AN ANALYSIS OF THE RESPONSE OF SINES' TERMINAL XXI BASIN TO LONG WAVES' ACTION

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Abstract

This paper describes the measurements and subsequent analysis procedures at the Terminal XXI of the Port of Sines, the operational problems at this location reported by ship authorities, and the numerical analyses carried out for the identified resonant situations during the period under scrutiny. The identified situations are studied to determine whether the reported problems are effectively due to resonance phenomena or to another nonrelated circumstance. A thorough characterization of the resonance characteristics of this harbor basin in its current configuration layout is made both using a simple approach of comparing data measured by tide gauge and buoy data, by relating characteristics of short waves and long waves within the basin, and a more complete study using wavelets to investigate the time evolution of the energy spectrum. Resonant oscillation periods of the basin are also computed with DREAMS numerical model.

1. Introduction

Some operational problems at the Terminal XXI of the Port of Sines were reported by ship authorities. Those may be consequence of resonant effects associated with the basin configuration and therefore an analysis of both wave data and reported problems was envisaged under this study. Such reported problem situations, including excessive horizontal movements of the moored ships and incidental breaking of mooring lines, were identified by the Port Authorities, who also provided data containing both short and long wave's information, from an wave buoy located offshore of Port of Sines and a tide gauge installed at Terminal XXI.

In this study one discusses the characteristics of the long period waves inside the harbor basin, as measured by a tide gauge, and the characteristics of the offshore waves, as measured by the offshore directional wave buoy of Sines, for selected wave conditions associated with identified resonant phenomena. Results of DREAMS (Fortes, 1993) model for identified situations are studied to determine whether the reported problems are effectively due to resonance phenomena or to another nonrelated circumstance. The methodology used and the long wave period numerical modeling will be analyzed in order to improve the methods and models used to attain a better understanding of the resonance phenomenon of Terminal XXI basin.

2. The Terminal XXI of port of Sines

The port of Sines is located in the south-west coast of Portugal. The basin of the Container Ships' Terminal, known as "Terminal XXI", is located in the southernmost area of the harbor and is sheltered by a 1 100 m-long rubble-mound breakwater (Figure 1), until February 2011. At the breakwater's head depths vary between 18 and 20 m while inside the basin depths are between 1 and 21 m, approximately. The berthing quay of Terminal XXI was 380 m long.

Since February 2011, an expansion plan of Terminal XXI has been under way and the eastern breakwater and quay have been modified in order to enlarge their current capabilities. Undergoing works are designed to extend the berth from 380 m to 730 m and the breakwater from 1 100 m to 1 500 m. That harbor basin has experienced wave resonance episodes, due to long waves, with occurrence of excessive wave heights inside the basin and significant horizontal movements of

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moored ships, before and during the expansion works. This type of phenomenon caused operational problems, particularly related to the disruption of port operations and also breaking of mooring lines.

Figure 1. Port of Sines. Terminal XXI configuration (until February 2011).

From February to December 2012, a number of works were performed at Terminal XXI by CONDURIL, which implied a new layout to the Terminal XXI basin, Figure 2 and Figure 3.

Figure 2. Port of Sines. New Terminal XXI layout as of May 2012. Google Earth$^{©}$ image and drawing provided by APS, the Port of Sines Authority, S.A..

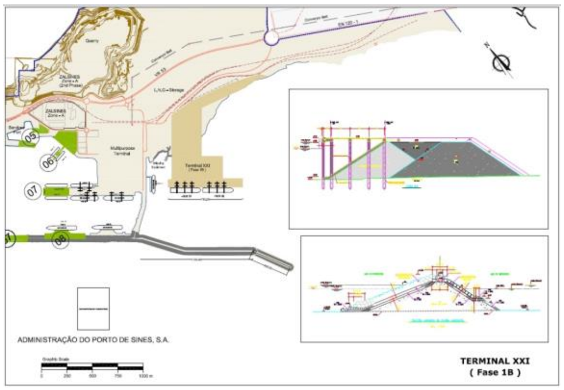

Figure 3. Port of Sines. New Terminal XXI layout as of March 2013. Drawing provided by APS.

