INFLUENCE OF THE FRICTION FORCES AT THE SHIP-FENDER'S INTERFACE ON THE BEHAVIOUR OF A MOORED OIL TANKER

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The Port of Leixões (Portugal) has one berth for oil tankers that is somewhat exposed to rough environmental conditions and has some operational problems. In order to improve operational and security conditions at that berth, several studies have been carried out along the years. Problems are now less frequent than in the past; however there is still room for further improvement of the present conditions.

The paper focuses in a physical model study that included the construction of two models: the first one corresponding to a simplified reproduction of the berth and its surroundings and the second one to a more detailed representation of the prototype’s characteristics. Based on the results obtained, it was concluded that the friction forces developed at the interface between the ship and the fenders play an important role in the moored ship behaviour, especially in the surge direction. In addition, the response of the oil tanker in rolling was significantly influenced by the characteristics of its mooring system, particularly in the vicinity of the roll natural period of oscillation.

Keywords: Port engineering; Mooring systems; Pretension forces; Oil terminal; Physical modeling; Operational conditions.

1. Introduction

The Port of Leixões is located in the northwest coast of Portugal and has an oil terminal composed of three berths, Figure 1. Berth “A” is the most exposed to the environmental conditions and, as a result, presents some operational problems. In this berth breakage of ship’s mooring lines can occur and excessive motions are sometimes experienced by the moored oil tankers, IHRH-FEUP/IST (2005).

Figure 1. Leixões Oil Terminal, Porto, Portugal.

In order to improve the operational and security conditions at Berth “A”, the Port Authority has commissioned several studies along the years, which have analysed downtime problems through different perspectives and proposed several alternative solutions. An R&D Project started in 2008 (DOLPHIN) with the aim of clarifying the contribution of some critical issues on the Berth “A” downtime and analysing the efficacy of some solutions proposed in previous studies. This project was divided in three major components: physical modelling, numerical simulations and prototype measurements at Berth “A” of the Leixões Oil Terminal. These components were integrated in a complementary way.
The results of the work carried out until the moment can be found, for instance, in Veloso Gomes et al., 2005, Rosa Santos et al., 2008a, Taveira Pinto et al., 2008, Rosa Santos et al., 2008b, Malheiros et al., 2009, Rosa Santos et al., 2009, and Rosa Santos et al., 2010.

This paper focuses on results from a physical model study on the behaviour of an oil tanker moored at Berth “A” of the Leixões Oil Terminal. This study was carried out on a geometric scale of 1/100 and included the construction of two physical models: the first one corresponding to a simplified representation of the berth and its surroundings, and the second one corresponding to a more accurate reproduction of the prototype characteristics (breakwaters, berthing structure, nearby beaches).

In particular, the present paper analyses the effect of increasing the mooring lines pre-tension (breast lines) on the response of an oil tanker moored at berth “A” for two different friction coefficients between the ship’s hull and the fenders. A special attention is given to the behaviour of the moored ship on the horizontal plane (i.e. surge and sway). Nevertheless, the influence of the friction forces at the ship-fenders’ interface on the roll motion is also discussed.

2. Case study: Berth “A” of the Leixões Oil Terminal

Tides are of the semi-diurnal type in the vicinity of the Port of Leixões, reaching amplitudes that range between 2 and 4 m. The wave conditions are highly energetic. During storms significant wave heights may exceed 8 m (about once per year) and wave periods can be on the order of 16 to 18 s. Wave directions between west and northwest prevail.

The operational and security conditions at Berth “A” are influenced by: the Leixões north breakwater overtopping and wave diffraction around its head (Figure 1), the characteristics of the ship’s mooring system (mooring lines and fenders), current transmission through the north breakwater core and possible resonance phenomena in the Berth “A” area, Veloso Gomes et al. (2005).

The Berth “A” jetty structure consists of two breasting dolphins and a loading platform, Figure 2. Each breasting dolphin is equipped with a pneumatic fender (floating type) and double mooring hooks. The remaining mooring points are located on the north breakwater superstructure. Alongside this berth the bottom level is regularly maintained about 16 m bellow CD (Chart Datum), which allows receiving oil tankers of up to 100,000 dwt.

