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Wave Disturbance Modelling in the Port of Sines, Portugal – with special emphasis on long period oscillations

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ABSTRACT

Shortly after the extension of the Multipurpose Terminal in the Port of Sines, Portugal in 1998-99, severe mooring problems were experienced during a storm. One of the reasons for this incident was attributed to the recent extension of the quay.

In order to determine more accurately the effect of the quay extension on the wave disturbance in the Multipurpose Basin, an extensive numerical model study was launched. This study investigated the wave disturbance both due to short-period waves and long-period oscillations. In order to analyse the potential long-period oscillation modes of the Multipurpose basin, the natural wave trains were replaced by a synthetic sea state generated on the basis of a so-called 'white noise' spectrum, which is characterised by having equal amounts of energy on all frequencies. Although not representative of a realistic natural sea state, the simulations with the 'white noise' spectrum revealed in a very clear manner the potential resonance periods and patterns of the Multipurpose Basin.

This paper presents the numerical modelling study carried out for the Port of Sines, with special emphasis on the method used to investigate the long-period resonance patterns of the Multipurpose Basin. The method proved very efficient and is generally applicable for investigating resonance patterns and long-period oscillations in other ports and harbours. Finally, recommendations are presented for minimising long-period wave disturbance in the Multipurpose Basin of the Port of Sines.

1 INTRODUCTION

The Port of Sines is located on the Atlantic coast of Portugal about 100 km south of Lisbon. The area is occasionally exposed to rather severe wave conditions.

In 1998-99, the Multipurpose Terminal, which is located in the eastern part of the Port of Sines (see Fig 1), was ex-tended by approximately 300m towards northwest, ie parallel with the eastern breakwater. The total length of the Multipurpose quay is now around 600m.

Fig 1 Present layout of the Port of Sines

After completion of the quay extension, mooring problems have been experienced at the Multipurpose Terminal. The worst incident occurred in December 1998, where several mooring lines on a bulk carrier (with L_{OA} = 370m) broke a number of times.

After the incident, it was suggested that the mooring problems were caused by the quay extension. However, other reasons such as wave reflections from the slope of the causeway connecting the eastern breakwater with the Multipurpose Terminal and the increased level of degradation of the remains of the old western breakwater (which failed prior to its completion in 1978-79) have also been suggested to play an important role.

The objective of the numerical model study performed for the Port of Sines was to determine whether the extension of the Multipurpose quay has changed the wave conditions at the Multipurpose Terminal in such a way that it can be concluded that the extension was a plausible cause for the experienced mooring problems.

This paper describes the numerical modelling applied in order to investigate the wave disturbance problems at the Multipurpose Terminal of the Port of Sines. The modelling approach is described and the results of the modelling are presented. Finally recommendations are given for minimising the long-period wave disturbance in the port. Long-period oscillations is a common problem for ports located on ocean coasts, see eg [1,2]

2 NUMERICAL MODELLING

The numerical model applied for modelling of the wave propagation into the Port of Sines was the Boussinesq Wave Module of DHI's MIKE 21 numerical model (MIKE 21 BW). This model is a time-domain model based on the numerical solution of the two-dimensional (2D) Boussinesq equations derived by Madsen et al (1991, 1992), which include non-linearity as well as improved frequency dispersion [3,4]. This makes the model suitable for simulation of the propagation of wave trains travelling from deep water to shallow water resolving the primary wave motion as well as the bound and free long waves. Further, the model is capable of reproducing the combined effects of most of the wave phenomena of interest to the harbour engineer. These include shoaling, refraction, diffraction and partial reflection of irregular, finite-amplitude waves propagating over complex bathymetries. Wave breaking is also included in a research version of the model as well as moving shoreline boundary conditions for simulation of swash zone dynamics, see Madsen et al (1997a, b) and Sørensen et al (1998), [5,6,7]. However, this model is not yet feasible to cover larger model areas, since the computation time is too extensive with the presently available CPU speeds.

As MIKE 21 BW is a non-linear model, it allows for the modelling of non-linear interactions between different components of the primary wave spectrum. These interactions are known to be important for the forcing of long waves, which may lead eg to seiching and resonance in a port. Even without any low-frequency motion imposed at the 'wave generation' boundary of the model, these low-frequency motions will still appear in the model as a result of non-linearity.

The applied Boussinesq equations allow for simulation of waves in relatively deep water (up to h/L~0.5, h being the water depth and L being the wave length, [3]), which is of importance for studying the wave disturbance in a deepwater port such as the Port of Sines. Figure 2 shows the applied model bathymetry corresponding to the present conditions.

