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SIMULATION OF LONG WAVE AGITATION IN PORTS AND HARBOURS USING A TIME-DOMAIN BOUSSINESQ MODEL

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Abstract: A time-domain Boussinesq type model including wave breaking is used to simulate long wave agitation in two different harbour configurations. The substantial seiche in the exposed Torsminde fishery harbour, Denmark is modelled, and the results are discussed and evaluated against measurements. The second case is a model application to modelling seiche in the Port of Long Beach, CA where low-frequency oscillations at Pier J have been measured. It is shown that a Boussinesq model is able to predict the nonlinear features for breaking and non-breaking waves, which are responsible for long wave agitation in the two harbours.

INTRODUCTION

In ports and harbour engineering, the term seiching is normally used as a synonym for long-period wave oscillations in harbours. Long-period waves are characterised by waves periods of, say, 0.5-30 minutes. Although various forces can generate seiches, the primary energy source for the occurrence of long-period waves in harbours is the non-linear interaction of short-period waves and swell. Due to the high correlation between the energy level of the short and long-period waves, strong seiching typically occurs during high seas. When sufficiently energetic, seiches cause moored vessels and pontoons to move to-and-fro their berthing positions resulting in breaking of mooring lines, damages on fenders and piers and sometimes collisions of vessels with each other. The long wave oscillation may also generate strong currents at the entrance as well as inside the harbour and thus carry vessels out of control. As seiching is often problematic and difficult to eliminate without major structural measures, it is of paramount importance to minimise seiching through hydraulic studies when planning new facilities, see e.g. Sloth et al (2000).

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Even though models based on the mild-slope equation are still used in practice for short and long waves, the models are usually not really adequate because of the neglect of e.g. non-linearity, frequency dispersion and directionality. With our improved understanding of the non-linear transformation of wave spectra, inclusion of wave breaking and swash zone dynamics and with more computer power, it is today feasible to simulate the long wave motions responsible for seiching in ports and harbours using time-domain Boussinesq type models.

In this paper, a Boussinesq model is used to simulate long wave agitation in two very different harbour configurations and with different wave input.

NUMERICAL MODEL

DHI's time-domain Boussinesq type wave model, MIKE 21 BW, is a state-of-the-art model for calculation and analysis of short- and long-period waves in ports, harbours and coastal areas. The model is based on the numerical solution of the enhanced Boussinesq equations formulated by Madsen and Sørensen (1992). The model has been extended into the surf zone by inclusion of wave breaking and moving shoreline as described in Madsen et al (1997a,b), Sørensen et al (1998) and Sørensen et al (2004).

TORSMINDE HARBOUR

Torsminde Harbour is a fishery harbour located on the West Coast of Jutland, Denmark, facing the North Sea, see Fig.1. Immediately after construction of a new entrance layout in Autumn 1990, significant low frequency oscillations were reported by the local harbour authority. The long waves caused the moored vessels to move to-and-fro from their berthing positions resulting in breaking of mooring. Field measurements (pressure gauges) showed significant long wave agitation with wave periods within the interval 30-60 s. Wave energy was also measured on wave periods larger than 5 minutes. A physical scale model was constructed at DHI (DHI, 1992) with the aim to investigate the seiching problem and test alternative layouts resulting in reduced long period wave agitation. Although the wave climate is relatively rough at this site (H_{m0} > 3 m in approximately 1 month per year), the short wave agitation is very limited in the main harbour basin.

Fig. 1. Torsminde Harbour, Denmark (2004). The red dot (right panel) shows the site location

Based on a comprehensive physical test programme a change of the harbour entrance was recommended by DHI. This was constructed in the Autumn 1992, see Fig. 2.

Numerical modelling of this seiching problem requires accurate description of wave breaking and non-linear energy transfer. The objective of this case is to model the low frequency wave disturbance in the harbour and compare the model results with field measurements and results from the physical model tests.

Modelling Approach

Fig. 2 below shows the MIKE 21 BW model bathymetry. The figure also shows the old harbour entrance. The model area is approximately 1.5 km x 1.5 km and includes approximately 450,000 computational points with a grid resolution of 2 metres. Maps of sponge layers and porosity layers are used in areas with full wave absorption and partial wave reflection/transmission, respectively. Model time step is 0.1 s and the length of simulation duration is 30 minutes. The run time is approximately 8 hours on a standard workstation PC.

