A PRACTICAL APPROACH TO SHALLOW WATER MOORING WITH VARYING SEABED

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A dynamic mooring analysis is performed for a tanker berth in shallow water over a sloping bathymetry. Two different modelling strategies are applied, (i) including the sloping bottom in the panel model as a second structure and (ii) replacing the sloping bottom by an equivalent horizontal bottom. It was found that panel models that are applied for 3D diffraction analysis cannot describe the wave conditions on a sloping seabed. They are unable to describe wave shoaling and wave refraction and predict instead an unrealistic waffled clapotis. Therefore, a sloping seabed seabed cannot be modelled as a second structure in a panel model. This approach will result in unrealistic RAO's with a strongly oscillating pattern, which are in turn the result of unrealistic partial standing waves on the slope. An oscillating pattern is further observed for added mass and damping coefficients; it is unclear if any aspects of the sloping seabed are captured realistically by this approach. Including a sloping seabed in a panel model is therefore not advisable. The simplified modelling approach with an equivalent horizontal seabed is more robust and is more likely to provide a realistic estimate of the actual line and fender forces.

Keywords: Dynamic mooring analysis; ship response analysis, sloping seabed; line forces, fender forces, modelling approach

INTRODUCTION

Exposed import and export terminals for LNG are presently developed in many places all over the world; examples that received a lot of public attention are PNG LNG by Exxon Mobile in Papua New Guinea, Gorgon LNG by Chevron in NW Australia and Angola LNG by Texaco/Chevron in Angola. The economic feasibility of these plants is determined amongst others by the operability of the loading or off-loading facilities for LNG carriers, which in turn largely depends on weather downtime.

Periods in time where the environmental conditions (i.e. wind, waves, currents etc.) are such that the ships cannot stay safely at berth or cannot be loaded or unloaded in limiting are called weather downtime. Dynamic mooring analysis is commonly performed to assess the weather downtime of a terminal. The prediction of line forces, fender forces and manifold displacements (in case of a tanker berth) requires a numerical analysis of the ship response to waves and gusting wind. Software packages like WAMIT, SESAM WADAM, MOSES and ANSYS AQWA became an industry standard for this analysis. These packages were originally developed for application in deep water, but have been refined and extended over the past 30 years. More recent versions include the interaction of ship and seabed and are thus applicable in shallow water. However, all available software packages require a constant water depth in the computational domain; the effect of a variable water depth, for example a seabed slope is not considered. Therefore, shallow water results require careful interpretation and a clear understanding of the limitations of these programmes.

A dynamic mooring analysis is performed using ANSYS AQWA for a tanker berth in shallow water over a typical sloping, coastal bathymetry. Two different modelling strategies are applied:

- The sloping bottom is included in the panel model as a second structure that is resting on the seabed. The actual bathymetry is thus represented by diffracting panels in this approach.
- The sloping bottom is replaced by an equivalent horizontal seabed. The actual bathymetry is thus simplified and described by a single parameter (constant water depth) in the panel model.

This paper describes the difficulties that arise when modelling a bathymetry as a submerged structure in a 3D diffraction analysis. The results that are obtained from this approach are presented and compared with the results from a conventional analysis with constant water depth. A simple modelling approach is proposed for a mooring analysis in shallow water.

PANEL MODEL WITH VARIABLE WATER DEPTH

General Approach

The dynamic mooring analysis is commonly performed by a two-step approach consisting of hydrodynamic analysis (step 1) and mooring analysis (step 2).

The *hydrodynamic analysis* (3D diffraction analysis) is a frequency domain analysis. The geometry of the ship hull (or any other floating structure) is described by a panel model. The ship characteristics in harmonic waves are determined by a 3D diffraction programme. Linear motion coefficients (response amplitude operators, RAO's) and resistance coefficients (added mass and damping coefficients) are determined and stored in a hydrodynamic data base. The analysis is performed with frequency and directional discretization; the motion and resistance coefficients are determined in 6 degrees of freedom and for a range of wave frequencies and wave directions. This information is stored in a ship characteristics data base that is subsequently applied for the time domain analysis.

The *mooring analysis* is a time domain analysis. The ship motions and mooring loads are calculated for a specific berth layout including mooring lines and fenders and for the ship characteristics from the above hydrodynamic data base. The wave conditions (external forcing) are varying in time; the waves are commonly defined by a spectrum. Additional wind loads (either constant or time varying spectral wind) and current loads (constant or time varying) can be applied.

The effect of a sloping bathymetry comes into play in step 1, the 3D diffraction calculation when the interaction between ship and waves is determined. The ship response (added mass, damping and motion operators) and the various wave fields (incoming, diffracted and radiated waves) are influenced by the seabed, i.e. by the water depth and by the geometry of the seabed (for example a sloping seabed). Ship response and wave fields would also be influenced by a second, either floating or fixed structure (for example a quay wall or a second ship). When the sloping bottom is included in the panel model as a second structure that is resting on the seabed, it will have some influence the waves and the ship response. This influence however may be different from the actual effect of a sloping seabed. The wave conditions in the 3D diffraction analysis and the resistance of the ship (added mass and damping coefficients) are described in the following sections.

Wave Conditions in the 3D Diffraction Analysis

The incoming waves are defined a priori in the 3D diffraction analysis. They are defined by a wave spectrum and include frequency spreading, but no directional spreading. The frequency components of the incoming wave spectrum are characterised by the direction of wave propagation, the wave amplitude and the phase angle. The direction of wave propagation of all frequency components and the amplitude of each frequency component are constant in the entire modelling domain. The phase angles of the frequency components differ between the panels; they are a function of time, panel coordinates, wave direction, wave number and a reference phase angle. The wave number is a function of wave period and water depth; the reference phase angle is commonly defined by a seed number for the generation of a wave spectrum with random phase angles. For given time, panel coordinates and incoming wave direction the calculation of phase angles is straightforward. Hence, the incoming waves in the 3D diffraction analysis have two characteristic features:

- The wave kinematics of incoming waves (water surface elevations and particle motions) are defined for all time steps and panels.
- The incoming waves propagate through panels; they are not affected by fixed or floating structures. Only the superposition of incoming and diffracted waves will leads to realistic wave conditions in the panel model.

The wave modelling in the 3D diffraction analysis comprises of three different wave components. The *incident waves* are defined a priori (see above). The *reflected and diffracted waves* are determined at each panel (depending on incident wave and panel orientation). The diffracted wave field is derived from the superposition of all diffracted wave components. The *radiated waves* are waves resulting from ship motions. Ship motions are caused by waves and vice versa, cause wave motion. The generation of radiated waves is a damping mechanism for the ship motion (also known as radiation damping).

