A COMPARATIVE STUDY OF THE SEISMIC ANALYSIS OF RECTANGULAR TANKS ACCORDIND TO EC8 AND IS 1893

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REZUMAT. În cazul rezervoarelor în care se stocheaza lichidele cutremurele au produs distrugeri sau daune majore, daune raportate în întreaga lume. Aceste daune au constat în scurgerea apei potabile şi industriale stocate în rezervoarele de apă sau de incendiu necontrolate sau scurgeri şi evaporări de substanțe toxice. Prin producerea şi propagarea incendiilor alimentate de cantități mari de combustibil sau prin scăpările de gaze şi substante toxice, de multe ori aceste pagube au depăşit pagubele produse de cutremurul însuşi asupra construcţiilor şi a căilor de acces. Din această cauză estimarea forțelor şi a presiunilor dezvoltate pe pereţii rezervoarelor în perioada unui cutremur reprezintă un proces foarte important în proiectarea unor rezervoare care să reziste acestor dezastre sau, în cel mai rău caz, să prezinte daune minore, fiind prevenite scurgeri ale fluidelor stocate.

Cuvinte cheie: rezervoare dreptunghiulare, analiză seismică, eurocoduri de proiecatare.

ABSTRACT. As known from very upsetting experiences, liquid storage tanks were collapsed or heavily damaged during the earthquake all over the word. Damage or collapse of the tanks causes some unwanted events such as shortage of drinking and utilizing water, uncontrolled fires and spillage of dangerous fluids. Even uncontrolled fires and spillage of dangerous fluid subsequent to a major earthquake may cause substantially more damage than the earthquake itself. Knowledge of forces, pressures acting on the walls and bottom of containers during an earthquake is important for good design of earthquake resistance structure/facility - tanks.

Keywords: rectangular tank, seismic analysis, eurocodes design.

1. INTRODUCTION

Ground-supported tanks are used to store a variety of liquids, e.g. water for drinking and fire fighting, petroleum, chemicals, and liquefied natural gas. Satisfactory performance of tanks during strong ground shaking is crucial for modern facilities. Tanks that were inadequately designed or detailed have suffered extensive damage during past earthquakes [2-8].

Knowledge of forces, pressures acting on the walls and bottom of containers during an earthquake is important for good design of earthquake resistance structure/facility – tanks, which are made from steel or concrete.

As known from very upsetting experiences, liquid storage tanks were collapsed or heavily damaged during the earthquake all over the word. Damage or collapse of the tanks causes some unwanted events such as shortage of drinking and utilizing water, uncontrolled fires and spillage of dangerous fluids. Even uncontrolled fires and spillage of dangerous fluid subsequent to a major earthquake may cause substantially more damage than the earthquake itself. Due to these reasons this type of structures witch are special in construction and in function from engineering point of view must be constructed well to be resistant against earthquakes. There have been numerous studies done for dynamic behavior of fluid containers; most of them are concerned with cylindrical tanks. But very few studies on the dynamic response of rectangular containers exist.

Hopkins and Jacobsen gave the first report on analytical and experimental observations of rigid rectangular containers under a simulated horizontal earthquake excitation. Graham and Rodriguez udes spring-mass analogy for the fluid in a rectangular tank. Housner proposed a simple procedure for estimating the dynamic fluid effect of a rigid rectangular container exited horizontally by earthquake. An extended application of Housner's concept in the sense of a practical design rule is given by Epstein.

After these important studies some researchers are carried out about rectangular tanks.

European Committee for Standardization prepared a new code named Eurocode-8, in 2006. Part 4 of this code is related to tanks, silos and pipelines. But, requirements for rectangular tanks are very limited according to cylindrical tanks in this code [2]. There is a statement related to rectangular tanks as „studies on the behavior of flexible rectangular tanks are not numerous, and the solutions are not amenable to a form suitable for direct use in design" in this code. Therefore, it is explained that the method suggested by India's IS 1893: (Part 2), in 2006 may by used as an approximation for design.