![Figure 2. Usual ship mooring layout at Berth “A” Oil Terminal: asymmetrical mooring layout.](image)

The mooring layout more frequently used by the largest class of oil tankers at Berth “A” is presented in Figure 2. This mooring layout is slightly asymmetrical and composed of eight double mooring lines, namely two double stern lines (ML1 and ML2), two double breast lines (ML3 and ML6), two double spring lines (ML4 and ML5) and two double head lines (ML7 and ML8). The largest tankers are usually moored with steel mooring lines with a nylon tail. The two pneumatic fenders have a maximum energy absorption capacity of 1300 kJ that is associated with a 2450 kN reaction force on the breasting dolphin.

3. Experimental set-up

The study was carried out at the Hydraulics Laboratory of the Hydraulics, Water Resources and Environment Division of the Faculty of Engineering of the University of Porto - FEUP. The physical models were scaled by Froude criteria of similitude for a geometric scale of 1/100. The wave tank used in the study is 28 m long, 12 m wide and 1.2 m in depth. Wave conditions were reproduced in the experimental facility by a multi-element wavemaker (HR Wallingford, UK) equipped with a dynamic wave absorption system.

The ship selected for the study intends to represent the largest class of tankers that regularly demanded Berth “A”. Prior to testing, the ship model was ballasted to obtain the required hydrostatic and dynamic characteristics of the full-scale tanker for the maximum loading condition. During calibration, concrete weights were carefully placed inside the ship’s hull in order to reproduce the correct displacement, draft, metacentric heights and natural periods of oscillation. Calibration was carried out through an iterative procedure that was concluded when a good agreement with the target values was found. These target values were defined based on the characteristics of the full-scale ship (105,000 dwt oil
tanker). Table 1 presents the main characteristics of the selected oil tanker for the maximum loading condition, either at full-scale or model scale.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Full-scale</th>
<th>Model scale (1/100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement (kg)</td>
<td>122,714,000</td>
<td>119,721</td>
</tr>
<tr>
<td>Length overall (m)</td>
<td>245.1</td>
<td>2.451</td>
</tr>
<tr>
<td>Length between perpendiculars (m)</td>
<td>236.0</td>
<td>2.360</td>
</tr>
<tr>
<td>Beam (m)</td>
<td>43.0</td>
<td>0.430</td>
</tr>
<tr>
<td>Maximum draft (m)</td>
<td>14.1</td>
<td>0.141</td>
</tr>
<tr>
<td>Vertical position of the centre of mass (m)</td>
<td>12.5</td>
<td>0.125</td>
</tr>
<tr>
<td>Transversal metacentric height (m)</td>
<td>5.83</td>
<td>0.058</td>
</tr>
<tr>
<td>Longitudinal position of the centre of buoyancy from stern (m)</td>
<td>128.4</td>
<td>1.284</td>
</tr>
<tr>
<td>Roll natural period in deep water conditions (s)</td>
<td>12.5</td>
<td>1.250</td>
</tr>
</tbody>
</table>

Mooring lines were reproduced by inelastic Kevlar string and a set of (precision) coil springs. It was considered that the oil tanker was moored with steel mooring lines with a synthetic tail (nylon). Its breaking strength was equal to 640 kN. The load-elongation curves of the mooring lines were simulated by the coil springs; nevertheless the stiffness of the associated cantilever force transducer was also taken into account. In addition, in the tests analysed in the paper, their non-linear behaviour was linearized. Therefore the stiffness of each mooring line (which depends on the mooring line elongation) was replaced by the constant stiffness of an equivalent linear mooring line having the same energy absorption capacity of the non-linear mooring line up to its maximum elongation, Figure 3 (right).

The non-linear behaviour of the fenders installed on Berth “A” was reproduced in the same way. Precision coil springs were carefully selected to provide the appropriate elasticity to each element of the ship’s mooring system. It is worth mentioning that in the prototype the oil tankers are usually moored at Berth “A” with eight double mooring lines (i.e. sixteen individual mooring lines). In the physical model, the mooring lines of the same group (with the same orientation, length and characteristics) were reproduced by only one mooring line with characteristics equivalent to the group of mooring lines.

