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HYDRODYNAMIC MODEL TESTS WITH A LARGE FLOATING HYDROCARBON STORAGE FACILITY

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ABSTRACT

The paper presents model tests with a floating hydrocarbon storage facility performed in SINTEF Ocean's basin. The system may be considered a very large floating structure with a footprint of 300m x 310m. Hydrocarbons are stored into independent tanks, which are soft moored to a modular floating frame which is kept in station by dolphins. The system is composed of 14 tanks and 21 frame barge modules, therefore 35 connected floating bodies.

The objective of the model tests was twofold. First, to verify the feasibility of the global system, namely in terms of tank and frame motions, connection loads, station keeping loads and relative wave elevations. Second, to acquire data for tuning and validation of numerical models, i.e. to investigate effects that cannot be reliably established by simulations alone.

The model tests were performed in wave, current and wind conditions corresponding to 1 year and to 100 years return periods, in addition to a set a simplified wave conditions. The paper describes the model test setup, the experimental program, the procedures for analysis of test data, it presents representative results and discusses the main observations.

INTRODUCTION

A very large floating structure (VLFS) is a concept for ocean structures characterized by large dimensions and associated complex hydrodynamic responses which go beyond the six degrees of freedom motions. Hydro-elastic effects are usually present, as well as multibody interactions in case of modular systems. Standard design analysis methods for conventional ships and offshore structures are not directly applicable.

VLFS can be classified in two types: (a) an assembly of pontoon or similar type of floaters, for operation in sheltered areas and (b) an assembly of semi-submersible hulls, designed for offshore operation. Many applications of VLFSs have been proposed, such as: airports, mobile offshore bases, storage and waste disposal facilities, offshore port facilities, floating bridges, energy production islands, food production, residential areas, etc. Probably the most studied VLFS concepts are the Mobile Offshore Base (MOB) concept, mainly for military applications with the research focused in the US [1] and the Mega-Float concept developments in Japan as a long floating runway (airport). The reader is referred to [2] and [3] for an overview of applications, research and developments on the topic of VLFS.

The present paper refers to a large multi-purpose floating facility (MPFS) for storage of hydrocarbons. With the aim of minimizing hydrostatic loads for different loading conditions, hydrocarbons are stored into independent floating tanks.

The system is designed for installation in relatively sheltered locations. It is a modular system composed of 16 independent storage tanks, which are soft moored to a frame of floating barge modules. The barges provide space for piping and equipment. The whole system is moored to the seabed with dolphins. Figure 1 shows an illustration of the concept.

Although the concept may be adapted to different costal areas, the present case study was designed for installation in Singapore coastal waters at a water depth of 18 m.

Structural design of the system presents several challenges related to the definition of design environmental loads. Hydrodynamic loads induced by waves and current are particularly difficult to calculate with state-of-the-art numerical methods. This is related to complex hydrodynamic interactions of the multi-body system, wave-current interaction effects and shallow water effects. Furthermore, since existing numerical methods need to simplify the physical effects, it might be that important non-linear responses are not identified by numerical tools and the real system includes unexpected critical responses.

Hydrodynamic model tests have been carried out with the aim of providing answers to some questions above. The objectives of the tests are: (a) to verify the feasibility of the concept for the design seastates, (b) to acquire preliminary design loads, (c) to acquire experimental data to support development and validation of numerical models.

The tests were performed in wave, current and wind conditions corresponding to 1 year and to 100 years return periods, in addition to a set a simplified wave conditions. The measured responses include: wave elevations, relative wave motions, motions of selected bodies, accelerations, loads in 4 connections between barge modules, loads on mooring lines and loads on the dolphins.

The paper presents the model tests setup, general conclusions from the model tests and it presents some motion responses for the storage tanks.

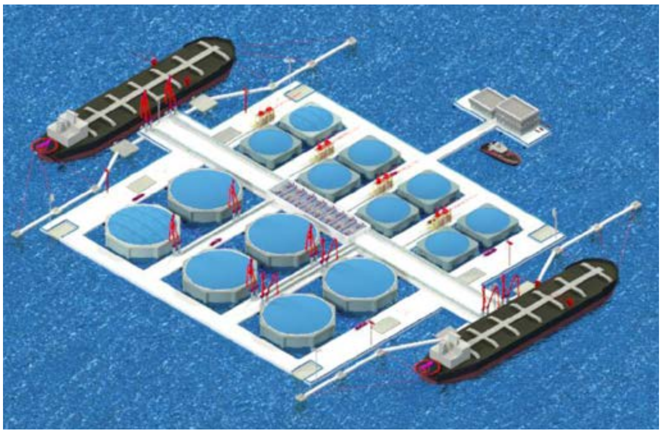


Figure 1. Conceptual design of the floating hydrocarbon storage facility (footprint of 300m x 310m).

OBJECTIVES AND TEST PROGRAM

Objectives

The model tests presented and discussed in this paper are the third phase of a wider testing program which included three phases, namely:

Phase 1: Tests with a single tank

The objective of these tests was to determine fundamental behaviour characteristics of a single tank with different filling levels and with different fendering. Phase 1 was carried out in the Hydraulics Laboratory at the National University of Singapore (NUS), [6].