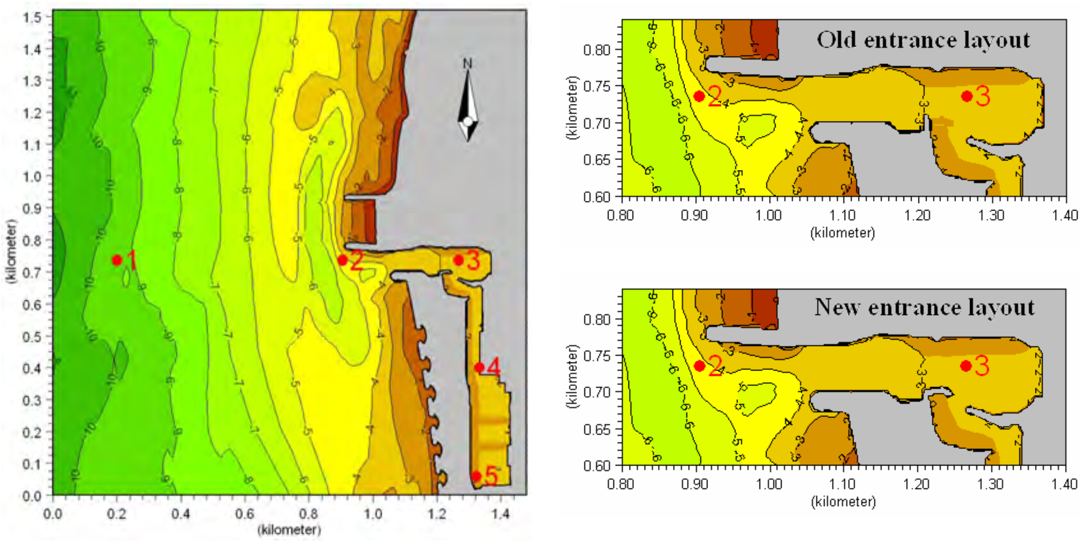


Fig. 2. MIKE 21 BW model bathymetry (left). A close-up of the old and new entrance layout is shown (right). The positions refer to the points where model data are extracted (see below)

A directional wave event with H_{m0} = 4.0 m, T_p = 9 s and *MWD* = 270°N is considered in this case based on a standard JONSWAP spectrum and a cos^8-directional distribution. Wave breaking is included in the simulation.

Model Results

A map of the simulated instantaneous surface elevation is shown in Fig. 3, which indicates that most of the short waves are broken before entering the navigation channel. Fig. 4 shows the frequency spectra at Positions 1, 2 and 3. At Position 3 (located just outside the entrance to the main harbour basin) it is seen that most of the wave energy has been transferred to the infragravity frequency band.

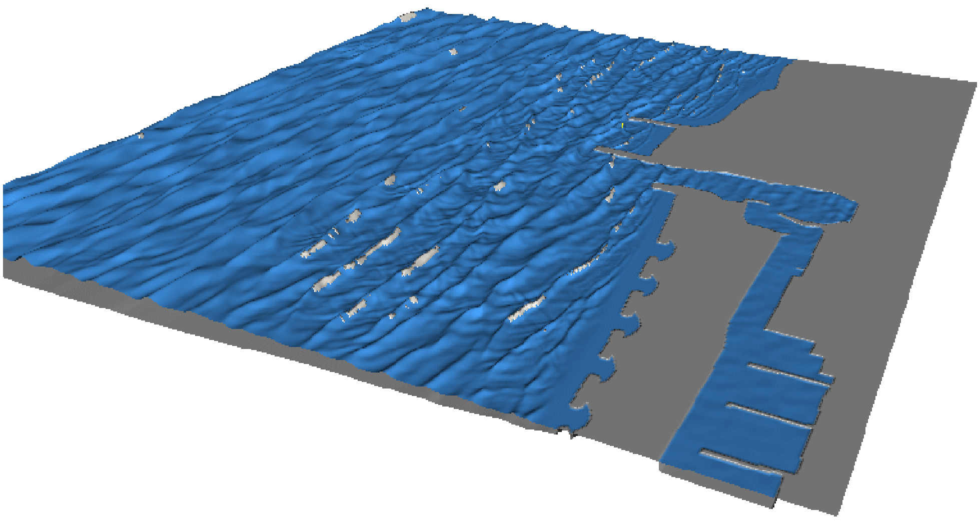


Fig. 3. Simulation of wave propagation and transformation (new harbour entrance). The breaking waves (surface rollers) are shown in white

