Physical Modelling of Leixões Oil Terminal - Portugal

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The Port of Leixões is located in the northwest coast of Portugal. Its oil terminal has one berth that is somewhat exposed to rough environmental conditions and has some operational problems. In order to improve operational and security conditions at that berth (Berth "A"), the Port Authority has commissioned several studies along the years that have analyzed downtime problems through different perspectives, and proposed several intervention alternatives. Problems are now less frequent than in the past; nevertheless there is still room for further improvement of the present conditions.
An R&D project started in 2008 with the aim of clarifying the contribution of some identified critical issues to the downtime of Berth "A" and analyzing the efficacy of some interventions proposed in preceding studies. The Project includes the use of physical modelling, numerical simulations and prototype measurements, all integrated in a complementary way.
The paper focuses in the physical modelling component that was carried out on a geometric scale of 1/100, and included the construction of two models: the first one corresponding to a simplified reproduction of the berth and its surroundings, and the second one corresponding to a more detailed representation of the prototype's characteristics.
Based on the physical model results, it was concluded that increasing breast lines' pretension effectively reduces the moored ship motions while a slight modification of the mooring layout has only a negligible influence in the moored ship response. Water depth was identified as an important factor controlling the behaviour of the moored ship.

Keywords: Moored ship behaviour, operational conditions, mooring layout, pretension.

1. Introduction

In a context of increasing sea trade worldwide, it is important to have port's terminals more efficient and secure, in order to improve their competitiveness as well as to maximize security and minimize environmental risks.
The Port of Leixões is located in the northwest of Portugal and its oil terminal, composed of three berths, is operated under concession by *Galp Energia*, Figure 1. Berth "A", located at the harbour entrance, is the one most exposed to adverse maritime environmental conditions despite the protection offered by the Leixões north breakwater. As a result, this berth has some operational problems, not assuring, in average, the operational and security conditions during about 20% of the time, IHRH-FEUP/IST (2005). Breakage of ship mooring lines can occur and moored ships sometimes have excessive movements. In some critical situations, the on or off-loading operations are made difficult or even impossible.

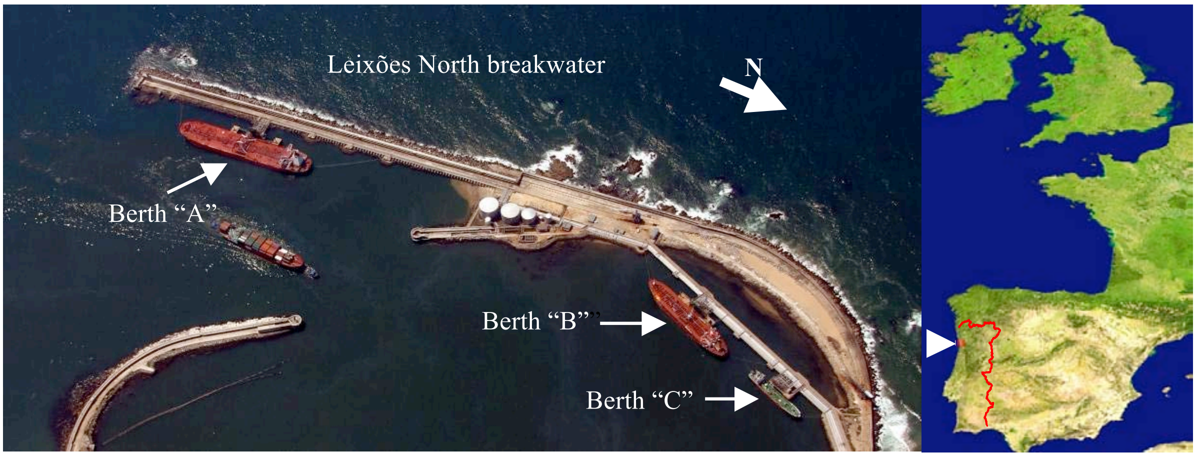


Figure 1. Leixões Oil Terminal, Porto, Portugal.

These facts result in operational costs as well as environmental and safety risks for the port authority, which are important to minimize in order to improve the terminal profitability. To attenuate the problem, a single point mooring system has been recently installed offshore. It is worth mentioning that operational problems are now less frequent than it were in the past; however there is still some room for further improvement of the present conditions.
In order to improve the operational and security conditions at Berth "A", the Port Authority has commissioned several studies, which have analyzed existing problems through different perspectives and proposed several intervention alternatives. An R&D Project started in 2008 with the aim of clarifying the contribution of some identified critical issues to the downtime of Berth "A" and analyzing the effectiveness of some intervention alternatives proposed in the previous studies. The DOLPHIN Project is supported by the Portuguese Foundation for Science and Technology and the Port of Leixões. It includes the use of physical modelling, numerical simulations and prototype measurements, all integrated in a complementary way.
The physical modelling studies were carried out on a geometric scale of 1/100, and included the construction of two models: the first one corresponding to a simplified reproduction of the Berth "A" and its surroundings, and the second one to a more detailed representation of the prototype's characteristics (breakwaters, berthing structure, nearby beaches).
The paper focuses on results of the physical model tests carried out with the aim of analyzing the influence of the mooring layout, the increase of the breast lines' pretension and the water depth near the berth, in the behaviour of an oil tanker moored at Berth "A".

2. Environmental conditions and Berth "A" characteristics

In the vicinity of the Port of Leixões tides are of the semi-diurnal type, reaching amplitudes that range between 2 and 4 m. The wave climate is highly energetic. The main storms come from the North Atlantic, mainly between the months of October to March. 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 with the storm persisting for up to 5 days. Wave directions between west and northwest prevail, also with some occurrences from southwest.
The Berth "A" jetty structure consists of two breasting dolphins and a loading platform. Each breasting dolphin is equipped with a pneumatic fender (floating type) and double mooring hooks. The remaining mooring hooks are situated on the north breakwater superstructure,

Figure 2. Alongside this berth the bottom level is regularly maintained about 16 m bellow CD, which allows receiving oil tankers of up to 100,000 dwt.

