To improve the efficiency of ports exposed to swell

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Abstract
Ships moored in harbour basins exposed to swell may experience large horizontal ship motions. In some cases mooring lines break. High downtime figures are not uncommon. The horizontal ship motions are driven by long waves (also called infra-gravity waves) that penetrate the harbour basin. This paper shows, by presenting two cases, how the efficiency for ports exposed to swell can be improved. The first case shows how large ship motions may be avoided in the design stage of a port exposed to swell and infra-gravity waves. The channel orientation was optimised based on the calculated ship motions. The second case shows how the motions could be reduced by applying the ShoreTension® mooring system, which actively dampens the horizontal ship motions.

Keywords: wave penetration, infra-gravity waves, vessel motions, Dynamic Mooring Analysis (DMA), downtime.

1. Introduction

Ships moored in harbour basins or coastal waters exposed to swell may experience large horizontal ship motions. The (un)loading process may be slowed down or even interrupted. High line tensions may occur. In some cases, lines may break yielding a dangerous situation for the crew (on shore or on board). The ship may also break loose of its moorings with subsequent damage to the port infrastructure or other moored vessels.
For mooring locations exposed to swell, high downtime figures are not uncommon. Downtime is defined as the time throughout a year that (un)loading cannot take place due to excessive motions or due to too high line tensions. In the latter case the mooring is considered unsafe and the ship has to leave the berth. The time the ship needs to sail out and return to the berth to finish the (un)loading is also considered downtime.

Long waves are the driving factor for excessive horizontal motions for ships moored in harbour basins or coastal waters exposed to swell (see for example [3][4][5][6][14]). There are 3 sources for low-frequency wave energy:

1. Bound long waves (also called wave set-down), associated with the swell wave groups travelling towards the shore;
2. Free long waves, the (reflected) bound long wave which is set free after the swell waves have broken on shore or on a shallow water[1];
3. Harbour oscillations (seiching), a standing wave related to the natural period of the harbour basin;

Long waves (also called infra-gravity waves, period between 30 and 300 s) induce resonance of the moored ship. High mass of the ship and soft springs (mooring lines) imply a long natural period for the surge, sway and yaw motion (longitudinal and lateral translation, rotation around the vertical axis respectively). The natural periods of the surge, sway and yaw motion of the moored ship are in the same range as the excitation (30-200 s). Furthermore, the damping for the horizontal motions (especially surge) is limited. Large motion amplitudes occur, yielding high tension peaks in the lines.

Long waves, excessive ship motions and breaking lines are still a problem today. Two examples of ports in Australia and New Zealand that have issues with large ship motions due to long waves are Geraldton[2] and Taranaki[3].

Over the last decades several methodologies have been derived to compute the behaviour of moored ships in complex wave fields (for the methodologies developed in the last decade, see [1][2][9][10][15]). These methodologies typically consist of 3 steps:

1. Assessment of the wave field at the mooring location, taking into account all wave processes (refraction, diffraction, shoaling, reflection, breaking, etc.);
2. Computation of the wave forces on the restrained ship using the outcome of step 1;
3. Computation of the response of the moored ship taking into account the nonlinearities of the mooring system;

Numerical modelling of the behaviour of moored ships is termed a Dynamic Mooring Analysis (DMA).

Even though it is possible to predict the behaviour of moored ships a mooring analysis is often not carried out for ports exposed to swell. Current

[1] A free long wave can also be a wave that originates due to storms at remote locations or other meteorological phenomena (not considered in this paper).