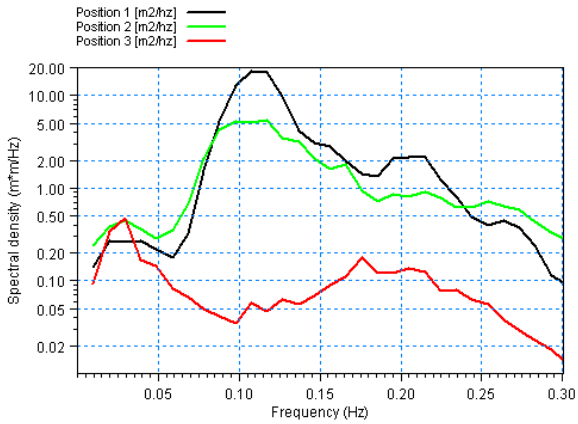


Fig. 4. Modelled frequency spectra at Position 1, 2 and 3 (new entrance layout). The location is depicted in Fig.2. Please note the ordinate axis is logarithmic

Fig. 5 shows a comparison between modelled frequency spectra for the old and new entrance layout, respectively, at Positions 4 and 5. A majority of wave energy is concentrated around frequencies corresponding to wave periods of 40-60 s, which is the excellent agreement with the field measurements and the physical model tests. Comparing the energy-based wave height (H_{m0}) on frequencies larger than 0.01 Hz for the two layouts shows an approximately 40 % reduction of the wave height with the new harbour entrance configuration. Similar wave height reduction was reported in DHI (1992).

Fig. 6 shows an example of a band-passed filtered surface elevation map (at a give time) from which the long waves (wave periods 30-60s) can be clearly seen. Fig. 6 also shows a map illustrating the reduction of long wave energy (m_0) with the new harbour entrance configuration (compared to the old layout).

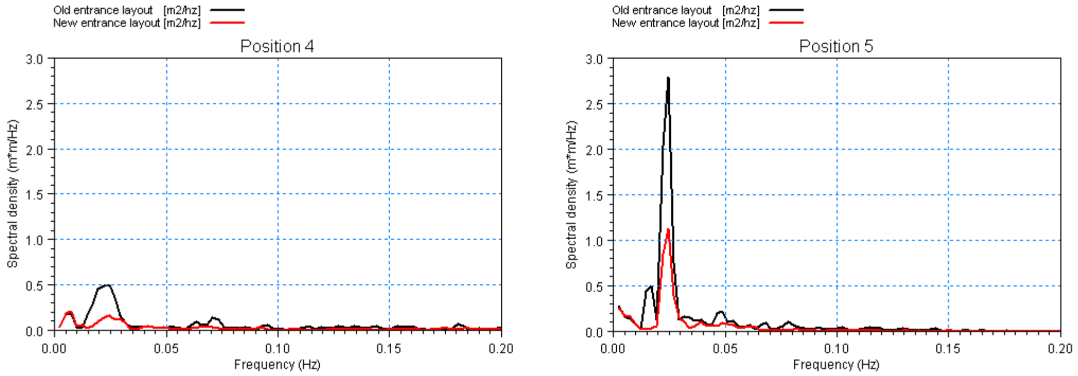


Fig. 5. Comparison between modelled frequency spectra for the old (——) and new (——) entrance layout, respectively. Right panel: Position 4 and left panel: Position 5

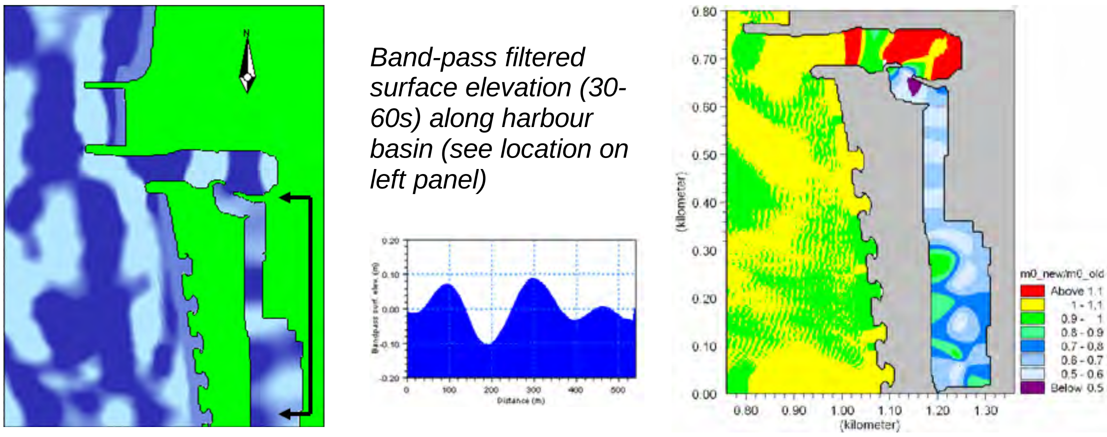


Fig. 6. Instantaneous band-pass filtered surface elevation map (left) and map of relative long period wave energy between new and old layout (30-60 s)

PORT OF LONG BEACH

The second case is related to seiche in the Port of Long Beach, in Long Beach, California, USA, one of the largest port facilities in the World.

