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Experimental Investigation on Effect of Horizontal Ring Baffles on the Sloshing Behaviour of Ground Supported Cylindrical Water Tank

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Abstract**: Liquid sloshing is generally caused by external container excitation, and often has significant influence on the response of the container. The liquid sloshing generates significant localized pressure on the tank walls and roof inflicting damage to the constituent parts and in the worst case scenario leads to the complete structural failure. Baffles are used effectively to reduce the sloshing response of liquid in the liquid storage containers by destroying the continuity of the pressure distribution on the wall along the vertical direction. In this study, the damping effect of the horizontal baffles inside a liquid storage tank is investigated. The horizontal ring baffle wall located at two heights equal to 0.8 and 0.9 of the water height was used for the study. A parametric study showed that the ring baffles are effective in reducing the sloshing oscillations.**

Keywords: Sloshing, Dynamic Behaviour, Baffle wall, Water Tank

I. INTRODUCTION

Water tanks are critical and strategic structures, and damage to them during earthquakes may endanger drinking water supply, cause failure in preventing large fires and contribute to substantial economic loss. This is because an active water supply is essential for controlling the outbreak of fires that may occur during earthquakes, which if left uncontrolled leads to a great deal of damage and the loss of lives (Aslam and Godden, 1979). Sloshing is the phenomenon which can be observed in the liquid storage tanks of large vessels, aircrafts, and automobiles. Sloshing is the free surface motion inside a container caused by any disturbance to partially filled liquid containers.

Freeboard is generally provided to allow liquids to slosh freely inside to prevent sloshing impact on the tank roof. If the liquid is allowed to slosh freely, it leads to the development of forces that cause additional hydrodynamic pressure in case of storage tanks and additional vehicle accelerations in case of moving tanker and space vehicles. However, in most of the tanks, especially those with small aspect ratio (i.e. height to length ratio), providing required freeboard leads to uneconomical design.

There are many failure of liquid storage tanks are observed in past history. In Japan, many petroleum tanks were damaged by the sloshing during 1964 Niigata earthquake, 1983 Nihonkai-chubu earthquake and 2003Tokachi-oki earthquake. During 2007 Chuetsu-okiearthquake, radiation-contaminated water in a nuclear power plant spilled. In Japan, large earthquakes, such as Tokai, Tonankai, and Nankai earthquakes, are predicted to occur within50 years, which will show similar, damage to the existing tanks. An example of such a failure is shown in figure 1 and figure 2.

Fig. 1. Sloshing Spill over the Rim of an Oil Tank (2010 Maule, Chile earthquake).

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Fig. 2. Damage seals of a tank from the sloshing of stored Liquid.

To prevent such effects, obstacles like baffles can be placed in the oscillating liquid; fluid separation around baffles results in energy dissipation and reduction in sloshing amplitude and consequent hydrodynamic loads. Baffle destroys the continuity of the pressure distribution on the wall along the vertical direction. Namely, the behaviour of the liquid can be divided into two parts. The liquid above the baffle behaves like a sloshing one. The liquid below the baffle behaves like a rigid one. In circular-cylindrical tanks the resonant frequency can be up to 15% higher than the un-baffled tank value when a horizontal ring baffle intersects the surface (partly by apparent reduction in the free surface diameter).

II. LITERATURE REVIEW

The aerospace industry has made important contributions to the research on the dynamic behaviour of liquid storage vessels. Baur (1964) developed a comprehensive mathematical model for application in the design of fuel tanks in space vehicles. The study was extended further by Abramson (1966) who thoroughly investigated, both analytically and experimentally, the sloshing problem pertaining to liquid propellants in launching vehicles of satellites and rockets.

