FLUID – STRUCTURE – SOIL INTERACTION OF CYLINDRICAL LIQUID STORAGE TANK SUBJECTED TO HORIZONTAL EARTHQUAKE LOADING

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Abstract. *Shallow founded tanks are strategic structures used to store a variety of kind of liquids. The fluid develops hydrodynamic effect on solid domain of container during an earthquake. This paper provides the theoretical background for numerical model on seismic response of fluid-structure-soil interaction. The Finite Element Method (FEM) was used for seismic response of shallow founded cylindrical container. The Fluid-Structure-Soil interaction of shallow founded tank was analysed according to theories of I. Limit States - the ultimate limit state (ULS) and II. Limit States - the serviceability limit state (SLS) pursuant to EN 1997-1. Summary of the results: the maximum rotation of foundation is growing with the reduction of the stiffness of the subsoil and the vertical and horizontal bearing capacity depends on the strength properties of the subsoil.*

Keywords

Container, fluid, interaction, soil.

1. Introduction

The shallow founded containers are substantial components in the commercial applications, they can be considered as the lifeline of the industrial facilities [1]. Liquid-containing structures are critical elements in the municipal water supply and firefighting systems and are used extensively for storage and processing of a variety of liquids and liquid-like materials, including oil, liquefied natural gas industries, chemical fluids, and different forms of wastes [2].

Earthquake is a natural catastrophe that have been observed in the past several cases of damage to tanks. Water supply is necessary for controlling fires that may occur during earthquakes, which can cause a great deal of damage and the loss of lives [3]. Shallow founded tanks are strategic structures, and their damage during earthquakes may endanger drinking water supply, cause failure in preventing large fires and contribute to substantial economic loss. The Shallow founded containers should remain functional in post-earthquake periods to ensure that a clean water supply is available in earthquake-affected regions [4]. Interaction of the fluid storage facilities with soil and contained liquids results in the modification of the system and dynamic properties, which changes its seismic response [5]. The seismic safety of the shallow founded facilities squired for avoiding adverse consequences of earthquake, such as fires, explosions and environment pollution, requires a better understanding of their seismic behaviour [6].

The methods described the interaction between fluids and solids have been the big research field of computational engineering in recent years [7]. The Shallow founded facilities consists of water-filled containers of various sizes are typical civil engineering application of fluid-structure-interaction (FSI) [8], [9] and [10]. The contained fluid effects liquid contributes to hydrodynamic fluid pressure that act together with hydrostatic fluid pressure on the walls and bottoms of the tanks, reduces the natural frequencies in comparing with the structure domain and fluid wave propagation due to seismic motion [11].

Storage tanks are stiff solid domain [12]. When these structures are placed on soft soils, Fluid-Structure-Soil interaction (FSSI) will significantly determine the seismic behaviour of storage facilities [13]. The difference in the seismic behaviour between the same structure placed on hard soil and on soft soil will be that the structures on a flexible foundation have more degrees of freedom and therefore different dynamic characteristics than structures on a rigid foundation [14]. The FSSI will have an essential role in the seismic response of storage tanks [15].

2. Seismic Analysis of Shallow founded Cylindrical Tank

The motion of contained fluid in a rigid cylinder container can be expressed as the sum of two separate fundamental contributions, which are called 'impulsive', and 'convective', respectively [17].

The dynamic analysis of a liquid-filled tank may be carried out using the concept of generalized single-degree-of freedom (SDOF) systems that represents the impulsive mode and convective modes of vibration of the tank - liquid system [18], see Fig. 1. The impulsive mode is represented by impulsive mass of fluid m_i that is attached rigidly to the container wall at height h_i (or h_i^*). The convective masses m_{cn} are connected to the tank walls at heights h_{cn} (or h_{cn}^*) by springs with stiffness k_{cn} [18].

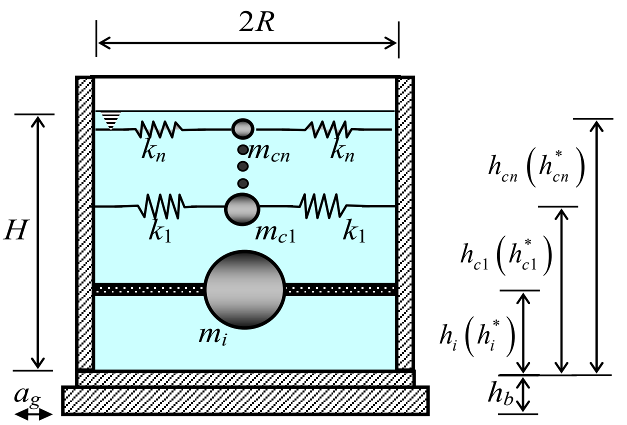

Fig. 1: Spring-mass system for shallow founded cylindrical tanks.

