Seismic Behavior of Ground Supported Tanks as per IS:1893 (Part II) Draft Code

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Earthquake induced motion causes sloshing of liquid. This accelerated liquid causes additional pressure on tank wall and its base. This type of behavior of liquid containing structure becomes hazardous during earthquake. Indian seismic code IS 1893:1984 had limited provisions on seismic design of liquid containing structures. Compared to present international practice, provisions of IS 1893:1984 are revised and published recently in different parts by Bureau of Indian Standards. IS 1893 (part II) is published as draft copy named as Criteria for Earthquake Resistant Design of Liquid Retaining Tanks. This study is based on codal provisions of IS 1893 (part II). In this paper, the effect of hydrodynamic forces on the circular and rectangular tank is presented. The behavior of liquid containing ground supported circular and rectangular tank in terms of impulsive and convective forces, base shear, moment at wall base and overturning moments are studied for varying capacity and their different configurations. From parametric study, it is observed that hydrodynamic forces are highly influencing the behavior of liquid containing circular and rectangular ground supported tank in severe earthquake zone.

Introduction

Liquid storage tanks are lifeline structures and strategically very important, since they are essential in industries and nuclear power plants. Large capacity ground supported tanks are used to store a variety of liquids, e.g., water for drinking and fire fighting, petroleum, chemicals, solid materials and liquefied natural gas. It may be possible that, in some cases tanks are found in populated area. In such type of cases safety is necessary, because leakage or collapse of tank, which is used for storage of hazardous material to environment, affect, surrounded area and human health. Tanks used for storing sewage and waste product, must be leak proof because due to leakage contamination of fresh ground water sources and infertility of soil take place around it. So this is the responsibility of structural engineer to protect such tanks against collapse or leakage and reduce their adverse effect on the environment.

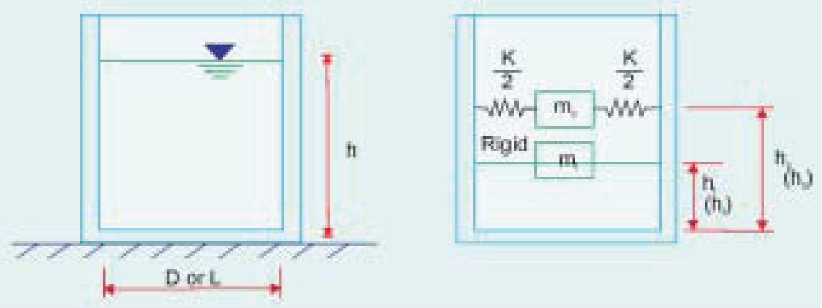

Figure 1: Spring mass model for ground supported tank

Earthquake causes random motion of ground. The vibration intensity of ground expected at any location depends upon the magnitude of earthquake, the depth of focus, distance from the epicentre and the strata on which the structure stands. The predominant direction of vibration is horizontal. During seismic excitation, liquid inside the tank exerts hydrodynamic forces on tank walls and base. Traditionally, hydrodynamic forces in a tank-liquid system are evaluated using spring-mass system, which simulate the impulsive and convective mode of vibration of a tank-fluid system. Ground supported tanks are damaged in form of cracking of wall and overturning of whole structure. It is possible to prevent such types of damages by adopting appropriate design methods. IS 1893 (part II) is introduced as draft copy with more specific provisions compared to IS 1893:1984 for seismic analysis of liquid containing structures [1,2]. In present paper, important codal provisions for calculation of hydrodynamic pressure is discussed along with parametric study for circular and rectangular tanks.