Phase 2: Tests with an arrangement of two tanks and frame

The frame is free to move with vertical motions and restrained on the horizontal motions. The tanks were connected to the barges with a scaled hawsers/fender system. The objective of these tests was to investigate fundamental hydrodynamic effects in a simple set-up. The experiments were performed at SINTEF Ocean basin. [9] presents details of these tests and comparisons with numerical results (see Figure 2).

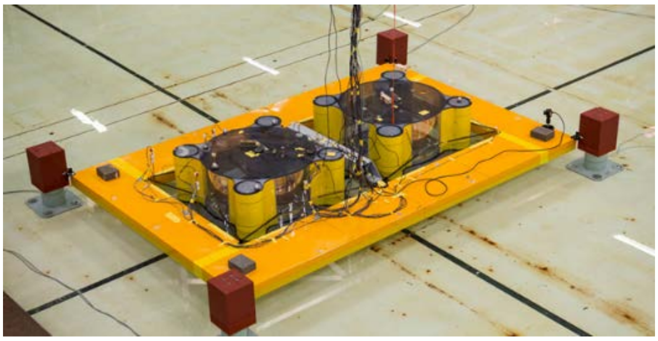


Figure 2. Setup for phase 2 tests with two tanks and frame body around.

Phase 3: Tests with the complete storage system

Refers to the model tests carried out at SINTEF Ocean basin with the complete floating storage system composed of 14 tanks and 21 frame modules.

The overall objectives of the tests were:

(a) To verify the feasibility of the global system, i.e. check and document: tank motions, connection loads (fenders and mooring lines), barge motions, station-keeping loads (mooring dolphin) and relative wave elevations.

(b) To acquire data for tuning and validation of numerical models, i.e. to investigate physical effects and hydrodynamic parameters that cannot be reliably established by simulations alone, such as: effects of internal fluid in the tanks, multi-body interaction and shielding effects, trapped waves, shallow water effects and wave-current interaction effects.

MODEL

A model of the floating storage system was built to a scale of 1:45. The scale is a compromise between global dimensions in the Ocean Basin and the quality of the waves for short period sea-states at quite shallow water depth. The horizontal dimensions outside the barges' frame is 6.9 x 6.8 meters. Figure 3 shows a plan view with the model layout and Figure 4 the actual scaled model prepared for tests.

Tanks and barges

Two sets of cylindrical tanks were manufactured:

- 8 tanks with 33 m internal radius, denoted "small tanks".
- 6 tanks with 58 m internal radius, denoted "large tanks".

Each small tank has 4 cylindrical ballast tanks called floaters fitted to it, evenly distributed on the border of the central tank. A square shaped heave plate is fitted in the bottom of the tank. Each large tank has 8 vertical and cylindrical outer floaters for reinforcement fitted to it, evenly distributed. A bottom mounted heave plate is also present. Figure 5 shows photos of one small and one large tank. Tank walls and cover were made of plexiglass and the base made of PVC. The material of the outer cylinders is PVC for the small tanks and aluminium for the large tanks. Table 1 and Table 2 present the geometric and mass properties of the tanks

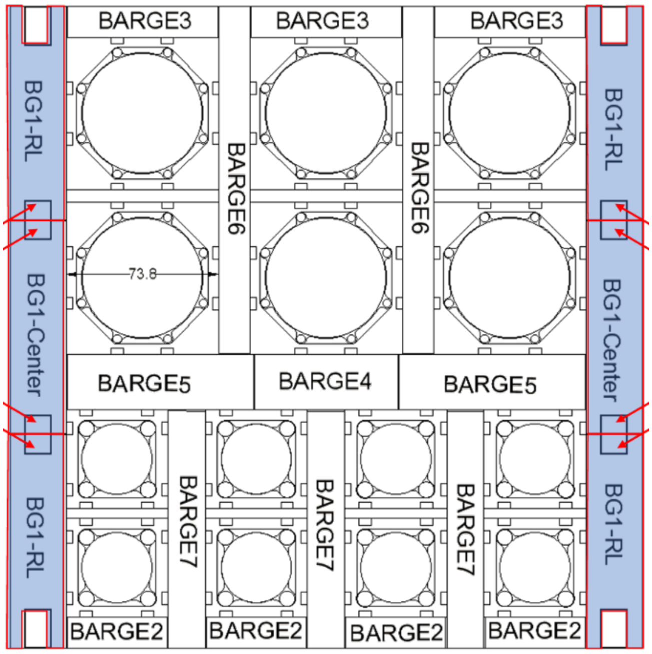


Figure 3. Plan view with the model layout

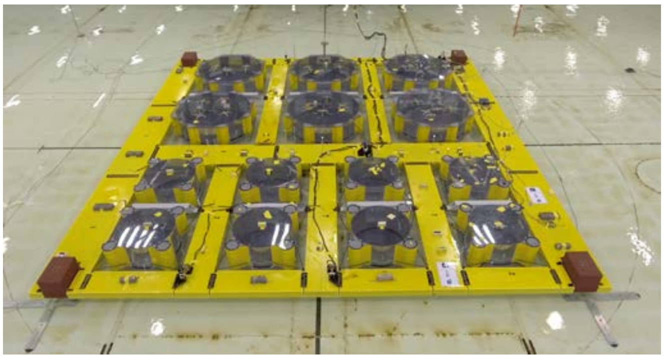


Figure 4. Scaled model of the floating storage system.

