PHYSICAL AND NUMERICAL MODELLING OF SHIPS MOORED IN PORTS

by

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ABSTRACT

The study of a moored LNG carrier vessel in presence of waves by numerical and physical modelling is presented in this paper. The objective is to compare the numerical modelling of this vessel in presence of an harbour structure (as a vertical quay or rubble-mound breakwater) with the results obtained with a physical model in order to improve our confidence and our practice when using the numerical model for engineering applications. The paper describes in details the model set-up, the instrumentation, the ship model characteristics to comply with Froude scaling and the results obtained.

Among the different harbour structures tested by physical model, the vertical quay quite far from the vessel is the structure which has a clear impact on vessel behaviour by increasing significantly the mooring lines tensions and the vessel motions comparing to a configuration without any structures. In addition, mooring lines tensions are in good agreement between the two models as well as motions, except for roll, which is twice larger in the numerical modelling and which requires to be further analysed in a next phase of the project.

1. INTRODUCTION

Study of moored vessel motions in presence of waves is a very important issue for all harbour design project as vessel dynamic behavior has a direct impact on safety of (un)loading operation as well as on berth equipment (mooring lines & fenders) integrity. In addition, wave conditions are one of the main factors which could affect the berth operational downtime. As this downtime shall be very low to ensure cost-effectiveness of the berth, it shall be demonstrated that wave-induced motions are acceptable to enable (un)loading operations in presence of the most frequent wave conditions.

Several numerical tools are available to perform dynamic mooring analysis of ships exposed to waves. However, despite the fact that these tools are very efficient to simulate rapidly a large amount of different environmental and mooring conditions, some parameters used in these numerical models need to be calibrated from physical model tests measurements. Physical model tests are hence required to calibrate numerical simulations but are also necessary to model some specific and complex hydrodynamic configurations for which a numerical approach is not sufficient such as moored vessel close to rubble-mound breakwater, with complex bathymetry for instance. In a general way, a vessel moored at berth inside a port can be exposed to a very complex wave disturbance pattern which could include several wave trains issued from reflective structures as quays or rubble mound breakwater or issued from diffraction of waves at the main breakwater roundhead.

In order to improve the reliability and relevancy of numerical mooring analysis as well as to improve our understanding of some specific hydrodynamic complex configurations, a research project has been launched in ARTELIA hydraulic laboratory which consists in carrying out series of physical modelling tests (a) to provide relevant experience feedbacks for numerical modelling and (b) to improve the methodology deployed in our laboratory for floating bodies physical modelling.

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2. DESCRIPTION OF THE PHYSICAL MODEL TESTS

2.1 Methodology

Using physical modelling for study of dynamic behavior of vessels moored at berth is a classical approach which is well described in several standards, guidance and literature (e.g. Sutherland, 2013; British Standards, 2013)

Froude's law is the similarity law applied, due to the fact that gravity forces predominate over the other forces (e.g; viscosity). However, it is necessary to verify that the Reynolds number is greater than 104 in accordance with Hydralab guidance (Sutherland 2013), to ensure that the forces of viscosity are sufficiently representative. The above criteria have been verified for the different waves and depth conditions which have been tested.

The modelled vessel is a LNG carrier which represents a type of vessels which is frequently studied by ARTELIA for mooring analyses we have to carry out as part of marine terminal design projects.

As one of the main objectives of this physical model tests campaign is to enable a direct comparison with numerical model results, some simplifications have been decided at the beginning of project:

- The bathymetry is represented in the wave basin as a flat bed at 0.225m depth (18m nature), in order to perfectly correspond to the numerical model.

- A linear behavior is modelled for stiffness of mooring lines as well as for fenders. This is to avoid a too complex model (as regard to construction aspects) and hence to facilitate understanding of dynamic behavior of physical model in comparison to numerical model.

2.2 Model set-up

The model tests were performed in one of the wave basin of the Hydraulic Laboratory of ARTELIA, in Pont-de-Claix, near Grenoble (France). The basin is 16m wide, 30m long, 0.8m high and is equipped with a piston-type wave paddle driven by a hydraulic jack, which generates long-crested waves. The model was built at 1/80 scale, based on Froude scaling.

A simplified flat bathymetric profile was built in hard cement in the basin slab. The seabed is reproduced as a non-erodible surface. Wave-absorbing beaches have been placed at the boundaries of the basin, to prevent as much as possible unwanted reflections (boundary effects).

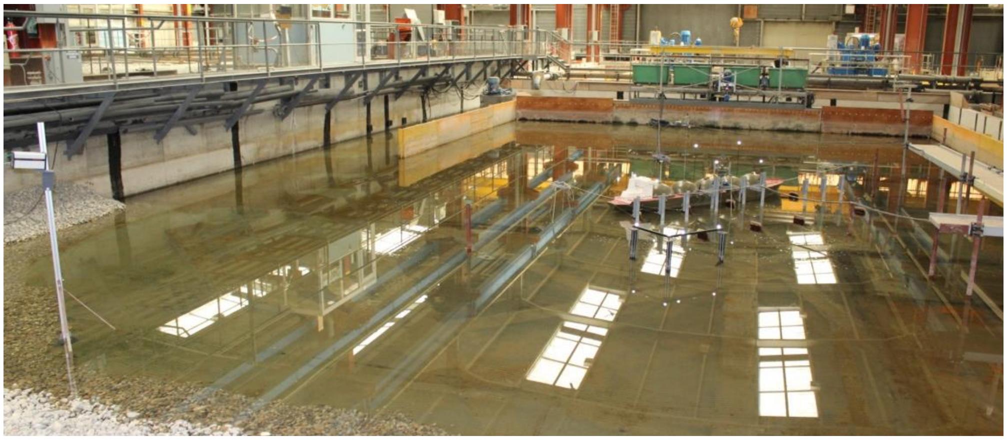


Figure 1. Overview of model implemented in the wave basin

The following components, representative of a typical LNG terminal berth have been implemented as follows:

The vessel, modelled with representative geometry, displacement, draught, COG, metacentric height & inertia

- The berth, modelled by 8 mooring dolphins and 2 breasting dolphins
- 8 mooring lines (representing actually 16 mooring lines, as two real mooring lines are represented in the model by a unique bundle).
- 2 fenders (representing actually 4 fenders)

The following figure details the studied berth and provides an overview of the deployed instrumentation:

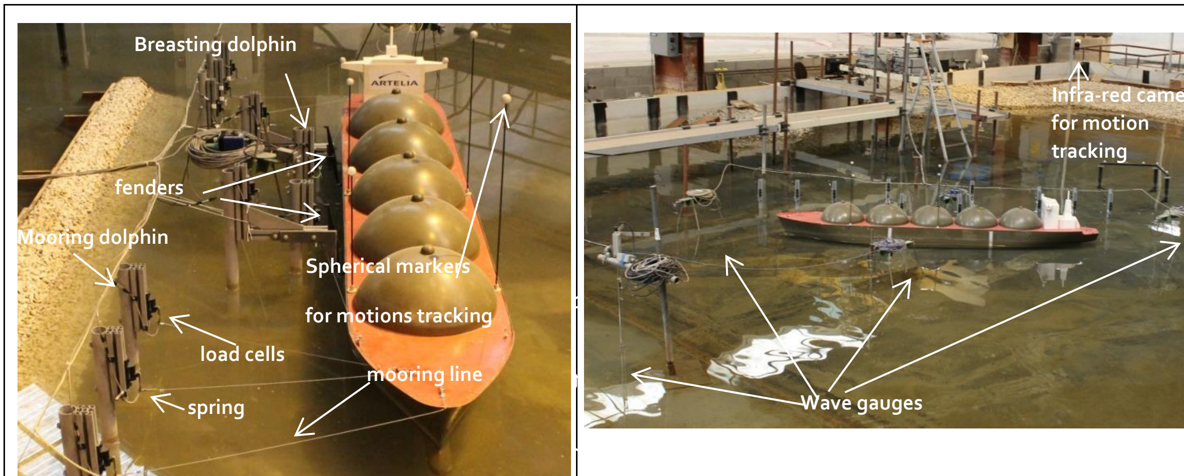


Figure 2. detailed view of berth & overview of deployed instrumentation

The modelled vessel is a 130 000m3 capacity LNG carrier, in loaded configuration, with the following characteristics:

Vessel characteristics	At prototype scale	At model scale
Length overall (m)	287.5	3.6
Lpp (m)	274	3.425
Breadth (m)	43.4	0.542
Depth (m)	25	0.312
Displacement (t)	92 365	0.176
Mean Draft (m)	10.8	0.135
Natural roll period (s)	16.40	1.83
Metacentric height GMt (m)	5.02	0.063

Table 1. Vessel model characteristics

2.3 Instrumentation

For each test, the following parameters have been monitored and recorded:

- Tensions in each of the 8 mooring lines
- Forces in the 2 fenders
- Motions of the ship in the six degrees of freedom
- Water surface elevation at five locations in the vicinity of the ship

Tensions in mooring lines and forces in fenders have been measured by strain gauge technology sensors (bending beam load cells utilized in compression) and motions of ship in the six degrees of freedom have been measured by the combination of 4 infrared cameras for motion tracking (Qualisys system).

Waves conditions have been assessed from omnidirectional and directional gauges. Omnidirectional wave gauges measure the water surface elevation. These capacitive gauges are made of two thin vertical wires, and relate voltage to water level. The directional wave gauges measure the wave orbital velocities, based on the principle of electromagnetic field distortion in the presence of currents. Coupled with omnidirectional wave gauges at given locations, they are used for separating incident and reflected wave energies (and then to determine reflection coefficients of the structures). The different types of gauges are used: for directional wave gauges to check the target input conditions at specific reference/control points and for omnidirectional gauges to measure local wave disturbance at specific areas.

The wave generator is controlled by the GEDAP comprehensive software system for the analysis and management of laboratory data. This state-of-art software, developed by the Canadian Hydraulics Centre of the National Research Council (NRC-CHC), enables wave generation, real-time data acquisition and post processing wave analysis.

All measurements have been synchronised and performed at a sampling frequency of 60Hz.