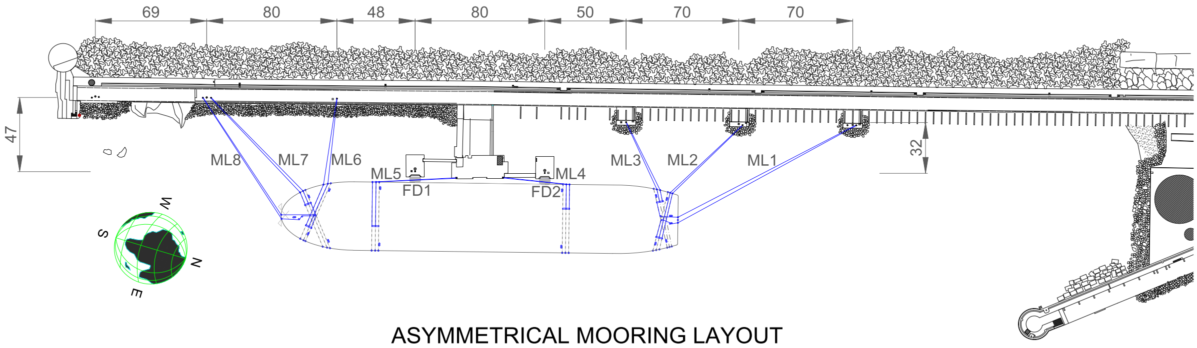


Figure 2. Usual ship mooring layout at the Berth "A" Oil Terminal.

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. Each pneumatic fender installed on Berth "A" has a maximum energy absorption capacity of 1300 kJ, which is associated with a 2450 kN reaction force on the breasting dolphin.
Berth "A" operational conditions are supposed to be influenced by Leixões north breakwater overtopping and wave diffraction around its head, the characteristics of the mooring system and fenders, current transmission through the north breakwater core, and possible resonance phenomena in the Berth "A" area, Veloso Gomes *et al.* (2005).

3. Experimental set-up

The physical model studies were carried out at the Hydraulics Laboratory of the Hydraulics, Water Resources and Environment Division of the Faculty of Engineering of the University of Porto, on a geometric scale of 1/100 and according to the Froude criteria of similitude. The wave tank is 28 m long, 12 m wide and 1.2 m in depth. The wave generation system is of the multi-element type (*HR Wallingford, UK*) and includes a dynamic wave absorption system.
The ship selected for the study is a 105,000 dwt oil tanker and intends to represent the largest class of tankers that regularly demand Berth "A". The first ship model was built in fibreglass reinforced plastic on a geometric scale of 1/100, based on the 3D hull shape definition of a real oil tanker.
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, which was concluded when a good agreement with the target values was found. The target values were defined based on the characteristics of the full-scale ship. Table 1 presents some of the characteristics of the oil tanker for the maximum loading condition, either at full-scale or model scale.

Table 1. Characteristics of the oil tanker in the tested condition.

Characteristic	Full-scale	Model scale (1/100)
Displacement (kg)	122,714,000	119.721
Length overall (m)	245.1	2.451
Length between perpendiculars (m)	236.0	2.360
Beam (m)	43.0	0.43
Maximum draft (m)	14.1	0.141
Vertical position of the centre of mass(m)	12.5	0.125
Transversal metacentric height (m)	5.83	0.058
Long. position of the centre of buoyancy, from stern (m)	128.4	1.284
Roll natural period in deep water conditions (s)	12.5	1.25

Mooring lines were reproduced by inelastic Kevlar string and a combination of two precision springs, Figure 3. It was considered that the ship was moored with steel mooring lines with a synthetic tail (nylon), having a breaking strength of 640 kN.

Figure 3. Oil tanker model moored to the berthing structure (left); Qualisys motion capture system (centre); force transducers for mooring line and fenders' forces measurements (right).

The load-elongation curves of the ship mooring lines were simulated by a set of coil springs, taking also into account the stiffness of the corresponding cantilever force transducer. Their non-linear behaviour was linearized. Hence 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. The non-linear behaviour of the two fenders installed on the berth was reproduced in the same way. Precision coil springs were carefully selected to furnish the appropriate elasticity to each mooring element.

Table 2 presents the length of the mooring lines (full-scale) in the layout sketched in Figure 2 (asymmetrical - ASY) and in an alternative mooring layout tested in the physical model study (symmetrical - SYM). The linearized stiffnesses (model scale) of those mooring lines and of the two fenders installed on Berth "A" are also included in the table. The alternative mooring layout is presented latter on (Figure 8). The elasticity of each mooring element was verified prior to testing. Forces on the mooring system were measured with force transducers made by *HR Wallingford, UK*.

In order to analyze the influence of an increase of the breast lines' pretension on the moored ship response two test conditions were considered: "base condition", with the initial force in all the mooring lines set between 100 kN and 120 kN; and "extra pretension", corresponding to the condition in which the initial force on the breast lines was increased to values between 250 kN and 270 kN.

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

Mooring line/Fender ID	length (m) (full-scale)	Stiffness (N/mm) (model)
ML1 (ASY & SYM)	150	0.0169
ML2 (ASY & SYM)	90	0.0341
ML3 (ASY & SYM)	55	0.0498
ML4 (ASY & SYM)	55	0.0493
ML5 (ASY & SYM)	82	0.0344
ML6 (ASY & SYM)	82	0.0343
ML7 (ASY & SYM)	90	0.0341
ML8 (SYM)	167	0.0165
ML8 (ASY)	120	0.0310
DF1 (ASY & SYM)	--	0.0865
DF2 (ASY & SYM)	--	0.0856

The motions of the moored oil tanker, in the six degrees of freedom (surge, sway, heave, roll, pitch and yaw), were measured using the *Qualisys – Motion Capture System*, composed of 3 digital infrared cameras, Figure 3. With this equipment ship's motions are measured without any contact with the model. Wave conditions in the tank were measured with resistive wave probes. Those conditions were calibrated before beginning the tests with the moored ship. All measurements were carried out with a sampling frequency of 24 Hz.
In the first phase of the study a simplified physical 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.