There is a total of 21 barge modules. Each module has one of 7 geometries as illustrated in Figure 3. The depth, the draft and the vertical centre of gravity with respect to the baseline is the same for all barge modules, namely: 6 m, 4 m and 3.4 m. The length varies between 48 m and 170 m and the width between 15 m and 27 m.

The barges were manufactured in steel and filled with foam. Barge modules are connected through hinged connections. Individually, these connections allow for a free relative rotation between the barges.

Table 1. Geometric properties of the tanks.

Dimension	Unit	Small tank	Large tank
Total Height	[m]	22.6	25.5
Overall Diameter	[m]	33.9	58.6
Internal Clear Diameter	[m]	33.0	57.7
Diameter of Floater	[m]	8.0	5.0
Draft (empty)	[m]	6.2	4.2
Draft (20%)	[m]	8.1	6.5
Draft (full)	[m]	15.5	15.7
Bottom Thickness	[m]	0.75	0.75

Table 2. Mass properties of the tanks.

Property	Unit	Small tank	Large tank
Total Mass (Empty)	[kg]	7.495E+06	1.300E+07
vCOG (empty)	[m]	8.17	7.74
Ixx (Empty)	[kg.m^2]	1.70E+09	5.00E+09
Iyy (Empty)	[kg.m^2]	1.70E+09	5.00E+09
Izz (Empty)	[kg.m^2]	2.00E+09	8.30E+09
Total Mass (20%)	[kg]	9.670E+06	2.00E+07
vCOG (20%)	[m]	6.83	5.77
Ixx (20%)	[kg.m^2]	1.90E+09	6.50E+09
Iyy (20%)	[kg.m^2]	1.90E+09	6.50E+09
Izz (20%)	[kg.m^2]	2.30E+09	1.10E+10
Total Mass (full)	[kg]	1.80E+07	4.70E+07
vCOG (full)	[m]	8.10	7.32
Ixx (full)	[kg.m^2]	2.60E+09	1.20E+10
Iyy (full)	[kg.m^2]	2.60E+09	1.20E+10
Izz (full)	[kg.m^2]	3.50E+09	2.20E+10

Mooring Dolphins

The prototype has 8 mooring dolphins to prevent horizontal motions of the unit, while allowing for the heave and, to some extent, pitch and roll motions. The tests used four dolphins only, positioned on the corners of the floating system (see Figure 4).

Flexibility of the mooring dolphins is qualitatively represented at the connection between a vertical pile and the dolphin box, which is established by the force transducers mounted on their interior. The dolphin piles are fixed to the Ocean Basin floor with magnets. Contact between the dolphin boxes and the barges is almost frictionless by using rollers.

Tanks' mooring system

The concept applies an innovative system to moor the tanks to the surrounding barges which consists of several compliant mooring ropes and fenders [8]. For the tests, the connection between tanks and barges was represented by springs with an equivalent horizontal stiffness set-up designed to model the restoring forces of the actual hawser system.

Eight diagonal springs were used for the small tanks, four for the large tanks. Pre-tension and anchorage points are different relative to the prototype, but as close as possible with respect to representing the correct physics in model scale. Tank anchor points on each of the four sets per tank are vertically aligned and the vertical location of each point is such that the springs remain horizontal in still water for each of the tank loading conditions.

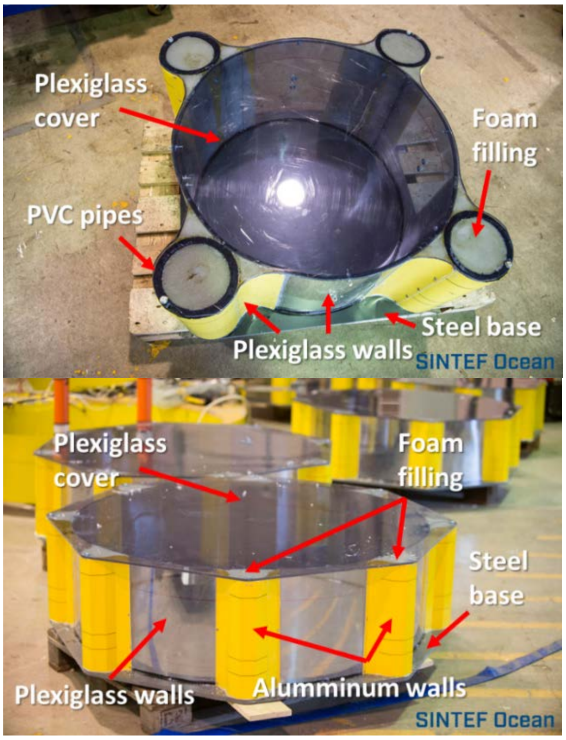


Figure 5. Small tank model (upper photo) and large tank model (lower photo).

TEST PROGRAM

The tests were performed at the Ocean Basin facility of SINTEF Ocean during May 2018. The model scale was 1:45.

Besides system identification tests, the program included:

- Two irregular JONSWAP seastates (1 year and 100 years return period).
- One broad band wave spectrum.
- Selected periodic (regular) waves.
- Current only; wind only (NPD spectrum).
- Waves.
- Waves + current.
- Waves + current + wind.
- Three wave directions.
- Three different filling levels (100%, 20% and 0).
- A number of "special" conditions, like accidental situations, and others.