To study the response of this basin to the action of long waves and to improve the local knowledge of the resonant phenomena, field data obtained inside the basin for a representative set of resonant episodes were analyzed, and the determination of resonant oscillation periods of the basin itself, using the numerical model DREAMS, was computed, Fortes *et al.* (2012) and Neves *et al*. (2013).

To analyze this resonance phenomenon within the basin DREAMS numerical model was applied considering a wide range of wave periods, in order to characterize the basin response curves (which reflect the variation of the wave heights at a given point dependent on the oscillation period). The numerical results are compared with the field data for the days where resonant problems were recorded at the Terminal XXI during 2012 winter.

3. Analysis of in-situ measurements

3.1 Data available

Tide levels and surface elevations were obtained by a tide gauge provided and operated by the Hydrographic Institute (HI) at a point inside the harbor basin, between December 22nd, 2011 and June 20th, 2012, see Figure 4. Data from an offshore waverider buoy located in front of the harbor in the same period of time was also used to identify resonant episodes.

Figure 4. Location of the tide gauge at the new Terminal XXI (source: Hydrographic Institute - HI).

The tide gauge data were preprocessed by HI by separating raw data into the following components: a) sea wave component (wave periods up to 32 s); b) long wave component (periods from 32 to 8192 s) and tide component (waves longer than 8192 s). In the above recording period (from December 22nd , 2011 to June 20th , 2012), PSA International (PSA) identified three problem occurrences on ships moored at Terminal XXI: from 23 to 31 October 2011; 3, 4, 19, 20, 22 and 23 November 2011; 15 December 2011; and also 3 January 2012, 25 February 2012 and 3 March 2012. Note, however, that, during this period, the harbor basin has experienced a number of geometrical changes, as referred, due to ongoing maritime works and also to the enlargement of the berth and breakwater.

3.2 Descriptive analysis of data

Between November 2011 and June 2012, at Sines offshore buoy the following storms (wave records associated with $Hs > 5$ m) were identified: i) on 24 and 27 October 2011; ii) on 3, 4 and 22 November 2011. These conditions would be, according to the PSA technicians, the most serious ones for ship maneuvering when docking at Terminal XXI. It should be noted that there were no occurrences of problems between January and June 2012.

Wave directions at the buoy were found to fall within the range W-NW, to which resonant problems within the basin were referred to. The days when problems in the terminal were identified do not always agree with storm conditions: only the storm of 3 and 4 of November 2011 agrees with the days where there was a record of “broken mooring lines" and the storms of 24 and 27 October agree with the days where there were records identified as "ship is moving due to waves". From November 2011, although there are some references to occurrences of “broken mooring lines”, no storms were reported at Sines offshore buoy.

In the days when there were problems in the terminal or a storm was identified at the buoy, the sea wave conditions were measured by the tide gauge located at Terminal XXI (Figure 4). Table 1 shows the characteristics of short-period waves (significant wave heights, $Hs\_{}_{OC}$, and average and peak periods, $Tz\_{}_{OC}$ and $Tp\_{}_{OC}$ respectively) and long-period waves ($Hs\_{}_{OL}$ and $Tp\_{}_{OL}$), obtained from the data collected by the referred to tide gauge installed at Terminal XXI. It should be noted that between November 19 and December 22, 2011 no tide gauge data exist.

Table 1. Sea wave conditions at the Sines offshore buoy and tide level conditions at Terminal XXI, for problematic events identified at the harbour basin - April 2011 and June 2012 storms.

