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Modified proposed provisions for aseismic design of liquid storage tanks: Part I – codal provisions

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Recognizing the limitations and shortcomings in the provision of IS 1893:1984; Jain and Medhekar had suggested a set of provisions on aseismic design of liquid storage tanks. In view of recent revision of IS 1893 and availability of new research results on aseismic design of liquid storage tanks, the provisions suggested by Jain and Medhekar need modifications. In this paper, which is in two parts, a set of modified provisions on aseismic design of liquid storage tanks are proposed. The major modifications are: (i) Design horizontal seismic coefficient given in revised IS 1893 (Part 1): 2002 is used and values of response reduction factor for different types of tanks are proposed. (ii) Different spring-mass models for tanks with rigid and flexible walls are done away with; instead, a single spring-mass model for both types of tank is proposed. (iii) Expressions for convective hydrodynamic pressure are corrected. (iv) Simple expression for sloshing wave height is used. (v) New provisions are included to consider the effect of vertical excitation and to describe critical direction of earthquake loading for elevated tanks with frame type staging.

Seismic safety of liquid storage tanks is of considerable importance. Ground supported and buried tanks are used by industries for storing toxic materials, petrochemicals and water. Elevated tanks are generally used in public water distribution system. These tanks must remain functional in post earthquake period and toxic contents in them should not leak.

In India, provisions for aseismic design of liquid storage tanks are given in IS 1893:1984[1]. These provisions are only for elevated tanks and there are no provisions for ground supported tanks. Limitations and shortcomings in the provisions of IS 1893:1984[1] have been discussed in the literature by Jain and Medhekar[2,3], Jain and Sameer[4] and Rai[5]. Jain and Medhekar[2,3] have also suggested a new set of provisions for aseismic design of tanks. The provisions suggested by Jain and Medhekar[2,3] are largely derived from recommendations of NZSEE (Preistley et al[6]). These provisions need revision mainly due to two reasons: Firstly, since 1993, IS 1893 itself has been revised and in its fifth revision, design horizontal seismic coefficient has been expressed in a form different than that in IS 1893:1984[1]. Secondly, in last one decade, considerable research has been carried out on aseismic design of liquid storage tanks and significant amount of new information is available on this topic. Moreover since 1993, many international codes on liquid storage tanks have revised their provisions in view of availability of new information.

In this paper, modifications to the provisions suggested by Jain and Medhekar[2,3] are proposed and some new provisions are also included. These modified provisions can be adopted in Part 2 of IS 1893.

Part I of the paper describes the modified provisions. Part II (to be published later) contains a detailed commentary on major provisions and solved numerical examples to illustrate application of modified provisions.

MAJOR MODIFICATIONS

Major changes in the provisions suggested by Jain and Medhekar[2,3] and some new provisions to be included are described below:

Design Horizontal Seismic Coefficient

As per IS 1893: 1984[1], design horizontal seismic coefficient is given by

$$\alpha_h = K \beta I F_0 S_a / g \tag{1}$$

Jain and Medhekar[2,3] suggested value of performance factor, $K = 3.0$ for all types of tanks. However, in the fifth revision of IS 1893 (i.e. IS 1893 (part1): 2002[7]), design horizontal seismic coefficient is expressed as

$$A_h = \frac{Z}{2} \frac{I}{R} \frac{S_a}{g} \tag{2}$$

IS 1893 (part 1): 2002[7] specifies values of I and R for buildings. For arriving at suitable values of I and R for

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liquid storage tanks, Jaiswal et al.[8] have performed a detailed study of design horizontal seismic coefficient used in various international codes. They observed that in most of the international codes liquid storage tanks are put in three categories for assigning importance factor I. Response reduction factor R, is assigned based on energy absorbing capacity and ductility of tank. Jaiswal et al[8] noted that in most of the codes, for a tank with low energy absorbing capacity and ductility, design horizontal seismic coefficient is about 6 to 7 times higher than that for a building with special moment resisting frame. Similarly, for a tank with good energy absorbing capacity and ductility, the design horizontal seismic coefficient is 3 to 4 times higher. Based on this study, a set of R values are suggested by Jaiswal et al.[8] for different types of tanks.

Spring-Mass Model

Liquid storage tanks are traditionally idealized as spring-mass models for evaluating hydrodynamic forces. Jain and Medhekar[2,3] have used different spring-mass models for tanks with rigid and flexible walls. For tanks with rigid wall, two-mass model was used whereas, for tanks with flexible wall three-mass model was used. For tanks with rigid wall, time period of impulsive mode was taken as zero and for tanks with flexible wall time period of impulsive mode was obtained using approach given by Preistley[6]. However, studies by Veletsos[9], Malhotra[10] and Jaiswal et al[11] revealed that there is no need to differentiate between the tanks with rigid and flexible walls, and parameters of spring-mass model for both types of tanks can be obtained using two-mass model without any significant loss of accuracy. Further, for all types of tanks, effect of wall flexibility should be included in the evaluation of time period of impulsive mode.

For impulsive mode time period of ground supported circular tanks, Jain and Medhekar[2,3] have adopted the expression from Preistley[6], in which the coefficient of impulsive mode time period is to be obtained graphically. However in subsequent studies, closed-form expression has been developed for time period of impulsive mode of ground supported circular tanks. One such expression given by Sakai et al.[12] has been used in Eurocode 8[13]. Thus, the spring-mass model suggested by Jain and Medhekar[2,3] needs to be modified along with expression for impulsive time period.

Convective Hydrodynamic Pressure

The expressions for distribution of convective hydrodynamic pressure on tank wall and base given by Jain and Medhekar[2,3] are taken from Housner[14]. However in the expressions given by Jain and Medhekar[2,3] numerical values of some of the constants need to be corrected.

Sloshing Wave Height

Jain and Medhekar[2,3] adopted the sloshing wave height expression from Housner[14]. However, in recent revisions of all the international codes (ACI 350.3[15], AWWA D-100[16], and Eurocode 8[13]), a much simpler form of this expression has been used.

Apart from the above mentioned modifications to provisions suggested by Jain and Medhekar[2,3], following new provisions need to be added:

i) Provisions on effect of vertical ground acceleration on hydrodynamic pressure.
ii) Provisions on critical direction of seismic loading for elevated tanks on frame type staging.
iii) Provisions on flexibility of piping system and connections between piping and tank wall.
iv) Provisions on buried tanks.

MODIFIED PROVISIONS

Hydrodynamic forces exerted by liquid on tank wall shall be considered in the analysis in addition to hydrostatic forces. These hydrodynamic forces are evaluated with the help of spring-mass model of tanks.

