

Seismic Analysis of RC Elevated Water Tanks

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Abstract: Elevated water tanks are one of the most lifeline structures in earthquake prone regions. These structures have large mass concentrated at the top of slender supporting structures and are especially vulnerable to horizontal forces due to earthquake. They are critical elements in municipal water supply, fire fighting systems and in many industrial facilities for storage of water. Hence elevated water tanks must remain functional even after the earthquake. In this paper manual seismic analysis of elevated circular water tank is carried out in accordance with IS: 1893-1984 (i.e. lumped mass model) and IS: 1893-2002 (Part-2) draft code (i.e. two mass model). The tank is located in zones III and V and on two different soil types i.e. hard rock and soft soil. Hence there are total four cases. Further comparison between the framed type and shaft type staging is done as per manually calculated responses such as base shear and base moment. Analysis is carried out for two different tank fill conditions i.e. tank full and tank empty conditions. In the analysis, response spectrum method has been used for seismic analysis of structures. Seismic responses such as base shear, base moment and hydrodynamic pressure are evaluated and compared. The results of this study show that the current practice (as per IS: 1893-2002) predicts the response of elevated tanks with reasonable accuracy.

Key words: Elevated water tanks, Seismic response, Base shear, Base moment, Hydrodynamic pressure, one mass model, two mass model.

INTRODUCTION

Water is human basic needs for daily life. Sufficient water distribution depends on design of a water tank in certain area. Water supply depends on overhead water tanks for storage in our country as the required pressure in water supply process is obtained by gravity in elevated tanks rather than the need of heavy pumping facilities. Indian sub-continent is highly vulnerable to natural disasters like earthquakes, draughts, floods, cyclones etc. According to seismic code IS: 1893 (Part 1)-2002, more than 60% of India is prone to earthquakes. Elevated water tanks consist of huge water mass at the top of a slender staging which are most critical consideration for the failure of the tank during earthquakes. Since, the elevated tanks are frequently used in seismic active regions also hence their seismic behavior has to be investigated in detail. Due to the lack of knowledge of supporting system and also due to improper geometrical selection of staging patterns some of the water tanks were collapsed or heavily damaged. There may be different ways for storage of liquid such as underground, ground supported, elevated etc. Liquid storage

tanks are extensively used by municipalities and industries for storing water, inflammable liquids etc. Hence water supply is essential for controlling fires that may occur during earthquakes, which cause damage and loss of lives. Therefore elevated water tanks should remain functional in the post-earthquake period. Some of damages caused to water tanks during the past earthquake include collapse of water tank in Bhachau due to severe damage in staging as it did not meet the ductility requirement. Also collapse of water tanks during Bhuj earthquake occurred due to flexural cracks in the shaft type staging of tank. Water tank collapsed in Manfera village due to slender and weak framed staging. The seismic analysis of this tank has been carried out by two different methods firstly as per IS: 1893-1984 (i.e. lumped mass model) and secondly as per IS: 1893-2002 (i.e. two mass model). Dynamic analysis of these tanks must take into account the motion of water relative to tank as well as motion of tank relative to ground. If a closed tank is completely full of water or completely empty, it is essentially a one-mass structure. If as usual the tank has free water surface there will be sloshing of water during the earthquake and this makes the tank essentially a two-mass structure. It is said that earthquake itself never kills people; it is badly constructed structures that kill. Hence it is important to analyze the structure properly for earthquake effects.

PROBLEM STATEMENT

A RC circular elevated water tank of 50m³ capacity has internal diameter of 4.8m and height of 3.3m (including freeboard of 0.3m). It is supported on RC staging consisting of 4 columns of 450mm diameter with horizontal bracings at four levels. The lowest supply level is 12.3m above ground level. Staging conforms to ductile detailing as per IS: 13920-1993. Staging columns have isolated rectangular footing at a depth of 2.2m from ground level. Tank is located in zone III and V on soft soil and hard rock respectively. Density of concrete is 25kN/m³. Analyze the tank for seismic loads. The grades of concrete and steel used are M20 and Fe415 respectively.

