10.1515/tvsb-2017-0010

Transactions of the VŠB – Technical University of Ostrava

Civil Engineering Series, Vol. 17, No. 1, 2017

paper #10

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INFLUENCE OF HORIZONTAL SEISMIC EXCITATION ON TANK – FLUID – SOIL SEISMIC INTERACTION

Abstract

Ground-supported tanks are used to store a variety of liquids. During the earthquake activity the liquid exerts impulsive and convective effects. This paper provides theoretical background for hydrodynamic pressure that is being developing during an earthquake in the liquid storage ground-supported rectangular container – the endlessly long shipping channel, is grounded on hard soil or sub-soil.

Keywords

Tank, fluid, sub-soil, earthquake.

1 INTRODUCTION

Large-capacity ground-supported tanks are used to store a variety of liquids, e.g. water for drinking and fire fighting, petroleum, liquefied natural gas and chemicals. 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 - 9].

The seismic analysis and design of liquid storage tanks is really complicated task, due to the high complexity of the problem.

Number of particular problems should be taken into account, for example: dynamic interaction between contained fluid and tank, sloshing motion of the contained fluid; and dynamic interaction between tank and sub-soil. Those belong to wide range of so called fluid structure interactions (FSI). Tank-soil interaction could under specific conditions have a significant effect on seismic response of the tank.

The knowledge of forces and pressure acting onto walls and the bottom of containers during an earthquake plays essential role in reliable and durable design of earthquake resistance structure/facility - tanks.

2 HYDRODYNAMIC PRESSURES – EUROCODE 8 (EC8)

The complete solution of the Laplace equation for the motion of fluid contained in a rigid containers can be expressed as the sum of two separate contributions, called "rigid impulsive", and "convective", respectively. The "rigid impulsive" component of the solution satisfies exactly the boundary conditions at the walls and at the bottom of the tank (compatibility between the velocities of the fluid and 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 the 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 [1,10-12].

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Let us to consider a rectangular ground supported container, having the width $2L$ as shown in Fig. 1. Walls have uniform thickness. Rectangular container is filled with fluid to the height H and the container is exerted by a horizontal acceleration $\ddot{x}_o$ in the x - direction, [14].

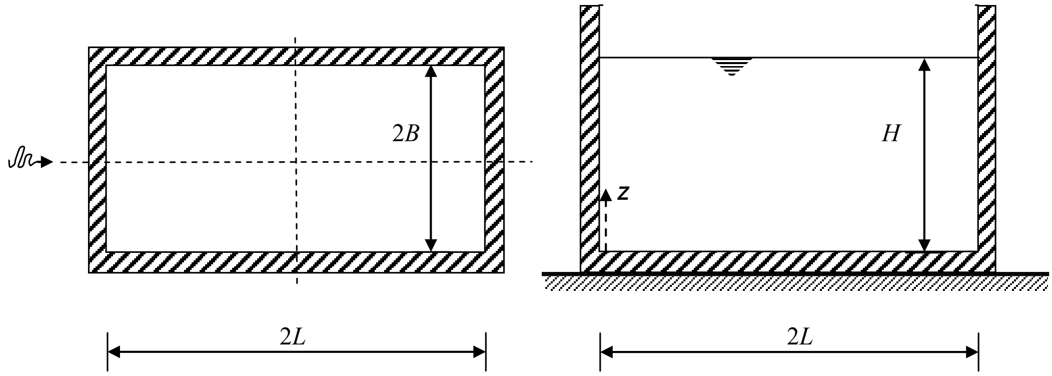
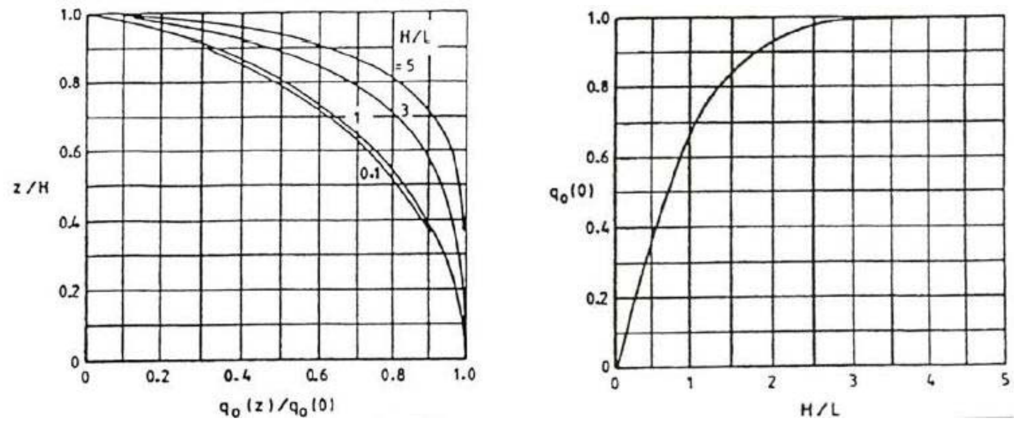