2. DYNAMIC MODEL

The motion of fluid contained in a rigid container may be expressed as the sum of two separate contributions, called "rigid impulsive" and "convective" respectively [2, 7 – 13]. The "rigid impulsive" component satisfies exactly the boundary conditions at the walls and the bottom of the tank, but gives (incorrectly, due to the presence of the waves in the dynamic response) zero pressure at the original position of the free surface of fluid in the static situation. The "convective" term does not alter those boundary conditions that are already satisfied, while fulfilling the correct equilibrium condition at the free surface. 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. Seismic design of liquid storage tanks has been adopted in [2, 3, 7, 8, 12 - 15].

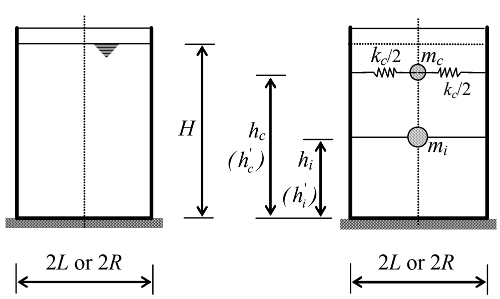

Fig. 1. Spring mass model.

The dynamic analysis of a liquid – filled tank may be carried out using the concept of generalized single-degree of freedom (SDOF) systems representing the impulsive and convective modes of vibration of the tank – liquid system as shown in Figure 1. For practical applications, only the first convective mode of vibration needs to be considered in the analysis, mechanical model (Fig. 4). 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 stiffness k_c. The mass, height and natural period of each SDOF system are obtained by the methods described in [6,9].

For a horizontal earthquake ground motion, the response of various SDOF systems may be calculated independently and then combined to give the base shear and overturning moment. The most tanks have slimness of tank γ, whereby $0,3 < \gamma < 3$. Tank's slimness is given by relation $\gamma = H/L$ *or* $\gamma = H/R$, where H is the height of filling of fluid in the tank and R is inside radius or $2L$ is insid width of tank [6 - 10].

2.1. Eurocode 8 - requirements

For a ground supported rectangular tank, in which the wall is rigidly connected with the base slab, the natural period of the impulsive mode of vibration $T_i = T_f$ in seconds, is given by [8, 13]

$$T_f = 2 \cdot \pi \cdot \sqrt{d_f / g} \tag{1}$$

where d_f is the deflection of the wall on the vertical centre-line and at the heigh of the impulse mass, when wall is loaded by a load uniform in the direction of the ground motion and of magnitude $m_i g/(4BH)$. Where B is the half with perpendicular to the direction of loading (earthquake direction) and m_i is the impulsive mass. The mass can be obtained from the equivalent cylindrical tank results and should include the wall mass [13]. For tanks without roofs the deflection d_f may be calculed assuming the wall to be free at the top and fixed on the other three sides.

For a ground supported rectangular, in which the wall is rigidly connected with the base slab, the natural period of the convective mode of vibration $T_c = T_1$, in seconds, is given by

$$T_1 = 2 \cdot \pi \sqrt{\frac{L/g}{\frac{\pi}{2}\tanh\left(\frac{\pi}{2} \cdot \frac{H}{L}\right)}} \tag{2}$$

Total base shear V of ground supported tank at the bottom of the wall can be also obtained by base shear in impulsive mode and base shear in convective mode, eq. (3). Total base shear V' of ground supported tank at the bottom of base slab is given also by base shear in impulsive mode and base shear in convective mode too, eq. (4).

The overturning moment M of ground supported tank immediately above the base plate is given also by, eq. (5) and the overturning moment M' of ground supported tank immediately below the base plate is given also by, eq. (6).

$$V = (m_i + m_w + m_r)S_e(T_i) + (m_c)S_e(T_c), \quad (3)$$

$$V' = (m_i + m_w + m_b + m_r)S_e(T_i) + (m_c)S_e(T_c), \quad (4)$$

$$M = (m_i h_i + m_w h_w + m_r h_r)S_e(T_i) + (m_c h_c)S_e(T_c), \quad (5)$$

$$M' = (m_i h_i' + m_w h_w + m_b h_b + m_r h_r)S_e(T_i) + (m_c h_c')S_e(T_c), \quad (6)$$