[2] http://www.abc.net.au/news/2014-07-22/iron-ore-exports-disrupted-by-tidal-surges/5611922

[3] http://porttaranaki.co.nz/sites/default/files/publications/Portal%20Magazine/PORTAL%20APRIL%202015%20EDITION.pdf.pdf

practice is that problems are solved when they arise, e.g.:

- Different mooring arrangements or other type of mooring lines are considered to reduce the vessel's response, but this is not always effective;
- In more extreme cases more expensive and more time-consuming measures may be required, e.g. change of basin dimensions (length, width or depth) to reduce/alter the harbour oscillation, extension of breakwaters to diminish the long wave penetration;

This paper shows how the efficiency of a port exposed to swell waves can be improved by other solutions:

- By means of a DMA: For new ports facing potential issues with long waves the problem could be diverted in the design stage when for a general layout (basin dimensions, orientation of the entrance channel, location and length of the breakwaters, etc.) the wave penetration and the vessel's response are properly combined;
- By applying ShoreTension®, a mooring system that actively dampens the motions [13]: ShoreTension® could be applied in existing ports experiencing problems with long waves and excessive ship motions, but could also be incorporated in the design of new ports (www.shoretension.com);

The solution is found in reducing the driving force and/or adding damping to the mooring system.

Two case studies are presented:

1. For a greenfield port development the relation between the orientation of the entrance channel and the behaviour of ships moored in the port is illustrated. The channel orientation was optimised based on the calculated ship motions;
2. Results of full scale ship motion measurements at the container terminal in Sines (Terminal XXI) are presented to show the motion reduction when the ShoreTension® mooring system was applied.

2. Methodologies to determine the wave forces on a ship moored in a complex wave field

Royal HaskoningDHV often uses one of the two approaches developed by Van Der Molen [10][12]. A Boussinesq wave model is used to calculate the wave penetration in the time-domain (Figure 1). The area for the simulation should be chosen large enough to ensure that the relevant reflected free long waves are accounted for. Time-domain diffraction analysis is carried out to calculate the wave forces on the restrained ship. The water elevations and the fluxes around the moored ship are used as input (Figure 2). On the panels of a 3D mesh of the underwater hull geometry the pressures are integrated (Figure 3). Nearby structures, like a quay wall or breakwater close to the ship are taken into account in the diffraction analysis. The calculated forces (in 6 Degrees of Freedom) are used as input for computational model to calculate the response of the moored ship. This method was used for the first case study.

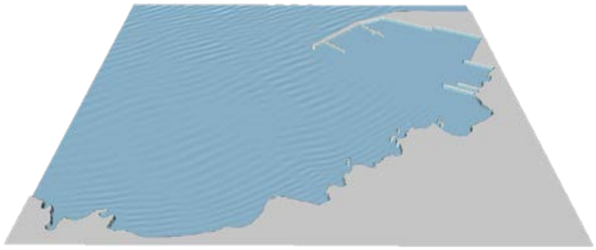

Figure 1 Area required for the simulation of the wave penetration of the port basin on the top right to ensure that the free long waves reflected from the coast are captured

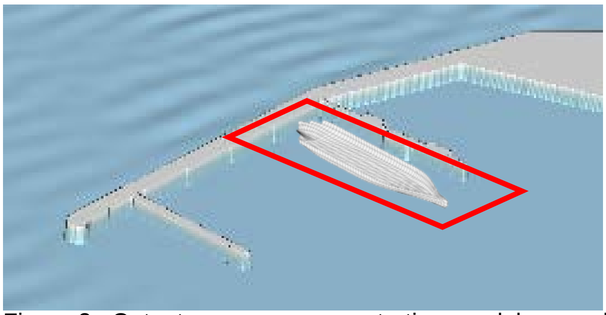

Figure 2 Output area wave penetration model around the ship required for time-domain diffraction analysis

