RESPONSE OF OVER HEAD WATER TANKS UNDER SEISMIC EFFECT

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ABSTRACT

Either in urban or rural areas over head water tanks forms an integral part of water supply scheme. Its functionality pre and post-earthquake remains equally important. These structures have heavy mass concentrated at the top of slender supporting structure and hence these structures are especially vulnerable to horizontal forces due to earthquakes. Majority of these structures are designed for static loads and the effect of dynamic loading is not considered during analysis. The failure in the past earthquakes reveals that a large number of overhead water tanks have failed because of not considering the effect of dynamic loads.

The present work is an attempt to study the behavior of overhead water tanks under dynamic loads. The dynamic behavior is studied using Indian code IS 1893(part 2):2014. Overhead water tanks supported on RC framed structure with different tank storage capacities are considered and effects of hydrodynamic forces on tank walls are obtained. Various parameters including sloshing wave height effects are studied for different capacities and different h/D ratios. Both impulsive and convective pressures have been evaluated and compared for different capacities and different h/D ratios. Analysis has been carried out using equivalent static and dynamic analysis. Modeling and analysis is carried out using STAAD pro software.

The results indicate that sloshing wave height increases with increase in capacity. Also, the convective pressure decrease and Impulsive pressure increases as height to diameter ratio increases. It is found that for higher capacities, dynamic behavior governs the design.

***KEYWORDS**: water tanks, hydrodynamic forces, Impulsive and convective Pressure, natural frequency.*

1. INTRODUCTION

An elevated water storage tank is a structure constructed sufficient height to cover the large area for supply of water. Elevated water tanks are considered as important city services in many cities. Their security performance during strong earthquakes is of critical concern. They should not fail due to earthquake, so that they can be used in meeting essential needs like preparing drinking water and putting out fires. The failure of these structures and the subsiding of water may cause some hazards for the health of city due to the shortage of water or difficulty in putting out fire during critical conditions. Many studies concentrated on the seismic behavior, analysis, and design of tanks, particularly water tanks on ground tanks. However in the past decade most of these studies have focused on the elevated tanks. In the past earthquakes, elevated tanks have been of the vulnerable structures and their seismic behavior has not been understood completely. Past earthquakes have shown that due to failure of elevated tanks with insufficient seismic resistance, firefighting and other emergency response efforts have been hindered. Haroun and Ellaithy (1985) developed a model including an analysis of a variety of elevated rigid tanks undergoing translation and rotation. The model considers fluid sloshing modes and it assesses the effect of tank wall flexibility on the earthquake response of the elevated tanks. Haroun and Temraz (1992) analyzed models of two-dimensional X-braced elevated tanks supported on the isolated footings to investigate the effects of dynamic interaction between the tower and the supporting soil-foundation system but they also neglected the sloshing effects. Marashi and Shakib (1997) carried out an ambient vibration test for the evaluation of the dynamic characteristics of elevated tanks. Dutta et al., (2004) studied the supporting system of elevated tanks with reduced torsional vulnerability and they suggested approximate empirical equations for the lateral, horizontal and torsional stiffness for different frame supporting systems. They also investigated how the inelastic torsional behavior of the tank system with accidental eccentricity varies with increasing number of panels. They showed that soil-structure interaction (SSI) could cause an increase in base shear particularly for elevated tanks with low structural periods. This study also concluded that ignoring the effect of SSI could result in potential large tensile forces in some of staging columns due to seismic loads. Livaoglu and Dogangun (2005) proposed a simple analytical procedure for seismic analysis of fluid-elevated tank-foundation-soil systems, and they used this approximation in selected tanks. they conducted a comparative study of seismic behavior of the elevated tanks considering both fluid-structure and soil-structure interaction effects on elevated tanks. Seismic designs of these tanks are done on the basis of different countries well-known creditable codes like IBC, UBC and ACI. There is no certainty about the performance of these structures during earthquakes due to their complexities and therefore more studies are needed in this regard.