The main objective of the study was to compare the long period wave disturbance in the Multipurpose Basin for different layouts of the Port, especially before and after the construction of the quay extension in 1998-99. For this purpose, simulations were carried out with mainly two different types of wave conditions:

(a) Simulations with a so-called 'white noise' spectrum, which is characterised by having equal amounts of energy at all frequencies.
(b) Simulations with the storm wave condition during the incidents in December 1998. It was informed that the wave direction during the incidents was 290ºN. The significant wave height was H_{m0} = 3-5m and the mean zero-crossing period was T_z ~ 12s. For a Pierson-Moskowitz spectrum, this corresponds to a peak period of T_p ~ 17s.

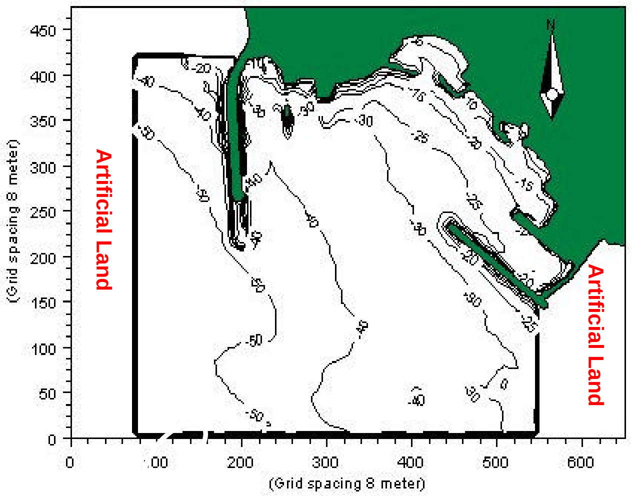


Fig 2 Applied model bathymetry (present conditions)

2.1 Port Layouts Investigated

In total, seven different layouts of the Port of Sines were investigated (see Fig 3):

Layout 1: Original layout before construction of the extension at the Multipurpose Terminal

Layout 2: Present layout (ie, including quay extension)

Layout 3: As Layout 2 but with the remains of the old western breakwater established at –10m ZH

Layout 4: As Layout 3 but with a less reflective slope of the causeway at the eastern perimeter of the Multipurpose Basin

Layout 5: Present layout but with reconstructed western breakwater

Layout 6: Present layout with the eastern breakwater extended by 200m

Layout 7: Present layout with a 200m spur breakwater at the head of the eastern breakwater

3 WHITE NOISE SIMULATIONS

The purpose of the white noise simulations was to investigate the *potential* for seiching (long wave oscillations) in the Multipurpose Basin and especially to investigate whether the quay extension of the Multipurpose Terminal has resulted in differences in the principle seiching modes of the basin. Thus, only ayouts 1 and 2 were investigated with the white noise spectrum.