where m_i is the impulsive mass of fluid, m_c – the convective mass of fluid, given in Figure 2 [8, 13]; h_i – height of wall pressure resultant for the impulsive component, given in Figure 3 [8, 13]; h_c – height of wall pressure resultant for the convective component, given in Figure 4 [8, 13]; h_i' – height resultant of pressures on the wall and on the base plate for the impulsive component, given in Fig. 3 [8, 13]; h_c' – height resultant of pressures on the wall and on the base plate for the convective component, given in Figure 4 [8, 13]; m_w – mass of the tank wall; m_b – mass of the tank base plate; m_r – mass of the tank roof; h_w – the height of center of gravity of wall mass; h_b – the height of center of gravity of base plate mass; h_r – he height of center of gravity of roof mass. $S_e(T_i)$ is impulsive spectral acceleration, is obtained from a 2% damped elastic response spectrum for steel and prestressed concrete tanks, or a 5% damped elastic response spectrum for concrete and masonry tanks; $S_e(T_c)$ – convective spectral acceleration, is obtained from a 0,5% damped elastic response spectrum.

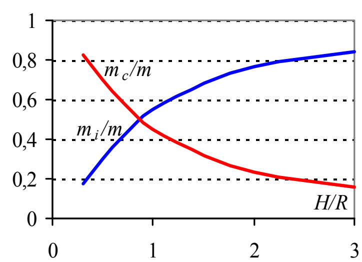

Fig. 2. Impulsive and convective masses as fractions of the total liquid mass in the cylindrical tank.

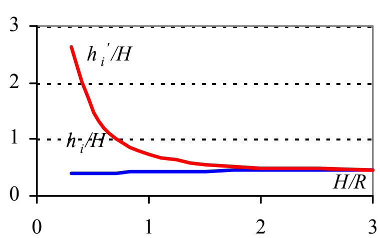

Fig. 3. Impulsive heights as fraction of the height of the liquid in the tank.

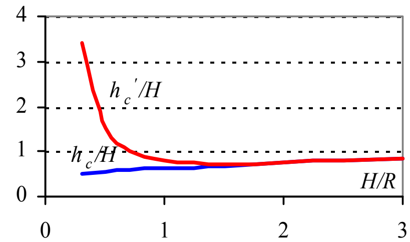

Fig. 4. Convective heights as fraction of the height of the liquid in the tank.

The base shear and the moment on the foundation may be evaluated on the basis of expressions (3) and (6). The values of the masses m_i and m_c, as well as of the corresponding heights above the base h_i, h_c, h_i', h_c', calculated for cylindrical tanks and given by Fig. 2 - 4, (by using of Malhotra's simple procedure for seismic analysis of liquid-storage tanks [8, 13]) may be adopted for the design of rectangular tanks as well (with *L* replacing *R*), with an error less than 15% [13].

2.2. IS 1893 - requirements

We consider ground supported rectangular tank of lenght *L* and breadth *B*, where horizontal earthquake loading acting along lenght *L*. The spring mass model for ground supported rectangular tank is based on work of Housner, (3, 14, 15).

$$\frac{m_i}{m} = \frac{\tanh(0{,}866\, L/H)}{0{,}866\, L/H} \quad (7)$$

$$\frac{m_c}{m} = 0{,}264\frac{\tanh(3{,}16\, H/L)}{H/L} \quad (8)$$

$$\frac{h_i}{m} = 0{,}375\text{, pre } H/L \le 1{,}5 \quad (9)$$

$$\frac{h_c}{m} = 1 - \frac{\cosh(3{,}16\, H/L) - 1{,}0}{3{,}16\, H/L \sinh(3{,}16\, H/L)} \quad (10)$$

$$= 0{,}5 - \frac{0{,}09375}{H/L}\text{, pre } H/L > 1{,}5 \quad (11)$$

$$\frac{h_i'}{m} = \frac{0{,}866\, L/H}{2\tanh(0{,}866\, L/H)} - 0{,}125\text{, pre } H/L \le 1{,}33$$

$$= 0{,}45\text{, pre } H/L > 1{,}33 \quad (12)$$

$$\frac{h_c'}{m} = 1 - \frac{\cosh(3{,}16\, H/L) - 2{,}01}{3{,}16\, H/L \sinh(3{,}16\, H/L)} \quad (13)$$

$$k_c = 0{,}833\frac{mg}{H}\tanh^2(3{,}16\, H/L) \quad (14)$$

The parameters showns in Figures 5 and 6 are slightky different from those given by Houser, and have taken from ACI 350.3 in 2001. Equivalent masses

m_i and m_c and heogts h_i, h_c, $h_i^{'}$ and $h_c^{'}$ of accelarating liquid can be determined from Figurea 5 and 6 depending on 2L/H ratios, where L is inside lenght of tank paralel to the direction of seismic force.

