Paper in Proceedings of 27th International Coastal Engineering Conference, 16-21 July 2000, Sydney, Australia.

COMBINED NUMERICAL AND PHYSICAL MODELLING OF SEICHING IN EXPOSED NEW MARINA

Henrik Kofoed-Hansen[1], Peter Sloth[2], Ole R Sørensen[3], and Jesper Fuchs[4]

ABSTRACT

This paper describes the modelling of seiching in an exposed new marina using the combination of numerical and physical modelling. The new Western Marina is part of the Beirut Central District reclamation scheme (Lebanon). Due to the rapidly changing shallow water bathymetry near the harbour entrance, hydraulic design studies paid particular attention to the potential for seiching in the new marina. Both models show that the long-period wave energy is concentrated around frequencies corresponding to wave periods of 50-80s (fundamental natural mode) and 6-7 minutes (Helmholtz mode). The non-linear Boussinesq type model is applied to understand the seiching phenomena, for calculation of the spatial variation of the long wave amplification, screening of alternative harbour configurations and to investigate possible model effects in the physical model. The physical model is interactively applied to investigate in detail the most promising layouts, especially for incident wave conditions associated with strong wave breaking, where the numerical model is not yet feasible. Comparison between physical and numerical model results is shown to be in excellent agreement supporting this strong approach in future studies of low frequency oscillations in ports and harbours forced by wind-waves and swell.

[1] *Senior Research Engineer, DHI Water & Environment, Agern Allé 11, DK-2970 Hørsholm, Denmark, Fax: +45 4516 8956, email: hkh@dhi.dk*

[2] *Research Engineer, DHI Water & Environment, Agern Allé 11, DK-2970 Hørsholm, Denmark, Fax: +45 4516 8956, email: prs@dhi.dk*

[3] *Senior Research Engineer, DHI Water & Environment, Agern Allé 11, DK-2970 Hørsholm, Denmark, Fax: +45 4516 8956, email: ors@dhi.dk*

[4] *Head, Ports & Hydraulics Structures Department, DHI Water & Environment, Agern Allé 11, DK-2970 Hørsholm, Denmark, Fax: +45 4516 8956, email: juf@dhi.dk*

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 (eg tsunamis, moving or fluctuating atmospheric pressure systems, shifting of wind stresses on the water surface, longshore-propagating edge waves), the primary energy source for the occurrence of long-period waves in harbours is the non-linear interaction of short-period waves and swell (say, wave periods less than 20-30s). Due to the high correlation between the energy level of the short and long-period waves, strong seiching typically occurs together with substantial short wave disturbance. When sufficiently energetic, seiches cause moored vessels and pontoons to move to-and-fro from 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.

As no single existing method or model allows for an exhaustive study of the seiching phenomena, the combination of physical and numerical models is a strong tool for assessing the performance of existing and new harbour configurations. Until recently, the numerical modelling of short and long wave motions was generally separated. Typically, Boussinesq type models modelled the short wave agitation and the long-period motions were modelled with models based on either the linear mild-slope equation or with non-linear models applying regular wave trains only. Even though models based on the mild-slope equation are still used in practice (also for short waves), the models are usually not really adequate because of the neglect of non-linearity, frequency dispersion and directionality. With our improved understanding of the non-linear transformation of wave spectra, continuous model development (Boussinesq type) and with more computer power, it is today feasible to simulate bound and free long wave motions responsible for seiching in many harbours.

This paper combines the use of a physical model with a Boussinesq type model in connection with the planning of Beirut Central District Western Marina, Lebanon. The numerical model was applied in the process of understanding the seiching phenomena and for a first screening of various Proposed Layouts. First, the paper includes a short description of the new marina followed by a description of the identified long wave oscillations and of the defined wave disturbance criteria. Next, the modelling approach is outlined including a brief description of the two complementary modelling tools. The approach is evaluated and discussed based upon a comparison between results obtained in the two models. Concluding remarks are given at the end of the paper.

BEIRUT CENTRAL DISTRICT WESTERN MARINA

The Beirut Central District Western Marina is a part of the ongoing Beirut Central District Marine Works project. In addition to the Western Marina considered in this paper, the project is envisaged to eventually also incorporate an Eastern Marina and in between the two marinas, a corniche on a new sea defence frontage. Figure 1 shows a location map of the site. A sketch of the proposed marina layout is shown in Figure 2. One of the most characteristic features of the configuration is a submerged artificial reef in front of the caisson seawall having a water depth of 6m MSL (mean sea level) (9m MSL at the harbour entrance) sloping down to about 20m MSL in front of the reef. Table 1 shows the wave conditions at the entrance used for the calculation of the wave agitation as well as the wave height criterion supplied by the Client.