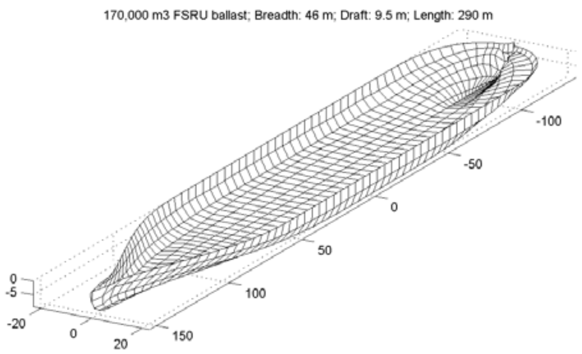

Figure 3 3D mesh of the ship used for time-domain diffraction analysis

Van Der Molen also developed a method in which only the long wave propagation is considered relevant [10][11]. The high frequency response is neglected. This method is an adequate approach in case the berth is sufficiently sheltered for short waves but is exposed to long waves or harbour oscillations. The wave penetration is calculated using a shallow-water wave model forced on wave-group scale [7] to calculate the (bound and free) long waves. For the calculation of wave forces on the ship, a strip theory approach is used. Within strip theory the ship is divided into a typical number of 20 cross-sectional strips. The force is calculated for each cross-section separately. By integration over the ships length the total wave force is found.

A similar approach was developed by Deltares and Marin for a ship moored in intermediate water depths (15-40 m) nearshore [9]. This paper summarises the main findings so far from the Joint Industry Project called Hawaii (2006-2012), in which a methodology to calculate downtime for a nearshore terminal is proposed. The reflected free long waves from shore cannot be neglected. They chose a shallow-water wave model forced on wave-group scale (XBeach [8]) over a Boussinesq wave model to calculate the (bound and free) long wave propagation.

More recently, Royal HaskoningDHV, together with Deltares, has developed a method where the wave penetration (both high and low frequency waves) is calculated using a multi-layer wave model called SWASH [16]. Time-domain diffraction yields the wave forces on the ship (similar to when a Boussinesq wave model would be used) [1].

3. Case study 1: Greenfield port development

3.1 Overview port and considered ships

The general layout of the greenfield port development is depicted in Figure 4. A general cargo vessel moored at location 1 is considered. Table 1 depicts the main dimensions of the ship.

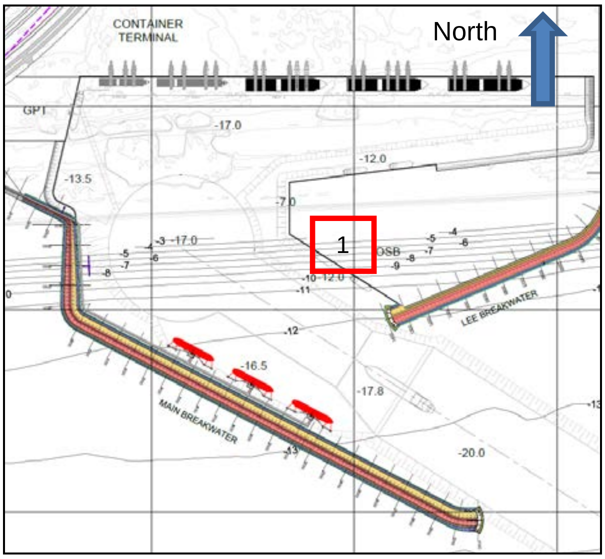

Figure 4 General port layout indicating the berths of the general cargo vessel (1) and the container ship (2)

Two orientations of the entrance channel were analysed, as depicted in Figure 5. The difference is the orientation of the outer channel, 173° N compared to 148° N. The inner channel, up to the curvature, is equal for both; the curvature in the entrance channel remains at the same location. The advantage of the first one is that the dredging volumes are less since deeper waters are reached quicker (more perpendicular to the depth contour). The orientation for an angle of 173° N is defined as the old layout throughout the rest of the paper, an angle of 148° N as the new layout.