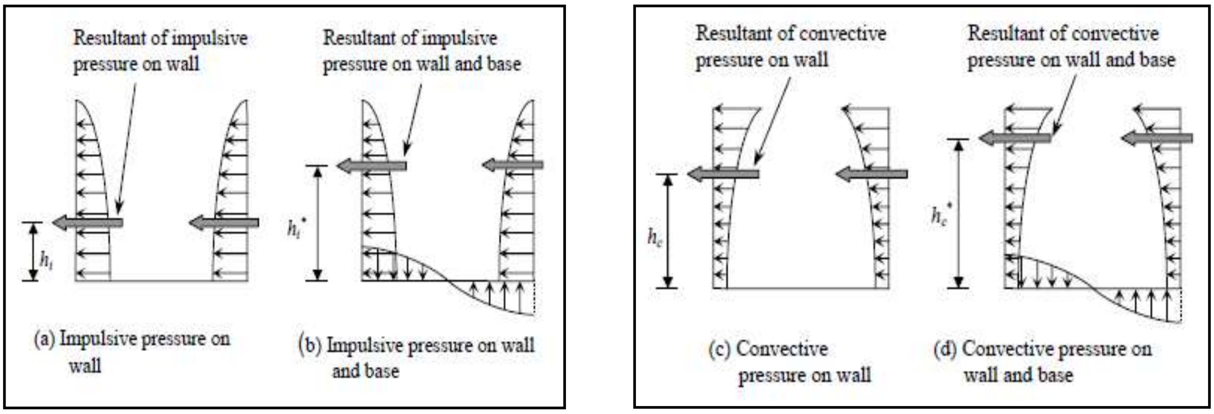
2. DYNAMIC RESPONSE OF OVER HEAD WATER TANK

Dynamic response of elevated water tanks is hard to define, as behavior of tank is unpredictable. Dynamic analysis of liquid storage tank is a complex problem involving water structure interaction. Based on numerous analytical, numerical and experimental studies, simple spring-mass models of tank-liquid system have been developed to calculate the hydrodynamic forces. During the earthquake, water contained in the tank exerts forces on tank wall as well as in bottom of the tank. These hydrodynamic forces should consider in the analysis in addition to hydrostatic forces.

In a liquid storage tanks, liquid in the lower region of the tank behaves as a liquid mass that is rigidly connected to tank wall. This mass is termed as impulsive liquid mass which accelerates along with the wall and induced impulsive hydrodynamic pressure on tank wall and tank base. Liquid mass in upper region of the tank undergo sloshing motion. This mass is termed as convective liquid mass and it exerts convective hydrodynamic pressure. Housner(1963) developed a spring mass model system for representing tank and fluid interaction. In spring mass model of tank-liquid system, these two liquid masses are to be suitably represented and parameters of this model depend on geometry of the tank and its flexibility.

2.1 Two mass model theory for overhead water tank

Elevated water tank containing the liquid with free surface is subjected to horizontal earthquake ground motion. Due to the ground motion, the tank wall and liquid get accelerate. The total liquid mass gets divide into two parts, i.e. impulsive mass and convective mass. In spring mass model for tank liquid system, these two liquid masses are to be suitably represented. A qualitative description of hydrodynamic pressure distribution on tank wall and base are shown in Fig. 1



(a) Impulsive pressure on wall (b) Impulsive pressure on wall and base (c) Convective pressure on wall (d) Convective pressure on wall and base

Fig. 1: Qualitative description of hydrodynamic pressure distribution on tank wall & base.

2.2 Spring mass model for two mass analysis of water tank

Most elevated water 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 is used in IS 1893 : 1984. Two mass models for elevated water tank were proposed by Housner (1963) and are being commonly used in most of the international code.

The response of two degree of freedom system can be obtained by elementary structural dynamics. However, for most elevated water tank it is observed that two periods are well separated. Hence, the system may be considered as two uncoupled single degree of freedom system. This method will be satisfactory for design purpose, if the ratio of the period of the two uncoupled system exceed 2.5. If impulsive and convective time periods are not well separated, then coupled two degree of freedom system will have to be solved using elementary structural dynamics. For elevated water tank, the two degree of freedom system can be treated as two uncoupled single degree of freedom systems, one representing the impulsive plus structural mass behaving as an inverted pendulum with lateral stiffness equal to the stiffness of staging, ks and the other representing the convective mass with a spring of stiffness, kc (Fig. 2)