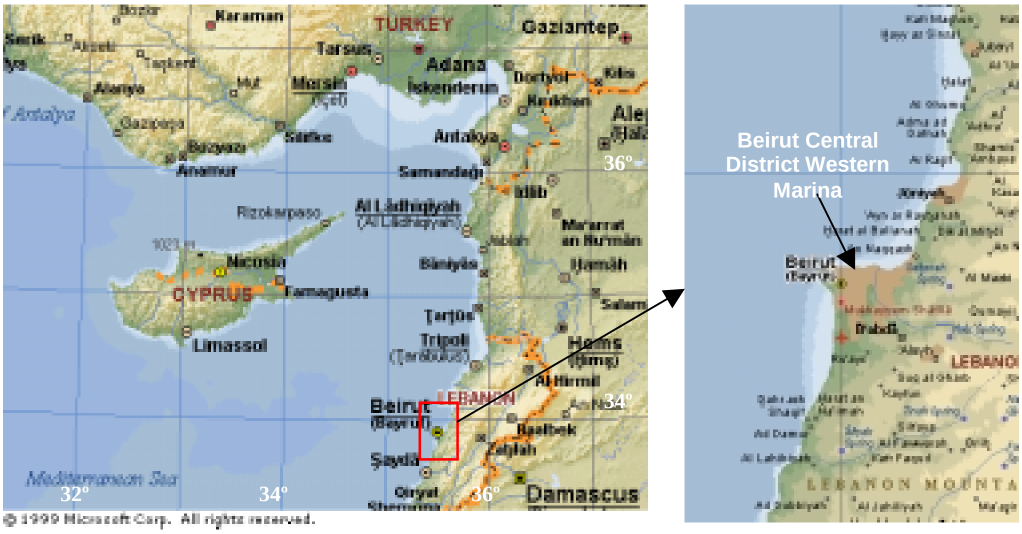

Figure 1. Location of Beirut Central District Western Marina

***Table 1**. Wave conditions offshore the site to be used in the wave disturbance calculation. Also the maximum allowed significant wave height inside the marina is shown.*

Wave conditions at marina entrance				**Maximum allowed significant wave height inside the marina**
Return period	Wave period T_p (s)	Wave height H_{m0} (m)	Wave direction (°N)	
1-year waves	6	1.5	30	0.45 m
	8	4.0	325	0.40 m
	8	4.0	360	0.40 m
50-year waves	15	8.0	325	0.80 m
	12	7.2	360	0.80 m

DESCRIPTION OF PROBLEM

It was expected that a large part of the wave disturbance in the basin consists of low-frequency oscillations caused by wave-wave interaction and wave breaking on the artificial submerged reef. The shoaling and breaking of the short-period wave trains are non-linear processes involving a number of complicated details. Quadratic interactions between harmonics in shallow water lead to substantial cross-spectral energy transfer over relatively short distances, and during shoaling still more energy will be transferred into bound sub-harmonics and super-harmonics. In a number of situations, part of the energy may be released as free harmonics, eg during passage over submerged bars or reefs, during diffraction around a breakwater, or during the process of breaking. When wave breaking occurs, the primary waves will start dissipating, and this will allow for a gradual release of the bound sub-harmonics and result in free long waves moving towards the shoreline and harbour entrance. Figure 3 shows a time series of surface elevations measured in the physical model. Also the low-pass filtered signal (frequency < 0.05 Hz) is shown in the figure. Frequency spectra for non-breaking and breaking wave conditions are presented in Figure 4. The figures support the initial expectations about substantial low-frequency wave energy in the marina.

Due to the occurrence of significant long-period wave disturbance in the basin, the measured wave field has been divided into short-period waves (frequency > 0.05 Hz) and long-period waves (frequency < 0.05 Hz) by spectral analysis.

