Time Stack methodology applied to the assessment of run-up and overtopping in 2D and 3D scale model tests

R. Lemos[a,*], C.J.M. Fortes[a], M. Carvalho[a] and U. Andriolo[b]
[a]*Department of Hydraulics, National Laboratory for Civil Engineering, Lisbon, Portugal*
[b]*Department of Electrical and Computer Engineering, University of Coimbra, Coimbra, Portugal*

[*] *Department of Hydraulics, National Laboratory for Civil Engineering, Lisbon, Portugal, rlemos@lnec.pt*

ABSTRACT: Physical modelling is a key tool for the characterisation of wave run-up and overtopping phenomena on maritime structures. Traditionally, these parameters have been measured using resistive wave gauges. Nowadays, modern non-intrusive methods have emerged. In particular, video cameras, combined with advanced video analysis such as the *TimeStack* method, provide a compelling alternative to conventional techniques. *TimeStack* involves the extraction of pixel arrays along a predetermined image line segment (transect) over the duration of the video. This results in a composite image, known as a TimeStack, which encapsulates the temporal evolution of the pixels. This study describes the application of the *TimeStack* method to assess the statistical parameters of wave run-up and overtopping events, as well as their spatial distribution in the 3D models of the Leixões breakwater. At the same time, an evaluation of the overtopping events and their extent is carried out in the 2D model of the Peniche breakwater. For the main section of the Leixões breakwater, statistical parameters of wave run-up (Ru_{max}, Ru_{min}, Ru_{mean} and $Ru_{2\%}$) derived from video analysis are determined for two sections (trunk and head) of the breakwater. In the case of the trunk section, the wave run-up was once again analysed for tests conducted under the same wave conditions but with different wave directions. Furthermore, the *TimeStack* method enables the determination of the zone of the breakwater that was most heavily overtopped and the range of overtopping distances. In the second case, it was possible to determine the number of overtopping events as well as statistical parameters such as h_{max} and $h_{2\%}$. These cases illustrate the advantages and disadvantages of the *TimeStack* method for different applications in scale model tests of breakwaters. The results confirm that video-based techniques are a viable alternative for measuring run-up across different sections of 3D scale models of breakwaters and for detecting overtopping events, including their peak heights and distances reached. Furthermore, this work outlines future improvements in image processing algorithms and procedural refinements aimed at mitigating some of the inherent drawbacks of the method.

KEYWORDS: Breakwaters, Run-up, Overtopping, Video Analysis

1.1 INTRODUCTION

Rubble-mound breakwaters are among the most prevalent maritime protection structures, built to provide sheltered areas for safe mooring, loading operations, vessel manoeuvering, and safeguarding harbour facilities.

The design or safety verification of these breakwaters necessitates the assessment of wave run-up and overtopping, as these phenomena pose risks to the operations and activities within the protected area or to the breakwater itself. Furthermore, the implications of climate change exacerbate this concern, as the anticipated escalation in both frequency and intensity of waves impacting these structures is likely to augment run-up, overtopping and flooding. Regrettably, a majority of these structures were not engineered with such increases in mind. Physical modelling (2D and 3D models) serves as an instrumental tool in characterizing wave run-up and overtopping. Conventionally, wave run-up is measured with wave resistance gauges along the breakwater slope. In contrast, wave overtopping volumes (individual or total) are deduced from the volume of water that overtops and is subsequently collected in a reservoir on a corresponding scale.

In 2D models, both techniques provide reliable estimations of wave run-up within a breakwater section (Andriolo et al. 2016 and Lemos et al. 2023a). However, in 3D physical models, such estimations are confined to the locations of the wave gauges, thus comprehensive values across the entire breakwater cannot be obtained. This limitation is significant, as wave run-up and overtopping can exhibit considerable variability along the breakwater. Waves do not approach uniformly, and their heights vary substantially due to the angle of incidence. Additionally, it is crucial to acknowledge that wave gauges may lead to underestimations of wave run-up in certain instances, as some waves pass beneath the gauge without being detected (Lemos et al. 2023a).

To overcome some of these limitations, non-intrusive parameter assessment methods are increasingly being used. These methods are not only cost effective but also easy to implement. The use of video cameras and the corresponding recordings over a period of approximately 20 to minutes (approx. 1000 waves at a model scale of 1:50 and peak wave periods of between 8 and 18 seconds) provides a viable alternative to traditional techniques. However, the effectiveness of these methods depends on optimal environmental and technical conditions during video recording, including adequate lighting, full camera stabilization, high quality images, precise camera orientation and sufficient colour contrast in the study area.

At the LNEC, encouraging results regarding wave run-up parameters in 2D physical models have been obtained by using a standard video camera in conjunction with the *TimeStack* method. This method facilitates the identification of run-up events in full-scale model tests (Andriolo et al. 2016) and assists in the assessment of nearshore wave transformation regions (Andriolo 2019). The *TimeStack* method extracts the pixel arrangement along a predetermined image line segment (transect) in the video.

