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EXPERIMENTAL STUDY OF HYDRODYNAMIC RESPONSES OF A SINGLE FLOATING STORAGE TANK WITH INTERNAL FLUID

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ABSTRACT

When floating structure with internal fluid compartment is close to other structures, the multibody interaction problem needs to be addressed in addition to the internal fluid influence. Furthermore, shallow water effects become important, especially when the gap between the floating structure and the sea floor is small. These issues are encountered when designing a novel floating oil storage facilities in nearshore area. To investigate these issues, floating models under 1:50 scale are built to perform model tests.

The test set-up uses a set of flexible constraints working as fenders placed on frames to restrain the motions of the models in the horizontal plane. Various tests in waves are carried out to measure motion responses of single model in waves with different filling levels and stiffness of “fenders”. The reaction forces on the “fenders” are also measured. Several regular wave conditions are selected to perform tests on double model system to investigate multibody interactions under the influence of internal fluid and effects of waves between the tanks. The drag forces for both single model and double models are measured by performing model tests under constant current from different directions, to check the shielding effects. The tests are performed in shallow-water wave basin, and the constant currents tests are performed by towing the models in a flume tank. Both facilities are located at National University of Singapore (NUS).

This paper presents the detailed setting of the model tests. The single model’s RAOs with 20% filling level of internal fluid are given to demonstrate the influence of internal fluid on the motions. The performances of a single tank, including six DOF motions are shown. The results will be used for validation of numerical analysis results in the near future.

KEY WORDS

Floating storage tank, hydrodynamic, model test, sloshing

NOMENCLATURE

F	Horizontal force on the fenders
F’	Reaction force on simple support
$\mathbf{L_1}$	Length of the flexible beam- hinged part
$\mathbf{L_2}$	Length of the flexible beam- free part
E	Young’s Modulus
I	Sectional moment of inertia
ω	Circular wave frequency
H	Wave height
K	Fender stiffness in model scale
$\mathbf{K_p}$	Fender stiffness in prototype scale
β	Wave heading

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[1]. The author works in MARINTEK which has merged into SINTEF Ocean since 01.Jan, 2017.

INTRODUCTION

A novel floating oil storage terminal (FOST) is being designed for use in coastal areas. Coastal areas are convenient for access to shipping. However, there are many competing demands for limited coastline, and these may impose economic and environmental challenges for hosting such facilities, particularly when major cities are located nearby busy shipping ports.

One feasible option is to make use of the nearshore waters for the storage terminal. One of the advantages compared to an onshore storage tank is that for a floating storage tank, the hydrostatic pressure loading between the interior stored product can be largely balanced by the external pressure of the seawater. Thus, the tank walls can be made much lighter and thinner than would normally be the case. The metocean conditions at such locations are relatively sheltered. As a result, the basic design of the system is much more dependent on hydrostatics than a typical offshore storage tanker such as a tanker or Floating Storage and Offloading vessel (FSO).

Design Basis requirements include a long design life of over 50 years, the need for high uptime. The interior of the tanks must remain open to allow for thorough mixing of additives into the stored hydrocarbon and each tank must be able to handle any filling level from empty to 100% full independently. The design should accommodate a number of different products from heavy crude to lighter clean petroleum products. There should be a minimum of maintenance and high uptime. The design should be adaptable to cater for varying capacities from about 5000m^3, up to as large as possible. Although this initial configuration is targeted for protected and nearshore applications, the design must be capable to be extended to additional applications including use in more open sea conditions and for different purposes other than pure hydrocarbon storage. Other uses for extended large floating structures include floating bridges [1].

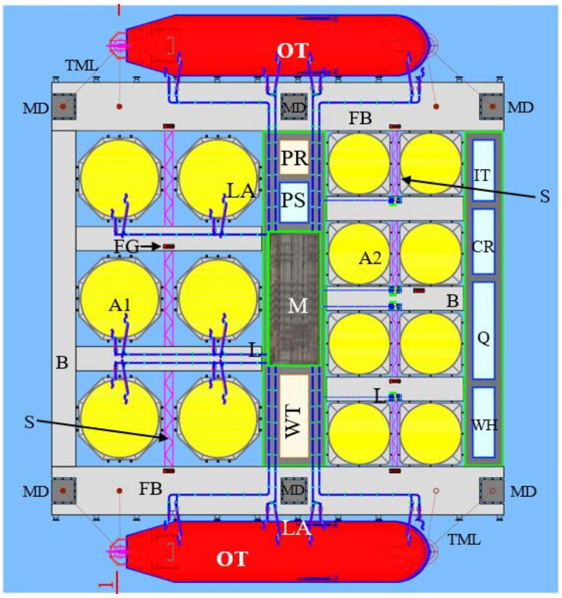

Figure 1: Configuration of floating oil storage facilities

A concept of combination of multiple and modular floating storage tanks is proposed to meet the requirements as above. The floating storage tanks will be constraint by fender system, while the fender system is supported by floating barges. The modular floating tank basis can be extended to a large facility which will be useful to store large amount of oil products in nearshore and offshore area. Figure 1 shows the overall configuration of the FOST system.