Fig. 7. Port of Long Beach, CA. The photography shows the Pier J terminal (from http://www.polb.com). The red dot (right panel) shows the site location

The main objective of this study is to demonstrate that a Boussinesq wave model can be used as an accurate and efficient tool for the assessment of long period waves in a large port facility such as the Port of Long Beach/Port of Los Angeles complex. Models based on the mild-slope equation have been used extensively in the past, see e.g. Lee et al (1998). A number of events have been selected where seiching occurred in Pier J (Port of Long Beach) and where wave measurements were available. Subsequently model results are compared to measurements. In this paper main focus is on the long wave oscillation at Pier J.

Modelling Approach

Fig. 8 below shows the location of the measurement stations. LB2 is located in the Southeast Basin, LB7 is located at the Navy Mole dock, LB8 is located at the Queen's Gate entrance, and LB9 is located within Pier J. The MIKE 21 BW model bathymetry is shown in Fig. 9. The model area is approximately 16 km x 21 km and includes approximately 2.2 mill. computational points with a grid resolution of 10 metres. Maps of sponge layers and porosity layers are used in areas with full wave absorption and partial wave reflection/transmission, respectively. Model time step is 0.5 s and the length of simulation duration is 3 hours. The run time is approximately 24 hours. The essential boundary conditions for the model are based on a combination of measured frequency spectra at Platform Edith (for southern wave events) and directional information from a regional spectral model, see Fig. 10. Wave breaking is not included in the simulations.

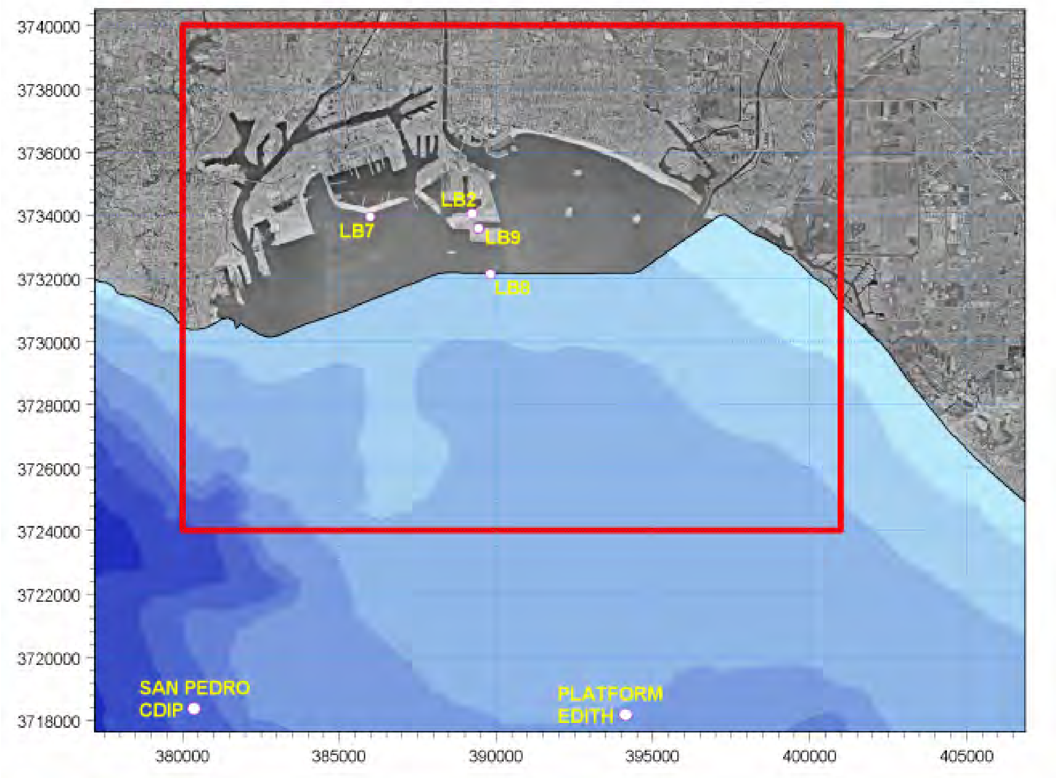


Fig. 8. Location of wave gages. The rectangle indicates the boundaries of the MIKE 21 BW model. Co-ordinates are UTM zone 11

