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Technical note

Experimental investigation of pressure distribution on a rectangular tank due to the liquid sloshing

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Abstract

Pressure variations and 3D effects on liquid sloshing loads in tanks have been carried out experimentally. Recently, considerable advances have been made in the development of numerical techniques for studying the liquid sloshing on large structures. However, there is a lack of high quality experimental data that may be used for validating the analytical and numerical solutions obtained. This paper describes the results of the research project conducted at the Hydroulics Laboratory of Civil Engineering Faculty of Istanbul Technical University. The primary objective of the project is to investigate the pressure distributions at different locations and 3D effects on liquid sloshing. In this purpose, an experimental setup is designed to study the non-linear behavior and damping characteristics of liquid sloshing in partially filled 3D rectangular tank. Both several configurations of baffled and unbaffled tanks are studied.

Keywords: Pressures variations; Free surface flow; 3D effects on sloshing loads; Experimental study

1. Introduction

Liquid sloshing is associated with various dynamical systems and engineering problems, such as the liquid oscillations in large storage tanks caused by earthquakes, the motions of liquid fuel in aircraft, the motions of liquid in containers and the water flow on

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the decks of ships. The dynamic behavior of these systems is greatly affected by the dynamics of the free liquid surface and it is very important with regard to the safety of transportation systems, human's life and environment.

Fluid motion in partially filled tanks may cause large structural loads if the period of tank motion is close to the natural period of fluid inside the tank. This phenomenon is called sloshing. Sloshing means any motion of a free liquid surface inside a container. Depending on the type of disturbance and container shape, the free liquid surface can experience different types of motion including simple planar, non-planar, rotational, irregular beating, symmetric, asymmetric, quasiperiodic and chaotic. The amplitude of the slosh, in general, depends on the nature, amplitude and frequency of the tank motion, liquid-fill depth, liquid properties and tank geometry.

Motions of liquid inside a container have an infinite number of natural frequencies, but it is the lowest few modes that are most likely to be excited by the motion of a vehicle. However, non-linear effects result in the frequency of maximum response being slightly different from the linear natural frequency and dependent on amplitude.

The dynamic behavior of a free liquid surface depends on the type of excitation and its frequency content. The excitation can be impulsive, sinusoidal, periodic and random. Its orientation with respect to the tank can be lateral, parametric, pitching/yaw or roll and a combination. Under lateral harmonic excitation, the free liquid surface may exhibit two types of non-linearity. The first is large amplitude response and the second involves different forms of liquid behavior produced by coupling or instabilities of various sloshing modes. The most important of these is the rotary sloshing or swirl motion. This type of motion usually occurs very near the lowest liquid natural frequency.

When the frequency of the tank motion is close to one of the natural frequencies of the tank fluid, large sloshing amplitudes can be expected. If both frequencies are reasonably close to each other, resonance will occur. The question is, how close should both frequencies be to excite sloshing. Under free oscillations, the motion of the free liquid surface decays due to damping forces created by viscous boundary layers. Basically, the damping factor depends on the liquid height, liquid kinematics viscosity and tank dimensions. From this point of view, we varied tank fill levels, tank excitation frequency and amplitude to study effects on pressure response. The tank was excited rotationally about a transverse axis through the tank center.

The objectives of this study are to develop an experimental system accounting for the effects of large tank motions, large amplitude wave motions, fluid viscosity and baffle arrangements (Akyıldız and Ünal, 2004; Akyıldız and Çelebi, 2001). Çelebi and Akyıldız (2002) presented the liquid sloshing in the 2D tanks based on a finite difference method. The Navier–Stokes equation with free boundary is solved using the SOLA scheme. Kim (2001) investigated the sloshing flows in the 2 and 3D liquid containers. The computational results were compared with experimental data and showed a favorable agreement of impact pressure as well as the global fluid motion. Sames et al. (2002) investigated sloshing in a rectangular tank with a baffle and in a cylindrical tank. They predicted time traces of pressures and forces compared favorably with measurements.

2. Experimental investigations

Liquid sloshing is a result of the motion of the partially filled tank. As the tank moves, it supplies energy to sustain the fluid motion. When the frequency of the tank motion is close to one of the natural frequencies of the fluid, large sloshing amplitudes can be expected. For a given rectangular prismatic tank, the natural frequencies of the fluid depending on the fill depth are given by:

$$\omega_n^2 = g\frac{n\pi}{L}\tanh\left(\frac{n\pi}{L}d\right)$$

where L is the tank width and d is the water depth and n is the mode number. Because of the non-linear feature of the sloshing problem, resonance does not occur exactly at the natural frequency of the fluid as computed from the above equation taking the mode number $n=1$, but at a frequency very close to that value. The liquid resonance frequency shifts for different baffle arrangements, excitation amplitudes, liquid densities and viscosities.

In this study, the problem was restricted to liquid sloshing in rectangular tank under pitch oscillations. Many series of physical model investigations were carried out. A wide model tank was built for the experiments in order to allow for 3D liquid motion. Thus, a 92 cm by 62 cm model tank, width of 46 cm or a 92×62×46 cm model tank. The tank was designed with interchangeable internal structure arrangements. These internal structure members were bottom transverse and side stringers. A larger baffle (15.4 cm high) made of 1.5 cm Plexiglas plate was used for the bottom transverse and the left side stringer. A smaller baffle (7.6 cm high) was also used for the right side stringer with the same thickness. Nine pressure transducers were installed to monitor pressure distributions at various locations. The locations of the pressure transducers and the baffle configurations tested are shown in Fig. 1.

