SURFACE GRAVITY WAVE INTERACTIONS WITH DEEP-DRAFT NAVIGATION CHANNELS – PHYSICAL AND NUMERICAL MODELING CASE STUDIES

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This paper addresses the interactions between surface gravity waves and deep-draft and wide navigation channels with steep side slopes, through numerical and physical modeling case studies. The underlying physical processes are illustrated and the consequences to port master planning, harbor agitation and design of coastal structures in proximity to navigation channels are discussed through detailed analysis of numerical and physical model response to the channel. A comparative evaluation of several numerical modeling paradigms exposes the strengths and limitations of each formulation when applied to describe such interactions. The consequences to the planning of numerical and physical modeling studies are discussed. To the authors' knowledge, this is the first comprehensive evaluation of wave-channel interactions with bathymetric gradients that define the steep side slopes of navigation channels that are becoming increasingly common in the continued expansion and design of existing and new ports and harbors.

INTRODUCTION

The primary purpose of port and harbor facilities is to facilitate on/offloading at vessel berths. To that end, port facilities are typically optimized to meet target design wave conditions or downtime limits through the design of outer breakwaters, the internal geometries of the port basins and absorbing structures. Multiple projects in recent years have consistently shown that the presence of a deep draft navigation channel a) alters the wave field approaching a harbor over a considerable spatial scale to the point of significantly affecting design wave conditions outside the harbor and adjacent shoreline morphology, and b) significantly alters the amount of energy penetrating into a harbor. While physical models may be applied at the final stage of design, in recent years port designers have typically relied upon numerical wave models to perform most of the initial studies required in terms of laying out the basic harbor geometry in a manner that meets the prescribed

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targets of port functionality, and in terms of providing design conditions for port structures.

Three numerical wave modeling paradigms are typically applied in support of harbor design, namely wave action models, mild slope models, and Boussinesq models. All these model formulations make the assumption of “slowly varying bathymetry”, and disregard or retain terms proportional to the bottom slope and curvature to varying orders of magnitude. A deep-draft access channel with steep side slopes creates a situation which numerically challenges all three types of models, to the degree that all may predict fundamentally different responses, which may in turn disagree with results generated in a physical model basin or measured in the field. It is our contention in this study that wave/channel interaction can significantly affect design conditions inside and outside a port/harbor, is often inadequately described by some of the wave models applied in support of port/coastal design, and that these interactions are not universally understood within the port/coastal engineering community.

WAVE-CHANNEL INTERACTIONS

For a typical deep-draft port and associated navigation channel geometry, Figure 1 schematically illustrates some of the effects which factor into the design of these structures and the design of the port basins and the navigation channel.

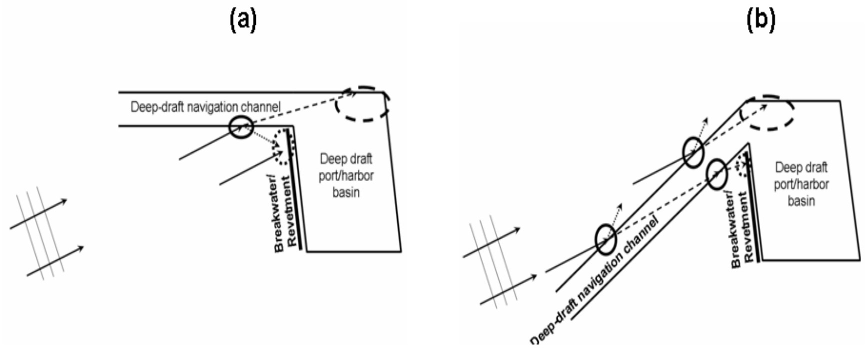

Figure 1. Schematic illustration of the consequences of wave interactions with the edges of navigation channels for design of coastal structures and harbor agitation

Panels (a) and (b) of Figure 1 differ only in terms of the orientation of the navigation channel with respect to the incident wave direction. It is clear from Figure 1 that the physical process of wave refraction, reflection/scattering and transmission, all of which are dependent on the interactions of waves with the side slopes of the channel, determine the design (amplified) wave heights for the breakwater/revetment as well as the (attenuated) energy penetrating into the harbor basin. Similarly, such interactions can play a significant role during port master planning, shoreline protection and channel sedimentation. In addressing any one or more of these engineering objectives, either through numerical or physical modeling, it becomes clear that the interactions of surface gravity waves with the side slopes of navigation channels is of critical importance.