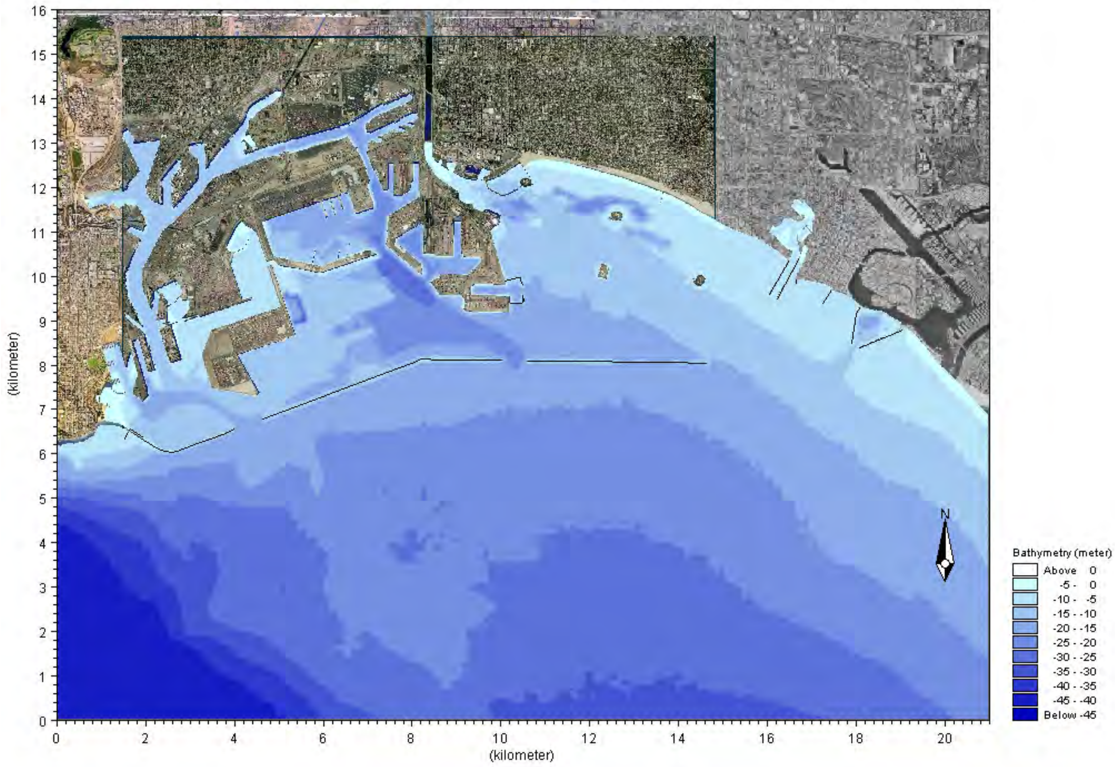


Fig. 9. Model bathymetry

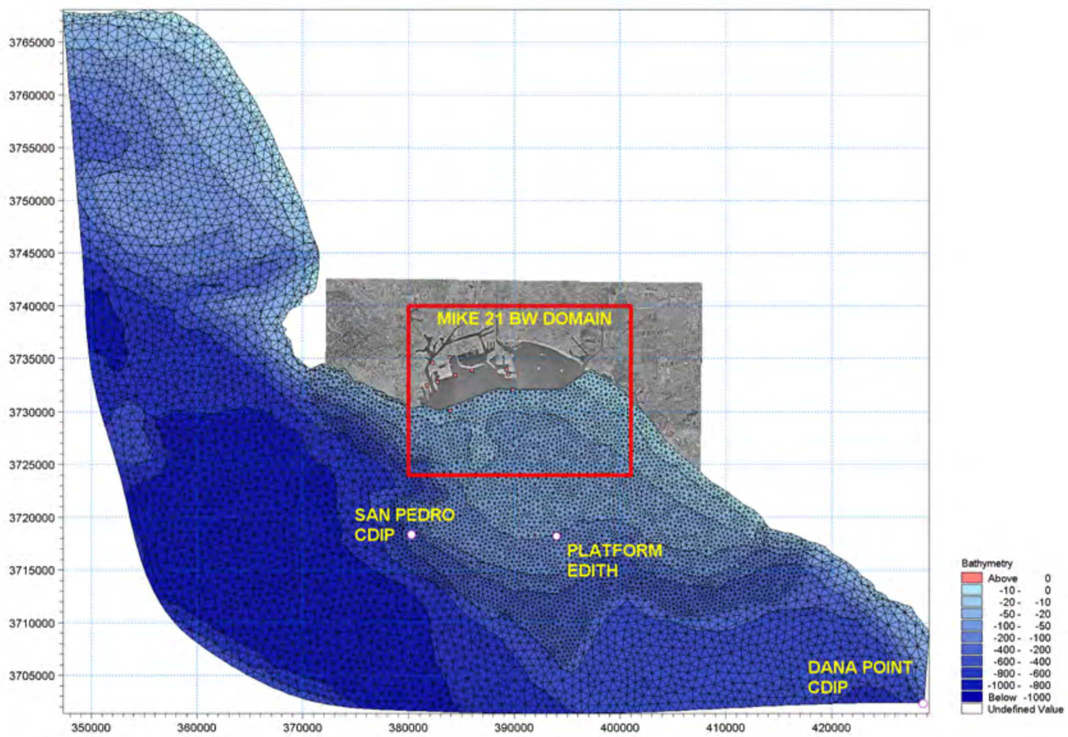


Fig. 10. Regional spectral model (MIKE 21 SW) mesh and bathymetry showing the location of MIKE 21 BW model area and location of offshore wave buoys

Model Results

White-noise Simulation

A white-noise simulation was performed to investigate the potential for and assessment of the natural frequencies with focus on the Pier J area. Although not representing a natural sea state, a simulation with a white-noise spectrum as input can reveal in a very efficient and clear manner the resonance periods of any port layout, see e.g. Gierlevsen et al (2001). The applied white-noise spectrum represented periods of 10s to 1000s. The white-noise simulation was simulated as directional waves from Southerly directions. It must be stressed that since the white-noise spectrum represents a synthetic sea state, the results can only be used as basis for a general assessment of the natural periods. Hence, it cannot be concluded on basis of the white-noise simulation whether or not long-period oscillations or resonance will develop under natural wave conditions. This has to be investigated using a natural sea state (see below).