2.4 Tests procedure and program

Different water depths (18m and 14m at prototype scale) and wave conditions (Hm0 in the range [0.5m – 1.5m] and Tp in the range [8s – 18s]) have been tested together with two wave incidences: (a) Waves coming abeam and (b) Quartering seas: waves coming from 45° with reference to the bow. Modelled wave spectrum is Jonswap type with a gamma factor of 3.3.

In addition, two harbour structures (vertical quay and a rubble mound breakwater) have been implemented for some tests into the model to analyse the impact of different kinds of structures (fully or partially reflecting the waves) on moored vessel behaviour. This mooring configuration in shallow water and in presence of harbour structures represents the context of typical harbour design project performed in ARTELIA.

For this purpose, four configurations have been tested as follows:

- Configuration A: a berth without any structure
- Configuration B: a berth with a vertical quay very close to the ship (distance of 4m between ship hull and quay at prototype scale)
- Configuration C: a berth with a vertical quay quite far from the ship (distance of 110m between ship hull and quay at prototype scale)

- Configuration D: a berth with a rubble-mound structure (typically half of a breakwater) far from the ship (at prototype scale distance of 100m between ship hull and intersection of rubble-mound structure with still water level)

It shall be noted that configuration B does not represent a realistic situation for LNG carrier, as this kind of vessel is generally not moored directly alongside and close a vertical quay. LNG carrier ships are rather moored at a dedicated berth where main mooring dolphins are at a distance of typically 50m from berthing line (as modelled in the present project and as presented in above Figure 2). However this configuration “B” is studied in order to provide a relevant feedback for numerical model representing a vessel moored alongside and close to a vertical quay as it is a common practice for general cargo, ferries or container vessel.

These four configurations are presented in the following figure:

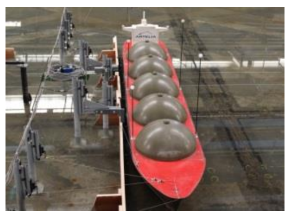
			
Configuration A: a berth without any structure	Configuration B: a berth with a vertical quay close to the ship	Configuration C: a berth with a vertical quay far from the ship	Configuration D: a berth with a rubble-mound structure quite far from the ship

Figure 3. Views of the different studied configurations

Tests have been performed in regular waves conditions as well as in random waves conditions. For random waves, tests are performed considering a 3 hours duration (prototype scale). At model scale, this represents a test duration of about 20 minutes. After completion of each test, a time-domain analysis of the measured data is carried out. For tensions in mooring lines, forces in fenders and motions for each of the 6 degrees of freedom, the following statistical results are output:

- F+1/10: Average value of the highest 1/10th of the peaks;
- F+max: Maximum value of the peaks;

The same statistical study is performed for the troughs (F-). Statistical analysis for post-processing of data is performed using WaveLab software, developed by the Hydraulics and Coastal Engineering Laboratory of Aalborg University (Denmark).

3. NUMERICAL MODEL AND SOFTWARE DESCRIPTION

Several configurations tested in wave basin were modelled in DIODORE™ software which is a general purpose hydrodynamics software package designed to solve a large number of problems in offshore and marine applications, such as stability, sea keeping and mooring analyses. DIODORE™ includes several modules:

- A Pre-processor, that defines the physical and geometrical characteristics of the floating body and its hydrostatic characteristics.
- An Hydrodynamic processor, which computes, from a mesh-model of the vessel hull shape, the hydrodynamics of the floating body and the corresponding wave diffraction/radiation loads. This software is based on the potential theory. Such

approach allows to compute, from a mesh-model of the immersed volume of the hull, the hydrodynamic characteristics of the floating structures in terms of diffraction (disturbance of the wave field incident to the fixed structure) and radiation (as generated by the wave field induced by the movement of the structure). Radiation is measured in the form of added masses and radiation damping. Diffraction is evaluated in the form of transfer functions of wave loads. The main assumption of the Potential theory is to neglect viscous effects. It is therefore necessary to use additional models to reproduce the effects due to the viscosity, especially for those degrees of freedom where radiation provides very little damping, as in roll. Viscous damping in roll is therefore added, based on coefficients found in the literature (or from basin model tests, when available). In the present case, the linear and quadratic damping coefficients which have been input in the numerical model have been evaluated by the physical modelling and dedicated decay test (see section 4).

- A Mechanical processor, which computes the linear and non-linear motions of the floating body, induced by waves (wave frequency and low frequency 2nd order drift), wind and current. It includes a time domain solver to analyse, over typically a 3 hours simulation, the dynamic motions of the floating structure, taking into account the (non-linear) stiffness of the mooring lines and the fenders.

- Post-processor, which is used to visualize the results and which provides statistical analysis of key parameters, such as tensions in the mooring lines, motions of particular point along the hull …etc.

In the present case, for assessment of slowly-varying drift forces, the Newman's approximation is used (Newman, 1974).

The Diodore^{TM} solver enables to model multi-body systems. Hence it is possible to model another (fixed) structure (e.g; a vertical wall) in presence of the vessel to take into account a coupling between hydrodynamics of the structure and of the vessel. This modelling enables to take into account of the reflective wave trains generated by the quay (fully reflective) on the vessel dynamic behavior in addition to the incident wave trains.

