Budownictwo 23
DOI: 10.17512/znb.2017.1.15

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SOIL-STRUCTURE-FLUID INTERACTION OF THE RECTANGULAR TANK - SEISMIC ANALYSIS

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. When subjected to external excitation like earthquake, liquid-containing structures are challenging to design due to sloshing effects. Indeed, fluid-structure interaction is the source of free surface fluctuation and hydrodynamic pressure loads that can cause unexpected instability or even failure of these structures [1-5].

The seismic analysis and design of liquid storage tanks is, due to the high complexity of the problem, in fact, really complicated task. Number of particular problems should be taken into consideration, 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 [6-8].

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

1. Mechanical 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 modes of vibration need to be considered in the analysis, mechanical model (Fig. 1). The impulsive

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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 [2-4, 6-9].

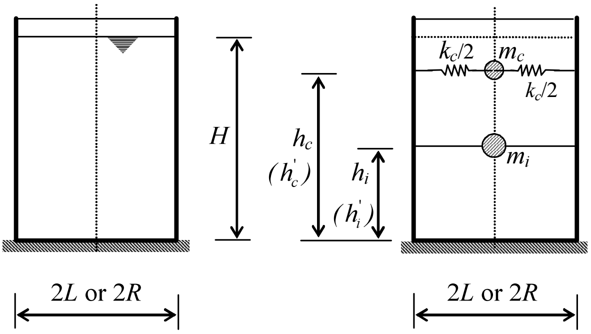

Fig. 1. Liquid-filled tank modelled by generalised single degree of freedom systems

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 slenderness parameter of tank γ, whereby $0.3 < \gamma < 3$. Tank's slenderness parameter is given by relation $\gamma = H/L$ or $\gamma = H/R$, where H is the filling height of fluid in the tank and R is inside radius or 2L is inside width of tank [2-6, 10-14].

2. 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 2.6 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. 2). As the excitation input we consider horizontal earthquake load given by the accelerogram of the earthquake in Loma Prieta, California (18.10.1989) (Fig. 3). In the analysis we use just the accelerogram for the seismic excitation in x-direction.

Dynamic time-history response of concrete open top rectangular liquid storage tanks - chipping channel was performed by application of Finite Element Method (FEM) utilizing software ADINA. Arbitrary-Lagrangian-Eulerian (ALE) formulation was used for the problem. Two way Fluid-Structure Interaction (FSI) techniques were used for simulation of the interaction between the structure and the fluid at the common boundary. The solid walls and base of the shipping channel was modeled by using 2D SOLID finite element under plain strain condition. The fluid inside the shipping channel was modeled by using 2D FLUID finite elements.

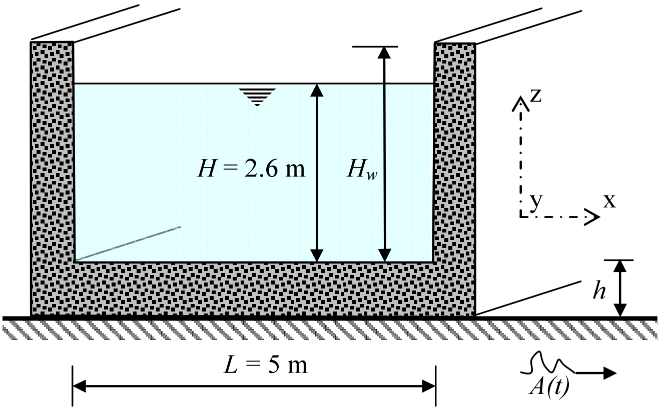

Fig. 2. Details of tank geometry

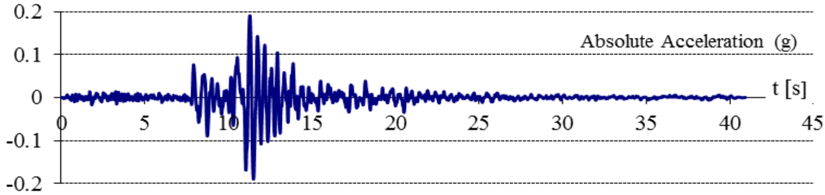

Fig. 3. Accelerogram Loma Prieta, California

As the excitation input was considered the load of input time dependent horizontal displacement measured during the earthquake Loma Prieta in California (Fig. 4). For the better overview FEM results are marked as "FEM".