Fig.1: Geometry of rectangular tanks a) plan, b) sectional elevation

For rectangular container whose walls can be considered as rigid, a solution of the Laplace equation due to the horizontal excitation, can be obtained in the form (1). The total pressure is given by the sum of an impulsive and a convective contribution using the absolute summation rule [14]:

$$p(z,t) = p_i(z,t) + p_c(z,t) \tag{1}$$



a) b)

Fig.2: (a) Dimensionalless impulse pressures at wall of rectangular reservoirs vertical at the direction of seismic excitation; (b) Maximum value of non - dimensional impulse pressures at the direction of seismic excitation [14]

The impulsive component is expressed by:

$$p_i(z,t) = q_0(z)\rho L A_g(t) \tag{2}$$

where L is the half-width of the tank in the direction of the seismic action, ρ is mass density of the liquid.. The function $q_0(z)$ gives the variation of $p_i(\cdot)$ along the height, as shown in Figure 5 and it is the function of the slenderness parameter $\gamma = H/L$. The time-dependence of the pressure p_i in eq. (2) is given by the function $A_g(t)$. $A_g(t)$ is the time-history dependent ground acceleration in free - field field motion of the ground. $p_i(\cdot)$ is constant in the direction that is orthogonal to the seismic action.

The convective pressure component is given by the summation of modal terms (sloshing modes), each one having a different variation in time. For rectangular tanks, the dominant contribution is that of the fundamental mode:

$$p_{c1}(z,t) = q_{c1}(z)\rho L A_1(t) \tag{3}$$

where the function $q_{c1}(z)$ is shown in Figure 6 together with the contribution $q_{c2}(z)$ of 2[nd] mode. $A_1(t)$ is the acceleration response function of the simple oscillator having the frequency of the first mode, the appropriate value of the damping, and subjected to an input acceleration $A_g(t)$.

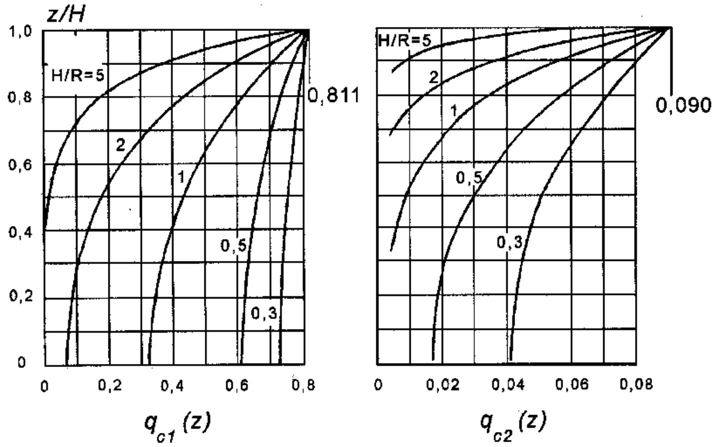


Fig.3: Dimensionaless convective pressures on rectangular tank wall which is perpendicular to the component of the seismic action [14]