The test platform is shown in Fig. 2. It was specially designed for the sloshing experiments. Thus, the tank is allowed to rotate freely about a transverse axis through the tank center. The tank platform on the base frame was driven by DC motor (15 kW) controlling the rotational oscillations. The testing system consists of an amplifier with analog–digital converter card for wave probe and a data logger type 34970 A for pressure transducers.

Pressure variations were sensed by piezoresistive pressure transducers which were installed on the end bulkhead of the model tank at various locations as shown in Fig. 1. These gauge type transducers have sensitivity ranges from 0 to 1 bar G. Waves produced in the model tank were transformed to the system using a twin wave electrode (see Fig. 2). Water between the electrodes close the circuit and resistance varies for different water levels. The results obtained as an electrical signal are amplified (Data logger for pressures) and digitized by an analog–digital converter card. Finally, these signals are stored in the computer and plotted as a pressure distribution and wave heights simultaneously.

2.1. Experimental facilities and procedures

A total of 17 test sequences involving 9 different tank configurations and 145 test runs were carried out. For each sequence of test, a number of frequencies were tested. The fill

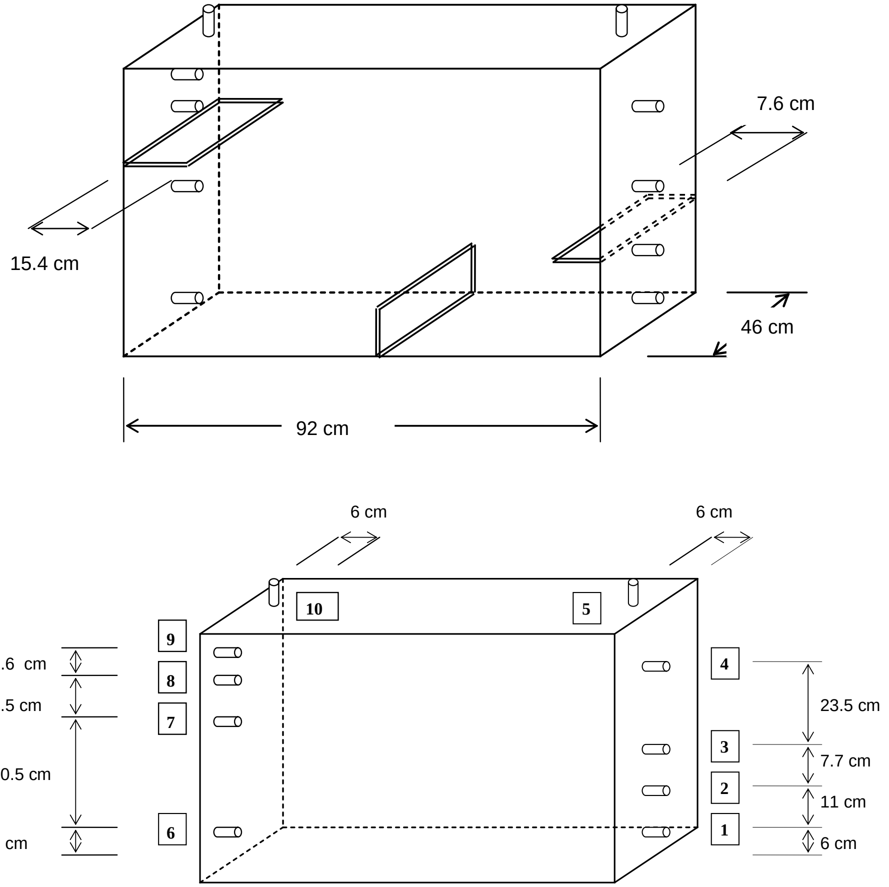

Fig. 1. Locations of the pressure transducers and baffle configurations.

Fig. 2. Test platform.

Table 1
Test sequences

Case No.	Fill depth ($d=H^*\%$)	Pitch angle (θ_0 degree)	Freq. ranges (ω_R rad/s)	Transducer locations
1	0.25	4	0.5–2.0	1,2,6
2	0.50	4	0.5–3.9	1,2,3,6
3	0.75	4	0.5–5.0	1,2,3,6,7,8,9
4	0.25	4	0.5–3.785	1,2,6
5	0.50	4	0.5–3.785	1,2,3,6,7,8
6	0.75	4	0.5–4.0	1,2,3,6,7,8,9
7	0.25	4	–	–
8	0.50	4	0.5–3.785	1,2,3,6,7
9	0.75	4	0.5–3.785	1,2,3,6,7,8,9
1	0.25	8	0.5–2.0	1,2,6
2	0.50	8	0.5–3.3	1,2,3,6
3	0.75	8	0.5–4.0	1,2,3,6,7,8,9
4	0.25	8	0.5–2.6	1,2,6
5	0.50	8	0.5–3.0	1,2,3,6,7,8
6	0.75	8	0.5–3.49	1,2,3,6,7,8,9,10
7	0.25	8	1.6–3.785	1,2,6
8	0.50	8	0.5–3.0	1,2,3,6,7
9	0.75	8	0.5–3.0	1,2,3,6,7,8,9

depth, excitation amplitude, frequency of oscillation and the locations of the pressure transducers are tabulated in Table 1.

