

DETERMINATION OF WAVE RUN-UP THROUGH THE TIMESTACK METHODOLOGY AND THROUGH A RESISTIVE WAVE GAUGE. A COMPARATIVE ANALYSIS

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Received: Mar 02, 2023

Reviewed: Mar 15, 2023

Accepted: Mar 22, 2023

ABSTRACT

The objective of this work is the comparison of two methodologies used for run-up measurements in a two-dimensional physical model, which represented the protection breakwaters of the Peniche and Ericeira's ports. Tests were carried out in the scope of the BSafe4sea project. The methodologies used were: a) the traditional measurement of the run-up height with a resistive wave gauge; b) the use of video cameras and image processing techniques images to infer the run-up heights, having its performance evaluated for some of the test conditions. Regarding the results obtained, in terms of $Ru_{2\%}$ and Ru_{max} , it was found that the magnitude of the values obtained with the two techniques were quite similar, although the video analysis returned slightly higher values than the wave gauge. Thus, it was found that the video image technique is a viable alternative to measure the run-up. It is recommended the use of diffused light during the tests, along with stabilizing the video camera, to improve the accuracy of the results obtained by the video-based technique. Besides, the quality of the video image and the use different colors of the armour units of the physical model, could contribute to achieve better results with the TimeStack methodology.

Keywords: run-up; video analysis; timeStack; physical model; breakwater

NOMENCLATURE

H_s	significant wave height, m
Ru_{med}	average of all measured run-up values, m
$Ru_{2\%}$	value exceeded only by 2% of all measured values, m
$Ru_{1/10}$	average of the tenth of the highest measured values, m
Ru_{max}	maximum of all measured values, m
Ru_{min}	minimum of all measured values, m
Rus	average of the third of highest measured values.
T_p	peak period, s

INTRODUCTION

Determining the run-up in rubble-mound breakwaters is fundamental to assess the risk of overtopping and flooding of this type of maritime structures, and thus important for the design of these structures.

Within the scope of the BSafe4sea project (bsafe4sea.lnec.pt), two-dimensional physical models of the protection breakwaters of the Peniche and Ericeira's ports were constructed at the National Laboratory for Civil Engineering (LNEC). The objectives were i) to determine run-up values during

different storm conditions (Fortes et al., 2021a, Mendonça et al. 2021), including climate change scenarios, and ii) to test different measurement methodologies to improve physical model techniques.

Usually, the determination of run-up in physical model tests is carried out using a resistive wave gauge placed along the slope. However, this technique has some limitations, since it does not perform correct measurements when the rising water sheet passes between the wave gauge and the slope, or when the overtopping causes splashes that reach the wave gauge in places where there is no run-up.

An alternative methodology is the use of video cameras and image processing techniques, as the TimeStack methodology, proposed in Andriolo et al. (2016) and in Andriolo (2022). This methodology is based on *TimeStack* images, created by sampling and concatenating a pre-defined single pixel transept collected from each of the video frames, during a certain time interval. Each TimeStack represents the chromatic variation of the transept pixels over the duration of the video segment under analysis.

This communication presents the application of these two methodologies on the 2D physical model tests, representing the cross-sections of the two breakwaters of the ports of Peniche and Ericeira. With both methodologies and using a temporal analysis, the statistical parameters are obtained and compared, namely: Ru_{med} , $Ru_{2\%}$, $Ru_{1/10}$, Ru_{max} and Ru_{min} .

The advantages and limitations of each methodology are commented and discussed.

THE PHYSICAL MODELS

The physical model tests were carried out in the channel of irregular waves, named COI1, at LNEC (Fig. 1), and comprised the construction and operation of scale models, corresponding to the quay sections of the breakwaters of the ports of Peniche and Ericeira. Both models were built and operated according to Froude’s similarity law, with a geometrical scale of 1:50.



Figure 1. Irregular wave flume COI1

The objective of the tests was the analysis of the response of the maritime structure to different sea states, including climate change scenarios. Thus, measurements of free surface elevation, run-up,

overtopping and pressure were carried out, along with the evaluation of the damage on these structures due to these sea states. A detailed description of these tests can be consulted in Fortes et al. (2021b) and Lemos et al. (2022).

The Peniche breakwater armour layer has a thickness of about 4.0 m, consisting of two layers of tetrapods of 160 kN, with a 2:3 slope developing between the crest level, at +8.0 m (ZH), and the toe of the breakwater, at -8.0 m (ZH) (Fig. 2).