The treatment of waves in a 3D diffraction analysis is illustrated in Fig. 1. Waves are calculated over a sloping bathymetry. The sloping bottom is included in the panel model as a fixed structure that is resting on the seabed; the bathymetry is thus represented by diffracting panels (Fig. 1a). No floating structures (ships) are considered. The panel model predicts wave diffraction at the sloping surface and at the edges of the seabed body (Fig. 1c). Shoaling and depth refraction of the incident waves are not considered (Fig. 1b). The superposition of incoming waves and diffracted waves results in a chaotic, partial standing wave field above the sloping seabed (Fig. 1d).

The wave diffraction at the edges of the seabed body cannot be controlled by enlarging the seabed body or by modifying the shape of the edges. This confirms the findings of Buchner (2006). He stated that it is not possible to model a sloping seabed as a second body in diffraction theory; a large size of the second body, representing the seabed and smoother edges of this body do not improve the situation. Radiated waves are not generated above the sloping seabed as it is modelled as a fixed structure.

In the panel model the water depth is not affected by fixed or floating structures. The model assumes a constant water depth and consequently a constant wave speed; it is thus by definition unable to describe the wave shoaling and wave refraction on a sloping seabed. The effect of the sloping seabed is approximated by diffracted waves with the same constant wave speed as the incoming waves. It is obvious that this will be, if at all, only a crude approximation of the actual wave transformation on the slope.

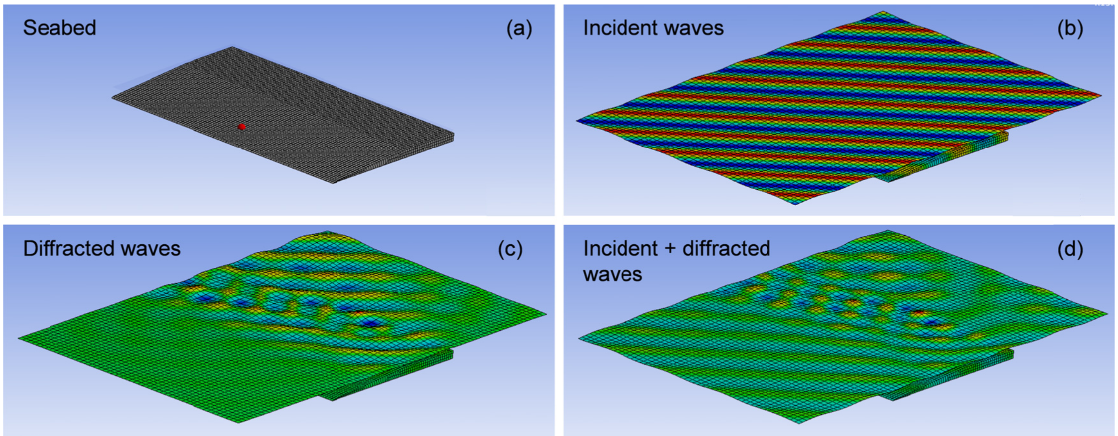

Figure 1. Waves over a sloping bottom in a panel model: (a) Panel model of the sloping seabed, (b) incoming waves, (c) diffracted waves and (d) superposition of incoming and diffracted waves

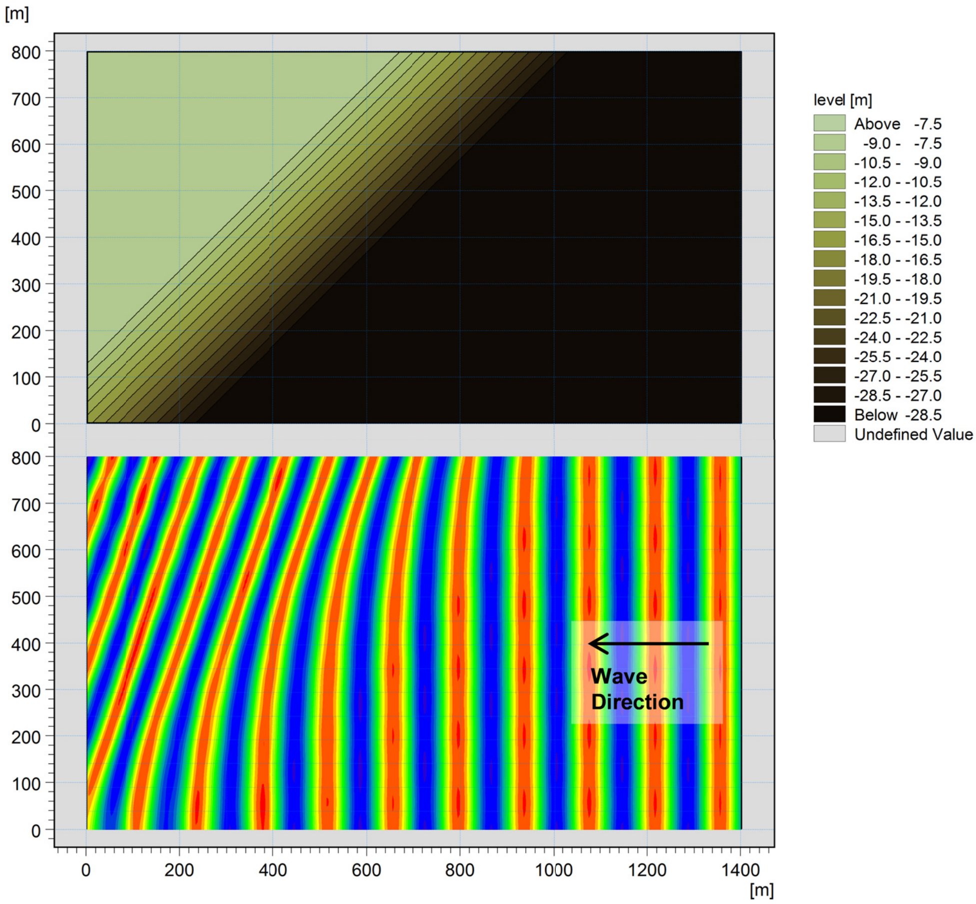

Figure 2. Boussinesq wave model: Bathymetry with an oblique underwater slope (top); monochromatic waves propagating across the slope (bottom)

The transformation of monochromatic waves on a sloping bottom is shown in Fig. 2. The waves are approaching the slope at an angle of 45° from the line of the greatest slope. The wave pattern in Fig. 2 (bottom) is determined with a Boussinesq wave model. Different from the panel model, where the slope is aligned with the boundaries of the computational domain and the waves propagate in oblique direction, the wave direction in the Boussinesq model is aligned with the computational domain and the orientation of the slope is oblique.