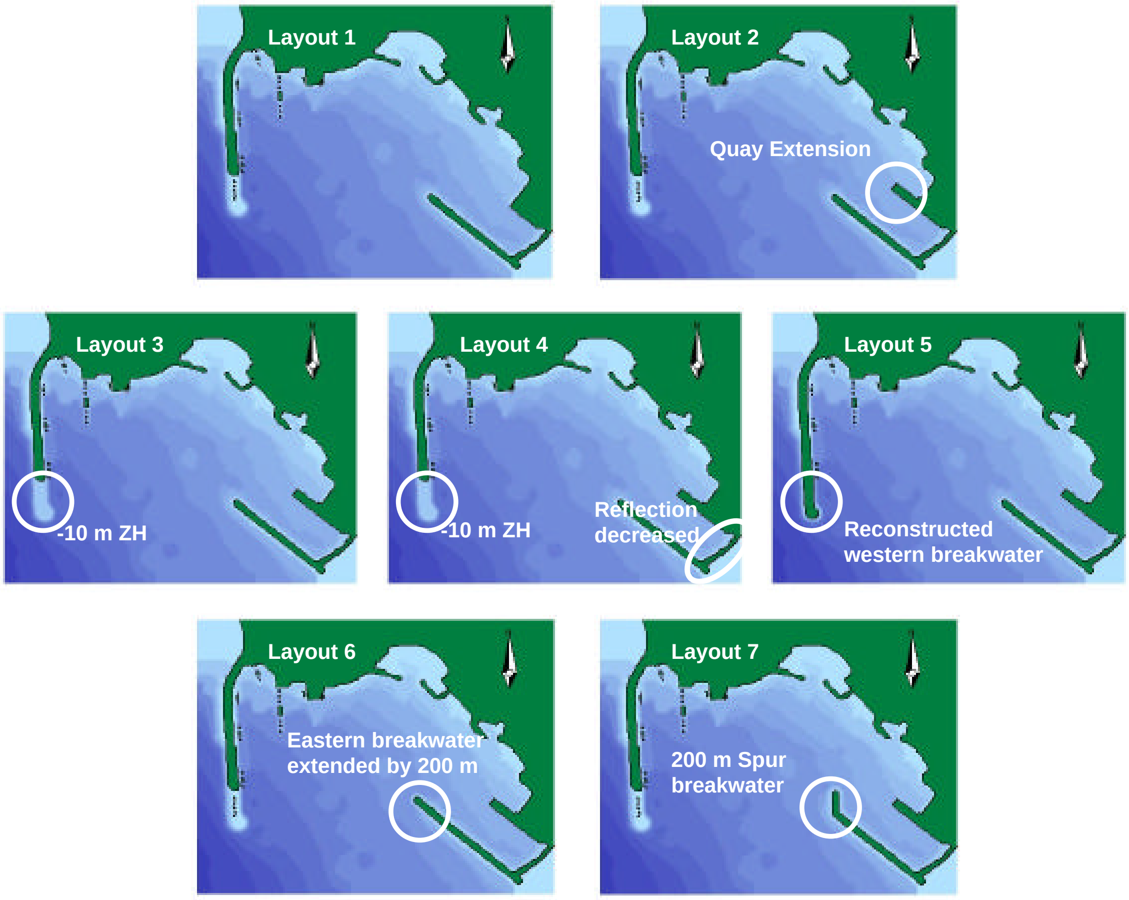


Fig 3 Investigated layouts of Port of Sines.

Although not representing a natural sea state, simulations with white noise spectra can reveal in a very efficient and clear manner the resonance periods of the port layouts investigated. The applied white noise spectrum represented periods from 20s to 500s. The white noise spectra were simulated as unidirectional waves from W.

It must be stressed that since the white noise spectrum represents a synthetic sea state, the results of the simulations can only be used as basis for a general comparison of the layouts. Hence, it cannot be concluded on basis of the white noise simulations whether or not long-period oscillations or resonance will actually develop under natural wave conditions. This has to be investigated using a natural sea state (see Section 4).

On the basis of extracted time series of surface elevations, spectral analyses of the white noise signals were performed in order to determine the different natural oscillation periods in the Multipurpose Basin. An example of a calculated wave spectrum in the Multipurpose Basin, which clearly shows the peaks corresponding to the different oscillation modes, is shown in Fig 4.

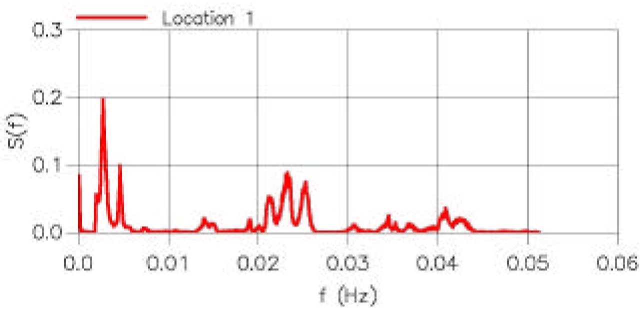


Fig 4 Example of calculated wave spectrum of the white noise signal in the Multipurpose Basin.

Table 1 Selected frequency bands for detailed analysis of wave energy in the Multipurpose Basin

Band No	Frequency range	Period range
1	f = 0.002 Hz – 0.0037 Hz	T = 270 s – 455 s
2	f = 0.0037 Hz – 0.0053 Hz	T = 189 s – 270 s
3	f = 0.0067 Hz – 0.0167 Hz	T = 60 s – 149 s
4	f = 0.0167 Hz – 0.0270 Hz	T = 37 s – 60 s
5	f = 0.0270 Hz – 0.05 Hz	T = 20 s – 37 s

On basis of the wave spectra obtained at different locations in the Multipurpose Basin, five frequency bands (or period ranges) were selected for detailed analysis of the wave energy within each band. The selected frequency bands are shown in Table 1. The wave energy was determined within each frequency band for an area covering the entire Multipurpose Basin.

As a measure of the wave energy within each frequency band, a characteristic wave amplitude (a_c) was used. This amplitude is defined as:

$$a_c = \sqrt{2m_0}$$

where m_0 is the 0^{th} moment of the wave spectrum within the considered frequency band. Since the white noise spectrum is a synthetic sea state, the characteristic amplitude (a_c) has no physical meaning, but is only a measure of energy.