For each test run, the tank was always started from an upright position with predetermined frequency and excitation amplitudes. The tank will rotate for 2 min and were monitored and recorded by the Agilant 34970 A data logger automatic data acquisition system.

3. Analysis of experiments and discussions

As the rectangular tank oscillates, different sloshing waves will be created depending on the liquid depth and frequency of oscillations. Four types of waves are possible. Standing wave, traveling wave, hydraulic jump and combination of these. For a shallow liquid oscillating at a frequency much lower than its resonance frequency, a standing wave will be formed. As the frequency increases, the standing wave transforms into a train of traveling waves of very short length. Hydraulic jump will take place due to a small disturbance and appear over a range of frequencies near the resonance frequency. With the further increase in frequency, the jump will pass into a solitary wave. For deeper liquid, sloshing near the resonance is characterized by the formation of large amplitude standing waves. These waves are asymmetric and, at large amplitude tank excitations may be combined with traveling waves.

The sloshing liquid can create two types of dynamic pressure. They are called non-impulsive and impulsive pressures. Impulsive pressures are rapid pressure pulses due to the impact between the liquid and the solid surface. Such an impulsive pressures are much localized and extremely high pressures. They are usually associated with hydraulic jumps and traveling waves. Non-impulsive pressures are the ordinary dynamic pressures in an oscillating fluid. They are slowly varying pressures that result from standing waves. The most severe impact pressures occur near the still water level or at the abrupt intersections of the tank walls. The variation of these pressures is neither harmonic nor periodic, even though the external excitation is harmonic. For a given liquid depth/tank width ratio and frequency of oscillation, sloshing pressure is in general proportional to the specific weight of the liquid, linear dimension of the tank and amplitude of excitation of the tank. At high excitation amplitudes of the tank, sloshing pressure is less sensitive to the excitation amplitude because of a non-linear softening effect.

The severity of sloshing and its accompanying dynamic pressure loads depend on the tank geometry, the depth of the liquid, the amplitude and nature of the tank motions. They also depend on the frequency of excitation over a range of frequencies close to the natural frequency of the fluid. For shallow liquid depths, the sloshing is characterized by a hydraulic jump. Under roll excitation, the liquid depth influences the frequency at which a jump will occur and it decreases as liquid depth is increased. The range of frequencies where jumps will exist is also influenced by the location of the roll axis. For roll oscillations about a fixed axis, the sloshing wave amplitude increases linearly with the excitation amplitude of the tank. The rate of increase is slower at the higher excitation amplitudes of the tank. The effect of the fluid viscosity is present, but more uncertain. However, viscosity does affect the sloshing wave amplitude at the resonance frequency. It can also be said that it has a pronounced effect on surface waves such as spray and breaking.

In the case no. 1, 25% fill depth in an unbaffled tank, increasing the amplitude from 4 to 8° led to increase in pressure, that is, increasing the excitation frequency increased pressure response. Thus, it is found that excitation amplitude significantly affects sloshing loads (Fig. 3).

Tank Dimensions = 92 x 46 x 62 cm Natural Frequency : ω_n = 4.025 r/s.	**Case (1)**	Fill Depth = 0.25 x (Height of Tank)

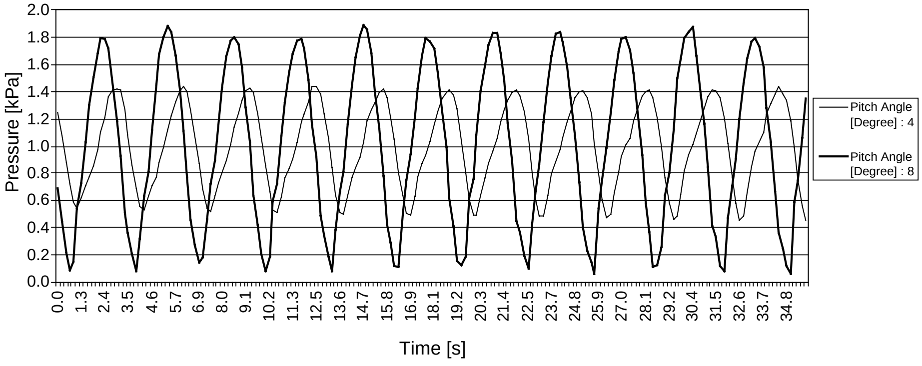

Fig. 3. Changing pressure values for the roll frequency = 2.0 rad/s at the transducer location no. 06, unbaffled tank.

Tank Dimensions = 92 x 46 x 62 cm Natural Frequency : ω_n = 5.128 r/s.	**Case (2)**	Fill Depth = 0.50 x (Height of Tank)

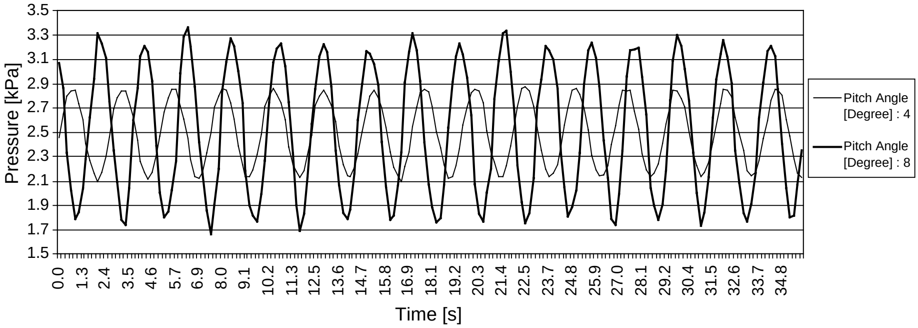

Fig. 4. Changing pressure values for the roll frequency = 2.0 rad/s at the transducer location no. 06, fill depth 50%, unbaffled tank.

