International Journal of Ocean System Engineering 3(4) (2013) 225-230
http://dx.doi.org/10.5574/IJOSE.2012.3.4.225

Comparison of Sloshing Pressures in 2D and 3D Tanks

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(Manuscript Received September 8 2013; Revised October 15, 2013; Accepted November 11, 2013)

Abstract

This paper introduces the experimental results of sloshing model tests carried out at Seoul National University. Two 1/50-scale tanks, i.e., 2D and 3D models with the same shape, were manufactured for the comparative study. Particular interest was taken in the differences in impact pressures between the 2D and 3D models. Regular motion tests were conducted for different filling depths. For each filling depth, 500 cycles of regular excitation were imposed at each frequency. To observe the characteristics and severity of sloshing from the acquired pressure data, statistical analyses were performed, not only for the peak pressure, but also for the area-concept indices, which represented the amount of impulse.

Keywords: Sloshing, Scale-model test, 2D vs. 3D, Peak pressure, Impulse area , LNG CCS

1. Introduction

There are many research activities for assessing the sloshing load of an LNG cargo. Sloshing in an LNG cargo is a very complicated issue because it is strongly nonlinear, and many unsolved physical phenomena are involved. So far, it is known that a model test can provide the most reliable data for evaluating sloshing loads.

In a real ship design stage, a 3D analysis is essential to represent a more realistic situation. Many classification societies suggest performing 3D tank tests under tank motion with six degrees of freedom (6 DOFs) derived from a seakeeping analysis (DNV [1], LR [2], BV [3]).

However, there are few experimental facilities equipped with such a 6-DOF motion platform, and 2D model tests are still useful for fundamental research. Bunnik and Huijsmans [4] performed a large-scale (1:10) sloshing model test using a 2D model tank, and their results were used to validate a numerical method for sloshing simulation [5]. Very recently, a sloshing benchmark test was carried out using a 2D rectangular model tank [6], and differences were seen between the experimental results in various experimental facilities.

In the present study, two series of sloshing model tests were carried out. One was a 2D transverse model tank test, and the other was a 3D model tank test. Both tanks were based on the same 140K LNGC tank model and had the same scale ratio. The tanks were excited under harmonic sway motions with different filling depths and excitation frequencies. The pressure peaks from the test results were sampled using the peak-over-threshold (POT) method, and the average of the 10 largest peak pressures was calculated to represent the sloshing severity of each test condition. From the model tests, the influence of the excitation frequency on the sloshing severity was investigated for each filling condition, and some 3D effects were observed. In both tanks, more than 100 sensors were installed to determine the hotspots for sloshing loads. As expected, the model results for the two tanks showed consistency in terms of the critical excitation frequency. However, it was observed that the magni-

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tude of the peak pressure could be different. In this study, the impulse area using the rising time was also considered as a comparison parameter, and the difference between the 2D and 3D tanks was more significant than the pressure peaks.

2. Experimental Setup

2.1 Pressure Measurement System

Fig. 1 shows the experimental facility established at Seoul National University (SNU). SNU has three hexapod motion platforms with different payloads and a large data acquisition system. A schematic diagram of the measurement system for the sloshing experiment is shown in Fig. 2. A motion platform controlled by a motion controller could simulate the scaled 6-DOF ship motion. Pressure sensors installed on the tank walls measured the dynamic pressure due to sloshing flow.

2.2 Model Tanks

For the scaled sloshing experiment, 2D and 3D tanks with a 1/50 scale were manufactured. These tanks were designed as models of a membrane tank for a 138K LNG carrier. The model tanks were made of 35-mm-thick acryl, which made it possible to visually observe the fluid motion inside the tanks. The breadth–length ratio (B/L) and height–length ratio (H/L) of this tank were 0.875 and 0.640, respectively. Fig. 3 shows snapshots of the 2D and 3D model tanks. The tanks were filled with ambient air and water.

To measure the dynamic pressures on the tanks, integrated circuit piezoelectric (ICP) sensors were installed on the tank walls. These sensors have a 5.54-mm sensing diameter and can measure pressures up to 700 kPa. The pressure sampling rate was set at 20 kHz. The specific pressure sensor locations are presented in Fig. 4. Totals of 112 and 185 pressure sensors were used in the 2D and 3D tank tests, respectively. In most regions, the pressure sensors were mounted as cluster panels, as shown in Fig. 4.

2.3 Test Conditions

For both tank models, tests were conducted using four different filling depths: 15%, 30%, 70%, and 95% of the tank height (H). The applied motion was a 1-DOF harmonic sway motion (motion amplitude = 5% of tank breadth). For one motion amplitude, tests were carried out at more than 10 frequencies. The time window of the test was fixed at a motion period of 500 cycles for all the tests. Ahn et al. [7] recommended at least 500 cycles as an appropriate time window for a regular model test.