Conditions with combination of waves, current and wind were always collinear.

The JONSWAP seastates correspond to the 1 year and 100 years return period for the coastal area near Singapore. More specifically, the operational and survival conditions selected are given in Table 3. The table includes also the broad band wave spectrum properties. The tests were carried out at a water depth of 18 m.

Table 3. Environmental conditions.

		1 year	100 years	BB
Waves	Hs (m)	1.0	1.8	2.0
	Tp (s)	5.0	7.0	4-20
Current	Uc (m/s)	1.56	1.9	0
Wind	Uw (m/s)	15.9	24.0	0

The system was tested with several combinations of individual tanks' filling ratios: empty, partial and full. Initial investigations with a single tank revealed that a filling level of 20% resulted in the largest motions of the fluid inside [8]. Therefore, this volume was used to represent partially filled tanks. Note that water was used rather than oil to fill the tanks. So, there are slight differences in the final level compared to prototype.

Measurements

Coordinate systems

Two right handed coordinate systems are used in the model tests. The global system is fixed to the Ocean basin, with the x-axis pointing to the wave maker and the z-axis pointing downwards. The origin is at the waterline at a location denoted as Blink. The Bilnk is approximately in the centre of the Ocean Basin and it represents the point where waves and wind are calibrated. The model is centred at this origin and this is the reference point used for environmental calibration. Body motions are represented in the global coordinate system.

The local coordinate system is parallel to the global one for 0 wave heading, however it rotates with the model for different wave headings. Figure 6 resents the coordinate systems.

Note that wave, current and wind are always travel along the negative x-axis of the global coordinate system and towards. Therefore, any heading angle between wave, current and wind and the model is set by rotating the model to an angle as shown in Figure 6.

Environment

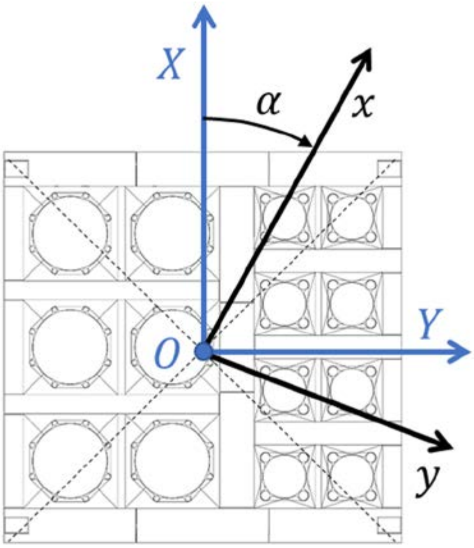
The waves were measured by resistance-type wave probes at the centre position of the model during wave calibration (undisturbed wave) and at two additional positions in the ocean basin for reference.

Both the wind and the current were measured during the calibration phase, prior to the tests with the model in the Ocean Basin. One additional electro-magnetic current sensor was used during calibration and during tests for reference.

Motions

Motions of selected bodies were tracked using an optical motion tracking system: OQUS. The system consists of a set of cameras and passive targets placed on the bodies to track, in addition to the specific software and auxiliary hardware. The system measured 6 degrees of freedom (DOF) motions for one small tank, one large tank and three barge modules (Figure 7).

Accelerations were measured on the same two tanks, in order to verify measurements of motions and also to identify possible impacts between the tanks and the barges, or the Ocean Basin bottom.



α : wave heading
$OXYZ$: global system
$Oxyz$: local system
O is located at the horizontal centre of the model, at the waterline

Figure 6. Coordinate systems.

Forces

The total force acting on the complete system is calculated from the horizontal loads measured at each mooring dolphin by force transducers. Forces are also measured with strain gauges installed on the hawsers connecting one large tank and one small tank to the surrounding barges. These are the same tanks as tracked by the OQUS system.

The loads at the connections between barge modules are given as forces in three directions and moments in two directions. Measurements were taken at five locations.

Local fluid flow

The following measurements were taken by resistance type wave probes:

- Free surface elevation inside two tanks, one large and one small to identify the internal fluid dynamics: 6 wave sensors.
- Relative motions outside of the barges on the side receiving the incoming waves: 2 wave sensors. The aim was to assess free board exceedances.
- Free surface elevation in gaps between tanks and barges to identify possible trapped waves: 4 wave sensors.

RESULTS

This Section presents and discusses some motion results for the storage tanks. The aim is not to present a comprehensive analysis, or state final conclusions on the feasibility of the concept, but rather point out some of the physical effects specific of the system and possible implications on numerical modelling. Still the discussion includes a general assessment on the measured responses as compared to design requirements.

Figure 8 presents the target and calibrated broad band wave spectrum and 100 years JONSWAP wave spectrum. The overall energy and the peak period are very close to target, while the measured waves show somewhat more energy at the high frequency tail.