OBJECTIVES AND FACILITIES DESCRIPTION

Many important hydrodynamic effects need to be investigated to assure a safe and cost-effective design of the floating oil storage system. These include the effects of sloshing of the interior fluid at various filling levels, shallow water effects, wave-current interactions, shielding, multibody interactions including possible resonance in the gaps between tanks, and the effects of the restraining fenders.

While some of these effects are included when numerical methods as presented in this conference [2, 3], software based on linear potential flow has some limitations and should be used with caution. Non-linear mechanical effects and viscous drag can be dealt with using time-domain simulations, after proper calibrations. In addition, sloshing is known to be a highly nonlinear. Model test are an effective way to investigate these nonlinear phenomena. Comprehensive model tests were performed to investigate these effects separately or just combining two of these effects, for example experiments to investigate gap resonance [4-6] and plenty of model tests to investigate sloshing [7-8]. However, when it comes to the combination of all these effects, a model test is still highly necessary and important.

A final test of the complete system test is planned to be carried out in Marintek, Norway. However, to guide the initial design, some preliminary tests are needed. These tests are being carried out in the Hydraulics laboratory at NUS. The objectives of the preliminary tests are as follows:

- Understand behavior of simplified configurations, prior to a complete test at Marintek
- Uncover any unexpected behavior to minimize risk of surprises
- Coupling effect (sway/roll)
- Fender stiffness
- Wave and current interactions
- Multi-body interactions
- Sloshing natural periods (but not the whole picture, due to scaling effects)
- Calibrate preliminary design values

The Coastal basin is shown in Figure 2. The following is a description of the test facilities:

- Basin dimensions: 24m x 10m x 0.9m
- 13 piston-type paddles
- Regular and irregular waves
- Long and short-crested waves

- Passive absorbing beach (made of gravel) at the end opposite the wave paddles
- Maximum wave height: 0.36m
- Wave period 0.5 secs < T < 3.0 secs
- Towing carriage speed = 4mm/s - 20mm/s
- Steady current flow at 90° to the waves
- Max water depth 0.7m (0.4m) *
- Max wave record length 700s

In this paper, we only focus on the single tank test with the designed fender system, and with empty tank and 20% tank filling level conditions. More tank filling level conditions and multi-tank system test will be the future work.

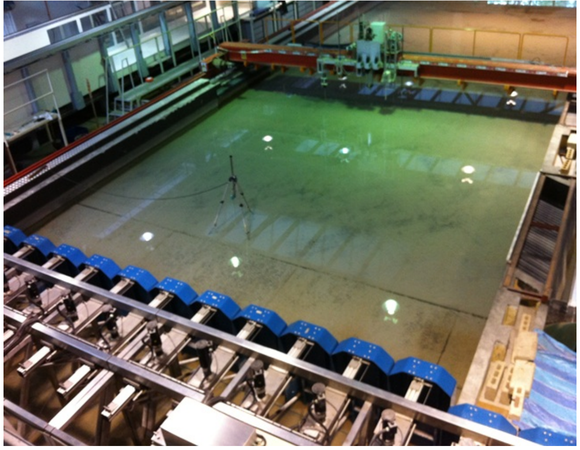

Figure 2: NUS Hydraulics Laboratory Coastal Basin.

MODEL TEST MEASUREMENTS AND SCALE FACTOR

The quantities which are being measured in the tests and the devices for measurement are shown as follow.

- Wave height (capacitance-type probes)
- 6-dof motions (optical tracking)
- Fender reaction forces

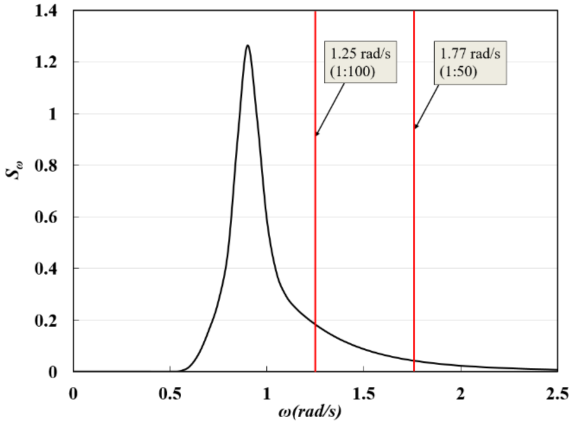

Figure 3: 100-year return period wave spectrum, with cut-off frequencies corresponding to two different possible scale factors.