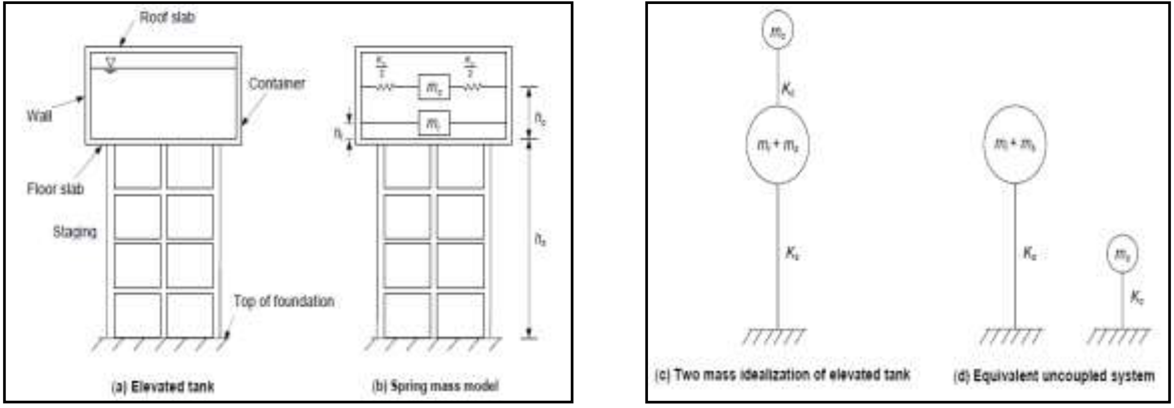


Fig. 2: Two mass model idealization of Elevated water tank and uncoupled single degree of freedom system

3. MODELING OF WATER TANK

The over head circular water tank is modeled using STAADProV8i (2011) software treating the model as continuous system. The water tank considered for study is shown in Fig. 3. The material properties were given and water load was added as a lumped mass acting at top of frame of model. Tank is analyzed for self weight of structure and the lumped water mass. Fig. 3 shows the description of water tank and modelingof tank carried out in STAADProV8i (2011) software.

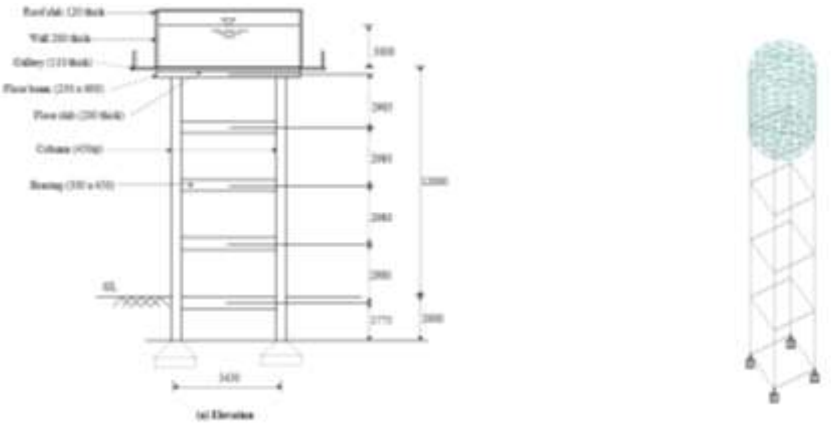


Fig 3: Description of Overhead water tank model and screen shot of model

4. PROBLEM DESCRIPTION

Circular water tanks of capacity ranging from 50m^3 to 200m^3 were analyzed for different h/D ratios. Height of staging is kept constant and bracings are assumed at four levels. The various parameters considered for the study is shown in Table 1. The tank is assumed to rest on soft soil and in seismic zone III. Analysis has been carried out for both water full and empty conditions. Both equivalent static analysis actual dynamic analysis have been carried out.

Table 1: Different combinations of height and diameter (h/D) of tank considered for analysis

Sl. No	Case	Volume(m^3)	No. of columns	Bracing beam size(mm)	Roof slab thickness (mm)	Floor beam (mm)	h/D Ratio
1	**Case 1**	50	4	300x450	120	250x600	0.65, 0.83, 0.21, 1.49, 1.88
2	**Case 2**	100	6	300x500	150	250x600	0.46, 0.59, 0.67, 0.76, 1.03
3	**Case 3**	150	6	300x525	170	300x600	0.47, 0.58, 0.69, 0.83, 0.99
4	**Case 4**	200	6	300x550	175	300x600	0.41, 0.50, 0.61, 0.74, 0.94

5. ANALYSIS OF WATER TANK

A sample calculation for capacity 50 m^3 with internal diameter 4.65 m and height 3.3 m (h/D=0.65) is shown. Both equivalent static analysis and dynamic analysis procedure is shown.