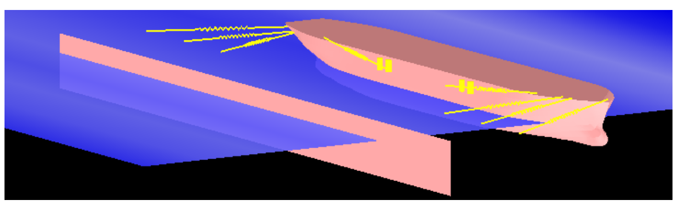


Figure 4.: Numerical model (including a vertical quay)

When the vertical quay is very close to the vessel, the close proximity of the ships creates a narrow volume of water in the gap between the ship and the quay. As it is a confined volume of water, hydrodynamic resonances in this area could occur. The method to handle correctly these phenomena numerically is presented in the article of Lecuyer et al (2012). The aim of this method (which has been originally developed to represent ship-to-ship configuration) is to model a free-surface with some additional damping representing the viscous effects due to the vortex shedding along the bilge of the ship. This is made in DIODORE^{TM} by a specific lid method, consisting in setting rigid dummy plates at the free surface in the narrow part of the gap. However, lid method, results obtained with numerical model and comparison with corresponding model tests cannot be further exhaustively presented in the frame of this article.

4. MODEL CHARACTERISTICS VERIFICATION

In order to ensure a correct representation of the vessel at laboratory scale, it has been verified that the target characteristics of the ship model have been checked.

Displacement, draft, as well as trim and heel angles have been verified using the measurements taken on 4 draft scale implemented on the hull of the ship at aft, bow, portside and starboard side.

In addition metacentric height (GM) was determined and verified by inclining test (method consisting in the displacement of a known weight from a side to the other side by a known distance and by measuring the induced modification in heeling angle)

Then, free decay tests in roll have been performed in order to check (a) the roll eigen period of ship and (b) to assess the roll damping coefficients. Each test (defined by an heel departure angle for starboard side and for portside) have been repeated twice. From free decay tests results, the roll damping coefficients have been assessed with reference to methodology exposed in ITTC standards procedures (ITTC 2011).

Once the damping coefficient have been evaluated from specific decay tests, these coefficients have been input in the numerical model and then a numerical decay test has been performed in the same conditions than physical model. The calculated roll motions have been observed to be in very good agreement as shown in the following figure:

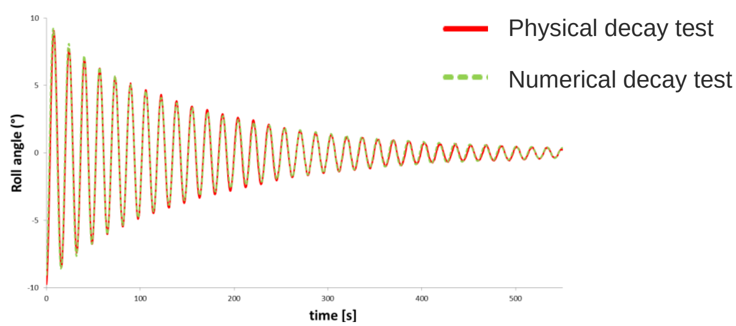


Figure 5.: Comparison of numerical model with physical model – decay test

5. REPEATABILITY OF PHYSICAL MODEL TESTS

In order to assess the variability of the results (in terms of motions as well as in terms of tensions in the mooring lines), some repeatability tests have been performed:

- For the same defined (Hm0, Tp) conditions, repetition of the same time series of wave trains
- For the same defined (Hm0, Tp) conditions, performance of a test with another time series of wave trains (randomly generated).

The following figure presents the results of two tests (with different time series of wave trains), performed in beam seas configuration, for a water depth of 18m, and considering that each mooring line is actually a bundle of two mooring lines. The results presented are F+1/10values.

