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Fluid-Structure-Soil Interaction Effects on Seismic Behaviour of Elevated Water Tanks
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Abstract
The multiple base motion effect on hydrodynamic pressure, acceleration of tank and fluid surface elevation problem in Elevated water tank is understood as a Fluid-Structure-Soil Interaction problem. Where, Soil-Structure interaction causes rocking motion and Fluid Structure interaction causes the hydrodynamic behaviour of water tank. According to the available literature, substantial amount of study has been done on behaviour of elevated steel water tank under pure rocking, but no study is done on water tanks with horizontal and vertical earthquake excitation, along with rocking motion. An experimental investigation for a 1:4 scale model of cylindrical steel elevated water tank has been carried out on shake table facility at CSIR-SERC, Chennai. Test program on elevated steel water tank consisted of combined horizontal, vertical and rocking motions, for a synthetic earthquake excitation for 0.1g and 0.2g accelerations, with increasing angle of rocking motion. The impulsive base shear and impulsive base moment values increase with increase in earthquake acceleration. Whereas, the convective base shear and base moment values increase for increase in earthquake acceleration, but decrease with increasing angular motion. Hence, there is no considerable effect of rocking motion on sloshing of water. The non-linearity in structure is observed, when the impulsive pressure of tank decreases with increase in tank acceleration. The pressure variation along tank height due to vertical excitation increased with increasing acceleration, and increased furthermore with added rocking. Using various codes available on water tanks, the recorded experimental results were used to calculate and compare the base shear, base moment, pressure variation in the tank.

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Keywords: Water tanks, Fluid-Structure-Soil Interaction, Seismic behaviour

1. Introduction
The forces due to earthquake-induced sloshing in fluid-filled water tanks are important considerations in the design of civil engineering structures. Seismic safety of elevated liquid-filled containers is of great concern because of the potential adverse economic and environmental impacts associated with failure of the container and liquid spillage on the surrounding area. As a result, a considerable amount of research effort has been devoted to a better determination of the seismic behaviour of liquid tanks and reservoirs and the improvement of associated design codes. In spite of this, there have been relatively few studies on the influence of simultaneous vertical, horizontal and rocking excitations with respect to the hydrodynamic problem of liquid sloshing.

The traditional approach to estimating earthquake-induced hydrodynamic loads as outlined for example, by Housner (1957) involves the use of an impulsive, or high frequency, effective fluid mass which accelerates with the container, together with an additional effective fluid mass which undergoes resonant motions at the lowest natural frequency of sloshing. The traditional approach is based on a number of assumptions which may not be applicable to the general case. Hence, the present study aims at understanding the basic mechanism of liquid sloshing in elevated water tanks according to traditional approach, studying the available standard methods of analysis and their comparison. Hydrodynamic behaviour of water tanks is observed by performing an experiment on water filled elevated cylindrical steel water tank model (1:4 scale) with multi-degree of freedom earthquake excitation (horizontal, vertical and rocking) given to it.
2. Literature Review
The study of hydrodynamic pressure on civil engineering structures dates back to 1930s, when Westergaard (1933) developed solution for impulsive pressure on harmonically excited, rigid vertical dams. Jacobsen and Ayre (1951) subsequently reported on analytical and experimental observations of rigid rectangular and cylindrical tanks under a simulated horizontal earthquake excitation.

Housner (1957, 1959) described an approximate solution for rigid rectangular, circular, elliptical, composite tanks and rectangular, cylindrical, segmental, stepped dams based on the assumption that the forces are made up of an impulsive component, corresponding to high frequency oscillations of the container, and a convective component corresponding to the lowest mode of liquid sloshing. Isaacson and Subbiah (1991) outlined the complete solution for rigid circular and rectangular tanks under harmonic and irregular base motion. Isaacson and Ryu (1998 a) described the hydrodynamic loads and fluid surface elevations for a rectangular reservoir for base motions in an oblique direction, based on an appropriate superposition of solutions for a uni-directional motion parallel to a pair of sides. They found that earthquake-induced motions in a direction of motion parallel to the shorter pair of sides always give the highest loads and surface elevations.

Earthquake-induced motions are three-dimensional and recent observations of recorded ground motions have shown that the maximum amplitude of the vertical component of ground acceleration can exceed the peak horizontal amplitude, especially near the epicenter. The fluid surface elevations and hydrodynamic pressures are affected during vertical excitation. Significant horizontal force is also observed in tanks with flexible walls.

The rocking motion of tanks can be idealized with the soil structure interaction effect. Furthermore, soil structure interaction on rigid tanks gives relatively very small displacement magnitudes, when compared to flexible tanks, R Livaoouglu (2009). The literature supports that there is no much effect on sloshing behaviour of water tanks due to additional rocking excitation.