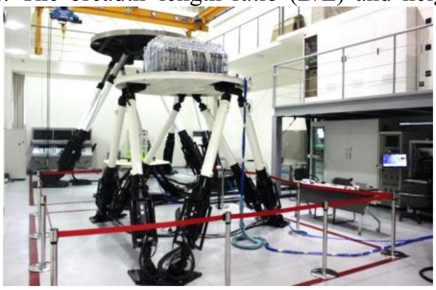


Fig. 1. Experimental facility at SNU

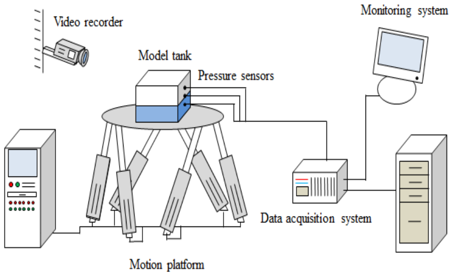
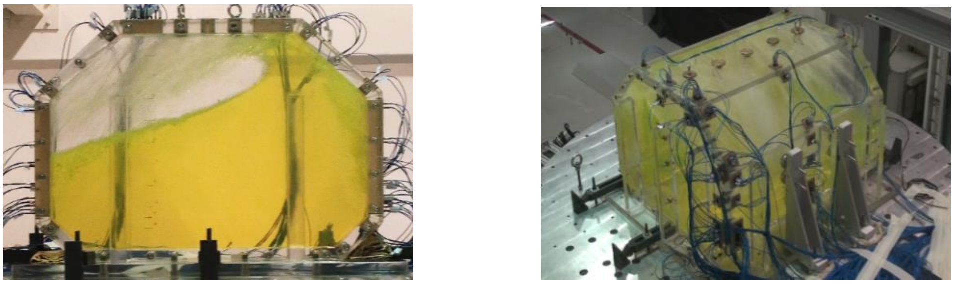
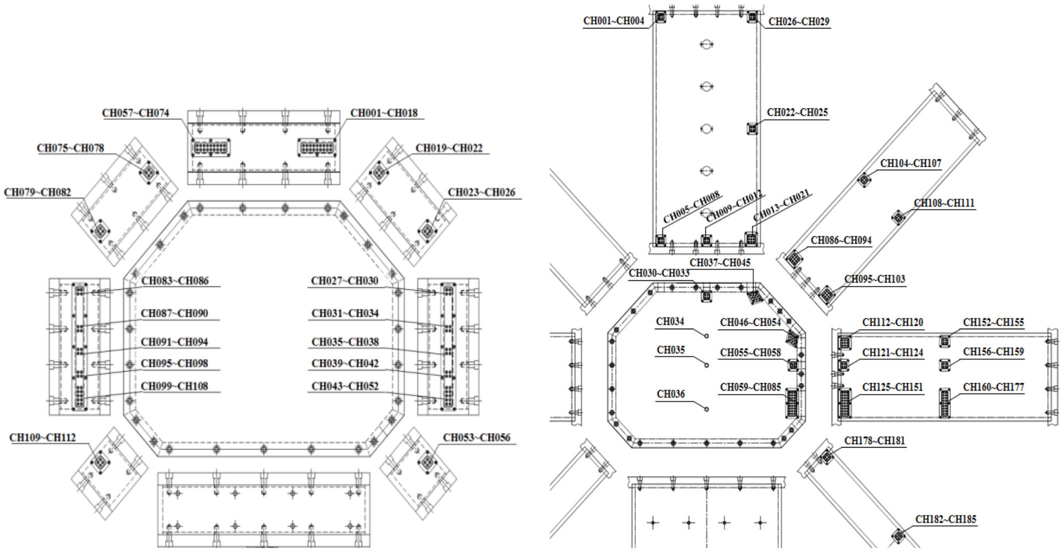


Fig. 2. Schematic diagram of measurement system



(a) 2D tank test (b) 3D tank test

Fig. 3. Snapshots of sloshing model tests



(a) 2D model tank (transverse section) (b) 3D model tank

Fig. 4. Locations for pressure measurement

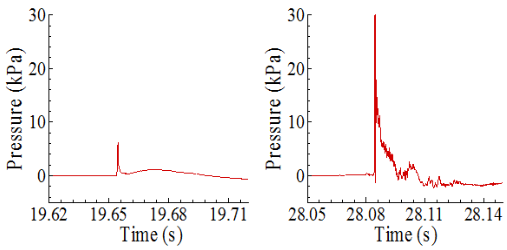
3. Experimental Results

3.1 Pressure Time Histories of Sloshing Events

Fig. 5 shows some examples of the pressure time histories measured during the 2D model tests. The measuring point was at a corner of the tank's ceiling. Because sloshing flows are highly nonlinear and stochastic phenomena, the magnitudes of the peak pressure showed irregular tendencies, even though the excitation was regular. The pressure signals showed significant differences between the two test conditions. When the motion frequency was close to the resonance frequency, the magnitudes of the peak pressures were relatively large and the decay time was long, e.g., see Fig. 5(b). In the case of a very low excitation frequency, the peak pressures were rather small, and the decay times were short, e.g., see Fig. 5(a).