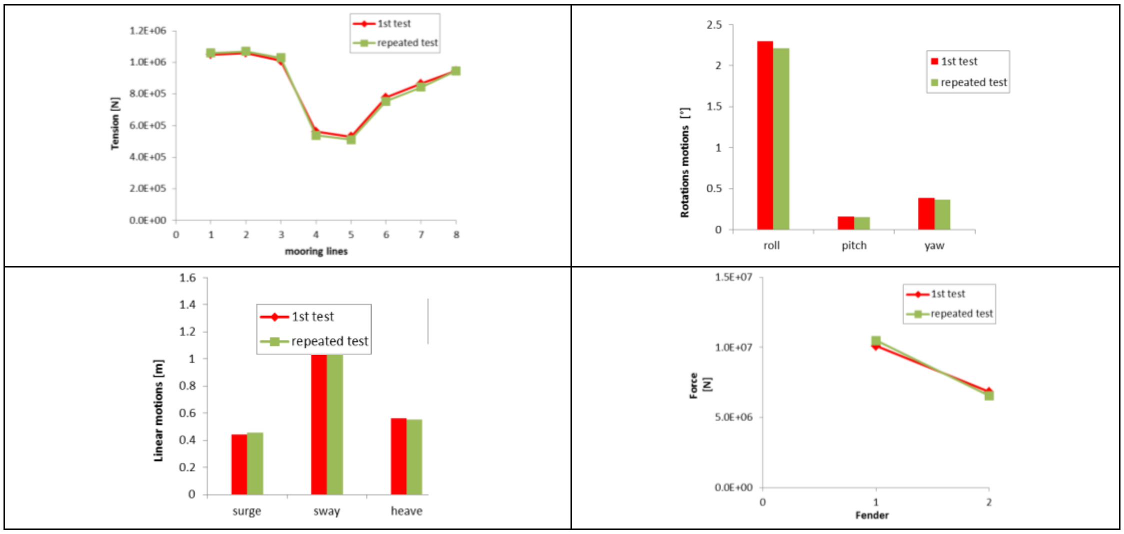
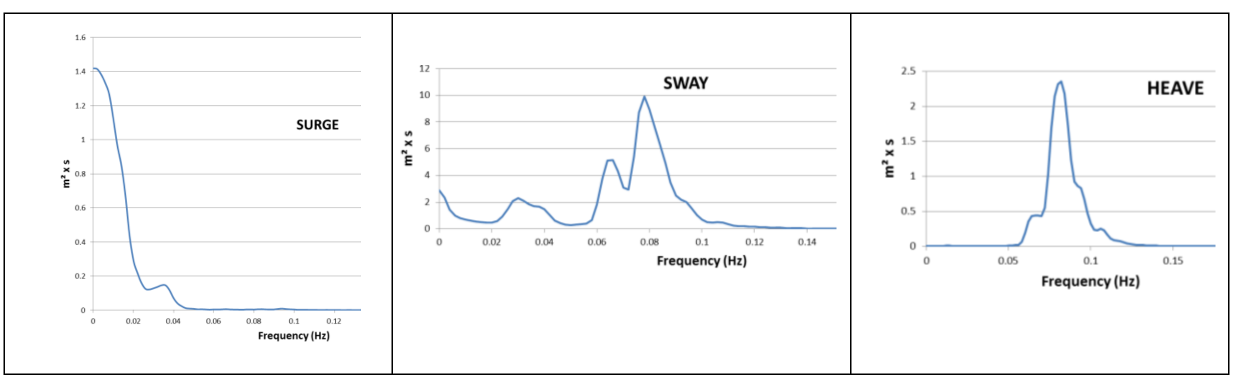


Figure 6. Repeatability tests (for Hm0= 1m /Tp=12s)

In above figure (as well as in this paper), the lines (bundle) n°1,2 & 3 refer to head lines, n°4 & 5 to spring lines and n°6, 7, 8 to stern lines. Regarding fenders, fender n°1 refers to fore fender and n°2 refers to stern fender. Variability from a test to another is low (about 4% for forces and 5% for motions). From the same performed tests, it has been observed that, for maximum values (F+max), the variability is increased (about 15% for forces and 7% for motions).

In addition, for variability tests based on similar wave trains the observed variability is about 3% for forces and 2% for motions for F+1/10values and is about 9% for forces and 4% for motions for F+max values. F+1/10values are less sensitive to random aspects of tests (comparing to F+max), hence, unless otherwise specified, results presented in this paper will be related to the F+1/10values.

In addition, for these test conditions, a spectral analysis has been performed on the time series of motions, in order to evaluate the energy distribution for the six degrees of freedom. Results are presented in the following figure:



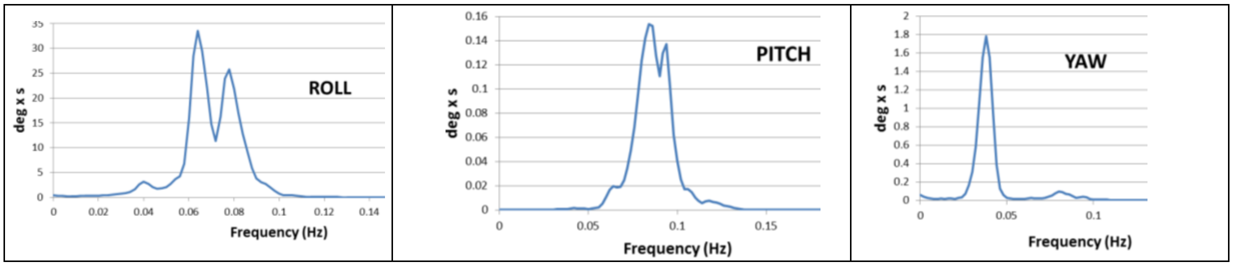


Figure 7. motions spectra for repeatability test (Hm0= 1m /Tp=12s – beam seas) at prototype scale

For these test conditions, the wave spectrum (issued from wave gauge located at wave control point) is presented in the following figure as well as the distribution of wave height (with comparison to a Rayleigh distribution).