The application of image analysis for run-up using video records dates back to 1989. For example, Aagaard and Holm (1989) employed the TimeStack methodology to measure beach swash, necessitating the digitalization of analog videos.

In Holland's (1995) study of foreshore dynamics, run-up measurements were conducted using the TimeStack methodology on manually digitized films, in addition to resistive wires. Run-up indicated sensitivity to the elevation of the wire sensor. The video-derived measurements corresponded closely with those obtained from near-bed elevation wire sensors.

The *TimeStack* methodology, derived from image processing toolbox codes, is now widely used by many researchers, who employ different algorithms for a range of applications. Gal et al. 2011 estimated nearshore wave heights based on the analysis of digital video sequences captured by a single on-shore mounted camera. Similarly, Yoo et al. 2011 used the *TimeStack* method to study the evolution of the surf zone, collecting an image pixel array along across-shore transect from sequential radar images to generate a cross-shore image TimeStack. (Özer 2019) used this methodology to estimate the overtopped volume in 2D scale model tests, where a sequence of frames of a wave are used as input to a network to predict the overtopping volume.

The *TimeStack* methodology was also employed in the study by Lemos et al. 2023a to ascertain wave run-up parameters in two-dimensional scale model tests. This methodology involves the use of MatLab algorithms that facilitate the extraction of frames from the video for analysis, and subsequently, the extraction of all pixels along a pre-defined path (transect). A more detailed description of the methodology is delineated in section 2.3.

For physical 3D models, the application of this methodology remains in preliminary testing phase; however, the initial results are promising. The *TimeStack* technique enables us to define the required number of virtual gauges by establishing multiple transects across various zones of the breakwater. Consequently, it becomes feasible to quantify the run-up in any area of the breakwater beforehand with the video footage acquired during the physical model tests. Lemos et al. 2023b compared results derived from the video technique in 3D tests with measurements from a wave gauge positioned on the slope, facing the frontal wave direction, and validated that the video imaging technique is a viable alternative for determining run-up parameters. However, the application of this methodology under oblique wave directions requires further development.

An additional limitation is that crest identification must currently be performed manually. The entire post-processing, which encompasses the identification of wave run-up positions in videos spanning 20-40 minutes may result in reduced accuracy. Moreover, this task must be executed for each video captured in physical model tests, rendering the analysis of videos computationally intensive and demanding significant memory resources.

In the current study, crest identification was conducted manually, limiting the video duration to a maximum of 10 minutes.

Consequently, algorithms for detecting run-up crests and optimizing computational time and requirements are currently under development although they remain in the experimental phase.

However, the same method can be used to estimate overtopping events, including their height and extent. Defining a vertical transect at the crest level facilitates the estimation of the frequency with which water passes the crest of the structure and the height of each overtopping event. On the other hand, a horizontal transect, perpendicular to the breakwater crest, can help estimate the reach of the overtopping.

The aim of this paper is to describe the applications of the video and *Timestack* methods for the estimation of wave run-up, overtopping distances and overtopping events.

This methodology has been used to estimate the following:

- Wave run-up heights, overtopping events and overtopping distance range.

  These parameters were derived from video recordings of tests carried out in a previous study at LNEC (3D physical scale model tests of the Leixões breakwater). However, wave run-up was not measured using resistive wave gauges, as the experiment did not focus on wave run-up, resulting in the absence of a resistive wave gauge on the slope.

  With regard to wave run-up heights, the video-derived statistical parameters (Ru_{max}, Ru_{min}, Ru_{mean} and $Ru_{2\%}$) were determined for two sections (trunk and head) of the breakwater. These statistical parameters can be defined as:

  - Ru_{max} – the height of the highest run-up in a record;
  - Ru_{min} - the height of the lowest run-up in a record;
  - $Ru_{2\%}$ - the run-up level exceeded by 2% of run-ups in a record;
  - Ru_{mean} – the average run-up, i.e., the average of the run-ups in a record.

  For a third section, at the trunk, the wave run-up was also compared between two tests conducted under identical wave conditions (Hs, Tp) but with different wave directions: The W direction, almost frontal to the trunk of the breakwater and the SW direction, characterized by greater obliquity.

  The assessment of overtopping using the *TimeStack* methodology involved determining the most overtopped zone along the superstructure of the breakwater, as well as its distance range.

- Overtopping events and thickness (height) of the water sheet.

  In this test case (2D model of Peniche breakwater), the number of overtopping events and the maximum height reached by the water sheet were determined. Results were compared with those obtained using a resistive wave gauge.

2 MATERIAL AND METHODS

2.1 *The physical models*

The 3D physical model of the Leixões breakwater, in Portugal, was built at the experimental facilities of the Department of Hydraulics and Environment (DHA) of the LNEC. It was located in one of the wave tanks of the Maritime Hydraulics Pavilion with dimensions 30.0 m x 19.6 m, and equipped with 2 mobile irregular wave generators, each6.0 m long, capable of generating waves in water depths up to 0.75 m (Figure 1). The model was designed and operated in accordance with Froude's law of similarity, at a geometric scale of 1:63.