Spring-Mass Model for Seismic Analysis

When a tank containing liquid vibrates, the liquid exerts impulsive and convective hydrodynamic pressure on the tank wall and the tank base in addition to the hydrostatic pressure. In order to include the effect of hydrodynamic pressure in the analysis, tank can be idealized by an equivalent spring-mass model, which includes the effect of tank wall – liquid interaction. The parameters of this model depend on geometry of the tank and its flexibility.

Ground Supported Tank

Ground supported tanks can be idealized as spring-mass model shown in Fig. 1. The impulsive mass of liquid, m_i is rigidly attached to tank wall at height h_i (or h_i^*). Similarly, convective mass, m_c is attached to the tank wall at height h_c(or h_c^*) by a spring of stiffnessK_c.

Circular and rectangular tank

For circular tanks, parameters m_i, m_c, h_i, h_i^*, h_c, h_c^* and K_c shall be obtained from Fig. 2 and for rectangular tanks these parameters shall be obtained from Fig. 3. h_i and h_c account for hydrodynamic pressure on the tank wall only. h_i^* and h_c^* account for hydrodynamic pressure on tank wall and the tank base. Hence, the value of h_i and h_c shall be used to calculate moment due to hydrodynamic pressure at the bottom of the tank wall. The value of h_i^* and h_c^* shall be used to calculate overturning moment at the base of tank.

Elevated Tank

(a) Elevated tanks (Fig. 4a) can be idealized by a two-mass model as shown in Fig. 4c. For elevated tanks with circular container, parameters m_i, m_c, h_i, h_i^*, h_c, h_c^* and K_c shall be obtained from Fig. 2. For elevated tanks with rectangular container, these parameters shall be obtained from Fig. 3. In Fig. 4c, m_s is the structural mass and shall comprise of mass of tank container and one-third mass of staging.

(b) For elevated tanks, the two degree of freedom system of Fig. 4c can be treated as two uncoupled single degree of freedom systems (Fig. 4d), one representing the impulsive plus structural mass behaving as an inverted pendulum with lateral stiffness equal to that of the staging, K_s and the other representing the convective mass with a spring of stiffness, K_c.

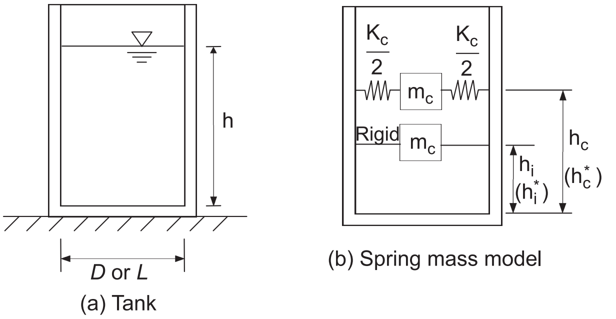


FIG. 1. SPRING-MASS MODEL FOR GROUND SUPPORTED CIRCULAR AND RECTANGULAR TANK

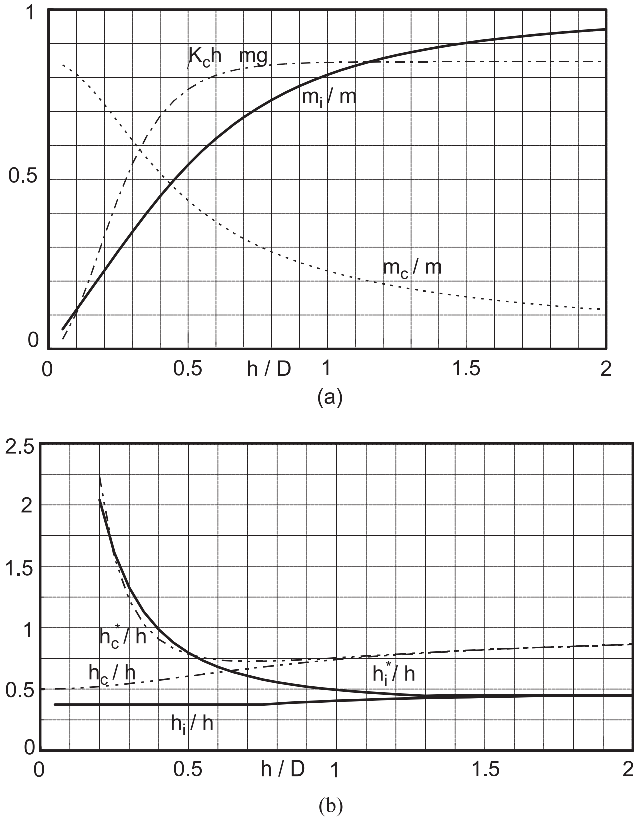


FIG. 2. PARAMETERS OF THE SPRING-MASS MODEL FOR CIRCULAR TANK (a) IMPULSIVE AND CONVECTIVE MASS AND CONVECTIVE SPRING STIFFNESS (b) HEIGHTS OF IMPULSIVE AND CONVECTIVE MASSES

