Dynamic Analysis of Rectangular Elevated Tank with Multiple Compartments as Per IS: 1893 Draft Code (Part–2)

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Abstract—**This paper presents the dynamic analysis of a rectangular elevated liquid storage tank with multiple compartments. Tank geometry has been taken as per standard height to length ratio and complete finite element models have been prepared using SAP 2000 software. The water mass inside the tank has been distributed appropriately to take into account the hydrodynamic forces developed due to impulsive as well as convective effects. Models have been prepared separately for impulsive and convective mass for all the geometry of the rectangular tank. From the analysis, time period and base shear have been compared with calculated value obtained from the expressions given in draft code IS 1893(part-2).**

The study reveals that the value of time period is differing in all the cases but change is not considerable in the case of base shear and moment. That indicates the provision of compartments in the tank serves the intended purpose without affecting economy.

Keywords—**Compartmental tank, Hydrodynamic pressure, impulsive mass, convective mass, two mass model, Sloshing height.**

I. INTRODUCTION

Earthquake, one of the natural disasters, causes the destruction of structures. Water Tanks are special structures and requires proper attention in seismic analysis and design. The dynamic response of liquid storage tanks subjected to earthquake has been a subject of numerous studies in the past 30 years. Up till now we have been considering only the hydrostatic effect of water and most of the studies were focused on the tank containing liquid considering only one mass.

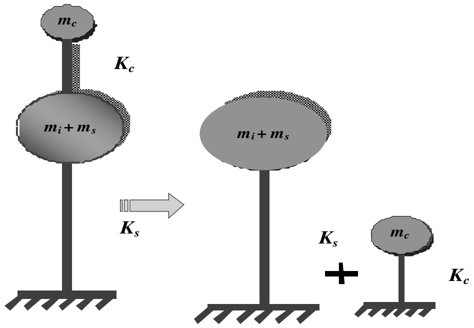
Moreover, it does not cover important aspects for analysis and design of water tanks related to hydrodynamic effect. After the Bhuj earthquake, revision of this code became inevitable. Hence it was decided to develop guidelines under the project “Review of Building Codes and Preparation of Commentary and Handbooks” assigned by the Gujarat State Disaster Management Authority (GSDMA), Gandhinagar to the Indian Institute of Technology Kanpur in 2003. The draft code for liquid retaining structures is one of the outcome of the project. The present study is based on the provisions of this draft code.

II. OVERVIEW OF DRAFT CODE

This draft code has been prepared in accordance with generally recognized engineering principles and practices. Many international codes, standards and guidelines have been referred. Seismic analysis of water tanks considering hydrodynamic effect has been explained in detail. The following important provisions and changes have been incorporated as compared to that of IS 1893:1984.

- Analysis of ground supported tanks.
- For elevated tanks, the single degree of freedom is replaced by two degree of freedom idealization.
- Bracing beam flexibility is explicitly included in calculation of lateral stiffness of tank staging.
- The effect of convective and impulsive hydrodynamic pressure distribution in the analysis.
- Effect of vertical ground acceleration on hydrodynamic pressure and pressure due to wall inertia.
- Sloshing effect of water and maximum sloshing wave height.
- P-Delta effect for elevated water tank.