The main characteristics (dimensions in prototype scale) of the trunk profile are:

- the crest, at +13.0 m (CD), has a 13.0 m wide superstructure;
- the outer slope extends from +14.7 m (CD) and -13.1 m (CD) with a slope ratio of 2.0H:1.0V. The armour layer consists of two layers of 680 kN regularly spaced cubic Antifer units. The toe of the structure is made up of 3 rows of 800 kN Antifer cubes
- the internal slope is between +9.75 m (CD) and -9.55 m (CD), with a slope of 1.5H:1.0V and consists of a single layer of 680 kN Antifer cubes.

The rotation profile of the head has similar characteristics to the external slope of the trunk, differing only in the weight of the 800 kN Antifer cubes used in the armour layer.

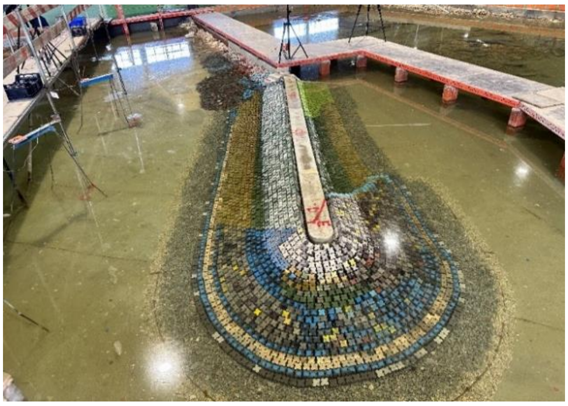


Figure 1. 3D Model of the Leixões breakwater at LNEC's experimental facilities

A commercially available 4K video camera (GoProHero8) was used to record the sequence of images during the test period at a rate of 25 frames/s. This allowed the capture of frames with 3840 horizontal lines, each 2160 pixels wide.

The 2D physical model tests were conducted in an irregular wave channel at the LNEC, which included the construction of a section of the breakwater for the port of Peniche (Figure 2). The model was built and operated according to Froude's similarity law at a geometrical scale of 1:50. The Peniche breakwater armour layer consists of two layers of tetrapods, each weighing 160 kN, with a 2:3 slope ratio, extending from the crest level, at +8.0 m (CD) to the toe of the breakwater, at -8.0 m (CD).

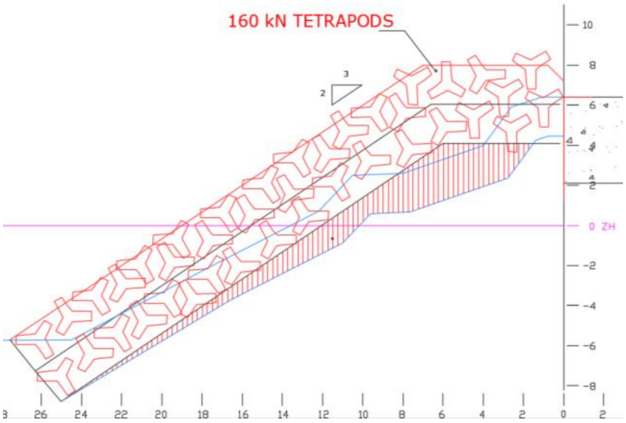


Figure 2. Cross-section of the Peniche breakwater

A resistive wave gauge was installed on the breakwater superstructure (Figure 3a) to detect overtopping events. In addition, a Canon HF56 video camera (Figure 3b) with a frame rate of 25 frames/s was positioned above the channel. This setup allowed the capture of frames with 1440 horizontal lines, each 1080 pixels wide.

In order to reduce computational time and increase storage efficiency, only the last 8 or 10 minutes of the videos were used. These segments correspond to approximately 300 waves. Although this duration is not a statistically representative time series for a comprehensive analysis of run-up and overtopping, it was considered sufficient for initial testing of the *TimeStack* methodology.

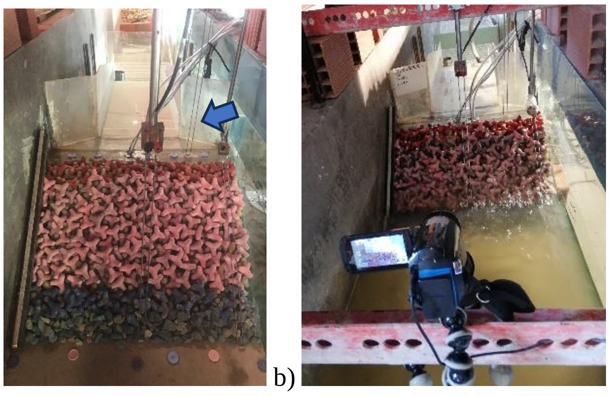
a)  b)

Figure 3. a) Resistive wave gauge b) video camera above t he model of Peniche breakwater

2.2 *Wave conditions*

For both experiments, tests were carried out over a period equivalent to 1000 irregular waves, at three tidal levels: low water level, 0.0 m (CD), and high-water level with superelevation at +4.0 m (CD). The wave conditions were:

- Leixões: Peak periods (Tp) of 12 s and 20 s (1.51 s and 2.52 s in the model) and significant wave heights, Hs, between 6.0 m and 12 m (between 0.095 m and 0.19 m in the model).
- Peniche: Peak periods of 12 s, 14 s and 16 s (1.70 s, 1.98 s and 2.26 s in the model) and significant wave heights, Hs, between 4.0 m and 9.0 m (between 0.08 m and 0.18 m in the model).