Table 2 presents the length of the mooring lines (full-scale) that constitute the layout sketched in Figure 2 as well as the linearized stiffness (model scale) of each element of the ship’s mooring system. The elasticity of those mooring elements was verified prior to testing. The forces applied on the mooring system during the experimental tests were measured with force transducers made by HR Wallingford, UK.

In order to analyze the influence of the friction forces at the ship-fenders’ interface on the behaviour of a moored oil tanker, two mooring lines’ pretension conditions and two types of interface between the ship and the fenders were considered in the study, Table 3. The pretension conditions analysed were: “base condition”, with the initial forces in all the mooring lines set between 100 and 120 kN; and “extra pretension”, corresponding to the condition in which the
initial forces on the breast lines was increased to values between 250 and 270 kN. In addition, two types of interface were studied: low and high friction. The friction coefficients were equal to 0.12 and 0.46 for the low and high friction interfaces, respectively, being the second one closer to the prototype conditions (pneumatic fenders).

Table 2. Characteristics of mooring lines (ML) and fenders (FD).

<table>
<thead>
<tr>
<th>Mooring line/Fender ID</th>
<th>length (m) (full-scale)</th>
<th>Stiffness (N/mm) (model scale)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ML1</td>
<td>150</td>
<td>0.0169</td>
</tr>
<tr>
<td>ML2</td>
<td>90</td>
<td>0.0341</td>
</tr>
<tr>
<td>ML3</td>
<td>55</td>
<td>0.0498</td>
</tr>
<tr>
<td>ML4</td>
<td>55</td>
<td>0.0493</td>
</tr>
<tr>
<td>ML5</td>
<td>82</td>
<td>0.0344</td>
</tr>
<tr>
<td>ML6</td>
<td>82</td>
<td>0.0343</td>
</tr>
<tr>
<td>ML7</td>
<td>90</td>
<td>0.0341</td>
</tr>
<tr>
<td>ML8</td>
<td>120</td>
<td>0.0310</td>
</tr>
<tr>
<td>FD1</td>
<td>--</td>
<td>0.0865</td>
</tr>
<tr>
<td>FD2</td>
<td>--</td>
<td>0.0856</td>
</tr>
</tbody>
</table>

Table 3. Mooring systems analysed in the study.

<table>
<thead>
<tr>
<th>Mooring system</th>
<th>Pretension condition</th>
<th>Interface ‘ship-fenders’</th>
</tr>
</thead>
<tbody>
<tr>
<td>PT Base &amp; FD Low friction*</td>
<td>Base condition</td>
<td>Low friction</td>
</tr>
<tr>
<td>PT Extra &amp; FD Low friction</td>
<td>Extra pretension</td>
<td>Low friction</td>
</tr>
<tr>
<td>PT Base &amp; FD High friction</td>
<td>Base condition</td>
<td>High friction</td>
</tr>
<tr>
<td>PT Extra &amp; FD High friction</td>
<td>Extra pretension</td>
<td>High friction</td>
</tr>
</tbody>
</table>

* Reference condition

The motions of the moored oil tanker, in the six degrees of freedom (surge, sway, heave, roll, pitch and yaw), were measured using a Qualisys – Motion Capture System. With this equipment, ship’s motions are measured without any contact with the model. Wave conditions were calibrated before the beginning of the tests with the moored ship. The instantaneous water surface elevation was measured with resistive wave probes. All measurements were carried out with a sampling frequency of 24 Hz.

The physical model study was carried out on a geometric scale of 1/100 and subdivided in two phases. In the first phase of the study a simplified model of Berth “A” and its surrounding area was tested. Water depth was considered uniform, with the bottom level near the berth at -16 m CD. The breasting and mooring dolphins were reproduced in the model; nevertheless, there was no need to construct the Leixões north breakwater as the tanker model, in this first stage, was only tested under the action of head waves, Figure 4. Those waves are the ones expected to reach the berth area after diffraction around the head of the north breakwater during relatively rough environmental conditions.