The 100-year return period metocean conditions in this mild coastal environment are Hs=2m, Tp=7.0s, Gamma=3.3 (JONSWAP spectrum). The model scale is limited by the truncation of short waves to be modeled. The available wave period range in the basin is 0.5s to 3.0s. Figure 3 shows the wave power spectral density with the corresponding high frequency cut-offs at two possible scales. Using a larger scale allows higher-frequency waves to be modelled within the limits of the basin's wave generation system. A scale factor of approximately 1:50 the truncation limit is considered acceptable and is therefore adopted for these tests. Except for specification, results and figures are shown in full scale.

FOST CONCEPT AND MODEL DESCRIPTION

Figure 4 shows the configuration of one of the tanks. Each tank consists of a central storage tank and four external buoyancy tanks. The central storage tank covered with a detachable dome roof is suitable for mixing additives into the hydrocarbons. As shown schematically in Figure 5, the hydrostatic pressure is nearly balanced across central tank wall and floor, regardless of the filling level. This allows for a relatively lightweight structure.

The external compartments that are called floaters provide additional buoyancy and stability to the whole tank. The larger hydrostatic differential pressure is more easily accommodated on these smaller diameter compartments. The reaction force from fender system will act on these floaters rather than the central tank, which will be helpful to decrease the risk on central compartment. The overall construction is well adapted to efficient and cost-effective slip-form construction.

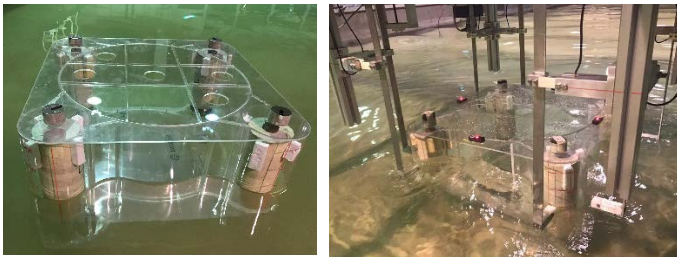

Figure 4: Configurations of one tank. The central storage compartment is covered by flat roof and the four external compartments work together to provide buoyancy and stability. Right hand figure shows the model in the waves retrained by fender systems

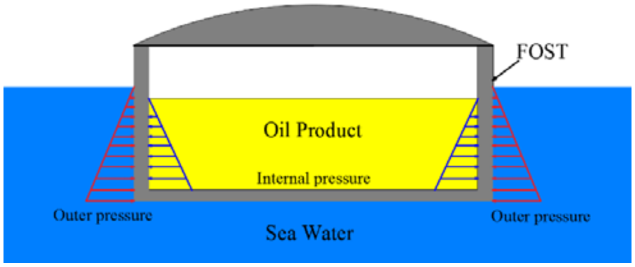

Figure 5: Schematic of the hydrostatic pressure for the floating tank in (a) empty and (b) filled load conditions.

Due to the requirement of fabrication, the model scale was finally selected to be 48.7. The principle dimensions of single model are shown in Table 1.

Table 1: principle dimensions of single model (in model scale)

Overall Diameter	530.0	mm
Inner Diameter	512.0	mm
Wall thickness	9.0	mm
Floater Overall diameter	150.0	mm
Floater thickness	5.0	mm
Wall height	261.0	mm
Bottom thickness	15.0	mm
Roof thickness	4.0	mm
Roof height (dome roof)	66.0	mm
Free board (full load)	40.0	mm
Weight (empty load)	33.5	kg
Weight (20% filling level)	39.1	kg
Weight (80% filling level)	61.6	kg
Weight (full load)	69.1	kg

To observe and record sloshing phenomenon easy, the model was made of transparent acrylic. Each part of the model is detachable and then assembled with screws and silicon to make the connection strong and watertight. The internal dimensions of the model tank have the scaled size as well so that the internal free surface area can be similar to the prototype. In case of green water occurrence and sloshing impact, both flat roof and dome roof are adopted to cover the center tank. They will also support the wave probes to measure sloshing induced varying internal free surface. In addition, two kinds of bottom are fabricated, one is square with round corner, and another is round by cutting off the edge along outer contour of the vertical wall, as shown in Figure 4. The purpose of setting two bottoms is to investigate the influence of bottom shape on motion of the tank. Transitions among all mentioned parts are polished to decrease their disturbance on the fluid fields. To decrease the friction, Teflon skin is covered on the fender contact areas of floaters' outer wall.

MODEL TEST SET-UP

Wave tests and current tests are being performed separately. Wave tests are being performed in the wave basin while current loads will be measured by towing the model in a flume. The setup for single tank in the wave basin is shown in Figure 6. The details on configuration of the single tank and the future double tanks are shown in Figure 7 and Figure 8 respectively. The models are supported by a stiff frame built with extruded aluminum profiles. The frame is mounted on the towing carriage and it can be extended for double tank model tests with different gap width easily. The installed frame is shown in Figure 9. In addition, the fender system is mounted on the frame to mimic fender stiffness. More details about fender system is introduced in the next chapter.