Table 1 presents the wave conditions relevant to the present work and parameters obtained from the video analysis.

Table 1. Test conditions and parameters obtained from video analysis

Model	Test	T_p (s)	Hm0 (m)	Water level	Wave direction	Run-up	Overtopping
Leixões (3D)	1	20	7.5	+4.0 m (CD)	W	Ru_{mean}, $Ru_{2\%}$ Ru_{max} (Head and trunk)	Location, events, and distance range
	2	20	7.0	+4.0 m (CD)	W	Ru_{mean}, $Ru_{2\%}$ Ru_{max} (Trunk)	-
	3	20	7.0	+4.0 m (CD)	SW	Ru_{mean}, $Ru_{2\%}$ Ru_{max} (Trunk)	-
Peniche (2D)	4	14	8	+4.0 m (CD)	-	-	Events and their heights

2.3 *The TimeStack methodology*

The *TimeStack* methodology involves the use of three MatLab algorithms (Extract.m, RunUpTSK.m and CreateProfile.m). The main steps are shown in Figure 4.

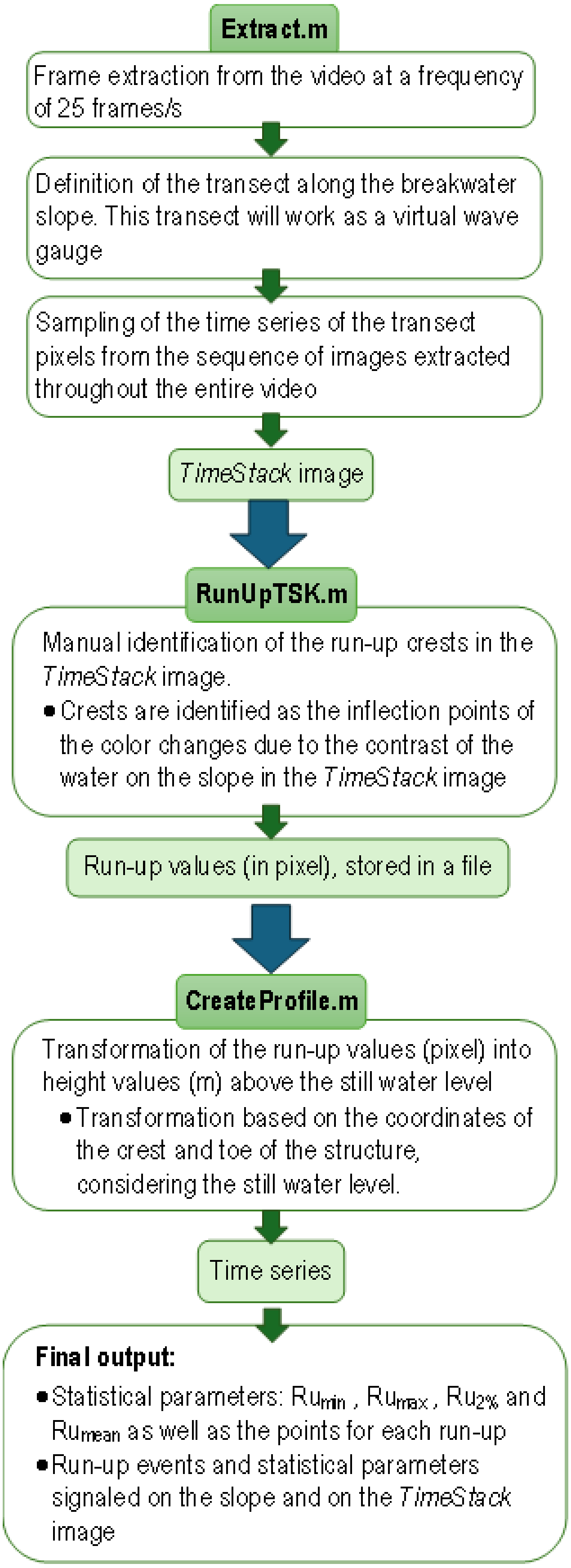


Figure 4. Main steps of the *TimeStack* methodology

Figure 5 and Figure 6 illustrate a selection of outputs generated by the application of the above algorithms.