Housner (1957, 1963) in his seminal works on the subject of dynamic analysis of liquid storage tanks, made analyses about the hydrodynamic pressures exerted on the walls of rigid tanks subject to unidirectional horizontal seismic ground motion. In a simplified procedure, he divided the liquid into two-mass system: a part of the liquid at the bottom of the container moves in unison with the container and behaves the same way as solid material will do while the liquid above it participates in sloshing with a different dynamics having long period of vibration. Thus, the hydrodynamic pressure was divided into two parts; first, the impulsive component caused by the portion of the liquid at the bottom accelerating with the container and the convective component associated with the sloshing liquid. The liquid was assumed to be incompressible and undergo small displacement. Due to its implementation simplicity, it has been adopted in many codes and standards with certain modifications. Later, with some modification, Epstein (1976) presented simplified expressions and curves to estimate bending, overturning moments and maximum free surface displacement.

Ma et al. (1982) proposed an alternative approach which included both acoustic and sloshing interaction of the fluid and the structure, and studied the seismic behaviour of liquid storage tanks. The influence of tank-wall flexibility on the hydrodynamic pressure and sloshing wave height was demonstrated. They used fluid-structure interaction program FLUSTR for implementation of the model. It was observed that proper inclusion of the fluid inertia is of paramount importance in assessing the dynamic characteristics of the fluid-tank system and higher mode sloshing response are important to post-earthquake sloshing analysis.

Kobayashi et al. (1989) conducted experimental and analytical studies to compute the liquid natural frequencies and the resultant slosh forces in horizontal cylindrical tanks. An effective calculation method of the small- amplitude slosh response was presented by substituting an equivalent rectangular tank for a horizontal cylindrical tank. The calculated natural frequencies, slosh wave height for longitudinal and transverse excitation were supported by experimental results. The study reported that longitudinal and transverse slosh responses were independent of each other and no effect of the vertical excitation on the slosh response was observed.

Biswal et al. (2006) studied 2D nonlinear sloshing response of liquid in non-deformable cylindrical and rectangular tanks with rigid baffles subjected to harmonic base excitation. Baffles close to the free surface of the fluid were found more effective in reducing the effect of sloshing.

Chen et al. (2007) conducted a nonlinear three-dimensional numerical study on the sloshing behaviours of cylindrical and rectangular liquid tanks under the assumption that the tanks were rigid and firmly fixed to the ground. The liquid was assumed to be incompressible, inviscid, and rigidly fixed. The sloshing response was studied under harmonic as well as recorded earthquake excitation. The results were experimentally verified by small scale model test. It was observed that linear model cannot treat the resonant excitation, if the forced frequency was equal or close to the natural frequency of the liquid.

Maleki and Ziyaeifar (2008) proposed a theoretical damping model to investigate the damping effect of baffles in circular cylindrical liquid storage tanks, and simultaneously carried out experiments for verification of the theoretical models. Their study concerned two kinds of baffles; horizontal ring and vertical blade baffles. They observed that the damping ratio of the sloshing mode in the presence of these baffles depended on the tank and baffle dimensions in addition to the location of the baffle. The ring baffles were found to be more effective in reducing the sloshing oscillations. They also showed that the damping ratio depended on the sloshing wave amplitude.

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Mirzabozorg et al. (2012) made use of stage of coupled liquid-tank system in three-dimensional space, subjected to an artificial as well as a three components earthquake ground motion, in time domain considering the surface sloshing effects. The highlight of the observation was that including the convective term may leads to phases of the convective and impulsive components in the liquid domain.

III. EXPERIMENTAL SETUP

The subject of the current study concerns a cylindrical steel water storage tank. The experimental model, prepared for the purpose of study has a diameter and total height equal to 500 mm and 600 mm respectively (Design as per IS 805, 1968). The model has been made of mild steel of thickness 0.7 mm. The structure has been fixed by to the platform of the shaking table by means of welding. The cross section detail of the tank is given below in figure 3, shaking table fabricated at the Federal Institute of Science and Technology, Angamaly, Kerala has been used in the experimental study (Fig. 4).

