and new grid parameters to guarantee the correct application of the procedure that requires images of same size and limits. It is also possible to choose colour levels that ranges from 0 (black) to 1 (white), for each one of the RGB colours (red, green and blue) to improve the visualization of each colour and guarantee an effective application of this procedure, which is explained below.

Figure 3 illustrates an image area of breakwater cross-section composed of tetrapods and its RGB pixel intensity values. Figure 4 shows the three split images obtained for the choice of level values for red, green and blue equal to respectively 0.4, 0.15 and 0.2. Figure 5 presents the image that results from the addition of the three images presented in Figure 4 b to d. The existence of this option in the menu enables the user to change colour level values to better distinguish armour units colours and shapes. The comparison of this image obtained from the addition of three split images and the original image is a good evaluation for the quality of the binary image (Figure 5).

The application of the procedure of pixel intensity difference is then made by subtraction the two binary pixels matrix corresponding to the images either to the pair of global images or to each pair of images red, green and black. The difference is done subtracting preceding and succeeding image and vice versa. Thus to visualize the results, the resulted matrix should be displayed as binary images. Using the Matlab® contour function we can draw their contours. Figure 6 illustrates the result of this procedure applied to the pair of global images, which shows a slight global tetrapods displacement of the rubble-mound that is not usual and normally quite hard to detect. This happens because the model was not properly prepared in this test. The application of the procedure to global image is hard to understand as can be observed in Figure 6. Other possibility it is to apply the technique to individual colour armour units' images. Figure 7 shows the resulted image obtained by the same procedure applied to the red tetrapods previously obtained using the "k-means" function.

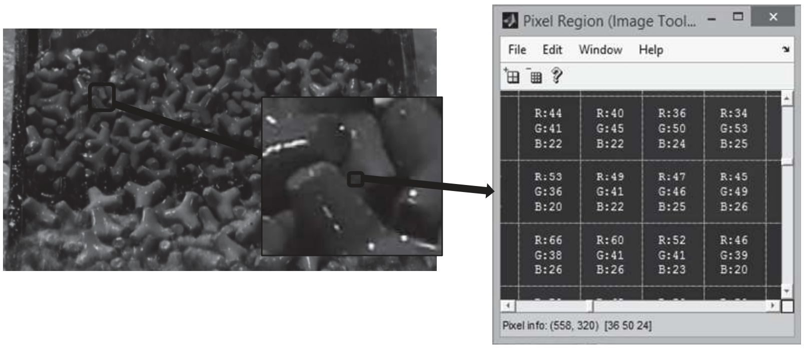


Figure 3. Pixel Intensity

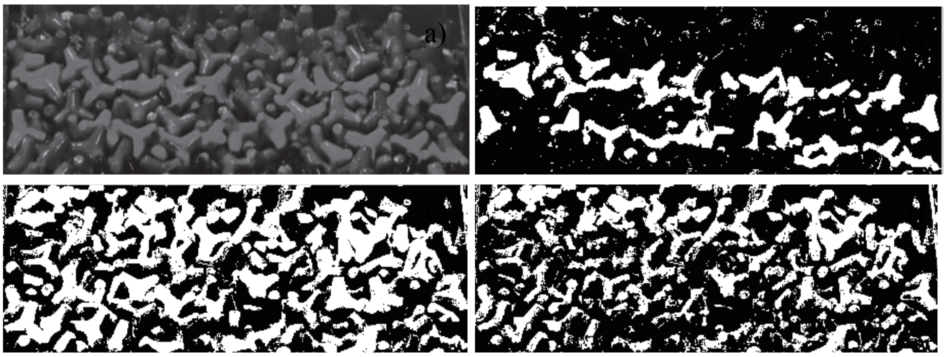


Figure 4. Colour levels. a) Original image; b) Red Level 0.4; c) Green Level to 0.15; d) Blue Level 0.2