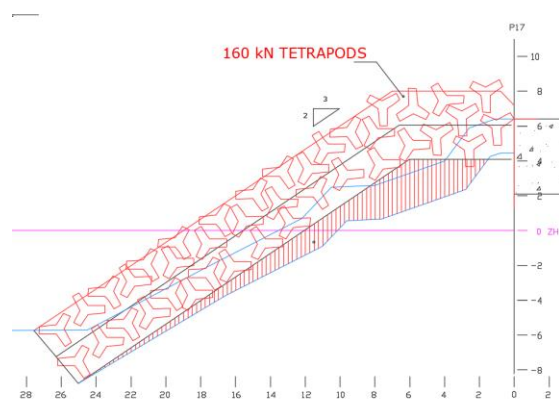


Figure 2. Peniche cross-section breakwater

The Ericeira armour layer is composed of tetrapods of 300 kN developing between the crest level at +10.2 m (ZH) and the toe of the structure at -4.5 m (ZH) on a 2:3 slope of (Fig. 3).

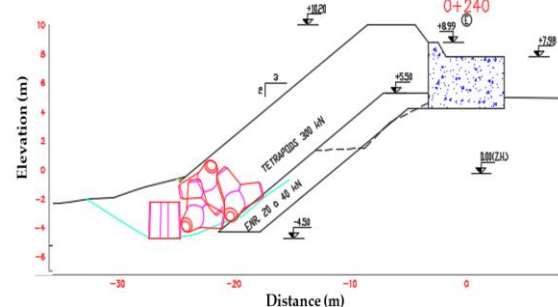


Figure 3. Ericeira breakwater cross-section

In both tests, to measure the wave propagation, a set of 5 wave gauges was used, one of which was located at the toe of the slope. To evaluate the run-up, a resistive wave gauge was placed along the slope (Fig. 4a) to measure the free surface elevation, while a video camera was positioned in front of the structure looking sideways the flume (Fig. 4b).



Figure 4. a) Resistive wave gauge b) video camera outside the flume

Tests were carried out with a duration corresponding to 1000 irregular waves, for three tidal levels: low water level (LWL), medium water level (MWL) and high-water level (HWL). The wave conditions were:

- Peniche: Peak periods of 12 s, 14 s and 16 s associated with significant wave heights, H_s between 4.0 m and 9.0 m;
- Ericeira: Peak periods of 12 s and 14 s associated with significant wave heights, H_s between 4.0 m and 9.5 m.

Table 1 and Table 2 present the wave conditions and water levels used for the comparison of the two methodologies.

Table 1. Peniche: Water levels and wave conditions

Test	T_p (s)	H_{m0} (m)	Water depth at the toe (m)
1	14	4	6.5
2	14	5	6.5
3	14	6	6.5
4	14	7	6.5
5	14	8	6.5
6	14	9	6.5

Table 2. Ericeira: Water levels and wave conditions

Test	T_p (s)	H_{m0} (m)	Water depth at the toe (m)
1	12	5.0	6.5
2	12	5.5	6.5
3	12	6	6.5
4	12	8	6.5

5	14	5.5	6.5
6	12	5	8.5
7	12	5.5	8.5
8	12	6	8.5
9	12	7	8.5
10	14	4	8.5
11	14	5	8.5
12	14	5.5	8.5

METHODOLOGY

Free surface elevation

A 0.5 m long resistive wave gauge was placed along the slope of each cross section of the breakwaters for the free surface elevation measurements. The wave gauges has an excitation frequency of 10 kHz, and an output voltage between -10V and 10 V. The acquisition rate was 128 Hz. An example of the free surface elevation measurements is presented in Fig. 5.

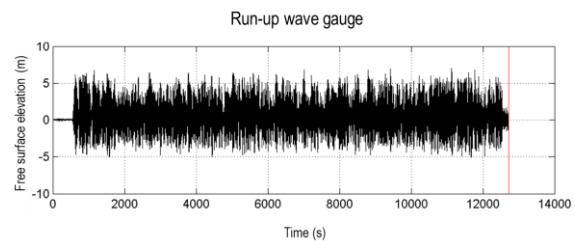


Figure 5. Resistive wave gauge measurement

Based on the time series of wave gauge measurements, the statistical parameters of Run-up values were obtained: Ru_{min} , Ru_{max} , $Ru_{2\%}$, Ru_m and Ru_{med} .