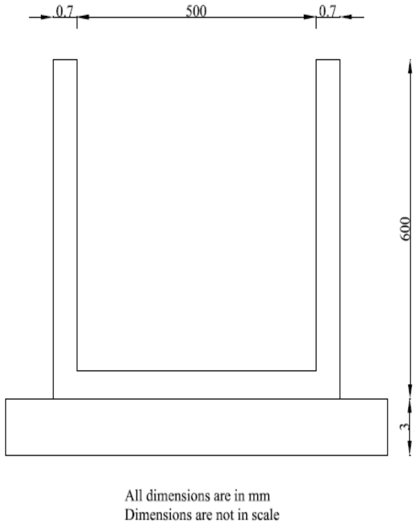


Fig. 3. Section of the Proposed Tank

Fig. 4. Water Tank attached to Shaking Table

For the purpose of taking readings, six small yet accurate scales were fabricated and placed inside the water tank. The sloshing waves were recorded using a high resolution video camera.

The Shaking Table is a unidirectional device with the platform dimension 1200 mm x 60 mm. The model is symmetrical, and for this reason, the vibration excitation of the model has been implemented for only one horizontal direction consistent with the movement of the shaking table platform

The natural frequency of sloshing is determined as per IS 1893 part 2 (2014) and it is obtained as 1.35Hz. The shaking table tests have been carried out at a constant excitation frequency of 1 Hz and variable amplitude of vibration. The shaking table test were conducted at different water levels of 300mm, 400mm and 500mm, for three different amplitudes of 5 mm, 10 mm and 20 mm respectively for each.

The design of baffle wall was done based on the test conducted by Abbas Maleki& Mansour Ziyaeifar.

The width of horizontal ring baffle was taken as 10% of radius of the tank, i.e. 25mm. Hence the outer diameter of horizontal ring baffle wall is fixed as 500mm and inner diameter is taken as 450mm. The thickness of baffle walls is taken as same as that of tank wall i.e., 0.7mm

An illustration of the designed baffle wall is shown in the figure 5. Figure 6 shows the schematic representation of horizontal ring baffle wall attached to tank.

Fig. 5. Horizontal Ring Baffle Wall

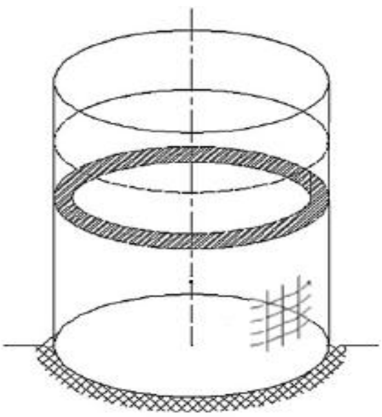


Fig. 6. Cylindrical Tank with Horizontal Ring

IV. THE EFFECT OF SLOSHING: WITHOUT BAFFLE WALL

The first set of dynamic response analyses of the modelled tank is related to the sloshing response to base harmonic excitation at constant frequency. The experiment was conducted at different water heights for amplitude of vibration 5mm, 10mm, &20mm. The maximum sloshing heights for each case were noted. The corresponding wave height at different points along the diameter simultaneously was also noted to get these results.

An illustration of experimental set up for measurement of water height is given in figure 7.

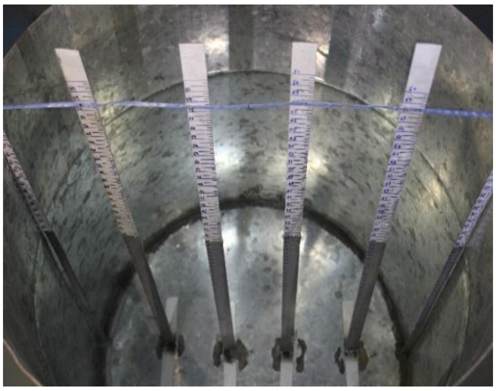
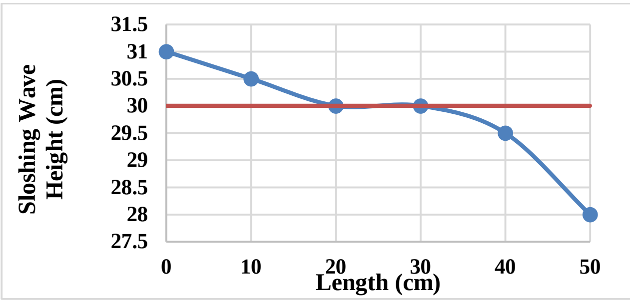