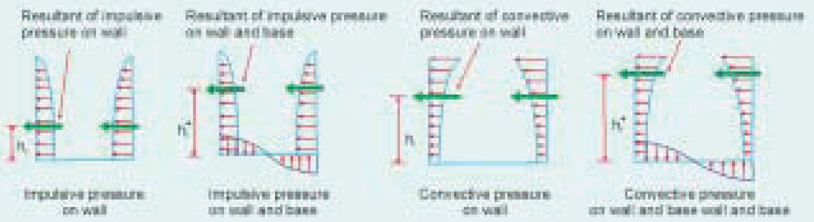

Figure 2: Hydrodynamic pressure distribution on tank wall and base

Spring Mass Model of Water Tank

Tanks resting on ground can be idealized as spring mass model as shown in Figure 1. The liquid in the lower region of tank behaves like a mass that is rigidly connected to tank wall. This mass of liquid is termed as impulsive liquid mass. This type of mass accelerates the pressure along increasing the depth. This pressure is known as impulsive hydrodynamic forces. Liquid mass in the upper region of tank undergoes sloshing motion. This mass is termed as convective liquid mass and it exerts convective hydrodynamic pressure on tank wall and base. This pressure is higher at the top and reduces along depth.

In Figure 1 m_i is rigidly attached impulsive mass to the tank wall at height h_i. Similarly, convective mass m_c is attached to the tank wall at height h_c by spring with stiffness K_c.

Hydrodynamic pressure distribution on tank wall and base of tank for impulsive and convective mode is as shown in Figure 2.

In Figure 2, h_i is height of the resultant of impulsive hydrodynamic pressure on wall, h_i* is height of the resultant of impulsive pressure on wall and base, h_c is height of the resultant of convective hydrodynamic pressure on wall, h_c* is height of the resultant of convective pressure on wall and base.

Expressions for calculation of various parameters of spring mass model like impulsive mass (m_i), convective mass (m_c), time period, base shear, moment at base of wall, overturning moment, hydrodynamic pressure are given in draft copy of IS:1893 (part II). Equations for parameters of spring mass model of tank are as shown in Table 1.