Notable among previous studies is the physical modeling study of Zwamborn and Grieve (1974) who conducted extensive (over 2 ½ years!) 1:100 scale physical modeling with channel side slopes varying from 1 V (vertical) : 20 H (horizontal) to 1 V : 100 H. Quite counter-intuitively, their testing led them to conclude that the direction of the entrance channel should preferably coincide with the dominant wave direction to minimize wave penetration into the harbor basin. Physical modeling studies are, however, expensive and time-consuming, and it may be impossible to include the full extent of a typical deep-draft and wide navigation channel at an acceptable scale. Therefore, the preferred tools for optimization of design alternatives (as well as for providing inputs to theoretical design) have to include numerical modeling techniques – preferably in conjunction with physical modeling.

Surface wave interactions with deep-draft and wide navigation channels result in essentially two competing effects – attenuation and amplification – which are physical consequences of the interactions at the edges of the channel. Quite simplistically, a portion of the incident wave energy interacting with the up-wave edge of the navigation channel gets scattered away from the channel and which, depending on the relative phases of the incident and scattered waves, can constructively interfere leading to local amplification zones with wave heights well in excess of either of these components alone. The energy which is transmitted past the up-wave edge of the channel, through the combined effects of refraction and diffraction, gets significantly attenuated within the channel, a portion of which propagates into the harbor and the rest of which gets re-transmitted to the down-wave side of the channel. Interactions between the various components of the transmitted energy can also cause complex interference patterns down-wave of the channel. All these processes are, to varying degrees, dependent on the geometry of the channel (the width, depth, side slopes etc.), the incident wave forcing (peak period, direction, frequency and directional content, etc.) and the ambient bathymetry characteristics.

Dictated by the economics of port expansion and dredging projects, navigation channel side slopes are becoming significantly steeper (side slope of 1V : 1H being a fairly common occurrence) than those which have been investigated in earlier studies (Li *et al.*, 2000). Therefore, the questions remain open whether a) the effects of these substantially steeper side slopes on incident waves are markedly different than milder slopes, and b) whether existing numerical wave modeling paradigms that are applied in port and harbor design studies, most of which are formulated under the assumption of mildly varying bathymetry, can accurately model wave transformation near these rapid changes in bathymetry.

Quite recently, revisiting Boussinesq formulations for wave propagation over rapid and large variations of bathymetry, Madsen *et al.* (2006) concluded that terms proportional to bottom slope (and its square) and curvature can have significant contributions to correctly reproducing the reflection coefficients for reflections from even mild slopes, let alone the steep slopes specifically addressed in this paper. In their investigations with wave propagation over submarine canyons with steep side slopes (1V : 1H to 3V : 1H), Magne *et al.* (2007) observed, for small wave incidence angles (relative to the channel longitudinal axis), that higher order bottom slope and curvature terms as well as evanescent and sloping-bottom modes can be important for an accurate representation of wave propagation over the canyons.

In summary, the occurrence of amplification and attenuation of surface waves due to interactions with navigation channels is hardly surprising in itself and has to some degree been addressed in literature. The objectives of this note are to demonstrate the significance of such interactions towards engineering design of ports and harbors which specifically incorporate navigation channels with steep side slopes, and to investigate the comparative capabilities (with regard to physical as well as numerical/computational considerations) of numerical models in accurately predicting such interactions. In this paper, we look at physical and numerical modeling studies which clearly demonstrate the effects such channels can have on waves incident at small angles relative to the channel longitudinal axis, the sensitivity of the wave-channel response to the incident wave field, the channel geometry, and the various numerical model formulations, and the consequences to both harbor agitation and the design of coastal structures. The main observations from these studies along with conclusions and ongoing work are presented at the end of the paper.