Fig. 7. Experimental set up for measurement of sloshing wave height

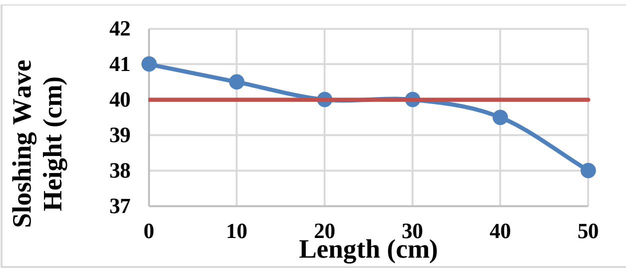
A. *Results and Discussion*

First the experiment was conducted without baffle wall for amplitudes of vibrations 5mm, 10mm and 20mm and water heights 300mm, 400mm and 500mm.

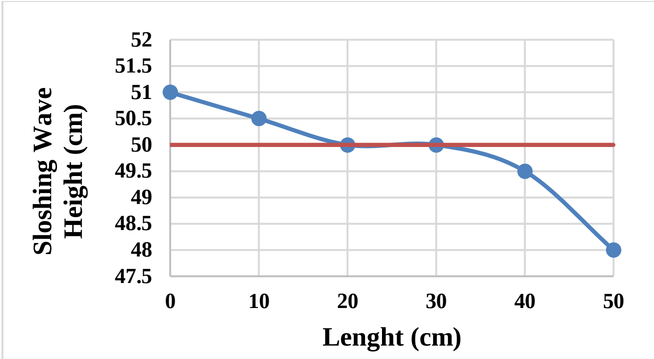
The sloshing curves for 5 mm amplitude obtained for 300 mm, 400 mm and 500 mm water height along the length of tank is shown in figures 8 a, b & c respectively.



(a) 300 mm water height



(b) 400 mm water height



(c) 500 mm water height

Fig. 8. Variation of sloshing wave height along length of tank-amplitude of vibration 5mm

Similarly, the sloshing wave heights for 10mm and 20mm amplitude were noted. The Table 1 gives a comparison between water heights the various test amplitudes.

Table 1. Sloshing Wave Height for Different Amplitude of Vibration

Amplitude of Vibration (mm)	Water Height (mm)					
	300	400	500	300	400	500
	Sloshing Wave Height (mm)					
	Rise			Fall		
5	10	10	10	20	20	20
10	30	30	25	25	30	30
20	50	60	Spill	55	55	Spill

From the above table, it can be seen that during the test for 300mm water height at 5mm amplitude of vibration, the rising sloshing wave height was found to be 10mm. When amplitude was increased to 10mm there was 200% increase in sloshing wave height. Similarly, a 400% increase in sloshing wave height was found for amplitude of 20mm.

The following observations were found during the study

I. As the amplitude of vibration increases the sloshing wave height also increases.

II. Sloshing wave height remains almost constant for different water height.

V. THE EFFECT OF SLOSHING: WITH BAFFLE WALL

Experiments have been carried out for each ring baffle with water height equal to 400mm and 500mm which are equivalent to height to radius ratios of 0.8 and 1. In each case the baffle was located at two heights equal to 0.8 and 0.9 of the water height and the tank was excited at corresponding sloshing frequency with three different excitation amplitudes of 5mm, 10mm and 20 mm. The position of horizontal ring baffle wall in the tank is illustrated in figure 9.