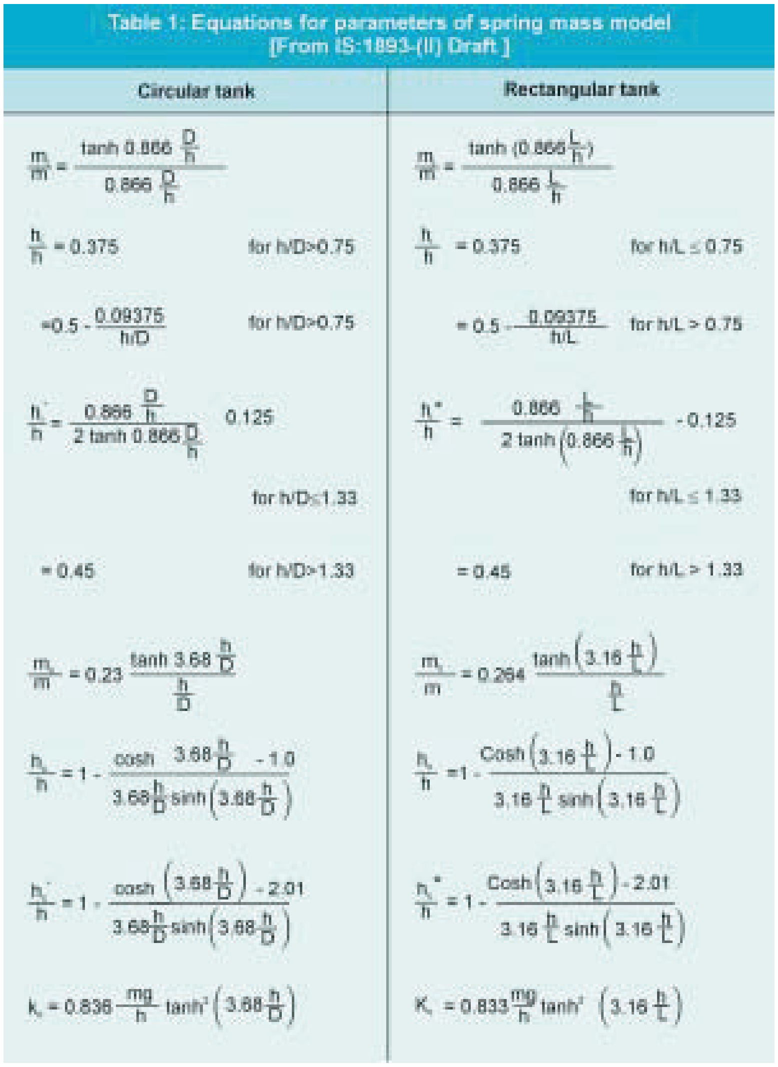

Table 1: Equations for parameters of spring mass model
[From IS:1893-(II) Draft]

Circular tank		Rectangular tank	
$\frac{m_i}{m} = \frac{\tanh 0.866\frac{D}{h}}{0.866\frac{D}{h}}$		$\frac{m_i}{m} = \frac{\tanh(0.866\frac{L}{h})}{0.866\frac{L}{h}}$	
$\frac{h_i}{h} = 0.375$	for h/D>0.75	$\frac{h_i}{h} = 0.375$	for h/L ≤ 0.75
$= 0.5 - \frac{0.09375}{h/D}$	for h/D>0.75	$= 0.5 - \frac{0.09375}{h/L}$	for h/L > 0.75
$\frac{h_i^*}{h} = \frac{0.866\frac{D}{h}}{2\tanh 0.866\frac{D}{h}}$ 0.125		$\frac{h_i^*}{h} = \frac{0.866\frac{L}{h}}{2\tanh\left(0.866\frac{L}{h}\right)} - 0.125$	
	for h/D≤1.33		for h/L ≤ 1.33
$= 0.45$	for h/D>1.33	$= 0.45$	for h/L > 1.33
$\frac{m_c}{m} = 0.23\frac{\tanh 3.68\frac{h}{D}}{\frac{h}{D}}$		$\frac{m_c}{m} = 0.264\frac{\tanh\left(3.16\frac{h}{L}\right)}{\frac{h}{L}}$	
$\frac{h_c}{h} = 1 - \frac{\cosh 3.68\frac{h}{D} - 1.0}{3.68\frac{h}{D}\sinh\left(3.68\frac{h}{D}\right)}$		$\frac{h_c}{h} = 1 - \frac{\text{Cosh}\left(3.16\frac{h}{L}\right) - 1.0}{3.16\frac{h}{L}\sinh\left(3.16\frac{h}{L}\right)}$	
$\frac{h_c^*}{h} = 1 - \frac{\cosh\left(3.68\frac{h}{D}\right) - 2.01}{3.68\frac{h}{D}\sinh\left(3.68\frac{h}{D}\right)}$		$\frac{h_c^*}{h} = 1 - \frac{\text{Cosh}\left(3.16\frac{h}{L}\right) - 2.01}{3.16\frac{h}{L}\sinh\left(3.16\frac{h}{L}\right)}$	
$k_c = 0.836\frac{mg}{h}\tanh^2\left(3.68\frac{h}{D}\right)$		$K_c = 0.833\frac{mg}{h}\tanh^2\left(3.16\frac{h}{L}\right)$	

Analysis of ground supported tank

Base Shear

As per draft code value of base shear is different for both the Convective and Impulsive modes. Base shear in impulsive mode and convective mode are V_i and V_c can be calculated by Eq. 1 and Eq. 2 respectively.

$V_i = (A_h)_i\,(m_i + m_w + m_t)\,g$ (1)

$V_c = (A_h)_c\,m_c\,g$ (2)

Where, $(A_h)_i$ is design horizontal seismic coefficient for impulsive mode, $(A_h)_c$ is design horizontal seismic coefficient for convective mode, m_i impulsive mass of water, m_w mass of tank wall, m_t is mass of roof slab, and g is acceleration due to gravity.