The results of the Boussinesq model illustrate the changes in wave length and wave direction on the slope. The effect of wave refraction is clearly visible (Fig. 2, bottom). A cross-hatched wave interference pattern or waffled clapotis as predicted by the panel model cannot be seen. The wave pattern in Fig. 2 (bottom) differs significantly from the wave pattern in the panel model (Fig. 1d). The panel model provides a surprisingly complex but unfortunately far from realistic wave field above the sloping bottom.

It follows from the above that panel models that are applied for 3D diffraction analysis cannot describe the wave conditions on a sloping seabed realistically. They assume a constant water depth and a constant wave speed. Therefore they are by definition unable to describe wave shoaling and wave refraction above a sloping seabed. When the sloping seabed is included in the panel model as a fixed seabed structure the wave diffraction at the edges of this structure results in a waffled clapotis. This is an unrealistic wave pattern; it reflects the limitations of the panel model. It can be expected that this unrealistic wave pattern will also result in unrealistic wave forces on a ship that is moored above the underwater slope.

Added Mass and Damping Coefficients

The ship's resistance to motion is described by added mass and damping coefficients. Both are frequency depended and have to be determined per wave direction and for all six degrees of freedom. The added mass and damping coefficients are determined by imposing an oscillatory translation or rotation with unit amplitude on the ship. The force on the panels that results from the imposed motion is the equivalent of the added mass; the radiated waves that are generated by the imposed motion are the equivalent of the damping.

The added mass corresponds to the mass of water that encloses the ship hull and that is accelerated when an oscillatory motion is imposed to the ship. It is obvious that added mass will be frequency depended; added mass is further increasing in shallow water.

The amount of energy that is dissipated by the damping corresponds to the wave energy flux of the radiated waves. The energy flux is defined by the product of wave energy density and wave group velocity. Shallow water will affect the amplitude of the radiated waves as well as the wave group velocity. Similar to the added mass, wave damping is frequency depended and increases in shallow water. When modelling the seabed as a diffracting structure (i.e. with panels) the radiated waves that are generated by the ship might be reflected by the seabed and propagate towards the ship. Hence, the wave energy flux away from the ship would be reduced and consequently the wave damping.

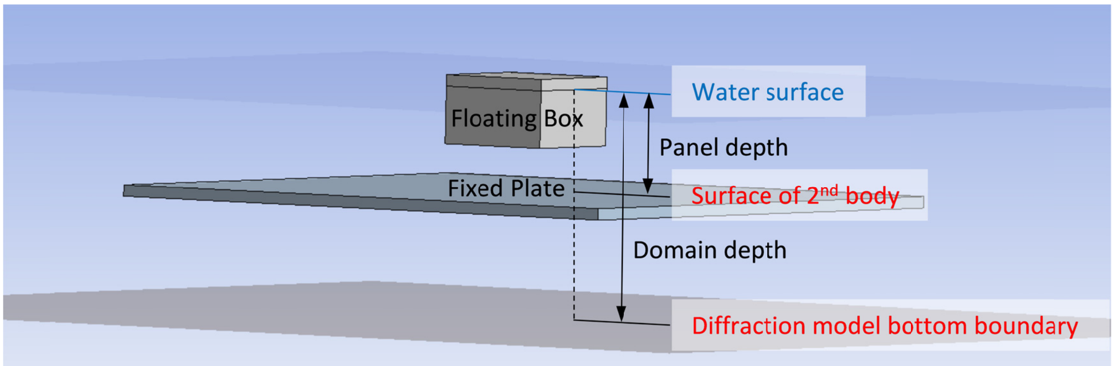

Figure 3. Panel model of floating box with domain depth of 20 m and panel seabed model (fixed plate) of size 50×50 m^2 with a panel depth of 8 m

The effect of a shallow seabed that is modelled by diffracting panels is demonstrated by a simple panel model consisting of a quadratic barge (in the following referred to as "box") and of a plane horizontal seabed (in the following referred to as "plate") as shown in Fig. 3. Two different water depths have to be distinguished in this model:

- *Domain water depth* refers to the vertical distance between water line and bottom boundary of the 3D diffraction model;
- *Panel water depth* refers to the vertical distance between water line and the panel model of the body that is representing the seabed (in this case the plate).

Added mass and damping of the floating box are determined accurately when the plate is excluded and the domain depth is equal to the actual water depth. Added mass and damping are subsequently determined in a model with increased domain depth, where the shallow seabed is modelled by a second body, a fixed plate. The box of size 10×10 m^2 with a draft of 5 m is floating above a horizontal seabed. The seabed is either defined by the bottom boundary of the 3D diffraction model or by a diffracting plate with 8 m submergence. The size of the plate is 50×50 m^2 or 300×300 m^2; the box position is above the centre of the plate. Domain depths of 8 m, 10 m and 20 m are considered here. With 8 m water depth, the shallow seabed is properly defined by the bottom boundary of the 3D diffraction model and the plate is thus evitable. With 10 m and 20 m domain depth, the model is run with and without plate. Model runs without plate show the actual effect of the increased water depth on added mass and damping coefficients. Model runs with plate should result in the same added mass and damping coefficients as the initial run with 8 m water depth, if the diffracting plate would have the same effect as a shallow seabed.

Added mass and damping coefficients of the floating box are presented in Fig. 4 for heave (i.e. vertical translation, coefficient Z-Z are on the principal diagonal of the added mass and damping matrices). The heave coefficients are more illustrative than the coefficients for other ship motions and are therefore presented here; the observations for heave apply for other ship motions as well.

In the runs without plate the added mass and damping coefficients are decreasing with increasing water depth. The effect of frequency is very much the same for all three water depths.

When modelling the shallow seabed with a horizontal plate of size 50×50 m^2 that is 8 m below the water surface the predicted added mass and damping coefficients are similar to the results from runs with increased domain depth and without plate. It can be seen in Fig. 4 (left) that a diffracting plate has some effect on the added mass and damping coefficients. But it is evident that both coefficients are primarily determined by the domain depth and not be the panel depth above the diffracting plate. None of the runs with diffracting plate results in added mass and damping coefficients that are similar to the initial run with 8 m water depth. In other words, the diffracting plate fails to reproduce the effect of a shallow seabed.