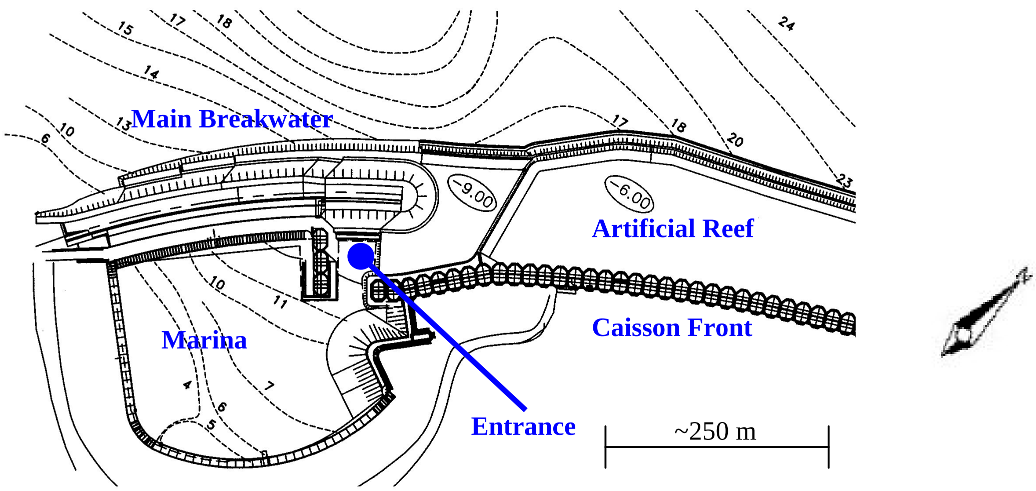

Figure 2. *Sketch of the Proposed Layout. Water depth relative to MSL.*

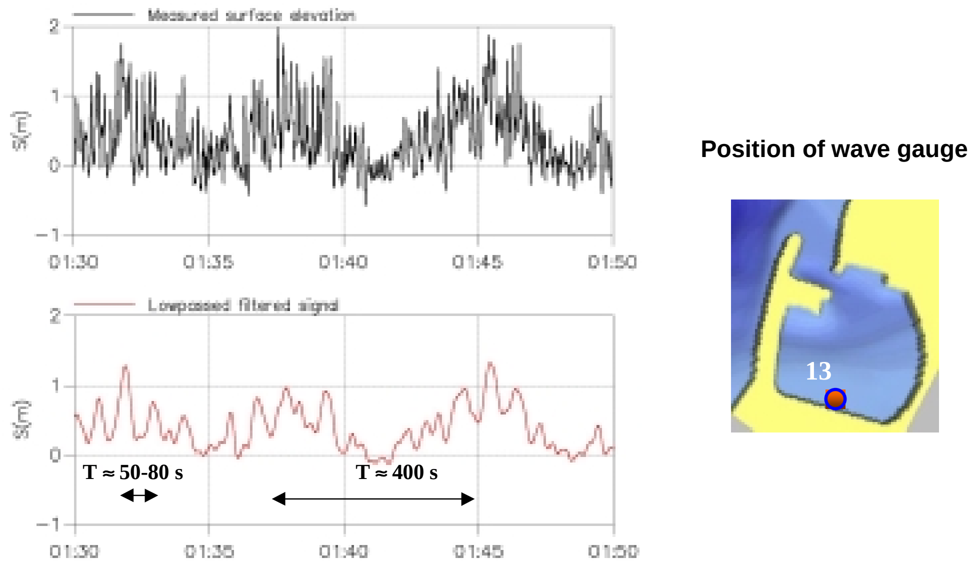

Figure 3. *Time series of surface elevation (upper panel) measured in the physical model at wave gauge No 13. The incident waves are* H_{m0}*= 7.2 m,* T_p*=15s and direction 360°N.*

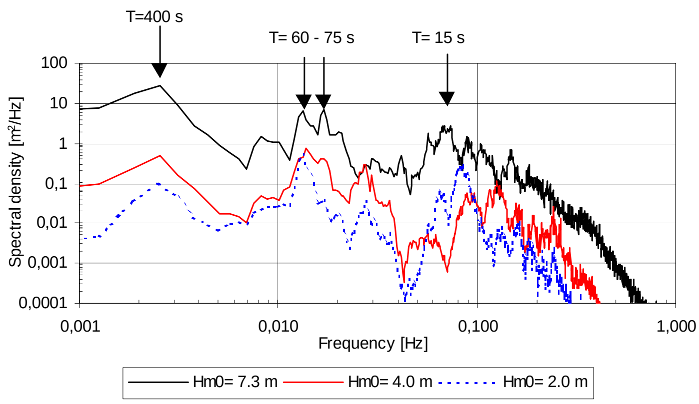

Figure 4*. Frequency spectra measured at wave gauge No 13 in the physical model for different incident wave heights. The incident wave conditions were given by* T_p*=15s and direction 360°N.*

WAVE DISTURBANCE CRITERIA

For small craft and pleasure boats, the ship movements are closely related to the short-period wave conditions. Therefore, the wave height is typically used as criterion for acceptable conditions. For the new marina, the wave disturbance criteria are shown in Table 1. It can be seen that the maximum significant wave height should be less than 0.40m for the one-year event and less than 0.80m for the fifty-year event. The significant wave height is defined as $4\sqrt{m_0}$, where m_0 is the total wave energy. Thus, the criteria are somewhat less restrictive than recommended by eg PIANC (1995). The criterion does, however, not distinguish between long-period and short-period waves.