Bending load cells are used to measure horizontal hydrodynamic forces. Four optical tracking cameras are fixed on the wall of the wave basin to capture six DOF motions of the tank. Wave probes are fixed at up-wave side and nearby the tank to monitor quality of the generated waves. To perform model tests in oblique wave, the only work should be done is to rotate the frame and adjust the intersection angle to 67.5° and 45° referred to the carriage.

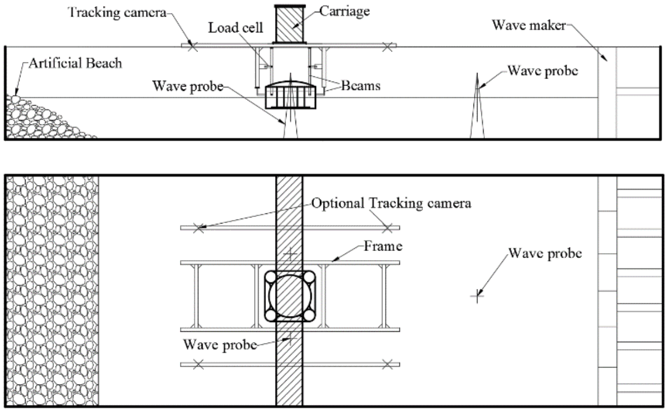

Figure 6: Schematic of the setup for the floating tank model test in the wave basin.

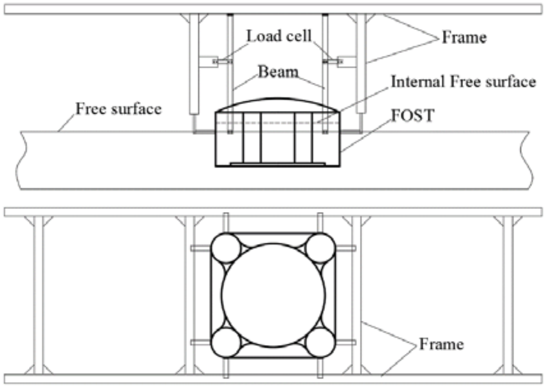

Figure 7: Configuration of frame and fender system for single tank model tests.

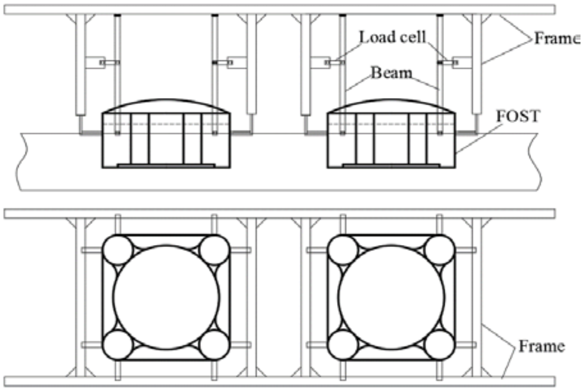

Figure 8: Configuration of frame and fender system for double tank model tests.

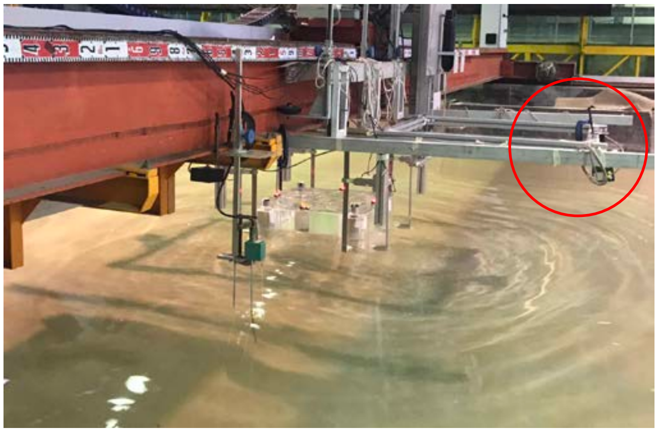

Figure 9: Aluminum frame attached to carriage on which optical motion tracking cameras (in red circle) were also mounted.

MODEL TEST MATRIX

In this experiment, single tank model tests will focus on response amplitude operators (RAOs). According to the content of model tests, the wave test matrix for single tank is shown in Table 2. System identification tests are being performed first to understand natural periods and damping of single tank. Regular wave tests will be performed. Random wave tests are critical for the safety of the tank, so 1-year, 100-year storm conditions are investigated to provide reliable design guidance for prototype design. Not all wave conditions are tested for all headings and all filling levels. In total about 100 wave conditions are going to be tested for the single tank tests. However, in this paper, only part of the tests are covered.