As the amplitude of excitation is increased, the liquid responds violently related to the fluid motion such as the occurrence of turbulence, hydraulic jump, wave breaking and 3D effects.

In the case no. 2, 50% fill depth in an unbaffled tank, the amount of the maximum pressures for the roll amplitudes 4 and 8° are greater than that of the shallow water case (Fig. 4).

In the case no. 3, 75% fill depth in an unbaffled tank, the amount of the maximum pressures for the roll amplitudes 4 and 8° are greater than 50% fill depth and 25% fill depth. It can be concluded that the rolling amplitude and frequency of the tank directly affected the degrees of non-linearity of the sloshing phenomena with the increasing fill depth (Figs. 5 and 6).

Tank Dimensions = 92 x 46 x 62 cm Natural Frequency : w_n = 5.551 r/s.	**Case (3)**	Fill Depth = 0.75 x (Height of Tank)

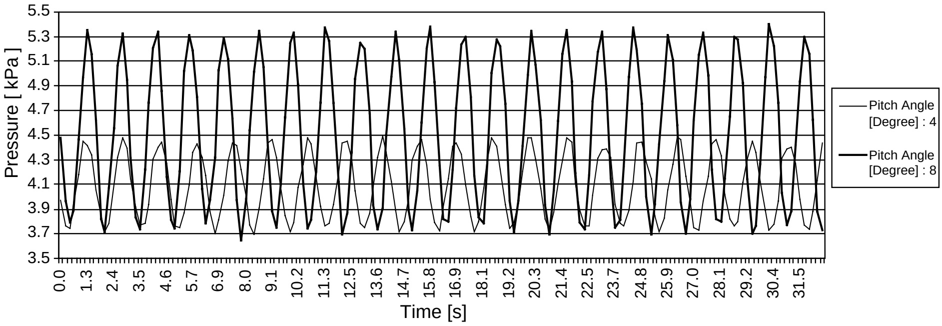

Fig. 5. Changing pressure values for the roll frequency = 2.0 rad/s at the transducer location no. 06, fill depth 75%, unbaffled tank.

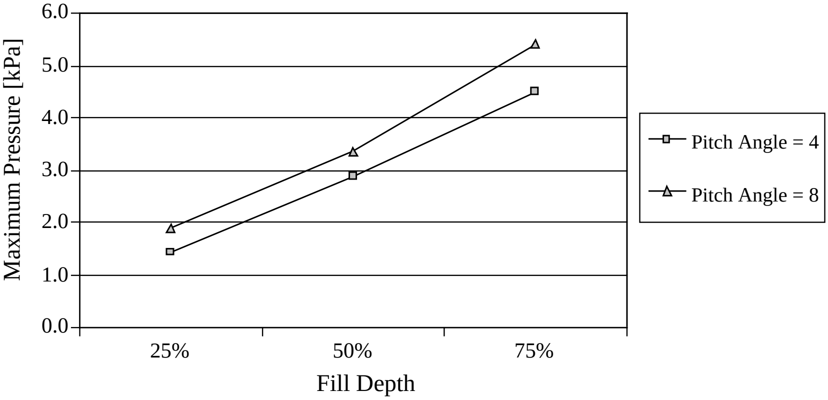

Fig. 6. Maximum pressure values for the roll frequency = 2.0 rad/s at the transducer location no. 06, unbaffled tank.

In the case no. 4, 25% fill depth in a vertical baffled tank, the effects of the vertical baffle were most pronounced in shallow water, that is especially the over turning moment was greatly reduced. Vertical baffle on liquid sloshing inside a tank revealed that the flow over a vertical baffle produced a shear layer and energy was dissipated by the viscous action. It can be concluded that the baffle located vertically on the center of the bottom of the tank reduces the maximum pressures on the sides of the tank compared to the unbaffled tank case, however, a significant pressure fluctuations occur due to the vertices at the both sides of the vertical baffle (Figs. 7 and 8).

In the case no. 5, 50% fill depth in a vertical baffled tank, it can be concluded that the effects of the vertical baffle were less pronounced as the fill depth increases. Vertical baffle at the center of the bottom reduces the maximum pressures on the sides of the tank with

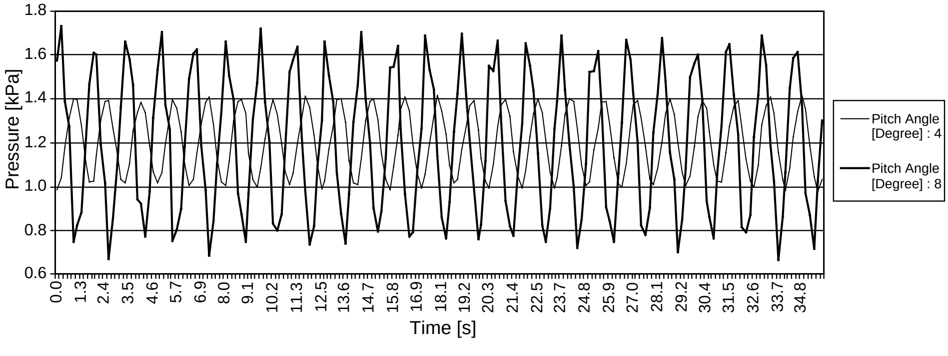

Fig. 7. Changing pressure values for the roll frequency = 2.0 rad/s at the transducer location no. 06, fill depth 25%, vertical baffled tank.