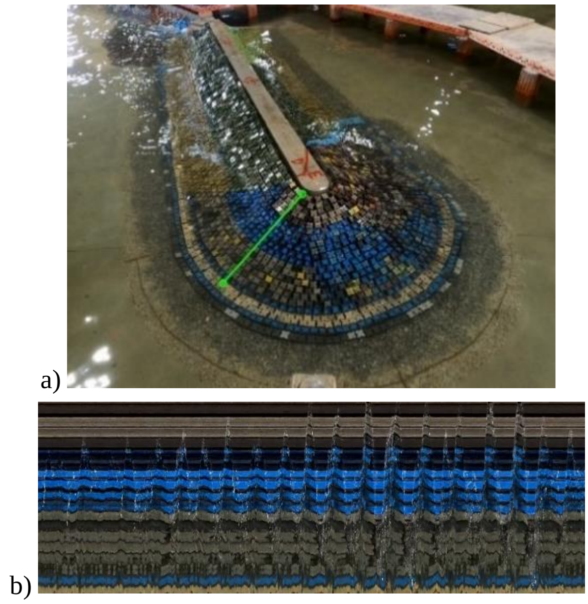


Figure 5. Extract.m algorithm. a) Location of the transect b) Segment of the *TimeStack* image

This step can be preceded by segmenting the film into multiple segments using a MatLab algorithm to optimize the computational efficiency of processing longer films. The algorithm "Extract.m" will process each segment of the film independently and then merges the individual TimeStacks at the end of the code.

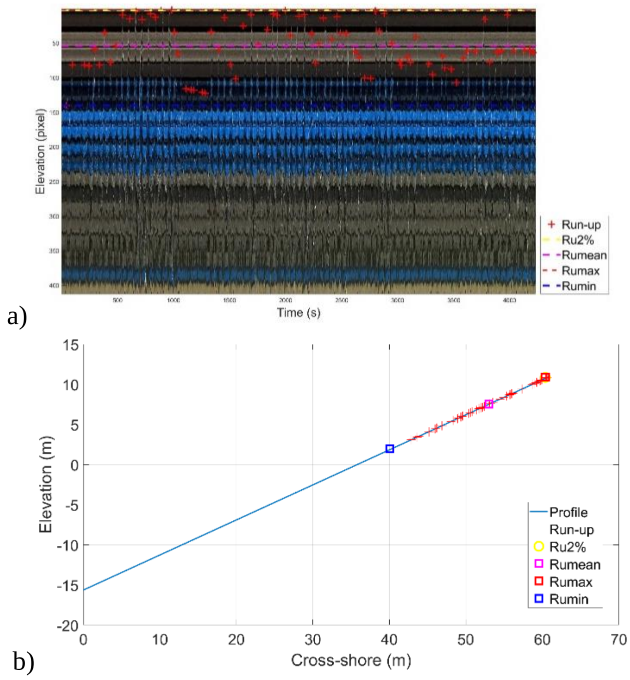
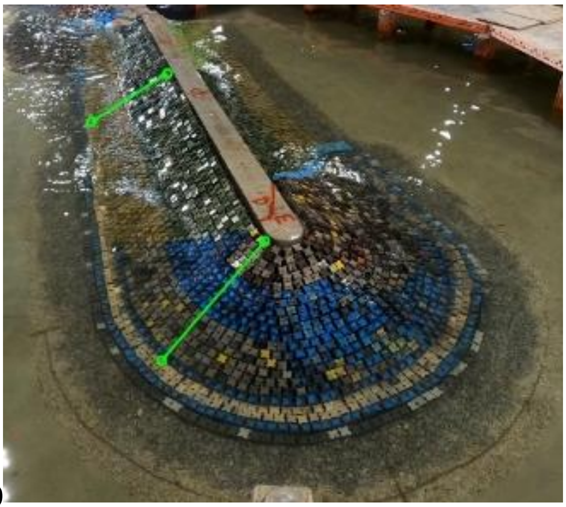


Figure 6. CreateProfile.m. a) Identification of each run-up a nd statistical parameters of the time series b) Identification of the points corresponding to Ru_{mean}, $Ru_{2\%}$ and Ru_{max}, in t he slope.

3 RESULTS

3.1 *Video analysis of run-up in the Leixões 3D model*

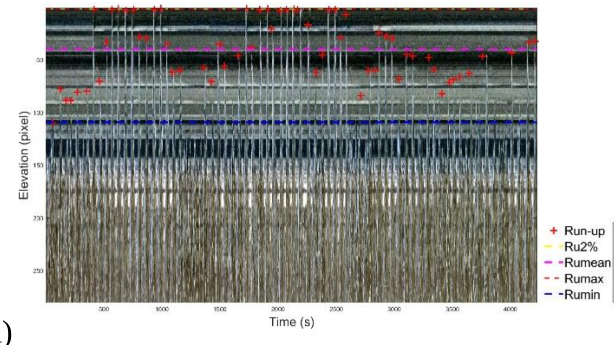
The run-up values derived from the *TimeStack* method are shown in Figure 7a), which illustrates the transects defined for Test 1 (H_s=7.5 m associated with T_p=20 s and wave direction of W). These transects correspond to two different sections of the stem and head of the breakwater, identified as the zones with the highest overtopping. Figure 7b) shows the transect defined for Tests 2 and 3 (H_s=7.0 m associated with T_p=20 s and wave directions of W and SW, respectively) in a section located at a mid-point along the length of the trunk.


a)