On the basis of simulated time series of surface elevations, spectral analyses of the white-noise signals were performed in order to determine the natural oscillation periods. The calculated wave spectrum at the measurement stations LB2, LB8, LB7 and LB9 is shown in Fig. 11. For a relative comparison, the measured spectrum at LB9 is also shown in Fig. 11. The results clearly show the peaks corresponding to the different oscillation modes. The model shows significant wave amplification at LB9 for the wave periods approximately 100s, 170s and 500s, which is in excellent agreement with the measurement. Please note only the modelled and measured frequencies can be compared and not the spectral density.

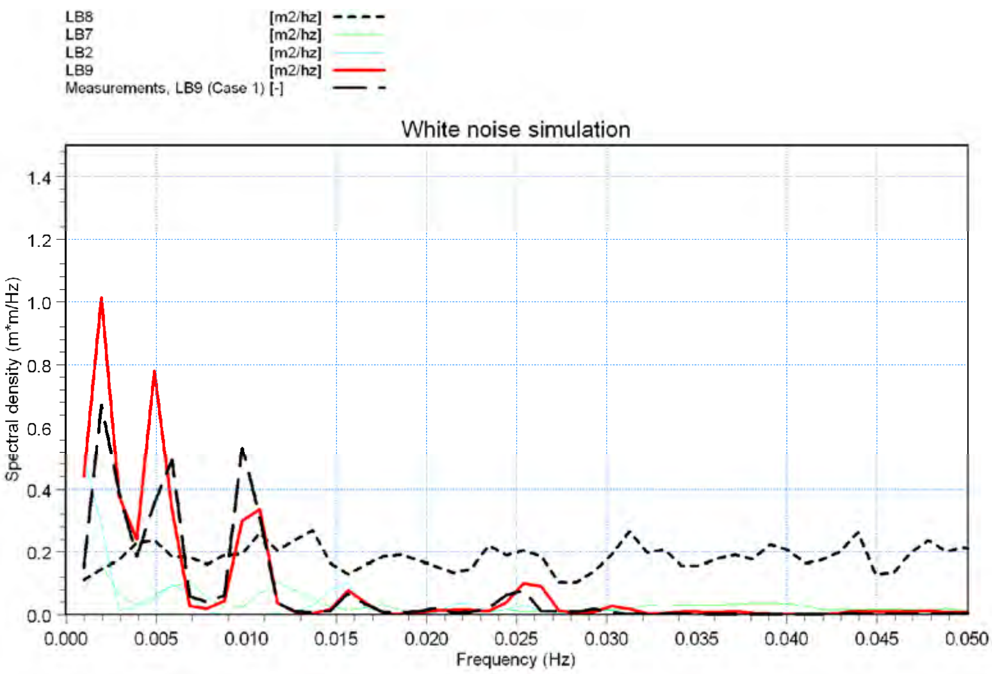


Fig. 11. Wave spectrum of the white-noise simulation at the stations LB2, LB7, LB8 and LB9 (PierJ), see Fig. 8 for location. For comparison the measured spectrum at LB9 (1 August 2000 20:00-23:00) is depicted