3. Need of Study
The present investigation aims at study of hydrodynamic behaviour of elevated water tanks during multiple degree earthquake excitations experimentally. The values for studied parameters i.e. sloshing frequency, hydrodynamic pressure, base shear, tank acceleration and sloshing height are calculated for the same tank analytically following the standard codes and same are compared with the work of G W Housner(1954).

4. Fluid-structure-soil interaction
It is the combination of fluid structure interaction and Soil structure interaction. Fluid-structure interaction (FSI) is the interaction of some movable or deformable structure with an internal or surrounding fluid flow, which in our case is an elevated steel water tank. The deformations of a structure during earthquake shaking are affected by interactions between three linked systems: the structure, the foundation, and the geologic media underlying and surrounding the foundation. A seismic Soil-Structure Interaction (SSI) analysis evaluates the collective response of these systems to a specified free-field ground motion.

5. Available standard codes on seismic analysis of water tanks
Seismic analysis of liquid storage tanks account for the hydrodynamic forces exerted by the fluid on tank wall. Knowledge of these hydrodynamic forces is essential in the seismic design of tanks. Evaluation of hydrodynamic forces requires suitable modelling and dynamic analysis of tank-liquid system. These mechanical models, convert the tank-liquid system into an equivalent spring-mass system. Design codes use these mechanical models to evaluate seismic response of tanks. While using such an approach, various other parameters also get associated with the analysis. Some of these parameters are: Pressure distribution on tank wall due to lateral and vertical base excitation, time period of tank in lateral and vertical mode, effect of soil-structure interaction and maximum sloshing wave height. Design Codes have provisions with varying degree of details to suitably evaluate these parameters.

In this study, codes considered are: ACI 350.3, NZSEE guidelines and IITK-GSDMA Guidelines for seismic design of liquid storage tanks. These codes use the mechanical model developed by G W Housner, which is discussed in theory part. Eurocode 8 mentions mechanical model of Veletsos and Yang (1977) as an acceptable procedure for rigid circular tanks. For flexible circular tanks, models of Veletsos (1984) and Haroun and Housner (1981) are described along with the procedure of Malhotra et. al. (2000).

An important point while using a mechanical model pertains to combination rule used for adding the impulsive and convective forces. Except Eurocode 8, all the codes suggest SRSS (square root of sum of square) rule to combine impulsive and convective forces. Eurocode 8 suggests use of absolute summation rule. For evaluating the impulsive force, mass of tank wall and roof is also considered along with impulsive fluid mass. ACI 350.3 and Eurocode 8 suggest a reduction factor to suitably reduce the mass of tank wall. Such a reduction factor was suggested by Veletsos (1984) to compensate the conservativeness in the evaluation of impulsive force.
6. Experimental investigation
The aim of the experiment was to study the behaviour of elevated steel water tank model during horizontal and vertical along with rocking earthquake motions.

Table 1. Details of Steel water tank

<table>
<thead>
<tr>
<th>Diameter of tank</th>
<th>1m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height of Tank(total)</td>
<td>3.6 m</td>
</tr>
<tr>
<td>Height of staging</td>
<td>3m</td>
</tr>
<tr>
<td>Height of cylindrical tank</td>
<td>0.6m</td>
</tr>
<tr>
<td>Total weight of Structure</td>
<td>846 kg</td>
</tr>
<tr>
<td>Weight of Staging</td>
<td>250 kg</td>
</tr>
<tr>
<td>Weight of Cylindrical tank</td>
<td>182 kg</td>
</tr>
<tr>
<td>Weight of water</td>
<td>314 kg</td>
</tr>
<tr>
<td>The stiffness of structure</td>
<td>1400 kN/m (Etabs9)</td>
</tr>
<tr>
<td>Fundamental Natural frequency of structure</td>
<td>8.24Hz</td>
</tr>
</tbody>
</table>

**The frequency of the model steel tank falls in the range of 4-10Hz, which is the range of frequency for elevated water tanks.**

6.1 Dimensional Analysis
In planning model tests and the presentation of results, it is useful to carry out a dimensional analysis of the problem in order to identify the governing parameters so that controlled variables in the model can be suitably varied.

6.2 Earthquake modelling of structure
The steel tank model being an elastic model, the earthquake modelling of structure is done based on the scale factors given in the table below.