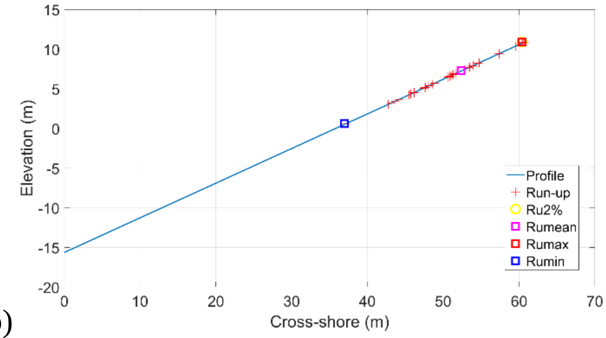

b)

Figure 7. Transects defined for Test 1 (a) and Tests 2 and 3 (b)

As an example, Figure 8a) illustrates the identification of run-up events and associated statistical parameters within the *TimeStack* image and along the profile (Figure 8b), which is derived from the video footage of Test 1 at the trunk section.



a)



b)

Figure 8. Identification of run-up points in the *TimeStack* image (a) and in the slope (b)

Table 2 lists up the statistical run-up parameters, namely Ru_{mean}, $Ru_{2\%}$ and Ru_{max}, obtained with the *TimeStack* methodology for Tests 1, 2 and 3.

Table 2. Leixões. Ru_{mean}, $Ru_{2\%}$ e Ru_{max} obtained with the video analysis

Test	T_p (s)	Hm0 (m)	Water level	Wave direction	Zone	Ru_{mean} (m)	$Ru_{2\%}$ (m)	Ru_{max} (m)
1	20	7.5	HWLS	W	Trunk	7.25	10.90	10.90
					Head	6.12	10.93	10.93
2	20	7.0	HWLS	W	Trunk	5.76	10.94	10.94
3	20	7.0	HWLS	SW	Trunk	4.47	10.92	10.92

It was observed that the occurrence of overtopping results in Ru_{max} values that are consistent with the 11 meter freeboard value at High Water Level. Moreover, these test cases present a significant frequency of overtopping events, resulting in Ru_{max} and $Ru_{2\%}$ values that are remarkably similar.

For Test 1, Ru_{mean} values recorded in the section trunk exceed those measured in the head section. This discrepancy can be attributed to the more direct impact of the W direction on the trunk compared to the head. As a result, waves reach a higher level (increased run-up) on the slope of the breakwater than in the head section.

In the case of Tests 2 and 3, the run-up parameter values derived from the W direction exceed those from the SW direction, as expected, due to the oblique nature of the SW direction.

The results obtained with frontal and oblique wave directions confirmed that the video imaging technique is a viable alternative for measuring run-up over different segments of the breakwater. The transect acts as a virtual wave gauge which can be strategically "deployed" anywhere on the image of the breakwater. Furthermore, this approach has the advantage of allowing retrospective data extraction from archived image records, particularly in cases where traditional instrumentation was not installed.

3.2 *Video analysis of overtopping in the 3D model of Leixões*

In order to identify the segment of the breakwater most affected by overtopping, a transect was drawn along the length of the superstructure (Figure 9a). The *TimeStack* image (Figure 9b) shows that the zone of highest overtopping corresponds to the last 115 m of the superstructure extension (yellow arrows).

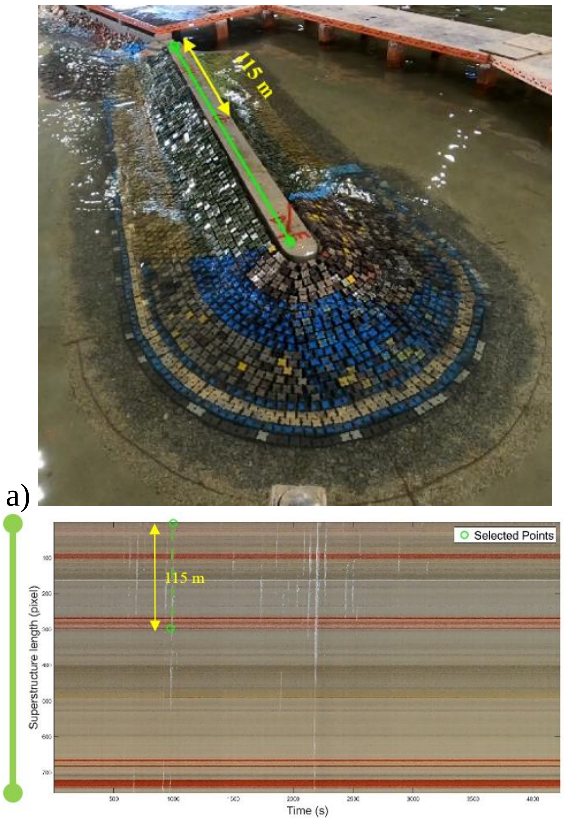


Figure 9. Identification of the most overtopped zone of the breakwater. Transect definition (a) and distance measured in the *TimeStack* image (b)

A transect perpendicular to the breakwater crest was established within this most overtopped zone (Figure 10a) This allowed the assessment of the overtopping area using the inner edge of the superstructure as a reference point (Figure 10b).