3.2 Comparison of 2D and 3D Test Results

Fig. 6 summarizes the measured pressures at a high filling condition. To represent the severity of sloshing, the average values of the 10 largest peaks are shown, rather than the maximum pressure. For each test, the average of the 10 largest pressures measured by all the channels was checked in the first step, and then the channel that showed the maximum value was selected and plotted in the graph. In the 0.95 × H filling condition, the pressure peaks from the 2D and 3D tanks showed somewhat different tendencies. In the 2D tank test, the magnitudes of the peak pressure were relatively smaller, and there were no large differences for the considered frequencies. In the 3D tank test, however, as the excitation frequency increased, larger sloshing peaks occurred. The range of the motion frequency was not large enough to reach a solid conclusion, but 3D effects such as swirling may have played a critical role in this 3D test. Unfortunately, a model test at a higher frequency could not be conducted because of the motion capacity limitation.



(a) $\omega/\omega_0 = 0.70$ (b) $\omega/\omega_0 = 0.95$

Fig. 5. Examples of pressure time histories for 2D model test (tank top, 0.70 × H filling, CH073)

Table 1. Significant channel numbers for each test condition for 2D tank test with filling depth = 0.70 × H

ω/ω_0	0.8	0.85	0.9	0.95	1	1.05	1.1	1.15
CH	73	73	74	73	73	27	84	29
Location	T.R.	T.R.	T.R.	T.R.	T.R.	S.W.	S.W.	S.W.

*S.W. = side wall, T.R. = tank roof

Table 2. Significant channel numbers for each test condition for 3D tank test with filling depth = 0.70 × H

ω/ω_0	0.8	0.85	0.9	0.95	1	1.05	1.1	1.15
CH	108	113	21	7	27	1	21	21
Location	U.C.	S.W.	T.R.	T.R.	T.R.	T.R.	T.R.	T.R.

*U.C. = upper chamfer, S.W. = side wall, T.R. = tank roof

In the case of the 0.70 × H filling condition, the 2D and 3D model tests showed similar results. Both tests showed maximum pressures near the resonance frequency, and the pressures became smaller as the excitation frequency moved away from the resonance frequency. Under most test conditions, the pressure values on the 3D tank were slightly larger than those from the 2D tank tests.

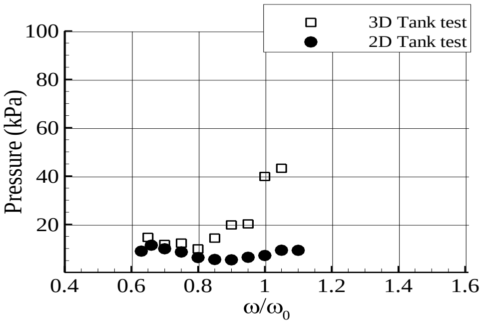
The sensor values that showed the maximum pressure at each excitation frequency are summarized in Tables 1 and 2. In the 2D tank tests, large sloshing pressures occurred at the corner of the tank roof at a low excitation frequency. As the motion frequency increased, the critical area moved to the corner of the upper side wall. The 3D tank test showed a more complex tendency. Around the resonance frequency, large pressures were observed at the corner of the tank top. However, as the excitation frequency moved away from the resonance frequency, the critical area moved to a lower part such as the upper chamfer or side wall. From these results, it can be found that, even though the filling level and motion amplitude were the same, the hotspots for the occurrence of a large impact could be changed by the excitation frequency.

Fig. 7 shows the test results under low filling conditions. In the case of the 0.30 × H filling condition, the pressure peaks obtained from the 2D and 3D tank tests showed similar tendencies. The maximum sloshing pressures could be observed at 95% of the natural frequency, and larger peak pressures were observed in the 3D tank test. It is known that, under a very low filling condition, the critical frequency region is higher than the linear resonance frequency, which is the so-called jump phenomenon [8]. The results at the 0.15 × H filling condition clearly showed this jump phenomenon. In both the 2D and 3D tank tests, large sloshing pressures occurred at a frequency of $\omega/\omega_0 = 1.30$, where ω_0 is the resonance frequency. Under the low filling condition, the pressure tendencies according to the excitation frequency showed very good agreement between the 2D and 3D tank tests. Similar to the results for the high filling condition, the magnitudes of the peak pressures from the 3D tank test were larger than those of the 2D tank test.

