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

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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

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\text{med}, Ru\text{2%}, Ru\text{1/10}, Ru\text{max} and Ru\text{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.

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).

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 (Fig. 3).
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).

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, Hs between 4.0 m and 9.0 m;
- **Ericeira**: Peak periods of 12 s and 14 s associated with significant wave heights, Hs 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**

<table>
<thead>
<tr>
<th>Test</th>
<th>Tp (s)</th>
<th>Hm0 (m)</th>
<th>Water depth at the toe (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14</td>
<td>4</td>
<td>6.5</td>
</tr>
<tr>
<td>2</td>
<td>14</td>
<td>5</td>
<td>6.5</td>
</tr>
<tr>
<td>3</td>
<td>14</td>
<td>6</td>
<td>6.5</td>
</tr>
<tr>
<td>4</td>
<td>14</td>
<td>7</td>
<td>6.5</td>
</tr>
<tr>
<td>5</td>
<td>14</td>
<td>8</td>
<td>6.5</td>
</tr>
<tr>
<td>6</td>
<td>14</td>
<td>9</td>
<td>6.5</td>
</tr>
</tbody>
</table>

**Table 2. Ericeira: Water levels and wave conditions**

<table>
<thead>
<tr>
<th>Test</th>
<th>Tp (s)</th>
<th>Hm0 (m)</th>
<th>Water depth at the toe (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>5.0</td>
<td>6.5</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>5.5</td>
<td>6.5</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>6.0</td>
<td>6.5</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>8.0</td>
<td>6.5</td>
</tr>
</tbody>
</table>

**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.

**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).

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\textsubscript{min} (blue dashed line), Ru\textsubscript{max} (red dashed line), Ru\textsubscript{2%} (black dashed line), Ru\textsubscript{m} (green dashed line) and Ru\textsubscript{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).

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.
Table 3 and Table 4 show the Ru2% 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. Ru2% and Ru max obtained with the video analysis and with the wave gauge time series

<table>
<thead>
<tr>
<th>Test</th>
<th>Ru2%</th>
<th>Wave gauge</th>
<th>dif</th>
<th>Video</th>
<th>Wave gauge</th>
<th>dif</th>
</tr>
</thead>
<tbody>
<tr>
<td>NM_Tp14_Hs4</td>
<td>6.45</td>
<td>6.97</td>
<td>7%</td>
<td>7.44</td>
<td>8.31</td>
<td>10%</td>
</tr>
<tr>
<td>NM_Tp14_Hs5</td>
<td>7.38</td>
<td>10.22</td>
<td>23%</td>
<td>7.87</td>
<td>11.71</td>
<td>33%</td>
</tr>
<tr>
<td>NM_Tp14_Hs6</td>
<td>7.88</td>
<td>8.53</td>
<td>8%</td>
<td>7.92</td>
<td>9.68</td>
<td>18%</td>
</tr>
<tr>
<td>NM_Tp14_Hs7</td>
<td>7.88</td>
<td>9.62</td>
<td>18%</td>
<td>7.88</td>
<td>10.28</td>
<td>23%</td>
</tr>
<tr>
<td>NM_Tp14_Hs8</td>
<td>7.88</td>
<td>9.88</td>
<td>20%</td>
<td>7.92</td>
<td>10.35</td>
<td>23%</td>
</tr>
<tr>
<td>NM_Tp14_Hs9</td>
<td>7.89</td>
<td>9.90</td>
<td>20%</td>
<td>7.92</td>
<td>10.39</td>
<td>24%</td>
</tr>
</tbody>
</table>

Table 3. Ericeira. Ru2% and Ru max obtained with the video analysis and with the wave gauge time series

<table>
<thead>
<tr>
<th>Test</th>
<th>Ru2%</th>
<th>Wave gauge</th>
<th>dif</th>
<th>Video</th>
<th>Wave gauge</th>
<th>dif</th>
</tr>
</thead>
<tbody>
<tr>
<td>NM_Tp12_Hs5</td>
<td>8.11</td>
<td>5.14</td>
<td>-37%</td>
<td>8.16</td>
<td>5.17</td>
<td>-37%</td>
</tr>
<tr>
<td>NM_Tp12_Hs6</td>
<td>8.17</td>
<td>5.41</td>
<td>-34%</td>
<td>8.20</td>
<td>5.44</td>
<td>-34%</td>
</tr>
<tr>
<td>NM_Tp12_Hs8</td>
<td>8.05</td>
<td>5.78</td>
<td>-28%</td>
<td>8.13</td>
<td>6.49</td>
<td>-20%</td>
</tr>
<tr>
<td>NM_Tp14_Hs5</td>
<td>8.17</td>
<td>6.37</td>
<td>-22%</td>
<td>8.20</td>
<td>6.48</td>
<td>-21%</td>
</tr>
<tr>
<td>PM_Tp12_Hs5</td>
<td>6.14</td>
<td>4.83</td>
<td>-21%</td>
<td>6.14</td>
<td>4.84</td>
<td>-21%</td>
</tr>
<tr>
<td>PM_Tp12_Hs5</td>
<td>6.14</td>
<td>5.93</td>
<td>-4%</td>
<td>6.16</td>
<td>5.93</td>
<td>-4%</td>
</tr>
<tr>
<td>PM_Tp12_Hs6</td>
<td>6.09</td>
<td>5.81</td>
<td>-5%</td>
<td>6.11</td>
<td>6.19</td>
<td>1%</td>
</tr>
</tbody>
</table>

Regarding the Peniche case study, Fig. 13 presents the results of Ru2% and Ru max obtained by the two methodologies. The red line delimits the height corresponding to the freeboard, Rc, corresponding to the height between still water level and the crest level.

![Figure 12. TimeStack from a video of Ericeira test case study](image)

![Figure 13. Peniche. Ru2% (a) and Ru max (b) obtained with both methodologies in tests carried out with the mean water level](image)
water level, with percentual differences ranging between 21% and 37%.

Figure 14. Ericeira. \( R_{u_{20\%}} \) obtained with both methodologies in tests carried out with the mean and high water level

Figure 15. Ericeira case study. \( R_{u_{\text{max}}} \) obtained with both methodologies in tests carried out with the mean and high water levels

Figure 14 shows the results corresponding to \( R_{u_{\text{max}}} \). 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.

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