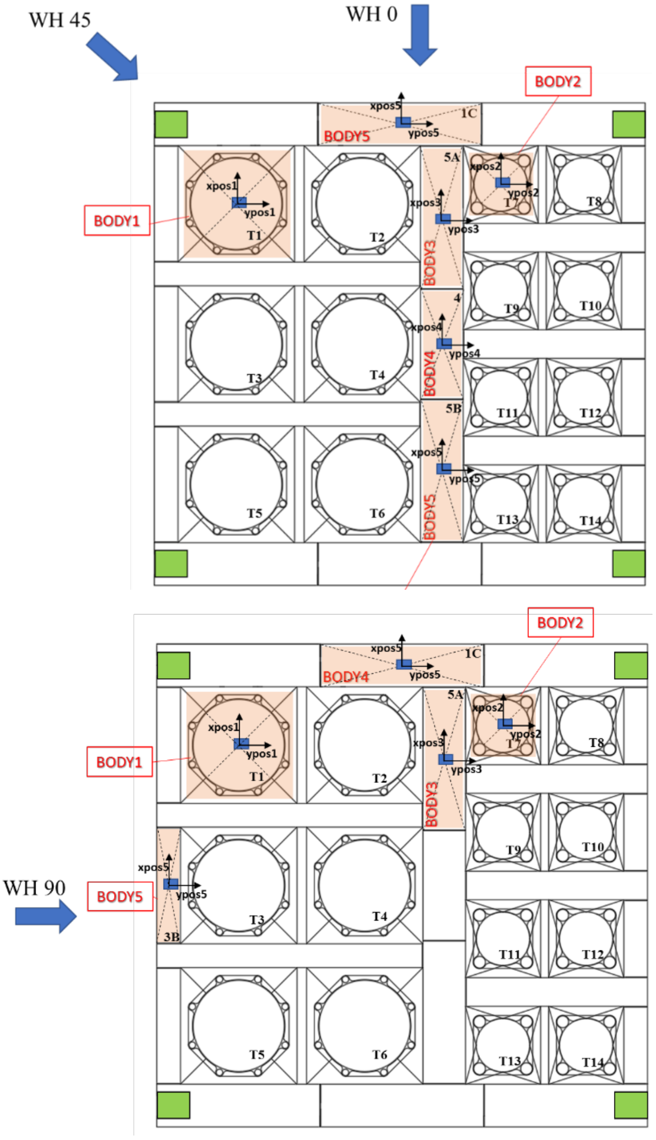


Figure 7. Bodies with tracked motion named BODY1 to BODY5. Upper sketch for 0 and 45 degrees wave headings and lower sketch for 90 degrees wave heading.

The six degrees of freedom motion RAOs estimated from the broad band spectrum test are presented in Figure 9. In this case the wave heading is 90 degrees and all tanks are empty. Motions of the large tank tend to be larger than those of the small tank, which is related to the latter being to leeward with respect to the incoming waves (see Figure 7).

Although the long-crested wave direction is along the sway direction, one observes significant motions in all degrees of freedom, including surge and pitch. This is due to multibody hydrodynamic interactions. Surge and sway for the large tank show a resonance amplification close to the single body natural frequencies, namely 0.065 and 0.06 Hz respectively. Single body natural frequency stands for estimation of the natural frequency neglecting multibody interactions. The resonance peaks are well above the design seastates frequency range.

Heave RAOs present two peaks, which are related to multibody interactions. The resonance peaks of roll and pitch are close to the single body natural frequencies.

Figure 10 compares the large tank surge, heave and pitch RAOs for the 100 years seastate with and without current and wind. All tanks are empty and the wave heading is 0 degrees. Figure 11 presents similar results for the small tank. The RAOs are plotted as function of the encounter frequency. There is a significant increase of the motions when the current and wind is included. This is due to wave-current interaction effects on the wave frequency responses (wind does not excite tanks' motions at the wave frequency range). The strong wave-current effects pose a challenge for hydrodynamic modelling. Apparently, the few existing wave-current potential flow codes have not been tested for complex multi-body system. The wave-current numerical solution is already challenging for single bodies. Limited water depth effects (18 m water depth) increase the complexity even further.

Figure 12 shows comparisons of the large tank sway, heave and roll motion RAOs for the system with all tanks empty and all tanks fully loaded. The results correspond to the 100 years seastate and the wave heading is 90 degrees. Increasing the tank loading from 0 to 100% increases the sway motions, but it significantly reduces the heave and pitch motions. The latter is beneficial since clearance between the tank bottom and sea bed is quite small (2.3 m).

Finally, Figure 13 presents simple statistics for the motions of the small tank and the large tank. These are results from the 100 years seastate with and without current. In this case all tanks are empty, and the wave heading is 0 degrees. The corresponding numerical values are given in Table 4. Again, one observes an increase of the motion responses due to wave-current interaction effects. It is also possible to conclude that the extreme motions for the design seastate are smaller than the design requirements.