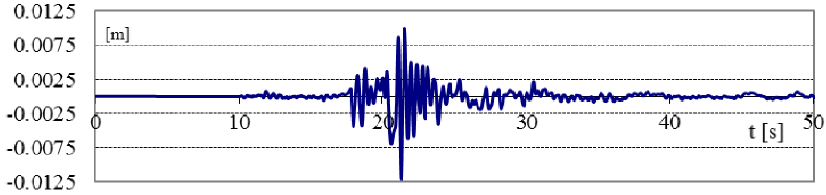

Fig. 4. Input time dependent horizontal displacement measured during of earthquake Loma Prieta

All of numerical solutions used finite element method were performed by computational code ADINA (Figs. 5-10). The results of chipping channel was grounded on hard soil are shown in Figures 5-8 and on sub-soil 30 MNm^{-3} in Figures 9 and 10.

The resulting time dependent response of the pressure of fluid was described in Figure 5 in point "RBEF" (Right Bottom Edge of Fluid). The time dependent response of the fluid pressure in points "LBEF" (Left Bottom Edge of Fluid) and "RBEF" are almost asymmetric.

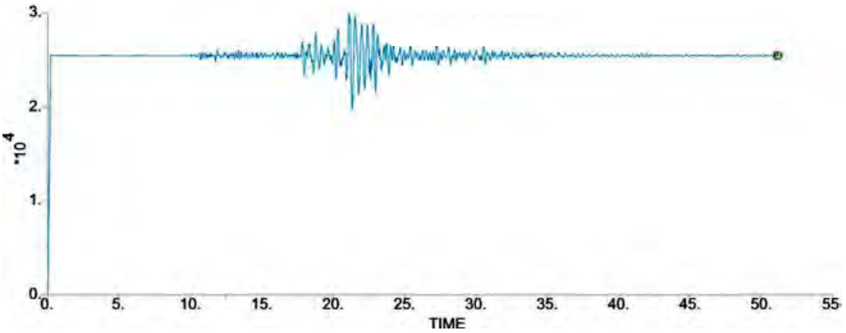

Fig. 5. Time dependent response of the fluid pressure in “RBEF” point

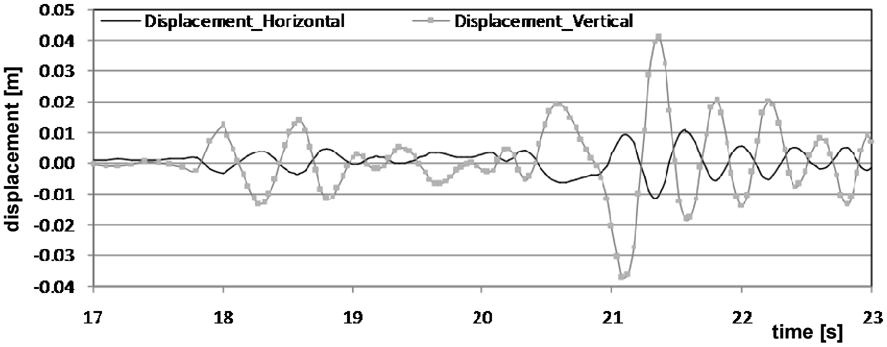

Fig. 6. Time dependent response of the horizontal and vertical displacement of fluid in “RTEF” point

The resulting time dependent horizontal and vertical displacements of fluid within time interval 17÷23 s in the point “RTEF” (Right Top Edge of Fluid on free surface) were documented in Figure 6. The timing of the peak response correlates well with peak excitation (Loma Prieta as in Figure 4), which the numerical analysis makes realistic enough.