In Table 2, the intensity of a_c in the Multipurpose Basin is shown for Layout 1 (original layout) and Layout 2 (present layout). The more redish the colour, the more intensive the wave energy.

To illustrate the oscillation modes dominating the different frequency bands, Table 2 also presents envelope plots of the surface elevations along the longitudinal and transverse lines in the basin (see Fig 5).

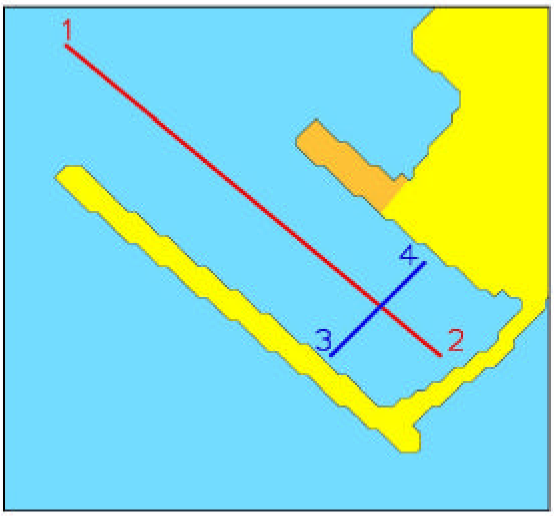


Fig 5 Extraction lines for surface elevation envelopes in the different frequency bands.

Table 2 clearly illustrates the potential natural oscillation modes of the Multipurpose Basin. However, it is important to keep in mind that it cannot be concluded that these oscillation modes will develop during natural sea states. For a natural sea state to trigger an oscillation mode, it must contain wave energy at the given oscillation periods. Alternatively, the natural oscillation mode can be triggered by non-linear wave-wave interactions in the incident wave train. The presence of long-period waves in the basin during a natural sea state is investigated in Section 4.

The potential long-period oscillation modes illustrated in Table 2 are described in the following:

Longitudinal Mode 1

The first natural oscillation mode of the Multipurpose Basin has a peak period of around 360s for both layouts. The natural oscillation mode is governed by the length of the eastern breakwater and corresponds to quarter of a wavelength ($^1/_4 \cdot L$) with antinode at the bottom of the basin and node outside the head of the eastern breakwater. Since the present layout is more closed than the original layout, the wave energy is more confined. Therefore, the intensity of the wave energy is slightly increased for the present conditions (ie after the quay extension) relative to the original layout.

Longitudinal Mode 2

This natural oscillation mode peaks at 213s for the original layout and at 233s for the present layout. The oscillation mode is partly governed by the length of the quay of the Multipurpose Terminal, and is thus influenced significantly by the quay extension (which is the reason for the different peak periods). The oscillation mode corresponds to quarter of a wavelength ($^1/_4 \cdot L$) with antinode at the bottom of the basin and node somewhere between the head of the eastern breakwater and the SE end of the quay of the Multipurpose Terminal. The intensity of the oscillation mode is slightly increased for the present conditions (ie after the quay extension) relative to the original layout.

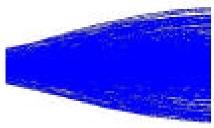
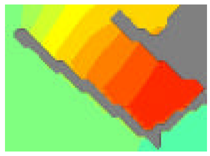
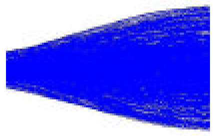
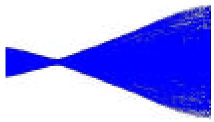
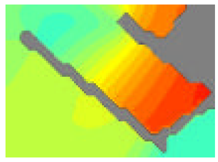
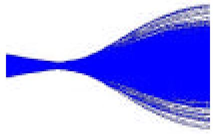
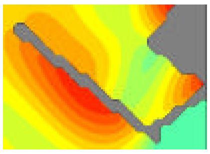
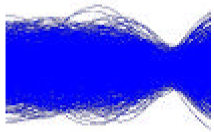
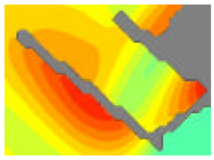
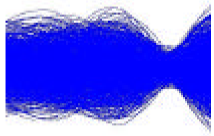
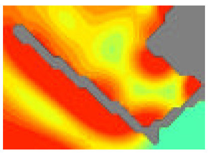
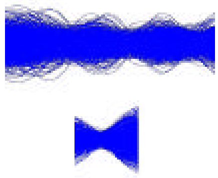
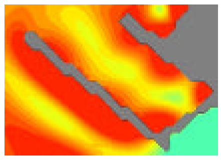
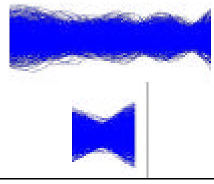
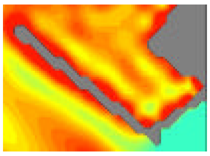
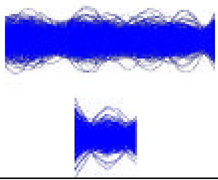
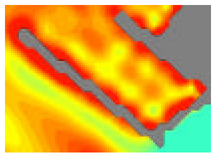
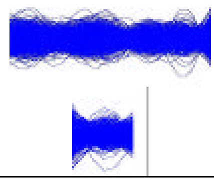
Longitudinal Mode 3