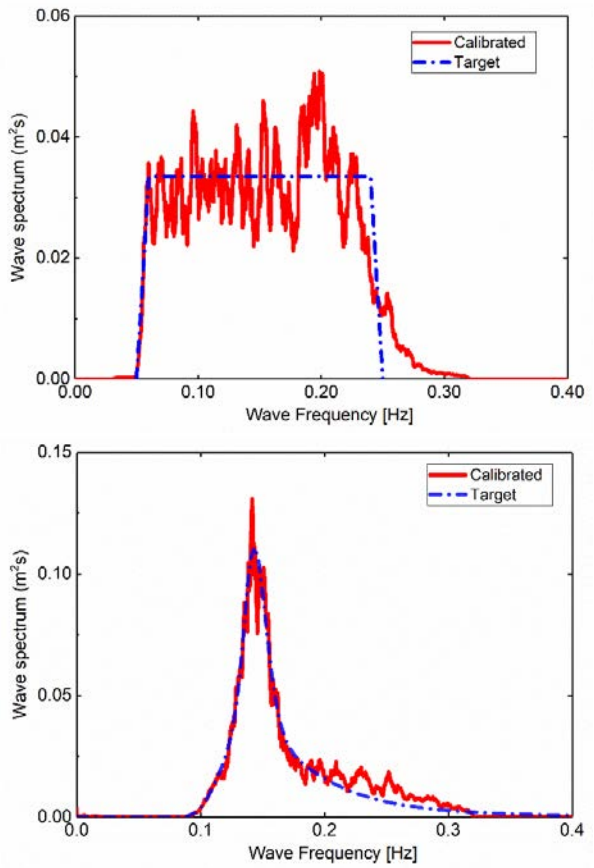


Figure 7. Target and calibrated wave spectra. Broad band spectra (Hs = 2.0 m, Tp = 4-20 s) and JONSWAP spectrum (Hs = 1.8 m, Tp = 7 s).

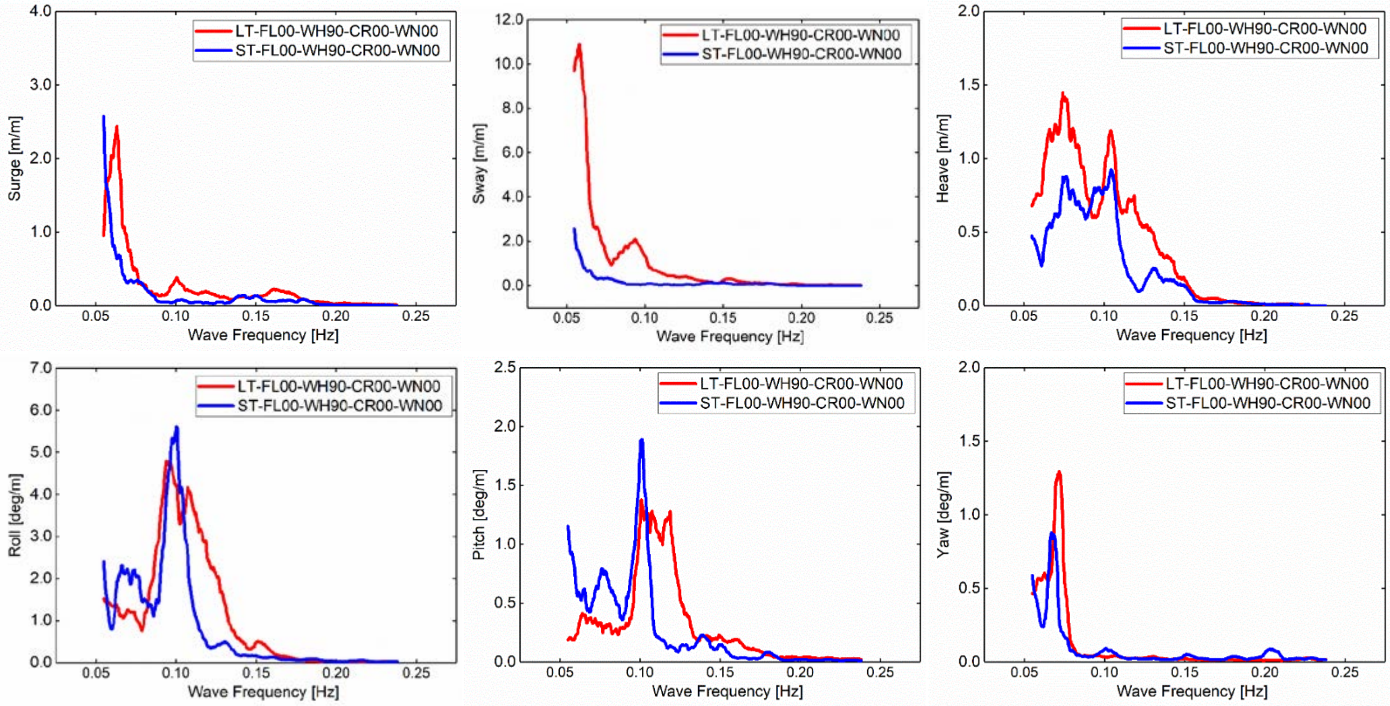


Figure 8. Motion RAOs for the large tank (LT) and small tank (ST) estimated from the broad band wave spectrum (Hs = 2.0 m, Tp = 4-20 s, Uc = 0, Uw = 0). All tanks are empty.