MODELLING APPROACH

Due to the complex bathymetry and harbour configuration, a combination of physical and numerical modelling was chosen in this study of seiching. A time-domain Boussinesq type model was applied mainly in the process of understanding the seiching phenomena and for a first screening of alternative layouts. The numerical model is particularly useful for calculation of the spatial variation of wave energy in various low-frequency bands. Further, the numerical model was applied to investigate possible model effects in the physical model. The physical model was used interactively with the numerical model to investigate in detail the most promising layouts, especially for wave conditions with breaking waves on the submerged reef. The two modelling tools are described below.

Numerical Model

DHI's time-domain Boussinesq type wave model, MIKE 21 BW, has been used to:

- investigate the natural frequencies of the marina
- investigate the long-wave forcing in the marina
- optimise the marina layout with respect to seiching
- study possible model effects in the physical model

The model is 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. 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. Also wave breaking is 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). However, this model is not yet feasible to cover an area as depicted in Figure 2. The computational time is too extensive with the present CPU power.

The model bathymetry is shown in Figure 5. This figure also presents pictures of the instantaneous surface elevation simulated by the MIKE 21 BW model.

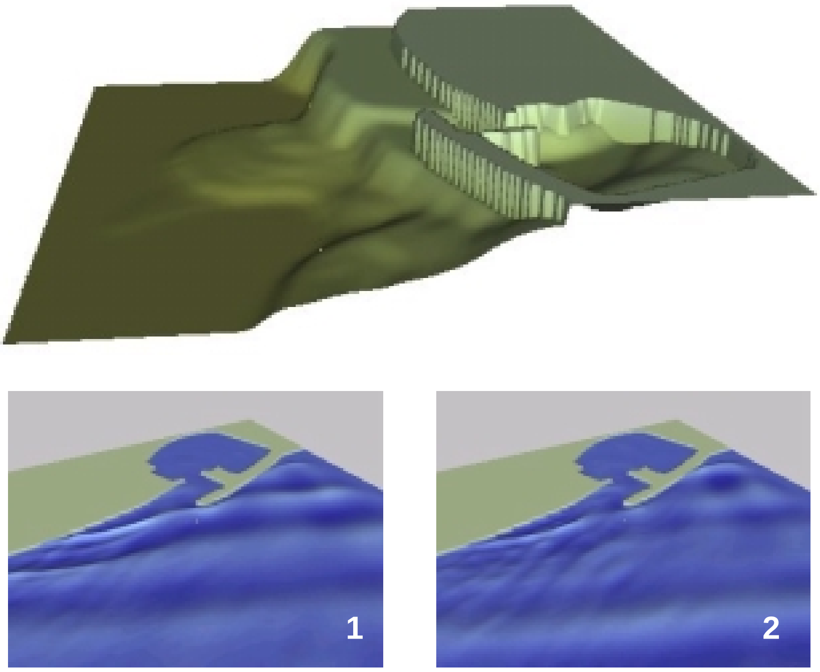

Figure 5. *Model bathymetry (upper panel, vertical distorted by a factor 5) and simulated instantaneous surface elevations at two instants (lower panels).*

Physical model

The physical model tests were carried out in a three-dimensional (3D) model built to a non-distorted linear scale of 1:60. A photo from the model is presented in Figure 6.