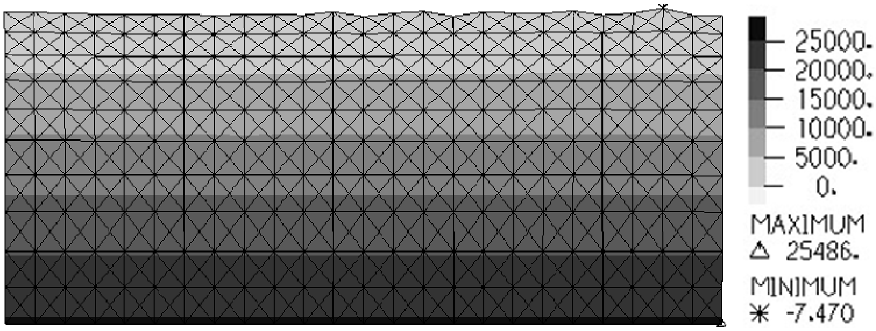

Fig. 7. Pressure of fluid in time 48 s

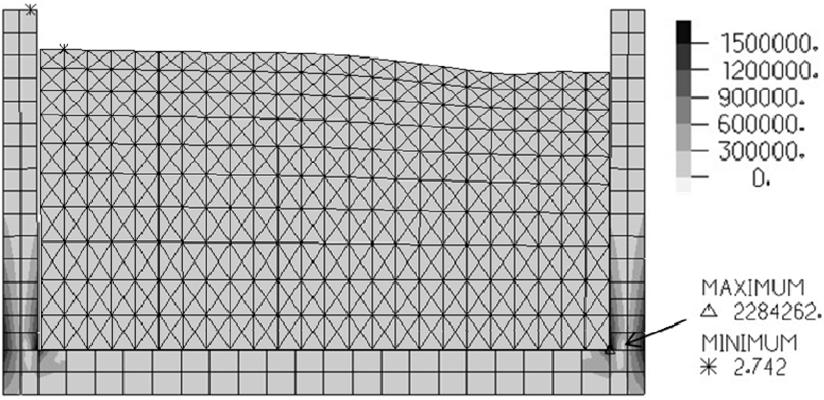

Fig. 8. Shape of free surface and Von Mises stress of tank in time t = 21.56 s

Figure 7 presents distribution of dynamic fluid pressure of fluid domain in time 48.0 s. Figure 8 shows shape of free surface of fluid and the distribution of von Mises stress over the domain of interest in time t = 21.56 s, when peak response of hydrodynamic pressure was measured.

The concrete open top rectangular liquid storage tanks - endlessly long chipping channel was grounded on hard soil or sub-soil 30 MNm^{-3}. To illustrate the influence of sub-soil comparative study was performed. Figure 9 shows the deformed shape of chipping channel grounded on hard soil in time 21.20 s (dashed lines), whereas the deformed shape of chipping channel grounded on or sub-soil 30 MNm^{-3} (solid lines) is in the same time. The deformable sub-soil condition shows the relative vertical deformation of the centre of the bottom 0.0034 mm.

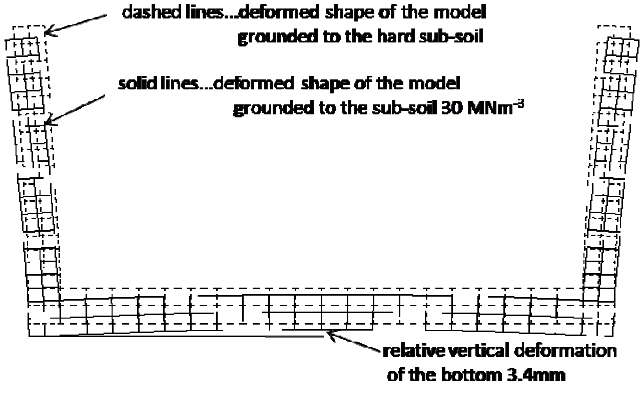

Fig. 9. Deformed shape of shipping channel grounded to the hard sub-soil (dashed lines) and to the sub-soil 30 MNm^{-3} (solid lines) in time t = 21.20 s

Figure 10 documents the time dependent response of the vertical displacement for very lower side points of chipping channel in point "RBET" (Right Bottom Edge of Tank). The peak value of the vertical amplitude measured at RBET is 0.25 mm.