The period of oscillation of the first sloshing mode is:

$$T_{c1} = \sqrt{\frac{L/g}{\frac{\pi}{2}\tanh\left(\frac{\pi}{2}\frac{H}{L}\right)}} \tag{4}$$

The wall flexibility of tank generally produces the significant increase of the impulsive pressures, while leaving the convective pressures practically unchanged. Studies on the seismic response of flexible rectangular containers are not numerous, and the solutions are not amenable to a form suitable for direct use in design: for a recent treatment of the subject see for example, ref. [14].

For design purposes the distribution of vertical pressure valid for rigid walls by the expression (2), regarding the recommendation published in [14], can be used in dynamic analysis of fluid filled flexible tank.

The ground acceleration $A_g(t)$ is the response acceleration of a simple oscillator having the frequency and the damping factor of the first impulsive tank-liquid mode. This period of vibration may be approximated as:

$$T_f = 2\pi\sqrt{d_f/g}\,, \tag{5}$$

where d_f is the deflection of the flexible wall on the vertical centre-line and at the height of the impulsive mass, when the wall is loaded by a load uniform in the direction of the ground motion and of magnitude: $m_i g/4BH$. The width of the tank $2B$ is perpendicular to the direction of the seismic loading.

3 MECHANICAL MODEL MALHOTRA 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 Fig. 4. For practical applications, only the first convective modes of vibration need 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 [14].

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 inside width of tank [14].

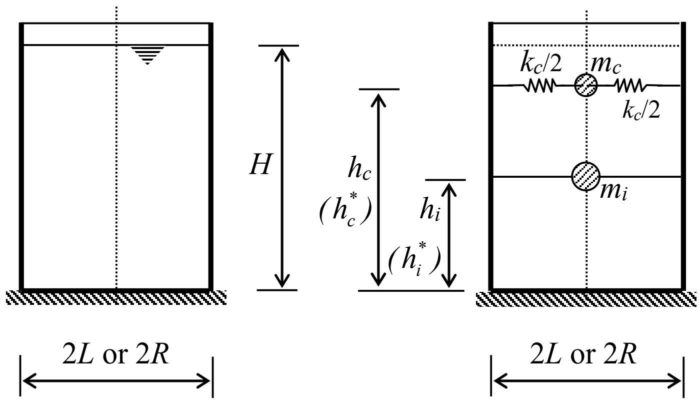


Fig.4: Liquid-filled tank modelled by generalised single degree of freedom systems

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 (5).

d_f is the deflection of the wall on the vertical centre-line and at the height of the impulse mass, when wall is loaded by a load uniform in the direction of the ground motion and of magnitude $m_i g/(4BH)$. 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 [14]. For tanks without roofs the deflection d_f may be calculate assuming the wall to be free at the top and fixed on the other three sides.

For a ground supported rectangular tank, in which the wall is rigidly connected with the base slab, the natural period of the convective mode of vibration Tc = Tc1, in seconds, is given by (4).

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. (6). 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. (7).

The overturning moment M of ground supported tank immediately above the base plate is given also by, eq. (8) and the overturning moment M* of ground supported tank immediately below the base plate is given also by, eq. (9).

$$V = (m_i + m_w + m_r) S_e(T_i) + (m_c) S_e(T_c), \tag{6}$$

$$V^* = (m_i + m_w + m_b + m_r)S_e(T_i) + (m_c)S_e(T_c), \quad (7)$$

$$M = (m_i h_i + m_w h_w + m_r h_r)S_e(T_i) + (m_c h_c)S_e(T_c), \quad (8)$$

$$M^* = (m_i h_i^{'} + m_w h_w + m_b h_b + m_r h_r)S_e(T_i) + (m_c h_c^{'})S_e(T_c), \quad (9)$$