PHYSICAL MODELING STUDY

As part of the studies undertaken for the design of the new terminal (JANCT – Jebel Ali New Container Terminal) for the port of Jebel Ali, Dubai, UAE, three-dimensional physical modeling studies were conducted at the Canadian Hydraulics Center, NRC, Canada. The physical model layout, constructed at an undistorted geometric scale of 1:60, is shown in Figure 2. The main navigation channel, part of which was included in the physical model as shown in Figure 2, is 320 m wide, and dredged to a depth of 17m with side slopes of 1V : 1H. The ambient depth was approximately 7m. Of the many tests that were conducted with irregular (JONSWAP spectrum), long-crested waves, a single test is described here that demonstrates the wave amplification zones that were observed and which subsequently led to modifications in the design of the revetment. The peak wave period for this test was 11.5 s, and the mean wave direction was five degrees relative to the channel longitudinal axis as shown in Figure 2. Even though amplification (relative to the average incident wave height as measured at gages #7 and #8) was noticed at gages #19, #27 and #21, the largest wave heights were observed at gage # 22, approximately 24 % larger than the incident wave height. Visual observations during testing confirmed that the amplifications resulted due to the superposition of the incident wave energy with the wave energy scattered by the channel. It was also visually observed that there were distinct focusing patterns which resulted in very local amplification zones.

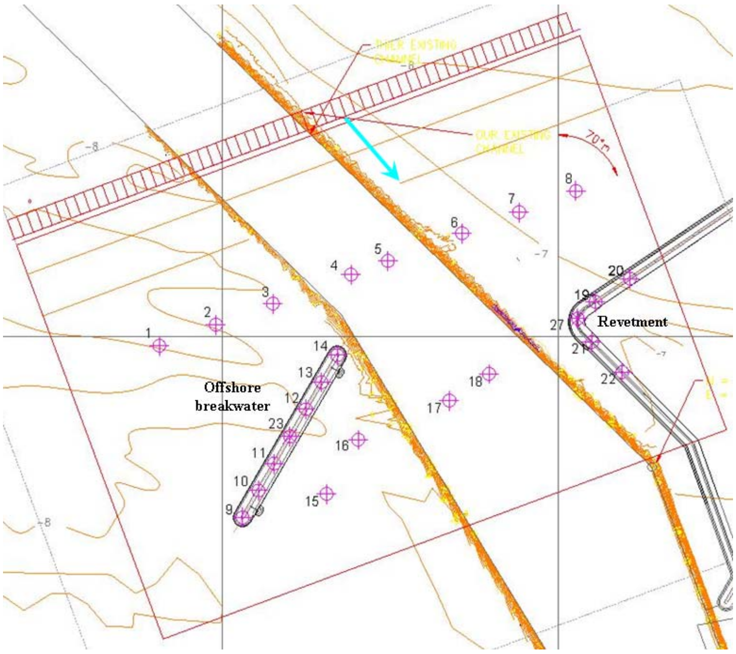

Figure 2. JANCT physical model showing gage locations during wave calibration (without any structures in the model). Light blue arrow shows incident wave direction (5 deg relative to channel longitudinal axis)

Even though the actual design considerations in the physical modeling study are outside the scope of the present discussion, it is worthwhile noting that once the structures were constructed in the model, the focusing zones changed in location, and the highest amplification was observed for gage locations #27 and #19, and in the general area shown encircled in red, in Figure 3 (a). The amplified wave heights led to significant increases in the theoretical prediction of overtopping and consequential damage to the crest and rear slope of the revetment. The structural design was consequently modified in the physical model, successfully tested, and implemented in the field, as shown in the satellite photograph in Figure 3 (b).

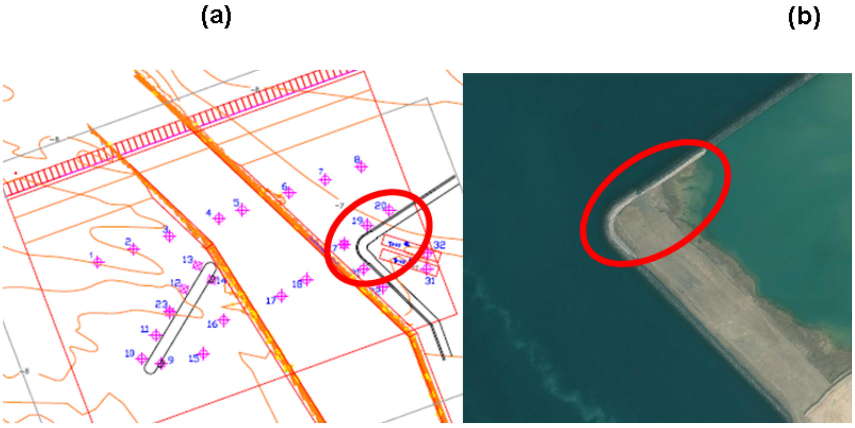

Figure 3. (a) Physical model layout showing area affected by local amplification which led to design modification, (b) Satellite photograph (Google Earth) showing implementation of design modification in the field

