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# ELEVATED TANK DUE TO EARTHQUAKE EVEN

## Abstract

Elevated reservoirs are mainly used for storing of variety water. During earthquake activity the fluid exerts impulsive and convective (sloshing) effects on the walls and bottom of tank. This paper provides theoretical background for analytical calculating of elevated water tank due to earthquake even and deals with simplified seismic design procedures for elevated tanks.

## Keywords

Elevated tank, fluid, earthquake.

## 1 INTRODUCTION

Seismic event is certainly one of the most critical external events regarding safety of industrial plants, as demonstrated by recent earthquakes.

Seismic safety of liquid storage tanks is of considerable importance. Water storage tanks should remain functional in the post-earthquake period to ensure potable water supply to earthquake-affected regions and to cater the need for fighting. Industrial liquid containing tanks may contain highly toxic and inflammable liquids and these tanks should not lose their contents during the earthquake. Liquid storage tanks are mainly of two types: ground supported tanks and elevated tanks. Elevated tanks are mainly used for water supply schemes and they could be supported on RCC shaft, RCC or steel frame, or masonry pedestal.

The current designs of supporting structures of elevated water tanks are extremely vulnerable under lateral forces due to an earthquake. The shaft type stagings suffer from poor ductility of thin shell sections besides low redundancy and toughness whereas framed stagings consist of weak members and poor brace columns joints.

Elevated tanks are vulnerable to earthquake excitation mainly because of the relatively small resistance that the supporting system can offer during seismic events. Most elevated tanks are regarded as essential facilities as they should remain functional even after a major earthquake. The seismic analysis and design of liquid storage tanks are complicated by many numbers of problems, for examples: dynamic interaction between contained fluid and vessel which is called fluid-structure interaction; sloshing motion of the contained fluid; and dynamic interaction between vessel and supporting structure. In addition, the supporting tower may need to be analyzed in post-elastic state, and for special cases, a three-dimensional analysis may be required to take into account torsional effect on the supporting structure. The many different geometric shapes of both vessel and tower dictate different techniques and methods of analysis for each application, and finally, soil-tower interaction could under specific conditions have a significant effect on seismic response of the tower.

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 [1 – 7]. Knowledge of pressures and forces acting on the walls and bottom of containers

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during an earthquake and frequency properties of containers is important for good analysis and design of earthquake resistant structures/facilities – tanks.

## 2 SEISMIC DESIGN OF LIQUID STORAGE TANKS

Elevated water tanks have different vibratory characteristics compared with ordinary structures, because "water" effects the vibration behaviour.

When a liquid storage tank vibrates, the liquid exerts hydrodynamic impulsive and convective pressure on the tank wall, and the tank base, in addition to the hydrostatic pressure. The dynamic analysis of a liquid - filled tank may be carried out using the concept of generalized two single – degree – of freedom (SDOF) systems representing the impulsive and convective modes of vibration of the tank – liquid system. For practical applications, only the first convective mode of vibration needs to be considered in the analysis (figure 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 stiffness $k_c$. The mass, height and natural period of each SDOF system are obtained by the methods described in [1, 3-6, 9-10]. For a horizontal earthquake ground motion, the response of various SDOF systems may be calculated independently and then combined to give the net base shear and overturning moment.

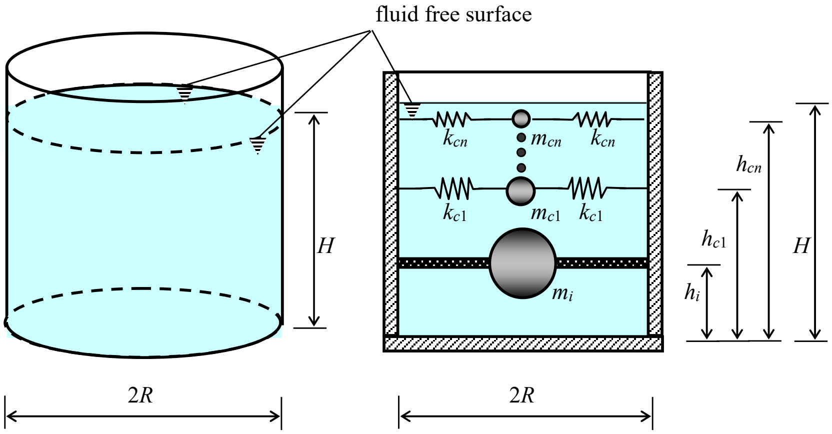

Fig.1: Two single – degree – of freedom systems for ground supported cylindrical tank