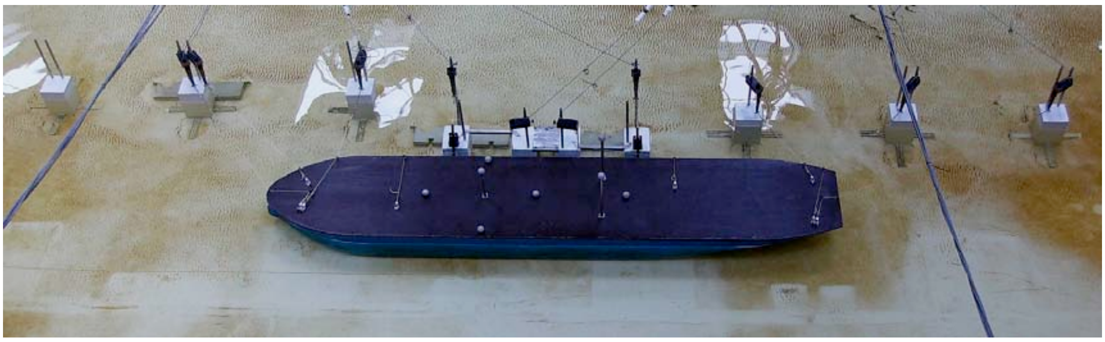


Figure 4. Ship model moored to the berthing structure (asymmetric mooring layout): first phase of the study.

An array of four wave probes was installed in the 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 is sketched in Figure 5. A dissipation beach was installed at the end of the wave tank to reduce wave reflections.

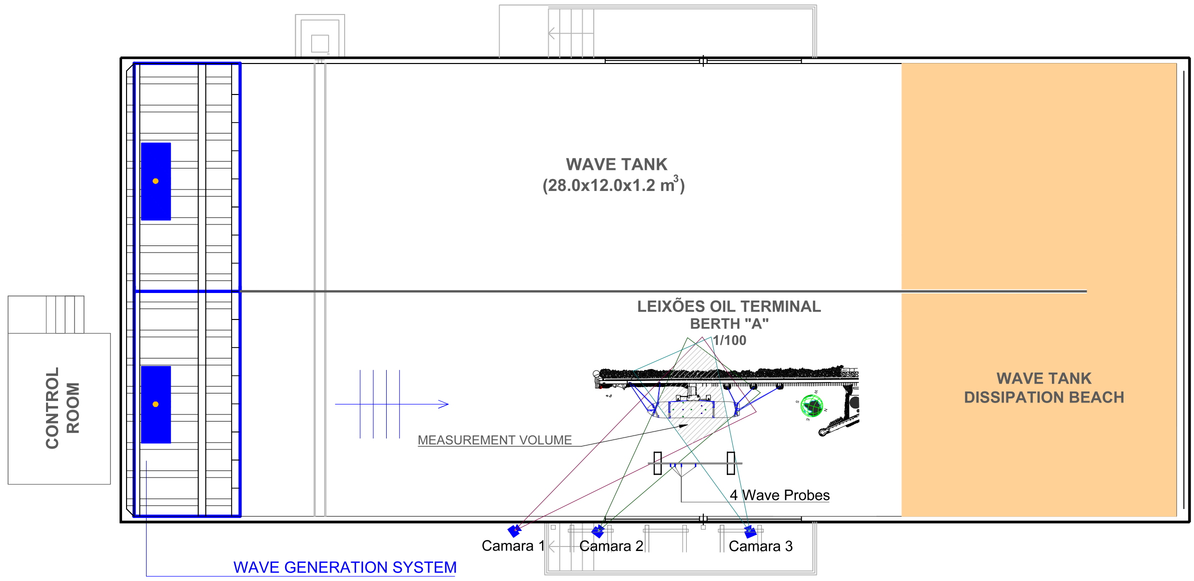


Figure 5. Physical model set-up in the wave tank: first phase of the study.

In the second phase of the study a more accurate model of Berth "A" and its surrounding area (Figure 1) was built inside the wave tank, which included harbour breakwaters, the berthing structure and nearby beaches. However, 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 in the wave tank is sketched in Figure 6. In this phase, the wave conditions at Berth "A" depend, essentially, on the diffraction of incident waves around the head of the north breakwater, and reflections on the south breakwater and Matosinhos Beach.

