Port of Póvoa de Varzim. Wave penetration study with field data and numerical models.

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Abstract

The present work focused on a study on the port of Póvoa de Varzim, specifically on the comparison of acquired wave data from a local measurement campaign with the results provided by hydrodynamic modeling, for known offshore wave conditions, retrieved from a buoy. Three offshore extreme events were selected for this study.

Also three numerical models available on the SMS interface were used: the first one (STWAVE) propagated the offshore sea states to a nearshore area, supplying the boundary conditions to the other ones (CGWAVE and BOUSS-2D). Some numerical model limitations were not overcome within these simulations, but one of the combined simulations produced satisfactory results.

An evaluation of the tranquility in the marina area was also made, that indicated a lack of sheltering conditions in the port.

**Keywords:** wave propagation; wave agitation; measurement campaign; numerical modeling; spectral analysis; STWAVE; CGWAVE; BOUSS-2D; data buoy

1. Introduction and case study characterization

The port of Póvoa de Varzim is located at Póvoa de Varzim, 35 km north from Oporto, Portugal (see Figure 1). The harbour is sheltered by two breakwaters: the north one is oriented South-Southwest and the south one North-Northwest, allowing some overlapping between them.

There are two mooring areas, being the northern intended for fishing ships, and the southern, where a marina is located.

This study had two main objectives. The first one was to validate wave transformation numerical models, comparing acquired data from a measurement campaign with the results provided by hydrodynamic modeling, for known offshore wave conditions, retrieved from a buoy. The SMS interface was used: STWAVE propagated the offshore wave states to a nearshore area, supplying the boundary conditions to CGWAVE and BOUSS-2D. The coastline characterization, and the respective coefficients used on the two nearshore models are shown in Figure 2 and Table 1.
The second main objective was to evaluate the tranquility in the marina area. This was carried out taking into account the tranquility criteria proposed by PIANC (1997). According to the marina user’s guide, vessels longer than 18 m, wider than 11 m or with draughts deeper than 3 m have no access to the marina. Therefore, and matching the information from the two sources, one can say that the maximum significant wave height permitted in order to assume tranquility in the marina basin is 30 cm, considering the longest allowed boats.

2. Measurement campaign and data processing

2.1. Description of the equipment and measuring plan

The measurement campaign was performed with an autonomous pressure sensor Infinity-WH, built by JFE ALEC CO., LTD, programmable via PC using a USB port.

At an initial stage, due to the easy accessibility, the equipment was installed near the retention works (Location 1 – see Figure 2). Because of the apparent wave reflection phenomena that was observed at that location, the equipment was moved to a more exposed and less propitious to reflection area (Location 2 – see Figure 2).

The measuring campaign lasted from March 16th to April 27th, 2012, totaling six weeks of continuous operation, with an acquisition frequency of 10 Hz, only interrupted for the maintenance, on a weekly basis.

The measurement plan characteristics for the campaign can be observed in Table 2.

### Table 1 - Reflection coefficients used on CGWAVE model (Hartwig, 2005) and BOUSS-2D damping layers configuration (Mazzolari & Teixeira, 2009)

<table>
<thead>
<tr>
<th>Coastline material</th>
<th>CGWAVE Reflection coefficient (-)</th>
<th>BOUSS-2D Layer width (m)</th>
<th>BOUSS-2D Damping coefficient (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy beach</td>
<td>0.10</td>
<td>20</td>
<td>1.00</td>
</tr>
<tr>
<td>Tetrapods</td>
<td>0.33</td>
<td>25</td>
<td>0.10</td>
</tr>
<tr>
<td>Rip-rap</td>
<td>0.25</td>
<td>20</td>
<td>0.15</td>
</tr>
<tr>
<td>Vertical wall</td>
<td>0.90</td>
<td>10</td>
<td>0.00</td>
</tr>
<tr>
<td>Retention works</td>
<td>0.25</td>
<td>20</td>
<td>0.15</td>
</tr>
<tr>
<td>Mild slope revetment</td>
<td>0.25</td>
<td>15</td>
<td>0.15</td>
</tr>
</tbody>
</table>
2.2. Definition of the study periods

During the measurement campaign wave data from the Leixões buoy was also collected, placed about 19 km in the West-Southwest direction, in order to define the pertinent study periods.

The coordinates of the Leixões buoy are shown in Table 3.