Video Analysis

A commercial video camera (Samsung Digital Camcorder HMX Q10BP) filmed the sequence of images during the test time, with a frequency of 50 frames/s. The tests were carried out during daily light. However, to avoid the effect of sunlight on the video recording, the model was “covered” with opaque curtains. Two VISICO VC 1000Q light spots were also placed aiming at the cross section, to provide artificial light, and thus improve the quality of video camera image.

The methodology used to obtain the run-up values through the video images is described in Andriolo *et al.* (2016) and Andriolo (2019). It consists of the application of three Matlab algorithms, whose main steps are described below, using the example of the Peniche breakwater profile model.

The first software algorithm (extract.m) loads the film to be analyzed, and extracts the images (frames) at a frequency of 25/30 images per second, at the video frame rate. The same algorithm also allows defining the transverse line (transect)

coinciding with the face of the breakwater slope of the physical model, according to the red line represented in Fig. 6.

The transect selected should correspond to the position of the wave gauge used to measure the run-up, although this is not always possible, as the wave gauge is subject to displacements due to waves during the tests.

The algorithm generates a *TimeStack* image, sampling the time series of color pixels from the sequence of images extracted throughout the entire video. The free surface elevation over the slope is obtained, in pixels, along the defined transect over time (Fig. 7).

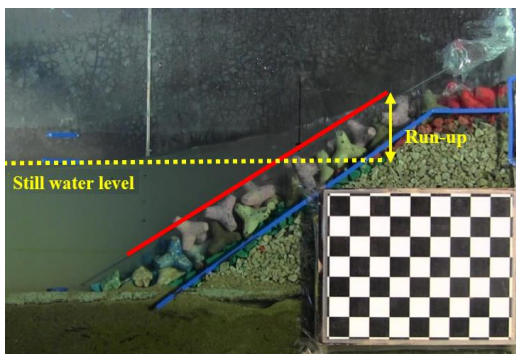


Figure 6. Identification of the still water level (yellow dashed line) and the transect over which the run-up is calculated (solid red line).

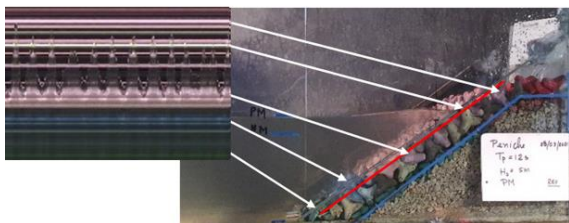


Figure 7. *TimeStack* image and its correspondence in the model

The second algorithm (RunUpTSK.m) allows to manually identify the positions of the highest elevation values in the *TimeStack* image, by selecting the points with the mouse (Fig. 8). The values of the coordinates obtained (in pixels) are saved in a file on the matrix type (.mat) for later calculation of the run-up values, based on a temporal analysis.

The last processing stage consists in applying the third algorithm (createprofile.m), where the discrete values of run-up (pixel) are transformed into heights values (m) above the still water level. Based on these time series, the calculation of the statistical parameters is obtained: Ru_{min} (blue dashed line), Ru_{max} (red dashed line), $Ru_{2\%}$ (black dashed line), Ru_m (green dashed line) and Ru_{med} (pink dashed line) and the points for each run-up (red crosses) - Fig. 9.

It also allows signaling the run-up events and statistical parameters on the slope of the structure (Fig. 10)

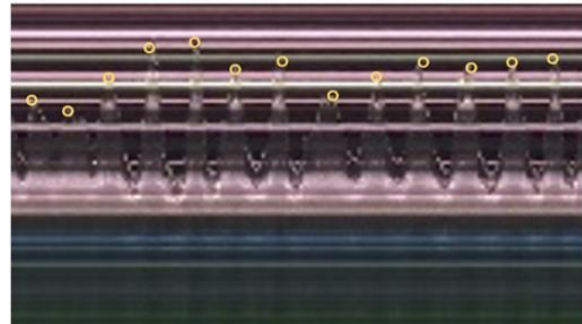


Figure 8. Selection of the run-up events

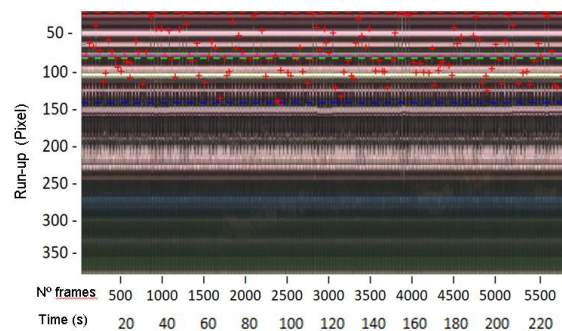


Figure 9. Identification of each run-up and statistical parameters of the time series