The third longitudinal natural oscillation mode peaks at 100s for both layouts. This oscillation mode corresponds to half a wavelength (½·L) with antinode at the bottom of the basin (towards the Multipurpose Terminal) and node approximately at the end of the original Multipurpose quay. The intensity of the mode is increased for the present conditions (ie after the quay extension) relative to the original layout.

Cross-mode 1

The first cross-mode of the basin peaks at 40-50s for both layouts. The oscillation mode corresponds to half a wavelength (½·L) with node at the middle of the basin and antinodes at the Multipurpose quay and at the eastern breakwater. Due to the more rectangular basin for Layout 2, the intensity of the cross-mode is generally more pronounced for this layout. Since the original length of the Multipurpose quay (Layout 1) corresponds more or less to the width of the basin, minor oscillations are seen also in the longitudinal direction for Layout 1.

Table 2 *Natural long-period resonance modes for Layouts 1 and 2. Long wave energy intensity and surface elevation envelopes along the longitudinal and transverse lines of the basin.*

Wave Periods	Layout 1 (Original Layout)		Layout 2 (Present Layout)	
T = 270-455 s $T_p \approx 360$ s				
T = 189-270 s $T_{p,Lay1} \approx 213$ s $T_{p,Lay2} \approx 233$ s				
T = 60-149 s $T_{p,lay1} \approx 100$ s $T_{p,lay2} \approx 100$ s				
T = 37-60 s $T_{p,Lay1} \approx 40$ s $T_{p,Lay2} \approx 47$ s				
T = 20-37 s $T_{p,Lay1} \approx 30$ s $T_{p,Lay2} \approx 27$ s				

Cross-Mode 2

This cross-mode peaks at 25-30s for both layouts. The oscillation mode corresponds to one wavelength (1·L) with antinodes at the middle of the basin, at the Multipurpose quay and at the eastern breakwater. For both layouts, minor longitudinal oscillations of the basins are observed.

For comparison of the intensity of the long-period natural oscillations for Layouts 1 and 2 (ie, before and after the construction of the quay extension at the Multipurpose Terminal), the long-period wave energy in each frequency band was extracted along the quay of the Multipurpose Terminal. The line for extraction of wave energy (a_c) is shown in Fig 6.