Moment at Base of Wall

Bending moments in impulsive mode and convective mode, at the bottom of the tank wall M_i and Mc are given by,

$M_i = (A_h)_i\,(m_i h_i + m_w h_w + m_t h_t)g$ (3)

$M_c = (A_h)_c\,m_c h_c\,g$ (4)

Where, h_w is height of centre of gravity of wall mass, h_t is height of centre of gravity of roof mass.

Overturning Moment

Overturning moments in impulsive mode (M_i*) and convective mode (M_c*) is calculated as per Eq. 5 and Eq. 6 respectively.

$M_i^* = (A_h)_i\,[m_i\,(h_i^* + t_b) + m_w\,(h_w + t_b) + m_t(h_t + t_b) + (m_b t_b/2)]g$ (5)

$M_c^* = (A_h)_c\,m_c\,(h_c^* + t_b)g$ (6)

Where, m_b is mass of base slab/plate, t_b is thickness of base slab/plate.

Hydrodynamic Pressure for Circular Tank

Hydrodynamic pressure in impulsive and convective mode is acting on tank as shown in Figure 2. Inertia of tank wall and vertical ground acceleration also increase hydrodynamic pressure.

Impulsive hydrodynamic pressure for circular tank

Lateral hydrodynamic impulsive pressure on the wall, p_{iw}, is given by,

$p_{iw} = Q_{iw}(y)(A_h)_i$ ñg h cosö (7)

$Q_{iw}(y) = 0.866\left[1-\left(\frac{y}{h}\right)^2\right]\tanh\left(0.866\frac{D}{h}\right)$ (8)

Where, ñ is mass density of liquid, ö is circumferential angle, and y is vertical distance of a point on tank wall from the bottom of tank wall, which are shown in Figure 3.

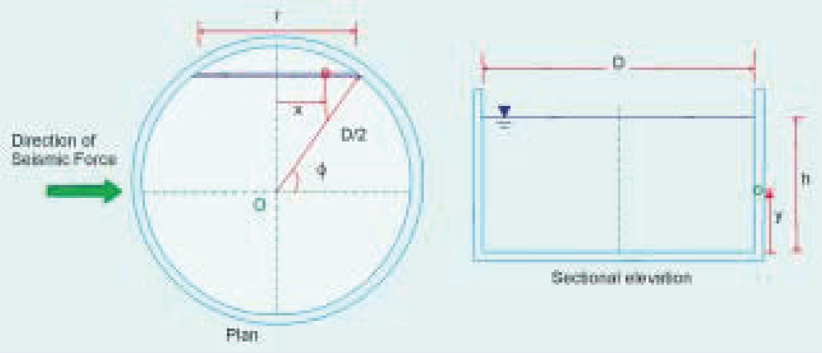

Figure 3: Circumferential angle and strip indication in circular tank

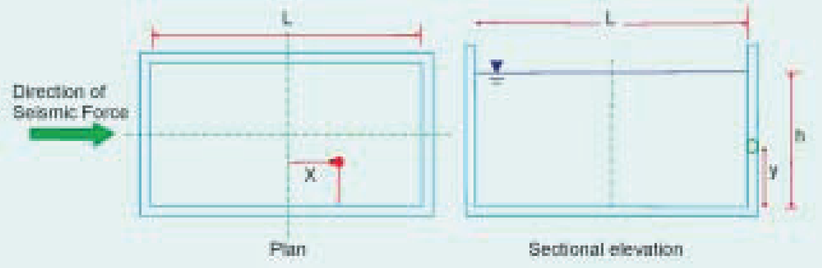

Figure 4: Plan and sectional elevation of rectangular tank

$$p_{ib} = 0.866 (A_h)_i \rho g h \frac{\sinh\left(0.866 \frac{x}{h}\right)}{\cosh\left(0.866 \frac{l'}{h}\right)} \qquad (9)$$

Impulsive hydrodynamic pressure in vertical direction, on base slab (y = 0) on a strip of length l', is given by,

Where, x is horizontal distance of a point on base of tank in the direction of seismic force, from the centre of tank.