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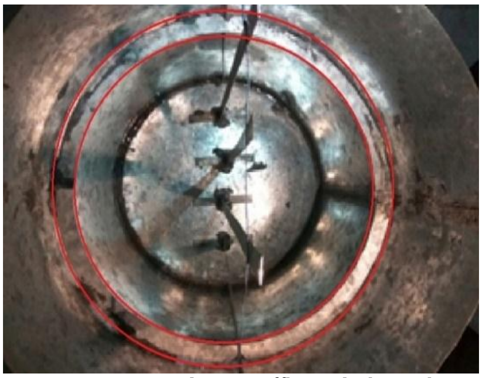

Fig. 9. Horizontal Ring Baffle inside the Tank

A. Results and Observations

From literature survey, it was found that baffle walls at lower water heights are not effective in controlling the sloshing effect. Hence no baffle walls are provided for 300mm water height. For 400mm water height, baffle walls are provided at 320mm (0.8 times water height) and 360mm (0.9 times water height). The comparison for sloshing water heights with and without baffle walls for 400mm water height obtained for 5mm, 10 mm and 20 mm amplitude along the length of tank is shown in figures 10, 11 & 12 respectively.

In Table 2, "WB" represents the sloshing wave height without baffle wall, "BR 320" & "BR 360" represents the horizontal ring baffle wall placed at 320mm& 360 mm from the bottom.