Table 1: Preliminary data

Parameters	Values
Capacity	50000lit
Dia of container	4.8m
Depth of water in container	3m
Free board	0.3m
Roof slab	120mm
Bottom slab	200mm thick
Floor beam	250x600mm
Wall	200mm thick
Braces	300x450mm
Columns	4 nos-450mm dia
Depth of footing below GL	2.0m
c/c distance betn columns	3.5m
c/c distance between each panel	3.0m

METHODOLOGY

The methodology involves selection of type of water tank, fixing its dimensions, performing the dynamic analysis using Response spectrum method by modeling the tank as one mass and two mass model. The tank with frame staging is analyzed for zones III and V and for two different soil conditions i.e. hard rock and soft soil strata. Seismic responses such as base shear, base moment and hydrodynamic pressures are evaluated for tank full and tank empty conditions. Procedures given in IS:1893-1984 and IS: 1893-2002 (Part 2) draft code are used to calculate the seismic responses of the tank. The two methods used for the seismic analysis include:

- 1) Lumped mass model method
- 2) Two mass model method

Lumped mass model method

For the purpose of this analysis, elevated tanks shall be regarded as systems with a single degree of freedom with their mass concentrated at their centre of gravity. The damping in the system may be assumed as 2 percent of the critical for steel structures and 5 percent of the critical for concrete (including masonry) structures. The free period T, in seconds, of such structures shall be calculated from the following formula:

$$T = 2\pi \sqrt{\Delta/g} \tag{1}$$

Where

Δ = the static horizontal deflection at the top of the tank under a static horizontal force equal to a weight W acting at the centre of gravity of tank.

g = acceleration due to gravity.

The design shall be worked out both when the tank is full and when empty. When empty, the weight W used in the design shall consist of the dead load of the tank and one-third the weight of the staging.

The lateral force shall be taken equal to:

$$a_h W \tag{2}$$

where

a_h - design horizontal seismic coefficient

$$a_h = B.I.Fo (Sa/g) \tag{3}$$

Where

B= a coefficient depending upon the soil foundation.

I= Importance factor

Fo= seismic zone factor

Sa/g= avg acceleration coefficient.

The Hydrodynamic pressure is calculated as per clause 5.2.7 of IS: 1893-1984.

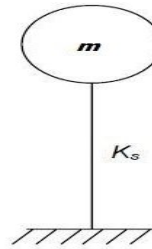


Fig. 1: One mass idealization of tank

Two mass model

Two mass model for elevated tank was proposed by Housner (1963) which is more appropriate and is being commonly used in all international codes. Most elevated tanks are never completely filled with liquid. The pressure generated within the fluid due to dynamic motion of tank can be separated into impulsive and convective pressures. When a tank containing liquid with free surface is subjected to horizontal earthquake ground motion, tank wall and liquid are subjected to horizontal acceleration. The liquid in the lower region of tank behaves like a mass that is rigidly connected to tank wall, termed as impulsive liquid mass. Liquid mass in the upper region of tank undergoes sloshing motion (Sloshing is the motion of the free liquid surface inside its container), termed as convective liquid mass. The base shear, base moment and hydrodynamic pressure is calculated as per clauses 4.6.2, 4.7.2 and 4.9 of IS: 1893-2002 (Part 2) respectively.

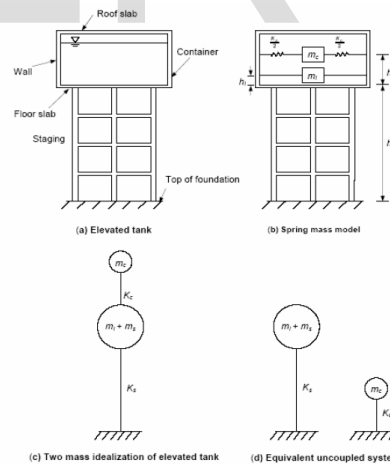


Fig. 2: Two mass idealization of elevated water tank

Results and Discussions

The base shear and the base moments obtained from lumped mass and two mass model for different zones III and V under soft soil and hard rock are as tabulated:

Table 2: Seismic responses as per lumped mass and two mass idealization of water tank

Base shear (Tank full)				
Soil type	Lumped mass model		Two mass model	
	Zone-III	Zone-V	Zone-III	Zone-V
Soft soil	60.82	121.64	84.46	206.29
Hardrock	40.54	81.09	55.3	124.59
Base shear (Tank empty)				
Soil type	Lumped mass model		Two mass model	
	Zone-III	Zone-V	Zone-III	Zone-V
Soft soil	38.59	77.49	71.25	160.32
Hardrock	26.12	51.56	43.94	98.57
Overturning moment (Tank full)				
Soil type	Lumped mass model		Two mass model	
	Zone-III	Zone-V	Zone-III	Zone-V
Soft soil	961.56	1923.13	1357	3311
Hardrock	641.04	1282.08	887.88	2000
Overturning moment (Tank empty)				
Soil type	Lumped mass model		Two mass model	
	Zone-III	Zone-V	Zone-III	Zone-V
Soft soil	610.21	1225.13	1127	2535
Hardrock	413.07	816.75	694.71	1558.4