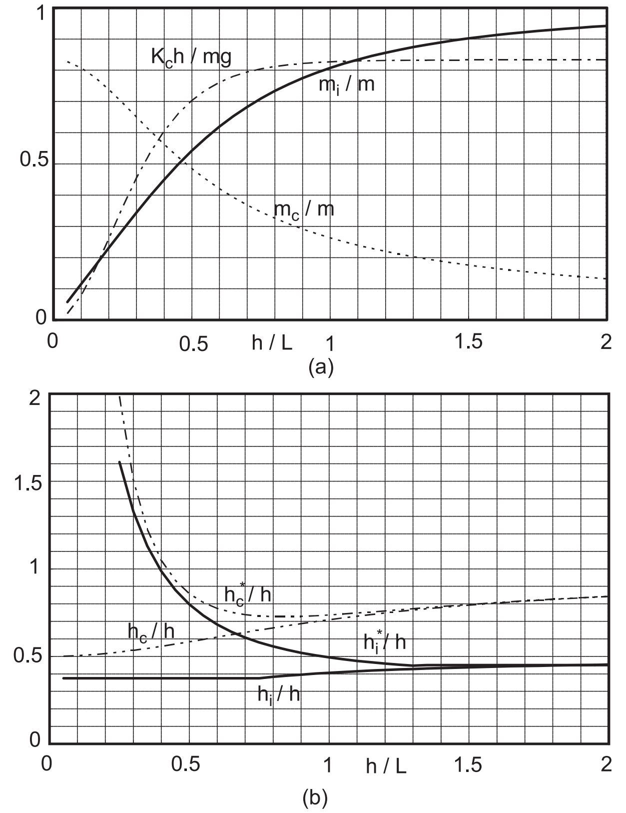
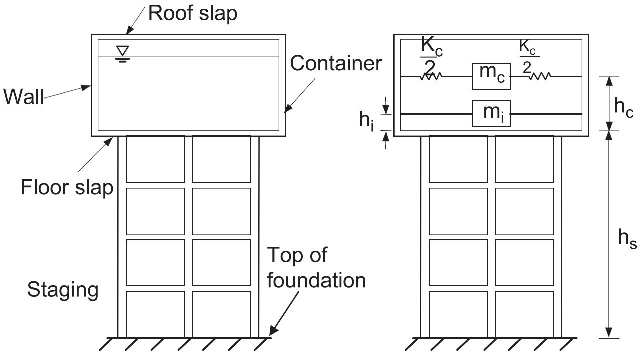
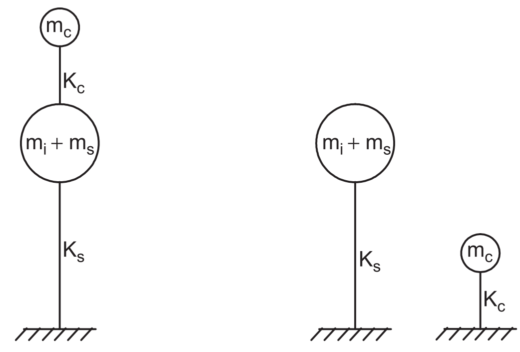


FIG. 3. PARAMETERS OF THE SPRING-MASS MODEL FOR RECTANGULAR TANK (a) IMPULSIVE AND CONVECTIVE MASS AND CONVECTIVE SPRING STIFFNESS (b) HEIGHTS OF IMPULSIVE AND CONVECTIVE MASSES



(a) Elevated tank

(b) Spring mass model



(c) Two mass idealization of elevated tank

(d) Equivalent uncoupled system

FIG. 4. TWO MASS IDEALIZATION FOR ELEVATED TANK

Tanks of Other Shapes

For tank shapes other than circular and rectangular (like Intze, truncated conical shape), the value of h/D shall correspond to that of an equivalent circular tank of same volume and diameter equal to diameter of tank at top level of liquid; and m_i, m_c, h_i, h_i^*, h_c, h_c^* and K_c of equivalent circular tank shall be used.

Time Period

Impulsive Mode

(a) Ground supported circular tank

For a ground supported circular tank, wherein wall is rigidly connected with the base slab (Fig. 5a, 5b and 5c), time period of impulsive mode of vibration T_i, in seconds, is given by

$$T_i = C_i \frac{h\sqrt{\rho}}{\sqrt{t/D}\sqrt{E}} \tag{3}$$

The value of C_i can be obtained from Fig. 6. In some circular tanks, wall may have flexible connection with the base slab. (Different types of wall to base slab connections are described in Fig. 5). For tanks with flexible connections with base slab, time period evaluation may properly account for the flexibility of wall to base connection.

(b) Ground supported rectangular tank

For a ground supported rectangular tank, wherein wall is rigidly connected with the base slab, time period of impulsive mode of vibration, T_i in seconds, is given by

$$T_i = 2\pi\sqrt{\frac{d}{g}} \tag{4}$$

where

$$q = \frac{\left(\frac{m_i}{2} + \bar{m}_w\right) g}{Bh} \quad \text{and} \quad \bar{h} = \frac{\frac{m_i}{2} h_i + \bar{m}_w \frac{h}{2}}{\frac{m_i}{2} + \bar{m}_w}.$$

(c) Elevated tank

Time period of impulsive mode, T_i in seconds, is given by

$$T_i = 2\pi\sqrt{\frac{m_i + m_s}{K_s}} \tag{5}$$

Lateral stiffness of the staging is the horizontal force required to be applied at the center of gravity of the tank to cause a corresponding unit horizontal displacement. The flexibility of bracing beam shall be considered in calculating the lateral stiffness, K_s of elevated moment-resisting frame type tank staging.

Convective Mode

Time period of convective mode, in seconds, is given by

$$T_c = 2\pi\sqrt{\frac{m_c}{K_c}} \tag{6}$$

The values of m_c and K_c can be obtained from Figs. 2a and 3a, respectively, for circular and rectangular tanks. Since the expressions for m_c and K_c are known, the expression for T_c can be alternatively expressed as:

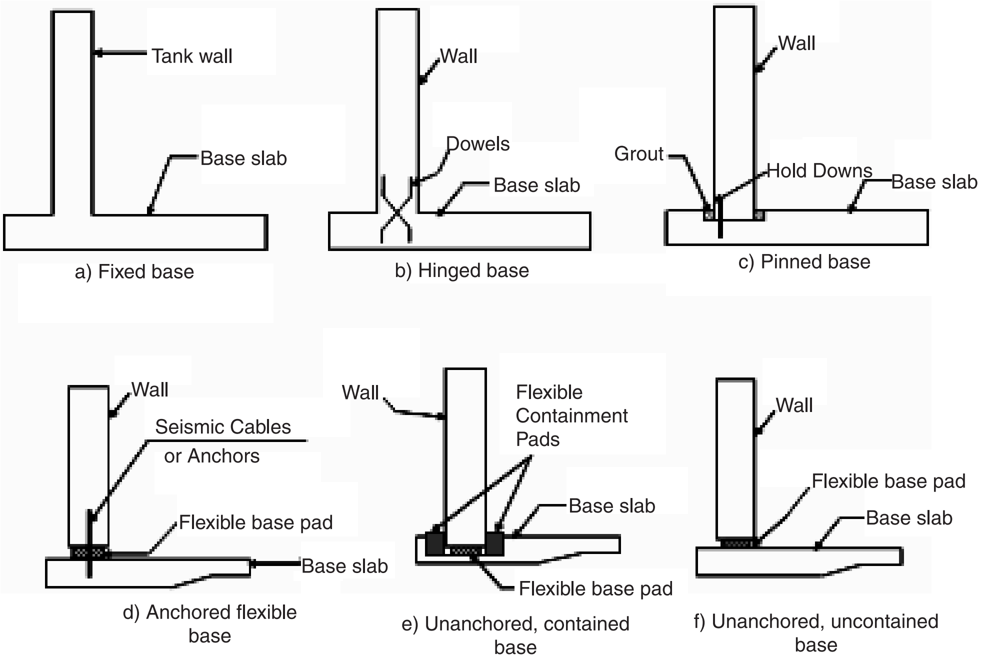


FIG. 5. TYPES OF CONNECTIONS BETWEEN TANK WALL AND BASE SLAB

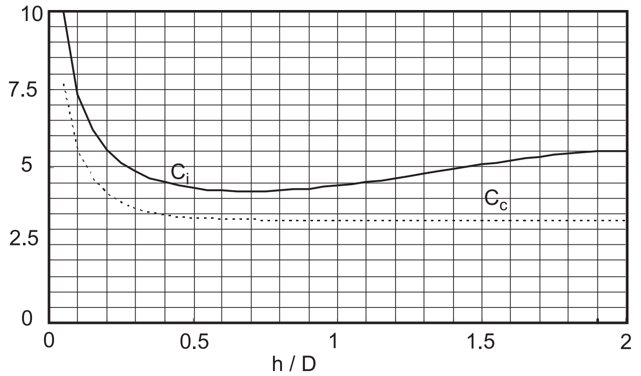


FIG. 6. COEFFICIENT OF IMPULSIVE (C_i) AND CONVECTIVE (C_c) MODE TIME PERIOD FOR CIRCULAR TANK

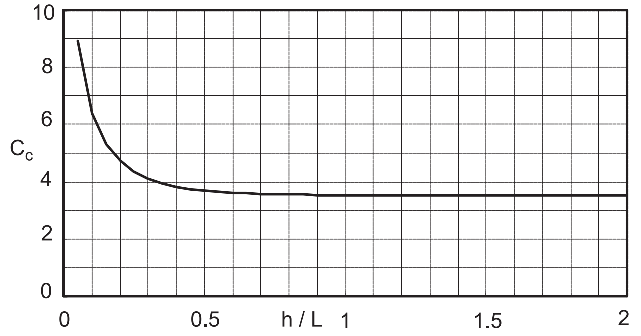


FIG. 7. COEFFICIENT OF CONVECTIVE MODE TIME PERIOD (C_c) FOR RECTANGULAR TANK

(a) Circular tank

Time period of convective mode, T_c in seconds, *is* given by

$$T_c = C_c\sqrt{D/g} \tag{7}$$

The value of C_c can be obtained from Fig. 7.

(b) Rectangular tank

Time period of convective mode of vibration, T_c in seconds, is given by

$$T_c = C_c\sqrt{L/g} \tag{8}$$

The value of C_c can be obtained from Fig. 7

Soil Structure Interaction

For tanks resting on soft soils, effect of flexibility of soil may be considered while evaluating the time period. Generally, soil flexibility does not affect the convective mode time period. However, soil flexibility may affect impulsive mode time period.

Damping

Damping in the convective mode for all types of liquids and for all types of tanks shall be taken as 0.5% of the critical. Damping in the impulsive mode shall be taken as 2% of the critical for steel tanks and 5% of the critical for concrete or masonry tanks.

Design Horizontal Seismic Coefficient

Design horizontal seismic coefficient, A_h shall be obtained by following expression, subject to modifications in section 3.4.2

$$A_h = \frac{Z}{2}\frac{I}{R}\left(\frac{S_a}{g}\right) \tag{9}$$

where Z = Zone factor given in Table 2 of IS 1893 (Part 1): 2002[7], I = Importance factor given in Table 1, R = Response reduction factor given in Table 2, and S_a/g= Average response acceleration coefficient as given by Fig. 2 and Table 3 of IS1893 (Part 1): 2002[7] and subject to modifications in section 3.4.2 of this paper.

TABLE 1

IMPORTANCE FACTOR, I

Type of liquid storage tank	I
Tanks used for storing toxic chemicals, explosives and other inflammable liquids, accidental release of which would be highly dangerous to society.	1.75
Tanks used for storing potable water, non-volatile material, low inflammable petrochemicals etc. and intended for emergency services such as fire fighting services. Tanks of post earthquake importance.	1.5
All other tanks with low risk to life and with negligible consequences to environment, society and economy.	1.0

Impulsive and Convective Mode

Design horizontal seismic coefficient, A_h will be calculated separately for impulsive $(A_h)_i$ and convective $(A_h)_c$ modes.

Average Response Acceleration Coefficient

If time period is less than 0.1 second, the value of S_a/g shall be taken as 2.5 for 5% damping and be multiplied with appropriate factor for other values of damping.

For time periods greater than three seconds, the value of S_a/g shall be obtained using the same expression which is applicable up to time period of three seconds.

Damping Factor

Value of multiplying factor for 0.5% damping shall be taken as 1.75.

Base Shear

Ground Supported Tank

Base shear in impulsive mode, at the bottom of tank wall is given by

$$V_i = (A_h)_i\,(m_i + m_w + m_t)g \tag{10}$$

TABLE 2

RESPONSE REDUCTION FACTOR, R

Type of tank	R
Elevated tank	
Tank supported on masonry shaft	
a) Masonry shaft reinforced with horizontal bands *	1.25
b) Masonry shaft reinforced with horizontal bands and vertical bars at corners and jambs of openings	1.5
Tank supported on RC shaft	
a) RC shaft with reinforcement in one curtain (both horizontal and vertical) at the center of shaft thickness	1.5
b) RC shaft with two curtains of reinforcement, each having horizontal and vertical reinforcement	1.75
Tank supported on RC frame	
a) Frame not conforming to ductile detailing, i.e., ordinary moment resisting frame (OMRF)#	1.75
b) Frame conforming to ductile detailing, i.e., special moment resisting frame (SMRF)#	2.5
Tank supported on steel frame#	2.5
Ground supported tank	
Masonry tank	
a) Masonry wall reinforced with horizontal bands*	1.25
b) Masonry wall reinforced with horizontal bands and vertical bars at corners and jambs of openings	1.5
RC / prestressed tank	
a) Fixed or hinged/pinned base tank (Figs. 6a, 6b, 6c)	2.0
b) Anchored flexible base tank (Fig. d)	2.5
c) Unanchored contained or uncontained tank (Figs. 6e, 6f)	1.5
Steel tank	
a) Unanchored base	2.0
b) Anchored base	2.5
Underground RC and steel tank+	4.0

*These tanks are not allowed in seismic zones IV and V.

+For partially buried tanks, values of R can be interpolated between ground supported and underground tanks based on depth of embedment.