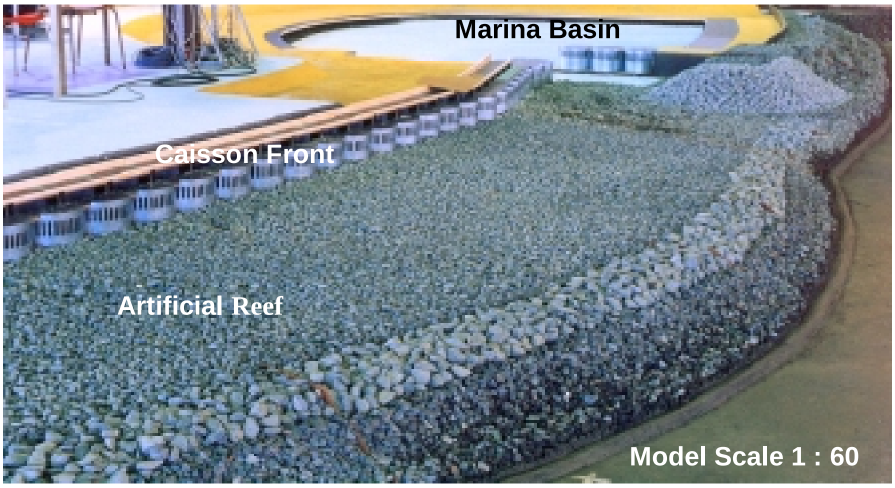

Figure 6. *Photo from the physical model.*

The main objective of the physical modelling was:

- to model the short and long-period wave agitation for particularly large waves breaking on the submerged reef
- to establish the relationships between incident wave conditions and the amount of low-frequency wave energy
- to optimise the marina layout

The model was also used to determine wave forces on the mooring pontoons in the marina and the forces on the vertical sea walls, hydraulic stability of the submerged reef and assessment of the overtopping on the caissons close to the marina entrance.

A number of different configurations of the entrance were tested in the physical as well as in the numerical model in order to limit the short wave agitation and seiching and for improvement of the navigational conditions. Figure 7 shows a sketch of the Proposed Layout and the Recommended Layout.

The wave generation, data acquisition and subsequent analysis were performed using DHI Wavemaker Technology and the DHI Wave Synthesizer software package.

Figure 7*. Optimisation of Marina Layout. The Proposed Layout is shown in the left panel and the optimised and Recommended Layout in the right panel. The figure also shows the position of the wave gauges used in the physical model.*

RESULTS OF INTERACTIVE APPROACH

Initially, the numerical model was applied to investigate the natural frequencies of the marina and the entire laboratory test basin. The natural frequencies or principal seiching modes are most efficiently determined by imposing a white noise spectrum at the offshore boundary of the numerical model. The white noise spectrum is characterised by a spectrum with equal amounts of energy on all frequencies/periods.

Although not representing a realistic natural sea state, the simulations with the white noise spectrum revealed in a very efficient and clear manner the resonance periods of the investigated harbour layouts. The applied white noise spectrum represented wave periods from 20s to 1000s. The spectral density at all frequencies was $0.01m^2/s$. White noise spectra were simulated as unidirectional waves from 360ºN. On the basis of the spectral analysis of the simulated surface elevation, it is possible to quickly identify the different natural oscillation periods. As the white noise spectrum represents a synthetic sea state, the results of the simulations can only be used relatively. Figure 8 shows a comparison between simulated spectra at position Nos 10 and 13 (similar location as wave gauges in the physical model) for the 'Model of Prototype' and 'Model of Physical Model' case. In the first situation, absorbing boundaries were used along the lateral and offshore boundaries for simulation of prototype conditions. The model set-up in the second case was similar to the physical model having fully reflecting boundaries along guiding walls and along the wave paddles. The frequency spectra in Figure 8 reveal a number of peaks where the wave energy is significantly amplified compared to the incoming signal. These peaks are indications of potential natural long-period oscillation modes in the marina or outer basin. As spectra are similar in the two situations, it was concluded that model effects are not expected to distort or blur the seiching phenomena in the marina basin.

A majority of wave energy is concentrated around frequencies corresponding to wave periods of 50-80s and of approximately 6-7 minutes. The first low-frequency oscillation mode (50-80s) corresponds to half a wavelength with antinode at the southern quay wall and near the entrance and a node approximately in the middle of the basin. Since the wavelength for 6-7 minutes oscillation is of an order of magnitude larger than the dimensions of the marina basin, this oscillation could not be explained as a classical harbour resonance phenomenon. For these very long periods, the phenomenon resembles that of a tidal variation in a large basin, which is connected to a small basin through a narrow entrance/channel (Miles, 1974), and is referred to as the Helmholtz or pumping mode. This kind of resonance represented the balance between kinetic energy of water flowing through the narrow harbour entrance channel and the potential energy from the rise in the surface level in the harbour. By combining the shallow water equations for mass and momentum conservation, it is straightforward to derive an expression for the natural frequency, f

$$f = \frac{1}{2\pi}\sqrt{\frac{gha}{SL_c}}$$

where h is channel depth, L_c channel length, S surface area of the basin and a the channel width. As the basic dimensions of the Proposed Layout (see Figure 2) are h~9-10m, L~ 200m, S~ $70000m^2$ and a~50m, the simple expression above yields approximately 6 minutes, which is in very good agreement with the simulation results.