Table 1 Main dimensions ship

		General cargo vessel
Capacity		20,000 DWT
Length over all	m	160
Beam	m	23
Depth	m	13.5
Draft	m	9.8
Displace-ment	m^3	25,677

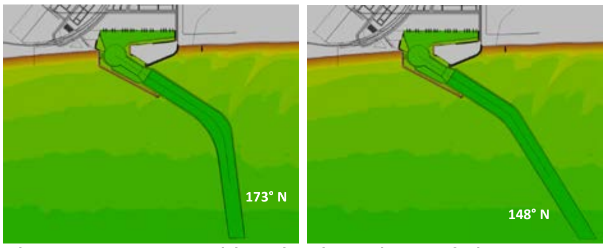

Figure 5 Two considered orientations of the entrance channel

3.2 Calculated wave penetration

Prior to the DMA a separate wave study was carried out. Several wave penetration simulations were carried out for waves coming from South and South-southwesterly direction (180° to 200°N, dominant wave direction for this location). Figure 6 shows the wave penetration in the port for a wave coming from 190°N. The offshore significant wave height was 1.5 m and the peak period of the wave spectrum (Jonswap, γ=3.7, σ_a=0.085, σ_b=0.095) was 15.5 s. Directional spreading was taken into account.

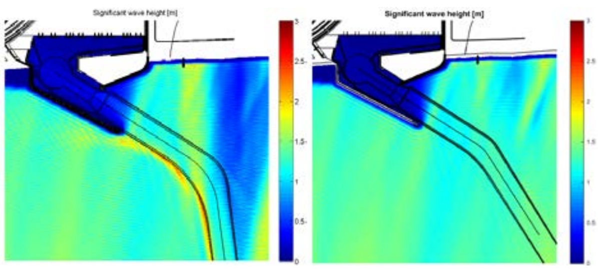

Figure 6 Significant wave height in entire domain for all frequencies

For wave directions in the range of 180° to 190°N (coming from) so-called wave trapping occurred at the side of the channel for the old layout (Figure 6). This effect was the largest for a direction of 180° N (Figure 7). Swell waves are not able to cross the channel. They bend towards the opening of the harbour basin.

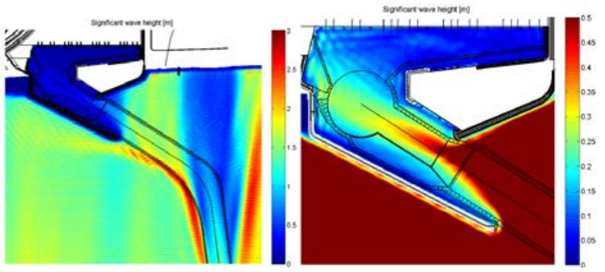

Figure 7 Wave trapping on the side of the entrance channel for 180°N wave direction

The wave trapping caused that more wave energy penetrates the harbour basin. The high frequency wave energy in the port is much higher in the old layout (Figure 8). Small differences were found in the low frequency wave energy in the port (Figure 9).

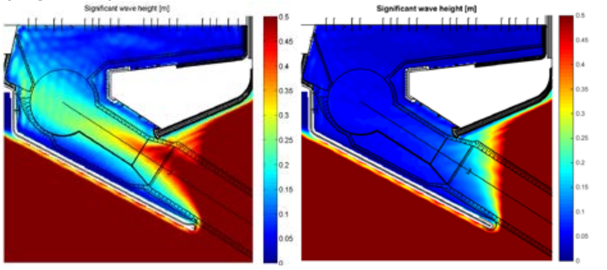

Figure 8 Significant wave height in the port for all frequencies (close up of Figure 6, different scale)

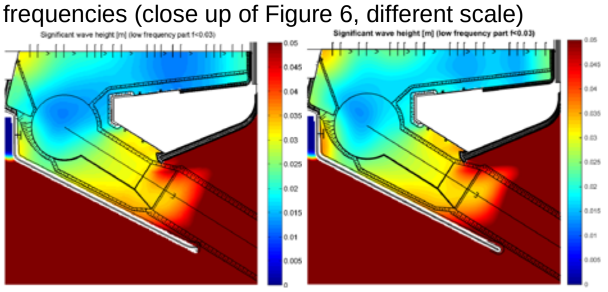

Figure 9 Significant wave height in the port, only low frequency part (<0.03 Hz)

3.3 Calculated ship motion response

First the wave forces on the restrained ship are calculated (see Section 2). Figure 10 shows the wave forces in surge, sway, roll and yaw direction on the general cargo vessel over the total frequency range. Figure 11 shows the same wave forces for the lower frequency range in surge and sway direction. The offshore wave direction was 190° N, the offshore significant wave height was 2 m and the peak wave period was 15 s.