Parameters of Spring Mass Model

Weight of water = 4,99,800 N
Mass of liquid in the tank, m = 50,948 kg
Weight of staging = 186.1 + 185.2 = 371.3 kN.
Weight of empty container = 502.1 kN.
Weight of container + one third weight of staging = 626 kN.
Mass of empty container + one third mass of staging m_s = 63,799 kg
$m_i/m = 0.65$; mi = 0.65 x 50,948 = 33,116 kg.
$m_c/m = 0.35$; mc = 0.35 x 50,948 = 17,832 kg

Lateral Stiffness of Staging (K_s)

Lateral stiffness of staging is the force to be applied at the CG of tank so as to get a corresponding unit deflection.

$$K_s = \frac{1}{\left(\sum_{i=1}^{Np} \left[\left(\frac{1}{K_{panel}}\right)\right]\right)}$$

Where, K_{panel} = Lateral stiffness of each panel.

$$K_{panel} = \frac{12EN_cI_c}{h^3} * \left(\frac{\frac{I_b}{L}}{\left(\frac{I_b}{L}\right)+2*\left(\frac{I_c}{h}\right)}\right)$$ For intermediate panels and

$$K_{panel} = \frac{12EN_cI_c}{h^3} * \left(\frac{\frac{I_b}{L}}{\left(\frac{I_b}{L}\right)+1*\left(\frac{I_c}{h}\right)}\right)$$ For top and bottom panels.

Where,
I_b = Moment of inertia of bracing beam.
I_c = Moment of inertia of column.
E = Modulus of elasticity of concrete.
N_c = Number of columns.
L = Length of panel.
h = Height of each panel.

$$K_s = \frac{1}{\left(\frac{3}{K_1}\right)+\left(\frac{1}{K_2}\right)+\left(\frac{1}{K_3}\right)} = \mathbf{6100\ kN/m}$$

5.1 Equivalent static analysis

For equivalent static analysis, water-structure interaction shows, both water and structure achieve a peak at the same time due to the assumption that water is stuck to the container and acts as a structure itself and both water and structure has same stiffness.

a) Tank full condition

1) Time period of water tank,

$$T = 2\pi\sqrt{\frac{m_s + m}{K_s}} = \mathbf{0.86sec}$$

2) Design Horizontal Seismic Coefficient

$$(A_h) = \frac{Z}{2}\,\frac{I}{R}\,(S_a/g) = \mathbf{0.08}$$

3) Base Shear

$$V = (A_h)\,m\,g = \mathbf{87.486\ kN}.$$

b) Tank empty condition

1) Time Period of water tank,

$$T = 2\pi\sqrt{\frac{m_s}{K_s}} = \mathbf{0.64sec}$$

2) Design Horizontal Seismic Coefficient

$$(A_h) = \frac{Z}{2}\,\frac{I}{R}\,(S_a/g) = \mathbf{0.088}$$

3) Base Shear

$$V = (A_h)\,m\,g = \mathbf{55.07kN}$$

5.2 Dynamic Analysis

Tank full condition

1) Time Period
   a) Impulsive mode,

$$T_i = 2\pi\sqrt{\frac{(m_i + m_s)}{K_s}} = \mathbf{0.806sec}$$

   b) Convective mode,

$$T_c = C_c\sqrt{\frac{D}{g}} = \mathbf{2.26sec}$$

2) Design Horizontal Seismic Coefficient
   a) Impulsive mode,

$$(A_h)_i = \frac{Z}{2} * \frac{I}{R} * \left(\frac{Sa}{g}\right) i = \mathbf{0.09}$$

   b) Convective mode,

$$(A_h)c = \frac{Z}{2}\frac{I}{R}\left(\frac{Sa}{g}\right)c = \mathbf{1.4}$$

3) Hydrodynamic Pressure

a) Impulsive Pressure(P_{iw})

$$P_{iw(y)} = Q_{iw(y)}(A_h)_i gh\cos\phi = \mathbf{1.88\ kN/m^2}.$$

b) Convective Pressure(P_{cw})

$$P_{cw} = Q_{cw(y)}(A_h)_c \rho gD(1 - 1/3\cos 2\phi)\cos\phi = \mathbf{0.16\ kN/m^2}$$