<table>
<thead>
<tr>
<th>Location</th>
<th>Start date</th>
<th>End date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location 1</td>
<td>March 16th, 2012 16h00</td>
<td>March 30th, 2012 12h00</td>
</tr>
<tr>
<td>Location 2</td>
<td>March 30th, 2012 16h00</td>
<td>April 27th, 2012 14h00</td>
</tr>
</tbody>
</table>

Table 2 – Infinity-WH data acquisition periods at each location

The buoy records information on the significant height (Hs), mean period (Tz) and direction of the waves, amongst others. Each 10 minutes time series is followed by a processing period, after within a new time series starts.

By observing the evolution of the significant height and the mean period over time, with associated wave directions it was possible to define three extreme events – see Table 4. Although the Event 2 does not refer to a peak, it corresponds to a maximum for West direction.

The date of occurrence and the parameters that characterize the selected wave states are shown in Table 4.

<table>
<thead>
<tr>
<th>Date of occurrence</th>
<th>Direction</th>
<th>Hs (m)</th>
<th>Tz (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event 1</td>
<td>April 18, 2012 (13h00 - 18h30)</td>
<td>NW</td>
<td>6.03</td>
</tr>
<tr>
<td>Event 2</td>
<td>April 25, 2012 (08h00 - 10h30)</td>
<td>W</td>
<td>3.78</td>
</tr>
<tr>
<td>Event 3</td>
<td>April 25, 2012 (16h00 - 21h30)</td>
<td>NW</td>
<td>5.32</td>
</tr>
</tbody>
</table>

Table 4 - Definition of the study periods

As mentioned before, the data collected from the Leixões buoy is referred to 10 minutes time series. However, to ensure that the duration of the record is long enough to obtain reasonable reliable averages, but still short enough to its sea state be stationary, it was decided to consider 30 minutes intervals instead (Holthuijsen, 2007). This may result in some errors, because although the average of the mean periods of three consecutive time series of 10 minutes is the same that the mean period of a single time series of 30 minutes composed by the three aforementioned, the same can’t be said about the calculation of the significant height. This option was deemed to represent in a more reliable way the offshore wave states that will constitute the wave and boundary conditions of the hydrodynamic modeling.

2.3. Data processing

Each file produced by the Infinity-WH contains information on the pressure, distance to the surface and battery level, over time.

The procedures for the data processing are described below:
Removal of the tide component, using a moving average (240 s) of the water surface elevation (Capitão & Fortes, 2011)

Removal of the seiche component, by an analogous method, but considering 10 s for the moving average (a prior sensitivity analysis was made in order to choose this value);

Split the total time series to 30 min partial time series;

Perform a spectral analysis with FFT on these time series;

Calculate wave parameters from the obtained spectra.

Regarding this last step, the considered formulation is presented below (see equations 1-4). Two \( H_{m_0} \) equations were used in order to represent the maximum and minimum values that can be obtained according to a study that characterized the significant height with the spectral width (Vandever, et al., 2008).

\[
H_{m_0}^{\text{max}} = [4.048 - 0.432v]\sqrt{m_0} \quad (1)
\]

\[
H_{m_0}^{\text{min}} = [3.852 - 0.642v]\sqrt{m_0} \quad (2)
\]

where \( m_0 \) is the zeroth-order moment of the variance density spectrum, given by

\[
m_n = \int_0^{+\infty} f^n E(f) \, df \quad \text{for } n = \ldots -3, -2, -1, 0, 1, 2, 3 \ldots \quad (3)
\]

being,

\( f \) – frequency

\( E(f) \) – variance density spectrum

and \( v \) is a parameter (Longuet-Higgins, 1952) that evaluates the spectral width, given by:

\[
v = \sqrt{\frac{m_0 m_2}{m_1^2} - 1} \quad (4)
\]

One of the advantages of using spectral analysis is the possibility of being able to identify the main energetic components that affect the surface water level. This feature is relevant because one of the main objectives of this work is to validate numerical models, so that measured values are comparable with the ones obtained through modeling.

3. Hydrodynamic modeling

Throughout this study three numerical models available on the SMS interface were used. A first one was the STWAVE model, that computed the transformation of offshore wave data to nearshore zones, providing the boundary conditions to the CGWAVE and BOUSS-2D models, as will be described later

**STWAVE**

The STWAVE model was used in order to transform and propagate the offshore sea states to the boundaries of the two nearshore models. The main assumptions of the model are: it does not provide phase information; it requires mild slopes bathymetry; it neglects the wave reflection; it is only valid for steady-state waves, currents and winds; it considers linear refraction and shoaling, depth-uniform currents and linear radiation stress (Massey, et al., 2011).