#Diagonal bracings in vertical plane is mandatory in zones IV and V

and base shear in convective mode is given by

$$V_c = (A_h)_c m_c g \tag{11}$$

Elevated Tank

Base shear in impulsive mode, just above the base of staging (i.e. at the top of footing of staging) is given by

$$V_i = (A_h)_i (m_i + m_s) g \tag{12}$$

and base shear in convective mode is given by Eq. (11)

Total Base Shear

Total base shear V, shall be obtained by combining the base shear in impulsive and convective modes through Square Root of Sum of Squares (SRSS) rule and is given as follows

$$V = \sqrt{V_i^2 + V_c^2} \tag{13}$$

Base Moment

Ground Supported Tank

(a) Bending moment in impulsive mode, at the bottom of wall is given by

$$M_i = (A_h)_i \, (m_i \, h_i + m_w \, h_w + m_t \, h_t) \; g \tag{14}$$

and bending moment in convective mode is given by

$$M_c = (A_h)_c \, m_c \, h_c \, g \tag{15}$$

(b) Overturning moment in impulsive mode to be used for checking the tank stability at the bottom of base slab/plate is given by

$$M_i^* = (A_h)_i \left[m_i \left(h_i^* + t_b \right) + m_w \left(h_w + t_b \right) + m_t \left(h_t + t_b \right) + m_b t_b / 2 \right] g \tag{16}$$

and overturning moment in convective mode is given by

$$M_c^* = (A_h)_c m_c (h_c^* + t_b) g \tag{17}$$

Elevated Tank

Overturning moment in impulsive mode, at the base of the staging is given by

$$M_i^* = (A_h)_i \left[m_i \left(h_i^* + h_s \right) + m_s h_{cg} \right] g \tag{18}$$

and overturning moment in convective mode is given by

$$M_c^* = (A_h)_c m_c \left(h_c^* + h_s \right) \, g \tag{19}$$

Total Moment

Total moment shall be obtained by combining the moment in impulsive and convective modes through Square Root of Sum of Squares (SRSS) rule and is given as follows:

$$M = \sqrt{M_i^2 + M_c^2} \tag{20}$$

$$M = \sqrt{M_i^{*2} + M_c^{*2}} \tag{21}$$

Tank Empty Condition

For elevated tanks, the design shall be worked out for tank empty and tank full conditions.

Direction of Seismic Force

- (a) Ground supported rectangular tanks shall be analyzed for horizontal earthquake force acting non-concurrently along each of the horizontal axes of the tank for evaluating forces on tank walls.
- (b) For elevated tanks, staging components should be designed for the critical direction of seismic force. Different components of staging may have different critical directions.
- (c) As an alternative, staging components can be designed for either of the following load combination rules:
  - i) 100% + 30% *Rule*:

    $$\pm EL_x \quad \pm 0.3EL_y \text{ and } \pm 0.3EL_x \quad \pm EL_y$$

  - ii) SRSS Rule:

    $$\sqrt{EL_x^2 + EL_y^2}$$

    where, EL_x is response quantity due to earthquake load applied in x-direction and EL_y is response quantity due to earthquake load applied in y-direction.

Hydrodynamic Pressure

During lateral base excitation, tank wall is subjected to lateral hydrodynamic pressure and tank base is subjected to hydrodynamic pressure in vertical direction.

Impulsive Hydrodynamic Pressure

The impulsive hydrodynamic pressure exerted by the liquid on the tank wall and base is given by

(a) For Circular Tank (Fig. 8a)

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

$$p_{iw} = Q_{iw}(y)\ (A_h)_i \rho\, g\, h\ \cos\phi \tag{22}$$

$$Q_{iw}(y) = 0.866\ \left[1 - \left(\frac{y}{h}\right)^2\right]\ \tan h\left(0.866\frac{D}{h}\right) \tag{23}$$

Coefficient of impulsive hydrodynamic pressure on wall, $Q_{iw}(y)$ can also be obtained from Fig. 9a.

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

$$p_{ib} = 0.866\,(A_h)_i\ \rho\, g\, h \frac{\sin h\left(0.866\frac{x}{h}\right)}{\cos h\left(0.866\frac{l'}{h}\right)} \tag{24}$$

(b) For rectangular tank (Fig. 8b)

Lateral hydrodynamic impulsive pressure on wallp_{iw}, is given by

$$p_{iw} = Q_{iw}(y)\ (A_h)_i\ \rho\, g\, h \tag{25}$$

where, $Q_{iw}(y)$ is same as that for a circular tank and can be read from Fig. 9a, with h/L being used in place of h/D.

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

$$p_{ib} = Q_{ib}(x)\ (A_h)_i\ \rho\, g\, h \tag{26}$$

$$Q_{ib}(x) = \frac{\sin h\left(0.866\frac{x}{h}\right)}{\cos h\left(0.866\frac{L}{h}\right)} \tag{27}$$

The value of coefficient of impulsive hydrodynamic pressure on base $Q_{ib}(x)$, can also be read from Fig. 9b.

Convective Hydrodynamic Pressure

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

(a) Circular Tank (Fig. 8a)

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

$$p_{cw} = Q_{cw}(y)\,(A_h)_c\,\rho\, g\ D\left[1 - \frac{1}{3}\cos^2\phi\right]\cos\phi \tag{28}$$

$$Q_{cw}(y) = 0.5625\frac{\cos h\left(3.674\frac{y}{D}\right)}{\cos h\left(3.674\frac{h}{D}\right)} \tag{29}$$

The value of $Q_{cw}(y)$ can also be read from Fig. 10a.

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

$$p_{cb} = Q_{cb}(x)\,(A_h)_c\,\rho\, g\ D \tag{30}$$

where,

$$Q_{cb}(x) = 1.125\left[\frac{x}{D} - \frac{4}{3}\left(\frac{x}{D}\right)^3\right]\sec h\left(3.674\frac{h}{D}\right) \tag{31}$$

The value of $Q_{cb}(x)$ may also be read from Fig. 10b.