4) Pressure Due to Wall Inertia(P_{ww})

$$P_{ww} = (A_h)_c t\rho_m g = \mathbf{0.32\ kN/m^2}.$$

5) Hydrodynamic Pressure on wall due to Vertical ground acceleration

$$P_v = (A_v)\left(\rho gh\left(1 - \frac{y}{h}\right)\right) = \mathbf{1.94\ kN/m^2}.$$

6) Maximum Hydrodynamic Pressure

$$P = \sqrt{\left(\left((P_{iw}) + P_{ww}\right)^2\right) + P_{cw}^2 + P_v^2} = \mathbf{3.02\ kN/m^2}.$$

7) Maximum Sloshing Wave Height

$$d_{max} = (A_h)_c\, R\,\frac{D}{2} = \mathbf{0.39\ m}$$

8) Base Shear

a) Impulsive mode,

$$V_i = (A_h)_i\,(m_i + m_s)g = \mathbf{83.67\ kN}.$$

b) Convective mode,

$$V_c = (A_h)_c\, m_c\, g = \mathbf{9.8\ kN}.$$

Total base shear, $V = \sqrt{V_i^2 + V_c^2} = \mathbf{84.24\ kN}.$

Tank Empty Condition

For empty condition, tank is considered as SDOF system.

Mass of empty container + one third mass of staging, m_s = 63,799 kg.

1) Time Period

Impulsive mode,

$$T = T_i = 2\pi\sqrt{\frac{m_s}{K_s}} = \mathbf{0.64\ sec}$$

Convective mode: Empty tank will not have convective mode of vibration.

2) Design Horizontal Seismic Coefficient

$$(A_h)_i = \frac{Z}{2} * \frac{I}{R} * \left(\frac{S_a}{g}\right)_i = \mathbf{0.088}$$

3) Base Shear

$$V = V_i = (A_h)_i\, m_s\, g = \mathbf{55.07\ kN}$$

6. RESULTS AND DISCUSSIONS

For various capacities and for different ratio of h/D analysis has been carried out and the results are presented

6.1Variation of time period

Time period is calculated using equivalent static method and dynamic analysis for each capacity and for different h/D ratios and are shown in Fig.4.

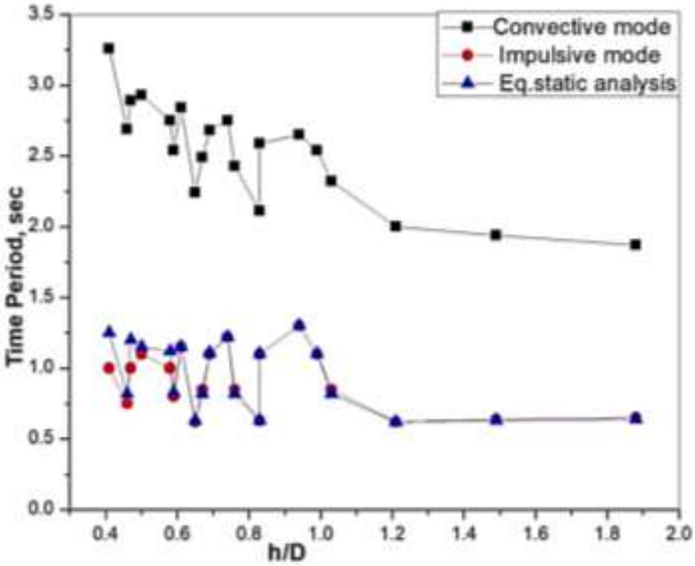


Fig. 4: Variation of time period for different h/D ratios

From the Fig 4 it is observed that the impulsive mode time period and the one mass idealization's time period correspond well however, the one mass idealization fails to recognize the convective time period.