		Tide level gauge				
DD-MM-YYYY	**Observation**	**Hs_{OC} (m)**	**Tz_{OC}(s)**	**Tp_{OC} (s)**	**Hs_{OL} (m)**	**Tp_{OL} (s)**
23-10-2011	Horizontal movements of moored ships	0.16	4.2	7.5	0.06	671.7
24-10-2011	Storm and horizontal movements of moored ships	0.24	4.4	8.3	0.08	649.6
25-10-2011	Horizontal movements of moored ships	0.27	3.8	11.3	0.09	149.5
27-10-2011	Storm and horizontal movements of moored ships	0.27	4.0	9.3	0.12	153.2
28-10-2011	Horizontal movements of moored ships	0.15	3.7	9.9	0.06	726.1
29-10-2011	Horizontal movements of moored ships	0.13	6.2	17.8	0.10	659.5
30-10-2011	Horizontal movements of moored ships and breaking of mooring lines	0.18	6.6	17.6	0.19	157.7
31-10-2011	Breaking of mooring lines	0.23	3.8	15.4	0.10	617.1
03-11-2011	Storm and breaking of mooring lines	0.26	7.1	17.8	0.27	159.4
04-11-2011	Storm and breaking of mooring lines	0.23	5.4	16.2	0.16	159.1
03-01-2012	Breaking of mooring lines	0.09	5.2	16.7	0.04	682.6
25-02-2012	Breaking of mooring lines	0.22	4.0	15.6	0.09	177.4
03-03-2012	Breaking of mooring lines	0.21	3.9	15.2	0.08	168.1

For the studied cases, significant wave heights associated to long waves were found to be quite relevant (between 0.04 m and 0.27 m) and their recorded highest values do not always agree (or belong) with storm periods. Also, a clear relationship between significant wave heights of both long waves and short waves is not apparent. The peak periods associated with long waves belong to two distinct frequency ranges (from 150 to 177 s and from 617 to 726 s). By analyzing the conditions for days where no operational problems were identified at Terminal XXI, one found that significant wave heights of both short waves and long waves were much lower than those recorded on days were problems were identified. However, peak period, of both short and long waves, are within the same range of values for days with and without operational problems, although the range of periods with significant energy is much narrower for days with operational problems; in other words, the same peak period of the waves can either generate or not generate operational problems at the Terminal XXI, depending on the associated significant wave height.

3.3 Wavelet analysis of data

For a deeper analysis of the resonant phenomena, a wavelet study was made in this paper by relating the characteristics of measured short and long waves within the basin. Thus, time evolution of the spectra of the measured signals at the basin is made in what follows, This analysis was restricted to existing tide gauge data since time series measured at the offshore buoy were not readily available at the time of the study. For the buoy, only tri-hourly values of significant wave height, peak period and mean wave direction are available.

Figure 5 shows the energy spectrum (wavelet) calculated for October 29th, 2011, a day where no storm conditions were identified at Sines (according to the buoy observations). However, significant ship movements were observed at Terminal XXI.

It is interesting to observe that in the early hours of the day, the maximum wave energy was attained for very long wave periods, of the order of 600-700 s, values that are of the same order of magnitude of the peak period (660 s) calculated assuming that the whole data is available for that day. Incidentally, for this range of periods, associated energy decreases considerably throughout the day. In the last hours of that day, there remain periods with increased energy of the order of 170 s (between 155 is 225 s), although there was still some energy in a range of higher periods. For this range of periods, one can observe nodes located in the area of berth, which may explain the observed, undesirable, movements on ships.

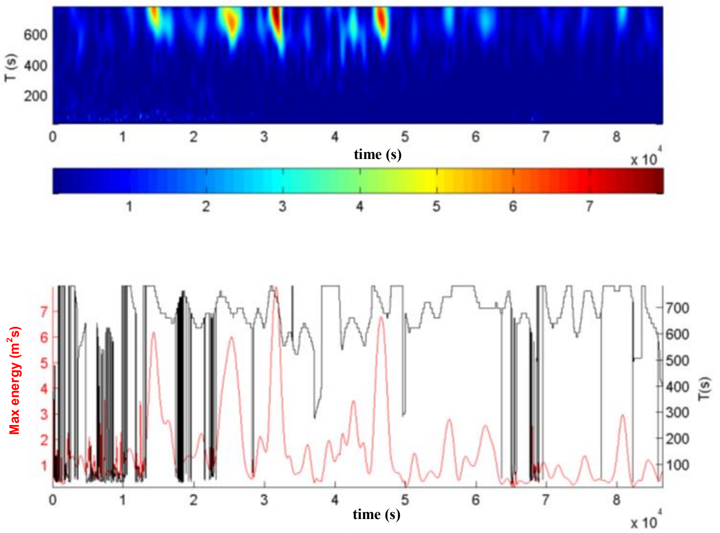

Figure 5. Time evolution of long-waves energy spectrum (wavelet) for October 22nd, 2011.