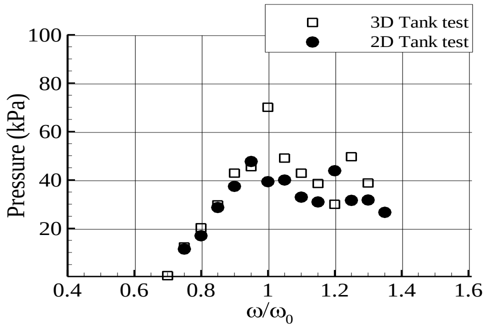
There is no doubt that the peak pressure is one of the most important parameters in a sloshing problem. In addition to the peak pressure, the impulse time is also an important element from the viewpoint of structural response. Kim et al. [9] introduced two area indices to represent the simplified impulse areas of the pressure signal. Fig. 8 shows the average of the 10 largest rise impulse areas of the two tests. Under the 0.70 × H filling condition, the impulse areas obtained from the 3D tank test are much larger than those from the 2D tank. In 0.15 × H filling condition, however, the results of both tests show similar maximum impulse areas.

4. Conclusions

In order to investigate the slosh-induced impact loads on an LNG tank, a series of experiments were carried out using 2D and 3D tanks with a 1/50 scale. A regular sway motion was applied, and experiments were performed using four filling depths and about 10 excitation frequencies. Based on observations of the measured pressure signals and comparisons of the statistical results, some findings were obtained. Under most filling conditions, the 2D and 3D tank results showed consistency in the critical excitation frequency. It was also observed that, even though the filling depths and motion amplitudes were the same, the hotspots for the occurrence of large impacts were dependent on the excitation frequency. Under the 0.15 × H filling condition, jump phenomena were clearly observed in both the 2D and 3D tank tests. Under most conditions, the 2D test results showed relatively smaller pressures and impulses.

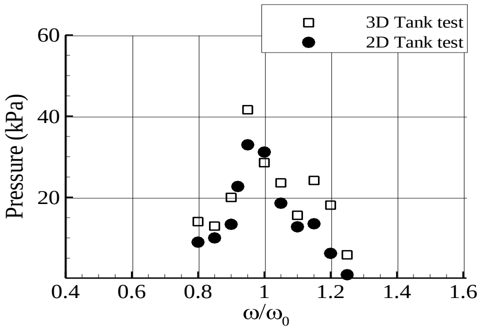


(a) Filling depth = 0.95 × H

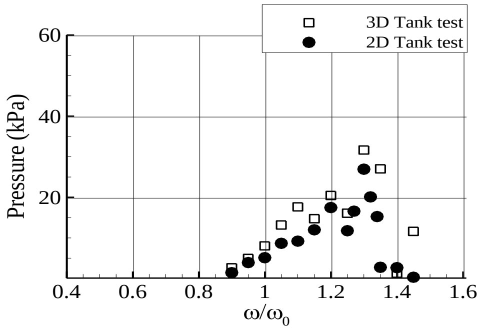


(b) Filling depth = 0.70 × H

Fig. 6. Average of 10 largest peak pressures at high filling depth

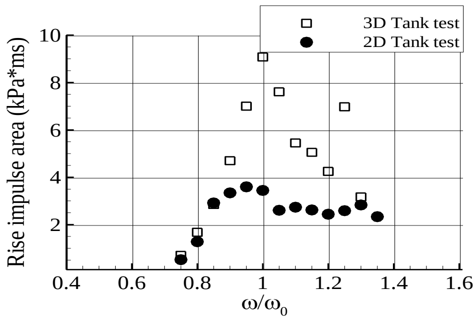


(a) Filling depth = 0.30 × H

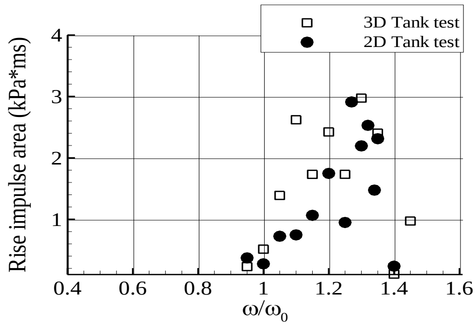


(b) Filling depth = 0.15 × H

Fig. 7. Average of 10 largest peak pressures at low filling depth



(a) Filling depth = 0.70 × H



(b) Filling depth = 0.15 × H

Fig. 8. Average of 10 largest rise impulse areas at high filling depth

5. Acknowledgement

This research was supported by the LRF*-Funded Research Center at Seoul National University. Their support was greatly appreciated. (*Lloyd's Register Foundation (*LRF: Lloyd's Register Foundation)

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