When modelling the shallow seabed with a horizontal plate of size 300×300 m^2 (8 m below the water surface) the predicted added mass and damping coefficients become similar to the results from the run with 8 m domain depth. It can be seen in Fig. 4 (right) that added mass and damping coefficients are significantly influenced by the panel depth above the diffracting plate. The results are similar to the initial run with 8 m water depth. It appears that a diffracting plate of sufficient size can reproduce the effect of a shallow seabed to some extent. However, the added mass and damping coefficients show an unrealistic oscillating pattern; the maximum error is about 30%.

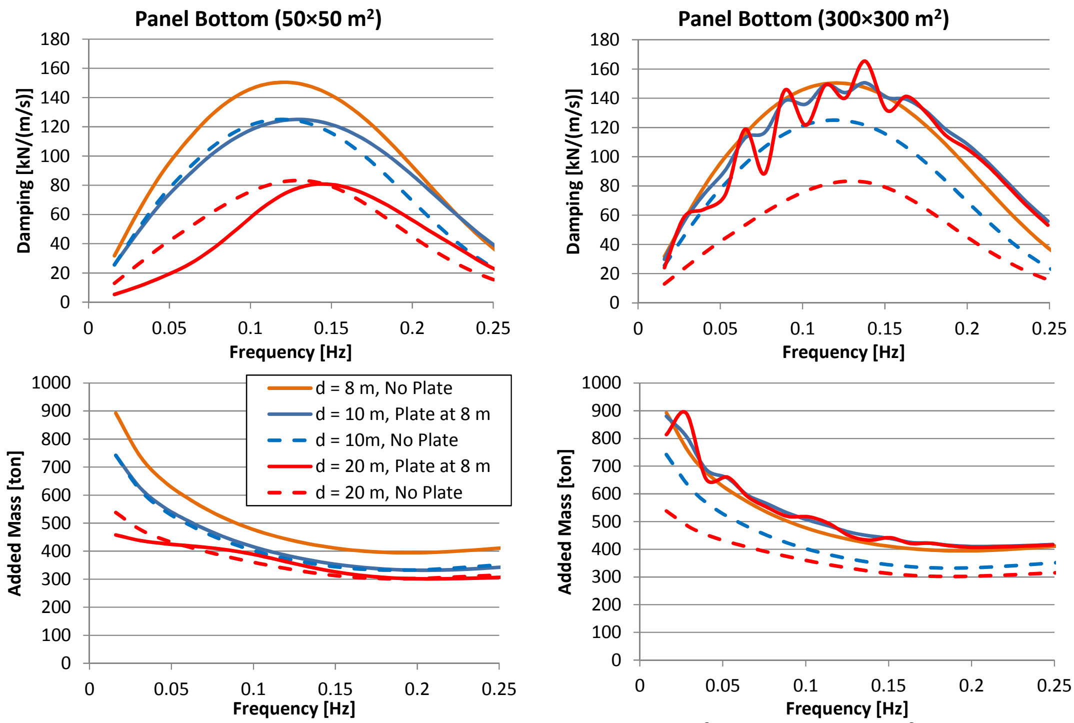

Figure 4. Resistance of floating box with panel bottom of size 2,500 m^2 (left) and 90,000 m^2 (right): Damping coefficients (top) and added mass coefficients (bottom) for heave (Z-Z)

Buchner (2006) concluded that a second body in diffraction theory, when chosen properly with respect to size and shape, can contribute to the correct calculation of the added mass and damping of ships on a sloping seabed. The conclusion of Buchner is partly confirmed in this study. The results of the simple floating-box-model (Fig. 4) demonstrate that the effect of a shallow seabed can be reproduced to some extent by a second structure of sufficient size in the 3D diffraction analysis. However, the accuracy of the predicted added mass and damping coefficients is limited. The errors of the simple floating-box-model reached 30%; larger errors can be expected in a more complex model with varying depth.

RESULTS OF ANALAYSIS WITH VARIABLE WATER DEPTH

A dynamic mooring analysis is performed for a tanker berth in shallow water with sloping seabed. The sloping bottom is included in the panel model as a second structure that is resting on the seabed; the actual bathymetry is thus modelled by diffracting panels. It is demonstrated in the previous sections that this modelling approach will result in distorted wave conditions at the berth and in distorted resistance coefficents for the ship. Nonetheless, this approach is applied to show to which extent line and fender forces will be affected by the shortcomings of the 3D diffraction analysis.

A tanker (LNG carrier with spherical tanks) of size 125,000 m3 (LPP 260 m, beam 47.2 m and draft 11.5 m) is moored above a sloping seabed with gradient 1:20 (Fig. 5). The line of maximum gradient is parallel to the longitudinal ship axis. The water depth varies along the berth from 17 m (stern) to 23 m (midships) and 29 m (bow).

A 3D diffraction analysis is performed to determine the response amplitude operators (RAO's) and resistance coefficients (added mass and damping coefficients) of the ship. Results from simulations with a second structure that represents the seabed are compared with two reference cases with horizontal seabed. The latter are performed with the midships depth (23 m) and the predefined water depth (domain depth, 32 m) of the simulations with sloping seabed.

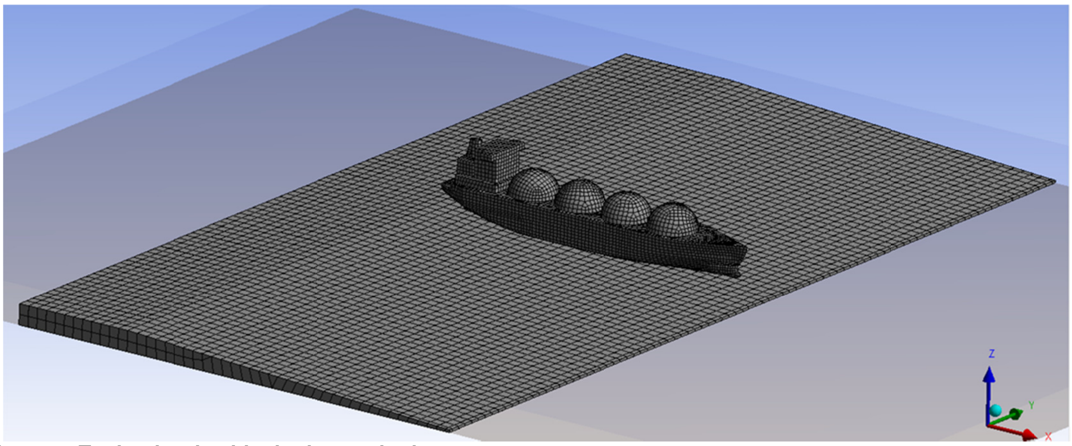

Figure 5. Tanker berth with sloping seabed

The damping coefficients of the tanker above the sloping bottom and from the two reference cases with horizontal bottom are plotted in Fig. 6. The overall characteristics of the damping coefficients above the panel bathymetry are similar to the damping coefficients in constant water depth, when the water depth is equal to the midships depth above the slope. In other words, the water depth that is "felt" by the ship is determined by the seabed structure (panel depth) and not by the domain depth. This is similar to the results of the above floating-box-analysis with a plate of size 300×300 m^2. The damping coefficients above the sloping seabed show an oscillating pattern for all translational and rotational ship motions. The largest amplitudes are found for motion periods of 10 – 25 s; the oscillation amplitudes are decreasing for longer and shorter periods. These oscillations are probably induced by the distorted wave pattern at the berth, i.e. the waffled clapotis (see Fig. 1d) is probably responsible for these oscillations.