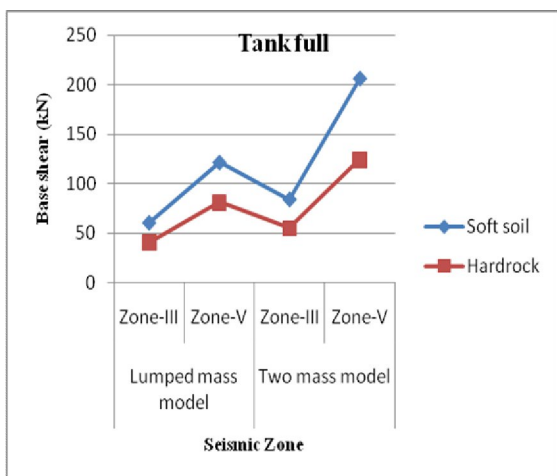


Fig. 3: Base shear Vs Seismic zone for framed staging (Tank full)

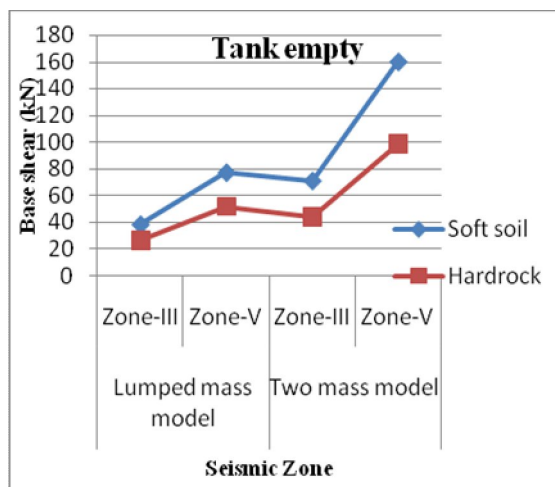


Fig. 4: Base shear Vs Seismic zone for framed staging. (Tank empty)

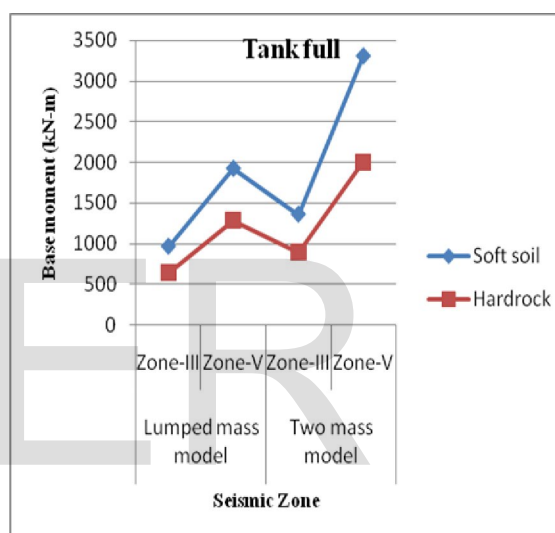


Fig. 5: Base moment Vs Seismic zone for framed staging. (Tank full)

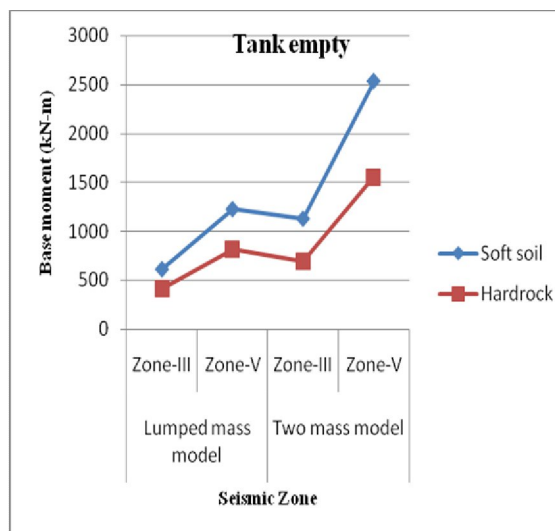


Fig. 6: Base moment Vs Seismic zone for framed staging. (Tank empty)