Figure 1 – Sum of colour levels presented in Figure 3

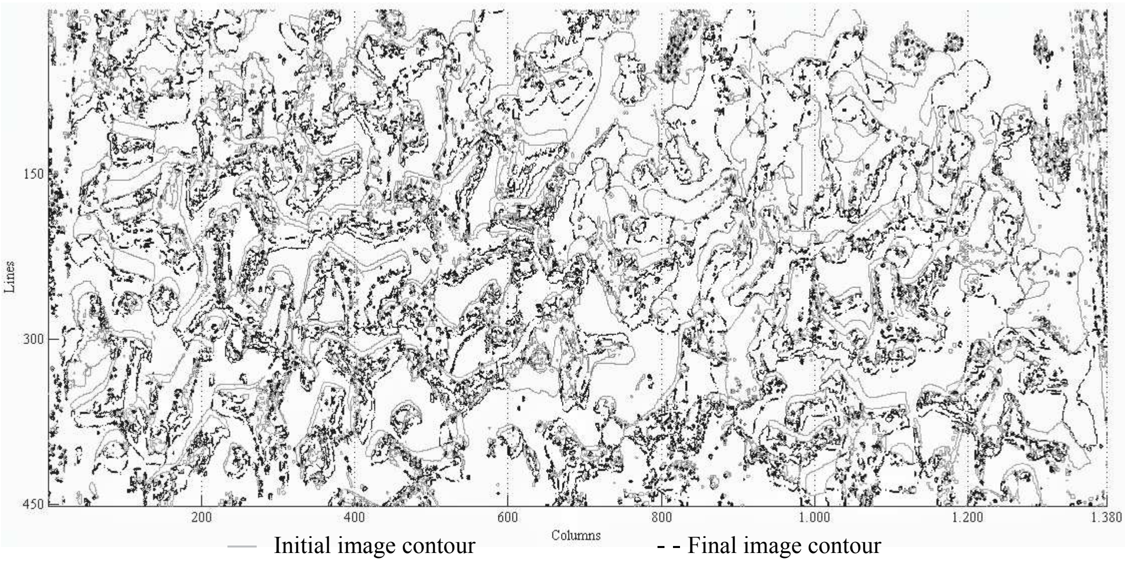


Figure 2 – Image differences overlay

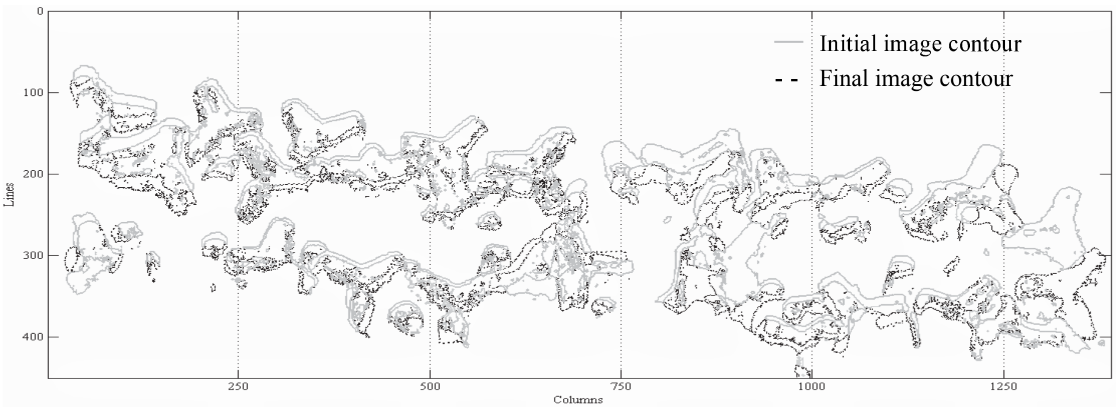


Figure 3 – Detected red tetrapods displacement.

3.4 *Location of displacements*

The armour units' displacement can be located by choosing the menu *location* where it is also possible to select new images and choose parameters. The user should define the number of rows and columns in which images will be segmented and *Max* and *Min* functions are then applied to evaluate from all segments where the greater displacement occurs, i.e., the location of maximum pixel number corresponding to absence of armour unit in one image and its presence in the second image and the opposite.

Figure 8 presents an example of the pixel intensity binary image difference between final and initial images in the first test using only the red tetrapods (Figure 2a) and segmented into 125 rows and 300 columns. Figure 9 illustrates the segment where maximum was verified, corresponding to line 4 of the fourth column. That procedure was verified and confirm manually.

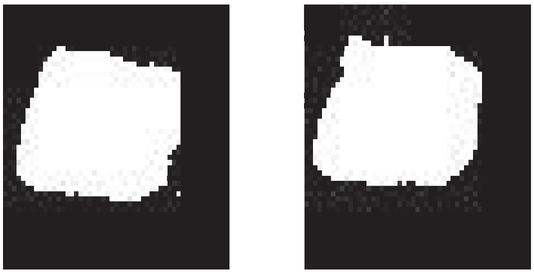
Figure 8 – Subtraction between initial and final segmented images

Figure 9 - Segment representation corresponding to line 2 of the first column: a) initial image; b) final image; c) pixel intensity difference between the final and the initial image.

3.5 *Edge detection and displacement characterization*

Edge detection consists on the detection of armour units limits and its representation. This can be done by comparing armour units limits at different times, allowing the displacement and rotation quantification. For this, images must have exactly the same dimensions and it is recommended to choose image limits on the same time.