Tank Dimensions = 92 x 46 x 62 cm Natural Frequency : w_n = 4.025 r/s.	**Case (4)**	Fill Depth = 0.25 x (Height of Tank) Roll Amp. $\theta_o = 4^o$; Roll Freq. w_R = 2.0 r/s

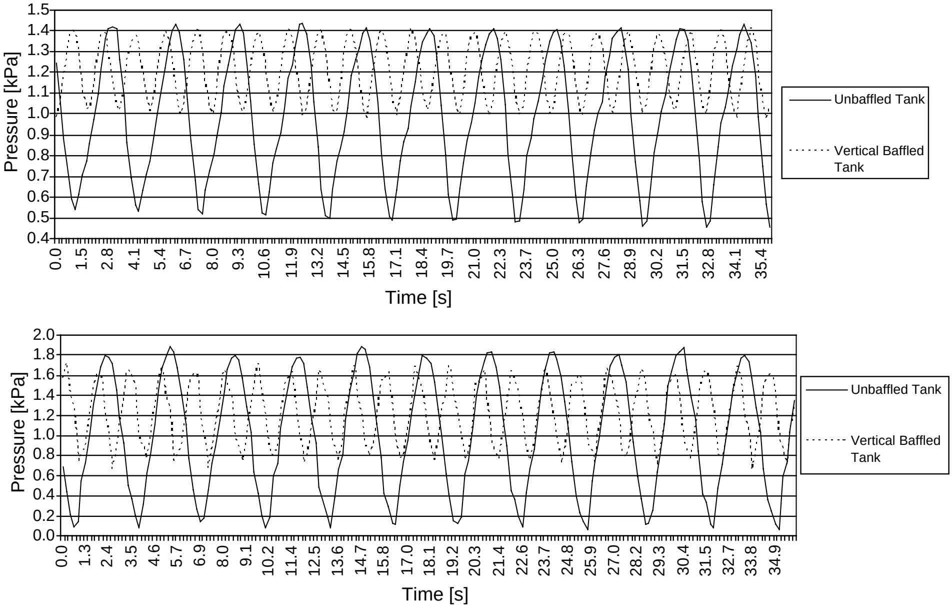

Fig. 8. Changing pressure values for the roll frequency = 2.0 rad/s at the transducer location no. 06, fill depth 25%, pitch angle (degree) = 4 and 8°.

the increasing rolling amplitude, and also pressure fluctuations and viscous damping effects decrease as the fill depth increases (Figs 9 and 10).

In the case no. 6, 75% fill depth in a vertical baffled tank, pressure fluctuations and viscous damping much more decrease in this case (Figs. 11–13).

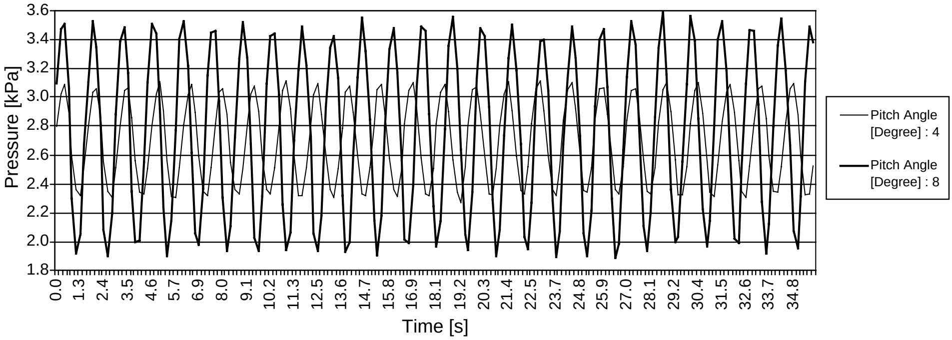

Fig. 9. Changing pressure values for the roll frequency = 2.0 rad/s at the transducer location no. 06, fill depth 50%, vertical baffled tank.