3.4 Fit analysis of data

Complementary to the wavelet analysis, a global fit analysis was made on data measured by the tide level gauge and the wave buoy. Therefore, one looked for a relationship between short waves, as measured by the buoy or predicted by numerical models, and the long waves measured inside the Terminal XXI basin, based on equation (Hernández, 2005):

$$Hs_{\_OL}=K\ Hs_{\_OC}^{\alpha}\ Tp_{\_OC}^{\beta} \tag{1}$$

where $Hs_{\_OL}$ and $Hs_{\_OC}$ are, respectively, the long and short wave significant wave heights, $Tp_{\_OC}$ is the short wave peak period and K, α and β are fitting coefficients. To get this relationship, simultaneous values of $Hs_{\_OL}$, $Hs_{\_OC}$ and $Tp_{\_OC}$ were considered to obtain a surface fitting function with coefficients K, α and β computed by finding the lowest sum of squared absolute error between experimental data and the values given by the surface model function.

To estimate the values of the three parameters, α, β and K, to existing data, it was necessary to previously calculate tri-hourly $Hs_{\_OL}$ and $Tp_{\_OL}$ values based on tide gauge data measured in the period between April 2011 and June 2012. The calculation was done by analyzing the energy contained in frequencies between 0.0013 Hz and 0.02 Hz, which correspond to periods between 50 to 770 s. As no information was available to allow one to select which spectral data was associated with so-called "swell" offshore sea states, one decided, initially, to select only the data corresponding to $Hs_{\_OC}> 3.5$ m. This selection allowed one to establish a sample containing trios of values, with size 58 (Figure 4), a sample that although somewhat small sized it may give some useful indications of a possible relationship between $Hs_{\_OC}$ and $Hs_{\_OL}$ parameters.

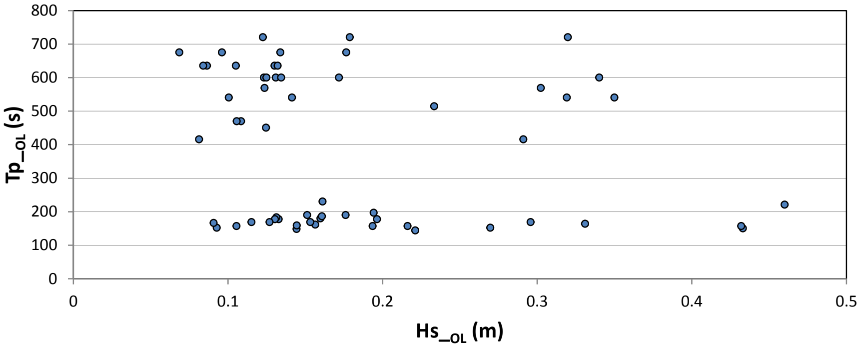

Figure 6. Three-hourly values of $Hs_{\_OL}$ associated $Tp_{\_OL}$ for $Hs_{\_OC} > 3.5$ m, from April 2011 to June 2012.

Although, as mentioned above, the number of data (58) considered for this analysis is clearly insufficient to draw definitive conclusions, the obtained fit was deemed quite good, with a correlation coefficient of 0.90 and a root mean square error (RMSE) of only 0.041. Based on a 3D adjustment (fitting surface) of the data to equation (1), one obtained the following estimates of the coefficients of that equation: $\alpha = 1.32$; $\beta = 1.71$ and $K = 0.0000288$. These obtained coefficients are within the values proposed by other authors, such as Hernandez (2005).

4. DREAMS application

4.1 Introduction

The DREAMS finite element model (Fortes, 1993) was used to analyze the behaviour of the harbour basin to different incident long waves. The configuration of the harbour considered in this study corresponds to an intermediate one between configuration of February 2011 and the final configuration of the harbour, namely the configuration presented at Figure 2. This configuration is the closest to the situation verified at the time of measurements to be analysed in this paper.