Table 2: Test matrix plan for single tank model test in the wave basin of hydraulic lab, NUS. This paper only focus on part of it.

Test content	ω (rad/s)	H (m)	β (deg)	Filling Level	D (m)	K_p (kN/m)	Bottom shapes	Objectives
System identification (static offset, inclining tests, decay test)	N/A	N/A	N/A	Empty, 20%, 80%, 100%, Solid mass (=20% filling level)	18.0	703.4/side, 1667.4/side, 3256.6/side,	2 bottom shapes	Stability, natural periods, damping
White noise	N/A	1.0	0, 22.5, 45					RAOs
Regular wave	0.2~1.6	1.0						Check RAOs from White noise
Random wave	N/A	1.0					Selected bottom shape	1-year wave conditions
		1.8						100-year wave conditions
		Survival condition						Extreme wave conditions

Solid ballast is used to adjust the draft, center of gravity (COG) and moment of inertia in empty tank, and water is used to simulate varying levels of cargo to change filling volume and draft. In 20% filling level loading conditions, to investigate the influence of sloshing, solid mass of the same weight will be used later to compare with conditions when there exists internal fluid, but it is not covered by this paper.

FENDER SYSTEM DESCRIPTION

Details about the effects of the fender system are presented in [3]. Fenders are set to restrain the motions of tanks in prototype design. To mimic the stiffness of fenders in the model test, a self-made flexible beam system was designed to work as fenders. Configuration of the “fender” is shown as Figure 10. Load cells are fixed onto the self-made clamps and the clamps are fixed onto the aluminum frame. Hydrodynamic force from the model will be transferred to the beam through horizontal bars, and the beams will react on floater of the model. The beams are simple-supported by bending load cells with cylinders, while the end of the beams are connected to the frame by hinges. To decrease friction caused by hinge connection and the simple support, lubricating oil is used, and Teflon material is used on both side of the interface to decrease friction forces. Then, the measured results from load cells will accurately reflect the hydrodynamic force act on the fenders. Overall, eight sets of fenders are used, with two sets of “fenders” acting on each side of the model.

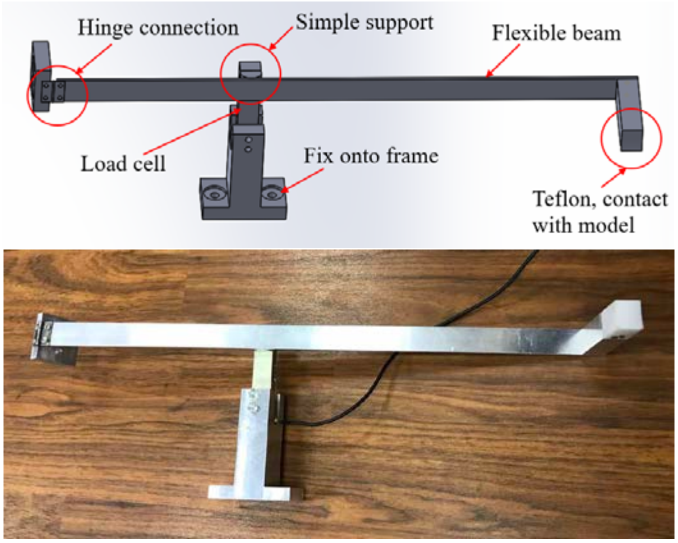

Figure 10: Configurations of the fenders (one set)

The stiffness and corresponding forces on load cell can be calculated by following formulas based on simple beam theory. Figure 11 shows its schematic diagram and notations in the formulas. By adjusting the thickness of the beams, different stiffness can be set.

$$k = \frac{3\mathrm{EI}}{(L_1 \cdot L_2{}^2 + L_2{}^3)}$$

$$F' = F \cdot \frac{L_1 + L_2}{L_1}$$

Application of simple beam theory implies the assumption of small deformation at the beam end. To make sure the results reliable, during model test, the relationship of deformation and force will be calibrated at times.

In this experiment, width and length of the flexible beams are 25mm and 557mm respectively. Three different thicknesses are chosen to simulate different stiffness in order to investigate influence of stiffness on the motion of the tank and help to find the most suitable fenders in prototype. The thicknesses and corresponding stiffness of these beams are shown in Table 3. The material of the beams is aluminum 6061 that has good mechanical properties. Its yield stress is 241Mpa, and its Young's modulus is 6.69×10^{10} Pa, which are compatible to the model tests according to largest force predicted by the numerical simulations.

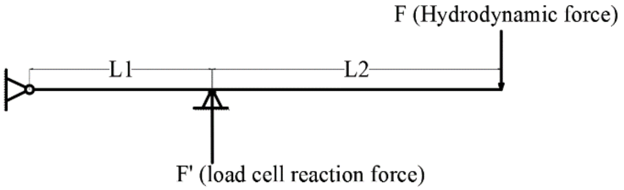

Figure 11: Schematic diagram of fender force calculation, based on simple beam theory.