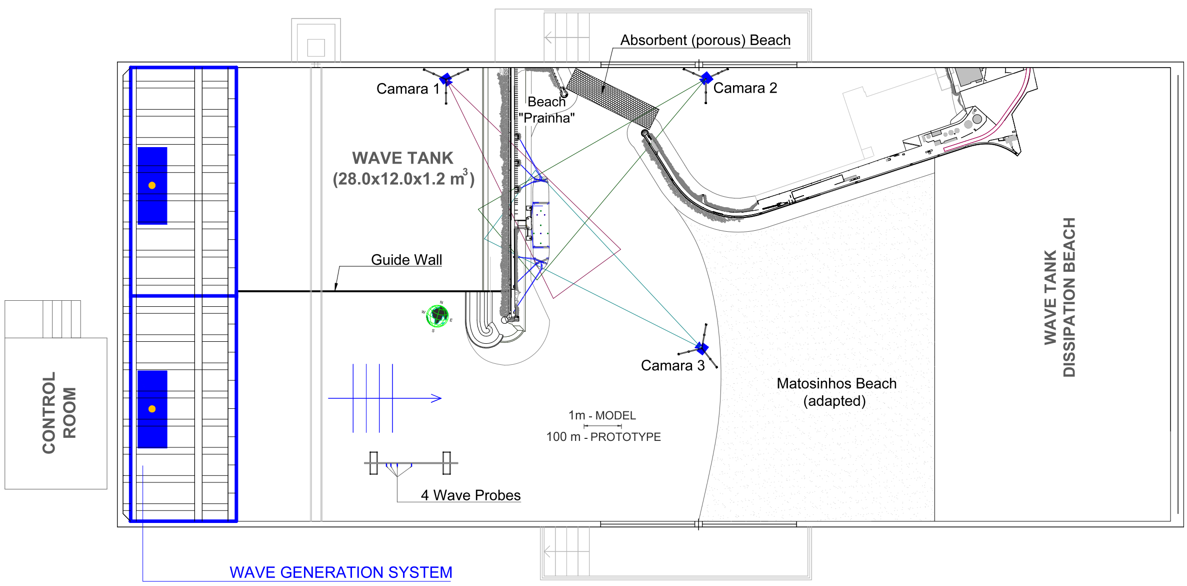


Figure 6. Physical model set-up in the wave tank: second phase of the study.

Scale effects should have a non negligible influence in the stability of the armour blocks used to reproduce the port's sheltering structures or in 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 aims were to properly reproduce the diffraction phenomenon and to minimize the construction works.
Wave reflections in the physical boundaries surrounding Berth "A" should have influence on the wave condition near the berth. Therefore, the reflection characteristics of the outer side of south breakwater and nearby beaches were reproduced as accurately as possible. However, the bathymetry and the length of the Matosinhos Beach had to be slightly adapted in order to minimize unwanted reflection from the right side wall of the 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.

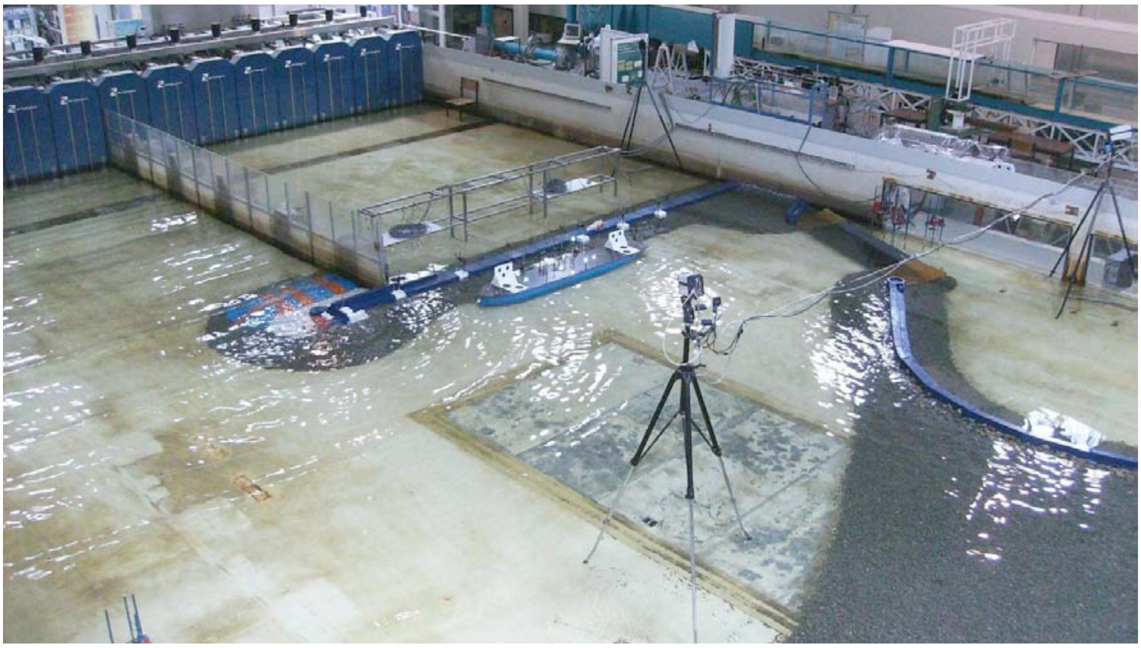


Figure 7. General view of the physical model tested in the second phase of the study.

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). Hence, the waves generated in the model had a direction of propagation perpendicular to the north breakwater (at the wavemaker).
The physical model tests analyzed in this paper were carried out with irregular long crested waves, characterized by a JONSWAP spectrum with a peak enhancement factor 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. Therefore the long wave conditions at the berth were not calibrated, and theoretical set-down compensation at the wavemaker was used. 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

As referred before, this paper focuses on the physical modelling component of the DOLPHIN project. Results of selected test conditions are used to present some of the conclusions drawn until the moment.
The influence of the ship mooring layout, the water depth near the berth and the increase of the breast lines' pretension on the response of an oil tanker moored at Berth "A" is analysed in the following sections.

4.1 Mooring layout

In what concerns mooring layouts, OCIMF (2008) refers to the concept of a generic mooring layout, specifying that such layout should be mostly used in a multi-directional environment, where no single direction dominates or where any of the environmental forces may become a dominant factor. Among other characteristics, that standard mooring layout is symmetrical about the midship point of the ship, to ensure a good load distribution, and does not includes head or stern lines. Nevertheless, OCIMF (2008) also states that for a berth located at a place with a directional environment (high swell, winds or currents), a site-specific mooring layout could be more efficient, namely one including head and stern lines and/or extra breast and spring lines.
As referred before, the mooring layout more frequently used by the largest class of oil tankers at Berth "A" is slightly asymmetrical (Figure 2) and includes head and stern lines. Despite the fact that this berth is exposed to directional actions, it is worth analyzing if a small change on the actual mooring layout can effectively improve existing operational conditions.
The alternative mooring layout selected for comparison is sketched in Figure 8, follows more closely the OCIMF's recommendations, and takes advantage of the mooring point situated near the head of the north breakwater (ML8). This layout is symmetrical and could be easily implemented, if proved to be technically safe and effective.