For the STWAVE model two domains were created, one for the Northwest events, and the other to the West event, both with an 100 m grid.
The first approach was to draw an imaginary circle centered in the port of Póvoa de Varzim with a radius equal to the distance to the Leixões buoy. As the Northwest end was no longer in deep waters for the wave conditions recorded in Event 1, the Northwest domain had to be extended.

To serve as input of STWAVE, the data collected at from the Leixões buoy was then converted into spectra form, in this case, JONSWAP type spectra (Hasselmann, et al., 1973). The definition of the spectral parameters was made according to a manual of recommended practices for this kind of operation (DNV, 2011) and the STWAVE user’s manual (Massey, et al., 2011).

<table>
<thead>
<tr>
<th></th>
<th>Event 1</th>
<th>Event 2</th>
<th>Event 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Direction</strong></td>
<td>NW</td>
<td>W</td>
<td>NW</td>
</tr>
<tr>
<td><strong>Hs (m)</strong></td>
<td>6.03</td>
<td>3.78</td>
<td>5.32</td>
</tr>
<tr>
<td><strong>Tp (s)</strong></td>
<td>12.7</td>
<td>9.1</td>
<td>11.6</td>
</tr>
<tr>
<td><strong>γ (−)</strong></td>
<td>4.5</td>
<td>3.3</td>
<td>4</td>
</tr>
<tr>
<td><strong>nn (−)</strong></td>
<td>12</td>
<td>4</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 5 - STWAVE boundary conditions - spectra definition

The γ letter refers to the peak shape parameter and nn to the directional or peak dispersion factor.

STWAVE simulations allowed one to verify that there are more sudden changes on the wave height for the Northwest oriented events, due to the steeper slopes. It was also found that the distances to the port entrance from which the wave height starts to suffer changes are approximately 15, 6.5 and 14 km, for events 1, 2 and 3, respectively.

For the Northwest events, changes in the direction of the waves were noticed as they approach the shore, while for the West event the wave direction suffers practically no changes, except in very shallow areas.

For the wave periods, it was observed that there weren’t large variations from deep to shallow waters for the three simulations.

**CGWAVE**

CGWAVE model combines the effects of the refraction and diffraction phenomena included in the mild slope equation, as well as the effects of wave dissipation by friction, breaking, nonlinear amplitude dispersion, and harbor entrance losses (Dermirbilek & Panchang, 1998). This model uses a linear triangular finite element mesh, on rectangular, semicircular, or circular (when applicable) domain. It can simulate short and long waves, monochromatic or spectral, being these last ones the combination of regular wave cases, but it doesn’t allow the input of wind conditions (Briggs, et al., 2004). Several output results are obtained using CGWAVE model, among which the wave heights and the wave phases.

The CGWAVE domain was defined according to the reflection coefficients shown in Table 1 and to a sensitivity analysis made for a previous study (Pipa, 2008). A scalar paving mesh with 72272 elements and 36757 nodes was created

For each event, the STWAVE results aren’t the same across the CGWAVE ocean boundary. In order to establish the wave conditions for the CGWAVE simulations, it was decided to calculate averages of the STWAVE results in specific areas of the CGWAVE ocean boundary, depending on the dominant direction of the wave propagation.

As previously stated, CGWAVE allows the simulations of irregular waves, by combining selected regular wave cases. This approach was tried out without success, due to excessive computational time required to end successfully a simulation (the simulations were...
aborted when run time exceeded 150 h). Instead, the CGWAVE simulations were made considering only one regular wave per event, presented – see Table 6.

<table>
<thead>
<tr>
<th></th>
<th>Event 1</th>
<th>Event 2</th>
<th>Event 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude (m)</td>
<td>2.39</td>
<td>1.71</td>
<td>2.08</td>
</tr>
<tr>
<td>Period (s)</td>
<td>9.2</td>
<td>6.3</td>
<td>8.5</td>
</tr>
<tr>
<td>Direction (°)</td>
<td>330</td>
<td>0</td>
<td>335</td>
</tr>
</tbody>
</table>

Table 6 – CGWAVE boundary conditions – one regular wave by event

The results of the CGWAVE simulations are shown in Figures 3, 4 and 5. Table 7 shows the output of the wave heights calculated on the Location 2 and on the surrounding mesh nodes, for each event.