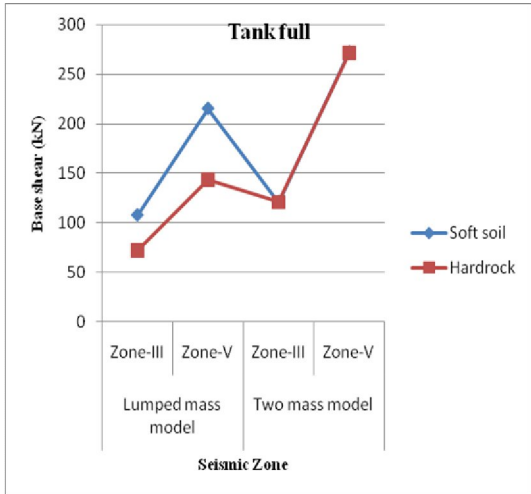


Fig. 7 Base shear Vs Seismic zone for shaft staging (Tank full)

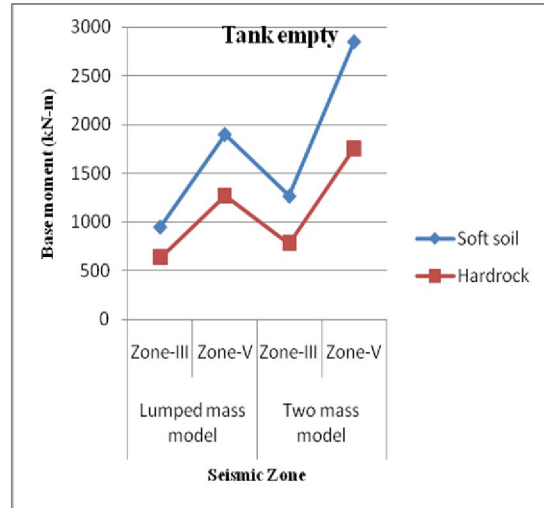


Fig. 10: Base moment Vs Seismic zone for shaft staging (Tank empty)

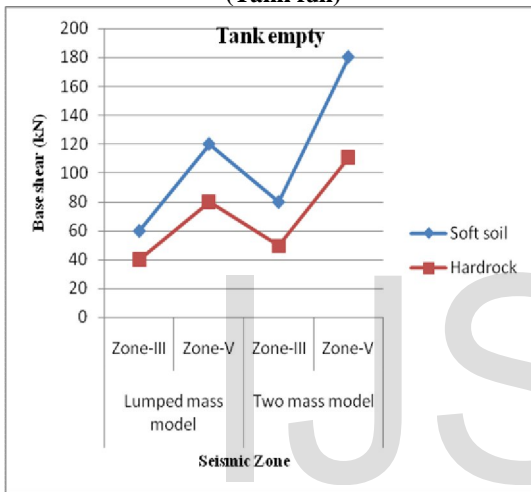


Fig. 8: Base shear Vs Seismic zone for shaft staging (Tank empty)

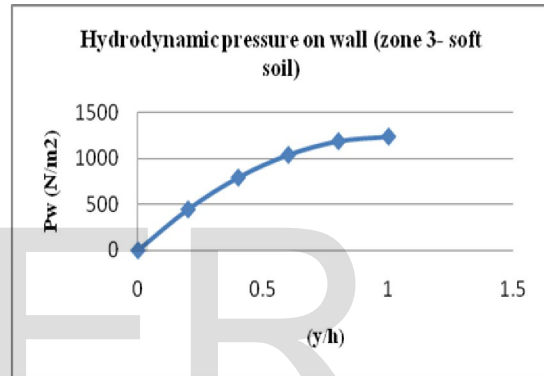


Fig. 11: Hydrodynamic pressure on wall (Pw) Vs (y/h) (Zone 3- soft soil) lumped mass model

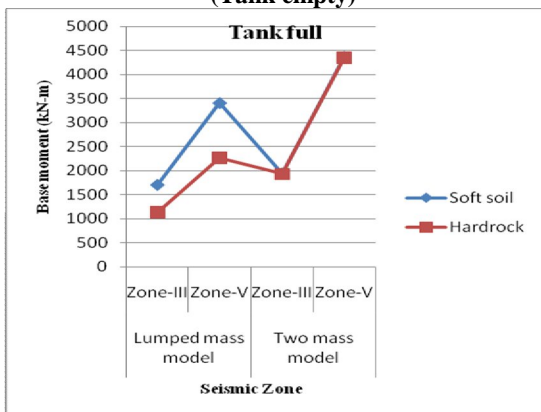


Fig. 9: Base moment Vs Seismic zone for shaft staging (Tank full)