Table 3: Stiffness of selected beams (with Aluminum 6061)

Thickness (mm)	K (N/m) (single)	K_2 (N/m) (per side)	K_p (kN/m) (prototype)
3.0	148.1	296.1	703.4
4.0	350.9	701.9	1667.4
5.0	685.4	1370.8	3256.6

DECAY TEST RESULTS

In the first stage of model testing, decay tests were carried out to identify the natural period and damping of the 6 degree D.O.F. For low damping ratio, typically $\xi<0.2$, the logarithmic decrement Λ and the damping ratio ξ have the relationship as follows:

$$\Lambda = \ln\left(\frac{x_i}{x_{i+n}}\right)/n \qquad \Lambda = \xi\omega_0 T_d = 2\pi\frac{\xi}{\sqrt{1-\xi^2}} \simeq 2\pi\xi \qquad (1)$$

in which, x_i is the i-th cycle amplitude, T_d is damped oscillation period, which is measured from decay time series. The damping listed here is the equivalent damping calculated from oscillations without transient effect.

Table 4: Identified natural period and damping ratio from decay test for the empty tank

D.O.F	Identified Natural Period [s]	Damping Ratio
Surge	16.71	7.00%
Heave	9.32	12.30%
Roll	11.24	5.03%
Pitch	11.24	5.41%

Several decay tests were performed for different D.O.F. The identified natural periods and damping ratios for the surge, heave, roll and pitch are shown in Table 4. It is noted that the heave has the damping ratio around 12.03% which is quite large. This may be due to the bottom heave plate applied in the test, and the bottom heave plate can generate strong vortex. The roll decay time series is shown in Figure 12. The time axis shows the real time of recording during the test. These data are in model scale.

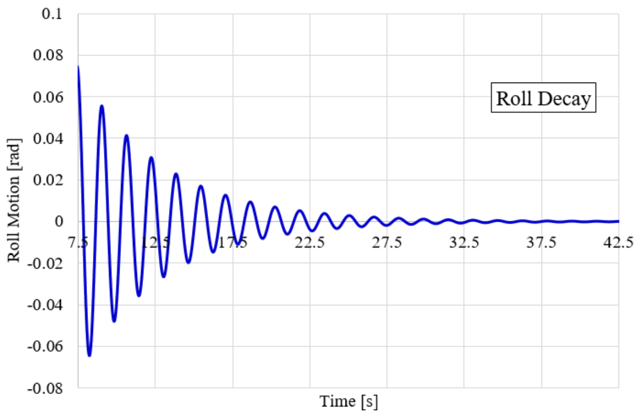

Figure 12: Roll decay time series for empty tank

REGULAR WAVE TEST RESULTS

The regular wave tests were carried out to determine the response amplitude operator (RAO) as well as possible nonlinear effects for large waves. It shows the response under sinusoidal waves for different wave periods and wave heights. Several wave periods were chosen for testing, and the wave height is around 1 m. The RAO is only defined when the response is assumed to be linear, so only the wave frequency responses are selected for analysis even in cases where there is nonlinear response components. The nonlinear components will be analyzed in later stage. For each test case, the calculation was based on around ten sinusoidal cycles in the steady state response. It should be noted that the response values of the motions are all referred still water level (SWL) position of the body under the empty tank condition. At this stage, empty tank condition and 20% tank filling level condition are tested. The RAO for surge, heave, pitch and roll D.O.Fs under the two filling conditions are plotted in Figures from 13 to 16, respectively.

It is clear from these figures that due to the water inside the tank, the motion responses are significantly changed. The sloshing first mode is at 8 s, which are observed as a peak RAO value for all these D.O.Fs, and due to the internal fluid, the motions at 11s are suppressed compared with the empty tank condition.

It is noted that there are small gaps between the fender system and the tank. In this case, when the 0 degree wave is coming, there will also be roll or yaw motion induced due to the unconstrained tank in the gaps and the misalignment of the tank x direction and incoming wave direction. Considering also the internal fluid effect inside the tank, the roll or yaw motion may be excited, which can be observed in Figure 16. However, these effects need further investigation.

The pitch resonant period is around 11s. However, there is strong coupling between surge and pitch, that when there is large surge, the fender can provide additional horizontal restoring force and restoring pitch moment on the body, so that the pitch resonant condition is changed, and the pitch motion trend mainly follow surge motion trend.