4.2 DREAMS application

For the application of DREAMS model, the following procedure was considered:

- Establishment of the set of long wave characteristics;
- Definition of the calculation domain and the corresponding finite element grid by using the automatic generator GMALHA, Pinheiro *et al.* (2006);
- Propagation of the long regular waves:
    - Calculation with DREAMS model;
    - Determination of the response curves in selected points in the domain.

The tested regular waves were characterized by periods between 20 s and 600s , with a 20 s interval, and wave directions of SW (225º), WSW (247.5º) and W (270º). Two tide levels were considered: +2.0 m (CD) - average level - and +4.5 m (CD) - high level. The computational domain and bathymetry used are shown in Figure 7.

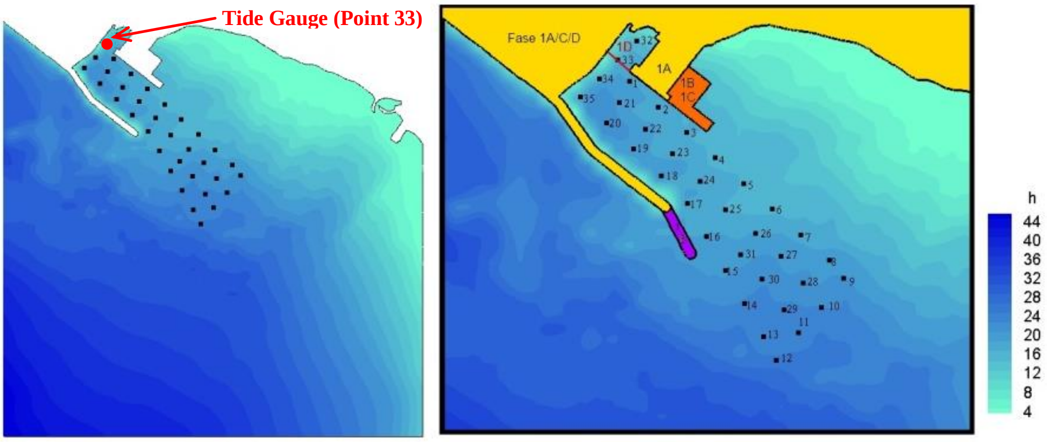

Figure 7. Bathymetry and calculation domain of DREAMS. Point for the determination of curve responses.

The domain was discretized by a finite element mesh with 172 329 nodes and 342 599 elements. The number of points per wavelength is 55 in the whole domain area, for a period of 20 s. Note that the larger the period the longer the wavelength and, consequently, the number of points per wavelength is always higher than 55, for the cases tested in this study.

Reflection coefficients in all boundaries were kept constant, equal to 1.0, since for this range of periods all boundaries acted as total reflective surfaces.

4.3 Results

For the above conditions, DREAMS results consisted of diagrams of amplification coefficients in the entire field of computation and corresponding values at the selected points located within the harbour basin shown in Figure 7.

Based on the results of DREAMS at point 33 (see Figure 7), which is the point located in the tide gauge position, response curves (which show the amplification coefficient variation with the period of oscillation) were computed for selected directions of incident waves and tide levels. Figure 8 shows the response curves for point 33, for both average tide level (+2.0 m CD) and high tide level (+4.5 m CD).

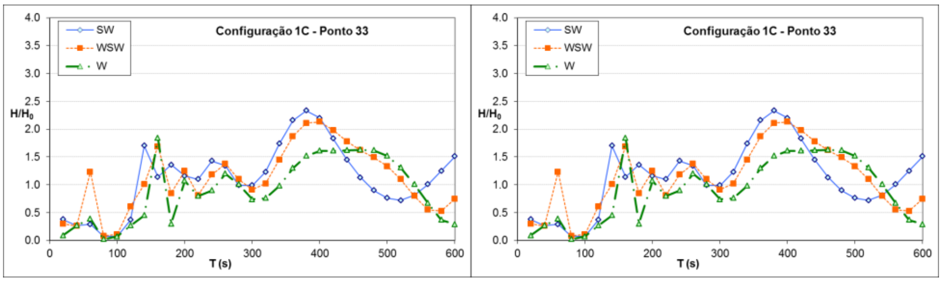

Figure 8. Point 33. Response curves for the average tidal level (+2.0 m CD) and high tide level (+4.5 m CD).