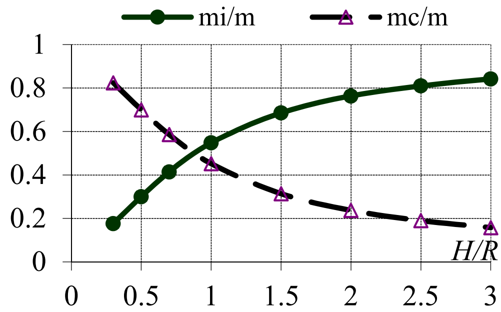


Fig.5: Impulsive and convective masses as fractions of the total liquid mass in the tank

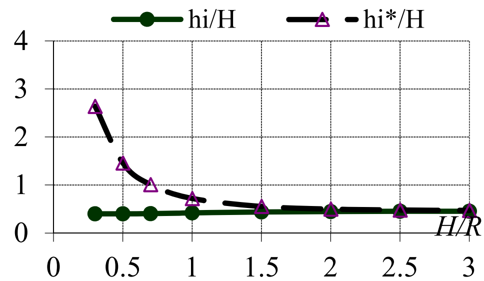


Fig.6: Impulsive heights as fraction of the height of the tank fluid full filling

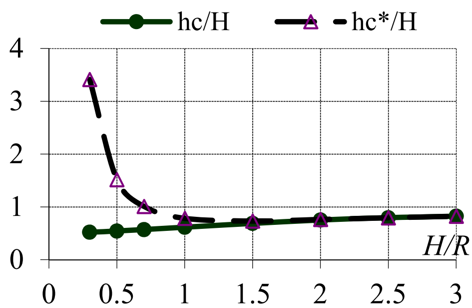


Fig.7: Convective heights as fraction of the height of the tank fluid full filling

where m_i is the impulsive mass of fluid, m_c is the convective mass of fluid, the impulsive and convective masses are obtained from Fig. 5 or Table in [14] as fractions of the total liquid mass m [14]. h_i and h_c are the heights of the centroids of the impulsive and convective hydrodynamic wall pressures, given in Fig. 6 or Table 1 in [14]. h_i^* is height resultant of pressures on the wall and on the base plate for the impulsive component and h_c^* is height resultant of pressures on the wall and on the base plate for the convective component, both are given in Fig. 7 or Table 1 in [14]. m_w is the mass of the tank wall, m_b the mass of the tank base plate and m_r the mass of the tank roof. h_w is the height of the center of gravity of tank wall; h_b the height of the center of gravity of base plate and h_r the height of the center of gravity of roof. $S_e(T_i)$ 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; $S_e(T_c)$ is convective spectral acceleration, is obtained from a 0,5% damped elastic response spectrum.

The base shear and the moment on the foundation may be evaluated on the basis of expressions (6) - (8). 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. 5 - 7, (by using of Malhotra simple procedure for seismic analysis of liquid-storage tanks [14]) may be adopted for the design of rectangular tanks as well (with L replacing R), with an error less than 15% [11].

4 SOLUTION, RESULTS AND DISCUSSION

As an example case we will assume the ground supported rectangular endlessly long shipping channel, with the length $L = 5$ m and the height $H_w = 3$ m. Channel surrounding walls have the uniform thickness of 0.25 m. The base slab of the channel is $h = 0.4$ m thick. Shipping channel is filled with water up to the height of 2.5 m. There is no roof slab structure covering the channel. This water filled tank is grounded on hard soil or sub-soil 30 MNm^{-3}, Fig. 8.

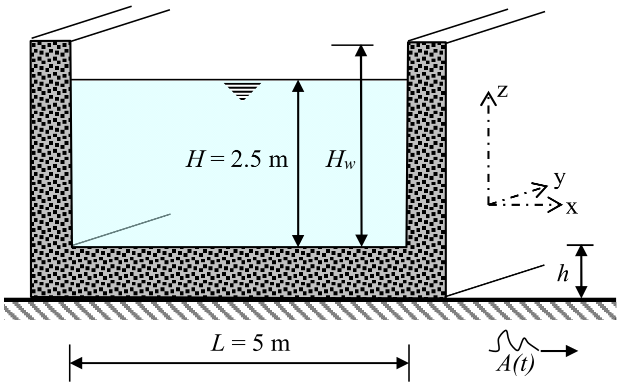


Fig.8: Details of tank geometry

As the excitation input we consider horizontal earthquake load given by the accelerogram of the earthquake in Loma Prieta, California (18.10.1989), Fig. 9. In the analysis we use just the accelerogram for the seismic excitation in x-direction.