NUMERICAL MODELING CASE STUDIES

This section describes extensive numerical modeling case studies that have been carried out with idealized bathymetric geometries that are representative of typical deep-draft navigation channels associated with port projects undertaken recently. The base case bathymetry is shown in Figure 4. The navigation channel is represented by a depth of 17m, width of 250m (between the toe lines of the channel), and side slopes of 1V:1H. The ambient bathymetry has a slope of 1:200 and the grid spacing (both x- and y-) is 2m (except for the BOUSS2D model where the grid is 8m square). The numerical wavemaker is placed at the South end of the bathymetry, and the convention followed for the incident mean wave direction (MWD) is also shown. Figure 4 shows the sponge layers to the North, East and West ends of the bathymetry for the Boussinesq models which effectively act as wave absorbers.

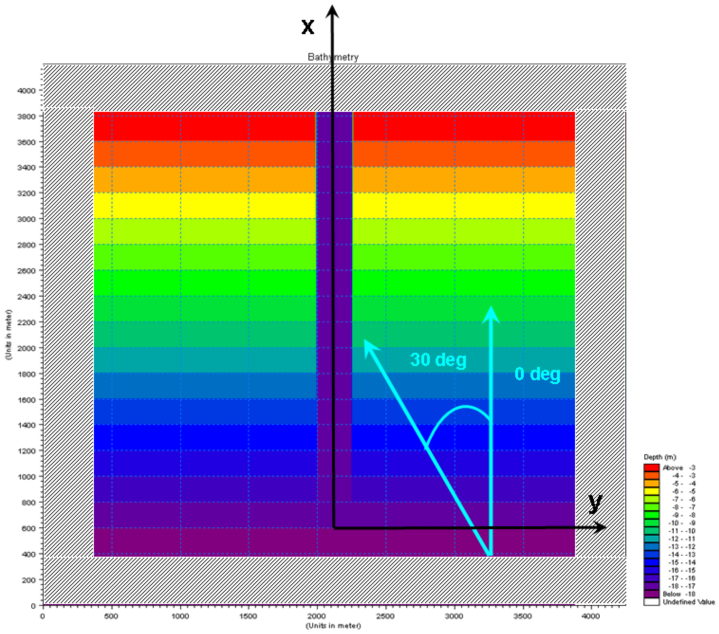

Figure 4. Idealized bathymetry (grid spacing of 2m and channel side slopes of 1V:1H). Light blue arrows show the convention followed here for the incident mean wave direction (MWD). The shaded rectangles denote sponge layers for absorbing incident waves. The ambient depth has a slope of 1:200 in the x-direction

The numerical models which have been used and are discussed in the following comparisons are Boussinesq models (MIKE 21 BW, Danish Hydraulics Institute; BOUSS2D, Nwogu and Demirbilek, 2001), a parabolic mild-slope model (MIKE 21 PMS, Danish Hydraulics Institute), an elliptic mild-slope model (MWAVE; Li, 1994) and a wave action model (MIKE 21 NSW; Danish Hydraulics Institute). The sensitivity of the channel response to incident wave forcing was tested by simulating wave periods of 6s, 8s, 10s and 15s, mean wave directions of 0 deg, 5 deg, 10deg and 20deg, and in addition to monochromatic and unidirectional waves, irregular (JONSWAP spectrum with a high frequency cut-off of 6s) and directional (Cos^n, n=5, maximum deviation from mean wave directions = +/- 30 deg). To investigate the sensitivity of the interactions to channel geometry, channel side slopes of 1V:1H, 1V:5H and 1V:10H, and channel widths (distance between toe lines of channel) of 114m, 172m, 228m and 250m were tested. All simulations are done with a wave height of 0.10 m at the offshore boundary, thereby ensuring that non-linear effects are negligibly small. All energy sources and sinks (winds, wave breaking & bottom friction) are turned off in all model simulations. The simulations were all run to till wave heights converged to a statistically steady state and for the irregular and/or directional simulations the spectral significant wave heights are compared.