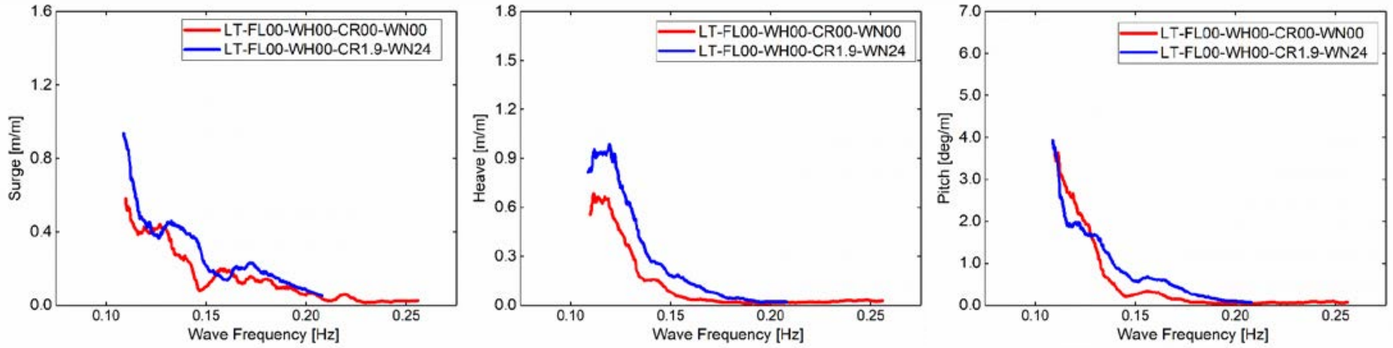


Figure 9. Surge, heave and pitch RAOs estimated from the 100 years seastate (Hs=1.8m, Tp=7s), 0 deg. heading. Empty large tank (LT). Results with waves only and results with waves, current and wind (Uc =1.9m/s, Uw=24 m/s).

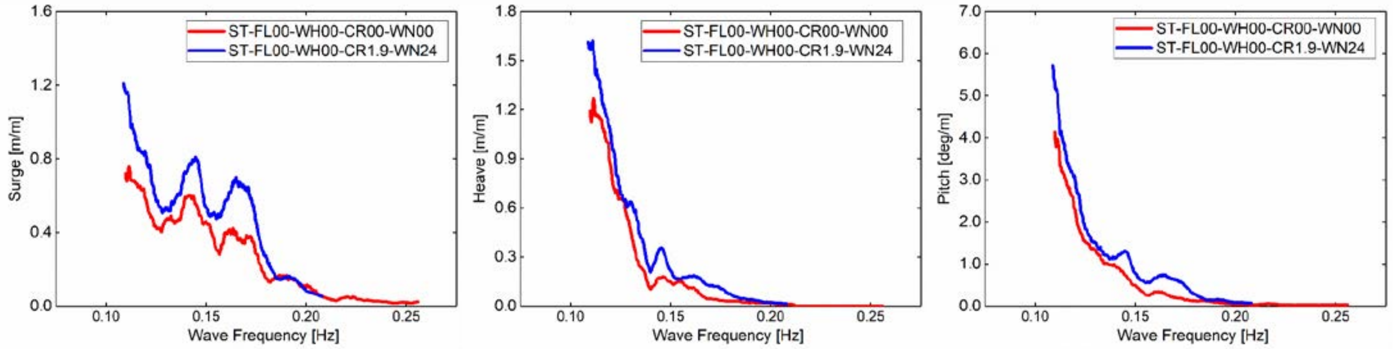


Figure 10. Surge, heave and pitch RAOs estimated from the 100 years seastate (Hs=1.8m, Tp=7s), 0 deg. heading. Empty small tank (ST). Results with waves only and results with waves, current and wind (Uc =1.9m/s, Uw=24 m/s).

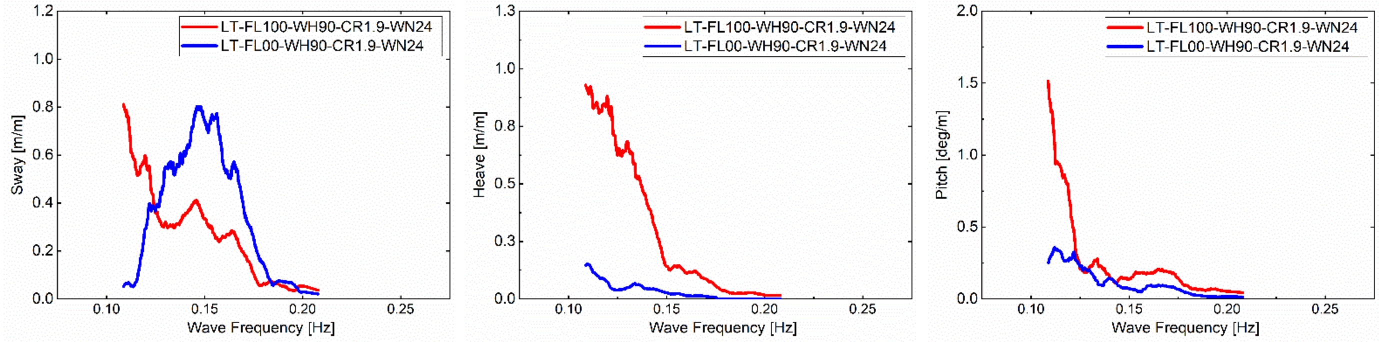


Figure 11. Sway, heave and roll RAOs for the large tank (LT) estimated from the 100 years seastate and 90 degrees heading (Hs = 1.8 m, Tp = 7 s, Uc = 1.9 m/s, Uw = 24 m/s). Comparison between empty and fully loaded tanks.