Tank Dimensions = 92 x 46 x 62 cm Natural Frequency : w_n = 5.128 r/s.	**Case (5)**	Fill Depth = 0.50 x (Height of Tank)

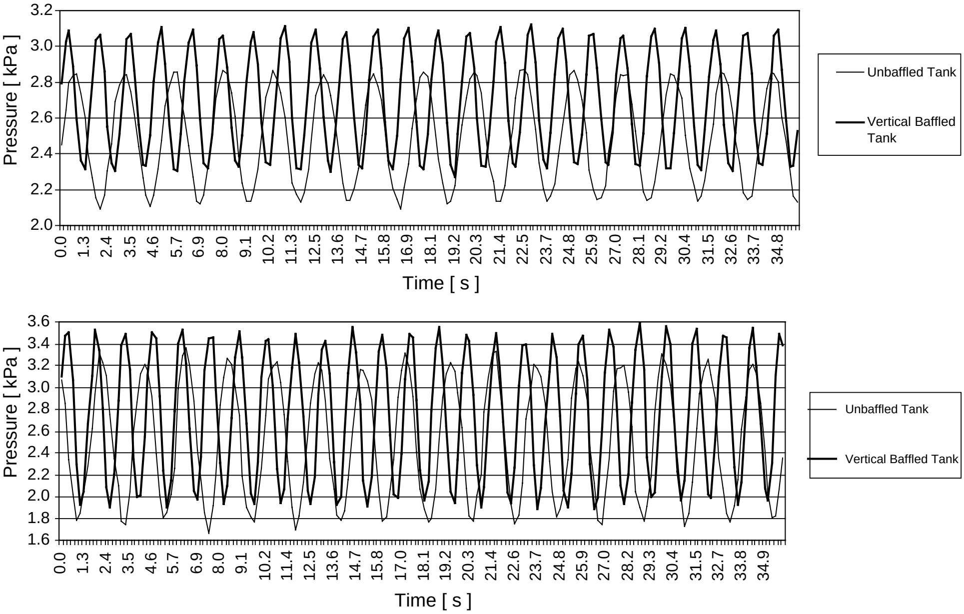

Fig. 10. Changing pressure values for the roll frequency = 2.0 rad/s at the transducer location no. 06, fill depth 50%, pitch angle (degree) = 4 and 8°.

In the case no. 7, 25% fill depth in the combination of a right side horizontal baffle and a vertical baffle, flow over a horizontal baffle exhibited a shallow water character, which dissipated energy by forming a hydraulic jump and a breaking wave. Furthermore, it is indicated that the horizontal baffle may enhance the traveling characteristics of

Tank Dimensions = 92 x 46 x 62 cm Natural Frequency : w_n = 5.551 r/s.	**Case (6)**	Fill Depth = 0.75 x (Height of Tank)

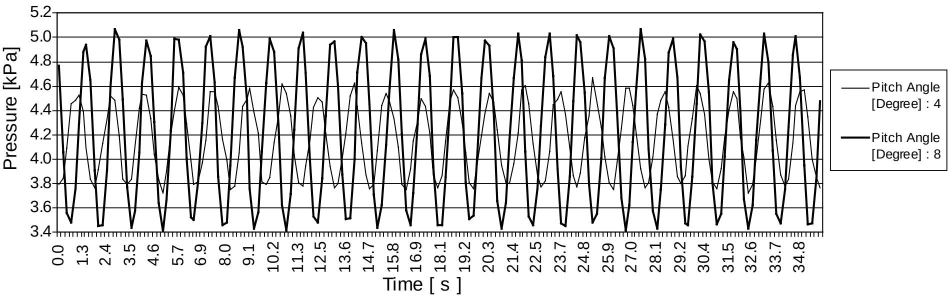

Fig. 11. Changing pressure values for the roll frequency = 2.0 rad/s at the transducer location no. 06, fill depth 75%, vertical baffled tank.

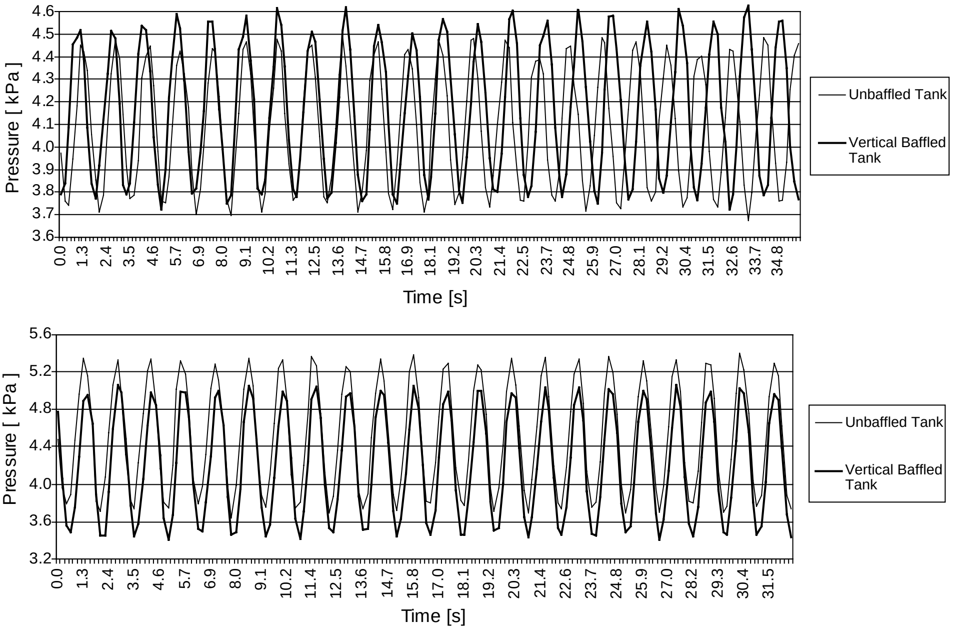

Fig. 12. Changing pressure values for the roll frequency = 2.0 rad/s at the transducer location no. 06, fill depth 75%, pitch angle (degree) = 4 and 8°.

the sloshing wave, which could result in a higher slamming pressure. As the amplitude of excitation is increased, the liquid responds violently related to the fluid motion such as wave breaking and 3D effects (Fig. 14).