Original image should be previously divided by colours using “k-means” (3.2) and transformed into a binary image (3.3), enabling a better definition of the edges. Thus, edge detection could be applied either to a single binary image or to a series of two images for example in an area located by the procedure described in 3.4. The detection is made by analysing the difference between neighbour pixels intensity values which in binary images is much more simple avoiding selection of parameters as in Ferraz et al. (2015). Figure 10 shows the analysis carried out for a cube belonging to the three-dimensional model of a breakwater, whose armour layer was composed of cubes.



c)

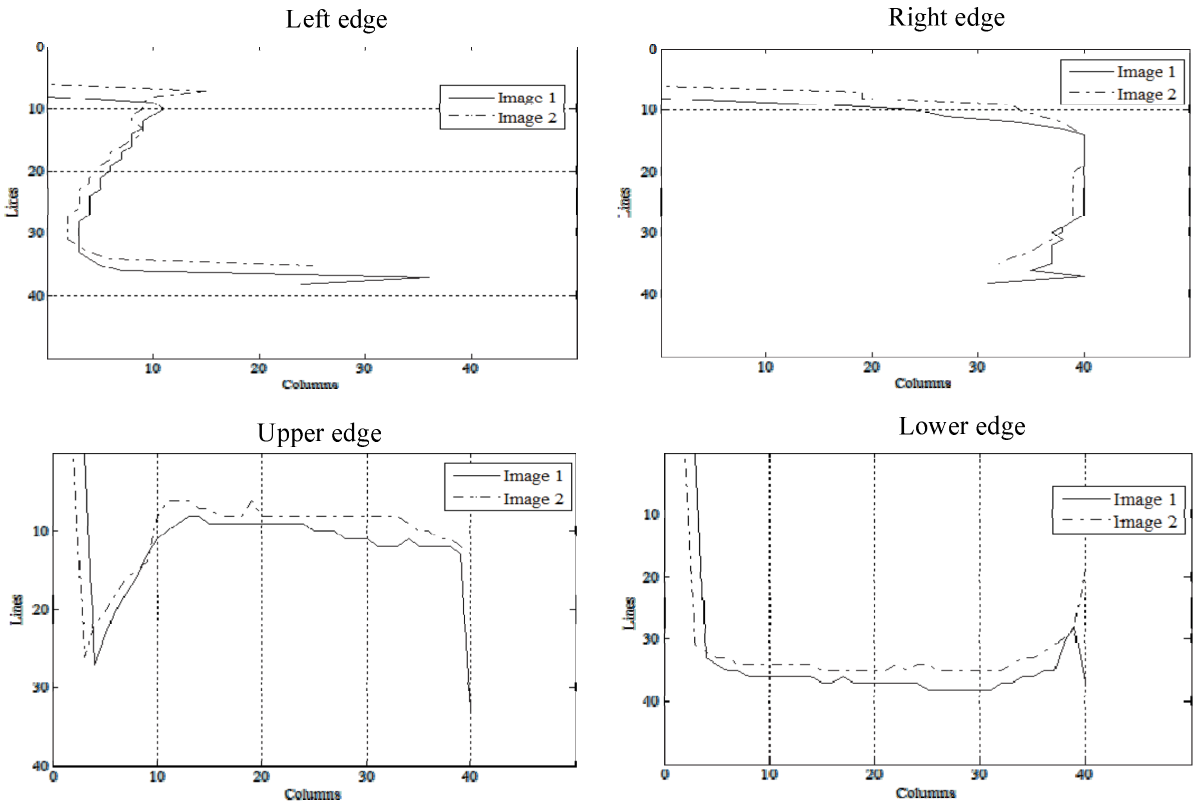


Figure 10- Selected cube from the three-dimensional model. a) Initial image; b) final image; c) Edge detection diagrams

4 RESULTS

A complete analysis was carried out, using the procedure presented in Section 3 sequentially to the initial and final images, for the both models, the cross-section model with tetrapods and three-dimensional model with cubes, and for the different tested significant wave height of Hs =3.5 m, 4 m and 4.5 m.

For the cross-section scale model the images were limited so that only the tetrapods were visible. Figure 11 illustrates the initial and final images corresponding to the Hs = 3.5 m test. The images were separated in their three main colours: red, green and black and for the red tetrapods the pixel intensity difference analysis was applied. Figure 12 illustrates initial and final position contours where tetrapods moved downward and some rocking was easily identified.