Natural sea states

Model results and measurements (at Pier J) are compared in the following two cases

- 1 August 2000 20:00-23:00 (offshore waves H_{m0} = 1.5 m, T_p =16.5 s and *MWD* = 187ºN)
- 30 September 2002 16:00-19:00 (offshore H_{m0} = 1.3 m, T_p=16.0 s and *MWD* = 180ºN)

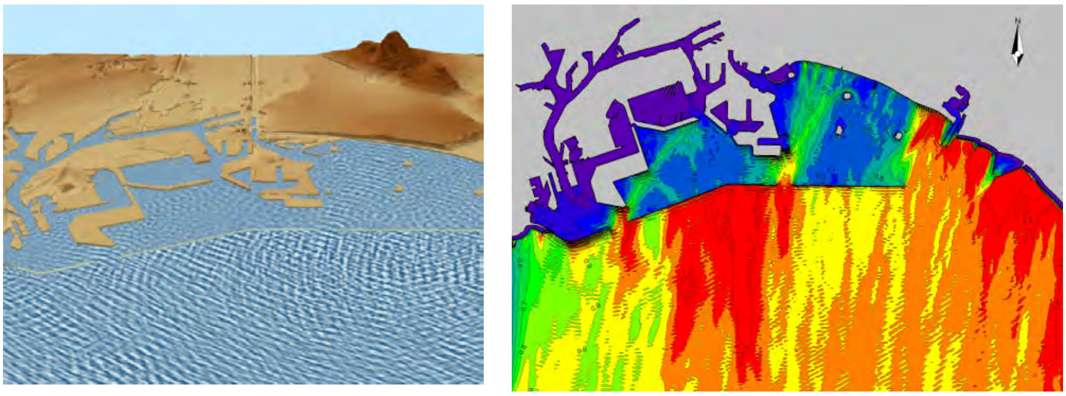


Fig. 12. Example of MIKE 21 BW model results. Left: instantaneous surface elevation map, right: relative wave height map

A comparison between measured and simulated frequency spectra at LB9 (Pier J) is presented in Fig. 14 for the selected two southern wave events. The comparison shows that the model does well predict the occurrence of long frequency waves (frequencies less than approximately 0.02 Hz) inside Pier J. The amplitude is slightly underestimated.

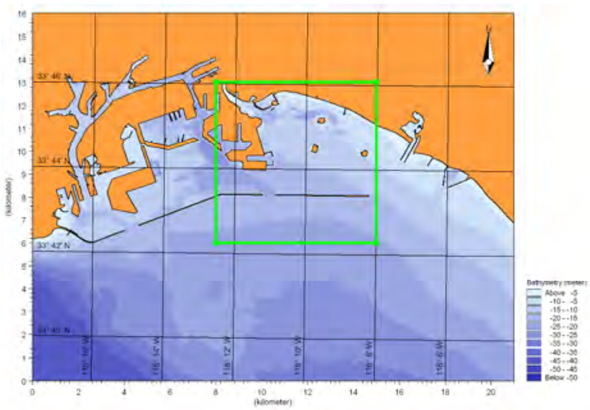
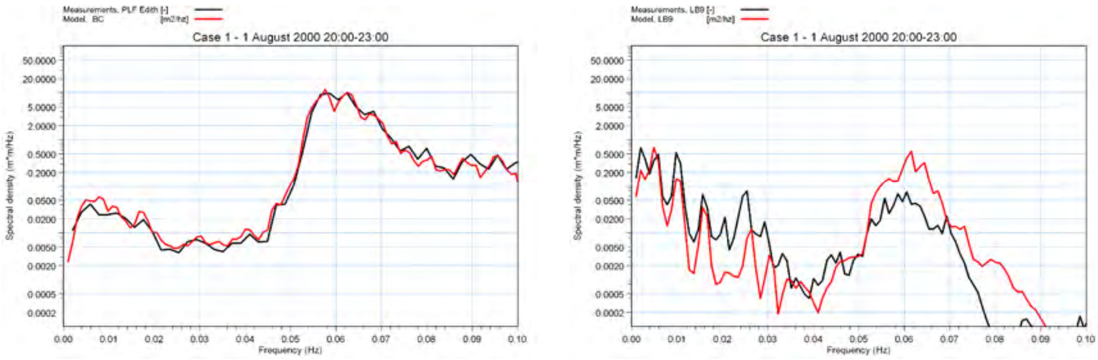
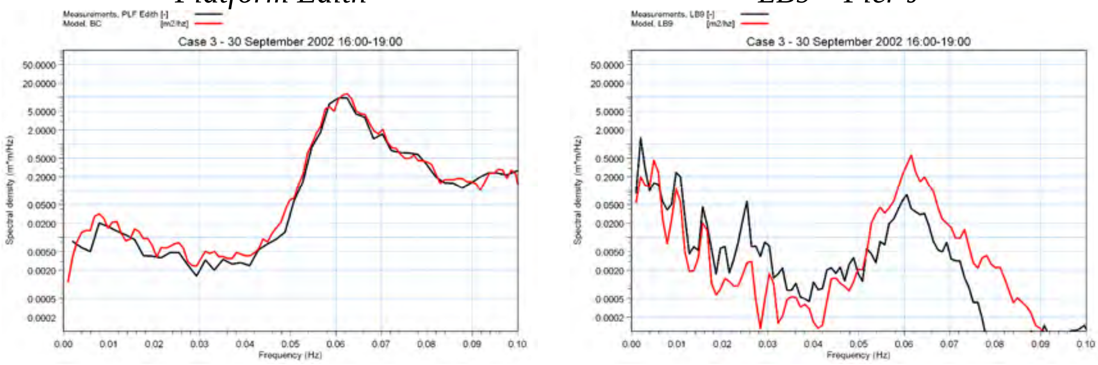