(b) Rectangular tank (Fig. 8b)

The hydrodynamic pressure on the wallp_{cw}, is given by

$$p_{cw} = Q_{cw}(y)(A_h)_c\rho\, g\, L \tag{32}$$

$$Q_{cw}(y) = 0.4165\frac{\cos h\left(3.162\frac{y}{L}\right)}{\cos h\left(3.162\frac{h}{L}\right)} \tag{33}$$

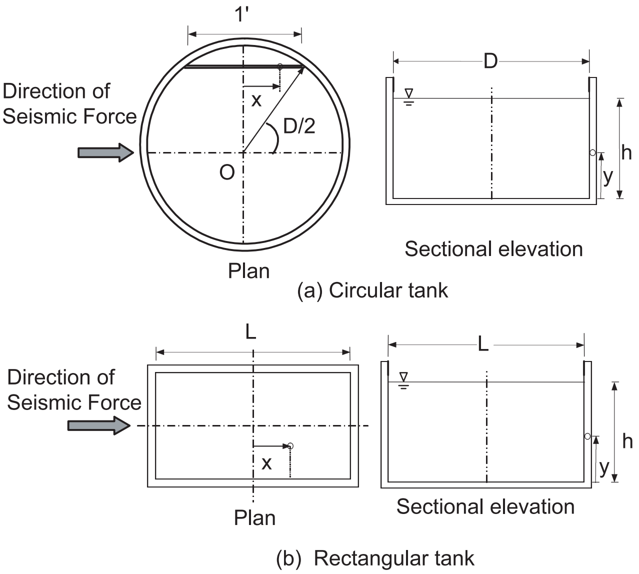


FIG. 8. GEOMETRY OF (a) CIRCULAR TANK AND (b) RECTANGULAR TANK

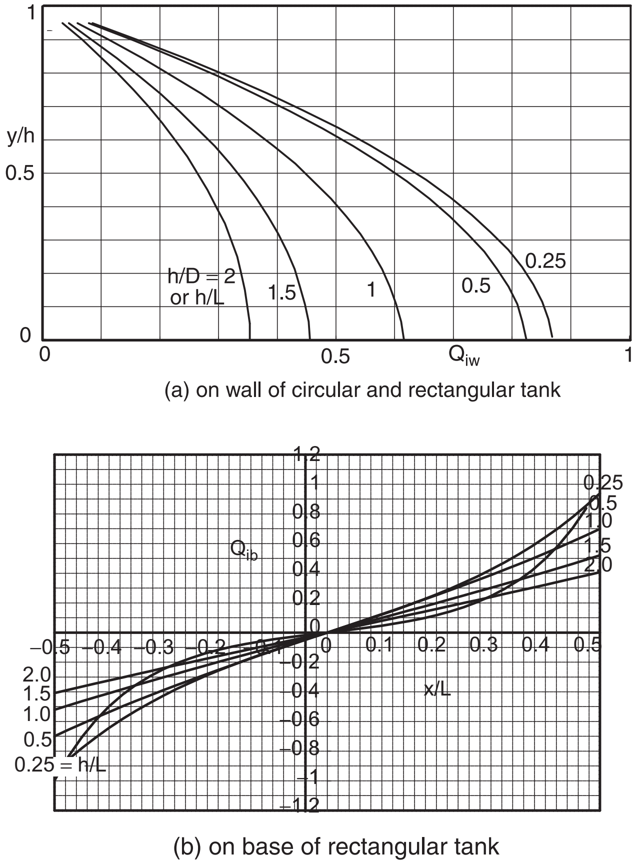


FIG. 9. IMPULSIVE PRESSURE COEFFICIENT (a) ON WALL, Q_{iw} (b) ON BASE, Q_{ib}

The value of $Q_{cw}\,(y)$ can also be obtained from Fig. 11a. The pressure on the base slab ($y = 0$) is given by

$$p_{cb} = Q_{cb}(x)\,(A_h)_c\,\rho\,g\,L \tag{34}$$

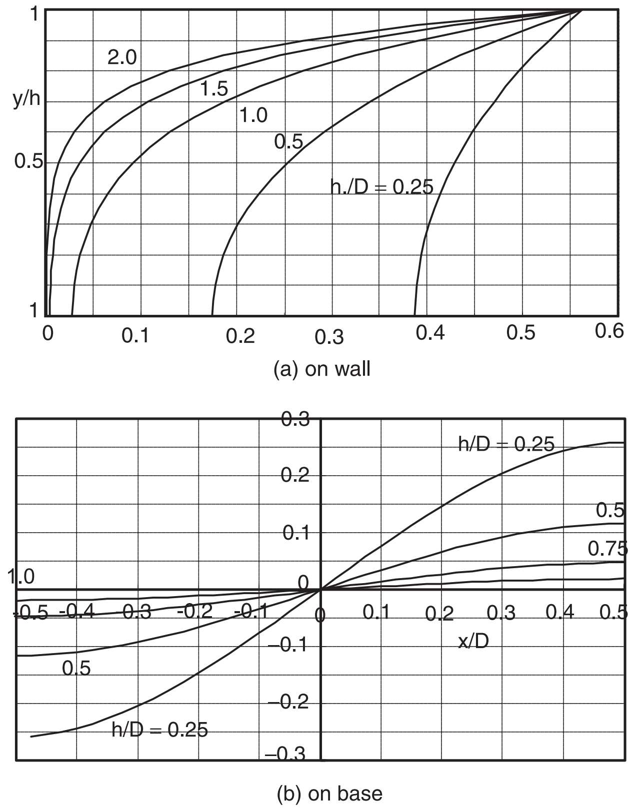


FIG. 10. CONVECTIVE PRESSURE COEFFICIENT FOR CIRCULAR TANK (a) ON WALL, Q_{cw} (b) ON BASE, Q_{cb}

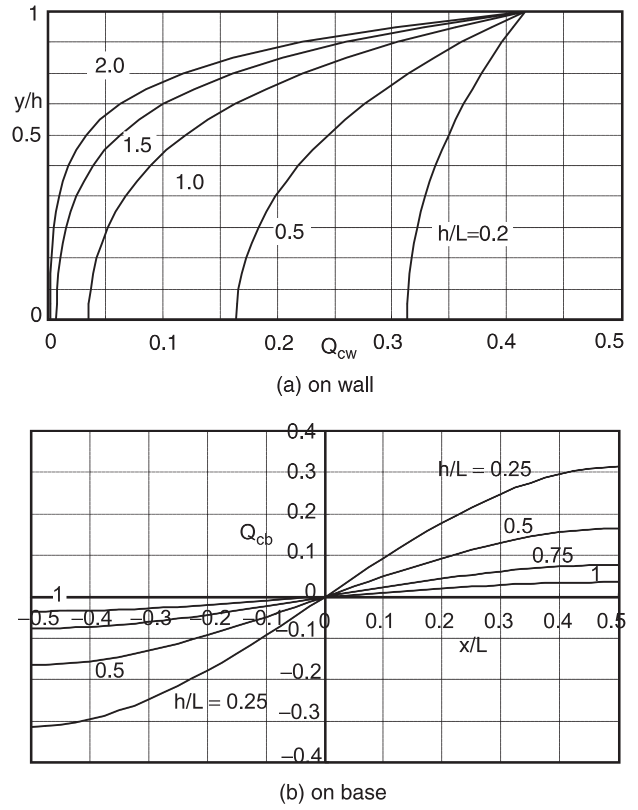


FIG. 11. CONVECTIVE PRESSURE COEFFICIENT FOR RECTANGULAR TANK (a) ON WALL, Q_{cw} (b) ON BASE, Q_{cb}

$$Q_{cb}(x) = 1.25\left[\frac{x}{L} - \frac{4}{3}\left(\frac{x}{L}\right)^3\right]\sec h\left(3.162\frac{h}{L}\right) \quad (35)$$

The value of $Q_{cb}(x)$ can also be obtained from Fig. 11b.