As an example, Figure 9 shows the amplitude coefficients for SW wave direction and periods 80, 100, 380 and 480 s.

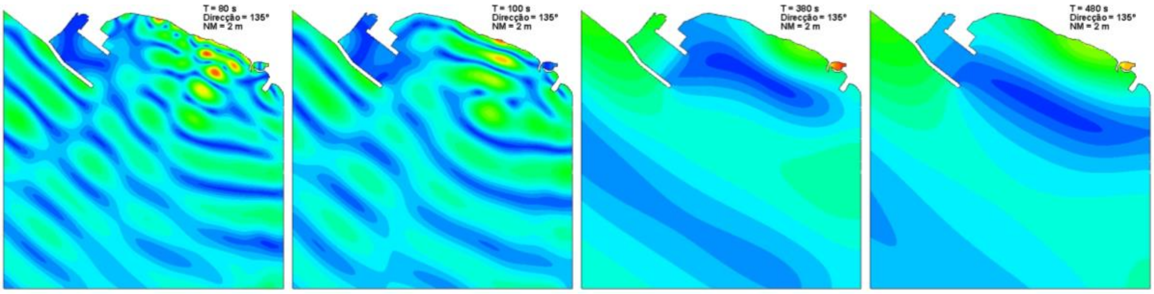

Figure 9. Amplification coefficients´ diagrams for wave periods of 80 s, 100 s, 380 s and 480 s.

In general, resonance occurs for three ranges of periods, 140-160 s, 240-260 s and 340-420 s, in the case of (+2.0 m CD) tide level, depending on the wave direction. For the tide level of (+4.5 m CD), the number of ranges associated with resonance situations is lower, i.e., only two ranges: 140-160 s and 240-260 s. In all configurations there are cases of resonance conditions associated with periods longer than 600 s for both tide levels tested.

For several resonant conditions, the area associated with higher values of the amplification coefficient is the area of the inner harbour basin of Terminal XXI. Although the values of the amplification coefficient do not exceed 4.0 for any of incident wave conditions and tide levels tested, the corresponding velocities are significant, especially along the berth areas. Those velocities can cause problems for ships moored at that location. Moreover, the nodal zone along the berth is located nearest the entrance to the inner harbour in the case of resonance with lower periods and deviates from that area for periods longer than 240 s to 260 s.

5. Comparison between in situ measurements and numerical calculations

A comparison between the numerical results and the measured data at the tide gauge for the days where resonant problems were recorded at the Terminal XXI is made in this section. The main goal is to identify to the resonant wave periods at the Terminal XXI basin and compare it with the measured periods associated with problems occurred in the harbour basin (vessels moving or broken mooring lines).

Problems occurred inside the basin between October, 23rd and November 4th, 2011. In this period, three ranges of peak periods associated with the more energetic conditions (30 s < $Tp_{\_OL}$ < 100 s, 100 s < $Tp_{\_OL}$ < 250 s, 250 s < $Tp_{\_OL}$ < 350 s), were identified based upon data measured inside the basin. For each of these ranges, a new long wave peak period was defined and is presented in Table 2.

Table 2. Peak wave periods measured at the tidal gauge located inside the o Terminal XXI on October 23rd, 25th, and 27th to 31st, 2011 and 3rd and 4th November, 2011.