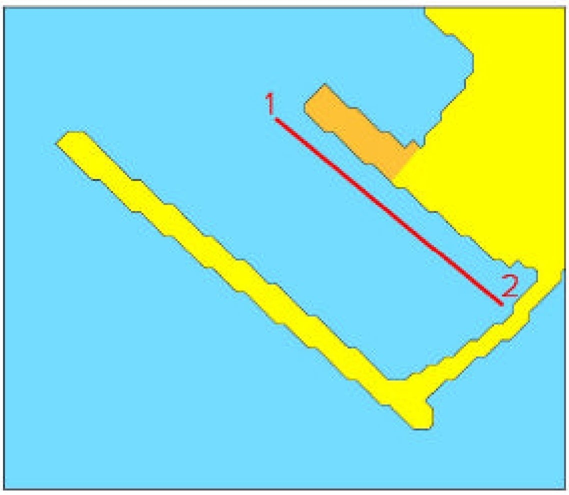


Fig 6 *Line for extraction of wave energy (a_c) in different frequency bands.*

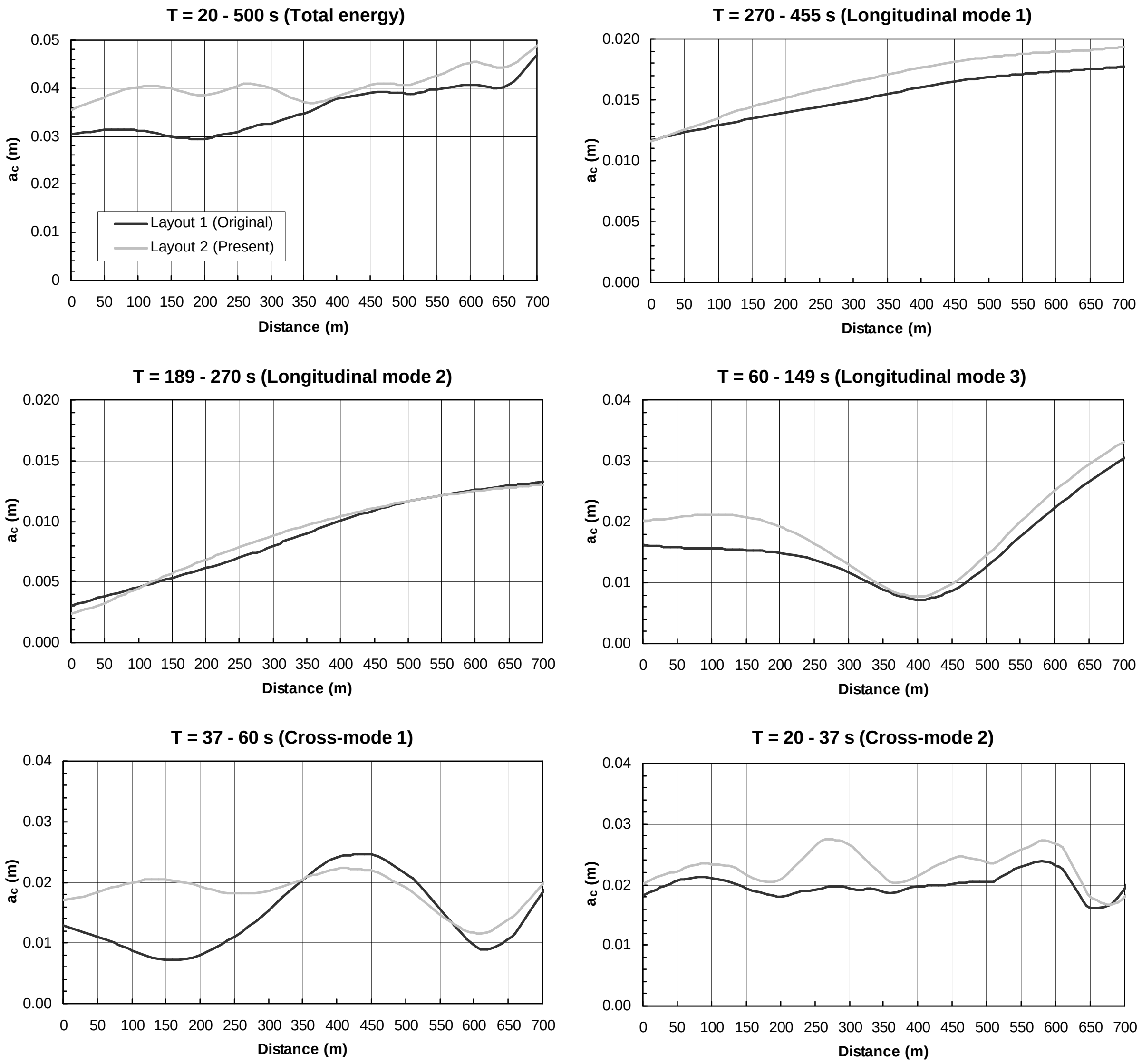


Fig 7 Comparison of long wave energy (a_c) in Layouts 1 and 2 for the different oscillation modes

In Fig 7, the long wave energy for Layouts 1 and 2 is shown for each of the described oscillation modes, as well as for the total wave energy (ie all frequencies). The charts in Fig 7 show the long-period wave energy (a_c) versus the distance from point 1 towards point 2 (cf Fig 6).

From Fig 7, it can be seen that the long-period wave energy is generally more intense for Layout 2 than for Layout 1. This is the case for all oscillation modes, except cross-mode 1, where the long-period wave energy along certain parts of the quay is higher for Layout 1.

The fact that the natural oscillation modes generally contain more energy for Layout 2 (present layout) than for Layout 1 (original layout) leads to the conclusion that the extension of the quay of the Multipurpose Terminal has resulted in a basin more prone to long-period oscillations and resonance.

Therefore, it must be expected that for a natural sea state the amount of long-period wave energy is higher for the present layout than for the original layout. This is further investigated in the following.

4 STORM WAVE CONDITION

To investigate the long period oscillations in the Multipurpose Basin during natural wave conditions, simulations were carried out with the storm wave condition which caused the severe mooring problems in December 1998. To avoid wave breaking in the model, the simulations have been carried out with an incident significant wave height of 1.0m. The consequences of this are discussed in a later paragraph.