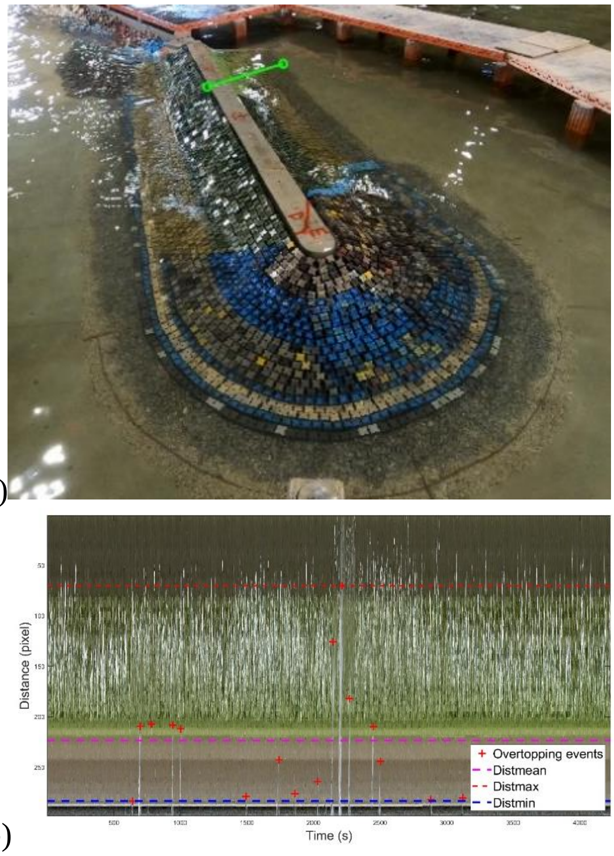
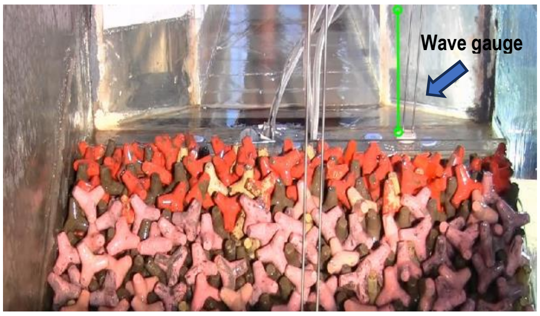


Figure 10. Transect definition (a). Measurement of the distance reached by overtopping events in the TimeStack image (b)

The maximum, minimum and average overtopping distances were recorded as 49.69 m, 3.14 m and 16.22 m, respectively. The TimeStack image recorded 16 overtopping events, while a visual count in the video documented 21 events within the transect zone. The results were relatively consistent, with minor discrepancies attributed to smaller events consisting of thin sheets of water, which lacked colour contrast with the superstructure and therefore went undetected.

3.3 *Video analysis of overtopping in the 2D model of Peniche*

To identify overtopping events in the Peniche cross-sectional model, a transect was defined parallel to the wave gauge positioned at the breakwater crest (Figure 11a). The *TimeStack* image facilitated the detection of overtopping events and the magnitude of their elevation (Figure 11b).

a) 

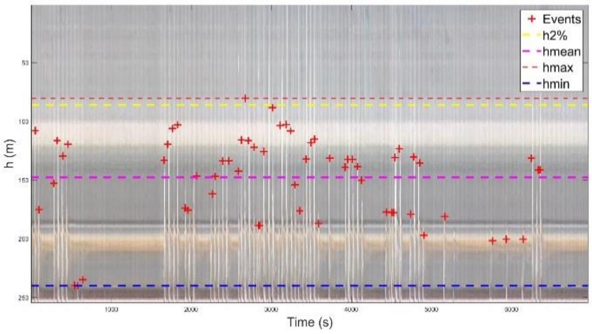
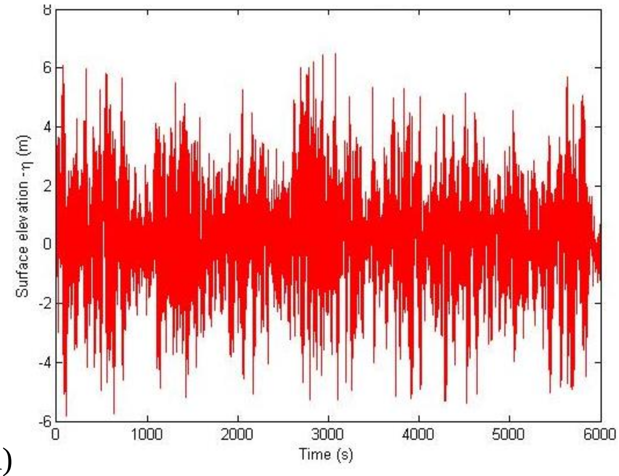
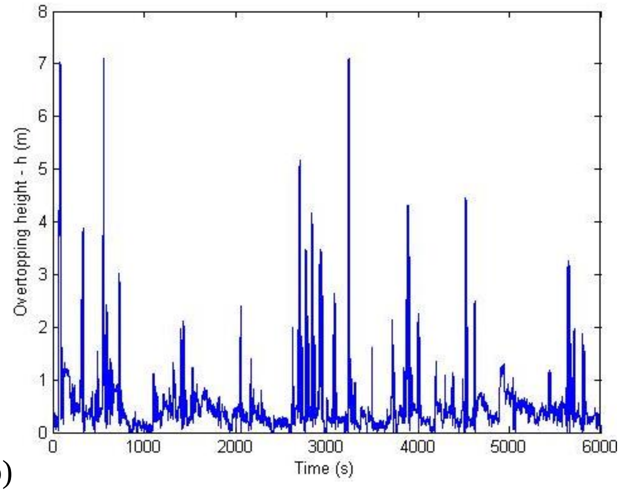
b) 