Figure 4. Ship model moored to the berthing structure (asymmetrical mooring layout): first phase of the study.

An array of four wave probes was installed in the wave tank to record the water surface elevations for reflection analysis, allowing a better control of the incident wave conditions. The set-up of the physical model inside the wave
tank in the first phase of the study is sketched in Figure 5. A dissipation beach was installed at the end of the wave tank to reduce wave reflections.

In the second phase of the study a more accurate model of Berth “A” and its surrounding area (Figure 1) was built in the wave tank, which included the harbour breakwaters, the berthing structure and nearby beaches. Nevertheless, the water depth was also considered uniform (except on the beaches) with the bottom level at -16 m CD. The set-up of the physical model inside the wave tank is presented in Figure 6. In this phase, the wave conditions at Berth “A” were, essentially, the result of the diffraction of incident waves around the head of the north breakwater and the reflections on the south breakwater and Matosinhos Beach.

Scale effects should have a non negligible influence on the stability of the armour blocks used to reproduce the port’s sheltering structures or on the transmission phenomena, either through the core of the north breakwater or by wave overtopping. Hence important conclusions about those subjects could never be drawn with such a small model. For those reasons only the head of the north breakwater (about 150 m in length) was reproduced accurately and the remaining length of the structure (outer side) was simplified (Figure 6 and 7). The aim was to properly reproduce the diffraction phenomenon and to minimize the construction works.

It is important to mention that the physical model was designed in order to reproduce the harbour structures with more importance for the study (analysis of the behaviour of moored ships in harbours), but also to leave the maximum clearance possible between the head of the north breakwater and the wave tank side wall.
Wave reflections on the physical boundaries surrounding Berth “A” should have influence on the wave condition near the berth. Hence, the reflection characteristics of the outer side of the south breakwater and nearby beaches were reproduced as accurately as possible. However, the bathymetry and the length of Matosinhos Beach had to be adapted in order to minimize unwanted wave reflections from the right side wall of the wave tank and due to the limited space available, respectively. A porous (absorbent) beach was designed and installed at the entrance to the inner harbour basin to reduce reflections, as shown in Figure 6 and 7.

Previous studies have concluded that the downtime of Berth “A” was mainly associated with waves coming from the W and NW directions. However, the terminal operators and the ship pilots have stated that the most problematic sea states were the ones approaching from the W (almost perpendicular to the north breakwater), as those waves can diffract around the head of the breakwater more easily (Figure 1). Waves from SW are less frequent and have smaller wave heights and periods, IHRH-FEUP/IST (2005). Therefore, the waves generated in the model had a direction of propagation perpendicular to the north breakwater (at the wavemaker). This direction is also advantageous because it reduces the importance of the (laboratory) effect that results from the reflection of incident waves on the head of the north breakwater followed by the re-reflection of those waves on the tank side wall. In fact, the importance of that effect would be much higher for an oblique wave incidence. Figure 8 presents some photographs of the construction of the second physical model.

The experimental tests were carried out with irregular long crested waves characterized by a JONSWAP spectrum with a peak enhancement factor ($\gamma$) of 3.3. Local wave measurements (i.e. near Berth “A”) or numerical simulations of wave propagation from offshore (Leixões wave buoy) to the harbour area, including non-linear wave transformation and sub-harmonics generation, were not available. Hence the long wave conditions at the berth were not calibrated, and theoretical set-down compensation at the wavemaker was used instead. It was considered that for the purposes of the present phase of the study the referred approach was acceptable.

The test program included two water levels near the berth, namely: high tide (corresponding to a water depth, d, equal to 20 m) and mean sea level (d=18 m). Tests were carried out with about 600 waves in the first phase of the
study and about 1200 waves in the second phase. The same temporal sequence of incident waves was used in the tests having the same peak wave period.