**Event 1**

![Figure 3 - CGWAVE results - Event 1](image)

**Event 2**

![Figure 4 - CGWAVE results - Event 2](image)
Event 3

Analyzing the wave phase layouts it is possible to observe the changes that the bathymetry causes on the wave direction and on the wavelength. Concerning the wave direction, the crests evolution is well noted, so that they become parallel to the bathymetry, as the depth decreases. On the other hand, the wave phase diagrams allows one to see the decrease of the wavelength, as the gap between crests gets smaller in shallower areas.

For the studied cases, in particular for the definition of the sea states as regular waves, only the Event 3 did not produced waves higher than 30 cm on the leisure ships mooring areas. In these areas, significant wave heights of 45 cm for the Event 1 and 55 cm for the Event 2 were obtained. These values widely exceed the tranquility limits recommended by PIANC (1997).

One also observed that the simulation made for the Event 2, with waves coming from West, despite being originated on less extreme boundary conditions than the other events (with Northwest oriented waves) produced higher waves in the harbour.

Also observing the wave height diagrams, and specifically in the Location 2 surrounding areas, it was noted that the wave heights recorded in consecutive nodes (spaced by 10 m) sometimes have significant differences.

BOUSS-2D

BOUSS-2D is a model for simulating the propagation and transformation of waves in coastal regions and harbors based on a time-domain solution of the Boussinesq-type equations. The equations include the effects of bottom friction and flow through porous structures. It simulates most of the hydrodynamic phenomena of interest in coastal regions and harbor basins, including shoaling, refraction, diffraction, reflection and transmission, bottom friction, nonlinear wave-wave interactions, wave breaking and runup, wave-induced currents and wave-current interactions (Nwogu & Demirbilek, 2001).
The model includes a numerical wavemaker which generates regular or irregular waves, for a necessarily rectangular domain. It allows the inclusion of damping layers to absorb the energy on the boundaries of the model and on the harbor basin boundaries.

Only Event 2 simulation will be described, as it was not possible to overcome the model limitations for the other simulations.

In this case, the wavemaker was placed 2150 m away from the harbor entrance, on a domain headed W-E (given the results from STWAVE). The waves were generated according to a JONSWAP spectrum defined with the parameters exhibited in Table 8.

<table>
<thead>
<tr>
<th></th>
<th>Event 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_s$ (m)</td>
<td>3.42</td>
</tr>
<tr>
<td>$T_p$ (s)</td>
<td>7.9</td>
</tr>
</tbody>
</table>

Table 8 – BOUSS-2D wavemaker configuration – Event 2

Similarly to what was made for the CGWAVE model, the coastline was characterized taking into account the respective type of material. On the present model, instead of reflection coefficients, damping layers, defined by a width and a damping coefficient, are used. The coastline materials are the same shown in Figure 2, and the widths and damping coefficients are the same used by Mazzolari & Teixeira (2009) (see Table 1). The bottom friction was defined by the assignment of a Chezy coefficient, considered equal to 30 (Chow, 1981), and the cell size was set to 10 m.

In order to prevent model instabilities, the depth was limited to 25 m to reduce the slope in the area of the wavemaker, and the side damping layers were removed as they were causing distortions near the wavemaker.

A wave height diagram for the Event 2 is presented in Figure 6 and the calculated wave parameters on a probe cell placed at Location 2 are shown in Table 9.

<table>
<thead>
<tr>
<th></th>
<th>Event 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_s$ (m)</td>
<td>0.15</td>
</tr>
<tr>
<td>$T_p$ (s)</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Table 9 – BOUSS-2D results – Spectral wave parameters - probe cell placed on Location 2– Event 2

Firstly, it is important to note that the simulations with BOUSS-2D for the events 1 and 3 were not successful due to model limitations, and therefore are not shown or discussed in this paper, as mentioned before.

For the Event 2, the biggest wave that hits the leisure vessels mooring areas has around 20 cm, meaning that the PIANC criterion for the tranquility evaluation is only exceeded if in that particular area there exists a ship shorter than 10 m receiving transversal waves
(this, however, due to the disposition of the mooring berths cannot happen). It was also possible to identify two energy peaks, one of which must correspond to the reflected wave. Note that the significant wave height shown on Table 9 was calculated based on the whole spectrum.

It was also possible to verify a tendency as to generate instabilities on the Northern areas of the domains, as there are visible high significant waves near the domain boundary. For the simulations performed in BOUSS-2D, the values near the Location 2 do not reveal significant changes.

4. Comparative analysis of the field data/numerical results

In this chapter the results of the measuring campaign are presented, for each event, as well as the results of the hydrodynamic modeling, when applied (see Figures 7 to 12).