Clearly, the wave forcing has been decreased. The high frequency response has been reduced significantly (Figure 10). The low frequency forces reduce due to a reduction in the tail of the high frequency part of the spectrum and by a change in (long) wave direction relative to the orientation of the moored vessel (Figure 11).

The response spectra confirm that what may be expected based on the calculated forces, i.e. a reduced response. Figure 12 shows the surge, sway, roll and yaw motion spectra for the general cargo vessel. The significant motion amplitudes are also given.

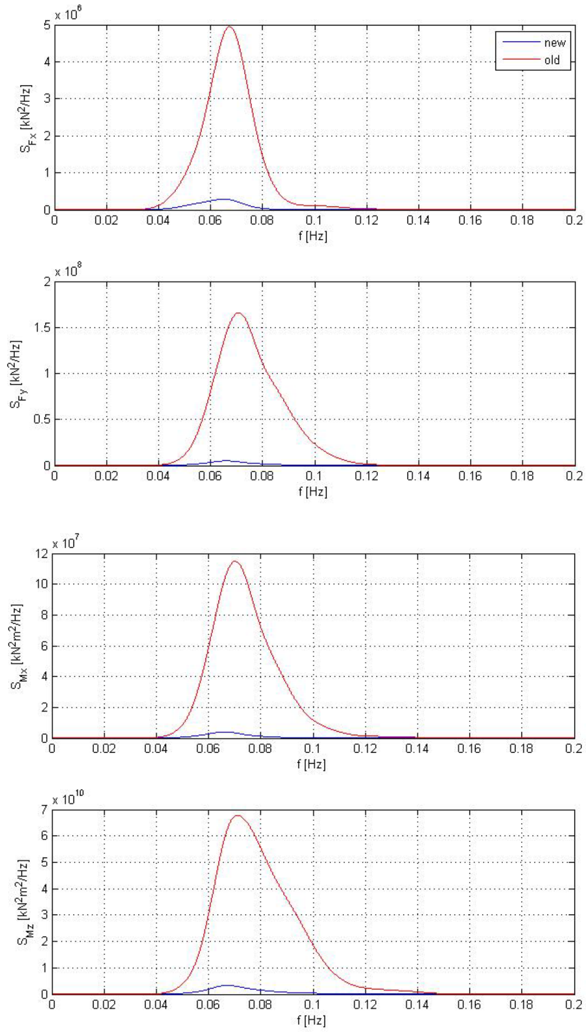

Figure 10 Surge, sway, roll and yaw wave force spectra on general cargo vessel

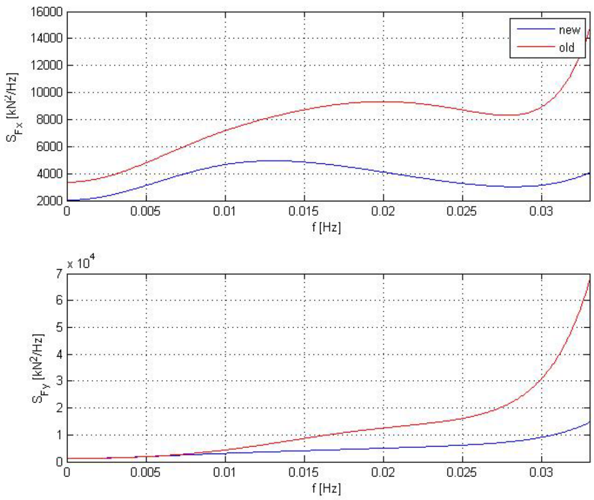

Figure 11 Surge and sway wave force spectra on general cargo vessel (low frequency range)