The influence of the incident wave energy on the generation of long-wave induced oscillations in the marina was studied next in the physical model as well as in the numerical model. The wave conditions were represented by an average JONSWAP spectrum described by peak wave period and significant wave height. The simulations were performed with long-crested waves. The relationship between the height of the incident significant wave height and the wave height of the generated long waves is shown in Figure 9 for a position at the harbour entrance. For non-breaking conditions ($H_{m0,i}$< 3m), model results show that the long-wave disturbance in the marina increases almost quadratic with the incoming wave height consistently with bound wave theory and near-resonance triad wave interaction included in the numerical model. For situations with wave breaking, this relationship is largely blurred as seen in Figure 9.

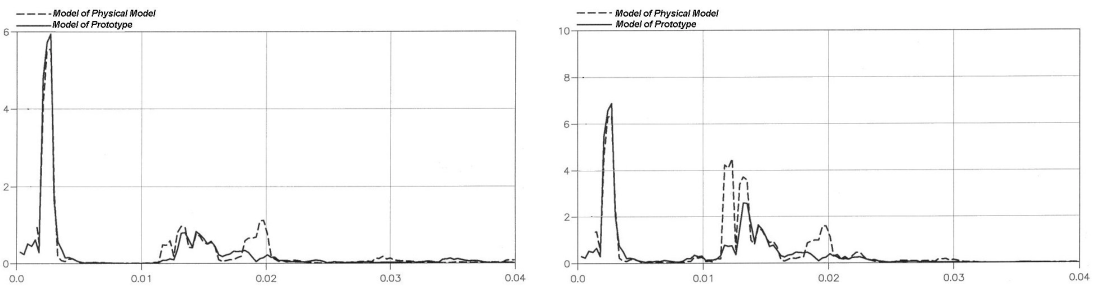

***Figure 8**. Frequency spectra of white numerical noise simulations at wave gauge/ position 9 (left panel) and 13 (right panel), see Figure 7 for location. The abscise and ordinate axis have units Hz and m^2/Hz, respectively.*

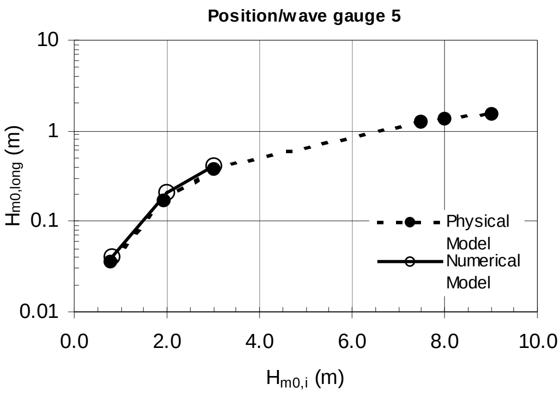

***Figure 9**. Relationship between low-frequency energy (f< 0.05 Hz) measured in terms of $H_{m0,\ long}$ and incident wave height of the short waves at position 5 in the Proposed Layout (see Figure 7 for wave gauge location). Note the ordinate axis is logarithmic.*

Second order wave theory (Schäffer, 1996) was used during the initial run phase to make sure that the wave generation was carried out correctly in the physical model. The water depth at the wavemaker corresponded to 25m MSL. From the tests with first and second order wave generation, it was concluded - as no change was seen when introducing second order generation - that the wave generation using first order theory was sufficient (as used in the numerical model).

Even with a large number of wave gauges deployed in the physical model, it is difficult to get an impression of the spatial variation of the short and long-wave oscillation. The numerical model is used for that purpose too. Examples of simulated wave fields are shown in Figure 10. The surface elevation is low and high-pass filtered using standard FFT-analysis. From this figure, it is readily seen that the low-frequency energy is substantial in the basin. Also the positions of nodes and anti-modes are easy to detect from the maps.

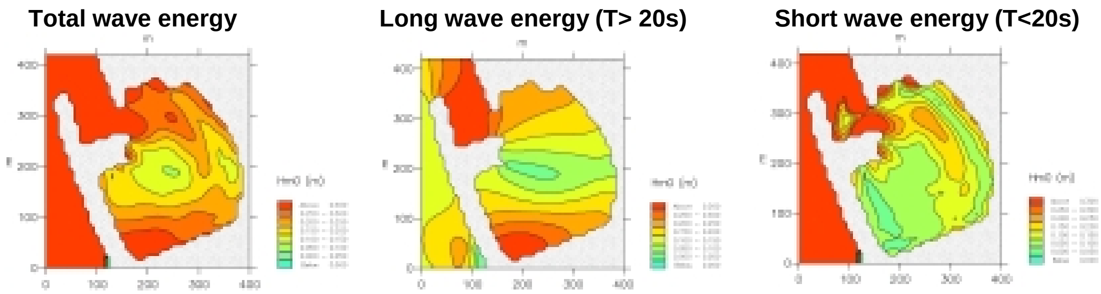

***Figure 10**. Examples of simulated spatial variation of the wave energy (measured by H_{m0}) inside the marina basin.*