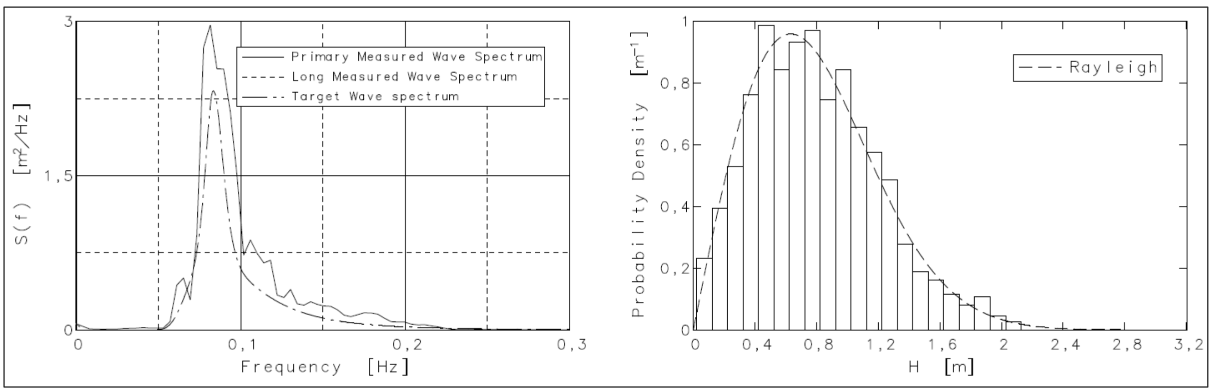


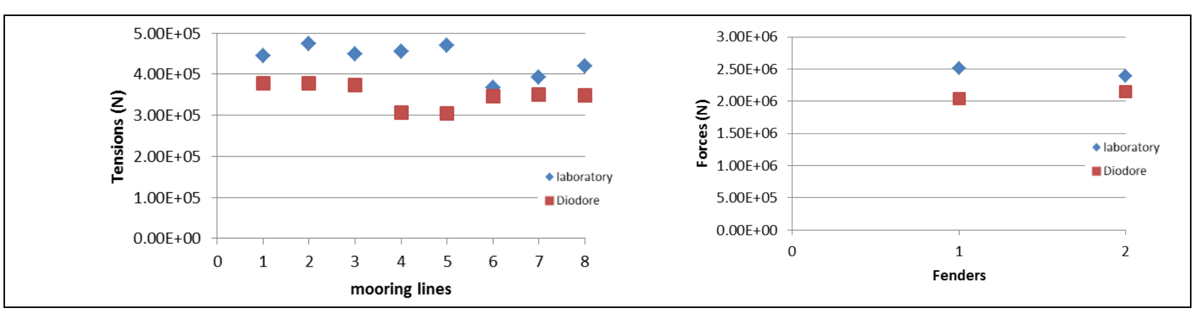
Figure 8. wave spectrum for repeatability test (Hm0= 1m /Tp=12s – beam seas) at prototype scale and distribution of wave height

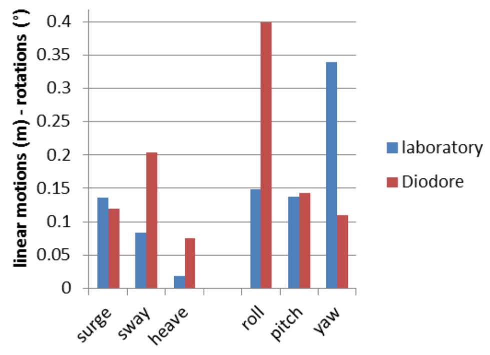
6. SIMULATIONS WITH NUMERICAL MODEL AND COMPARISON WITH PHYSICAL MODEL TESTS

At this stage, the physical modelling tests campaign is just finished. All the performed tests have not been exhaustively post-processed and analyzed. Thus, the results presented in the following sections correspond to the first tests which have been analyzed.

6.1 Without structure

The following figure presents some of the results of the numerical modelling in comparison to the physical modelling for quartering seas conditions.





Quartering Seas - Hm0 = 1.0m – Tp= 10s – 18m water depth

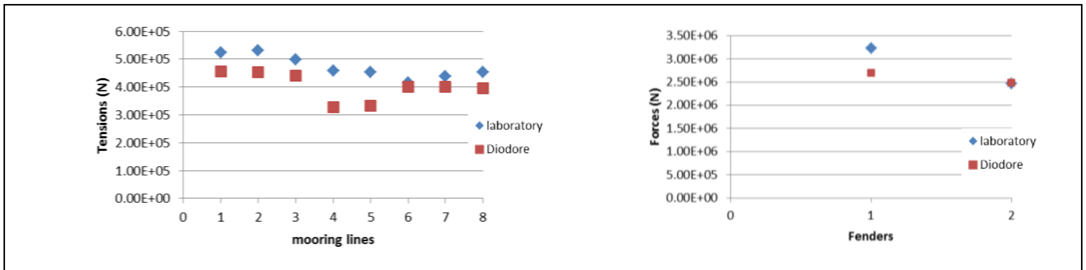
Figure 9.: Comparison of numerical model with physical model – without structure

The above results show that

- Tensions are in fairly good agreement in the two models (physical and numerical). This is particularly true for head and stern lines for which the difference between the models is about 20% to 25%.
- Forces in fenders are quite in good agreement too. Maximal difference between the models is 20%.
- The motions are quite in good agreement for surge and pitch, but for the other degrees of freedom, some discrepancies are observed.
- For roll motion, the values are more than twice larger in the numerical model than the values assessed with physical model. This is quite surprising as the numerical model uses the quadratic and linear damping coefficients specifically evaluated from decay test (following roll axis) performed with the physical model (as explained in above section 4)

6.2 In presence of vertical quay far from vessel

The following figure presents some of the results of the numerical modelling in comparison to the physical modelling