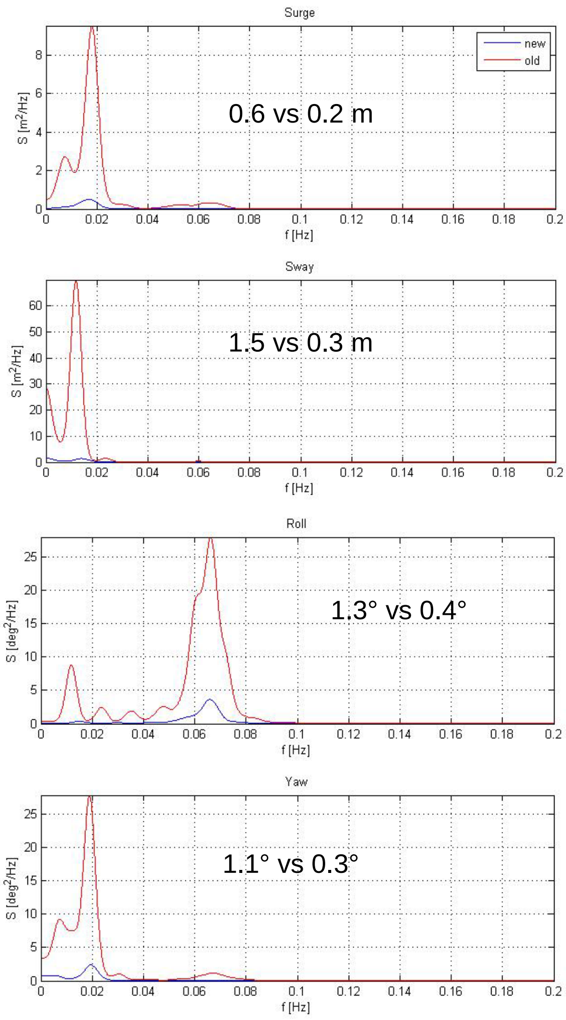

Figure 12 Surge, sway, roll and yaw response spectra, including significant motion amplitude, for the general cargo vessel

4. Case study 2: Application of ShoreTension® in Sines

4.1 Overview port

Sines is located in Portugal and is exposed to swell waves from the Atlantic Ocean. The prevailing wave direction is Northwest. Figure 13 shows an aerial photo of the total port. The red circle indicates the Port of Singapore Authority (PSA) container terminal (Terminal XXI).

Swell waves refract towards the coast Southeast of the terminal and break on the shore. The bound long wave is set free. The reflected free long wave propagates straight into the basin. Once the long wave energy is captured in the basin it does not easily dampen out. The low frequency wave energy in the basin negatively affects the surge motion of the vessel and the (un)loading of containers.

Figure 13 Aerial photo port of Sines (Google Earth). The red circle indicates the location of the PSA container terminal (Terminal XXI).

4.2 PSA and ShoreTension®

To reduce the downtime PSA decided to utilise the ShoreTension® mooring system. ShoreTension® is a flexible stand-alone mooring system, based on a permanent tension of shore mooring lines. When the tension in the lines exceeds a preset Safe Working Load the lines are paid out. Tension peaks in the lines are avoided in this way. Figure 14 depicts a photo of a unit. Typically, 2 to 4 cylinders are applied for a container ship, depending on the size of the ship. They are often added as additional head or stern lines and/or as additional spring lines. The ShoreTension® units are applied in combination with (stiff) Dyneema mooring lines that are attached to the ship's mooring bitts.

The main advantage of this system is that it adds a significant amount of damping to the mooring system. When the cylinders pay out energy is dissipated (work). The response is significantly dampened. The fender friction is increased when two cylinders are positioned on the breast lines, increasing the damping even further.