The added mass coefficients of the tanker (sloping bottom and two reference cases with horizontal bottom) are plotted in Fig. 7. Similar to the damping coefficients (Fig. 6) the overall characteristics of the added mass coefficients above the sloping seabed are similar to coefficients in constant water depth, when the water depth is equal to the midships depth above the slope. The added mass coefficients above the sloping seabed show the same oscillating pattern as for the damping coefficients, which is probably a result of the distorted wave pattern at the berth.

Figs. 6 and 7 give the impression that added mass and damping coefficients above a sloping bottom that is modelled as a second structure are similar to the coefficients that ate determined for the midships depth above the slope modelled with horizontal bottom.

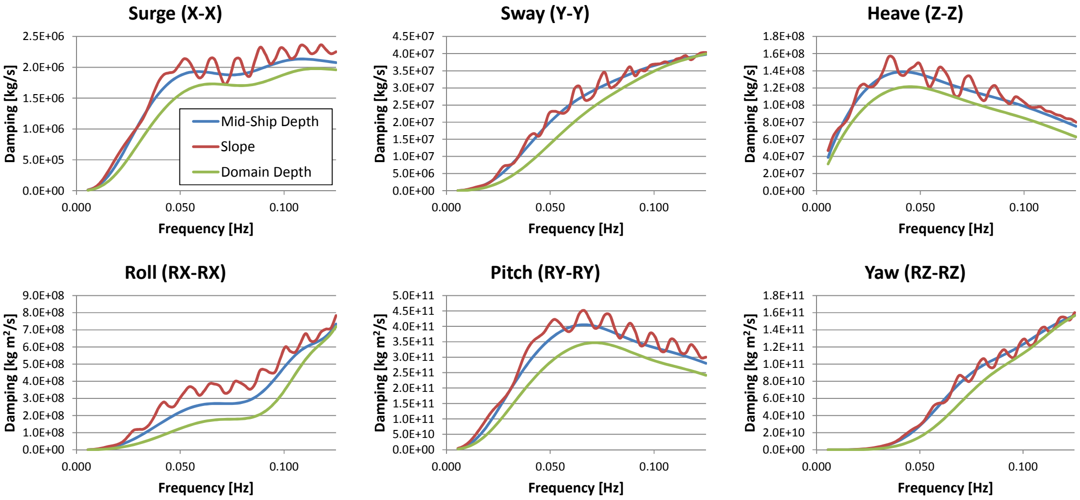

Figure 6. Damping coefficients of tanker above sloping seabed and two reference cases with horizontal seabed

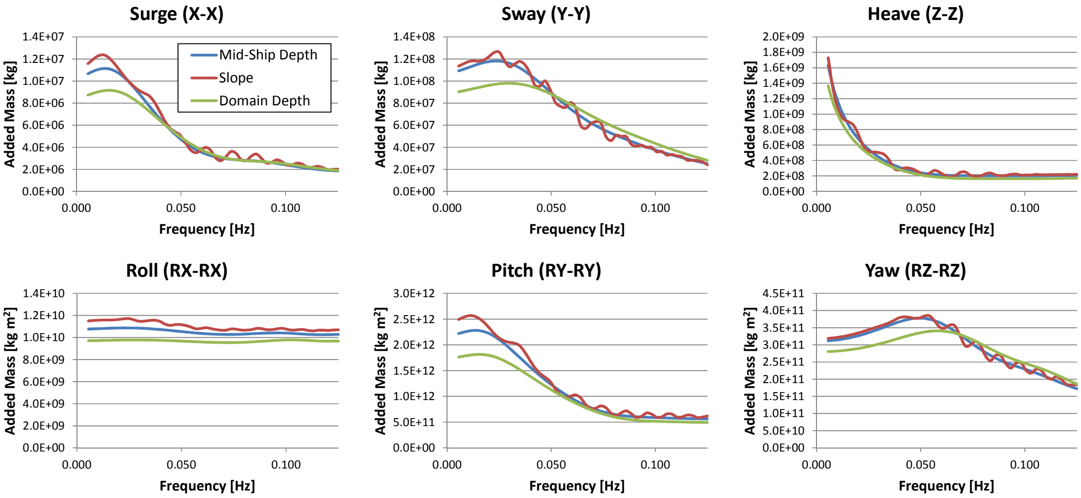

Figure 7. Added mass coefficients of tanker above sloping seabed and two reference cases with horizontal seabed

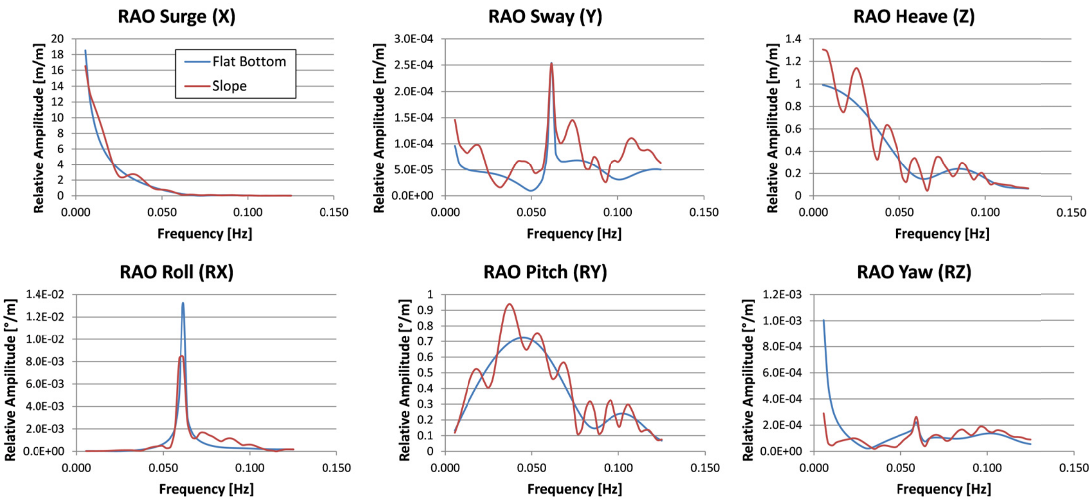

Figure 8. RAO's of tanker above sloping seabed in head on waves and two reference cases with horizontal seabed