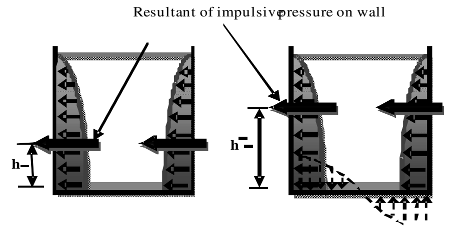
Hydrodynamic effect is considered by dividing water into two different masses, namely impulsive and convective. When the tank containing liquid with free surface is subjected to horizontal earthquake ground motion, tank wall and liquid are subjected to horizontal acceleration. The liquid in the lower region behaves like a mass that is rigidly connected to the tank wall. This mass is termed as impulsive liquid mass, which, accelerates along with the wall and induces impulsive hydrodynamic pressure on tank wall and on base. The liquid mass in the upper region of the tank undergoes sloshing motion. This mass is termed as convective liquid mass and exerts convective hydrodynamic pressure on wall and base. For representing these two masses and in order to include the effect of their hydrodynamic pressure in analysis, spring mass model is adopted for ground-supported tanks and two-mass model for elevated tanks. In spring mass model convective mass (m_c) is attached to the tank wall by the spring having stiffness K_c, whereas impulsive mass (m_i) is rigidly attached to tank wall. For elevated tanks two-mass model is considered, which consists of two degrees of freedom system. Spring mass model can also be applied on elevated tanks, but two-mass model idealization is closer to reality. The two mass model is shown in fig.1. where, m_i, m_c, K_c, h_i, h_c, h_s etc are the parameters of spring mass model and charts as well as empirical formulae are given for finding their values. The parameters of this model depend on geometry of the tank and its flexibility. For elevated tanks, if the shape is other than circular or rectangular, then the values of spring mass parameters can be obtained by considering an equivalent circular tank having same capacity with diameter equal to that of diameter at top level of liquid in original tank.



(a) (b)

Fig.1: Two mass model for elevated tanks

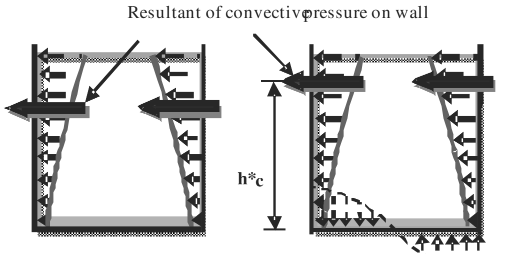
The two-mass model was first proposed by G.M.Housner and is being commonly used in most of the international codes. The response of the two-degree of freedom system can be obtained by elementary structural dynamics. However, for most of elevated tanks, it is observed that both the time periods are well separated. Hence, the two-mass idealization can be treated as two uncoupled single degree of freedom system as shown in Fig.1 (b). The stiffness (K_s) shown in Fig.1 is lateral stiffness of staging. The mass (m_s) is the structural mass and shall comprise of mass of tank container and one-third mass of staging, as staging will act like a lateral spring. Mass of container comprises of roof slab, container wall, gallery if any, floor slab, floor beams, ring beam, circular girder, and domes if provided.



(a) Impulsive pressure pressure on wall

(b) Impulsive pressure on wall and base

Fig.2: Hydrodynamic pressure in impulsive mode



(a) Convective pressure on wall

(b) Convective pressure on wall and base

Fig.3: Hydrodynamic pressure in convective mode

Hydrodynamic Pressure

There are two types of hydrodynamic pressure acting on the tank wall, i.e. impulsive hydrodynamic pressure and convective hydrodynamic pressure as stated earlier. If vertical columns and shaft are present inside the tank, then impulsive and convective masses will change. The pressure distributions for both impulsive and convective modes are shown in Fig. 2 and Fig. 3 respectively.

As shown in Fig.2, the maximum impulsive hydrodynamic pressure is at the base of wall while at the top it is almost zero. Hence in spring mass model impulsive mass is considered as rigid mass at the base. The second figure shows the impulsive hydrodynamic pressure distribution when base pressure is also considered. If the effect of the base pressure is considered then the height of the resultant of the impulsive hydrodynamic pressure is more as clearly observed in the Fig.2(b). In the case of convective hydrodynamic pressure, the distribution is exactly opposite than that of impulsive hydrodynamic pressure. The maximum hydrodynamic pressure is at the top while the minimum pressure is at the bottom as shown in the Fig.3. The sloshing phenomenon observed during earthquake is due to convective mass.