For comparison of the wave disturbance at the Multipurpose Terminal for the various layouts investigated, average wave disturbance coefficients (k) (defined as the significant wave height at a certain location divided by the incident significant wave height) have been extracted in five areas along the Multipurpose Terminal. The five extraction areas are shown in Fig 8.

The wave energy has been split into two intervals. One interval representing wave periods below 25s (short-period waves) and one interval representing wave periods above 25s (long-period waves).

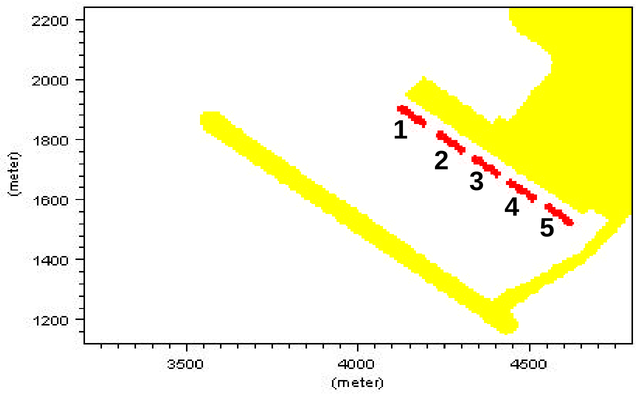


Fig 8 Extraction areas for average wave disturbance coefficients (k).

Fig 9 shows comparisons of the average wave disturbance coefficients for short waves (T<25s) in areas 1 to 5 for the different layouts.

From Fig 9 it is seen that the wave disturbance in areas 3 to 5 is significantly higher for Layout 2 (present layout) than for Layout 1 (original layout). The increase in terms of wave disturbance coefficient or significant wave height is 30-40 percent. Hence, it can be concluded that the extension of the Multipurpose quay has caused an increase in the wave disturbance at the Multipurpose Terminal, at least for the storm wave condition that caused significant mooring problems in December 1998.

Establishing the remains of the old western breakwater at –10m ZH (Layout 3) increases the wave disturbance significantly compared to Layout 2 (present layout). This indicates that possible increased degradation of the remains of the old western breakwater may be a contributor to the increased wave disturbance at the Multipurpose Terminal. However, no information was available to identify whether or not an increased degradation of the remains of the old western breakwater has in fact occurred during the recent years.

Comparing the wave disturbance coefficients for Layouts 3 and 4 shows that a slight reduction of the wave disturbance at the Multipurpose Terminal can be obtained by reducing the reflection from the causeway at the bottom of the basin. However, a reduced reflection coefficient will have no influence on the long waves, for which reason reducing the reflection from the causeway is not recommended as a viable option for improving the wave disturbance at the Multipurpose Terminal.

Layouts 5, 6 and 7 all reduce the wave disturbance considerably, with Layout 5 (reconstruction of western breakwater) being the most efficient.

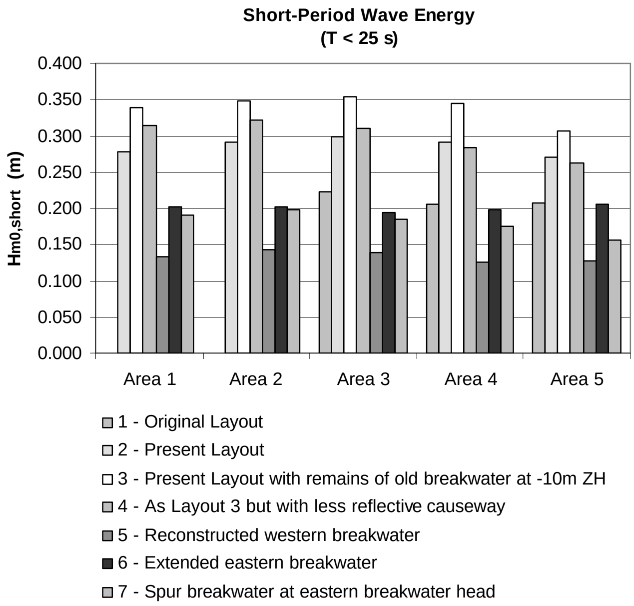


Fig 9 Comparison of average short-period (T<25s) wave disturbance coefficients in areas 1 to 5.