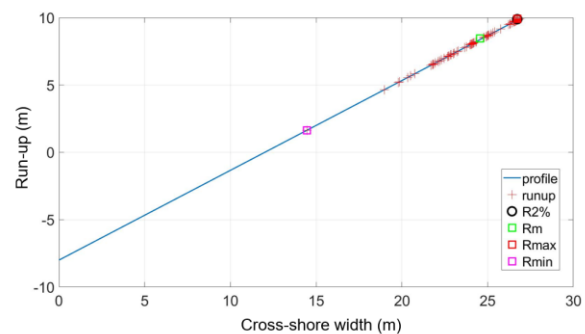


Figure 10. Identification of the points corresponding to Ru_{max} , Ru_{min} , $Ru_{2\%}$ e Ru_{med}

RESULTS

A comparison of the statistical analysis of the time series obtained with both methodologies was carried out, for the case studies of Peniche and Ericeira, corresponding to videos of approximately 10 and 3 minutes, respectively.

Fig. 11 and Fig.12 present the TimeStacks obtained from two videos of Peniche and Ericeira respectively.

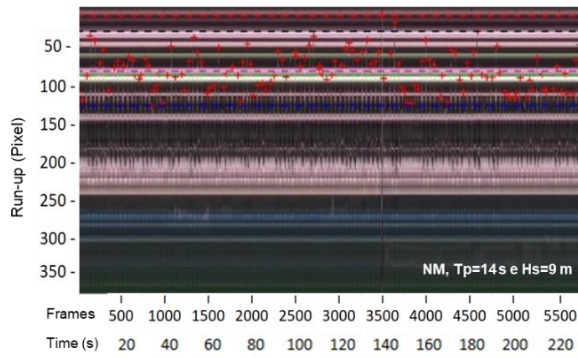


Figure 11. TimeStack from a video of Peniche test case study

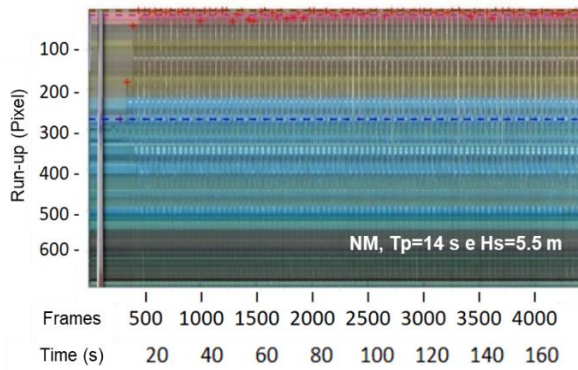


Figure 12. TimeStack from a video of Ericeira test case study

Table 3 and Table 4 show the $Ru_{2\%}$ and Ru_{max} values obtained in the Peniche and Ericeira case studies, respectively. These tables summarize the comparative analysis between the values obtained with the video methodology and with the wave gauge time series.

Table 4. Peniche. $Ru_{2\%}$ and Ru_{max} obtained with the video analysis and with the wave gauge time series

Test	$Ru_{2\%}$			Ru_{max}		
	Video	Wave gauge	dif	Video	Wave gauge	dif
NM_Tp14_Hs4	6.45	6.97	7%	7.44	8.31	10%
NM_Tp14_Hs5	7.83	10.22	23%	7.87	11.71	33%
NM_Tp14_Hs6	7.88	8.53	8%	7.92	9.68	18%
NM_Tp14_Hs7	7.88	9.62	18%	7.88	10.28	23%
NM_Tp14_Hs8	7.88	9.88	20%	7.92	10.35	23%
NM_Tp14_Hs9	7.89	9.90	20%	7.92	10.39	24%

Table 3. Ericeira. $Ru_{2\%}$ and Ru_{max} obtained with the video analysis and with the wave gauge time series