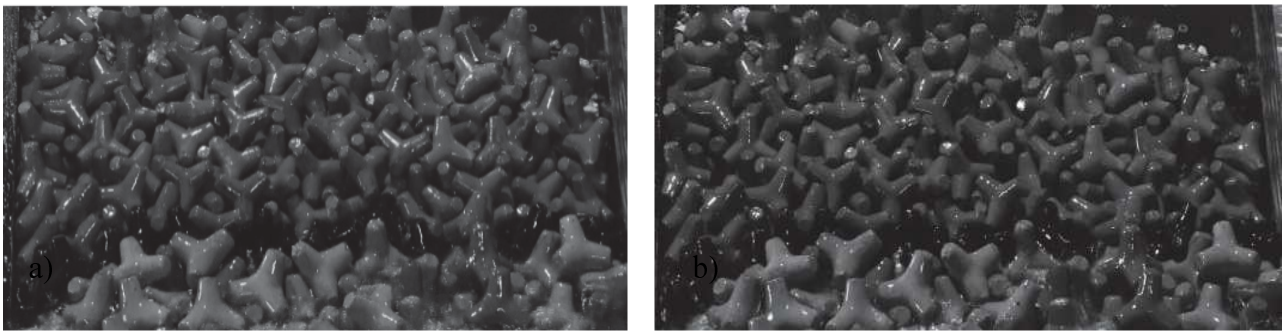


Figure 11 – Cross-section scale model with Hs =3.5 m: a) Limited initial image; b) Limited final image

It is more difficult to identify the green tetrapods displacements, due to the existence of two green tonalities (Figure 13). Command k-means cannot make a clear division between both green tonalities as it does with the red colour, making it difficult to analyse. The same happens with the black tetrapods in the image. The division into black contains the black tetrapods as well as all the other gray tones and all the reflexes that were not possible to prevent, making the analysis difficult.

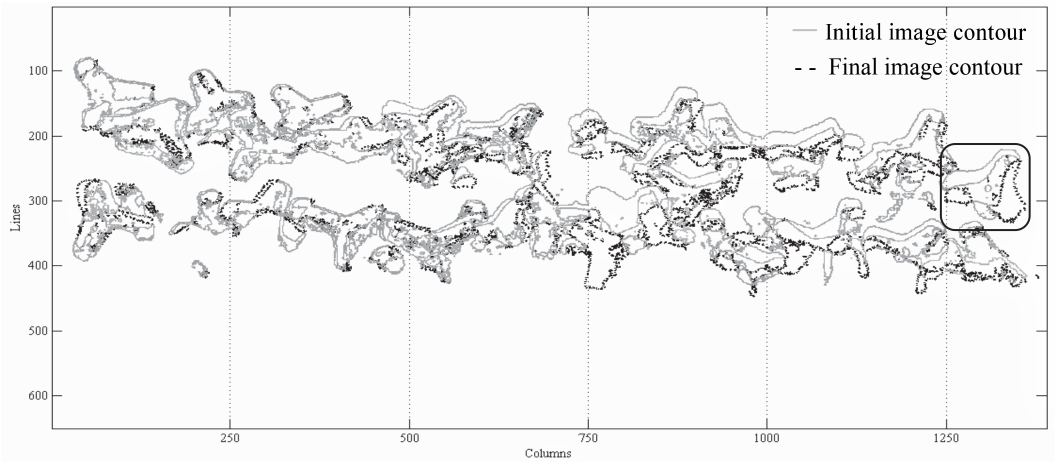


Figure 12 – Movement of red tetrapods for a wave height of 3.5 m

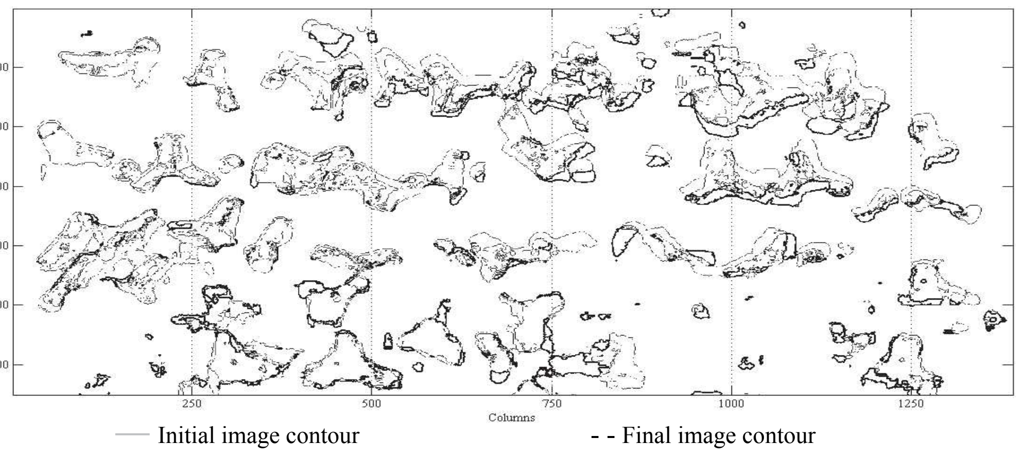


Figure 13 – Green tetrapods displacements

The location analysis of red tetrapods displacement between initial and final images, obtained for a test with a significant wave height (Hs) of 4.5 m, were done dividing the images into 100 rows by 100 columns, where we can see that the largest rocking is due to the difference between images of 1342 pixels (Figure 14).