In the case no. 8, 50% fill depth in the combination of a right side horizontal baffle and a vertical baffle, the amount of maximum pressures decrease as the fill depth and the rolling

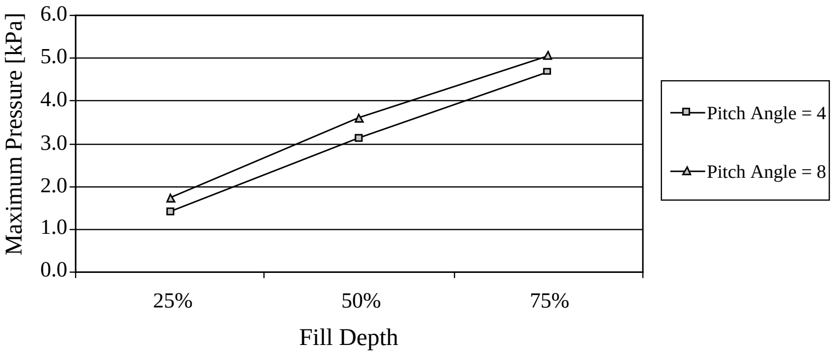

Fig. 13. Maximum pressure values for the roll frequency = 2.0 rad/s at the transducer location no. 06, vertical baffled tank.

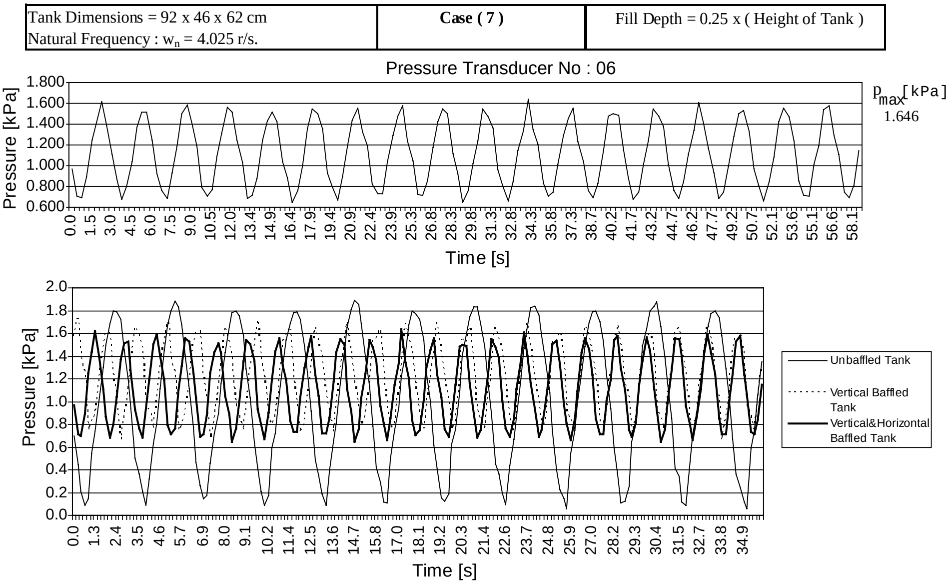

Fig. 14. Changing pressure values for the roll frequency = 2.0 rad/s at the transducer location no. 06, fill depth 25%, pitch angle (degree) = 8°.

amplitude increase compared to the vertical baffled case. Therefore, it is concluded that a side horizontal baffle represents shallow water effects in deep water case and may enhance the traveling characteristics of the sloshing wave. This causes higher slamming pressures (Fig. 15).

In the case no. 9, 75% fill depth in the combination of horizontal baffles at both sides with different height and a vertical baffle, increasing fill depth bring about a much more

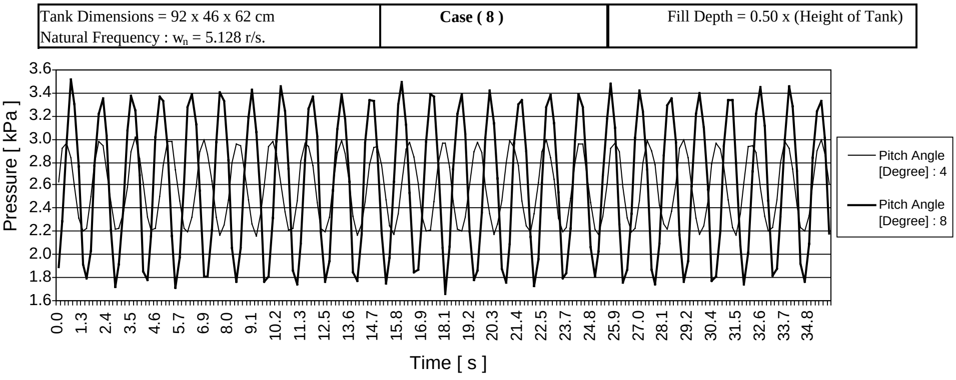

Fig. 15. Changing pressure values for the roll frequency = 2.0 rad/s at the transducer location no. 06, fill depth 50%, vertical and horizontal baffled tank.