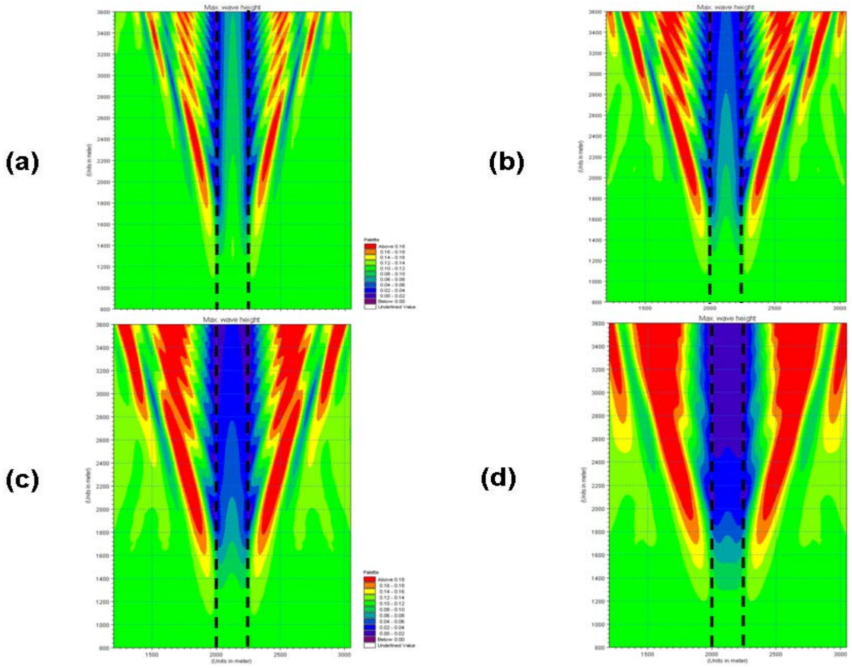

Figure 5. MWD = 0deg (Monochromatic, Unidirectional), Channel Slope = 1V:1H. Comparison of Boussinesq (MIKE 21 BW) model results for (a) Tp = 6s, (b) Tp = 8s, (c) Tp = 10s and (d) Tp = 15s (d). The dashed black lines show the toe lines of the channel

Figure 5 shows a comparison of the Boussinesq model (MIKE 21 BW) response for uni-directional (MWD = 0 deg), monochromatic waves for wave periods of 6s, 8s, 10s and 15s. The cooler colors denote wave heights smaller than the incident wave height and the warmer colors denote wave heights larger than the incident wave height. Several observations are immediately clear. The footprint of the channel can be clearly seen in the spatial variation of wave height in all the plots, with a significant relative attenuation in the channel. Outside the channel, the interference of the scattered and incident waves leading to concentrated regions of amplifications (more than double the incident wave height!) and attenuation (less than half the incident wave height) are also clearly observed. Larger wave periods lead to a decrease in wave energy penetration into the channel and an increase in the amplification outside the channel. Accordingly, the cross-channel extent of the amplification “lobe” immediately adjacent to the channel increases with the wave period. It is clear from these observations that structures placed in proximity to the channel would be subject to wave heights much larger than the incident wave height, solely as a consequence of the interactions of the incident waves with the channel. Further, with the channel orientation being aligned with the incident mean wave direction, it appears that shorter wave periods would cause larger penetration of wave energy into the port/harbor basin.