Figure 14 - Largest movement is due to the "appearance" for a red tetrapod; a) Start-up Image; b) Final Image; c) Subtraction between the two images.

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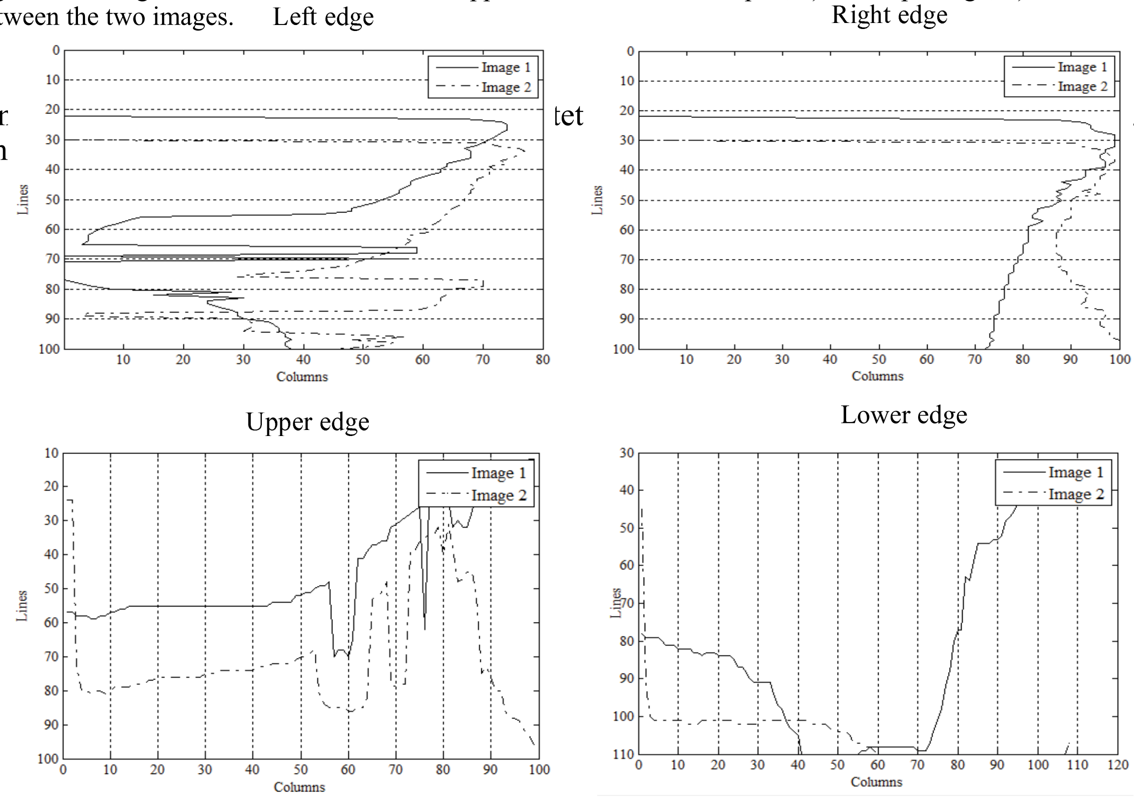

Figure 15– Edge detection of a red tetrapod

Table 1 presents tetrapod data in the two images, the preceding and the succeeding. We can verify a decrease in the area, which could occur since tetrapods can rotate in the plan perpendicular of the Figure, and thus the visible area could changes accordingly as well as axis.

Table 1 - Data related with the red tetrapod movement

	Preceding image	succeeding image
Area	5675	5599
Major axis	110.6341	109.4105
Minor axis	86.5057	88.7126
Orientation	29.5751	24.7661

The analysis is complemented with the computation of differences between images, taken during the run-down to prevent water to be present in the images. The obtained differences could be accumulated and represented in a graph making it possible to locate along time. When a pixel indicate an armour unit in the preceding image and not on the succeeding, the analysis by pixel intensity difference of previous and succeeding image detects it, we can called it "disappeared area". On the other hand, when a pixel indicate an armour unit in the succeeding image and not on the preceding, the analysis by pixel intensity difference of succeeding and preceding image detects it, we can called it "appeared area".