4. Results and discussion

The influence of the friction forces developed at the interface between the ship and the fenders on the behaviour of an oil tanker moored at Berth “A” was analyzed for two pretension conditions of the mooring lines and two types of interface between the ship and the fenders. Figure 9 presents the reduction of the surge and sway motion significant amplitudes, of three combinations of fender friction coefficients and pretension conditions, in relation to a reference condition (c.f. Table 3). That condition consists in the consideration of low friction fenders at the berth and in the application of pretension forces on the mooring lines that correspond to the base condition. The experimental results presented refer to physical model tests carried out during the first phase of the study. The sea states reproduced in the facility were characterized by peak wave periods between 10 and 18 s and two significant wave heights, namely 1.5 and 2.0 m. The water depth near the berth was 18 m, which corresponds to the mean sea level.

Figure 9 shows that, in general, the test condition that combines the use of high friction fenders with an increase of the breast lines’ pretension (i.e. “PT Extra & FD High Friction”) leads to the highest reductions of the significant amplitudes of the surge and sway motions. For that condition, reductions of the surge motion are on the order of 50 to 70% and reductions of sway on the order of 25 to 45%. The influence of the mooring system’s characteristics on the sway motions was less significant, however still important. This conclusion may be explained by the coupling effect introduced by the mooring system on the ship’s motions (especially on the horizontal plane). In addition, and specially for surge, it is possible to observe a trend characterized by a reduction of the efficacy of the tested conditions with the increase of the peak wave period, possibly due to the fact that the ship model is less time in contact with the fenders when the peak wave period is increased.

The experimental results have also shown that the substitution of low friction fenders by high friction fenders was more effective reducing the amplitudes of the ship motions than an increase of the pretension forces applied on the breastlines with low friction fenders installed on the berth. Moreover it is possible to conclude that an increase of the breastlines’ pretension leads to better results when the berth has fenders that present a high friction coefficient at the interface with the ship.

The influence of the friction forces at ship-fender’s interface on the moored ship behaviour was also addressed during the second phase of the study with a more complete and complex physical model (Figure 6 and 7). For that purpose, the pretension conditions and the types of interface considered in the first phase of the study were reproduced.
in the physical model. Tests were carried out with the tanker model moored with the asymmetrical layout (Figure 2) for the high tide water level (d=20 m near the berth). The sea states reproduced in the experimental facility (in front of the wavemaker) were characterized by a significant wave height of 3.0 m and by the following peak wave periods: 10, 12, 14, 16, 18 and 20 s. Those wave conditions refer to sea states outside the port, however in the vicinity of the north breakwater. Those waves travel to the Berth “A” area, diffracting around the north breakwater and undergoing some reflections on the physical domain boundaries.

Figure 10 presents the significant amplitude of the surge and sway motions, for the different mooring systems tested in the physical model, as function of the incident peak wave period. That figure also shows the reduction of the amplitude of those motions, in percentage, due to the increase of the breast lines’ pretension, either when low friction fenders are reproduced or when the model fenders have a friction coefficient similar to the floating fenders installed on Berth “A” (high friction fenders).

It can be observed that both pretension forces and the type of interface between the fender and the ship’s hull have a significant effect on the horizontal ship motions, Figure 10. The best results were obtained when high pretension forces are used to moor the oil tanker to a berth having high friction fenders installed. In general the reduction of the motions’ amplitude is higher in the case of the surge oscillation. It is also important to mention that the increase of the breast lines’ pretension is clearly more effective, in the reduction of surge motions, when high friction fenders are installed on the berth. This conclusion was already presented when analysing the results of the first phase of the study (Figure 9). In fact, under those conditions, reductions of the surge motions between 35 and 60% can be achieved, with the higher values being related to the smaller peak wave periods. In the case of the sway motions, differences are less significant (reductions between 11 and 24%).

It is worth mentioning that the development of high friction forces at the interface between the ship’s hull and the fenders, although advantageous in terms of the moored ship behaviour, may require a more frequent and rigorous control of the ship mooring conditions, in order to adjust pretensions forces to the local environmental conditions, as well as, to changes of the ship loading condition and water level near the berth.