III. SEISMIC AND HYDRODYNAMIC PRESSURE CALCULATIONS

Both the water mass, i.e. impulsive and convective, have different time periods and they are,

$$T_i = 2\pi\sqrt{\frac{m_i + m_s}{K_s}} \;\&\; T_c = \sqrt{\frac{m_c}{K_c}} \qquad \text{... (1)}$$

Where,

T_i =Time period for impulsive mode T_c =Time period for convective mode

m_i =Impulsive mass from draft code m_c =Convective mass from draft code

m_s =Mass of container & one-third mass of staging

K_s =Lateral stiffness of staging

As time period is known, therefore spectral acceleration coefficient (S_a/g), horizontal acceleration coefficient (A_h), base shear and base moment for impulsive and convective mode will be obtained as follows.

$$A_h = \frac{Z}{2}\frac{I}{R}\frac{Sa}{g} \quad \ldots (2)$$

$$V_i = (A_h)_i (m_i + m_s)\cdot g \quad \&$$

$$V_c = (A_h)_c (m_c)\cdot g \quad \ldots (3)$$

$$M_i = (A_h)_i \left[m_i \left(h_i^{*} + h_s \right) + m_s h_{cg} \right] g$$

$$\& \; M_c = (A_h)_c \, m_c \left(h_c^{*} + h_s \right) g \quad \ldots (4)$$

$$V = \sqrt{V_i^2 + V_c^2} \;\; \& \;\; M = \sqrt{M_i^2 + M_c^2} \quad \ldots (5)$$

Where,

$(A_h)_i$ =Design horizontal seismic coefficient for impulsive mode

$(A_h)_c$ =Design horizontal seismic coefficient for convective mode

g = acceleration due to gravity

Z = Zone factor from IS 1893 (P-1):2002

I = Importance factor

R = Response reduction factor

$\frac{Sa}{g}$ = Average response acceleration coefficient

V_c =Base shear in convective mode

V_i =Base shear in impulsive mode

M_c =Base moment in convective mode

M_i =Base moment in impulsive mode

V =Total Base shear

M = Total Base moment

Hydrodynamic Pressure

The hydrodynamic pressure is acting not only due to impulsive and convective masses but also due to wall inertia and vertical ground excitation.

Impulsive Hydrodynamic Pressure

The impulsive hydrodynamic pressure exerted by the liquid on the tank wall and base is as follows,

a) Lateral hydrodynamic pressure on wall, p_{iw} is

$$p_{iw} = Q_{iw}(y)(A_h)_i \rho g h \quad \ldots (6)$$

$$Q_{iw}(y) = 0.866\left[1 - \left(\frac{y}{h}\right)^2\right] \tanh\left(0.866\frac{L}{h}\right) \quad \ldots (7)$$

W where,

ρ ρ = Mass density of liquid

$Q_{iw}(y)$ =Coefficient of impulsive hydrodynamic pressure on wall

y = Vertical distance of a point on tank wall from the bottom of tank wall.

h = height of container & L = Length of container

Vertical hydrodynamic pressure on base slab, p_{ib} is

$$p_{ib} = (A_h)_i \rho g h \frac{\sinh\left(0.866\frac{x}{h}\right)}{\cosh\left(0.866\frac{L}{h}\right)} \quad \ldots (8)$$

Where,

x= Horizontal distance of a point on base of tank in the direction of seismic force, from center.

Convective Hydrodynamic Pressure

The convective hydrodynamic pressure exerted by the oscillating liquid on the tank wall and base is as follows

b) Lateral hydrodynamic pressure on wall, p_{cw} is

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

$$Q_{cw}(y) = 0.4165\frac{\cosh\left(3.162\frac{y}{L}\right)}{\cosh\left(3.162\frac{h}{L}\right)} \quad \ldots (9)$$

Where,

$Q_{cw}(y)$= Coefficient of convective hydrodynamic pressure on wall

Vertical hydrodynamic pressure on base slab, p_{cb} is

$$p_{cb} = Q_{cb}(x)(A_h)_c \rho g L \quad \&$$

$$Q_{cb}(x) = 1.25\left[\frac{x}{L} - \frac{4}{3}\left(\frac{x}{L}\right)^3\right] \sec h\left(3.674\ \frac{h}{L}\right) \qquad \ldots (10)$$

Where,

$Q_{cb}(x)$= Coefficient of convective hydrodynamic pressure on base slab.