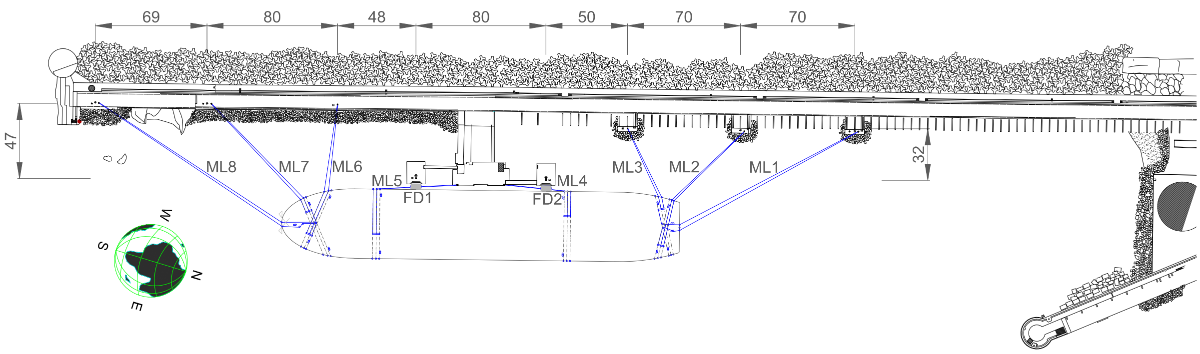


Figure 8. Symmetrical mooring layout used in the physical model tests.

Asymmetrical versus symmetrical mooring layout
In this section, the behaviour of a ship moored at Berth "A", for the actual and the proposed mooring layouts, is analyzed based on results of the simplified physical model (first phase of

the study). The only forcing actions considered in the study are the waves that are expected to reach the Berth "A" area after diffract around the head of the north breakwater.
The oil tanker was tested under the action of irregular long crested waves characterized by a significant wave height of 2.0 m and by peak wave periods between 8 and 14 s, for a water depth near the berth of 20 m (high tide). The initial tension on all the mooring lines was set between 100 and 120 kN (base condition). The friction coefficient at the interface between the ship's hull and the fenders was equal to 0.12.
Figure 9 compares the maximum loads (prototype) recorded in each one of the ship mooring lines (ML) and fenders (FD), for the asymmetrical (ASY) and symmetrical (SYM) mooring layouts. These loads correspond to the initial tension on each mooring element in addition to the maximum load recorded during the test (above that initial level). Maximum loads that the mooring lines and the fenders can withstand (Max Load) are also presented in the figure.

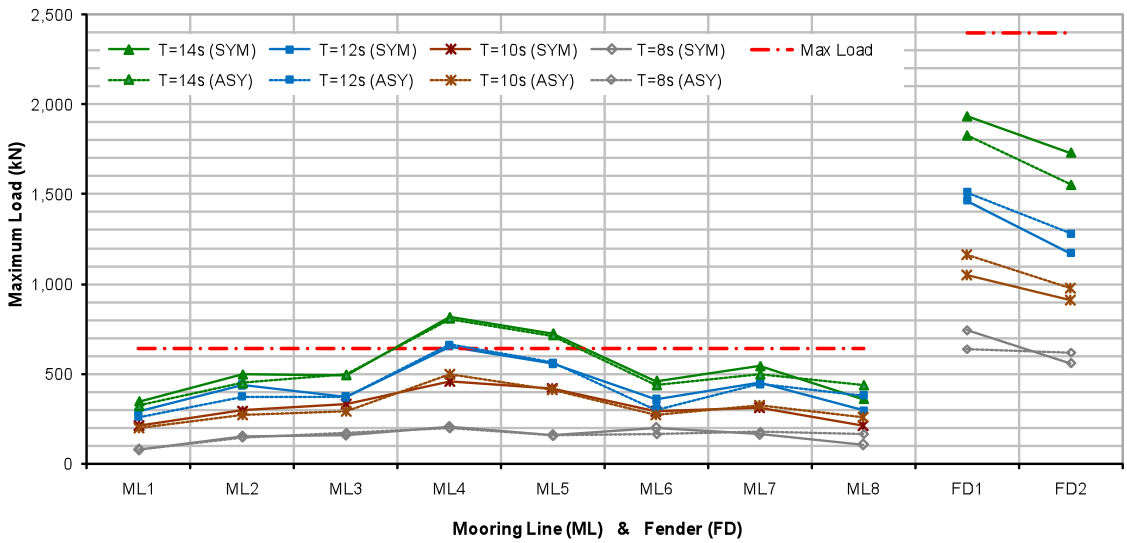


Figure 9. Maximum loads on the ship mooring lines and fenders for the asymmetrical and symmetrical mooring layouts.

Differences between the two mooring layouts are quite small, as the maximum loads recorded on equivalent mooring lines are nearly the same. However, some differences can be observed in ML7 and ML8. Due to the smaller length of ML8 (higher stiffness) in the asymmetrical layout, the maximum loads on this line are higher for that condition than in the symmetrical layout, for all the tested wave periods. In the asymmetrical layout, ML7 and ML8 withstand nearly the same load, due to their similar orientation and length. For the same reason, loads on ML7 are, in general, smaller for that condition. Maximum loads on the fenders were found to be smaller in the case of the symmetrical layout at intermediate wave periods, but for the peak wave period of 14 s, loads on the fenders are higher for that mooring layout. In all the tests the maximum loads on the fenders are smaller than the maximum acceptable loads.
Spring lines (ML4 and ML5), as expected, were the most loaded mooring lines. This is due to their orientation (restrain of surge) and lower length (higher stiffness), Table 2. Based on the results presented in Figure 9, the spring lines would be the first mooring lines to break. This agrees with the experience of the mooring personnel working at Berth "A".
In what concerns the motions of the moored ship (results not presented here), and as observed for the maximum loads on the mooring system, differences between the two tested mooring layouts are, in general, small.