It was earlier concluded by Buchner (2006) that unrealistic partial standing waves above a sloping seabed that is modelled as a second structure in the 3D diffraction analysis will result in distorted wave exciting forces on a ship and in distorted ship response to waves. According to Buchner the predicted ship motions are unrealistic; modelling a sloping seabed as a second body is thus not possible. The linear response amplitude operators (RAO's) that are linking the wave pressure on panels to ship motions are presented in Fig. 8 for head on waves. RAO's are presented for the sloping seabed and for a reference case with horizontal seabed, where the water depth is equal to the midships depth above the slope. The RAO's have a strong oscillating pattern for all translational and rotational motions. These oscillations are obviously induced by the interference pattern of the partial standing waves at the berth (see Fig 1d). This waffled clapotis is unrealistic and so are the ship motions that are induced by the waffled clapotis and are described by the RAO's.

A time domain mooring analysis is performed using the results of the 3D diffraction analysis (RAO's, added mass and damping coefficients). The ship motions at berth and the mooring loads (line and fender forces) are calculated for a given berth layout, mooring arrangement and for specific mooring line and fender characteristics. A typical jetty mooring configuration (3 head lines, 3 forward breasting lines, 2 forwards spring lines, 2 aft spring lines, 3 aft breasting lines, 3 stern lines and 4 fenders) are applied as shown in Fig. 9. The lines (40 mm steel ropes with nylon tail) have a breaking load of 127 ton and a stiffness of 30% breaking load at 0.78% elongation. The fenders have a rated load of 4,390 kN at 60% deflection.

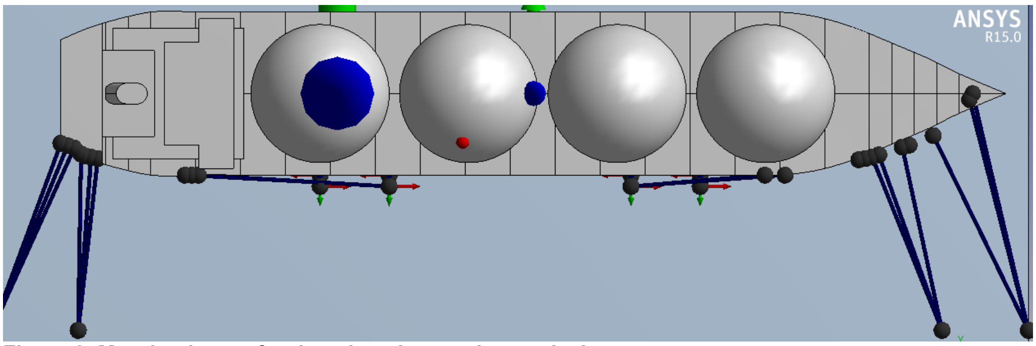

Figure 9. Mooring layout for time domain mooring analysis

Three different wave conditions are considered in this mooring analysis; these are head on waves, quarterly bow waves and beam on waves. For head on waves and quarterly bow waves a JONSWAP spectrum with significant wave height, H_s of 2.0 m and a peak wave period, T_p of 10 s is applied. For beam on conditions the significant wave height is reduced to 1.0 m.

Results from the mooring analysis with sloping seabed and with horizontal seabed are presented here. The latter are performed with the midships depth (23 m) of the simulations with sloping seabed.

For head on conditions the simulations with sloping seabed result in slightly higher line loads for the spring lines Fig. 10, left). They are probability caused by second order drift forces; the surge RAO's on the slope are increased for long waves as compared to a horizontal bottom (see in Fig. 8). He differeces for all other line and fender forces are insignificant.

For quarterly bow waves the simulations with sloping seabed result in lower line and fender loads (Fig. 10, centre). This is is surprising as the RAO's for sway above a sloping seabed are mostly larger than with a horizontal bottom. The RAO's for yaw are similar for sloping and horizontal seabed except for long waves.

For beam on waves the fender and mooring line loads are significantly lower above a sloping seabed than for the reference case with horizontal seabed. As for the quarterly bow conditions the reason for this load reduction cannot be identified in the RAO's for sway and yaw, except for the yaw response to long waves. The results of simulations with horizontal bed that are presented in the following section indicate that head and stern lines face larger loads in deeper water. Reduced line loads as found for the stern lines in the shallow part of the slope are in line with this observation. However, the reduced line loads for the bow lines in the deeper part of the slope are incomprehensible.

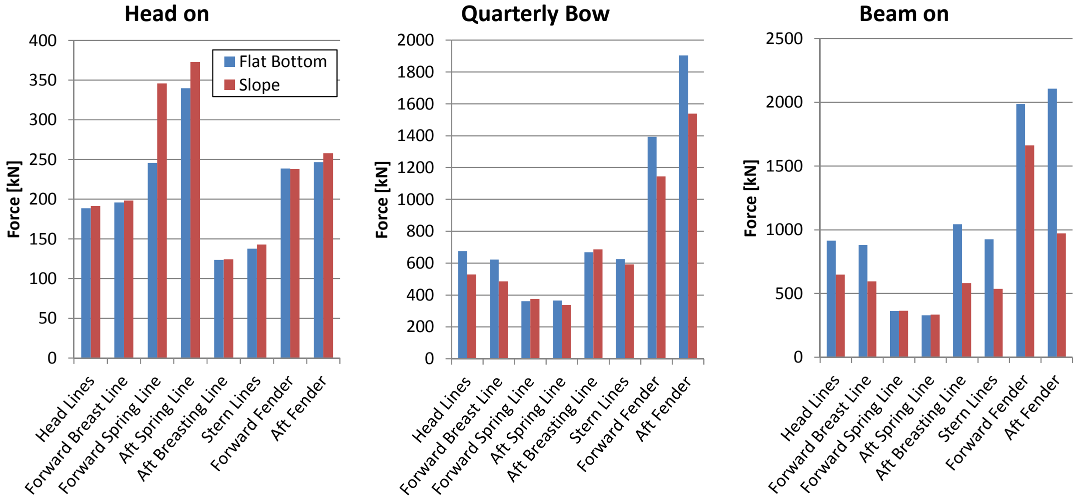

Figure 10. Line and fender forces above sloping bottom and reference cases with horizontal seabed

It appears from the above that the distorted wave field will affect not only the results of the frequency domain analysis (3D diffraction analysis) but also the results of the mooring analysis in the time domain. The predicted line and fender forces above a sloping seabed differ from the results that are obtained with a horizontal seabed. It is not clear to which extent these deviations are caused by the distorted wave field and the resulting incorrect RAO's, by the oscillating pattern of added mass and damping coefficients or by the actual effect o the sloping seabed.