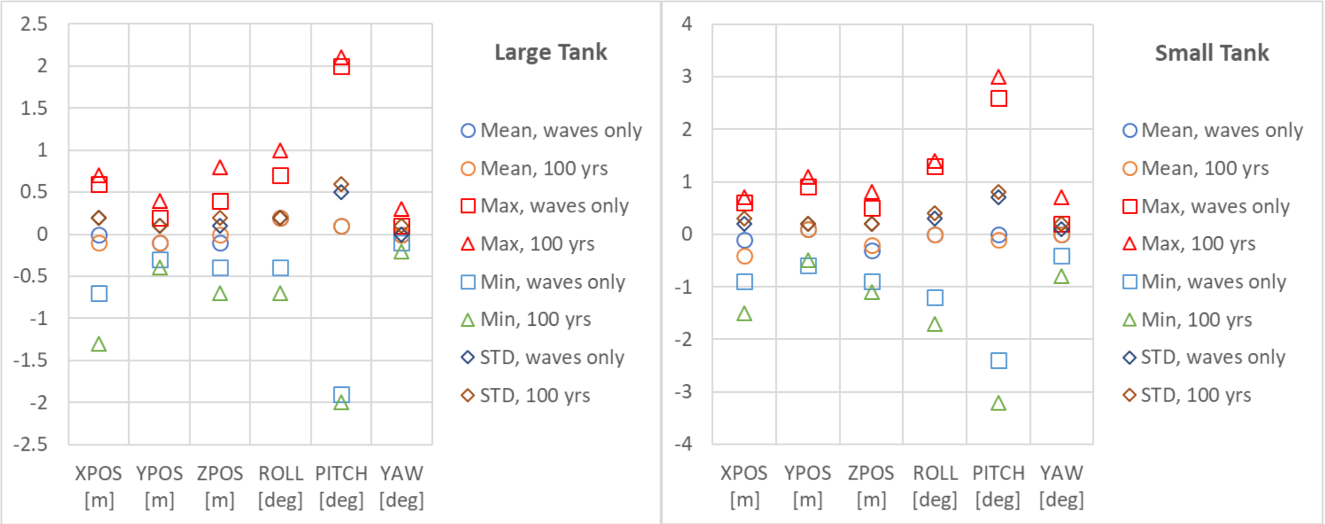


Figure 12. Statistics of tanks motion responses for the 100 years seastate. All tanks empty and 0 degrees wave heading.

Table 4. Statistics of tanks motion responses for the 100 years seastate. All tanks empty and 0 degrees wave heading.

Motions of tanks		Large tank				Small tank			
Test description	Motion	Mean	Min	Max	STD	Mean	Min	Max	STD
TEST: 6070	XPOS [m]	0.04	-0.69	0.56	0.15	-0.06	-0.95	0.64	0.20
FILL: 0% ALL	YPOS [m]	-0.06	-0.30	0.21	0.07	0.06	-0.57	0.93	0.16
DIR: 0 deg	ZPOS [m]	-0.05	-0.40	0.35	0.11	-0.26	-0.92	0.49	0.18
CUR, HS, TP: 0m/s, 1.8m, 7s	ROLL [deg]	0.17	-0.44	0.71	0.15	-0.02	-1.24	1.30	0.29
WIND: 0 m/s	PITCH [deg]	0.09	-1.95	2.00	0.52	0.01	-2.45	2.56	0.69
	YAW [deg]	0.02	-0.10	0.14	0.03	-0.03	-0.37	0.24	0.08
TEST: 6210	XPOS [m]	-0.13	-1.31	0.71	0.22	-0.39	-1.52	0.70	0.28
FILL: 0% ALL	YPOS [m]	-0.06	-0.44	0.40	0.11	0.09	-0.47	1.14	0.17
DIR: 0 deg	ZPOS [m]	-0.01	-0.67	0.78	0.19	-0.22	-1.06	0.80	0.23
CUR, HS, TP: 1.9m/s, 1.8m, 7s	ROLL [deg]	0.18	-0.74	0.96	0.20	-0.04	-1.69	1.41	0.36
WIND: 24 m/s	PITCH [deg]	0.15	-2.02	2.08	0.56	-0.09	-3.20	2.97	0.80
	YAW [deg]	0.02	-0.20	0.26	0.06	-0.04	-0.77	0.66	0.19

CONCLUSIONS

Hydrodynamic model tests were performed at SINTEF's ocean basin with a very large floating structure for storage of hydrocarbons. The modular system is composed by an assemble of 14 tanks soft moored to a floating frame which is moored with dolphins. The paper describes the model tests setup, the experimental program and it presents motion results for the storage tanks.

As a general conclusion, the motions of the storage tanks are small and below the design requirements. The mooring system performs adequately and not touching of the tanks and barges occurred. Multibody hydrodynamic interactions are important, as well as wave-current interaction effects on the tanks wave frequency motions. Wave-current interactions increase the motion amplitudes within the wave frequency range of interest. Such effects cannot be neglected by a numerical model representing the system hydrodynamics. Regarding the fluid inside the tanks, it shows some dynamics, but no violent sloshing.

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