## 3 THE SIMPLIFIED PROCEDURE OF SEISMIC ANALYSIS

The first simplified analysis procedure has been probably suggested by Housner, in 1963 [8], for fixed base elevated tanks. In this approach, the two masses ($m_i$ and $m_c$) are assumed to be uncoupled and the earthquake forces on the support are estimated by considering two separate single-degree-of-freedom systems. This two-mass model suggested by Housner has been commonly used for seismic design of elevated tanks. The dynamic characteristic of these model are estimated by using the expressions given in [8]. The similar equivalent masses and heights for this model based on the work of Velestos and co-workers Malhotra, with certain modification that make the procedure simple, are also suggested in the Eurocode 8 ( next only EC8). The periods are necessary after determination of the two masses of $m_i$ and $m_c$ with their locations and stiffnesses. The base shear and the overturning moment for design can be estimated using standard structural dynamic procedures. Except EC8 all international codes use rule Square of Sum of Squares (SRSS rule) to combine response from impulsive and convective mode [7]. In EC8 absolute summation rule is used, which is based on work of Malhotra.

The basis for absolute summation is that the convective mode time period may be several times the impulsive mode period, and hence, peak response of impulsive mode will occur simultaneously when convective mode response is near its peak. However, recently through a numerical simulation for a large number of tanks, Malhotra shoved that SRSS rule gives better results than absolute summation rule, [9].

$m_i$ – is impulsive mass of the fluid [kg],

$m_c$ – is sloshing - convective mass of the fluid [kg],

$h_i$ – is height of wall pressure resultant for the impulsive component [m],

$h_c$ – is height of wall pressure resultant for the convective component [m],

$h_i^*$ – is height resultant of pressures on the wall and on the base plate for the impulsive component [m],

$h_c^*$ – is height resultant of pressures on the wall and on the base plate for the convective component [m],

$H$ – is height to the free surface of the liquid [m],

$R$ – is tank's radius [m],

$D$ – is tank's diameter [m],

$C_c$ – is the coefficient dimension [s/m$^{1/2}$].

The the tank slenderness parameter is given

$$\gamma = H/R \tag{1}$$

Effect of seismic excitation – the total base shear

$$V = V_i + V_c \tag{2}$$

Effect of seismic excitation – the total overturning moment

$$M^* = M_i^* + M_c^* \tag{3}$$

The natural period of the convective mode of vibration $T_c$ in [s] is given

$$T_c = C_c \sqrt{R} \tag{4}$$

where $C_c$ is in figure 2:

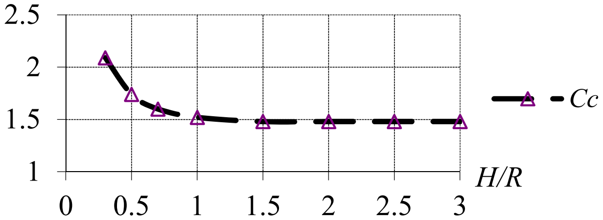

Fig.2: Coefficient $C_c$ as function of the parameter tank slenderness

The natural period of the impulsive mode of vibration $T_i$ in second for elevated tank is given [10]

$$T_i = 2\pi \sqrt{(m_i + m_s)/K_s} \tag{5}$$

where $m_s$ is mass of container and one-third mass of standing, $K_s$ is lateral stiffness of standing, $m_i$, $m_c$, $h_i$, $h_c$, $h_i^*$ and $h_c^*$ are given in figure 3 – figure 5.

All international codes, except EC8, use rule Square of Sum of Squares (SRSS rule) to combine response from impulsive and convective mode.