Hydrodynamic Pressure Due to Wall Inertia

Pressure due to wall inertia will act in same direction as that of seismic forces. For steel tanks, wall inertia may not be significant. However, for concrete tanks, wall inertia may be substantial due to heavy mass of concrete. Pressure due to wall inertia, which is constant along the walls of uniform thickness, should be added to impulsive hydrodynamic pressure. The expression for calculating wall inertia is

$$p_{ww} = (A_h)_i t \rho_m g h \qquad \ldots (11)$$

Where, t = wall thickness ρ_m = wall density

Pressure Due to Vertical Ground Acceleration

Due to vertical ground acceleration, effective weight of the liquid increases, this induces additional pressure on tank wall, whose distribution is similar to that of hydrostatic pressure.

Hydrodynamic pressure due to vertical ground acceleration, p_v is,

$$p_v = (A_v)\ \rho g h\left(1 - \frac{y}{h}\right) \&$$

$$(A_v) = \frac{2}{3}\left(\frac{Z}{2}\frac{I}{R}\frac{S_a}{g}\right) \qquad \ldots (12)$$

Where,

A_v = Design vertical seismic coefficient

y = vertical distance of point under consideration from bottom of tank wall.

Maximum 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.

c) Maximum hydrodynamic pressure, p is

$$p = \sqrt{\left\langle p_{iw} + p_{ww}\right\rangle^2 + p_{cw}{}^2 + p_v{}^2} \qquad \ldots (13)$$

IV. PARAMETRIC STUDY

Models are prepared separately for impulsive and convective masses. Impulsive and convective masses are applied at respective heights for all the compartments of tank as shown in Fig. 4. For the convective mass a link with the stiffness of Kc has been used. The fundamental period (T) and base shear (V) has been estimated for all the analysis as shown in Table 1.

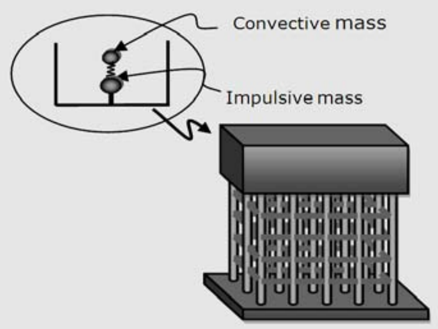


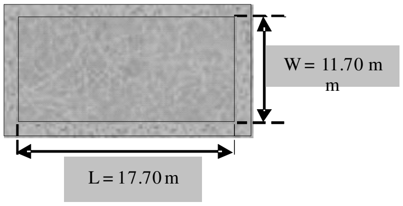
Fig.4: Tank models with different mass application

Behaviour of hydrodynamic pressure and seismic forces has been studied by varying number of compartments in the tank as shown in Fig.5.