RESULTS OF ANALAYSIS WITH CONSTANT WATER DEPTH

An alternative, more straightforward modelling approach is investigated whereby the sloping bottom is replaced by an equivalent horizontal seabed (Fig. 11). The actual bathymetry is thus simplified and described by a single parameter (constant water depth) in the panel model. The tanker berth is further unchanged. The same LNG carrier as in the previous analysis has been applied; the water depth of 17 m, 23 m and 29 m corresponds to the bow, midships and stern water depths on the slope. The 3D diffraction analysis is performed for each water depth to determine the RAO's and added mass and damping coefficients of the ship.

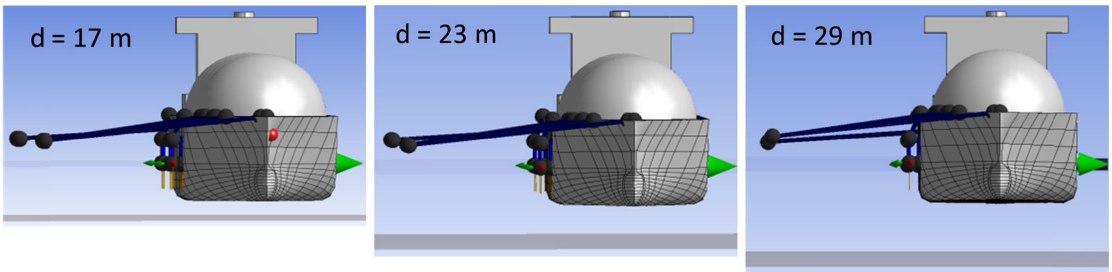

Figure 11. Tanker berth with horizontal seabed: Water depth 17 m (left), 23 m (centre) and 29 m (right)

The damping coefficients are presented in Fig. 12; the added mass coefficients are shown in Fig. 13. The damping coefficients are increasing in shallow water. The added mass coefficients are also typically increasing in shallow water, especially for low frequencies. The RAO's are presented in Fig. 14. The 3D diffraction analysis with horizontal bottom is not distorted by the development of a waffled clapotis. Consequently, and different from the simulations with sloping bottom, the RAO's and the resistance coefficients do not show an oscillating pattern. The RAO's are similar for all three water depths. However, a slight shift in natural frequencies can be observed leading to longer natural periods in shallow water. This shift is related to the increased damping and added mass coefficients in shallow water.

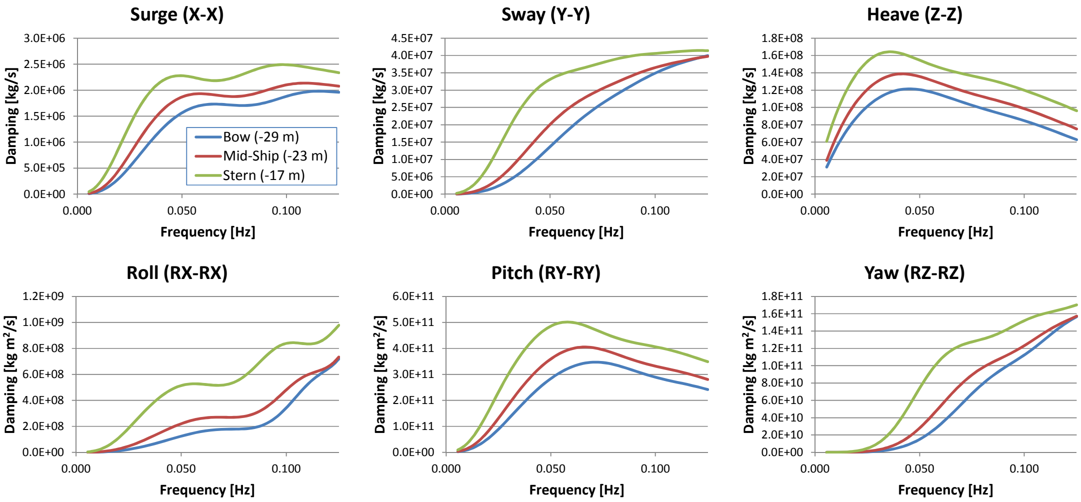

Figure 12. Damping coefficients of tanker above horizontal seabed (water depth 17 m, 23 m and 29 m)

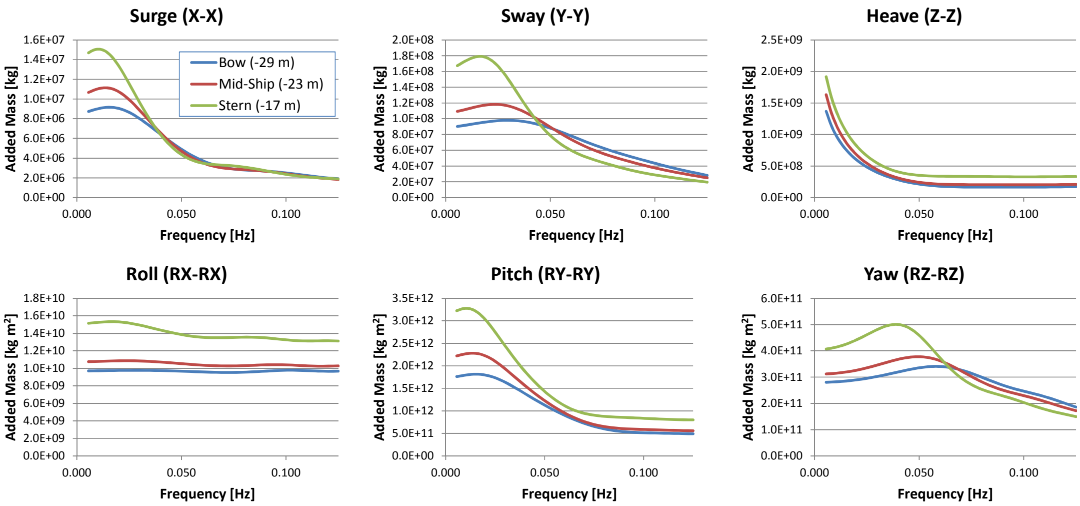

Figure 13. Added mass coefficients of tanker above horizontal seabed (water depth 17 m, 23 m and 29 m)