DD-MM-YYYY	**Observação**	**Tp (s)**		
		30s < $Tp_{\_OL}$ < 100 s	**100 s < $Tp_{\_OL}$ < 250 s**	**250 s < $Tp_{\_OL}$ < 350 s**
23-10-2011	Horizontal movements of moored shipd	62	159	300
24-10-2012	Storm and horizontal movements of moored ships	63	155	327
25-10-2012	Horizontal movements of moored ships	62	149	270
27-10-2012	Storm and horizontal movements of moored ships	69	153	286
28-10-2012	Horizontal movements of moored ships	64	163	334
29-10-2012	Horizontal movements of moored ships	63	200	281
30-10-2012	Horizontal movements of moored ships and breaking of mooring lines	62	158	284
31-10-2012	Breaking of mooring lines	63	200	281
03-11-2012	Storm and breaking of mooring lines	67	159	301
04-11-2012	Storm and breaking of mooring lines	64	159	288

For each of these three ranges, the resonant periods based on the analysis of the amplification coefficients resulting from DREAMS model were identified, leading to a narrower range of periods to be analysed. Consequently, DREAMS model was applied considering three ranges of long wave periods, with a 2 s step: between 54 and 72 s, between 140 s and 200 s and between 270 and 340 s. All calculations were made for (+2.0 m CD). As an example, Figure 10 shows the amplification coefficients for regular wave periods coming from S, with T=62 s and T=160 s. For both periods, a node is clearly visible at the berth location.

For $Tp_{\_OL}$ greater than 350 s the nodal line does not cross the berth area and therefore, for these conditions, horizontal movements of moored ships due to resonance are not expected to occur.

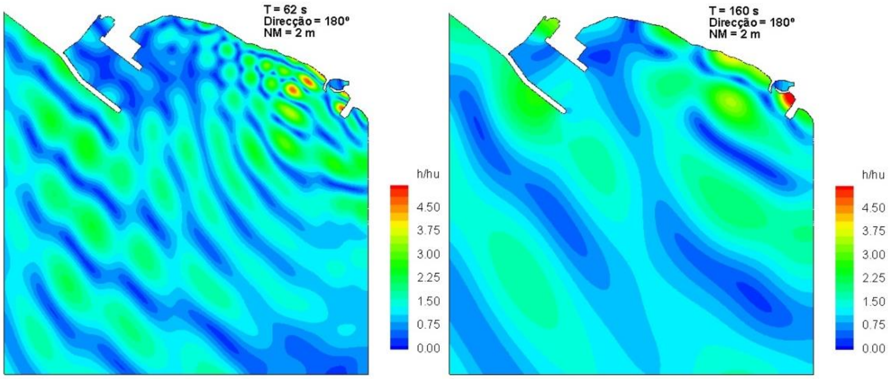

Figure 10. Amplification coefficient for wave periods T=62 s and 160 s. Tidal level of (+2 m CD) and wave direction of S.

Figure 11 shows the amplification coefficients, H/Ho, for the range of periods selected for model application and for the tide level of (+2.0 m CD). The results are compared with the values of the long wave peak periods measured by the gauge between October 23rd and November 4th, 2011, shown in Table 2.

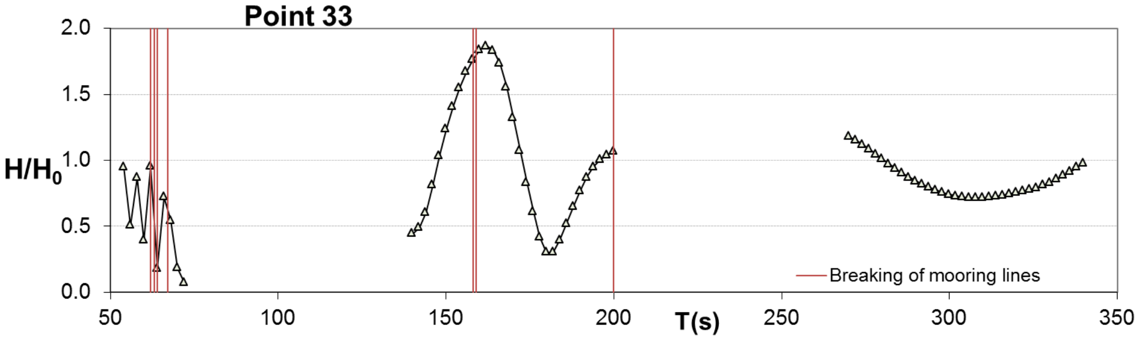

Figure 11. Amplification coefficients at point 33. for tidal level (+2.0 m CD)

For this tide level, the higher amplification is obtained for the range between 140 and 200 s, in particular for periods between 150 s to 160 s, corresponding to the periods of higher energy in tide gauge measurements, see Table 2. For the other range of periods, usually less energetic, the amplification obtained with the model is always less than 1.5, i.e., no significant amplification of the incident wave is apparent in the numerical model results.