Table 2. Test Facilities

<table>
<thead>
<tr>
<th>Shake Table</th>
<th>Accelerometers (8 Numbers)</th>
<th>Pressure Transducers (2 Numbers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size=4m×4m</td>
<td>Measuring range ± 70 ms⁻²</td>
<td>Type: Charge</td>
</tr>
<tr>
<td>Max. displacement X,Y : ±150mm, Z : ±100mm</td>
<td>peak (± 7 g peak)</td>
<td>Capacitance: 129pF</td>
</tr>
<tr>
<td>Max. velocity X,Y,Z: ±80cm/s</td>
<td>Case material: Titanium ASTM grade 2</td>
<td>Sensitivity: 9.290 pC/PSI</td>
</tr>
<tr>
<td>Max. acceleration X,Y,Z: ±10m/s² at 30ton</td>
<td>Sensing element: Piezoelectric</td>
<td></td>
</tr>
<tr>
<td>Mass</td>
<td>Construction: Theta Shear</td>
<td></td>
</tr>
<tr>
<td>Frequency range 0.1 to 50Hz</td>
<td>Sealing: Hermetic</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Weight: 4.6 g</td>
<td></td>
</tr>
</tbody>
</table>

6.3 Test Program
The purpose of the experimental study was to measure the hydrodynamic characteristics of the tank due to the sloshing motion. The hydrodynamic characteristics of interest are the fluid surface elevation, the horizontal force on the tank, the overturning moment at the base of the tank and the hydrodynamic damping. It was expected that the parameters that would have the greatest influence on the performance of the tank would be the fluid depth d, the tank size characterized by the diameter, the exciting frequency for horizontal, vertical and rocking motion.

To record the behaviour of tank to excitation, 8 numbers of accelerometers were strategically placed on the tank, staging and shake table as shown in fig.2. Three pressure transducers were also placed on the tank wall at equal heights to measure hydrodynamic pressure of water due to sloshing.

A pulse signal is initially given to the water filled structure to experimentally calculate the natural frequency.

The following series of tests were carried out:
1. Horizontal excitation at 0.1g with no rocking.
2. Horizontal excitation at 0.2g with no rocking.
3. Horizontal excitation at 0.1g with rocking (75ms delay)
4. Horizontal excitation at 0.1g with rocking (150ms delay)
5. Horizontal excitation at 0.2g with rocking (150ms delay)

Fig.2. Line diagram of experimental setup

6.4 Earthquake Excitation
For the laboratory tests, the synthetic earthquake record has been used as the basis for simulating the earthquake excitation. In the present study, the maximum acceleration is scaled to 0.1g and 0.2g without time scale change, so that the velocity and displacement maxima differ from the full-scale condition. The frequency is 0.5 - 12 Hz and overall duration is about 30s. The time history applied is squeezed to 30 seconds from 60 seconds following the scale factors given by Harris and Sabnis.

6.5 Rocking motion
Effect of soil structure interaction can be brought by producing rocking motion in earthquake excitation. This is done by introducing lag between the two vertical actuators of shake table facility, in their vertical excitation signal. The lag between two actuators is calculated based on the shear wave velocity of soil (considered 100m/s) and frequency input as 3Hz. The rocking motion is introduced by considering one-half and one-fourth of the time period of frequency input considered, i.e. 150ms and 75ms. It can be understood that maximum rocking motion will be observed in 150ms lag between two actuators motion.

The signal is given such that the signal at Z1=Z4 and Z2=Z3, with corresponding lags of 0ms, 75ms and 150ms.

7. Results and discussions
Impulsive mass is a rigid mass of high frequency, assumed being attached to the tank. Whereas convective mass is a low frequency fluid mass that is vibrating in the structure. The response of impulsive and convective mass of water in the structure is separated by filtering the high frequency and low frequency values respectively from the response recorded.

7.1 Base Shear Calculations
Impulsive base shear for experiment is calculated using the recorded tank acceleration at the bottom of tank and calculated
theoretical impulsive mass from the standard guidelines. The convective base shear for experiment is calculated by working out the acceleration from recorded pressure values and calculated theoretical impulsive mass from the standard guidelines. The variation of impulsive and convective base shear values (kN) for all the five applied earthquake excitations are shown in the Fig.3(a) and (b).

![Convective Base Shear (kN)](image)

![Impulsive Base Shear (kN)](image)

**Fig.3.** Base Shear (a) Convective (b) Impulsive

7.2 Base moment calculation

Base moment is moment acting at the base of structure by the force exerted by impulsive and convective mass, and is calculated using the base shear values. The variation of base moments for all the five types of earthquake excitations is shown in the Fig. 3(a) & (b).