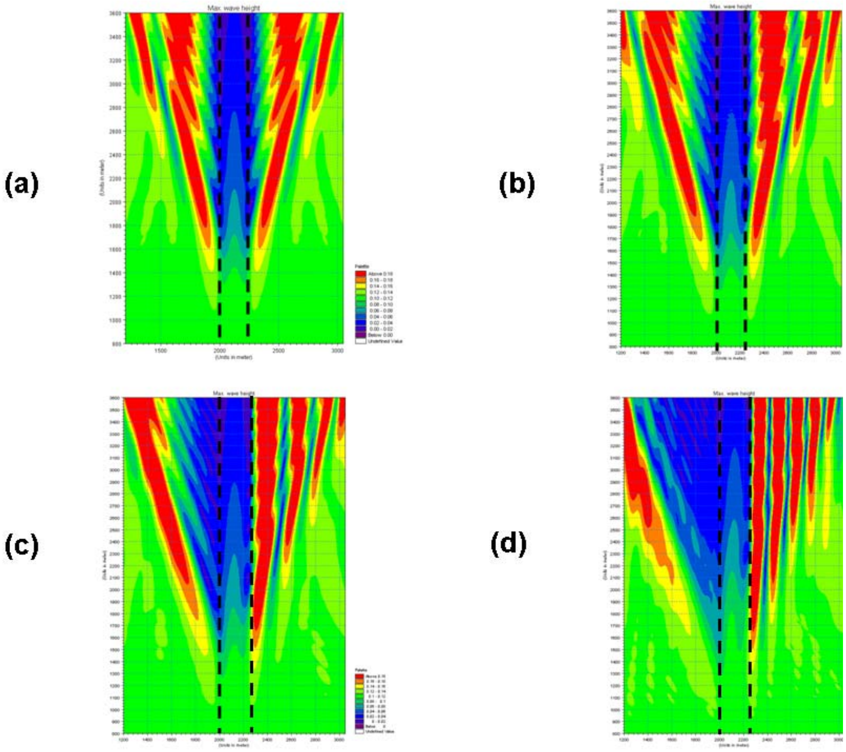

Figure 6. Tp = 10 s (Monochromatic, Unidirectional), Channel Slope = 1V:1H. Comparison of Boussinesq (MIKE 21 BW) model results for MWD = 0deg (a), MWD = 5deg (b), MWD = 10deg (c) and MWD = 20 deg (d). The dashed black lines show the toe lines of the channel

Figure 6 shows a comparison of the Boussinesq model (MIKE 21 BW) response for monochromatic (T = 10s) waves for mean wave directions of 0 deg (a), 5 deg (b), 10 deg (c) and 20 deg (d). As the obliquity of the incident waves increases, it is clear that the “shadow zone” down-wave of the channel increases in the y-direction although amplification of wave height is still evident further away from the channel even for the case with MWD = 20 deg. On the up-wave side, increasing obliquity appears to result in a larger number of distinct focusing regions with alternative “lobes” of amplification and attenuation. With regard to penetration of energy into the channel, it is observed that increasing obliquity results in larger wave heights in the channel as observed by Zwamborn and Grieve (1974).

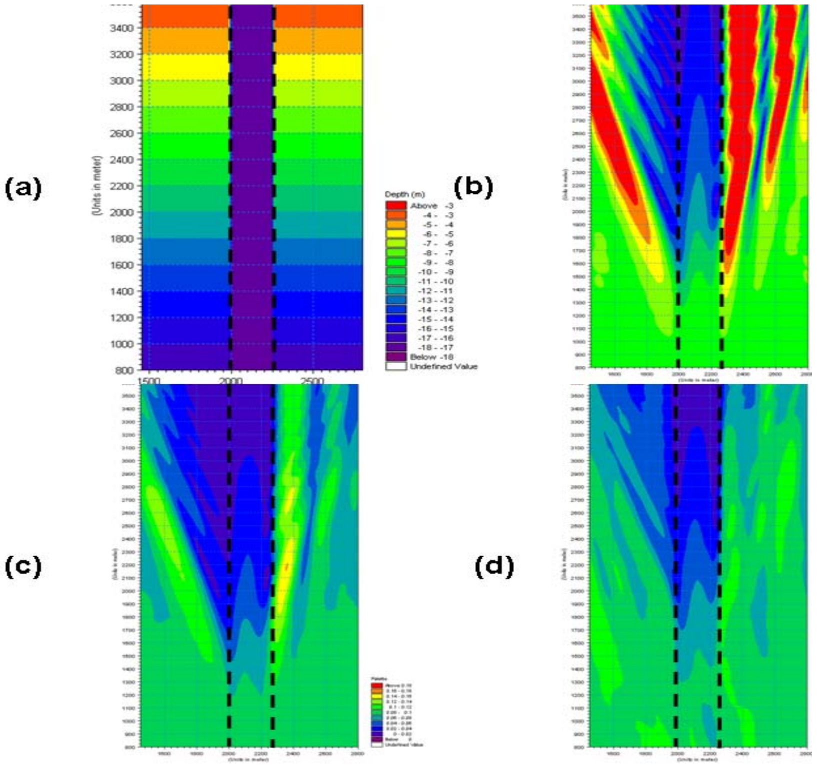

Figure 7. Tp = 10s, MWD = 10deg; (a) Bathymetry (b) Monochromatic and uni-directional waves (MIKE 21 BW) (c) Irregular and uni-directional waves (MIKE 21 BW) (d) Directional and irregular waves (MIKE 21 BW)