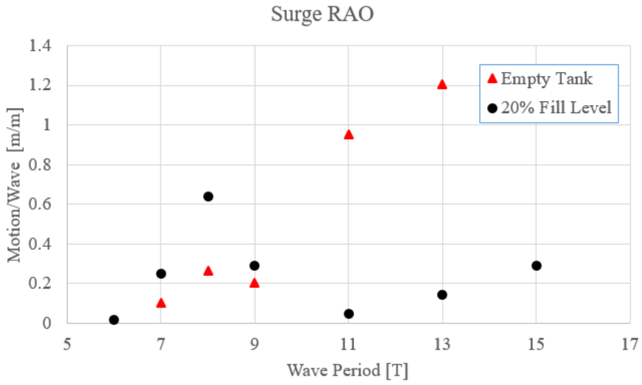

Figure 13: Surge RAO for empty tank and 20% tank filling level conditions.

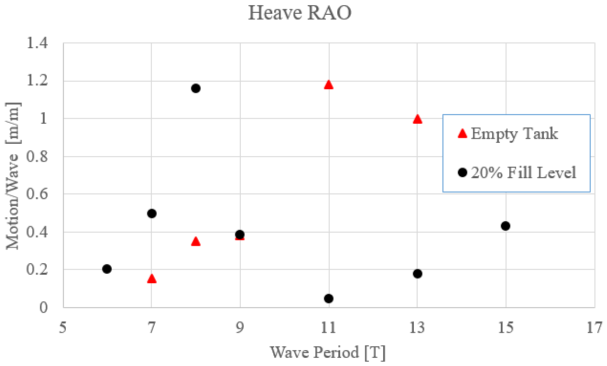

Figure 14: Heave RAO for empty tank and 20% tank filling level conditions.

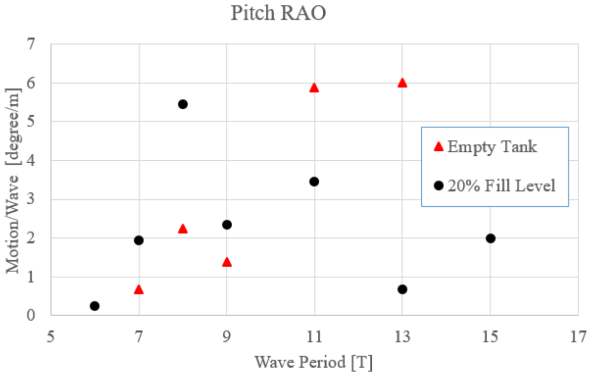

Figure 15: Pitch RAO for empty tank and 20% tank filling level conditions.

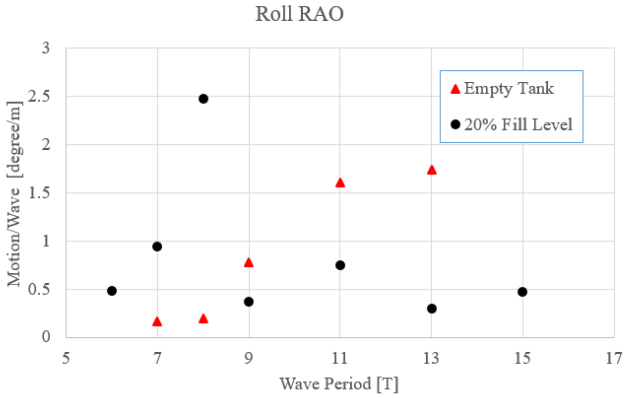

Figure 16: Roll RAO for empty tank and 20% tank filling level conditions.

The above initial test results shown are for a fully open tank, with sharp corners. The sloshing effects appear to be quite pronounced near 8 seconds period. So, mitigations such as baffles or chamfered corners may be required. This will be explored in a future study.

IRREGULAR WAVE TEST RESULTS

The response of the model in irregular waves with different sea states was tested. Two sea states were selected in this model test, one is based on the 1-year return period storm with Hs=1m, Tp=5.7s and the other is based on the 100-year return period storm with Hs=1.8m and Tp=7s. The 100-year return period storm results are shown here.

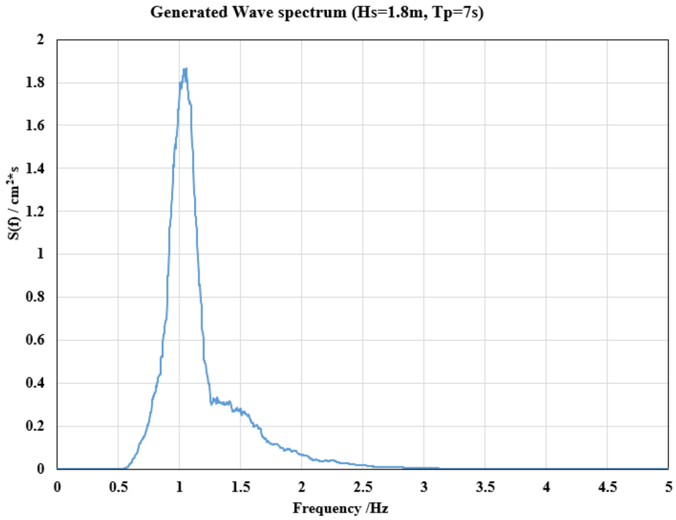

Figure 17: Generated Wave spectrum in the wave basin, Hs=1.8m, Tp=7s.