Effect of seismic excitation – the total base shear

$$V = \sqrt{V_i^2 + V_c^2}\ . \tag{6}$$

Effect of seismic excitation – the total overturning moment

$$M^* = \sqrt{M_i^* + M_c^*}\ . \tag{7}$$

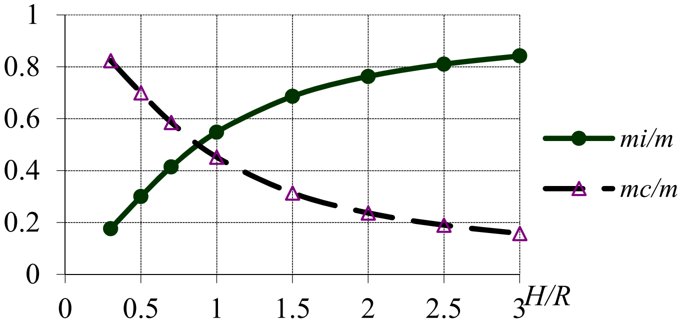

Fig.3: Ratios $m_i/m$ as function of the tank slenderness parameter

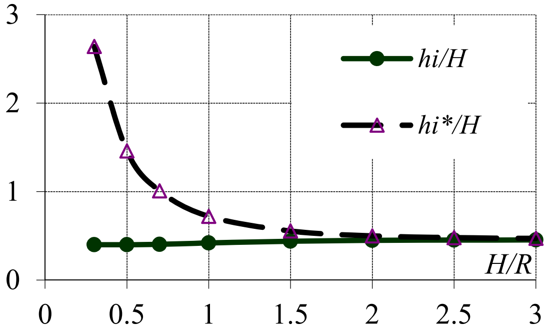

Fig.4: Ratios $h_i/H$ and $h_i^*/H$ as functions of the parameter tank slenderness

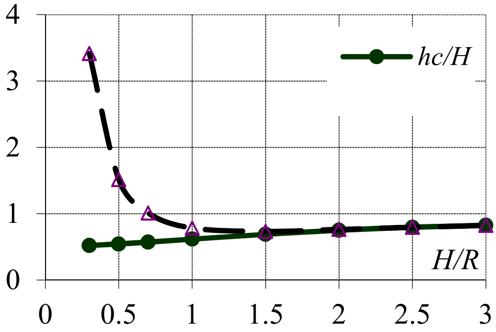

Fig.5: Ratios $h_c/H$ and $h_c^*/H$ as functions of the tank slenderness parameter

## 4 SOLUTION, RESULTS AND CONCLUSION

The reinforced concrete elevated tank given EC8 with the container capacity of 255 m$^3$ is considered in seismic analyses (figure 6). The elevated tank has frame supporting system in which six columns ($\phi$ 0.65 m) are connected by the horizontal bracing at regular interval at 4 m, 8 m and 12 m elevations. Young's modulus and the weight of concrete per unit volume are selected as 32,000 MPa and 25 kN/m$^3$, respectively. The container is also filled with the water density of 1,000 kg/m$^3$ as seen from figure 6. The six staging columns are in edge of regular hexagon with hexagon length 3,140 mm. Tank is located on hard soil in seismic zone 1 of Slovak republic.

The damping values for the reinforced concrete elevated tank are taken as 5% for the impulsive mode and 0.5% for convective mode, as recommended in most literature. [9,10].

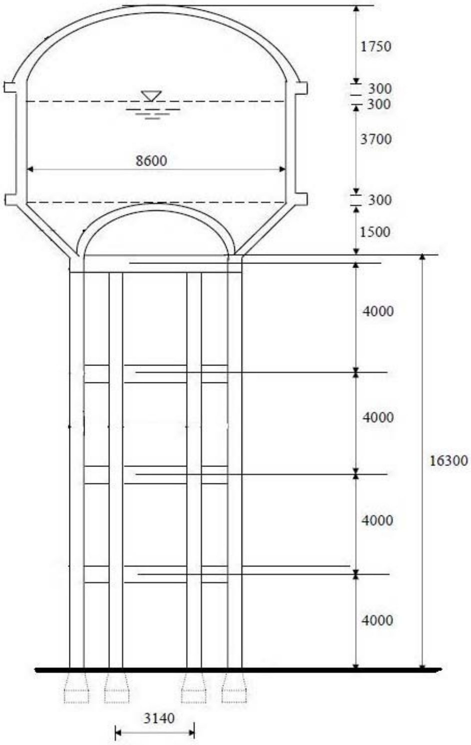

Fig.6: Vertical cross section of the elevated tank

The dynamic characteristic: similar equivalent masses and heights of two-mass model are using for seismic analyses of the selected elevated tanks. The dynamic characteristic of fully reinforced concrete elevated tank: periods, equivalent masses and heights are: $T_i = 0.86$ s, $T_c = 3.15$ s, $m_i = 140\ 100.58$ kg, $m_c = 115\ 557.16$ kg, $h_i^* = 3.17$ m, and $h_c^* = 3.45$ m. Time period of impulsive mode of empty elevated tank is $T_i = 0.66$ s.