Figures 16, 17 and 18 illustrate the two kinds of difference area detected by the difference between preceding and succeeding image and the opposite for the three test with different irregular waves. Conducting a comparative analysis using each Figure (16, 17 or 18) as well as the corresponding images, we can see that displacement can be detected over time. However most of the peaks obtained in the Figures result from different light incidence on the armour units, which conducted to different images due to reflections. This can be reduced using artificial light.

Table 2 summarizes the results of images processing and analysis made with the proposed methodology for all the tested significant wave heights performed with the first model. Average area that appear and disappear were calculated. We can conclude that in all tests some rocking occurred and maximum was attained for the test with Hs=4.0 m.

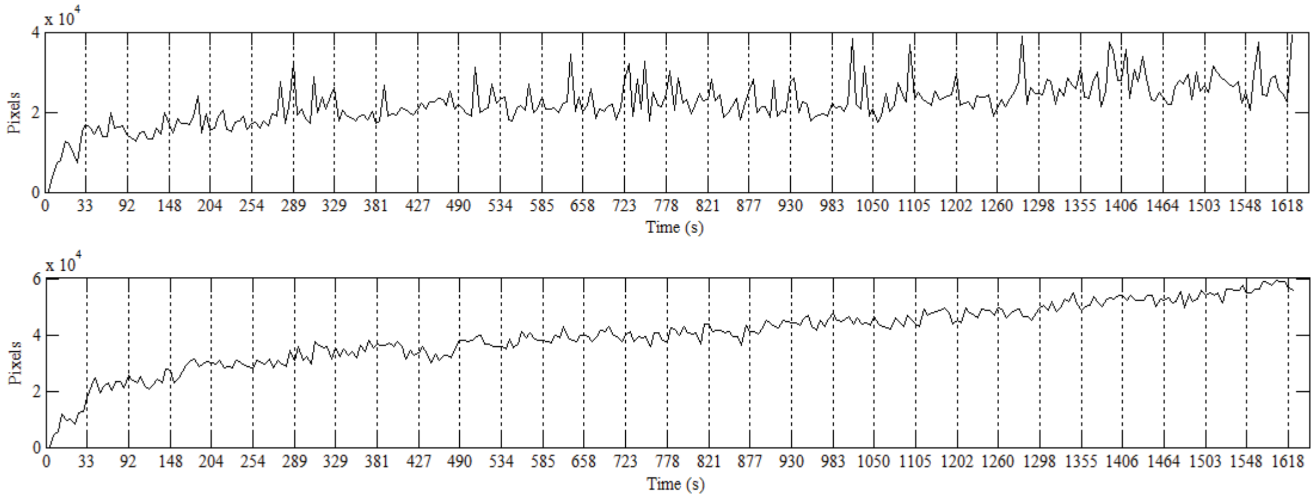

Figure 16 – "Disappeared" and "Appeared" area over time for Hs = 3.5 m

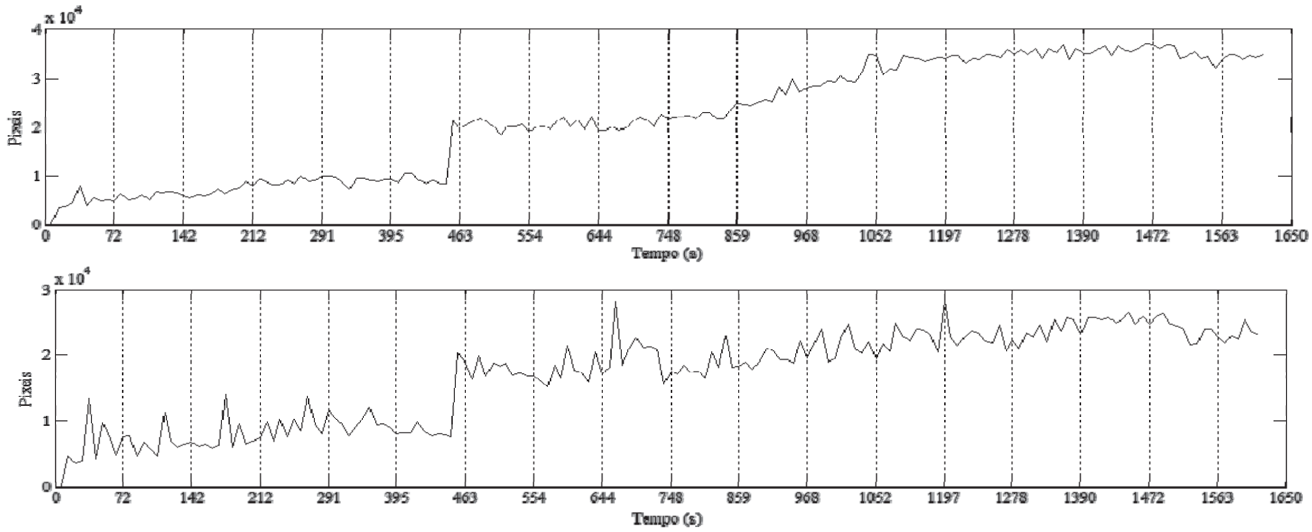

Figure 17 –“Disappeared” and “Appeared” area over time for Hs = 4.0 m

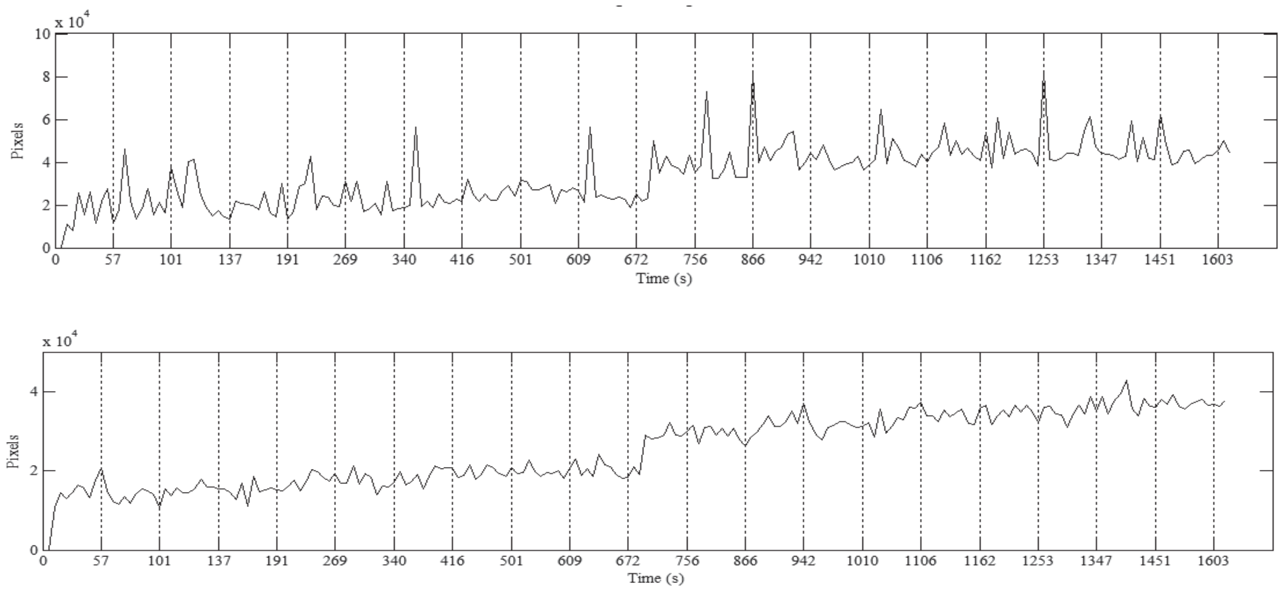

Figure 18 –“Disappeared” and “Appeared” area over time for Hs = 4.5 m

Table 2 - Parameters obtained for all the tested significant wave heights

	“appeared”	“disappeared”
Hs (m)		
3.5	40548	21654
4.0	38739	38191
4.5	23571	34751

Table 2 shows more rocking for the wave with significant height of 4.0 m and less for the 4.5 m. This wave height breaks before hitting the structure, dissipating energy and therefore, reaches the breakwater with less energy. Further, the 4.5 m test was made after 4.0 m test and then is possible that some bricking improve the stability of armour units.

The same methodology was applied to the three-dimensional model where cubes were painted with white gray and red and using Hs = 3.5 m; 4.0 m; 4.25 m and 4.5 m. The images were also corrected and limited and divided in three colours using k-means. However only the red cubes were analysed, as the remaining two colours (white and grey) do not show a clear block division.

The initial and final images for a test conducted with Hs = 4.25 m have been selected to present. Figure 19 illustrates initial and final images of the test. The images were divided into three colours and the movement of the red cubes was analysed (Figure 20).