Convective hydrodynamic pressure for circular tank

The convective pressure exerted by the oscillating liquid on the circular tank wall and base shall be calculated as follows.

Lateral convective pressure on the wall P_{cw} is given by,

$$p_{cw} = Q_{cw}(y)(A_h)_c \rho g D\left[1 - \frac{1}{3}\cos^2\phi\right]\cos\phi \qquad (10)$$

$$Q_{cw}(y) = 0.5625 \frac{\cosh\left(3.674 \frac{y}{D}\right)}{\cosh\left(3.674 \frac{h}{D}\right)} \qquad (11)$$

Convective pressure in vertical direction, on the base slab (y = 0) is given by,

$$p_{cb} = Q_{cb}(x)(A_h)_c \rho g D \qquad (12)$$

$$Q_{cb}(x) = 1.125\left[\frac{x}{D} - \frac{4}{3}\left(\frac{x}{D}\right)^3\right]\sec h\left(3.674 \frac{h}{D}\right) \qquad (13)$$

Hydrodynamic Pressure for Rectangular Tank

Hydrodynamic pressure in impulsive and convective mode is acting on tank as shown in Figure 2. Inertia of tank wall and vertical ground acceleration also increase hydrodynamic pressure.

Impulsive hydrodynamic pressure for rectangular tank

Lateral hydrodynamic impulsive pressure on the wall, p_{iw}, is given by,

$$p_{iw} = Q_{iw}(y)(A_h)_i \rho g h \qquad (14)$$

Where

$$Q_{iw}(y) = 0.866\left[1 - \left(\frac{y}{h}\right)^2\right]\tanh\left(0.866 \frac{L}{h}\right) \qquad (15)$$

Where, ρ is mass density of liquid, h is total height of liquid and y is vertical distance of a point on tank wall from bottom of tank wall, which is shown in Figure 4.

Impulsive hydrodynamic pressure in vertical direction, on the base slab (y = 0), is given by

$$p_{ib} = Q_{ib}(x)(A_h)_i \rho g h \qquad (16)$$

Where,

$$Q_{ib}(x) = \frac{\sinh\left(0.866 \frac{x}{h}\right)}{\cosh\left(0.866 \frac{L}{h}\right)} \qquad (17)$$

Convective hydrodynamic pressure for rectangular tank

The convective pressure exerted by the oscillating liquid on the rectangular tank wall shall be calculated as follows.

$$p_{cw} = Q_{cw}(y)(A_h)_c \rho g L \qquad (18)$$

$$Q_{cw}(y) = 0.4165 \frac{\cosh\left(3.162 \frac{y}{L}\right)}{\cosh\left(3.162 \frac{h}{L}\right)} \qquad (19)$$

Convective pressure in vertical direction, on the base slab (y = 0) is given by,

$$p_{cb} = Q_{cb}(x)(A_h)_c \rho g l \qquad (20)$$

Where,

$$Q_{cb}(x) = 1.25\left[\frac{x}{L} - \frac{4}{3}\left(\frac{x}{L}\right)^3\right]\sec h\left(3.162 \frac{h}{L}\right) \qquad (21)$$

Hydrodynamic pressure due to wall inertia and vertical ground acceleration

Pressure on tank wall due to its inertia (P_{ww}) is given by

$$p_{ww} = (A_h)_i t \rho_m g \qquad (22)$$

Where, ρ_m is mass density of material. Due to vertical ground acceleration, effective weight of liquid increases, this induces additional pressure on tank wall, whose distribution is similar to that of hydrostatic pressure. Hydrodynamic pressure on tank wall due to vertical ground acceleration may be taken as,

$P_v = (A_v)$ñ g h (1-y/d) (23)

$A_v = (2/3)(z/2)(I/R)(S_a/g)$ (24)

Where, y is vertical distance of point under consideration from bottom of tank wall, Sa/g is average response acceleration coefficient as per IS: 1893 (Part 1):2002.