Fig. 13. Full model area showing a sub-domain model area (green square)

Numerical tests have been performed on a sub-domain model to investigate if a smaller model area could provide reasonable results, while improving (reducing) the computational effort. Fig. 13 shows the extent of the sub-domain model area. Boundary conditions are based on measurements at LB8 (Queens Gate) and directional information from the regional spectral model. Fig. 15 shows a comparison at LB9 (Pier J) obtained from the sub model and measurements for the two events. As can be seen from the figures exceptionally good results are obtained for the August 2000 and September 2002 event using this approach. These results indicate that good results can be found in Pier J using LB8 as input to the MIKE 21 BW sub-domain model for southerly events.

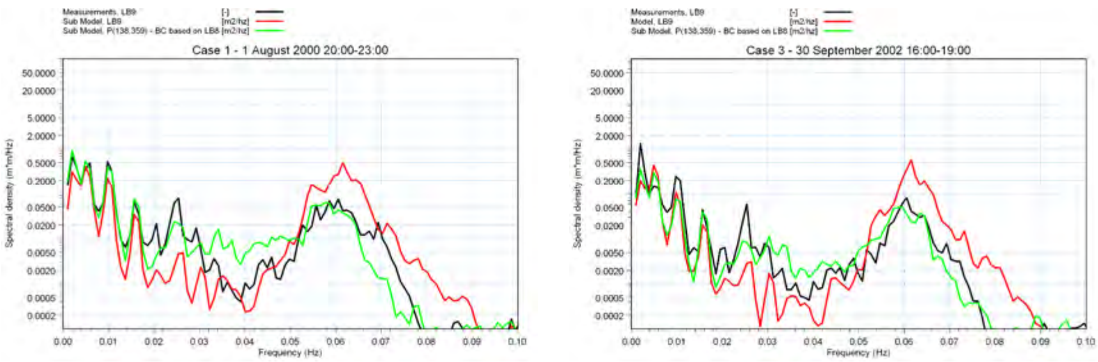


Platform Edith *LB9 – Pier J*



Platform Edith *LB9 – Pier J*

Fig. 14. Comparison of wave spectra at Pier J for the selected two events. Upper panels (1 August 2000) and lower panels (30 September 2002). (——) measurements and (——) model results. Please note the ordinate axis is logarithmic



LB9–Pier J (Aug 2000) *LB9–Pier J (September 2002)*

Fig. 15. Comparison of spectra at LB9 (Pier J) when LB8 was used as input to the sub model. (——) measurements, (——) model results sub model with Platform Edith input and (——) sub model with LB8 as input

CONCLUSIONS

A Boussinesq type model (MIKE 21 BW) was used to simulate the long wave agitation in the exposed Torsminde fishery harbour and in large-scale of the Port of Long Beach and Los Angeles. In both cases the model showed occurrence of low-frequency energy caused by non-linear interaction of the primary short waves. In particular the model results with a white-noise spectrum in Port of Long Beach/Port of Los Angeles was in very good agreement with the measured natural periods at Pier J. In both cases the predicted frequencies and amplitudes of all significant important seiche periods were in excellent agreement with field measurements and physical test data. Hence, it can be concluded that the present Boussinesq model is able to predict the nonlinear features for breaking and non-breaking waves, which are responsible for long wave agitation in many ports and harbours worldwide.

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