Figure 14 ShoreTension® cylinder added to the mooring layout as an additional breast line

4.3 Measurement campaign

Royal HaskoningDHV and ShoreTension® B.V. have conducted three series of full scale measurements over the last two years. The goal for ShoreTension® B.V. was to show that their system reduces the ship motions. The goal for Royal HaskoningDHV was to obtain measured data of the ShoreTension® cylinders and ship motions. Royal HaskoningDHV has used the data to implement the ShoreTension® response characteristics in its DMA software.

During the measurements the surge, sway, yaw and roll motions, the cylinder excursions and the forces on the cylinder were recorded. The motions of the moored vessel were measured with two GPS receivers located on the wings of the bridge. During most of the time, the GPS receivers operated in RTK (Real-Time Kinematic) mode, which relies on a single reference station to provide real-time corrections, providing up to centimetre-level accuracy. Each ShoreTension® unit constantly logs its excursion and force. The water elevation in the port was also measured at one location.
The results for 1 ship (a container ship of 366 x 48 m) are presented in this paper, 2 measurements in total. These measurements were taken in January 2015 in severe wave conditions. Based on the National Oceanic and Atmospheric Administration (NOAA) hindcast data a significant wave height of 4 m, a wave peak period of 15 s and a direction of 315° N was found for a location offshore for that day (LAT 38, LON 350.5). The ship was initially moored without ShoreTension® units. For the 2nd measurement 4 ShoreTension® cylinders were added to the mooring layout (2 as breast lines, 2 as spring lines). The duration of the measurements was typically in the order of 30 minutes.

4.4 Results full scale measurements

The measurements were carried out subsequently, meaning that the wave excitation was more or less simular during the measurements. Figure 15 and Figure 16 show that the low frequency wave energy in the basin was comparable.

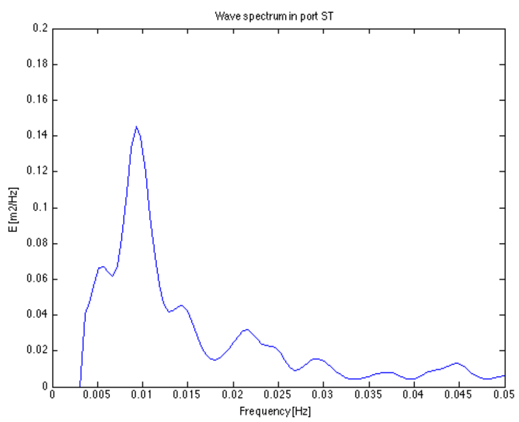

Figure 15 Measured spectrum water elevation in the port basin during the 1st measurement

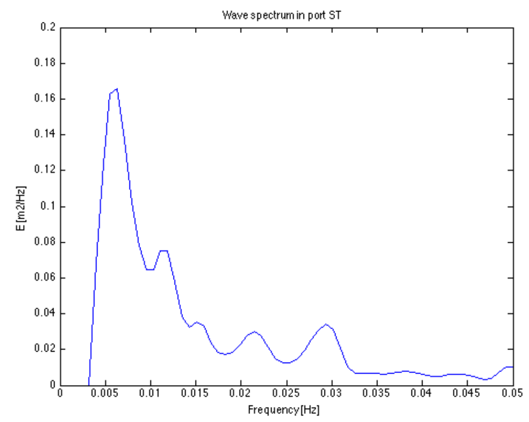

Figure 16 Measured spectrum water elevation in the port basin during the 2nd measurement

The measured response (surge, sway and yaw) motion was significantly reduced. Figure 17 to Figure 20 show the time-series and surge motion response spectra for the 1st and 2nd measurement. The surge motion reduction was about 65%. The sway motion reduction was 50%. Table 2 shows the measured significant surge and sway motions for both measurements.

