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Investigations on the Sloshing Behavior of Elevated Rectangular Water Tanks with and Without Internal Obstruction

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***Abstract*:-- Sloshing has been one of the major concerns in the design of liquid storage tanks, particularly under seismic excitation. There are evidences of failures of liquid storage tanks due to sloshing, during the past earthquakes. The consequential increase in the hydrodynamic forces on the tank walls depend on a variety of factors such as geometry of the tank, height of liquid in the tank , fluid tank interaction etc.,. Added to these, the presence of an internal obstruction in the form of protruded columns or a shaft in to the tank structure will make the sloshing behavior all the more complicated.**

This paper presents the results from an experimental study conducted on elevated rectangular tank models, on a mini shake table , simulating the seismic excitation . Sloshing heights and sloshing patterns are recorded from the experiments and their variation was studied by varying parameters such as tank capacity, spacing of bracings, water level in the tank and the amplitudes of vibration. All the studies were made with and without the presence of internal obstruction. Results obtained were compared with those obtained theoretically from the relevant code and also with those obtained from a software tool SaE Ca net. It is observed that the experimental results are in close agreement with the theoretical ones.

***Index Terms*— Elevated rectangular liquid storage tanks , Sloshing behavior , seismic excitation.**

I. INTRODUCTION

A. Definition and meaning of sloshing

Sloshing means any motion of the free liquid surface inside its container. It is caused by any disturbance to partially filled liquid containers and is one of the major concerns in design of liquid storage tanks, moving tankers fuel tank of space vehicles and also in ships. During lateral base excitation seismic ground acceleration causes hydrodynamic pressure on the tank wall which depends on the geometry of tank, height of liquid, properties of liquid and fluid-tank interaction. There are evidences of failures of liquid storage tanks during earthquakes in the past , particularly due to sloshing.

B. Effect of sloshing

Earthquake induced sloshing in tanks is caused by ground motions which attenuate slowly with distance. A minimum freeboard is needed to accommodate the sloshing waves. Since freeboard results in unused storage capacity, many tanks lack the required freeboard. As a result, sloshing waves impact the roof, generating additional forces on the roof and tank wall. In spite of the fact that many tanks have suffered extensive damage due to sloshing waves in the past earthquakes, the effect of sloshing waves is usually ignored in seismic design of tanks.

Insufficient freeboard causes upward load on the roof due to impacts from the sloshing wave, and increase in impulsive mass due to constraining action of the roof. The upward force on the roof can damage the roof, break the roof shell connection or tear the shell. Sloshing causes extreme lateral forces, moments and shears in various components of tank structures (supporting structures or tank structures as the case may be) which may cause even failures, if not accounted properly.

II. REVIEW OF WORKS DONE ON QUANTIFYING SLOSHING EFFECT IN ELEVATED WATER TANKS REVIEW STAGE

Many researchers and scientists did their research to quantify the sloshing effect in elevated tanks. Housner (1963) was the first to propose models to quantify the sloshing .and those models are being used even today .Sloshing of liquid in a tank is basically accounted by splitting the liquid in to two components viz., Convective and Impulsive . These components will be acting on the tank walls at different heights that depend on the geometry proportions of the tank and the level of liquid in the tank as well .

Tang, M. and Chang (1991) shows that the sloshing motion in a tank containing two liquids are quite different from in a identical tank containing only one liquid, and the sloshing wave height computed based on the one liquid assumption may lead to an un conservative result. This finding make it a necessity to consider the effect of two liquids on the computation of hydrodynamic pressure in the fuel recycling tank .This deal with the dynamic response of a tank containing two different liquid subjected to seismic excitation. Both analytical and numerical methods are employed in the analysis. Subhash Babu and Bhattacharyya (1994) developed a numerical scheme based on finite element method to estimate the sloshing height in the seismically excited tank and to calculate the resulting pressure.

Choun and Yun (1998) also studied the sloshing response of rectangular tanks considering linear wave theory. Shenton et al., (1999) presents the results of an analytical investigation of the seismic response of isolated elevated rectangle water tanks. A discrete three-degree-of-freedom model of the isolated structure is presented that includes the isolation system, tower structure, and sloshing fluid. Seismic responses of base – isolated elevated tanks were studied by H W Shenton III & P Hampton (1999) seismic response of elevated water tanks‟. The study involves a discrete three-degree of freedom model of the base – isolated structure & sloshing fluid. The results of their studies show that the seismic isolation system is effective in reducing the tower drift, base shear, overturning moment. The study also concluded that the isolation is most suitable for small capacity tanks.

Shenton and Hampton(1999) presented the result of an analytical investigation of the seismic response of isolated elevated rectangle water tanks. A discrete thee-degree-of-freedom model of an isolated structure has been developed that includes the isolation system, tower structure, and sloshing fluid. Fluid-structure interaction is modeled using the mechanical analogy proposed by Housner. Premasiri (2000) also completed a concentrated research on the sloshing in the reservoirs subjected to multi DOF base motion. Comparing the result of experimental test on the rectangular tanks subjected to multi DOF base motion, with the analytical solution using linear superposition method.