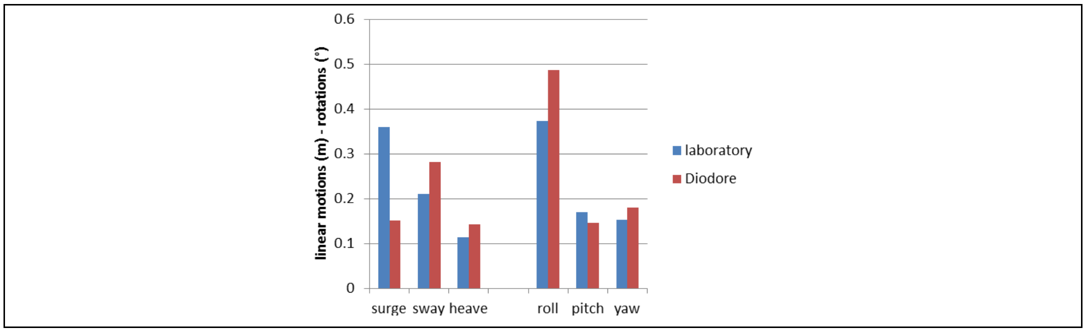


Figure 10.: Comparison of numerical model with physical model – with a vertical quay far from vessel

These results show that:

- The mooring line tensions are in good agreement for head lines and stern lines (maximum discrepancies of 15%). For spring lines, tensions assessed from physical model are up to 35% larger than tensions from numerical model

- Forces in fenders are in very good agreement as well.

- Regarding motions, except for surge and for roll, the results obtained for the two models are quite in good agreement

7. PHYSICAL MODELLING AND INFLUENCE OF HARBOUR STRUCTURES

For the four configurations studied (one configuration without structure and three different structures, as shown in above Figure 3), the tension in mooring lines as well as motions are plotted in the following figures for the quartering seas direction and for a water depth of 18m.

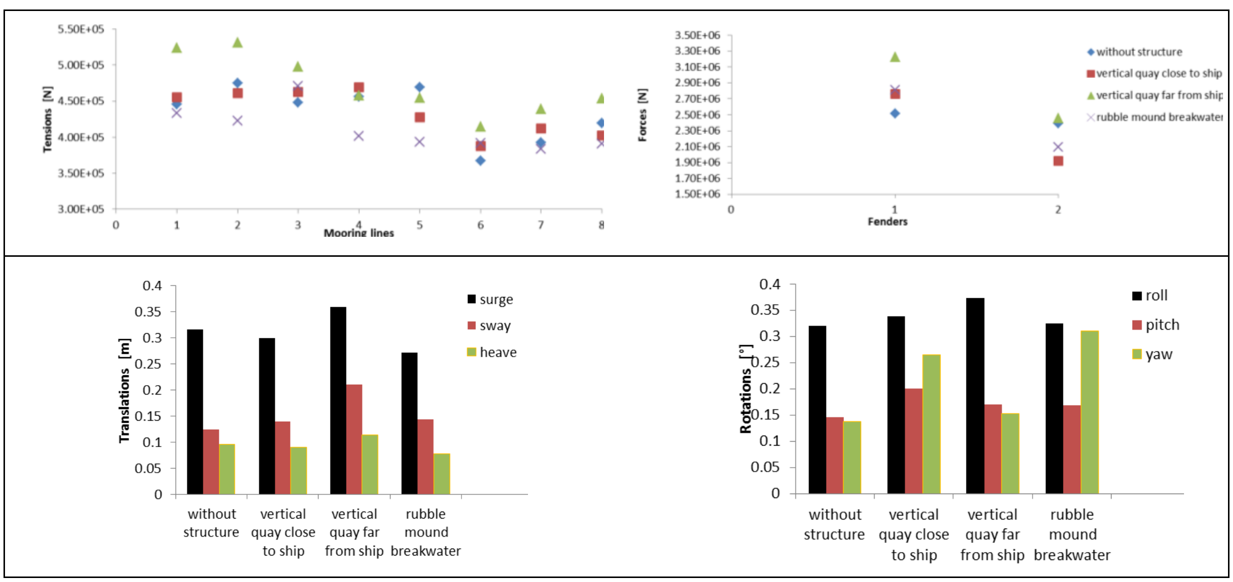


Figure 11.: Influence of harbour structures - quartering seas - Hm0 = 1m – Tp= 10s - 18m water depth

From these tests, the following findings can be drawn:

- For the four studied configurations, the structure consisting in a vertical quay far from the ship is the harbor structure which leads to the largest tensions in mooring lines and to the largest forces in fenders and as well as the largest motions of vessels. Depending on the mooring line location, the tension is up to 20% larger in presence of a vertical quay far from the vessel comparing to a configuration without structure.

- The three other studied configurations induce mooring lines tensions rather in the same range of values, even if the configuration consisting of a vertical quay close to the ship seems to induce slightly larger values.

- The structure which leads to the lowest tensions in mooring lines is the rubble mound breakwater. This result is quite surprising as this (partially) reflective structure leads to tensions slightly lower than tensions observed for a configuration without any structure. At first glance, it could have been expected, that this (partially) reflective structure increases wave disturbance in the area between vessel and rubble-mound and thus increases wave energy reaching the vessel and as a consequence increases motions of vessels as well as tensions in mooring lines.