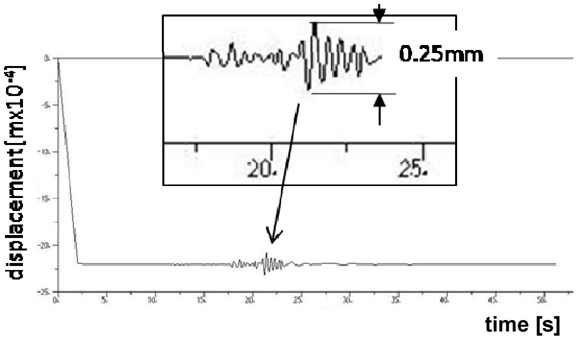

Fig. 10. Time dependent response of the vertical displacement in the "RBET" point of the shipping channel on sub-soil 30 MNm^{-3}

The alternative approach of numerical simulation by application of Finite Element Method (FEM) and utilizing software ADINA was considered. Only the solid walls and base (excluding physical representation of fluid field) of the shipping channel were 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 was given by recommending of code Eurocode 8 - Design of structure for earthquake resistance - Part. 4: Silos, tanks and pipelines. The results from this kind of analyses are marked as "EC8". The elastic response spectrums of accelerogram Loma Prieta were used with the damping ratio 5 and 0.5%.

TABLE 1

Comparison of results by using procedure in EC8 and by modeling FEM ALE FSI

	The tank is located on hard soil		The tank is located on soil 30 MNm^{-3}	
	EC8	FEM	EC8	FEM
Maximal horizontal displacement at reservoirs [mm]	1.07	0.84	3.34	2.68
Maximal von Mises stress in reservoirs [MPa]	2.56	2.28	2.48	1.99
Maximal stress in sub-soil [kPa]	–	–	62.6	46.4
Maximal pressure of fluid [kPa]	29.34	29.63	29.35	29.70
Maximal height of wave [mm]	50.0	41.7	50.0	39.9

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 Table 1 for two types of sub-soils (hard soil and sub-soil 30 MNm^{-3}).

"FEM" results were obtained from numerical simulation of dynamic time-history response of concrete open top rectangular chipping channel performed by application of FEM, ALE and two way FSI techniques for simulation of the interaction between the structure and the fluid at the common boundary. The solid walls and base of the shipping channel were modeled by using 2D SOLID finite element under plain strain condition and the fluid inside the shipping channel by using 2D FLUID finite elements. The "EC8" results are given from numerical solution of FEM application. Only the solid walls and base (excluding physical representation of fluid field) of the shipping channel were modeled by using 2D SOLID finite element under plain strain condition. 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 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. Eurocode 8 - Design of structure for earthquake resistance - Part. 4: Silos, tanks and pipelines is recommended adopting of the "simple procedure for seismic analysis of liquid-storage cylindrical tanks", of authors Malhotra, Wenk and Wieland "MWW model", for the design of rectangular tanks as well, with an error less than 15% [15, 16]. The comparison of hydrodynamic parameters (impulsive mass, convective mass and equivalent heights related to these masses) of rectangular tanks according to two-mass model suggested by Housner [3] "Housner model" and model based on the work of authors Malhotra, Wenk and Wieland and their differences are seen from Table 2. The comparison of total base shears, the total bending moments is shown in Table 3. It is seen, that the differences of the base shears and the moments are less than 4.71%.