Praveen Malthotra (2006) presented a simple method to estimation additional loads on tank roof, wall and foundation due to the impact from sloshing wave. He divided the mass of the mass into impulsive and convective mass and both mass are attached by linear spring.

Akyildiz et al. (2006) investigated the three-dimensional effects on the liquid sloshing loads in partially filled rectangular tanks by introducing non-linear behaviour and damping characteristic of the sloshing motion using Volume of Fluid (VOF) techniques. Livaoglu (2007) also investigated the effect of parameters such as fluid-structure interaction, soil structure interaction and presence of embedment on the dynamic responses of rectangular tanks. Ghaemmaghami and Kianoush (2010) conducted intensive research on the dynamic time-history responses of the rectangular tanks and also concluded the wave amplitude at the corner of the three-dimensional tank is higher than the wave amplitude at the middle cross section of the walls. The amplification of wave height at the corner of the tank against the one at the middle of the wall is profoundly related to tank configuration as well as the water depth.

Waghmare and Madhekar (2013) has conducted experimental investigation on Behavior of Elevated Water Tank under Sloshing Effect and also concluded Sloshing of water in tank depends not only on the volume of water in tank but also on staging height and h/D ratio. A detailed note on the computation of the sloshing effects is given in the draft code (IS 1893 Part II)

III. NEED FOR FURTHER STUDIES ON TANKS CONSIDERING SLOSHING AND INTERNAL OBSTRUCTION

Several special situations crop up in the practical field such as, presence of internal obstructions (in the form of columns / shafts protruding in to the tank part) . This aspect is still unexplored properly and requires attention. Keeping the non-availability of formulae for the computation of sloshing effects on tanks for such special situations in rectangular water tanks which are very commonly built in practice, an attempt is made in this work to study the dynamic behavior of rectangular water tank models considering the effects of sloshing and internal obstruction. For this purpose, rectangular tank models of two capacities are tested on a unidirectional

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Dimension of Sliding Platform	500mmX500mm
Operating Frequency	0-25Hz
Amplitude Resolution	1mm to 10mm
Max. Payload	50 kgs

mini shake table, giving two excitation amplitudes as inputs. By varying the parameters such as water levels in the tank, spacing of bracings, frequency of excitation and capacity of the tank, the sloshing response of the tank models is noted in terms of Sloshing heights and Sloshing patterns, with and without internal obstruction in the tank. Sloshing heights obtained experimentally are compared with the theoretical values obtained from the formulae given in code and those obtained from a dedicated software as well.

IV. GSDMA GUIDELINES FOR SEISMIC DESIGN OF LIQUID STORAGE TANKS

Most elevated tanks are never completely filled with liquid. Hence a two-mass idealization of the tank is more appropriate as compared to a one-mass idealization, which was used in IS 1893: 1984. Two mass models for elevated tank was proposed by Housner (1963) and is being commonly used in most of the international codes.

A. *Sloshing Wave Height*

Maximum sloshing wave height for a rectangular tank is given by

$$d_{max} = (A_h)_C \, R \, L/2$$

Where, $(A_h)_C$ = Design horizontal seismic coefficient corresponding to convective time period Given in IS 1893 Part II

V. SIMULATION TESTS

To investigate the real behavior of the structures against earthquakes, several seismic test methods are used. Most popular methods are Real earthquake experiences, In situ tests, Static tests (pushover analysis), Shake table tests, Pseudo-dynamic tests, and Centrifuge tests. Among these tests, Shake table testing is being widely used as it is the only available means to reproduce nearly true dynamic effects of the earthquakes imposed on structures. Shake table generates harmonic motion in required direction to study the behavior of an earthquake of similar pattern.
Throughout the world there are variety types of shake tables appropriate for use in a seismic certification program. For the present study a mini-shake table is used with the following features.

A. *Horizontal Shake Table*

Table.1. Features of the Horizontal Shake Table

table will be able to generate harmonic motions of different amplitudes and, the amplitude of base motions can be varied by changing the eccentricity of the cam. By varying the speed of the motor, the frequency content of the base motion can be varied. Accelerometers, Data Acquisition System, a lap top and a Vibration analyzer software "Kampana" are provided for measuring vibrations of the structural models , acquiring the Data, Plotting different Graphs etc.,. Information appearing on the display screen can be seen in real time and in offline mode with the help of the software. Display Layout consists of Configuration and control, Time/Frequency domain display, Display configuration and Vibration Parameter display.

VI. MODELS CONSIDERED FOR STUDY

The setup consists of four rectangular columns of aluminum (1200mmx25mmx3mm) ,two sets of top plate & base plate with dimensions(300mm X 200mm) and (200mm X 200mm) ,Water tank model of Perspex material of thickness of 5 mm and tank dimensions are 300mmx200mmx200mm- 12L capacity and 200mmx200mmx200m-8L capacity which are molded on top plate. Horizontal braces of sizes of 200mm X 25mmX3mm, 300mmX25mmX3mm which are placed @ 200mm c/c to column and @400mm c/c to column, respectively.