![Convective Moments(kN.m)](image)

![Impulsive Moments(kN.m)](image)

**Fig.3.** Base Moment (a) Convective (b) Impulsive

7.3 Pressure variation along height:

![Convective Pressure Variation along tank height](image)

![Impulsive Pressure Variation along tank height](image)

**Fig. 4.** Convective Pressure due to horizontal excitation
Fig. 5. Impulsive Pressure due to horizontal excitation

![Pressure on tank wall due to vertical excitation](image)

Fig. 6. Pressure variation due to vertical excitation

Pressure due to vertical excitation is calculated using the observed tank vertical acceleration values and its variation along tank height is computed using simple mechanics equation of mass and gravity.

7.5 Acceleration variation along tank height

![Variation of acceleration along structure](image)

Fig. 7. Acceleration variation along structure height

7.6 Comparison of results by various standard codes

The type of earthquake excitation applied during the experiment was a synthetic spectrum, so the computation of values from codes was done in accordance with the recorded acceleration values.

<table>
<thead>
<tr>
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<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Convective Frequency (Hz)</td>
<td>0.9</td>
<td>0.89</td>
<td>0.9</td>
<td>0.843</td>
<td>0.909</td>
</tr>
<tr>
<td>Impulsive Frequency (Hz)</td>
<td>-</td>
<td>0.264</td>
<td>0.335</td>
<td>0.357</td>
<td>0.196</td>
</tr>
<tr>
<td>Convective Time Period (s)</td>
<td>1.103</td>
<td>1.117</td>
<td>1.1</td>
<td>1.18</td>
<td>1.11</td>
</tr>
<tr>
<td>Impulsive Time Period (s)</td>
<td>-</td>
<td>3.78</td>
<td>2.98</td>
<td>4.67</td>
<td>5.08</td>
</tr>
<tr>
<td>Impulsive Base Shear (kN)</td>
<td>-</td>
<td>1.382</td>
<td>2.84</td>
<td>1.62</td>
<td>6.35</td>
</tr>
<tr>
<td>Convective Base Shear (kN)</td>
<td>-</td>
<td>0.00263</td>
<td>0.0159</td>
<td>0.008</td>
<td>0.0259</td>
</tr>
<tr>
<td>Impulsive Pressure on wall (kPa)</td>
<td>3.06</td>
<td>0.921</td>
<td>0.843</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Convective Pressure on wall (kPa)</td>
<td>0.000265</td>
<td>0.002501</td>
<td>0.001588</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
8. Observations

1. There is no much effect of rocking on sloshing of water in the tank by visual observation.
2. Effect of rocking is observed maximum as amplification of acceleration, base shear and base moment values.
3. Because of the tank geometry, i.e. circular shape, a big sloshing wave that develops during the excitation divides itself into very small waves, which are developed as a result of interference of waves produced due to collision of produced wave with the walls of the tank.
4. Pressure on tank wall due to vertical excitation increases with increase in rocking and amplitude of excitation.
5. Sloshing wave height is observed maximum as 0.18m in case of 0.1g acceleration excitations and for 0.2g acceleration excitations, water splashes out of the tank.

Fig. 8. Interference of waves

9. Conclusion

The available literature supports behaviour of elevated steel water tank under pure rocking, but no study is done on water tanks with horizontal and vertical earthquake excitation, along with rocking motion. The problem is understood as a Fluid-Structure-Soil Interaction problem, with Soil-Structure interaction causing rocking motion and Fluid Structure interaction causing the hydrodynamic behaviour of water tank. A synthetic spectrum was applied and following observations were made.

The high frequency impulsive mass behaviour and low frequency convective modes behaviour under earthquake excitation was studied after filtering high and low frequencies.

The base shear and base moment values for impulsive modes were found to be higher (increased) in rocking excitation. Whereas, the convective base shear and base moment values were found to be lower (decreased) during increasing angular motion. This happens due to cancelling out of convective waves already produced due to pure horizontal excitation with waves produced by increased rocking motion of the tank under consideration.

Impulsive pressure decreased with increasing base acceleration, whereas the convective pressure increased with increased base acceleration. Impulsive pressure decreases due to the non-linearity in the structure.

The pressure variation along tank height due to vertical excitation increased with increasing acceleration, and increased furthermore with added rocking. Moreover, the stiffness of staging plays an important role in tank acceleration in magnifying the acceleration at the tank level.

All the codes discussed in this paper suggest higher design seismic force for tanks by specifying lower values of the response modification factor or its equivalent factor in comparison to the building system. There are substantial differences, however, in the manner and extent to which design seismic forces are increased in various codes. American codes and standards provide a detailed classification of tanks and are assigned a different value of the response modification factor. In contrast, Eurocode 8 and NZSEE do not have such detailed classification, although NZSEE has given classification for ground supported steel tanks. Provisions on soil-structure interaction are provided in NZSEE and Eurocode 8 only.

11. Acknowledgement

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10. References