Conclusions
The behaviour of an oil tanker moored at Berth "A" of the Leixões Oil Terminal was studied for two mooring layouts. The analysis was based on results of the simplified physical model of the berth and its surrounding area.
The results showed only small differences between the two tested mooring layouts in terms of the maximum loads measured on the mooring system or moored ship motions. Therefore one can conclude that the modifications introduced in the mooring layout more frequently used at Berth "A" have only minor effects on the behaviour of the moored ships. The tested mooring layouts only differ on the position of one double mooring line (head line).

4.2 Underkeel clearance

In many ports around the word, the size of the ships than can safely enter the harbour basins and moor at one of the berths is conditioned by the available water depths. In the other hand, the water depths near the berth, or more correctly the ship´s underkeel clearance, have also a strong effect on the moored ship behaviour. Indeed, added inertia and damping can increase significantly when the ship's underkeel clearance is reduced. Therefore, the natural periods of oscillation of the moored ship and its hydrodynamic behaviour are also affected.
Underkeel clearance also depends on the ship size, tide level, and ship loading condition. In this section, the influence of the tide level on the behaviour of an oil tanker moored at Berth "A" is analyzed. The ship loading condition is not changed. Conclusions are drawn based on the analysis of the horizontal motions of the moored ship, which are the most important ones for the security and efficiency of the operations usually carried out at an oil terminal, Bruun (1983). However, because the unloading arms are positioned in the central part of Berth "A" and usually the unloading valves are located amidships, yaw is probably the less important of those motions.

Mean sea level versus high tide
The behaviour of an oil tanker moored at Berth "A" is analyzed based on the results of the physical model tested in the first phase of the study, for two water level conditions, namely the mean sea level (d=18 m) and the high tide water level (d=20 m).
The tanker was moored with the symmetric layout (Figure 8) and was tested under the action of irregular long crested waves characterized by a significant wave height of 2.0 m and by the following peak wave periods: 8, 10, 12 and 14 s. The initial tension on the mooring lines was set between 100 and 120 kN. The friction coefficient at the interface between the ship and the fenders was equal to 0.12.
The significant amplitudes of the ship's horizontal motions are compared in Figure 10 for the two water level conditions (prototype). It can be observed that the increase of the water depth near the berth (increase of the ship's underkeel clearance) results in an important reduction of the significant amplitude of those ship motions. This is valid for all the peak wave periods analyzed. Similar conclusions could be drawn based on the maximum forces on the mooring system (results not presented). This is not surprising as the mooring forces and the amplitude of the moored ship motions are closely related, particularly surge motions and spring lines' forces, and sway motions and breast lines' forces. However, it may worth to further analyze the influence of the underkeel clearance on the moored ship response.
As referred previously, added inertia and damping can increase significantly when the ship's underkeel clearance is reduced. From that, one could anticipate that a reduction of the water depth near the berth could result, for the same wave forcing, in smaller moored ship motions or mooring system loads. The influence of those effects would depend on the type of motion.

For instance, it is know that the reduction of the ship's underkeel clearance leads to a higher increase of the added inertia associated with heave, pitch, sway and yaw oscillations than that of surge and roll, PIANC (1995).

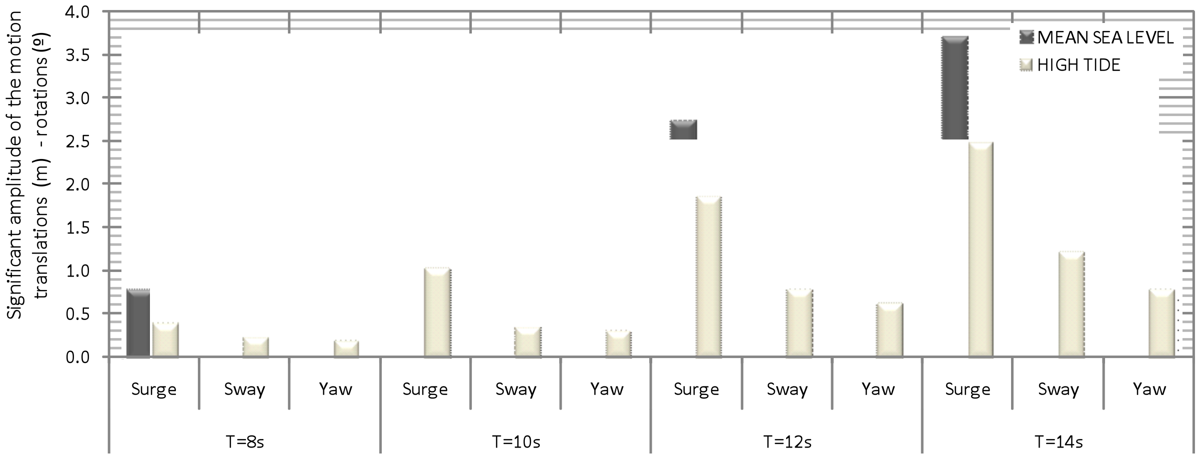


Figure 10. Significant amplitude of the horizontal moored ship motions for the two water levels studied: mean sea level and high tide water level.