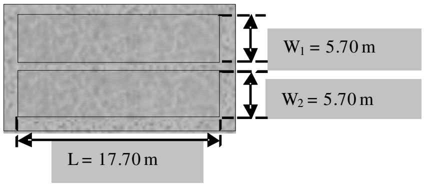
Capacity of Tank = 1000 m^3

Height = 5.2 m

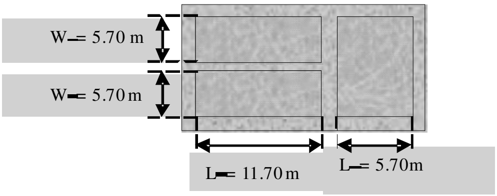
Freeboard = 0.3 m



(a) Single Compartment Rectangular Tank



(b) Two Compartment Rectangular Tank



c) Three Compartment Rectangular Tank

Fig. 5: Rectangular Tank with different no. of compartment

V. RESULTS AND DISCUSSION

As shown in Table 1, base shear and moment in Rectangular and Circular Compartmental Tank slightly increases with no. of compartments, but it is more due to additional internal wall which is provided to make compartments. The impulsive mass would increase; it would also contribute in an increment of base shear and base moment. Moreover minor change in base shear and moment has been observed in all the cases. That means, provision of compartments in tank serves intended purpose without affecting economy. But the time period for convective and impulsive mass in Fig. 6 & 7, reveals different values in SAP 2000 and as per code.

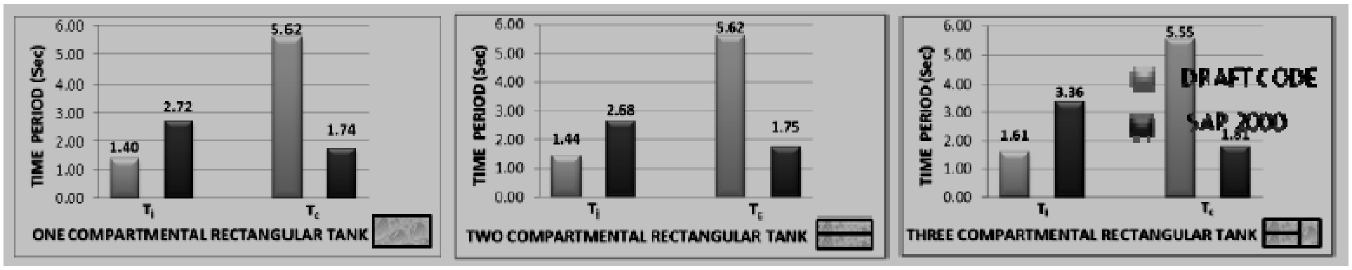


Fig. 6: Time Period Rectangular Tank (1000m^3)

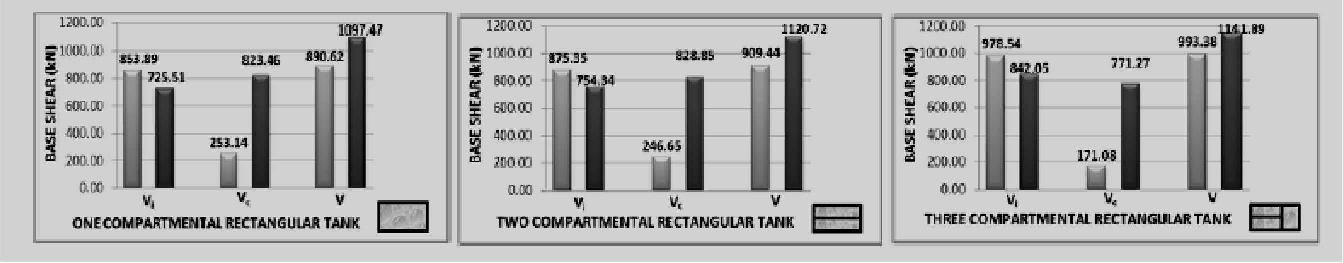


Fig.7: Base Shear in Rectangular Tank (1000 m3)

REFERENCES

[1] IITK-GSDMA Guidelines for Seismic Design of Liquid Storage Tanks Provisions with commentary and explanatory examples.

[2] IS 11682:1985, “Criteria for Design of RCC Staging for Overhead Water Tanks”, Bureau of Indian Standards, New Delhi.

[3] Wilson. E.L. and Habibullah. A. 2003, “*Structural Analysis Program SAP2000*. “ Users manual, Computers and Structures, Inc., Berkeley, Calif.

[4] Yu Tang, “Dynamic Response of Tank containing two liquids”, *Journal of Engineering Mechanics, ASCE, March*-1993, Vol-125, No. 3 Pg-531.