Time period of impulsive mode

$$T_i = 2 \cdot \pi \cdot \sqrt{d_f / g}\ , \tag{15}$$

where d is deflection of the tank wall on the vertical centre-line at a height $\overline{h}$, when loaded by un oformly distributed pressure q.

$$q = \frac{\left(\frac{m_i}{2} + \overline{m}_w\right) g}{Bh} \tag{16}$$

$$\overline{h} = \frac{\frac{m_i}{2} h_i + \overline{m}_w \frac{h}{2}}{\frac{m_i}{2} + \overline{m}_w} \tag{17}$$

$\overline{m}_w$ is mass of one tank wall perpendicular to the diraction of seismic force, and B is inside width of tank.

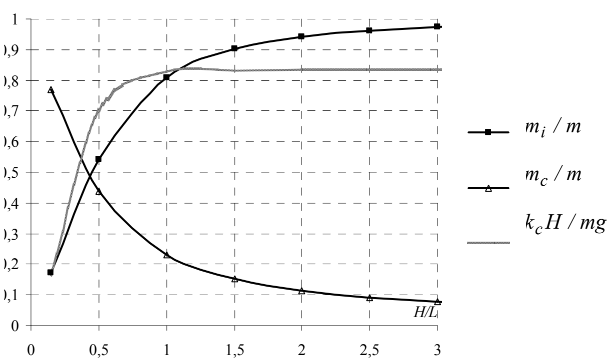

Fig. 5. Impulsive and convective masses as fractions of the total liquid mass in the rectangular tanks versus ratio 2L/H.

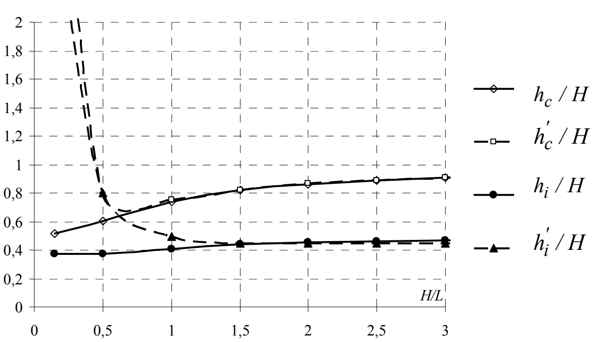

Fig. 6 Impulsive and convective heights as fraction of the height of the liquid in the rectangular tanks versus ratio 2L/H.

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

$$T_c = C_c \sqrt{L/g}\ , \tag{18}$$

where C_c is time period for convective mode. Value of C_c can be ontained from (19) and Fig. 7, and L is inside lenght of tank paralel to the direction of seismic force.

$$C_c = \frac{2\pi}{\sqrt{3{,}16 \tanh\left(3{,}16\left(H / L\right)\right)}} \tag{19}$$

We consider ground supported rectangular tank of lenght L and breadth B, where horizontal earthquake loading acting along lenght L.

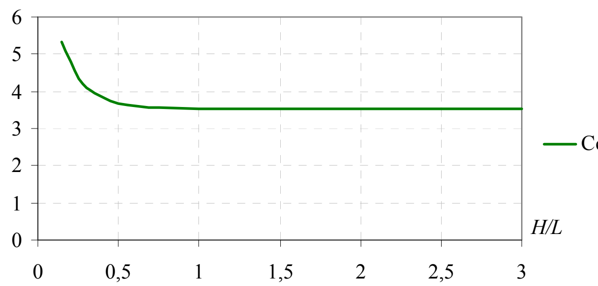

Fig. 7 Coefficient of convective mode time period C_c for rectangular tank

The base shear due to seismic forces applied at the bottom of the tank wall shall be determined by the following equation:

$$V = \sqrt{\left(V_i + V_w + V_r\right)^2 + V_c^2} \tag{20}$$

Bending moment M on the entire tank cross section just above the base of the tank wall and overturing moment $M^{'}$ at the base of the tank, including the tank bottom and supporting structure are given as:

$$M = \sqrt{\left(M_i + M_w + M_r\right)^2 + M_c^2} \tag{22}$$

and $$M^{'} = \sqrt{\left(M_i^{'} + M_w^{'} + M_r^{'}\right)^2 + M_c^{'2}}\ . \tag{23}$$

We consider ground supported rectangular tank of lenght L and breadth B, where horizontal earthquake loading acting along lenght L.