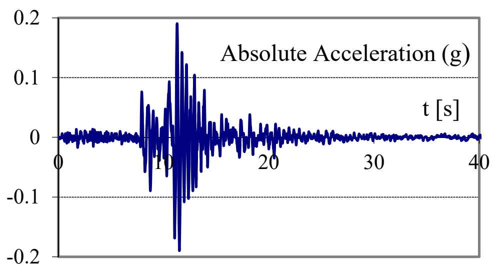


Fig.9: Akcelerogram Loma Prieta, California

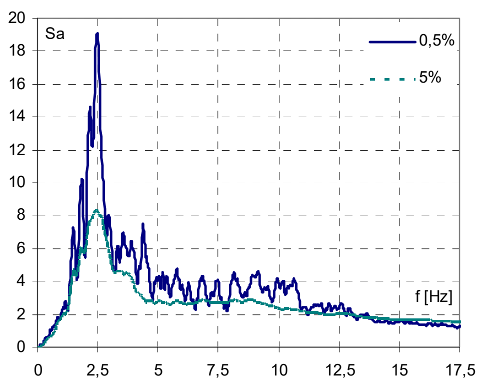


Fig.10: Elastic response spectrums for accelerogram Loma Prieta from Fig. 9

The maximal horizontal displacement and maximal Von Mises stress in the reservoir, maximal stress in the sub-soil, the maximal pressure of fluid and the maximal height of the wave of fluid (behavior of the free surface of the fluid) are listed in Tab. 1 for two types of sub-soils (hard soil and sub-soil 30 MNm^{-3}). Results in Tab. 1 are given from numerical solution by application of FEM. Only the solid walls and base (excluding physical representation of fluid field) of the shipping channel was modeled by using 2D SOLID finite element under plain strain condition. The effect of fluid interaction was simulated under the quasistatic conditions. The hydrostatic and hydrodynamic components of the pressure were applied as the static load acting onto the walls and the bottom of the tank. The hydrodynamic pressure were given by procedure proceded by EC8 [14]. For the numerical simulations by application of FEM was used software ADINA.

Tab.1: Comparison of results by using procedure in EC8 for two types of sub-soils

	The tank is located on hard soil	**The tank is located on soil 30 MNm^{-3}**
Maximal horizontal displacement at reservoirs [mm]	1.072	3.340
Maximal Von Mises stress in reservoirs [MPa]	2.555	2.478
Maximal stress in sub-soil [MPa]	-	0.0626
Maximal pressure of fluid [kPa]	29.340	29.354

5 CONCLUSION

Ground supported rectangular endlessly long shipping channel having the length of $L = 5$ m and the height $H_w = 3$ m was analyzed. The channel is partially filled with the water up to the height 2.5 m. No upper roof slab above the channel is considered. This water filled tank is grounded in hard soil or or subsoil 30 MNm^{-3}. As the excitation input we consider the horizontal acceleration load by the accelerogram of the earthquake Loma Prieta in California. Focusing on dynamic response of the structure due to the earthquake excitation the analytical method was successfully applied in the complex analysis. The comparison of resulting measures (displacements, pressure, stresses) based on FEM with analytical results show very good correspondence. Basic responses of the interest were: pressure in the fluid, displacement of the free surface of the fluid, structural deformation and stress distribution over the tank.

ACKNOWLEDGMENT

This work was supported by the Scientific Grant Agency of the Ministry of Education of Slovak Republic and the Slovak Academy of Sciences under Project VEGA 1/0477/15.

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