Figure 7 shows the sensitivity of the interactions between the incident waves and the channel to the frequency and directional content of the incident waves, for MWD = 10 deg. The intensity as well as the extent of the amplification outside the channel decreases with waves which are irregular and directional, when compared to monochromatic and unidirectional waves. It is also observed that for small angles of obliquity, even for irregular waves, a concentrated zone of amplification still exists on the up-wave side of the channel with wave heights nearly double that of the incident wave height. The ambient depth in this location is approximately 10m. The intensity as well as the distinct interference patterns is much more reduced, although still evident, for multi-directional waves with a maximum amplification of approximately 11 % of the incident wave height.

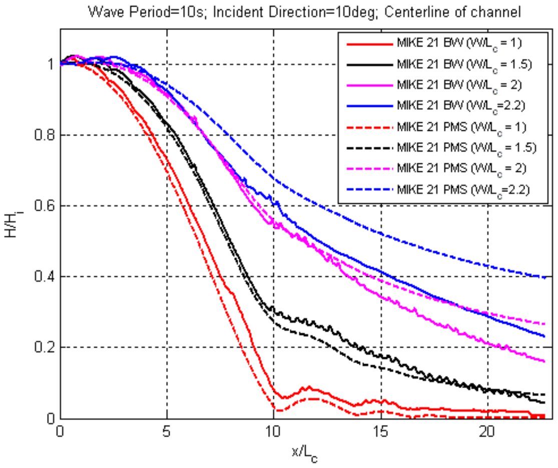

Figure 8 Tp = 10s, MWD = 10deg, Side slope = 1V:1H; Attenuation along channel centreline for Boussinesq (MIKE 21 BW) and parabolic mild-slope (MIKE 21 PMS) models for varying channel widths (between toe lines).

Figure 8 shows the influence of the width of the channel on the wave attenuation along the centerline of the channel for both Boussinesq and parabolic mild-slope models. To isolate and enable an objective comparison, the normalization for each model result is done by the wave height for that model at the beginning of the extraction line. The width of the channel is given here as the distance between the toe lines of the channel and is normalized by the linear theory wavelength, Lc = 114m, corresponding to T = 10s and a depth of 17m. The rate of wave height decay along the channel is highest for the case where the normalized width approaches unity. Further, the differences between the two model results increases as the width increases and with decreasing ambient depth, and for the largest width and an ambient depth of 4 m ($x/L_c \sim 23$), this difference is as large as 15 % of the wave height at the beginning of the channel.

Figure 9 shows a comparison of along-channel and across-channel variations of normalized wave heights for the various numerical models, for the case of T = 10s (monochromatic and uni-directional), MWD = 10deg. h_c and h_a are the channel depth and ambient depth, respectively. Two across-channel profiles are shown for $h_c/h_a = 2$ (c) and $h_c/h_a= 4$ (d). It is clear that the wave action model fails to capture the details of the interactions with the channel. Both the Boussinesq models and the elliptic mild slope model in general agree with each other, except at the shallower depth where the coarser grid of the

BOUSS2D model leads to slight differences with the other model results. The parabolic mild slope model also shows differences compared to the Boussinesq and elliptic mild-slope model, and in general predicts higher wave heights inside the channel.