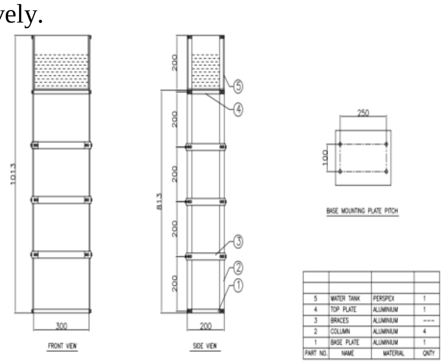

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Figure 1. Details of a typical structural model of the tank

VII. PARAMETERS VARIED

A. *Water Levels*.
a. Empty
b. 25% (50 mm water depth)
c. 50% of water(100 mm water depth)
d. 75% of water (150mm water depth)

B. *Spacing of Bracings*
a. 200 mm C/C
b. 400 mm C/C

C. *Capacity of Tanks*
a. 12L (300mmx20mmx200mm)
b. 8L (200mmx200mmx200mm)

D. *Amplitude input*
a. 3mm
b. 2mm

All these variations are done for two cases i.e., with and without internal obstruction in the tank.

VIII. RESPONSE PARAMETERS STUDIED

Frequencies, Peak displacements, Peak Accelerations, Sloshing patterns and Sloshing heights were studied as a part of the experimental work. However, only the sloshing heights and patterns are discussed here

IX. RESULTS AND DISCUSSIONS

A. *Sloshing Heights and Patterns*

It was practically difficult to record the sloshing heights and patterns for the tanks, particularly with higher amplitude input and for full water levels. However, a sincere effort is made to capture the sloshing patterns through photographs and video recordings. similarly efforts were made to record the sloshing heights with reference to the original water levels in the tanks before vibrations , by physical measurements with scale .This was also difficult for the case of full water levels for greater amplitude. Some of the photographs captured for different water levels and vibrating conditions are shown in figure 2. Based on these and the sloshing heights recorded, the following discussion is made.

Figure 2 : Typical sloshing patterns observed during the experimentation

B. *Absolute Maximum sloshing height*

Sloshing height is recorded as 180 mm for larger tank with 75% of water condition , 3mm amplitude input , 400mm spacing of bracing and without internal obstruction

C. *Variation with Water Levels*

Sloshing heights have in general increased gradually with increase in water levels for all conditions of tanks . However , for larger tank with 3mm amplitude , without internal obstruction the sloshing heights were gradually increasing up to a frequency input corresponding to zone 4 acceleration and then onwards decreasing for the frequency input corresponding to zone 5

D. *Sloshing Heights Using SaECa Net tool*

Sloshing height (mm) = Water height (h) + Wave height obtained from tool (W)
Calculation of Wave height by Sloshing Response:
Inputs: Water level: h (m) , Breadth of water tank : L (m) ,Velocity Response Spectrum : Sv (m/s) , Gravitational

acceleration (g) = 9.80665 (m/s2) ; X-axis : h (m) , Y-axis : W(m)

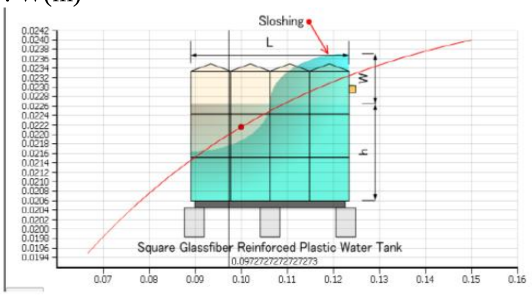

Figure 3 : Typical sloshing wave height for zone V

Table 2: Comparison of experimental and SaE Ca Net values of Sloshing heights

Input Acceleration	Experimental values (mm)			Dmax (mm)		
	25% of water level	50% of water level	75% of water level	25% of water level	50% of water level	75% of water level
0.1g	15	10	15	12.66	15.97	17.86
0.16g	18	25	22	20.16	25.56	28.58
0.24g	20	15	37	30.2	38.34	42.88
0.36g	25	17	28	45.33	57.51	64.31

Table 3: Comparison of Sloshing heights obtained experimentally and from code As per 1983:2002 (part II))

Input Acceleration	Experimental values (mm)			SaECa Net tool (mm)		
	25% of water level	50% of water level	75% of water level	25% of water level	50% of water level	75% of water level
0.1g	65	110	155	50.35	108.63	158.91
0.16g	68	125	160	56.35	120.8	165.32
0.24g	70	150	175	60.4	176.16	178.45
0.36g	75	117	165	61.41	122.1	151.23

X. CONCLUSIONS

Mini Shake table experiments provide an affordable and near true dynamic effect on structural models . They are thus useful tools in conducting simulation studies on models of liquid storage tanks . In the present study sloshing patterns and sloshing heights were observed experimentally , for structural models of elevated rectangular water tanks of two different capacities . The sloshing heights obtained experimentally for these two models are in good agreement with 'SaE Ca Net' tool results as well as those computed from draft code.

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