Figure 11. a) Transect definition b) Identification of the overtopping events on the *TimeStack* image

Figure 12 shows the surface elevation in front of the structure and the overtopping height at the breakwater crest, as recorded by the wave gauge, corresponding to the duration of the video. An analysis with zero overtopping time was carried out, including a threshold to exclude wave heights below $0.01{*}H_{max}$.



a)



b)

Figure 12. Surface elevation in front of the structure (a) and overtopping height at the crest (b)

Table 3 presents a comparative analysis of the overtopping height values above the superstructure (h) derived from *TimeStack* and those obtained from a time analysis of the resistive wave gauge.

Table 3. h_{max} and $h_{2\%}$ obtained with the video analysis

Test	T_p (s)	Hm0 (m)	Water level	Methodology	Number of events	h_{max} (m)	$h_{2\%}$ (m)
4	14	8	HWLS	TimeStack	60	6.83	6.62
				Wave gauge	62	7.09	7.09

The statistical parameters h_{max} and $h_{2\%}$ derived from the wave gauge were found to be 3.8% and 7.1% higher, respectively, when measured with the wave gauge in comparison to the *TimeStack* methodology. This discrepancy can be attributed tto the spray on the wave gauge, which contributes to overestimate the values of h_{max}. Implementing a filter to remove outlier values from the wave gauge time series data enhanced the alignment of both methodologies, in terms of h_{max} and $h_{2\%}$. On the other hand, smallerovertopping events may be subject to underestimation of their height, due to the insufficient contrast between the sheets of water and the white/gray background.

The quality of the image, contingent upon the camera's characteristics, lighting conditions, orientation, and stabilization, significantly influence the efficacy of the image analysis technique.

The number of overtopping events detected by both methodologies exhibited a high degree of convergence. This was achieved through meticulous manual selection of the crest in the *TimeStack* image and the application of a filter designed to remove some "noise" caused by water oscillation in the crest wave gauge

4 CONCLUSIONS

The present paper presents the application of the *TimeStack* methodology for the evaluation of wave run-up parameters, overtopping events and their distance range in the 3D physical scale model tests of the Leixões breakwater. In this case study, the video-derived statistical parameters of wave run-up (Ru_{max}, Ru_{min}, Ru_{mean} and $Ru_{2\%}$) were determined for two different sections (trunk and head) of the breakwater. In the case of the trunk section, a comparison of wave run-up was made between tests with identical wave conditions but different wave directions.

For the 2D model tests at Peniche, the study successfully identified the number of overtopping events and calculated statistical parameters, such as h_{max} and $h_{2\%}$.

Overall, the results of both the 2D and 3D video technique tests confirm that the video imaging technique is a viable alternative for measuring run-up over different sections of the breakwater. The technique has shown consistent reliability in detecting overtopping events and determining their extent.

However, discrepancies were observed between the results obtained by the two techniques, which are due to the inherent limitations of each method.

To overcome the limitations of both methodologies, careful preparation of the setup is of utmost importance. Accurate positioning of the wave gauge as close to the slope surface as possible is essential for accurate run-up height measurements.

On the other hand, securing the upper part of the wave gauge is essential to prevent overestimation of overtopping event due to spray.

In the context of the *Timestack* methodology, which relies on image analysis, certain precautions are warranted. The use of well-defined colour bands in the painting of armour blocks greatly aids the delineation of the transect for crest selection in the run-up assessment.

For overtopping detection, the use of a dark background increases the contrast between the water layers and the background.

In addition, accurate definition of the profile geometry, using the tide level as a reference, is essential for accurate run-up calculations. The points that define these dimensions are calibration points for pixel-to-metric unit conversion. The pixel coordinates,which define the transect correspond to specific prototype dimensions in metric units, as do the dimensions associated with the transect aligned with the vertical wave gauge placed vertically above the superstructure.

The duration of the video should not exceed about 10 minutes, otherwise the manual selection of the crests in a populated, dense *TimeStack* (a longer timeline in a *TimeStack* image with the same size) may become inaccurate. The computational time and memory requirements would become increasingly demanding.

Future work comprises the development of an automatic crest detection algorithm, which is expected to improve the accuracy of crest identification. At the same time, an algorithm is being developed to optimize the computational time and computational requirements, enabling the processing of longer videos.

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