6.2 Variation of Base shear

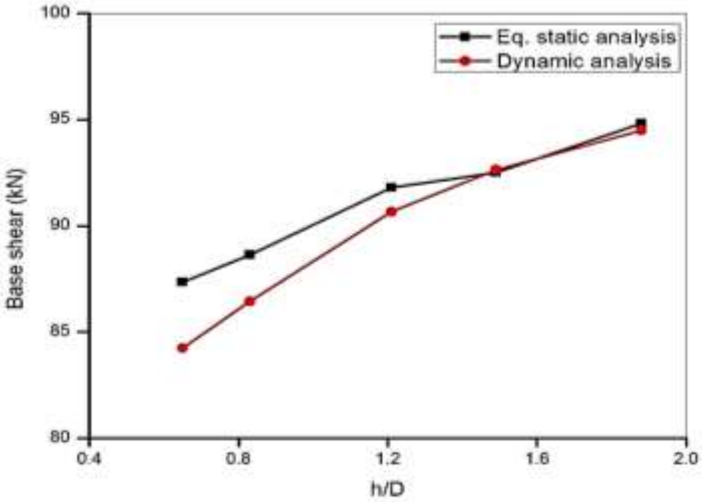


Fig. 5: Comparison of Base shear with h/D ratio for both Eq. static and dynamic analysis for 50m^3 tank

From Fig. 5 it is observed that as the h/D ratio increases, base shear increases. However, the base shear determined by Equivalent static analysis and dynamic analysis tends to meet at the same location for a specific ratio of h/D, at around 1.5. Therefore, static analysis results are in good agreement with dynamic analysis results when the tank's dimensions, such as height and diameter, are nearly the same. Also, the base shear obtained from Equivalent static analysis is significantly higher than that of dynamic analysis for tanks with tanks with a larger capacity at lesser h/D ratios.

6.3 Variation of Impulsive and convective hydrodynamic pressure

The variation of Impulsive and convective hydrodynamic pressure are obtained for different capacities of tank and h/D ratio. However, equivalent static analysis fails in determining impulsive and convective hydrodynamic pressure. Fig. 6 shows the pressure for various capacities of tank.

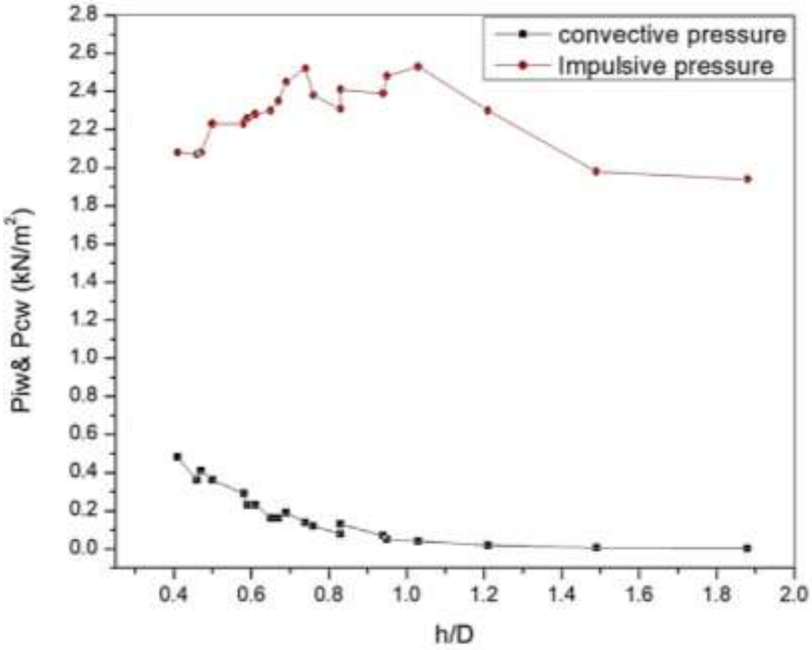


Fig. 6: Comparison of impulsive and convective hydrodynamic Pressure for various capacities of tank

- It is observed that for all values of h/D ratios, impulsive pressure is always more on the wall than that of the convective pressure. The one reason to justify above statement is, during earthquake, water body in convective is always in the sloshing position, hence convective force is unstable to exert any convective force on the wall region. But on the other hand, water, in the impulsive region is quite stable and hence it is able to exert enough pressure on the wall.
- It is observed that the convective pressure goes on decreasing and impulsive pressure increases as h/D ratio increases for all capacities except for 50m^3 capacity, where in both impulsive and convective pressure do not change much.

6.4 Variation of Sloshing wave height

Sloshing is defined as the periodic motion of the free liquid surface in partially filled container. It is caused by any disturbance to partially filled containers. The sloshing wave height is obtained for all capacities of tank for a single value of h/D ratio of 0.65 and is shown in Fig. 7.