**Event 1**

![Graph showing measurement campaign data vs. hydrodynamic modeling for Event 1](image1.png)

**Figure 7 – Measurement campaign data vs. hydrodynamic modeling – Significant height – Event 1**

![Graph showing peak period for Event 1](image2.png)

**Figure 8 – Measurement campaign data – Peak period – Event 1**

**Event 2**

![Graph showing measurement campaign data vs. hydrodynamic modeling for Event 2](image3.png)

**Figure 9 – Measurement campaign data vs. hydrodynamic modeling – Significant height – Event 2**
Figure 10 – Measurement campaign data vs. hydrodynamic modeling – Peak period – Event 2

Event 3

Figure 11 – Measurement campaign data vs. hydrodynamic modeling – Significant height – Event 3

Figure 12 – Measurement campaign data – Peak period – Event 3
For Event 1, by observing of Figure 7, one verifies that the results in terms of significant wave height of the numerical modeling are much lower than the obtained through the spectral analysis of the field data. As the CGWAVE model does not provide quantitative information about the period and because it was not possible to perform the BOUSS-2D simulations for the Northwest oriented events, Figure 8 shows only the progression of the peak period for the measured data. Still, for this event, the results for the CGWAVE model were only shown between 15h30 and 18h30 since the offshore sea states that led to the simulations were recorded at that time, with no explanations found for the upper significant heights that occurred before.

Analyzing the results related to the significant wave height for Event 2 (see Figure 9), note that the CGWAVE model provides an estimate far superior to the values obtained on the measurement campaign, unlike BOUSS-2D that closely agrees with them. This agreement is also apparent in the peak period (see Figure 10) since 3 s was the maximum difference obtained.

Finally, for Event 3, it can be seen that the results are similar to that obtained for Event 1, since the significant heights obtained by the numerical modeling are considerably lower than those measured, following the same order of reasons. It is not possible to make comparisons about the wave periods as well, and therefore only the evolution of the peak period for the measured data is shown.

5. Conclusions

One of the main objectives of this work was to perform a tranquility analysis to the marina of Póvoa de Varzim, comparing the results obtained from a measurement campaign with the PIANC proposed criteria that limit the significant height inside the marina to 30 cm, in this case. During the six weeks of field data acquisition three offshore extreme states (identified at the Leixões buoy) were selected, two of them with Northwest direction (Event 1 and Event 3) and a third with West direction (Event 2). It could also be interesting to select a Southwest oriented sea state, as this is the more exposed direction of the port of Póvoa de Varzim, but unfortunately there was no data available in the period of measurement.

For the measurement campaign, a pressure sensor (Infinity-WH) was installed in the marina area. The raw data had to be processed in order to calculate the relevant wave state parameters, with the removal of the tide and seiche components. The performed spectral analysis led to waves with significant wave height greater than 30 cm inside the marina for the Northwest directed events. It is also important to emphasize that the West event originated smaller waves at the data acquisition location, since the offshore conditions were not as extreme as the Northwest events.

The most usual formulation for the calculation of significant heights via spectral analysis was not applied, but an alternative one which comprises the use of the spectral width was adopted. Based on this formulation two expressions corresponding to the minimum and maximum values of significant wave heights were calculated for the range of application of two coefficients. It was concluded that the differences between the values calculated by the two expressions do not exceeded 2 cm, for the analyzed cases.

The other primary purpose of this work was the validation of numerical models usually used for design without an a priori calibration. Three SMS computational models were considered: STWAVE, CGWAVE and BOUSS-2D. STWAVE was used in order to transform the offshore agitation to the ocean boundaries of the other two models.

Computation of spectral sea states was not possible using CGWAVE because of the long computational time required for the simulations. Instead, regular waves were used. CGWAVE presented low estimates for the significant height in the data acquisition location for the Northwest oriented events and a high estimate for the West one. The use of spectral information for this case study should be investigated in future work, by performing a sensitivity analysis to the spectra shape and resolution.
Some constraints were also found in the use of BOUSS-2D, as this model did not allow one to simulate the Northwest events without generating instabilities. However, in the Event 2, where the transformation of the wave states defined as spectra was possible, the combined use of STWAVE and BOUSS-2D showed similar results to the ones obtained from the measured data, suggesting models validity.

Despite not being able to overcome the model’s limitations, it is believed that this work has reached many of the goals initially set, not only in the model validation, but also on the evaluation of the marina’s tranquility, which corroborates the user reports.

**Bibliography**