Until now the analysis was focused exclusively on the horizontal motions of the moored ship. Figure 11 presents, however, results obtained for the roll mode of oscillation (vertical motion) namely: the reduction of the roll significant amplitude as function of the peak wave period for three mooring system characteristics and in relation to the reference condition defined previously, Figure 11 (up); and the roll maximum and significant amplitudes as function of the peak wave period for four combinations of fenders and pretension conditions, Figure 11 (down). The tests were carried out during the second phase of the study under the conditions described previously. The significant wave height was equal to 3.0 m.
The results presented in Figure 11 (up) show that the roll motion amplitudes do not follow the trends observed before in the analysis of the horizontal motions of the moored ship (Figure 9 for instance) neither the trends associated with the motions in the vertical plane (results not presented in the paper). On one hand, the condition “PT Extra & FD High Friction” is the one that seems to present the worse results (smaller motion reductions). In fact, for some peak wave periods, that test condition can even lead to an important increase of the amplitude of the roll motion in relation to the reference condition (“PT Base & FD Low Friction”). On the other hand, the results presented show a maximum reduction of the roll motion’s amplitudes for the peak wave period of 14 s. For other peak wave periods the results are worse. Hence it can be concluded that the roll motion is significantly influenced by the characteristics of the mooring system.

In general the results presented in Figure 11 (down) show a trend characterized by an increase of the roll motions’ amplitude (maximum and significant) with the peak wave period. Nevertheless, it is also possible to observe that the curves present a “peak of amplitude” for the peak wave period of 14 s, except for the condition “PT Extra & FD High Friction”. That peak of amplitude is more or less important (or evident) depending on the characteristics of the tested mooring system and the category of motion considered in the analysis (maximum or significant amplitude). It is worth mentioning that the “peak” observed for the 14 s wave period is related to the roll natural period of oscillation of the moored ship (~13.4s) for the tested load condition and local water depth.

Therefore, although some experimental results (Rosa Santos, 2010) have shown that the mooring system has only a minor effect on the roll natural period of oscillation; its characteristics have an important influence on the magnitude of the roll damping. Indeed, the increase of the friction forces at the ship-fenders’ interface increases the magnitude of the roll damping. For the tested conditions, that damping is higher for the condition “PT Extra & FD High Friction” and minimum for the reference condition. The effect of the roll damping increase on the reduction of the amplitude of roll motions, in the vicinity of its natural period of oscillation, can be clearly observed in Figure 11 (down), especially when roll maximum amplitudes are considered. In fact, the curve associated with the mooring system that is supposed to present the maximum roll damping (“PT Extra & FD High Friction”) does not present a (clear) “peak of amplitude” in the vicinity of the period 14s.

5. Conclusions

The influence of the friction forces developed at the interface between the ship and the fenders on the behaviour of an oil tanker moored at Berth “A” of the Leixões Oil Terminal was analyzed based on the results of two physical
models (geometric scale 1/100). The analysis was initially focused on the type of motions that are more important for the operational and security conditions on a terminal of that type (surge and sway motions). However, the influence of those friction forces on the roll oscillation was also discussed.

The experimental results have shown that important reductions of the surge motions’ amplitude can be achieved by increasing the magnitude of the pretension forces applied on the breastlines, especially if high friction fenders are installed on the berth. The influence on the sway motions was less significant, but still important. This last conclusion may be explained by the coupling introduced by the mooring system on the ship’s motions. In addition, the response of the moored oil tanker in rolling was significantly influenced by the characteristics of its mooring system, especially in the vicinity of the roll natural period of oscillation.

Apart from some drawbacks related to its recoiling behaviour, the pneumatic fenders installed on Berth “A” may be a good solution for the reduction of excessive surge motions, because high friction forces may be developed at the interface with the ship. On the other hand, high friction fenders increase the efficacy of an increase of the pretension forces applied on the ship mooring lines.

Acknowledgements

The DOLPHIN project (PTDC/ECM/72835/2006) is being supported by the Portuguese Science and Technology Foundation (FCT) through the POCI/FEDER program. The authors are also indebted to the Port Authority of Douro and Leixões, SA, for their support to the study and to LNEG-IST for lending the Qualisys – Motion Capture System.

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