Total hydrodynamic pressure

The maximum value of hydrodynamic pressure should be obtained by combining pressure due to horizontal and vertical excitation through square root of sum of squares (SRSS) rule, which can be calculate as per Eq.25.

$$p = \sqrt{(p_{iw} + p_{ww})^2 + p_{cw}^2 + p_v^2} \qquad (25)$$

Parametric Study of Analysis Results for Circular Tank

Parametric study carried out for open circular tank considering earthquake zone IV and V. Soil type considered as soft soil, thickness of wall is 250 mm, thickness of base slab is taken as 400 mm. Tank is considered as resting on the ground so response reduction factor (R) considered as 2, and importance factor (I) is considered as 1.5. Free board is considered as 0.5 m for all cases.

In this study 8,00,000 liters to 12,00,000 liters capacity tanks are considered with different h/D ratio as per Table 2.

Total hydrodynamic pressure on wall is calculated for all circular tanks and is expressed as a

Table 2: Dimension of Circular tanks considered for analysis

Capacity	8,00,000 lit		9,00,000 lit		10,00,000 lit		11,00,000 lit		12,00,000 lit	
h/D	h(m)	D(m)	h(m)	D(m)	h(m)	D(m)	h(m)	D(m)	h(m)	D(m)
0.1	2.16	21.66	2.25	22.54	2.33	23.35	2.41	24.1	2.48	24.81
0.2	3.44	17.2	3.57	17.89	3.7	18.53	3.82	19.13	3.94	19.69
0.3	4.51	15.03	4.69	15.63	4.85	16.19	5.01	16.71	5.16	17.2
0.4	5.46	13.65	5.68	14.2	5.88	14.71	6.07	15.18	6.25	15.63
0.5	6.33	12.67	6.59	13.18	6.82	13.65	7.04	14.09	7.25	14.51
0.6	7.15	11.93	7.44	12.4	7.71	12.85	7.96	13.26	8.19	13.65
0.7	7.93	11.33	8.25	11.78	8.54	12.2	8.82	12.6	9.08	12.97
0.8	8.67	10.84	9.02	11.27	9.34	11.67	9.64	12.05	9.92	12.4
0.9	9.38	10.42	9.75	10.84	10.1	11.22	10.43	11.59	10.73	11.93
1	10.06	10.06	10.46	10.46	10.84	10.84	11.19	11.19	11.52	11.52

Table 3: Dimensions of rectangular tanks considered for analysis

Capacity	8,00,000 lit			9,00,000 lit			10,00,000 lit			11,00,000 lit			12,00,000 lit		
L/h	L(m)	h(m)	B(m)	L(m)	h(m)	B(m)	L(m)	h(m)	B(m)	L(m)	h(m)	B(m)	L(m)	h(m)	B(m)
1	10.50	10.50	7.36	11.00	11.00	7.44	11.50	11.50	7.58	12.00	12.00	7.64	12.50	12.50	7.68
2	12.50	6.25	10.24	13.00	6.50	10.65	13.50	6.75	10.97	14.00	7.00	11.22	14.50	7.25	11.42
3	14.50	4.83	11.42	15.00	5.00	12.00	15.50	5.17	12.49	16.00	5.33	12.89	16.50	5.50	13.22
4	16.50	4.13	11.75	17.00	4.25	12.48	17.50	4.38	13.06	18.00	4.50	13.58	18.50	4.63	14.02
5	18.50	3.70	11.69	19.00	3.80	12.47	19.50	3.90	13.15	20.00	4.00	13.75	20.50	4.10	14.28

fraction of hydrostatic pressure. If hydrodynamic pressure is less than 33% of static pressure, then there is no need to consider hydrodynamic pressure, but if hydrodynamic pressure is more, then it must be considered in the design of tank. Comparison is made for ground supported circular tank with capacity of 8,00,000 liters to 12,00,000 liters for earthquake zone IV and zone V. Hydrodynamic pressure in terms of hydrostatic pressure is presented in Figure 5. In Figure 5, horizontal line indicates permissible limit of hydrodynamic pressure.