TABLE 2

Determined dynamic parameters and their differences

Model	m_i [kg]	m_c [kg]	h_i [m]	h'_i [m]	h_c [m]	h'_c [m]
MWW	7267	5723	1.034	1.871	1.607	2.032
Housner	7266	6124	0.975	2.000	1.530	2.173
% Differences	0.01	–6.56	6.05	–6.45	1.53	–2.49

TABLE 3

The total base shears, the total bending moments and their differences

Model	V [kN]	V' [kN]	M [kNm]	M' [kNm]
MWW	12.81	16.58	18.13	28.76
Housner	12.80	15.89	18.21	30.18
% Differences	0.08	–4.16	–0.44	4.71

Conclusions

The ground supported rectangular endlessly long open top shipping channel having the length of L = 5 m and the height H_w = 3 m was analyzed. The channel was partially filled with the water, grounded on hard soil or sub-soil 30 MNm^{-3} and excited by the accelerogram of the earthquake Loma Prieta in California. Focusing on dynamic response of the structure due to the earthquake excitation the analytical methods (by Eurocode 8 - Design of structure for earthquake resistance - Part. 4: Silos, tanks and pipelines) together with numerical simulation (by FEM ALE FSI) was successfully applied in the complex analysis. Basic responses of the interest were: pressure in the fluid, displacement of the free fluid surface, structural deformation and stress distribution over the tank, base shears and moments.

The resulting measures (displacements, pressures, stresses, height of wave) based on FEM ALE FSI and analytical results "EC8" (the numerical solution of the earthquake problem, where the fluid was simulated by hydrostatic and hydrodynamic components of the pressure applied as statically loading on the walls and bottom of tank) are shown very good correlation hereof tank slenderness parameter $\gamma = 1.0$ (Table 1).

The comparison of the hydrodynamic parameters, the total base shears and the total bending moments given by model of Malhotra, Wenk and Wieland "MWW model" and by Housner "Housner model" for rectangular tanks is seen from Tables 2 and 3. The maximum difference of hydrodynamic parameters is documented 6.56% for m_c (Table 2) and for V, M, V' and M' is 4.71% for M' (Table 3).

Acknowledgements

This work was supported by the Scientific Grant Agency of the Ministry of Education of Slovak Republic and the Slovak Academy of Sciences the project VEGA 1/0477/15 "Numerical analysis and modeling of interactive problems in multilayered composite structural members".

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Abstract

Ground-supported tanks are used to store a variety of liquids. The fluid develops hydrodynamic pressure on walls and bottom of tank during an earthquake. This paper provides theoretical background for specification of impulsive and convective actions of fluid in liquid storage rectangular container by using analytical methods. Numerical model of tank seismic response - the endlessly long shipping channel was obtained by using of Finite Element Method (FEM), Arbitrary-Lagrangian-Eulerian (ALE), Fluid Structure Interactions (FSI) formulation in software ADINA. The results of the analytical methods and the numerical solution were compared for partially water filled channel grounded on hard soil or sub-soil 30 MNm^{-3}. It was considered the horizontal ground motion of the earthquake in Loma Prieta.

Keywords: rectangular tank, fluid, earthquake, fluid-structure interaction

Interakcja grunt-konstrukcja-ciecz zbiornika prostokątnego - analiza sejsmiczna

Streszczenie

Zbiorniki naziemne są używane do przechowywania różnych płynów. Obecność płynu powoduje powstawanie ciśnienia hydrodynamicznego na ścianach i dnie zbiornika podczas trzęsienia ziemi. W artykule przedstawiono teoretyczne podstawy przy użyciu metod analitycznych dla określenia działań impulsywnych i konwekcyjnych płynu w prostokątnym pojemniku do magazynowania cieczy. Numeryczny model reakcji sejsmicznej zbiornika - nieskończenie długi kanał uzyskano, stosując metodę elementów skończonych (MES), równania Eulera-Lagrange'a, interakcję pomiędzy płynem i konstrukcją (FSI) w oprogramowaniu ADINA. Wyniki metod analitycznych i rozwiązania numerycznego porównano dla kanału częściowo wypełnionego wodą, uziemionego na twardej glebie lub podłożu 30 MNm^{-3}. Analizowano ruch poziomy w trzęsieniu ziemi w Loma Prieta.

Słowa kluczowe: zbiornik prostokątny, płyn, trzęsienie ziemi, oddziaływanie płyn-struktura