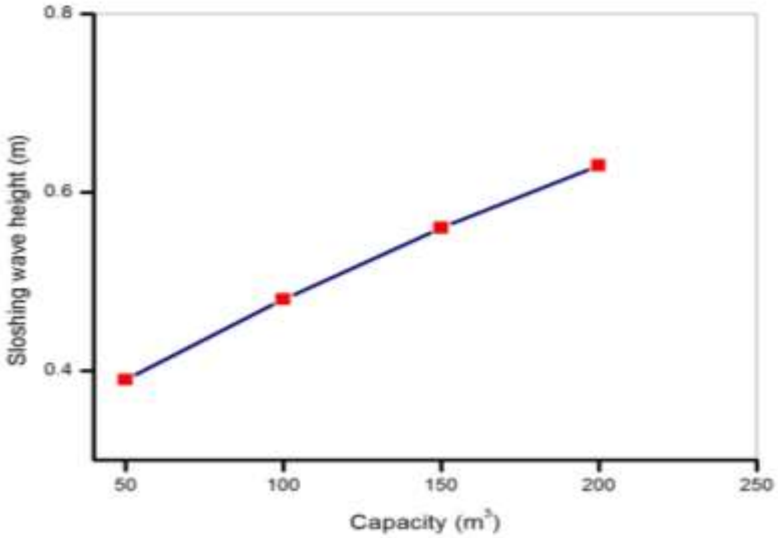


Fig. 7: Relation between sloshing wave height and capacity of tank for h/D ratio of 0.65

- As the Capacity of water tank increases, the sloshing wave height also increases.
- Generally, for water tanks the free board height is kept 0.3m. The study shows that for higher capacities there is a need to increase the height of free board.

6.5 Variation of maximum hydrodynamic pressure

Maximum Hydrodynamic pressure due to sum of impulsive and convective mode acting on the walls of tank is computed for all capacities of tank for a particular h/D ratio of 0.7.

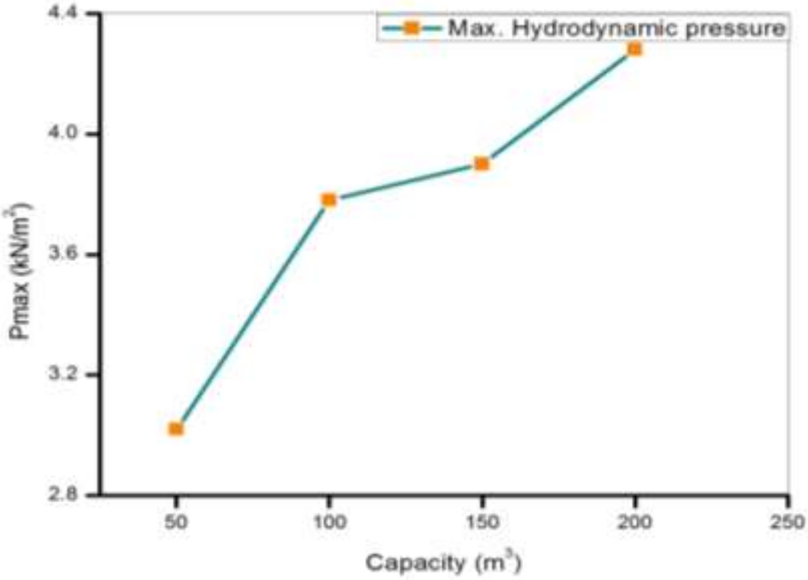


Fig. 8: Comparison of Max. Hydrodynamic pressure on wall with capacity for h/D ratio of 0.70.

From Fig. 8 it is observed that, the maximum hydrodynamic pressure of the water tank increases with increasing capacity. Thus, the tank is subjected to additional pressure during earthquake shaking.

7. CONCLUSIONS

From the study following conclusions are made

- Natural time period do not depends only on mass of tank and static weight of water, but it also depends on dynamic behaviour (i.e., convective mode).
- It is observed that as height to diameter ratio increases, the convective pressure decrease and Impulsive pressure increases.
- As the Capacity of water tank increases, the sloshing wave height also increases and indicates the requirements of higher free board for higher capacities.
- The maximum hydrodynamic pressure of the water tank increases by about 10 to 15% with increase in capacity of tank.

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