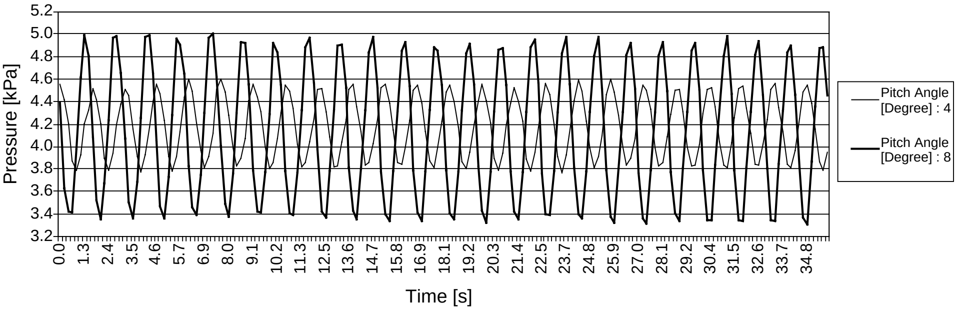

Fig. 16. Changing pressure values for the roll frequency = 2.0 rad/s at the transducer location no. 06, fill depth 75%, vertical and horizontal baffled tank.

slamming pressures, because the horizontal baffles on the sides represent a shallow water effects in deep water cases and consequently enhance the traveling characteristics of the sloshing wave. As the amplitude of excitation and the forcing frequency are increased, the liquid responds violently due to the 3D effects (Figs. 16–18).

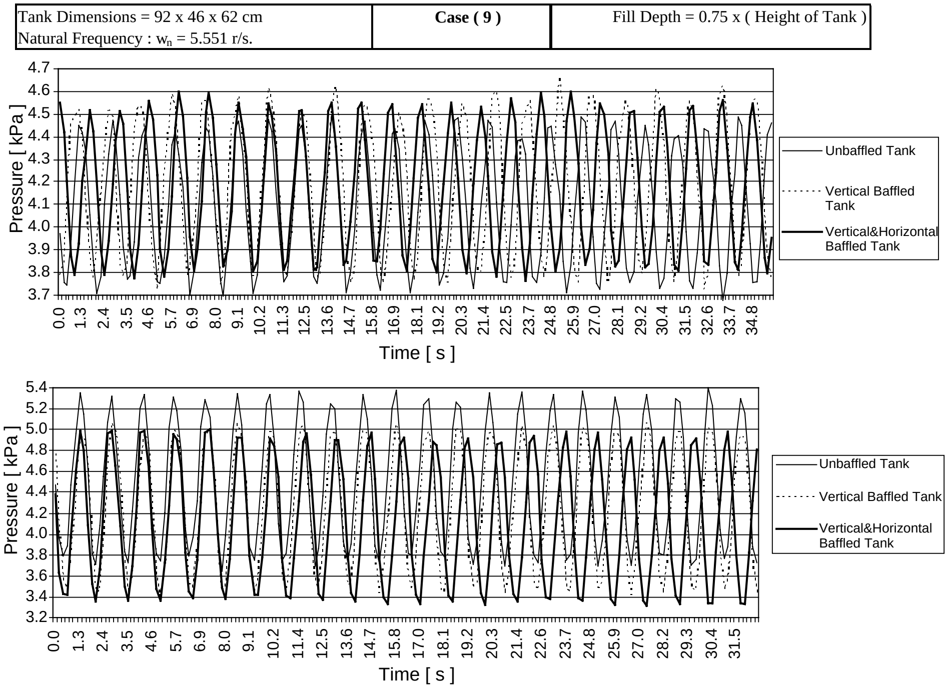

Fig. 17. Changing pressure values for the roll frequency = 2.0 rad/s at the transducer location no. 06, fill depth 75%, pitch angle (degree) = 4 and 8°.

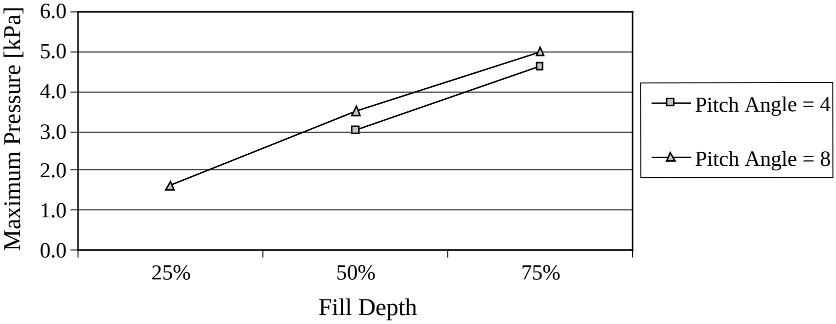

Fig. 18. Maximum pressure values for the roll frequency = 2.0 rad/s at the transducer location no. 06, vertical and horizontal baffled tank.

4. Conclusions

Sloshing in a rectangular tank at a model scale with various fill levels and baffles was experimentally investigated. Excitation parameters were systematically changed to assess the sensitivity of sloshing loads. It can be concluded that baffles significantly reduce fluid motion and also more experimental investigations are needed considering the effects of fluid viscosity on impact pressures. Furthermore, model studies for sloshing under multi-component random excitations with phase difference should be carried out to investigate sloshing loads.

Acknowledgements

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