Test	$Ru_{2\%}$			Ru_{max}		
	Video	Wave gauge	dif	Video	Wave gauge	dif
NM_Tp12_Hs5.5	8.11	5.14	-37%	8.16	5.17	-37%
NM_Tp12_Hs6	8.17	5.41	-34%	8.20	5.44	-34%
NM_Tp12_Hs8	8.05	5.78	-28%	8.13	6.49	-20%
NM_Tp14_Hs5.5	8.17	6.37	-22%	8.20	6.48	-21%
PM_Tp12_Hs5	6.14	4.83	-21%	6.14	4.84	-21%
PM_Tp12_Hs5.5	6.14	5.93	-4%	6.16	5.93	-4%
PM_Tp12_Hs6	6.09	5.81	-5%	6.11	6.19	1%

PM_Tp12_Hs7	5.61	5.91	5%	5.61	6.44	15%
PM_Tp14_Hs4	6.10	5.22	-14%	6.11	5.22	-14%
PM_Tp14_Hs5	6.12	6.21	2%	6.13	6.61	8%
PM_Tp14_Hs5.5	6.12	6.44	5%	6.12	6.53	7%

Regarding the Peniche case study, Fig. 13 presents the results of $Ru_{2\%}$ and Ru_{max} obtained by the two methodologies. The red line delimits the height corresponding to the freeboard, R_c , corresponding to the height between still water level and the crest level.

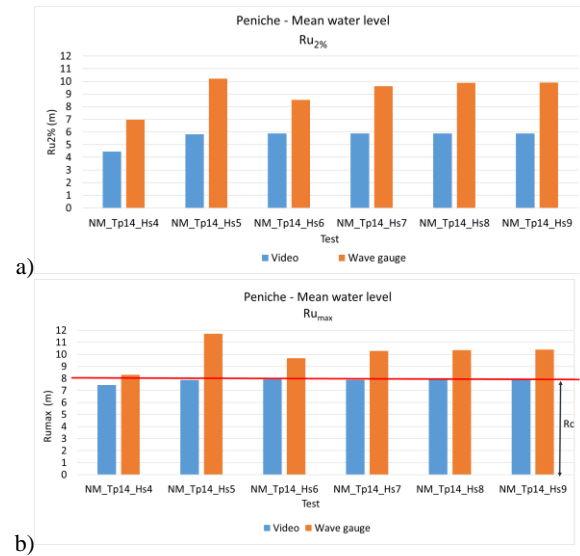


Figure 13. Peniche. $Ru_{2\%}$ (a) and Ru_{max} (b) obtained with both methodologies in tests carried out with the mean water level

Regarding $Ru_{2\%}$, the values obtained using the wave gauge are higher than those measured using the video technique, with percentage differences ranging between 7% and 23%.

Analyzing the figure corresponding to Ru_{max} , it appears that the freeboard ($R_c=8.0$ m) is reached in most tests for H_s greater than 4.0 m, evidencing the occurrence of overtopping. However, the Ru_{max} values measured with the wave gauge are much higher than the crest level. Assuming that the height reached by the run-up cannot be higher than the crest level, the analysis using the *TimeStack* technique appears to be the most realistic. The overestimation of the wave gauge analysis is justified by the occurrence of splashes that reach points of the wave gauge located above the crest level.

For the Ericeira case study, Fig. 14 and Fig. 15 show the results of $Ru_{2\%}$ and Ru_{max} , respectively, obtained by the two methodologies, for the tests carried out with mean and high tide levels.

In the Ericeira case study, $Ru_{2\%}$ and Ru_{max} values obtained with the wave gauge analysis are generally lower than those measured with the *TimeStack* technique, especially with the mean water level or with the smallest wave heights of the high

water level, with percentual differences ranging between 21% and 37%.

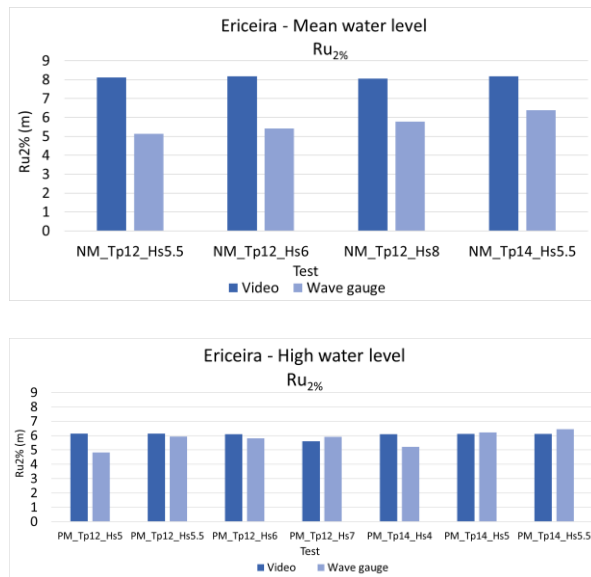


Figure 14. Ericeira. $Ru_{2\%}$ obtained with both methodologies in tests carried out with the mean and high water level