Pressure Distribution in Circumferential Direction

In circular tanks, hydrodynamic pressure due to horizontal excitation varies around the circumference of the tank. However, for convenience in stress analysis of the tank wall, the hydrodynamic pressure on the tank wall may be approximated by an outward pressure distribution of intensity equal to that of the maximum hydrodynamic pressure (Fig. 12a).

Linearised Pressure Distribution on Wall

Hydrodynamic pressure due to horizontal excitation has curvilinear variation along wall height. However, in the absence of more exact analysis, an equivalent linear pressure distribution may be assumed so as to give the same base shear and bending moment at the bottom of tank wall (Figs. 12b and 12c).

Pressure Due to Wall Inertia

Pressure on tank wall due to its inertia is given by

$$p_{ww} = (A_h)_i \, t \, \rho_m \, g \quad (36)$$

Effect of Vertical Ground Acceleration

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

Hydrodynamic pressure on tank wall due to vertical ground acceleration may be taken as

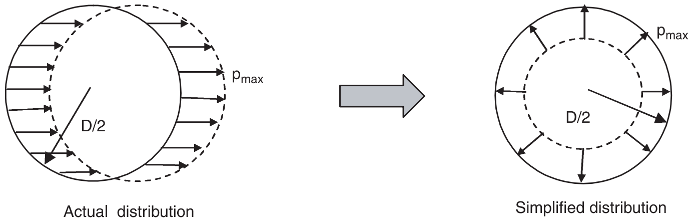
$$p_v = (A_v) \; \rho \, g \, h \; \left(1 - y/h\right) \quad (37)$$

$$A_v = \frac{2}{3}\left(\frac{Z}{2}\frac{I}{R}\frac{S_a}{g}\right) \quad (38)$$

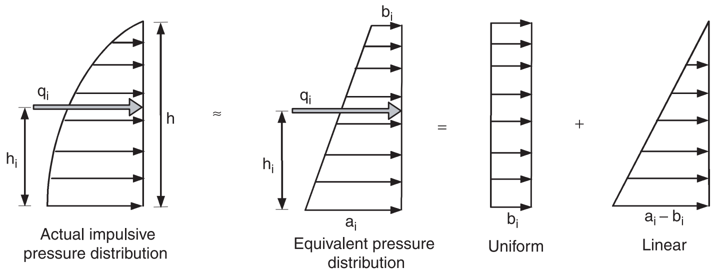
where $\frac{S_a}{g}$ = Average response acceleration coefficient given by Fig. 2 and Table 3 of IS 1893 (Part 1): 2002 and subject to section 3.4.2 of this paper. In absence of more refined analysis, time period of vertical mode of vibration for all types of tank may be taken as 0.3 sec.

Maximum Hydrodynamic Pressure

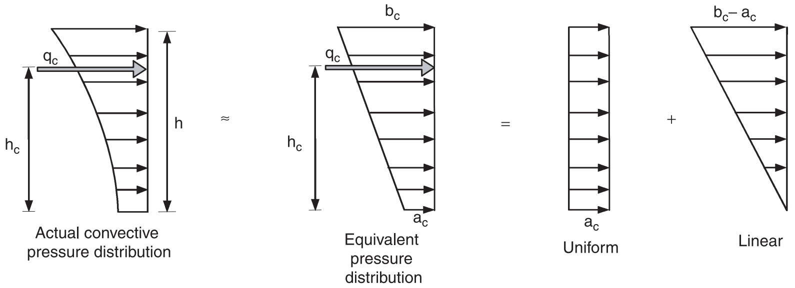
The maximum value of hydrodynamic pressure should be obtained by combining pressure due to horizontal and



(a) Simplified pressure distribution in circumferential direction on tank wall



(b) Equivalent linear distribution along wall height for impulsive pressure



(c) Equivalent linear distribution along wall height for convective pressure

FIG. 12. HYDRODYNAMIC PRESSURE DISTRIBUTION FOR WALL ANALYSIS

vertical excitation through square root of sum of squares (SRSS) rule, which can be given as

$$p = \sqrt{(p_{iw} + p_{ww})^2 + p_{cw}^2 + p_v^2} \tag{39}$$

Sloshing Wave Height

Maximum sloshing wave height is given by

$$d_{\max} = (A_h)_c R \frac{D}{2} \qquad \text{For circular tank} \tag{40}$$

$$d_{\max} = (A_h)_c R \frac{L}{2} \qquad \text{For rectangular tank} \tag{41}$$

Anchorage Requirement

Circular ground supported tanks shall be anchored to their foundation (Fig. 13) when $\frac{h}{D} > \frac{1}{(A_h)_i}$. In case of rectangular tank, the same expression may be used with L instead of D.

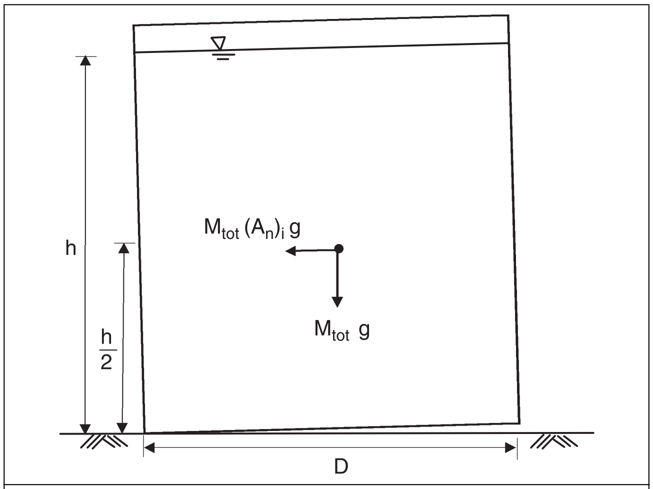


FIG. 13. INITIATION OF ROCKING OF TANK

Miscellaneous

Piping

Piping systems connected to tanks shall consider the potential movement of the connection points during earthquake and provide for sufficient flexibility to avoid damage. The piping system shall be designed so as not to impart significant mechanical loading on tank. Local loads at pipe connections can be considered in the design of the tank. Mechanical devices, which add flexibility to piping such as bellows, expansion joints and other special couplings, may be used in the connections.