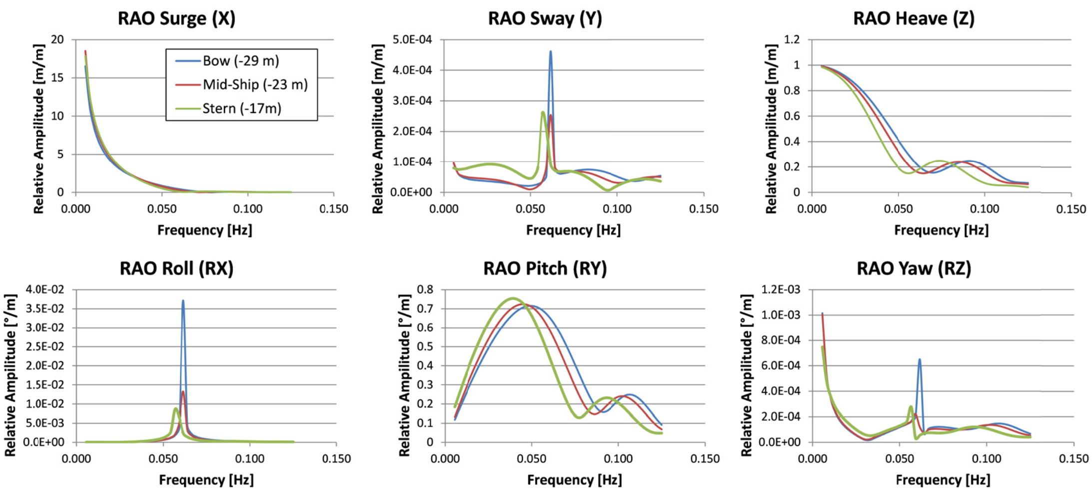

Figure 14. RAO's of tanker above horizontal seabed (water depth 17 m, 23 m and 29 m) in head on waves

A time domain mooring analysis is performed; the ship motions at berth and the mooring loads (line and fender forces) are calculated for the three different water depths. The mooring configuration with 16 lines and 4 fenders is identical to the analysis with sloping seabed (see Fig. 9). The same applies for the line and fender characteristics and for the environmental conditions (H_s of 2.0 m for head on and quarterly bow conditions, H_s of 1.0 m for beam on conditions). Results from the mooring analysis are presented in Fig. 15. The line and fender for head on conditions are of similar size for all three water depths. For quarterly bow conditions and for beam on conditions the differences can be significant for specific lines. There is not a persistent increase or reduction of line and fender forces in shallow water. The behaviour of a ship at berth is the result of a complex interaction of ship, environment and mooring system; the prediction of line and fender forces requires therefore an analysis of the entire system.

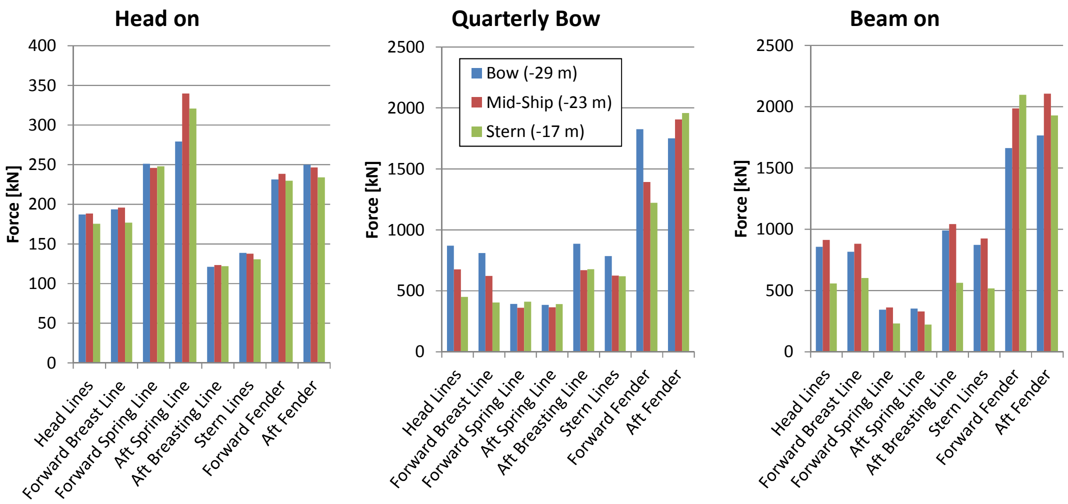

Figure 15. Line and fender forces above horizontal bottom (water depth 17 m, 23 m and 29 m)

CONCLUSIONS

When performing dynamic mooring analysis for a berth with varying seabed, the geometry of the seabed cannot be modelled as a second structure in a panel model. This approach will result in unrealistic RAO's with a strongly oscillating pattern, which are in turn the result of unrealistic partial standing waves on the slope. An oscillating pattern is further observed for added mass and damping coefficients when the seabed is modelled as a second structure in a panel model. It is unclear if any effects of the sloping seabed on added mass and damping can be captured realistically by this approach.

A dynamic mooring analysis for a berth with varying seabed bears large uncertainties when the seabed is included as a second structure in the panel model. This approach is therefore not advisable.

A simplified modelling approach with an equivalent horizontal seabed is more robust and is more likely to provide a realistic estimate of the actual line and fender forces. The uncertainties of this approach are related to the definition of the equivalent water depth and to the influences of the sloping bottom that are neglected in this approach. Influences that are not addressed are for example the variation of added mass between the bow and stern of the ship. The equivalent constant water depth at a berth with sloping seabed can be assessed by as follows:

- The equivalent water depth for a berth with sloping seabed is most probably within the range of minimum and maximum water depth at the berth;
- The mid-ships water depth can be applied to determine a best estimate of line and fender forces; the minimum and maximum water depth (water depths at bow and stern) can be applied to determine a likely range of line and fender forces.

It is further recommended to analyse the variation of wave conditions along the berth with a suitable wave model. The likely range of line and fender forces should preferably be determined for all combinations of the relevant water depths (at bow, midships and stern) and wave conditions (at bow, mid-ship and stern). If the wave conditions vary significantly along the berth, for example in case of a partly sheltered berth a hybrid Boussinesq-panel approach (Bingham, 2000) should be considered. Examples of a dynamic mooring analysis with a hybrid Boussinesq-panel approach can be found in Wenneker et al (2006) and Christensen et al. (2009).

ACKNOWLEDGMENTS

This study would not have been possible without the support of Delta Marine Consultants. This support is gratefully acknowledged.

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