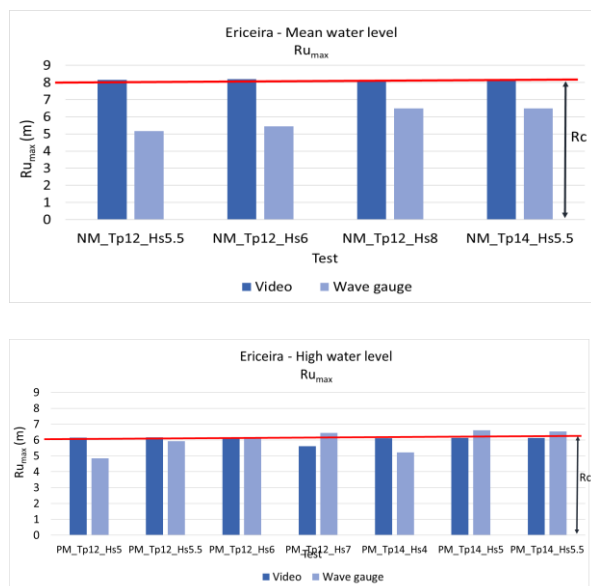


Figure 15. Ericeira case study. Ru_{max} obtained with both methodologies in tests carried out with the mean and high water levels

Figure 14 shows the results corresponding to Ru_{max} . Once again using the value corresponding to the freeboard of high and low water levels ($R_c=6.2$ m and $R_c=8.2$ m, respectively) and knowing that the crest level was always reached, due to overtopping, the results obtained by the *TimeStack* technique seem to be the most credible.

Lower values obtained with wave gauge measurements are justified by its vertical offset from

the surface of the slope. This displacement is almost impossible to eliminate due to the irregular nature of the tetrapod armour layer. Because of this, the water sheet that reaches the highest zones of the slope passes under the wave gauge, reducing the extent of the run-up measured by the wave gauge. This effect is more attenuated in tests conducted with high water level and with the highest significant wave heights, leading to smaller differences in the values measured by both methodologies.

In both case studies, the differences between the two techniques are related to the limitations of both methodologies. In the case of the wave gauge, the turbulence caused by the impacts of the waves, could lead to its deviation. Thus, the transect previously defined for *TimeStack* production will not match the location of the gauge. Also, the passage of water sheets under the wave gauge or the measurement of splashes can lead to underestimation or overestimation of the measured values. In the case of the *TimeStack* methodology, the quality of the image, the good definition of the transect, the use of bands of very different colors for the painting of the armour units could contribute to a better identification of the crests in the *TimeStack* image. The manual selection of the crests on the *TimeStack* is not an accurate methodology.

CONCLUSIONS

The application of two methodologies (wave gauge and video camera techniques) for the determination of the run-up in rubble-mound breakwaters with artificial armour units is described. These techniques were applied during tests on a physical scale model of cross-sections of the Peniche and Ericeira breakwaters. Tests were conducted for mean and high-water levels and peak periods of 12 s and 14 s, associated with wave heights ranging between 4 and 9 m.

The results obtained with the video technique were compared with the measurements of a wave gauge placed on the breakwater armour layer, and confirmed that the video image technique is a viable alternative to measure the run-up on physical models.

There are, however, some very important factors to improve the image analysis technique. The use of well-defined color bands for painting the armour layer blocks is very useful for defining the *TimeStack* transect and for selecting the points corresponding to the wave crests.

An automatic detection of the wave crests in the *TimeStack* image is under development.

ACKNOWLEDGEMENTS

This work was carried out within the scope of the projects: PTDC/EAM-OCE/31207/2017 To-Sealert-Wave overtopping and flooding in coastal and port areas: Tools for an early warning, emergency

planning and risk management system and PTDC/ECI-EGC/31090/2017 BSafe4Sea—Breakwaters SAFETY control through a FORecast and decision support SystEm Analysis, both funded by the Portuguese Research Foundation (FCT).

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