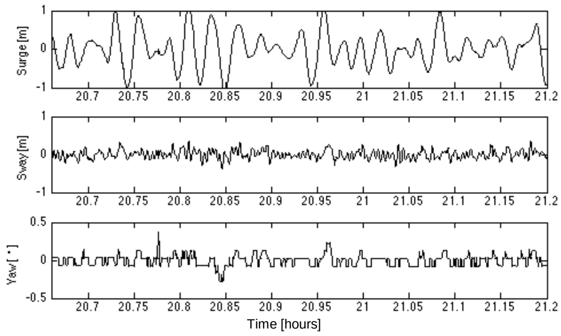

Figure 17 Time-series measured surge, sway and yaw motion, without ShoreTension® (1st measurement; x-axis in hours)

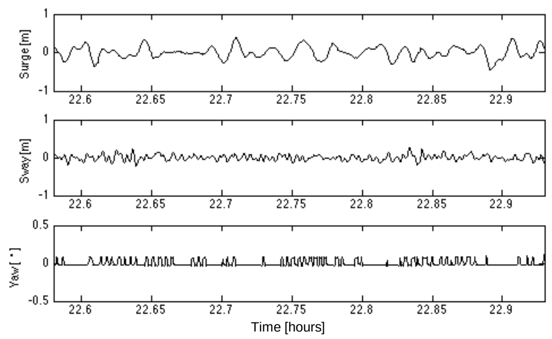

Figure 18 Time-series measured surge, sway and yaw motion, with ShoreTension® (2nd measurement; x-axis in hours)

The results of the measurements in Sines have enabled Royal HaskoningDHV to validate the implementation of ShoreTension® in its DMA software. This software can now be used for the prediction of the effect of the use of ShoreTension®

mooring system in existing and new ports that experience ship motion related problems.

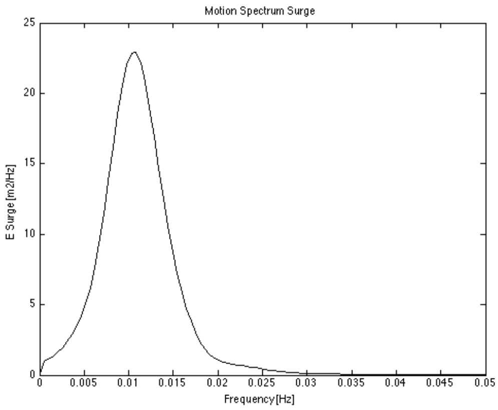

Figure 19 Surge motion response spectrum, without ShoreTension® (1st measurement)

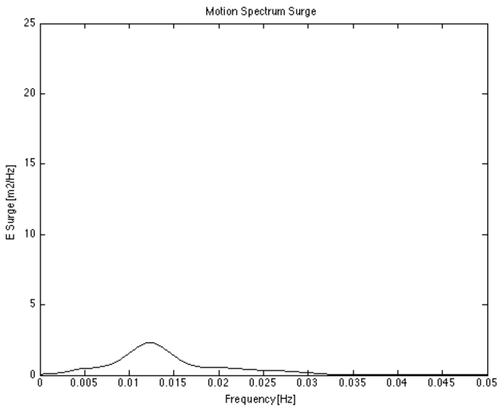

Figure 20 Surge motion response spectrum, with ShoreTension® (2nd measurement)

Table 2 Measured significant surge and sway motions

		Surge	Sway
Measure-ment	Shore-Tension	m	m
1	no	1.7	0.4
2	yes	0.6	0.2

5. Conclusions

The two case studies presented in this paper have shown how the efficiency of a port exposed to swell can be improved. The first case has shown that the ship motions were reduced when the orientation of the entrance channel was changed. The wave penetration into the basin was reduced, yielding a diminished motion response. This was based on numerical modelling of the wave penetration and vessel's response (Dynamic Mooring Analysis). The second case has shown that the resonance response of the moored ships could be reduced by applying ShoreTension®, an active motion dampening system. This system introduces a significant amount of damping. Large horizontal motion amplitudes at the resonance period could therefore not occur.

The response of the moored ship was reduced because of a reduced wave excitation and/or increased damping. A reduced vessel response implies an increased productivity and uptime, meaning increased revenues. Furthermore, high line tensions are less likely to occur and snapping of mooring lines is prevented. The mooring can also be considered safer.

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