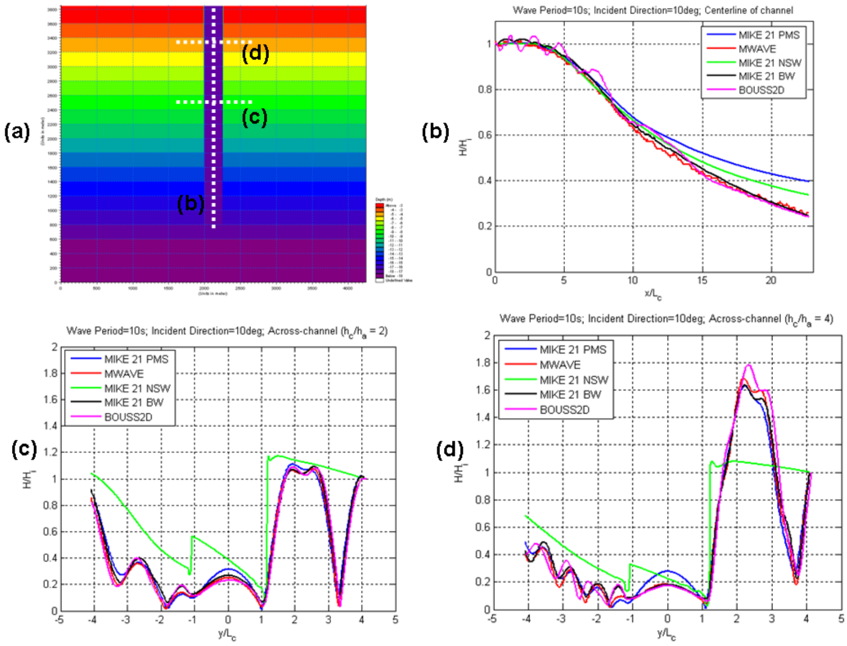

Figure 9 Tp = 10s, MWD = 10deg, Side slope = 1V:1H; Comparison of along-channel and across-channel variations in normalized wave height for different models – Blue (Mike 21 PMS), Red (MWAVE), Green (MIKE 21 NSW), Black (MIKE 21 BW) and Magenta (BOUSS2D).

DISCUSSION

In this paper, surface wave interactions with the deep-draft and wide navigation channels have been shown to significantly influence the incident wave field and lead to competing effects of wave amplification and attenuation. Both these effects in turn critically influence inputs to design, planning of port infrastructure as well as assessment of harbor agitation and downtime.

Compared to short-crested waves, long-crested waves are seen to result in a significantly higher intensity as well as larger spatial extent of amplification/focusing zones due to the superposition of incident and scattered wave energy. Conversely, compared to short-crested waves, long-crested waves can result in an under-prediction of the penetration of incident wave energy into the channel and agitation levels inside the harbor. In general, for a given channel and ambient bathymetry, as well as for a fixed mean wave direction and frequency content of the incident waves, the penetration of wave energy into the channel decreases with increasing peak wave periods. Conversely, the scattering effects leading to amplification in proximity to (and outside of) the channel increases with increasing peak wave period.

Parabolic mild-slope models should be applied with care for wave transformation studies involving deep-draft and wide navigation channels with steep side slopes, if local effects in the vicinity of the channel are deemed important. Due to their inability to incorporate wave scattering, phase-averaged wave action models would appear to be particularly challenged by such applications, especially in accurately resolving the intense local amplification zones that might be created by narrow-banded incident waves at small grazing angles.

During port planning stages, the interactions of waves with channels as discussed in this paper, and the consequences with regard to amplification and attenuation, should factor into the geometry and orientation of the navigation channel as well as the conceptual design of coastal structures in proximity to the channel. These considerations should preferably be optimized through preliminary and limited numerical modeling (preferably with Boussinesq models) of at least the dominant wave directions and wave periods at the site, and confirmed through three-dimensional physical modeling. Presently, we are looking into isolating the potential effects of curvature and slope terms as well as the bottom boundary condition by including comparisons with other recently developed models such as the one discussed in Belibassakis *et al.* (2001).

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REFERENCES

Zwamborn J. A., Grieve, G. (1974*), Proc. 14th ICCE*, ASCE, 1974, 2068 - 85
Li *et al.* (2000), *Applied Ocean Research*, 22, 199-213
Madsen *et al.* (2006), *Coastal Engineering*, 53, 487-504
Magne *et al.* (2007), *J. Geophys. Res*., Vol 112, C01002
Belibassakis *et al.* (2001), *Appl. Ocean Res*., 23, 319-336
Nwogu, O., and Z. Demirbilek (2001), ERDC/CHL TR-01-25
Li, B. (1994) *Coastal Engineering*, 23, 227-242

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