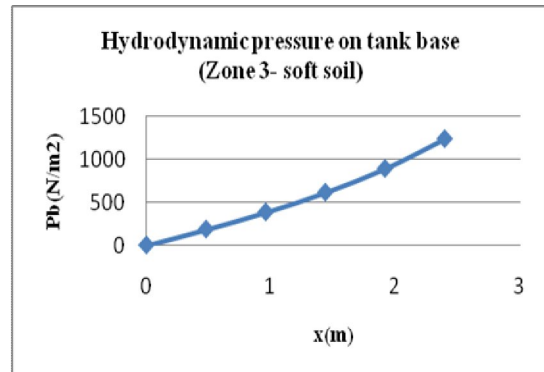


Fig. 12: Hydrodynamic pressure on base slab (Ph) Vs x(m) (Zone 3-soft soil) lumped mass model

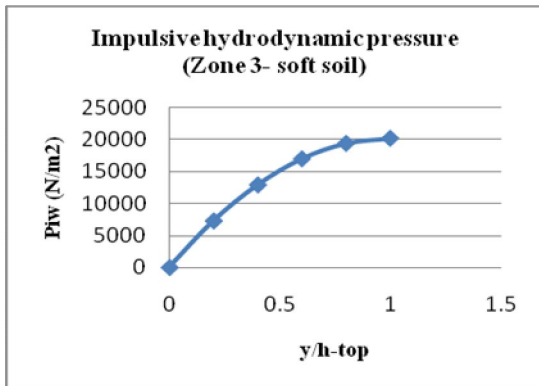


Fig. 13: Impulsive hydrodynamic pressure on wall (Piw) Vs (y/h)

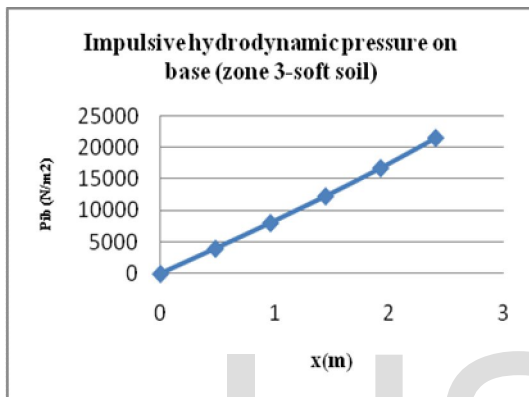


Fig. 14: Impulsive hydrodynamic pressure on base slab (Pib) Vs x (m)

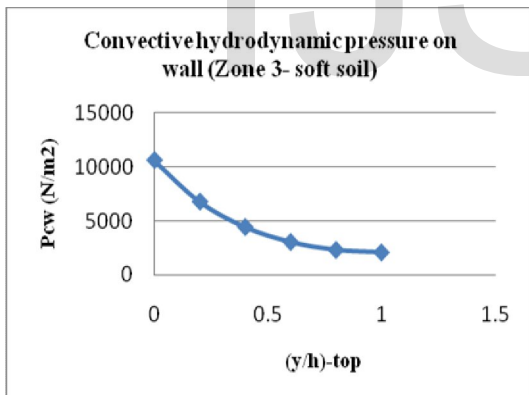


Fig. 15: Convective hydrodynamic pressure on wall (Pcw) Vs (y/h)

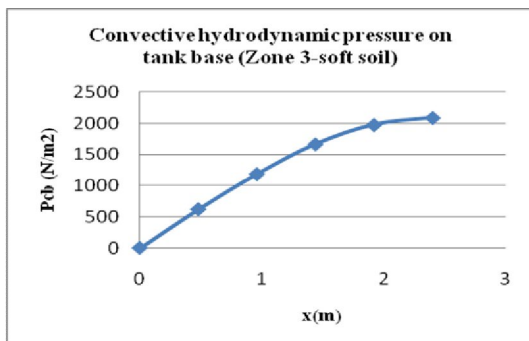


Fig. 16: Convective hydrodynamic pressure on base slab (Pcb) Vs x(m)