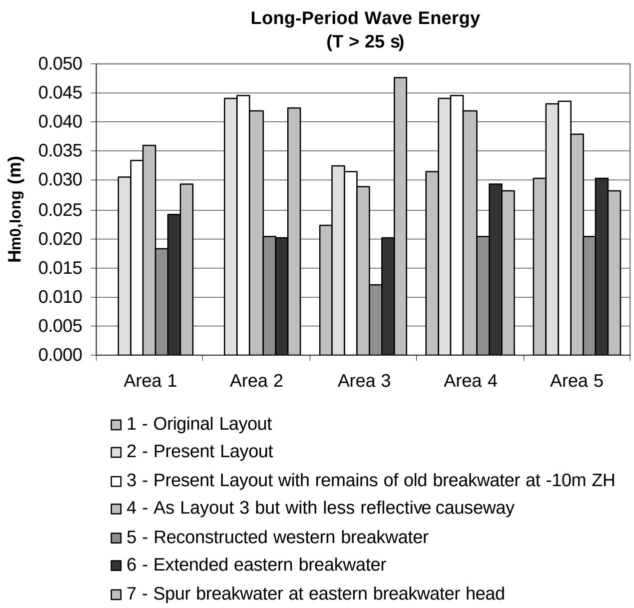


Fig 10 Comparison of average long-period (T>25s) wave disturbance coefficients in areas 1 to 5.

Fig 10 shows comparisons of the long wave energy in areas 1 to 5 for the different layouts. The long-period wave energy shown in Fig 10 is represented by the H_{m0}-value of wave components with periods above 25s.

Since MIKE 21 BW is a non-linear numerical model, long-period waves will be released due to non-linear wave-wave interaction between wave components of the primary wave spectrum. This non-linear wave-wave interaction takes place during the transformation (in this case primarily shoaling, diffraction and breaking) of the waves of the primary wave spectrum. The amount of non-linear energy transfer depends significantly on the wave breaking occurring at the head of the western breakwater, which cannot yet be modelled in a numerical model covering a relatively large area. Furthermore, the amount of bound long-period wave energy increases with the wave height.

Secondly, the actual amount of long wave energy in the 1998 storm wave condition is unknown and no long-period wave energy has therefore been imposed on the boundaries of the numerical model.

Due to the above-mentioned reasons and the fact that the 1998 storm wave condition is represented by a significant wave height of 1.0m, the determined amounts of long-period wave energy is underestimated. It must therefore be stressed that the data presented in Fig 10 can only be used for relative comparisons between the different layouts and not for determining the absolute amount of long-period wave energy, which may be higher than shown in the figure. However, relative comparisons between the different layouts are extremely useful for evaluating the effect of eg the extension of the Multipurpose quay and to identify layout modifications that do not only decrease the short waves at the Multipurpose Terminal, but also decrease the long wave energy.

Comparing the long wave energy for Layout 1 (original layout) and Layout 2 (present layout), it is seen that the long wave energy has increased due to the extension of the Multipurpose quay. This is in line with the conclusions of the white noise analysis in Section 3 that the quay extension has made the Multipurpose Basin more prone to long wave oscillations. The reason for this is that the present layout is more closed than the original layout, and therefore the wave energy is more easily confined in the basin.

Furthermore, it is seen from Fig 10 that Layouts 3 and 4 do not change significantly the amount of long wave energy in the basin. Both Layout 5 (reconstructed western breakwater) and Layout 6 (extended eastern breakwater) are seen to decrease the long wave energy significantly compared to Layout 2 (present layout). Layout 6 reduces the long wave energy to the same levels as before the quay extension, whereas Layout 5 reduces the long wave energy even more. Layout 7 (spur breakwater) increases the amount of long wave energy significantly at areas 2 and 3, most likely due to the wave energy in the basin being even more confined than for the other layouts.

5 CONCLUSIONS

The present study has shown that simulations with white noise spectra is a very efficient method for identifying the potential oscillation or seiching modes of a harbour. Furthermore, white noise simulations is an excellent tool for comparing the potential for the development of long-period oscillations in different port layouts. In the present case study, the results of the white noise simulations confirmed that the construction of the quay extension of the Multipurpose Terminal of the Port of Sines in 1998-99 has made the basin more prone to long-period oscillations.

This conclusion was confirmed by the simulations performed with a natural sea state corresponding to the one that caused severe mooring problems at the Multipurpose Terminal in December 1998. These simulations showed that the construction of the quay extension has increased significantly both the short-period and the long-period wave disturbance in the Multipurpose Basin

On the basis of simulations with various modified layouts of the Port of Sines, it can be concluded that the most efficient solution for improving the wave disturbance and mooring conditions at the Multipurpose Terminal would be to reconstruct the demolished part of the western breakwater. However, significant improvements can also be obtained by extension of the eastern breakwater.

6 ACKNOWLEDGEMENT

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