Regarding the wave pattern in front of a reflective structure, in case of normal (i.e. frontal) attack, the significant wave height oscillates, featuring nodes and antinodes which reduce when moving away from the structure to reach an asymptotic value (typically 1.4 time the incident significant wave height for a vertical structure) for a distance from structure equal to about 1.5 time the wave length (Goda, 2010 and Klopman et al, 1999). Spacing between nodes and antinodes is 0.25 x Lp (with Lp: the wave length).

With oblique waves, there is again a system of nodes and antinodes with a spacing of 0.25 x Lp x sin (angle of attack).

In the present case:

- The angle of attack is 45°.

- The wave length (for a water depth of 18m and a period of peak of 10s) is 117m.

Hence, in the present case, the distance from which the significant wave height oscillations are damped is 124m. This distance corresponds roughly to the distance between structure and vessel Center of gravity (131m for the vertical structure and 121m for the rubble mound breakwater). Therefore, it can be considered that the vessel is out of the area where large oscillations of significant wave height can be observed.

8. ACCURACY, SCALE EFFECTS AND MODELS LIMITATIONS

In addition to the usual scale, laboratory effects and limitations inherent to physical modelling of floating structures (Hydralab, 2013; Goda, 2010; Hughes, 1993), this physical model tests campaign has highlighted some limitations and some constraints:

- Generation of small waves conditions: the waves conditions which have been tested are typical waves values which could be observed inside harbour in presence of moored vessel (i.e. in waterways protected by breakwaters). Hence the tested wave heights are quite small (Hm0 up to 1.5m). At the scale model (1/80), the corresponding wave height is small (19mm). In this context, the verification of the waves generated and reaching the vessel model is less accurate for these small waves than it would be for higher waves. This is induced by the deployed instrumentation (directional wave gauge) with which the assessment of coefficient of reflection is less accurate for small waves conditions. This is due to the accuracy of current measurement in presence of very low values of velocities, for these gauges which in most cases measure larger wave height. In addition, the maximal significant wave height modelled in our campaign (2cm) represents the limit commonly used (Wolters 2007) for the lowest waves modelling to avoid significant model effects.

- Influence of temperature: the tests campaign has been carried out during a period of several months, with different temperature conditions for the water used for the tests. Particularly, the decay tests have been performed in winter with a water temperature of 8 to 10°C, and some of the tests with the moored model have been performed during a hot summer period with sea water larger than 20°C. It is possible that this situation could have induced some distortions on results obtained in summer comparing to results obtained in winter as regard to the difference in viscosity (reduction of about 25%) which is observed when the temperature is increased from 10°C to 20°C. However, this phenomenon should need to be further studied to assess the real impact of water temperature on model behavior.

9. CONCLUSIONS, EXPERINCE FEED-BACK AND FUTURE WORKS

At completion of this first stage of in-house research project, the following findings have been provided:

For the case where a vessel is moored at berth without any port structure at proximity, above results have shown that a good agreement between numerical and physical models can be obtained. This configuration (typically a terminal in open sea, with a very simple bathymetry) can be modelled and studied by dedicated numerical tool for instance to determine operational thresholds induced by waves with relevant criteria regarding mooring line tensions.

In addition, for berth and port designers, another usual situation consists in a vessel moored at vicinity of an harbour structure which could modify the wave pattern reaching the vessel. In this configuration, impact of these reflective structures (e.g. a vertical quay) is not marginal as for instance for the mooring lines tensions which could be significantly increased. In this context, comparison between numerical and physical modelling shows that we could be quite confident in the numerical model to analyze the behavior of a vessel moored in presence of a vertical structure (typically a quay) far from the vessel.

However, results show that roll motions seem to be over-estimated in numerical modelling (compared to motions measured on physical model). The impact is marginal for mooring lines tensions and also for forces in fenders, but this could induce potentially conservative results in numerical analysis for which a strict criteria is to be fulfilled as regard to roll motion (e.g. when (un)loading operations could be governed by roll motions).

Analysis of a moored vessel in presence of other port structure as quay close to the vessel and rubble-mound breakwater by numerical modelling is quite more complex and requires an additional work we intend to perform in a next stage of our project.

In addition, comparisons by physical modelling of the different configurations of a moored vessel (without structure, with rubble mound breakwater and with vertical quay close to the vessel or far from vessel) have shown that the vertical quay is the structure which leads to the largest tensions in mooring lines as well as the largest motions.

However, the post-processing and the analysis of all performed tests need to be completed to potentially draw additional findings.

This campaign is a first step and some further developments could be envisaged. For numerical approach: to go on the modelling of vessel behavior in presence of partially reflective structure (as rubble-mound breakwater), on the basis of the performed physical model tests or additional tests to be performed. Regarding physical modelling, the following future actions are envisaged:

- To model non-linear stiffness for mooring lines and fenders, as it is recommended for an accurate modelling of hydrodynamic behavior (Sutherland et Al, 2013)

- To extend analysis to other harbor structures or others ports configuration (e.g. complex bathymetry with steep slope).

- To go on the identification and mitigation (when possible) of laboratory effects we experienced in our facility.

10. ACKNOWLEDGEMENTS

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