Variation of base shear and base moments

Graphs of base shear and base moments Vs Seismic zone as calculated by Lumped mass and two mass models for tank full and tank empty conditions are plotted. (For both frame and shaft type of staging). The base shear values increases with increasing zone factor (from zone III to zone V). Base shear values are approximately 50% more in soft soil as compared to those in hard rock strata. Base moment also increases in the same proportion for tanks located in soft soils. The responses for soft soil are more because of structural response factor (Sa/g) which is greater for soft soils. As per results of analysis the base shear as well as base moments is increased for two mass model as compared to that in lumped mass model for both tank full and tank empty conditions. The base shear increases by 100% for tanks located in zone V as compared to those in zone III (lumped mass model) whereas it increases by 125-146% as the zone changes from zone III to V (Two mass model). The base shear value of lumped mass model increases between 55-58% for tanks located on soft soil and hard rock for tank full condition in comparison to tank empty conditions. Increase in base shear was between 18-30% for tank full condition in two mass model idealization. Hence tank full condition is the most severe condition of water tank. The base shear increased in the range of 95-130% as the zone factor changed from zone III to zone V. Increase in values of base moments are found to be in the range of 100-150% as the zone factor increases. The base shear increases by 77% for the lumped mass model of tank when having shaft type of staging as compared to the framed staging when located in soft soil and hard rock for tank full condition. The base shear increases in the range of 32-44% for shaft staging for the two mass model of tank located in soft soil whereas it increases by 118% when located on hard rock for tank full condition. Similar is the variation of base moments.

Variation of hydrodynamic pressures

During lateral base excitation, tank wall is subjected to lateral hydrodynamic pressure and tank base is subjected to hydrodynamic pressure in vertical direction. In circular tanks, hydrodynamic pressure due to horizontal excitation varies around the circumference of the tank. The hydrodynamic pressure on wall is plotted against (y/h) ratios. The hydrodynamic pressures acting on base of the tank are plotted against the distance “x” which is measured from the central axis of the tank. As seen from the graphs of hydrodynamic pressure there is approximately an increase of 50% in pressure values on the wall as well as on base of the tank located in soft soil as compared to that of hard rock when idealized as lumped mass model. The impulsive pressures also increased by 52-53% in soft soil as compared to hard rock strata whereas the convective pressures increased by 62-65% in the two mass model analysis. The hydrodynamic pressure values goes on increasing with increasing zone factor. Hydrodynamic pressure due to horizontal excitation has curvilinear variation along wall height.

CONCLUSIONS

1) The procedure suggested in IS: 1893-1984 considers the tank as single degree of freedom system (lumped mass model) which is applicable to closed tanks completely full of water.

Hence for tanks with free water surface, two mass idealization of tank are used which is incorporated in IS: 1893-2002 Draft code (Part 2).

2) IS: 1893-2002 (Part 2) has considered the sloshing motion of water surface. Due to effect of sloshing, convective pressure acts on the tank which were not given due consideration in the analysis of tank using lumped mass model concept of IS: 1893-1984.

3) With the consideration of convective hydrodynamic pressures, bases shear and base moment's values increases considerably which were quite small for lumped mass idealization of tank. Hence the bases shear and base moment values obtained from two mass idealization i.e. as per IS: 1893-2002 (Part 2) are more realistic. Hence convective pressures play a major role in seismic analysis of the elevated water tank.

4) Base shear and base moment values obtained from two mass idealization are far greater than that in lumped mass model. Hence idealization of water tank as single degree of freedom system is not appropriate for seismic analysis of water tanks. Hence two mass idealization should be used for dynamic analysis of water tanks.

5) The base shears, base moments and hydrodynamic pressures increase with increasing zone factors.

6) The hydrodynamic pressures calculated using IS: 1893-1984 codal provisions are by considering the rigidity of the tank wall whereas those calculated using IS: 1893-2002 (Part 2) codal provisions are by considering the flexibility of the tank wall. The impulsive pressures obtained considering flexibility of wall are very large as compared to those obtained by lumped mass model. The impulsive hydrodynamic pressures obtained by two mass model concept are almost sixteen times more than that obtained using two mass model concept. Hence lumped mass model underestimates the impulsive pressure values.

7) From the graphs, it is clear that shaft type stagings should be avoided as far as possible in the near future to avoid damage to the water tanks and thus prevent loss of lives.

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