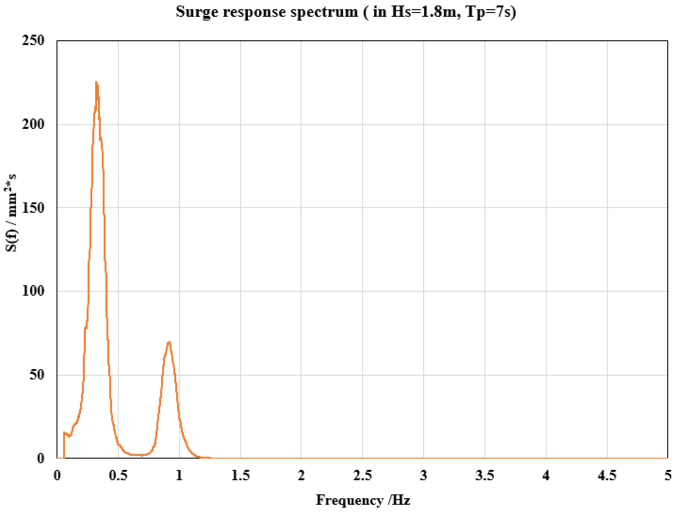

Figure 18: Surge response spectrum of the model in extreme sea state Hs=1.8m, Tp=7s.

The spectra of the incoming wave with Hs=1.8m and Tp=7s, and the surge responses are shown in Figure 17 and Figure 18, respectively. Statistical analysis results of both sea states are shown in Table 5 and Table 6. Spectral analysis are performed based on the 1 hour steady-state response in model scale. From the statistical results, even in 100-year storm, the motion of the oil storage tank is still moderate, for example, the maximum heave motion is less than 0.7m, which shows a good design of FOST for specific sea area. The secondary peak in the surge motion at approximately 0.9 Hz, model scale is likely due to the sloshing.

Table 5: Results of statistical analysis in 1-year storm, Hs=1.0m, Tp=5.7s.

D.O.F	Max	Min	Mean	STDV
Surge (m)	0.46	-0.89	-0.17	0.20
Heave (m)	0.21	-0.26	-0.01	0.06
Sway (m)	0.55	-0.22	0.11	0.12
Roll (deg)	1.06	-1.06	0.00	0.24
Yaw (deg)	6.82	-2.59	1.41	1.53
Pitch (deg)	3.88	-2.23	0.12	0.71

Table 6: Results of statistical analysis in 100-year storm, Hs=1.8m, Tp=7.0s.

D.O.F	Max	Min	Mean	STDV
Surge (m)	1.18	-1.10	-0.02	0.33
Heave (m)	0.66	-0.70	-0.02	0.22
Sway (m)	0.71	-0.59	0.02	0.18
Roll (deg)	3.53	-3.76	0.00	0.82
Yaw (deg)	8.35	-7.53	0.35	2.35
Pitch (deg)	10.23	-7.17	0.35	2.82

DISCUSSION AND FUTURE WORK

In this paper, the model test set up and initial test results in terms of decay test, regular wave test and irregular wave test are presented for a single hydrocarbon storage tank. This test is the first step of validation of the whole hydrocarbon storage tank system, which is developed for coastal waters.

Model test set-up for modular tank system is developed considering mooring fender system with different fender stiffness. A beam model is designed to achieve different fender stiffness by adjusting the beam thickness and the measurement or load cell installation position. In this paper, only the cases for 1667 kN/m fender stiffness are investigated. Calibration of the beam system verified the design.

From decay tests, the heave damping is found to be large, which may due to the large bottom plate. The other bottom plate will be tested in a later stage to investigate the bottom heave plate effects. From regular wave tests on two filling level conditions, it is found the internal fluid can significantly affect the tank responses. The sloshing is excited at 8s, while at some periods around sloshing mode, the motion is suppressed, which is also described numerically in papers [2] and [3].

Time series, spectral analysis and statistical analysis were performed based on irregular wave test. Under 1 year storm and 100 year storm cases, the motions are all moderate, the largest pitch motion is around 10 degree and the largest surge motion is less than 1m, which shows this concept is good design for the specific sea states.

In the near future, more tests will be performed in terms of more internal water filling levels, double tank system with gap resonance and shielding effects, as well as multi-tank system and the whole concepts with tanks and barges.

The initial test results shown are for a fully open tank, with sharp corners. The sloshing effects appear to be quite pronounced. So, mitigations such as baffles or chamfered corners may be required. This will be explored in a future study.

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