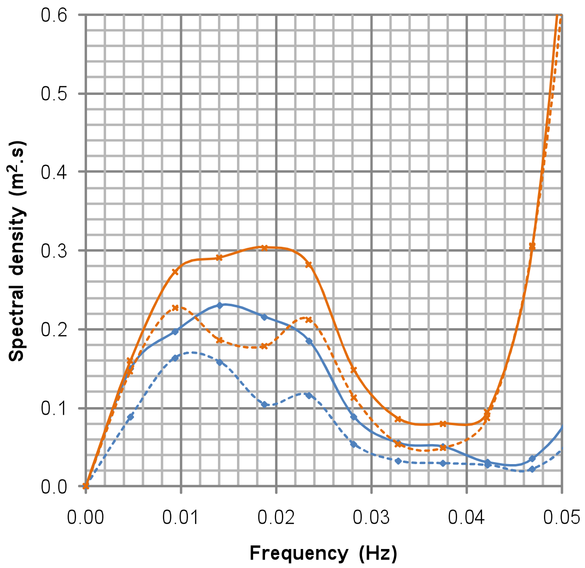
However, the results presented in Figure 10 do not shown the expected trend, and the reasons for that may well be related to the wave forcing. As referred earlier, the tests analyzed in this section were carried out with sea states having the same significant wave height and the wave conditions inside the tank were controlled accurately. Moreover, the same temporal sequence of incident waves was used in the tests having the same peak wave period. The variation with the water depth of the natural periods of oscillation of the moored ship should not explain the obtained results.

The energy spectrum of any irregular sea state can be separated in two parts: the short period component and the infra-gravity band. Without going into many details, the amount of infra-gravity energy in an irregular sea state depends on the significant wave height and peak wave period of the short period component, local water depth, surf zone bathymetry, among others.

In what concerns water depth, d, assuming the steady-state equilibrium solution and shallow water conditions, according to the theory of Longuet-Higgins and Stewart (1964), for uniform depths, the amount of low-frequency energy in a wave spectrum should vary, approximately, with d^{-2}. Therefore, and despite the fact that the total amount of wave energy being the same in the tests carried out for the two water levels, the infra-gravity energy should increase about 24% when the water depth is reduced from 20 to 18 m. For instance, Figure 11 presents the influence of the water depth inside the wave tank in the infra-gravity energy levels of two sea state conditions characterized by a significant wave height of 2.0 m and by peak wave periods of 12 and 14 s.

Moored ships are very much sensitive to the infra-gravity energy levels in a wave spectrum. Therefore, even if the ship's added inertia and damping are higher when the mean sea level is considered, the increase of the low frequency energy when the water depth is reduced should, not only compensate those effects, but also lead to a worsening of the moored ship response.

In the physical model tests carried out, incident waves approached the moored oil tanker from a heading direction, Figure 5. This could justify why the surge motions have larger significant amplitudes than the other motions. Nevertheless, significant sway and yaw motions were also observed, without any important external forcing action acting on those directions. This could be related with the ship mooring layout.



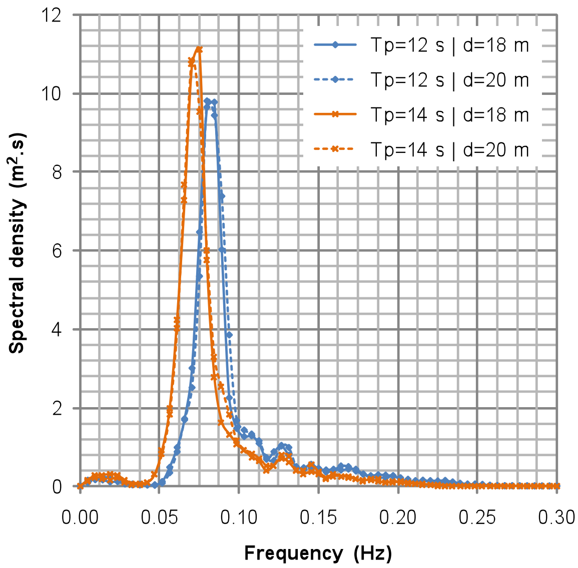


Figure 11. Influence of the water depth, d, in the infra-gravity energy content of two sea state conditions measured in the wave tank: low frequency band (left), complete spectrum (right).

Conclusions

The effect of the underkeel clearance on the behaviour of an oil tanker moored at Berth “A” was studied with a simplified physical model of this berth and its surrounding area.

The results have shown that the water depth in the vicinity of the berth, and hence the ship’s underkeel clearance, are very important factors controlling the behaviour of moored ships.

Possibly due to an increase of the infra-gravity energy levels in the reproduced sea conditions when the water depth is reduced, and despite the effect of the underkeel clearance reduction in the ship’s added inertia and damping, changing from the high tide water level to the mean sea level increased significantly the mooring forces and the amplitudes of the ship motions.

It is important to mention that these results should be interpreted with some care as they refer to a simplified physical model of the prototype. As mentioned previously, several phenomena (acting alone or together) can influence the operational and security conditions at Berth “A”.

4.3 Mooring line pretension

Downtime at ocean facing ports is often related with excessive moored ship motions caused by wave action. To minimize this type of problems, and as an alternative to the construction of new sheltering structures or the modification of existing ones, the possibility of adopting ‘soft’ measures should be analyzed, which may be less expensive and equally effective.

The increase of the pretension forces applied on the ship’s mooring lines could be one of such alternatives, by allowing the ship to be more effectively pulled against the fenders and, this way, to take better advantage of the friction between the fenders and the ship’s hull to reduce the amplitude of the ship motions. Ship motions and mooring forces may also be reduced if the natural periods of the moored ship, due to the pretension change, are shifted way from the resonant periods of the harbour or the frequencies of the incoming infra-gravity waves.

In this section the influence of an increase of the breast line’s pretention in the response of an oil tanker moored at Berth “A” is analyzed for two different types of interface between the ship’s hull and the fenders, based on results obtained with the model built for the second phase of the study (Figure 6 and 7).

Increase of the breast lines' pretension

The response of the moored ship to different pretention conditions was analyzed in order to address the influence of the friction forces developed at the interface between the ship's hull and the fenders: the base condition (PT-Base) and the extra pretension (PT-Extra). In addition two types of interface were studied: low (FD-LF) and high friction (FD-HF). 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 (i.e. pneumatic fenders). Tests were carried out with the tanker model moored with the asymmetric layout (Figure 2) for the high tide water level (d=20 m). Wave conditions in front of the wavemaker (outside the port) 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. These waves travel to the Berth "A", diffracting around the north breakwater and undergoing some reflections on the physical domain boundaries.