2.3. hydrodynamic pressures and Resultant

Hydrodynamic impulsive and convective pressures distribution for tectangular tank wall and bottom and resultants of hydrodynamic pressures.

3. SOLUTION, RESULTS AND DISCUSSION

Let us have a ground supported rectangular endlessly long shipping channel, dimension of L = 5 m and height H_w = 3 m. Walls have uniform thickness of 0.25 m. The base slab is h = 0.4 m thick. Shipping channel is filled with water to the height 2.5 m, Figure 10. There is no roof slab on the tank. The tank is located on hard soil.

We consider only horizontal earthquake loading by using of recording of real accelerogram Loma Prieta, California (18.10.1989) along x direction. We consider with 1 m lenght of shiping chanel.

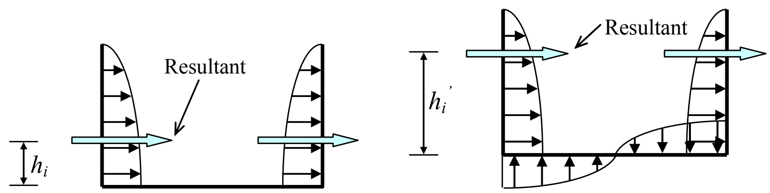

Fig. 8. Impulsive pressures and resultants.

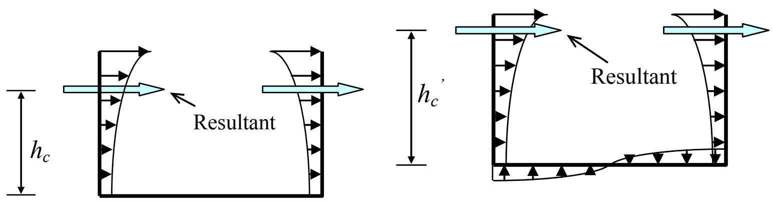

Fig. 9. Convective pressures and resultants.

Impulsive mass, covective mass and equivalent heights related to these masses, periods, base shears, bending moments and height are given in Table 1. The determined dynamic parameters and resultant forces and moments considering requiments in Eurocode 8 and IS 1893.

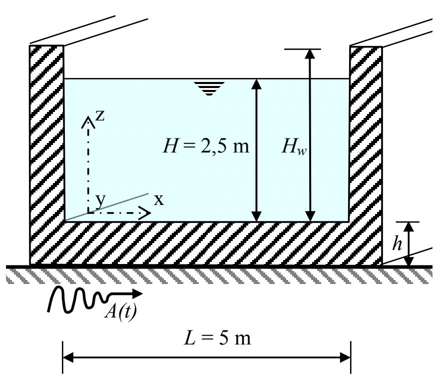

Fig. 10. Details of tank geometry.

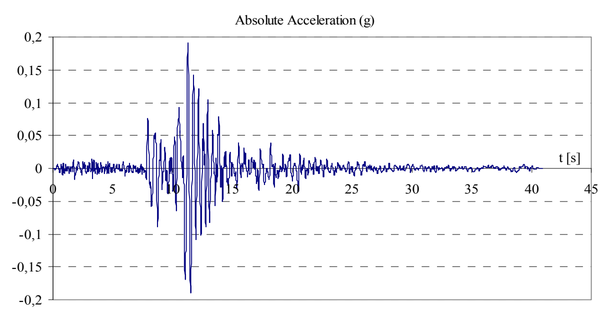

Fig. 11. Accelerogram Loma Prieta.