A larger number of harbour configurations were investigated using the combination of the two modelling tools. Typically, the numerical agitation model was used to get preliminary ideas about changes in the short and long wave agitation for major or minor modification of the layout. Promising layouts were tested in the laboratory for breaking and non-breaking waves. With respect to seiching, the largest reduction in amplification was achieved with a straight entrance, reduced depth and entrances width, see Figure 7. From Figure 11, it is seen that the total average wave height (based on the wave gauges shown in Figure 7) is about 35 per cent less for the Selected (and Recommended) Layout compared with the Proposed Layout.

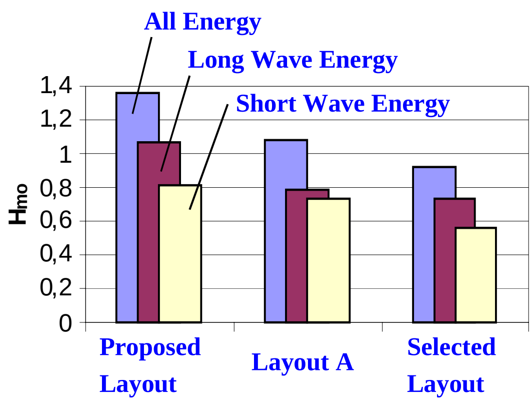

***Figure 11**. Distribution of the average wave energy for three layouts. The incident wave condition corresponds to a 50-year event from N.*

The wave height criteria shown in Figure 1 are fulfilled for the one-year event. This is also the case for the 50-year event taken into account the short waves only (f>0.05 Hz), cf Figure 11. Due to the substantial seiching, the energy of the low-frequency oscillations results in levels exceeding the height criteria for this extreme event. Most part of the low-frequency energy is limited to oscillations having periods of 6-7 minutes. For pleasure craft having L_{oa}= 10-20m and for floating mooring pontoons, such long waves are usually not considered as a severe problem.

EVALUATION OF APPROACH

The justification for using the combined modelling approach is that the two modelling tools produced comparable results. Both models show that the majority of the wave energy in the marina was concentrated around frequencies corresponding to wave periods of approximately 6-7 minutes and 50-80s. This supports the use of simulations of white noise for an efficient assessment of the relative harbour response function and associated natural oscillation periods.

The relationship between the height of the incident significant wave height and the wave height of the generated long waves is shown in Figure 12 for four positions located inside the marina. The result of the physical model tests is seen to be in excellent agreement with the numerical model results for the considered (non-breaking) wave conditions.