The total base shear at the bottom of staging tank and the total overturning moment at base of staging are obtained by combining part of impulsive and convective modes through absolute summation rule. The total base shear at the bottom of staging empty tank is 356.57 kN and the total overturning moment at base of staging empty tank is 6 823.28 kNm. The total base shear at the bottom of staging fluid filled tank is 495.69 kN and the total overturning moment at base of staging fluid filled tank is 9 802.57 kNm.

The rule Square of Sum of Squares (SRSS rule) to combine response from impulsive and convective mode are used for calculating of the total base shear at the bottom of staging tank and the total overturning moment at base of staging. The total base shear at the bottom of staging empty tank is 356.57 kN and the total overturning moment at base of staging empty tank is 6 823.28 kNm. The total base shear at the bottom of staging fluid filled tank is 495.69 kN and the total overturning moment at base of staging fluid filled tank is 9 802.57 kNm.

Table 1 and 2 present the total base shear at the bottom of tank staging and the total overturning moment at base of tank staging for empty tank, for full filling tank using SRSS rule and using absolute summation rule too as well as their % deviation.

Tab. 1: The total base shear at the bottom of tank staging

| The total base shear at the bottom of staging tank *V* [kN] | |
|---|---|
| *V* using SRSS rule | 495.69 |
| *V* using absolute summation rule | 496.20 |
| % deviation of *V* | 0.10 |
| *V* of empty tank | 356.57 |

Tab.2: The total overturning moment at base of tank staging

| The total overturning moment at base of staging $M^*$ [kNm] | |
|---|---|
| $M^*$ using SRSS rule | 9 802.57 |
| $M^*$ using absolute summation rule | 9 762.41 |
| % deviation of $M^*$ | -0.41 |
| $M^*$ of empty tank | 6 823.28 |

## ACKNOWLEDGEMENTS

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## LITERATURE

[1] MEL-RAKABAWY, M. M., EL-ARABATY, H. A. & EL-SHERBINY, M, G. Response of elevated water tanks yo seismic load. In: *11th ICSGE*, 17.-19. May 2005, Cairo - Egypt.

[2] JUHÁSOVÁ, E., BENČAT, J., KRIŠTOFOVIČ, V. & KOLCÚN, Š. Expected seismic response of steel water tank, In: *12th European Conference on Earthquake Engineering*, Paper reference 595, London 2002.

[3] KRÁLIK, J. Dynamic analysis of soil-fluid-tank interaction due to earthquake even. In: *Dynamic of ridig and deformable bodies.* Ústí nad Labem. Univerzita J. E. Purkyně v Ústí n. L.: Univerzita J. E. Purkyně v Ústí n. L., 2012*,* ISBN 978-80-7414-500-0.

[4] LIVAOĞLU, R. & DOĞANGÜN, A. Simplified seismic analysis procedures for elevated tanks considering fluid-soil interaction. In: *Journal of fluid and structures.* 22, 2006. p. 421-439.

[5] 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.

[6] MELCER, J. & LAJČÁKOVÁ, G. Dynamický výpočtový model asfaltovej vozovky In: *Stavebné a environmentálne inžinierstvo*. Roč. 7, č. 1 (2011), s. 2-12 ISSN: 1336-5835.

[7] JAISWAL, O. R., RAI, D. C. & JAIN, S. K. *Review of code provisions on design seismic forces for liquid storage tanks*. Kanpur, Indian Institute of Technology Kanpur, 2005.

[8] HOUSNER, G. W. *Earthquake pressures on fluid containers*, California institute of technology, Pasadena, California, 1954.

[9] EN 1998-4: 2006 EUROCODE 8. *Design of structures for earthquake resistan*ce. Part 4: Silos, tanks and pipelines. CEN, Brussels, 2006.

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