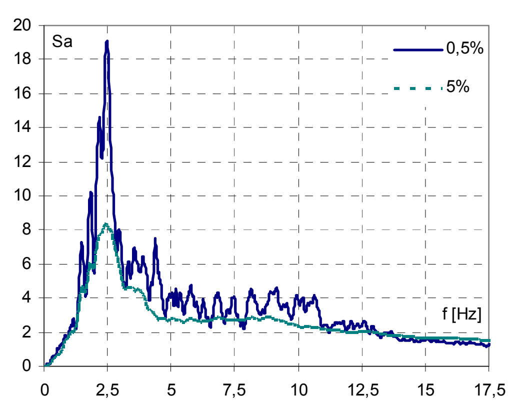

Fig. 12. Seismic response spectrums of the accelerogram Loma Prieta, 5% damped and 0.5% damped.

Table 1. **Determined dynamic parameters and resultant forces and moments considering equiments in Eurocode 8 and IS 1893**

Codes	m_i [kg]	m_c [kg]	h_i [m]	h_i' [m]	h_c [m]	h_c' [m]	T_i [s]	T_c [s]	V [kN]	M [kNm]	M' [kNm]	d_{max} [m]
Eurocodes 8	7267	5723	1.094	1.871	1.607	2.032	0.041	2.63	12.81	16.58	28.76	-
IS 1983	7266	6124	0.975	2.000	1.530	2.173	0.041	2.62	12.89	15.83	30.18	0.051

BIBLIOGRAPHY

[1] Benčat, J., Papán, D.: *Buildings Structure Response Due to Rail-Way Traffic Prediction Model* In: *ICSV18: 18th International Congres on Sound & Vibration*: 10 - 14. july 2011, Rio de Janeiro, Brazil P. 1-8 ISBN: 978-85-63243-01-0.

[2] Dogangun, A., Livaoglu, R.: *A comparative study of the seismic analysis of rectangular tanks according to different codes*. In: The 14th World Conference on Earthquake Engineering. China. 2008.

[3] Housner, G., W.: *Earthquake pressures on fluid containers*, California institute of technology, Pasadena, California, 1954.

[4] Kotrasová, K.: *Simple procedure for seismic analysis of vertical cylindrical liquid storage tanks*. In: *Transcom* 2005. Section 8, Civil Engineering. - Žilina : University of Žilina, 2005 S. 75-78. - ISBN 8080704201.

[5] Kotrasová, K., Grajciar, I.: *Seismic analysis of shipping channel*. In: Selected Scientific Papers : *Journal of Civil Engineering*. Roč. 5, No. 3 (2010), s. 13-20. - ISSN 1336-9024.

[6] Králik, J.: *Safety and reliability of nuclear power buildings in Slovakia*. Bratislava: STU, 2009. 279 s. ISBN 978-80-227-3112-6.

[7] Livaoglu, R., Dogangun, A.: *Simplified seismic analysis procedures for elevated tanks considering fluid-structure-soil interaction*. In: Journal of fluids and structures. 2006.

[8] Malhotra, P. K., Wenk, T., Wieland, M.: *Simple procedure for seismic analysis of liquid-storage tanks*, Structural Engineering International, No. 3, 2000, s. 197-201.

[9] Melcer, J.: *Amplitude and frequency composition of seismic load due to transport around transport ways*. In: *Proceeding DYN-WIND'2003*, SvF ŽU Tále, 19.-22. may 2003, ISBN 80-8070-066-4.

[10] Sanjay, P. J.: *Equivalent mechanical model for horizontal vibration of rogod intze tanks*. In: ISET Journal of Earthquake Technology, USA. 2000.

[11] Sumec, J., Jendželovský, N.: *Seismic analysis of reinforced concrete water tank*. In: *Proceedings of DYN-WIND 2008*. SvF ŽU, Papradno-Podjavorník, May 26-29, 2008, pp. 63-66. ISBN 978-80-8070-827-6.

[12] Wozniak, R., S, Mitchell, W., W.: *Basic of seismic design provisions for welwed steel oil storage tanks*. In. Midyear meeting, Toronto, Canada. 1978.

[13] EN 1998-4 Eurocode 8. *Design of structures for earthquake resistance. Part 4: Silos, tanks and pipelines*. CEN, Brussels, 2006.

[14] IS 1893: (Part 2), 2006: *Criteria for earthquake resistant design of structures: Part 2 Liquid retaining tanks* (revision of IS 1893 (part 2)), 2006.

[15] IITK-GSDMA. *Guidelines for seismic design of liquid storage tanks – provisions with commentary and explanatory examples*. Kanpur, Indian Institute of Technology Kanpur, 2005.

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