Figure 12 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". 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 moored ship motions. The best results are always obtained when high pretension forces are used to moor the tanker to a berthing structure with high friction fenders installed. In general the reduction of the ship motions' amplitude is higher in the case of the surge oscillation.

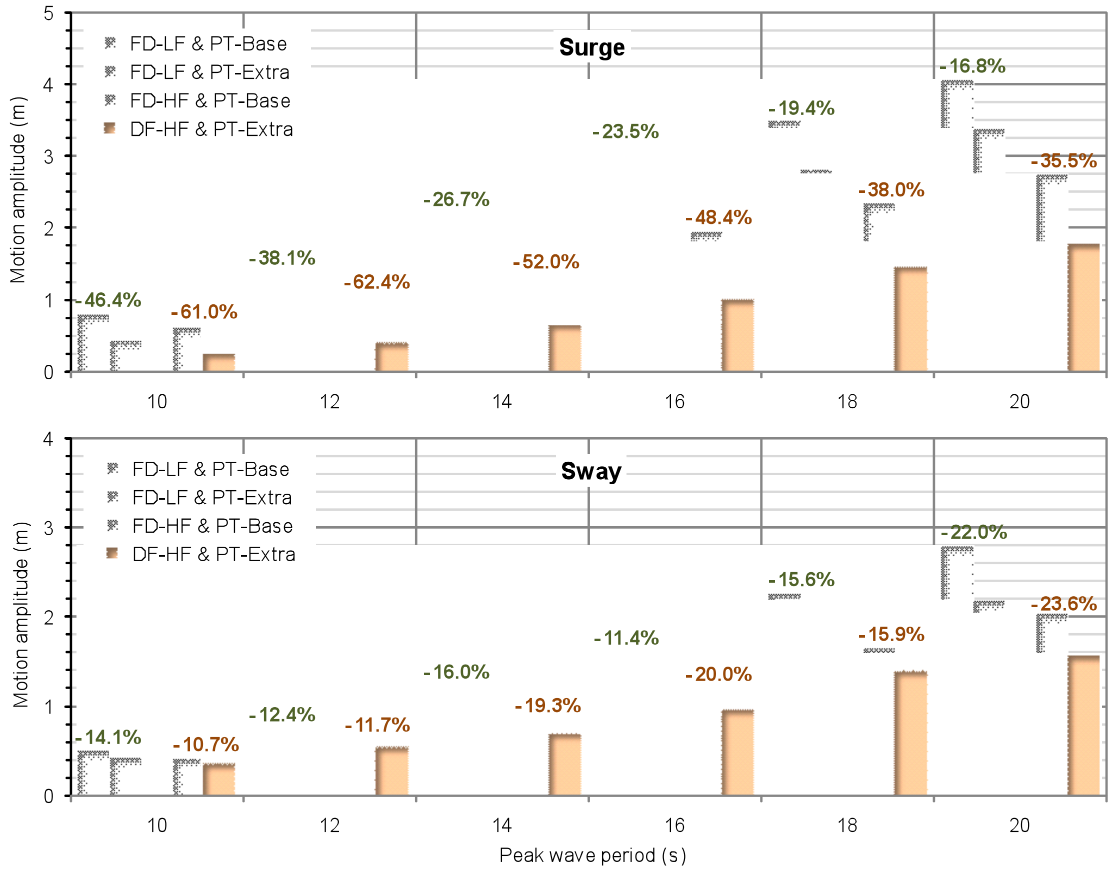


Figure 12. Significant amplitudes of surge (upper) and sway (down) motions for different characteristics of the mooring system. Results of the second phase of the study.

It is also important to state that the increase of the breast lines' pretension is most effective in the reduction of surge motions when high friction fenders are installed on the berth. In fact, under these 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.

Conclusions
The influence of the friction forces developed at the interface between the ship's hull and the fenders on the behaviour of a tanker moored at Berth "A" was analyzed with a more detailed physical model of that berth and its surrounding area, which included the reproduction of the harbour's breakwaters and nearby beaches. The analysis was focused on the type of motions that are more important for the operational and security conditions at an oil terminal.
The presented results have showed that important reductions of the surge motions could be achieved by increasing the pretension forces on the breast lines, particularly if high friction fenders are installed on the berth. The influence on the ship sway motions is less significant, but still important.

5. Conclusions

The behaviour of a ship moored at Berth "A" of the Leixões Oil Terminal was analyzed for different test conditions based on the results of two scale-models: the first one corresponding to a simplified representation of the berth and its surroundings, and the second one to a more detailed reproduction of the prototype characteristics. The effectiveness of some interventions on Berth "A" to reduce its downtime was also analyzed.
It was concluded that the modifications introduced in the mooring layout more frequently used at Berth "A" had only a slight influence in the ship response; nevertheless the increase of the breast lines' pretension can effectively reduce the moored ship motions, particularly if high friction fenders are installed on the berth. The water depth near the berth was identified as an important factor controlling the behaviour of the moored ship.
Berth "A" operational conditions are supposed to be affected by several phenomena, namely: Leixões north breakwater overtopping and wave diffraction around its head, characteristics of the mooring system and fenders, current transmission through the north breakwater core, and possible resonance phenomena near the Berth "A". As mentioned in the paper, some of those phenomena could not be accurately reproduced in the physical models, even in the second phase of the study. Therefore, and without understating the work carried out, the presented results and conclusions should be interpreted with some care, especially if extrapolated to the prototype.
In addition to physical modelling, the DOLPHIN project also includes a numerical approach to the simulation of the behaviour of moored ships in harbours, and a component related with the development (and application) of a system to measure the motions of a moored ship in the prototype. The results of the preliminary numerical model simulations and their comparison with physical model tests results, as well as, the results of the experimental tests carried out in

the laboratory to verify and validate the system developed to measure moored ship motions were presented in Rosa-Santos *et al*. (2009).

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