Summing up, it was found that, for the selected days considered in this study, the periods measured by the tidal gauge and the occurrence of problems of broken mooring lines or horizontal movements of mooring ships generally agree with the resonance periods obtained by the numerical model for this configuration (which is the closest to the situation at the time of the measurements). That indicates that the model is adequately reproducing the phenomenon.

6. Conclusions

Based on data collected at the tide gauge located within Terminal XXI basin between April 2011 and June 2012 and also on the wave data coming from the offshore wave buoy at Sines, one made a brief analysis of the possible primary resonance conditions and a more detailed analysis of the time evolution of the spectrum within the basin, using wavelets.

An equation relating the significant wave height of long waves ($Hs_{\_OL}$) and the significant wave height and peak period of short waves ($Hs_{\_OC}$ and $Tp_{\_OC}$) inside the harbor basin was found. Although the number of data (58) used in this analysis was deemed insufficient to draw definitive conclusions, the obtained fit was reasonably good, with a correlation coefficient of 0.90 and a root mean square error (RMSE) of only 0.041.

The practical interest of this relationship may however be extended if one increases the period of analysis, to enable a better fit. Therefore, this analysis should be supplemented by an in-depth analysis of the measured data at the directional buoy and at the tide gauge of Sines Terminal XXI for a larger number of problematic situations, for which the PSA has verified resonant phenomena (additional information to be provided) and for a stable configuration of the basin.

Resonance calculations with the numerical model DREAMS were made for a terminal configuration corresponding to an intermediate situation between the initial situation and the planned end of expansion works and the closest to the configuration for the period of data analysed in this paper. The calculations with the numerical model were done for a tidal level (+2.0 CD) and (+4.5 m CD) and for wave periods between 20 s and 600 s. It was found that, in general, resonance occur for three ranges of periods, 140-160 s, 240-260 and over 420 s, for tide level (+2.0 m CD). For tide level of (+4.5 m (CD), the number of ranges associated with situations of resonance is only two (140-160 s and 240-260 s). There are also resonance situations associated with periods longer than 600 s, for both tide levels tested. Usually, the inner zone of the Terminal XXI basin, where the tide gauge was fixed, shows the largest resonant amplifications. Although the amplification does not exceed 4.0 for any of the conditions tested, for some cases a nodal zone (the corresponding velocities are expected to be significant) is presented along the berth and nearest the entrance to the inner harbour in the case of smaller periods. Ships moored at those locations are more susceptible to experience large movements. For periods larger than 350 s there is no nodal zone at the berth.

Finally, it was found that for the occurrences of broken mooring lines and horizontal movements of moored ships (observed by PSA, since February 2011) on the analysed days (between October 24th and November 3rd, 2011) there is an agreement between the resonance periods given by the numerical model for the configuration tested (which is the closest to the situation in which measurements were carried out), and the periods of highest energy measured by the tidal gauge. This indicates that the model is adequately reproducing the phenomenon. The model leads to higher values of amplification for periods between 150 and 160 s, and these were the periods of highest energy on the days when problems were reported within the Terminal XXI basin.

This analysis will be completed by studying the transformation of sea waves from offshore to the interior of the XXI Terminal, at the Port of Sines, for the days when problems within Terminal XXI were identified. In particular, it is intended to transfer some sea wave conditions measured by the Sines wave buoy using two numerical models (SWAN, Booij *et al., 1999*, and DREAMS) to: a) the inner Terminal XXI basin, where tide gauge data are available b) to the position of an ADCP equipment, that was, for a short period of time, collecting data along the coastal bay of St. Torpes. This analysis will enable a better validation of the numerical models.

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