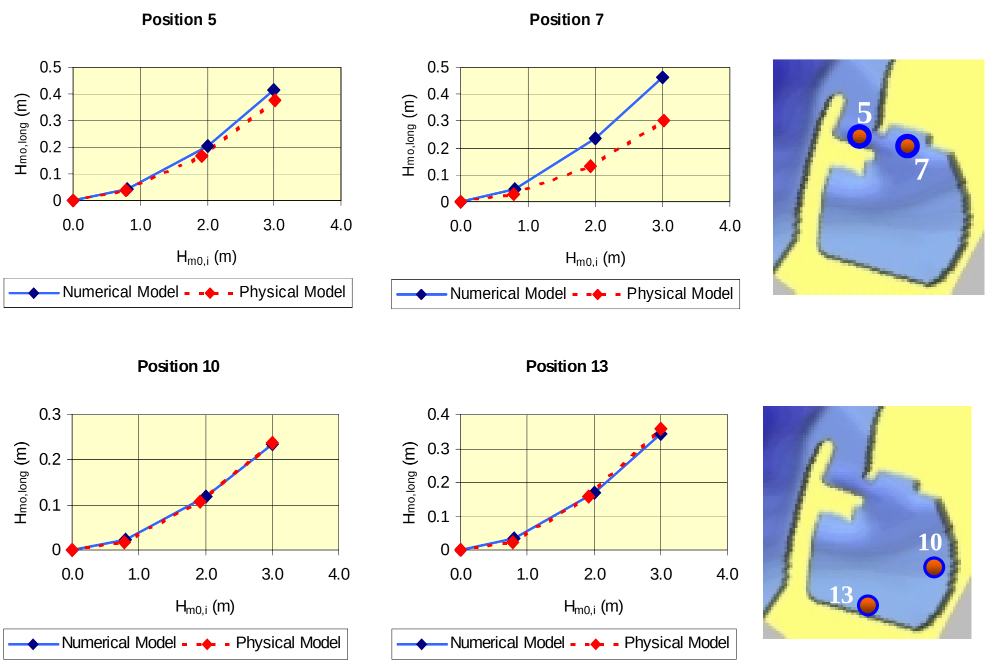

Figure 12. *Comparison between numerical and physical model results for long waves (f 0.05 Hz) for different incident wave heights of the short waves (f >0.05 Hz). The incident wave direction is 325°N and the peak period 15s.*

In Figure 13, frequency spectra are compared at position 13. In general, the agreement is good although the Boussinesq model shows somewhat more energy in the frequency band close to the Helmholz resonance mode. It should be noticed, though, that the FFT-analysis has been based on three hours in the physical model and one hour in the numerical model, which may have an influence on the spectral density for particularly the low-frequency oscillations.

By comparing the results from the physical modelling with the results of the numerical simulation, it is concluded that the two models are in good agreement both with respect to magnitudes and the spatial variation of the seiche amplification in the marina.

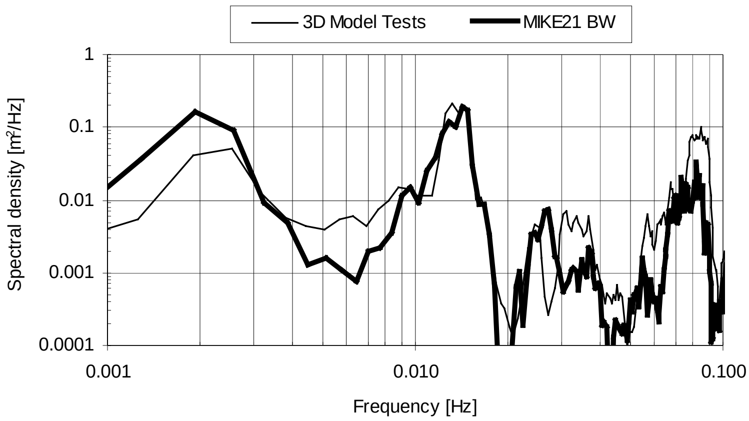

Figure 13. *Comparison of frequency spectra at position 13 obtained from the physical and numerical model, respectively.*

CONCLUDING REMARKS

In this paper, we have modelled seiching in an exposed new harbour using the combination of numerical (Boussinesq type) and physical modelling tools. Both models showed occurrence of substantial low-frequency energy in the Beirut Central District Western Marina caused by non-linear interaction of the primary short waves. The artificial submerged reef located in front of the harbour entrance is believed to be the main reason for the strong seiching particularly during storm conditions. The seiching is concentrated around frequencies corresponding to wave periods of 50-80s (natural fundamental mode) and 6-7 minutes (Helmholtz resonance mode). Results of the numerical model showed that the long-period waves were not significantly affected by the artificial boundaries inherent in the physical model. The numerical model was found particularly useful for determination of the spatial variation of the seiche amplification in various frequency bands as well as for an efficient screening of alternative layouts.

Comparison of results from the numerical and physical model is seen to be excellent. This may support the use only of numerical models in determination of short as well as long wave disturbance in ports and harbours. Similar agreement is also expected when applying directional waves at the boundary/wavemaker. However, the energy of the low-frequency waves is smaller for directional waves. Even though wave breaking is included in a research version of the applied numerical model, it is not yet computational feasible to use it in large areas. During the development of more computationally efficient engines, exhaustive harbour studies are best served by using numerical and physical models interactively.

Figure 14 shows a couple of photographs during the construction of the Beirut Central District Western Marina. The constructed configuration is identical to the optimised layout found in this study, see Figure 11. Future prototype measurements of particularly the long-period waves will be of unique value for a further verification of the suggested approach.

***Figure 14**. Pictures from construction site, August 1999.*

ACKNOWLEDGEMENTS

The hydraulic model study was carried out for the Client Solidère, Beirut, Lebanon, through High-Point Rendel, UK, the Design Consultant. Thanks are also addressed to the Construction Manager, a joint-venture between Christiani & Nielsen, UK, and COWI Consulting Engineers, Denmark.

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