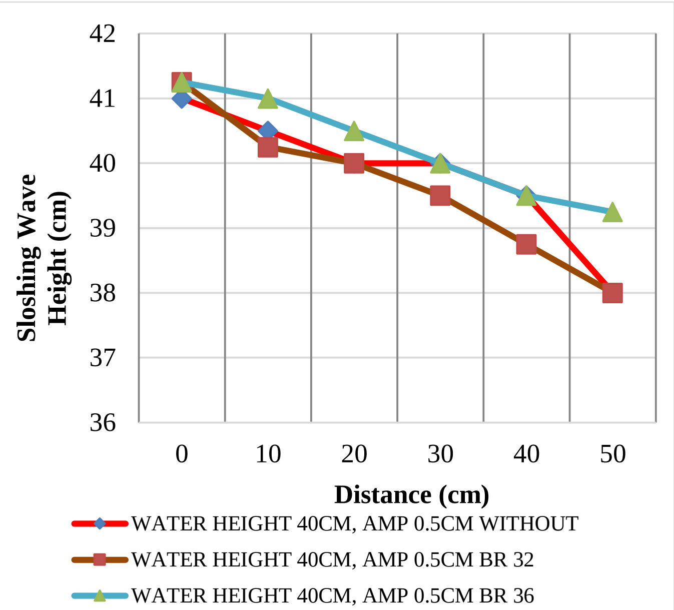

Fig. 10. Sloshing Curves for 5mm Amplitude of Vibration @ 400 mm Water Height

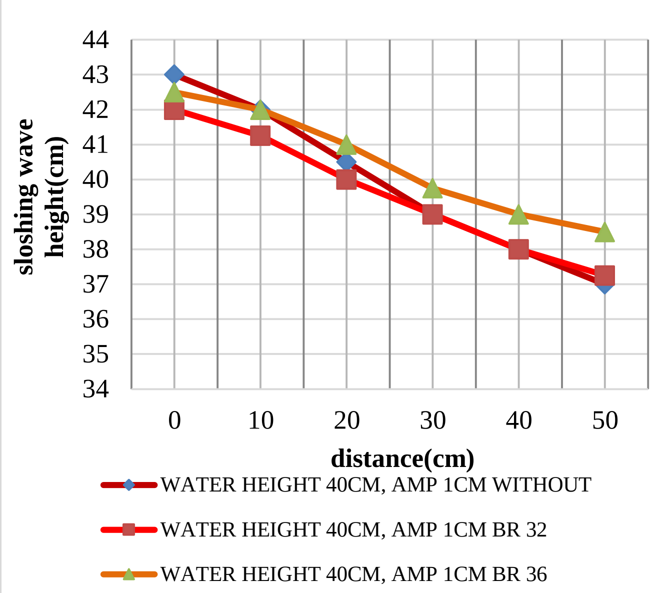

Fig. 11. Sloshing Curves for 10 mm Amplitude of Vibration @ 400 mm Water Height

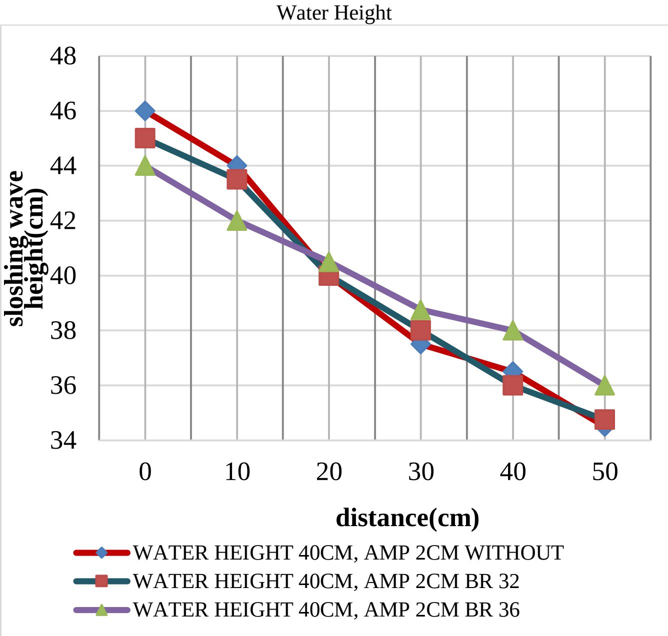

Fig. 12. Sloshing Curves for 20 mm Amplitude of Vibration @ 400 mm Water

The comparison between sloshing water heights with "with & without baffle walls" for 500 mm water height obtained for 5mm, 10 mm and 20 mm amplitude respectively is shown in table 5.1.1and figures 13, 14 & 15. For 500mm water height, baffle walls are provided at 360mm (0.72 times water height), 400mm (0.8 times water height) & 450mm (0.9 times water height) of water heights.

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Table 12. Sloshing Wave Height for 500mm Water Height

LENGTH (mm)	WATER HEIGHT 500 mm, AMP 5 mm				WATER HEIGHT 500 mm, AMP 10 mm				WATER HEIGHT 500 mm, AMP 20 mm		
	WB	BR 360	BR 400	BR 450	WB	BR 360	BR 400	BR 450	BR 360	BR 400	BR 450
0	1	0.5	0.5	0.75	2.5	1.75	2.25	2.25	6.5	5	4
10	0.5	0	0.25	0.25	2	1	1	1	4	3	1.5
20	0	1	0	0	0.5	0	0	0	1	0	0
30	0	1.5	0.5	0.75	1.5	1.5	1	1	3.25	2.25	1.5
40	0.5	2	1	1	2.5	2.25	2	2	5	3.25	3
50	2	2.5	1.25	1.5	3	3	3	3	6.5	5	3.5