1 Parametric study of analysis results For Rectangular tank Rectangular water tank of 8,00,000 liters to 12,00,000 liters with different length to height ratio from 1 to 5 are considered for seismic analysis. Earthquake forces are considered in both the directions i.e. parallel to length and parallel to width and critical forces are presented here. Dimensions of tanks considered for water tank are given in Table.3. oil considered as soft soil. Total hydrodynamic pressure on wall is calculated for all circular tanks and is expressed as a fraction of hydrostatic pressure and presented in Figure 6.

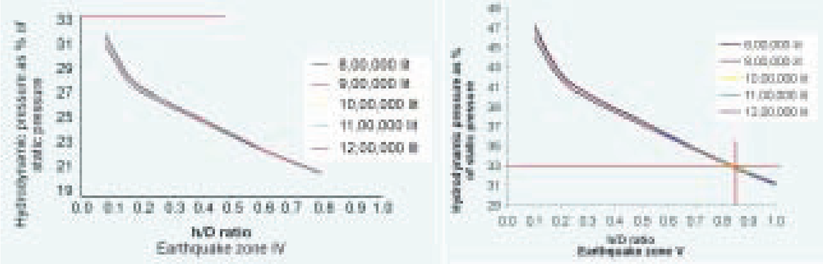

Figure 5: Comparison of hydrodynamic pressure in terms of hydrostatic for zone 4 and zone 5

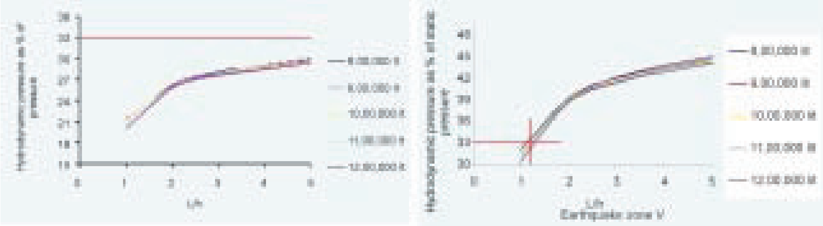

Figure 6: Comparison of hydrodynamic pressure in terms of hydrostatic for zone 4 and zone 5

Conclusion

In draft code IS: 1893 (Part II) there are number of provisions for ground supported tank for seismic analysis. From seismic analysis of circular and rectangular tank having capacity from 8,00,000 liters to 12,00,000 liters with different dimensions following conclusions can be drawn.

Hydrodynamic pressure of various capacity of circular and rectangular tank in earthquake zone up to IV is within permissible limit in circular tank (less than 33% of static pressure), so there is no need to consider hydrodynamic pressure while designing of water tank up to earthquake zone IV.

Hydrodynamic pressure of various capacity of circular tank in zone V with height to diameter ratio less than 0.85, are beyond the permissible limit (more than 33% of static pressure), so hydrodynamic pressure must be considered while designing of ground supported circular tank in zone V.

Hydrodynamic pressure at the base of rectangular tank wall for various capacity of tank in zone V with length to height ratio more than 1.2, are beyond the permissible limit (i.e. more than 33% of static pressure), so hydrodynamic pressure must be considered while designing of ground supported rectangular tank.

References

- Jain, S.K., Jaiswal, O.R., 'Indian Institute of Technology Kanpur–GSDMA Guidelines for Seismic Design of Liquid Storage Tanks,' October 21, 2005.
- Jaiswal, O.R., Durgesh C. Rai, Jain,S.K., "Review of Seismic Codes on Liquid-Containing Tanks" Earthquake Spectra, Vol. 23, No. 1, pp 239–260, February, 2007.