Buckling of Shell

Ground supported tanks (particularly, steel tanks) shall be checked for failure against buckling. Similarly, safety of shaft type of staging of elevated tanks against buckling shall be ensured.

Buried Tanks

Dynamic earth pressure shall be taken into account while computing the base shear of a partially or fully buried tank. Earth pressure shall also be considered in the design of walls. In buried tanks, dynamic earth pressure shall not be relied upon to reduce dynamic effects due to liquid.

Shear Transfer

The lateral earthquake force generates shear between wall and base slab and between roof and wall. Wall-to-base slab, wall-to-roof slab and wall-to-wall joints shall be suitably designed to transfer shear forces. Similarly in elevated tanks, connection between container and staging should be suitably designed to transfer the shear force.

P-Delta Effect

For elevated tanks with tall staging (say, staging height more than five times the least lateral dimension) it may be required to include the P-Delta effect. For such tall tanks, it must also be confirmed that higher modes of staging do not have significant contribution to dynamic response.

SUMMARY AND CONCLUSIONS

Jain and Medhekar[2,3] had suggested a set of provisions on aseismic design of liquid storage tanks, which could be included in IS 1893. However since 1993, many new research results have been published in open literature and other international codes have also been modified. Moreover, part 1 of fifth revision of IS 1893 has also been published in 2002. In view of these developments some of the provisions suggested by Jain and Medhekar[2,3] are modified and some new provisions are included. The major modifications are: (i) Design horizontal seismic coefficient as given in IS 1893 (Part1): 2002[7] has been used for tanks and suitable values of importance factor I and response reduction factor R are proposed (ii) Spring-mass model of Veletsos[9] which is common for tanks with rigid and flexible wall has been included (iii) Some errors in the expression for convective hydrodynamic pressure are rectified (iv) Sloshing wave height expression is simplified and (v) new provisions on effect of vertical ground acceleration, critical direction of seismic loading and buried tanks are included. The provisions suggested in this paper can be readily adopted for IS 1893 (Part 2).

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NOTATIONS

A_h	Design horizontal seismic coefficient
$(A_h)_c$	Design horizontal seismic coefficient for convective mode
$(A_h)_i$	Design horizontal seismic coefficient for impulsive mode
A_v	Design vertical seismic coefficient
B	Inside width of rectangular tank perpendicular to the direction of seismic force
C_c	Coefficient of time period for convective mode
C_i	Coefficient of time period for impulsive mode
D	Inner diameter of circular tank
E	Modulus of elasticity of material of tank wall
EL_x	Response quantity due to earthquake load applied in x-direction
EL_y	Response quantity due to earthquake load applied in y-direction
I	Importance factor given in Table 1
I_w	Moment of inertia of wall strip
K_c	Spring stiffness of convective mode
K_s	Lateral stiffness of elevated tank staging
L	Inside length of rectangular tank parallel to the direction of seismic force
M	Total bending moment at the bottom of tank wall
M^*	Total overturning moment at base
M_c	Bending moment in convective mode at the bottom of tank wall
M_c^*	Overturning moment in convective mode at the base
M_i	Bending moment in impulsive mode at the bottom of tank wall
M_i^*	Overturning moment in impulsive mode at the base
Q_{cb}	Coefficient of convective pressure on tank base
Q_{cw}	Coefficient of convective pressure tank wall
Q_{ib}	Coefficient of impulsive pressure on tank base
Q_{iw}	Coefficient of impulsive pressure on tank wall
R	Response reduction factor given in Table 2 of this paper
(S_a/g)	Average response acceleration coefficient as per IS 1893 (Part 1): 2002 and Clause 3.4 of this paper
T_c	Time period of convective mode (in seconds)
T_i	Time period of impulsive mode (in seconds)
V	Total base shear
V_c	Base shear in convective mode
V_i	Base shear in impulsive mode
Z	Seismic zone factor as per Table 2 of IS 1893 (Part 1): 2002
d	Deflection of wall of rectangular tank, on the vertical center line at a height $\overline{h}$ when loaded by a uniformly distributed pressure q, in the direction of seismic force
$d_{\max}$	Maximum sloshing wave height
g	Acceleration due to gravity
h	Maximum depth of liquid
$\bar{h}$	Height of combined center of gravity of half impulsive mass of liquid $(m_i/2)$, and mass of one wall $(\overline{m}_w)$
h_c	Height of convective mass above bottom of tank wall (without considering base pressure)
h_i	Height of impulsive mass above bottom of tank wall (without considering base pressure)
h_s	Structural height of staging, measured from top of footing to the bottom of container wall
h_t	Height of center of gravity of roof mass above bottom of tank wall
h_w	Height of center of gravity of wall mass above bottom of tank wall
h_c^*	Height of convective mass above bottom of tank wall (with considering base pressure)
h_i^*	Height of impulsive mass above bottom of tank wall (with considering base pressure)
h_{cg}	Height of center of gravity of the empty container of elevated tank, measured from base of staging
l'	Length of a strip at the base of circular tank, along the direction of seismic force
m	Total mass of liquid in tank
m_b	Mass of base slab/plate
m_c	Convective mass of liquid
m_i	Impulsive mass of liquid
m_s	Mass ofcontainer of elevated tank and one-third mass of staging
m_t	Mass of roof slab
m_w	Mass of tank wall
$\bar{m}_w$	Mass of one wall of rectangular tank perpendicular to the direction of loading
p	Maximum hydrodynamic pressure on wall
p_{cb}	Convective hydrodynamic pressure on tank base
p_{cw}	Convective hydrodynamic pressure on tank wall
p_{ib}	Impulsive hydrodynamic pressure on tank base
p_{iw}	Impulsive hydrodynamic pressure on tank wall
p_v	Hydrodynamic pressure on tank wall due to vertical ground acceleration
p_{ww}	Pressure on wall due to its inertia
q	Uniformly distributed pressure on one wall of rectangular tank in the direction of ground motion
t	Thickness of tank wall
t_b	Thickness of base slab
x	Horizontal distance in the direction of seismic force, of a point on base slab from the reference axis at the center of tank
y	Vertical distance of a point on tank wall from the bottom of tank wall
ρ	Mass density of liquid
ρ_w	Mass density of tank wall
ϕ	Circumferential angle as described in Figure 8a

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