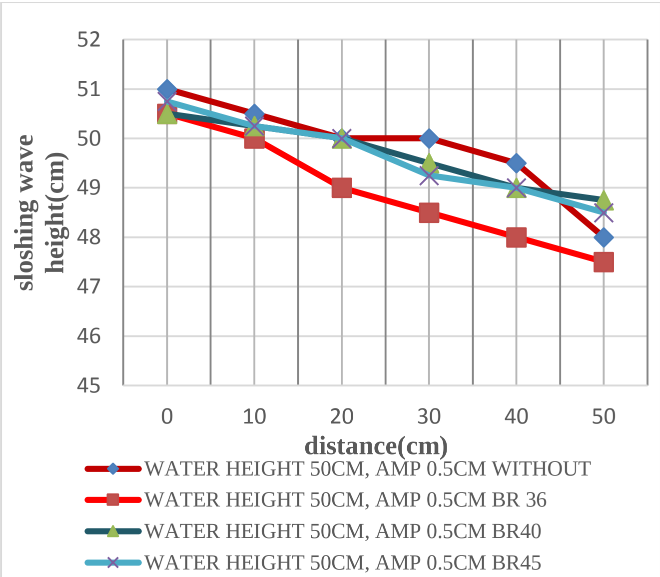

Fig. 13. Sloshing Curves for 5 mm Amplitude of Vibration @ 500 mm Water Height

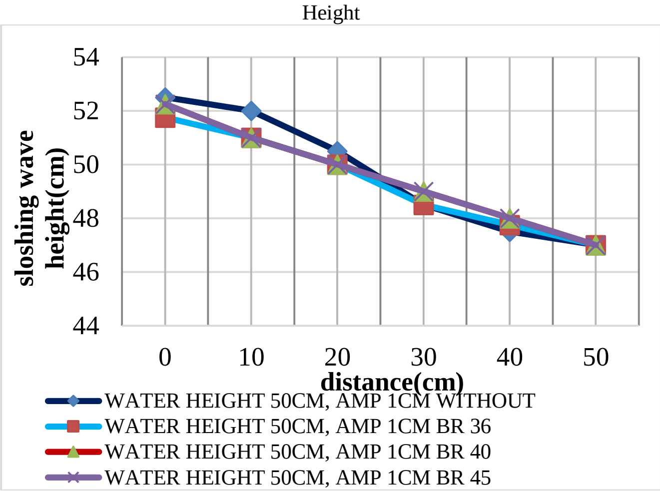

Fig. 14. Sloshing Curves for 10 mm Amplitude of Vibration @ 500 mm Water Height

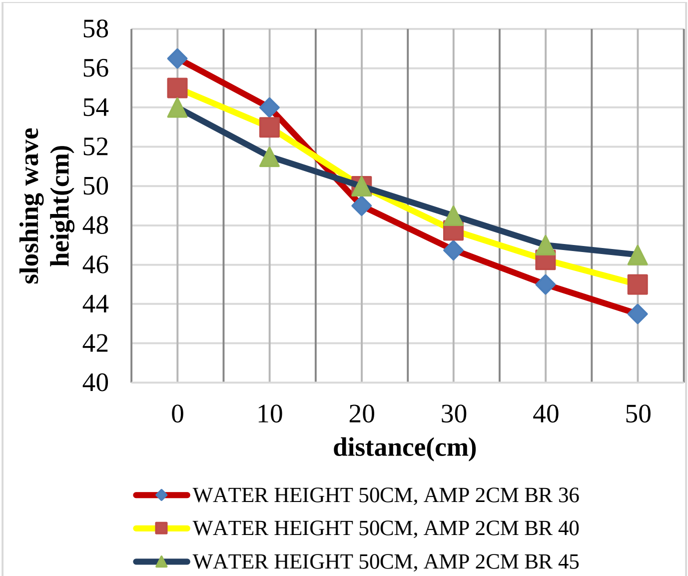

Fig. 15. Sloshing Curves for 20 mm Amplitude of Vibration @ 500 mm Water Height

For 20mm amplitude of vibration for 500mm water height spilling of water is observed, when there is no baffle walls are provided.

The following observations were found during the study

1. The horizontal ring baffle wall is found to be effective in reducing sloshing wave height, in all amplitudes of vibration.
2. For lower amplitude it is found that baffles at lower position is more effective
3. For higher amplitude it is found that baffles at higher position is more effective

VI. CONCLUSIONS

The results from the experimental study confirm that knowing the water height within the tank is essential for the structural analysis of a storage steel tank. Dynamic behaviour under earthquakes has been found to be considerably different for different levels of liquid filling.

Comparison between water heights for various test amplitudes show that as the amplitude of vibration increases the sloshing wave height also increases. Also it is found that sloshing wave height remains almost constant for different water height.

The developed model show that the sloshing dynamics at the presence of the baffle depends on tank and baffle dimensions and its configuration in addition to the location of baffle and sloshing height amplitude. The horizontal ring baffle wall provided at all water height is found to be more effective. For lower amplitude it is found that baffles at lower position is more effective whereas for higher amplitude it is found that baffles at higher position is more effective.

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