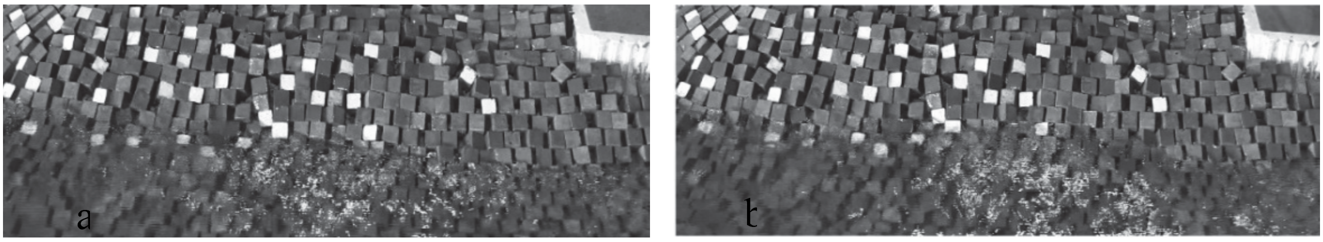

Figure 19–Three-dimensional model with Hs =4.5 m: a) Limited initial image; b) Limited final image

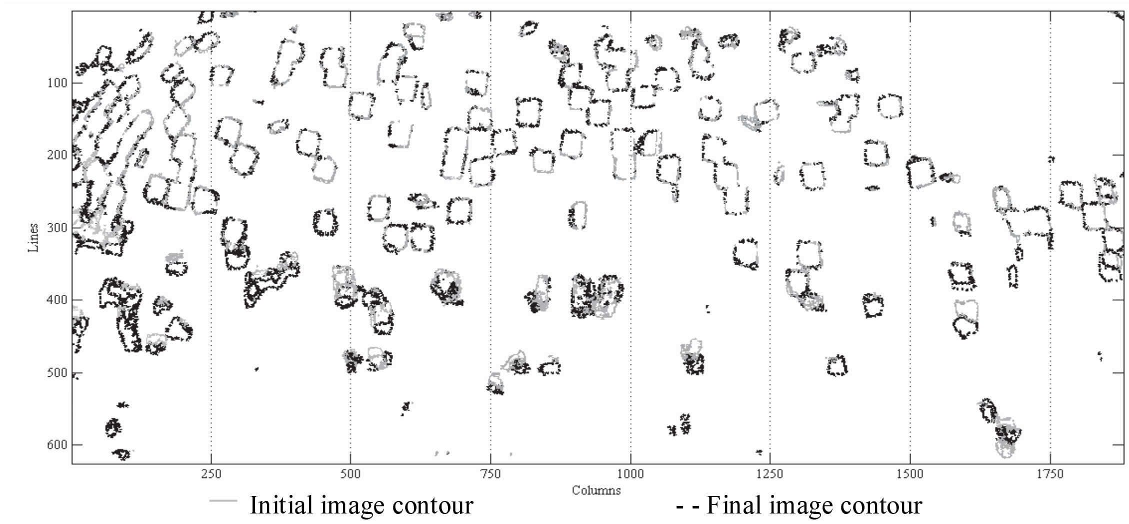

Figure 20 - Three-dimensional model with Hs =4.5 m: Red cubes total displacement contours (between initial and final images).

Note that in Figure 20 the more pronounced displacements occur on the lower part of the image, corresponding to an underwater zone, where the image analysis is difficult, since they suffer distortions caused by the water and wave dynamics. Excluding this part of the image, the location of the largest displacement was done by dividing the images into segments of 100 rows by 100 columns and reaching the value of 174 pixels, which is much lower compared with those obtained during the tests with the breakwater cross-section (1342 pixels).

5 CONCLUSIONS

The proposed algorithm to detect displacements in armour units of a rubble mound breakwater, developed in Matlab® enables a sequential analyse of a pair of images to identify displacements between successive images, locating them in space and time and quantify the displacement for a particular armour unit chosen by the user. The studies may be performed independently or sequentially according to a proposed methodology using different functions:

- Intensity difference between pixels in - to analyse initial and final images of a test or in the case of any displacement detection a set of images over time to locate eventual displacements in time;
- Analysis by groups of colours when a special arrangement of colours is done in the layer of the rubble-mound breakwater - Process images by separating them into the several presented colours in the image to better detect displacement of any armour unit;
- Analysis by pixel intensity difference in binary images - calculate the difference between images for each colour and the images obtained by dividing colours to improve the detection;

- Location of displacements - Divide images/matrix into columns and rows and sign those ones corresponding to a larger displacement by difference between pictures, using pixels intensity;
- Edge detection and Displacement characterization - Perform edge detection in the images by selecting a particular block and identify and quantify its movement.

Although the study was effective to study rocking, it can be enhanced in what concerns to software and tests conditions as:

- The use of a wider range of bright colours for the armour units for example red, green, blue, yellow deployed in rows on the armour layer in order to make it easy to detect any armour unit' displacement and also the division by colours.
- The light in the test facilities should be controlled in order to avoid unwanted reflections in the blocks. Blocks with different shades, leads to different pixels intensity values which can cause errors in the edge detection or in area calculations.

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