For a shallow founded cylindrical tank, in which the wall is rigidly connected with the foundation slab, the circular frequency is given by

$$\omega_{cn} = \sqrt{\frac{g\lambda_n \tanh(\lambda_n \gamma)}{R}} \tag{1}$$

λ_n are the roots of the first-order Bessel function of the first-order Bessel function of the first kind (λ_1=1.8412; λ_2=5.3314; λ_3=8.5363, λ_4=11.71, λ_5=14.66 and $\lambda_{5+i}=\lambda_5+5i$ (i=1,2,...)), g is acceleration due to gravity, $\gamma = H/R$ is the dimensionless tank slenderness parameter, R is inner tank radius and H is full fluid filling of tank [18]. The first oscillating, or sloshing, mode and frequency of the oscillating liquid (n = 1) is significantly dominant [17].

Pursuant to Eurocode 8 - 4 [18] that was acquired from the simplified procedure for seismic analysis of liquid-storage tanks [17] developed by P. K. Malhotra, T. Wenk and M. Wieland, where the tank-liquid system is modelled by two single-degree-of-freedom systems, one corresponding to the impulsive component, moving together with the flexible wall, and the other corresponding to the convective component. The impulsive and convective responses are combined by taking their algebraic-sum. For practical applications, only the first convective mode of vibration is enough to consider in the analysis of mechanical model [17] and [18].

The natural period of the convective response T_c, in [s], is taken in Eq. (2), where coefficient C_c is in $[\mathrm{m} \cdot \mathrm{s}^{-\frac{1}{2}}]$, and R is inner radius of tank in [m], considered in the simplified procedure for fixed base cylindrical tanks, given in [17] and in [18]

$$T_c = C_c\sqrt{R}\,. \tag{2}$$

The natural period of the impulsive response, in [s], is taken as [17] and [18]

$$T_i = C_i \frac{H\sqrt{\rho}}{\sqrt{s/R}\sqrt{E}}\,. \tag{3}$$

The results of the dynamic analysis of a liquid-filled container considered only horizontal ground motion are the base shears and moments. Total base shear V of shallow founded immediately at the bottom of the tank wall can be also obtained by base shear in impulsive mode and base shear in convective mode. Eq. (4) gives recommendation for calculating of total base shear V^* of shallow founded tank at the bottom of foundation. The bending moment M of shallow founded immediately at the bottom of the tank wall can be also obtained by bending moment in impulsive mode and in convective mode. The overturning moment M^* of shallow founded tank immediately below of the foundation is dependent on the hydrodynamic pressure on the tank wall as well as that on the tank bottom, is given by Eq. (5).

$$V^* = \left(m_i + m_w + m_b + m_r\right) S_e\left(T_i\right) + \left(m_c\right) S_e\left(T_c\right) \tag{4}$$

$$\begin{aligned} M^* = &\left(m_i h_i^* + m_w h_w + m_b h_b + m_r h_r\right) S_e\left(T_i\right) + \\ &+ \left(m_c h_{c1}^*\right) S_e\left(T_c\right) \end{aligned} \tag{5}$$

where m_i [kg] is the impulsive mass of fluid, m_c [kg] is the convective mass of fluid, the impulsive and convective masses are obtained from Fig. 3 as fractions of the total liquid mass m [kg]. m_w [kg] is the mass of the tank wall, m_b [kg] the mass of the tank base plate with foundation and m_r [kg] the mass of the tank roof. h_i [m] and h_c [m] are the heights of the centroids on the impulsive and convective hydrodynamic wall pressures from tank bottom. h_i^* [m] is height of the centroid on the impulsive hydrodynamic tank wall pressures as well as that on the tank bottom and h_c^* [m] is height of the centroid on the convective hydrodynamic tank wall pressures as well as that on the tank bottom, see Fig. 1, Fig. 4 and Fig. 5. h_w [m] is the height of the centre of gravity of tank wall; h_b [m] and h_r [m] are the heights of the centres of gravity of tank base plate with foundation and roof, respectively. $S_e(T_i)$ is the impulsive spectral acceleration 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 the convective spectral acceleration obtained from a 0.5% damped elastic response spectrum [17] and [18].

Fig. 2 is documented the dependence the values of C_i [dimensionless] and C_c [$\mathrm{m \cdot s^{-\frac{1}{2}}}$] as function of the tank height-to-radius ratio H/R, i.e. dimensionless variable tank slenderness parameter $\gamma = H/R$, Table in [17] and [18].

Fig. 3 is presented the dependence the impulsive masses m_i [kg], and convective masses m_c [kg] as fraction of the total liquid mass m [kg] as function of the dimensionless tank slenderness parameter $\gamma = H/R$, Table in [17] and [18].

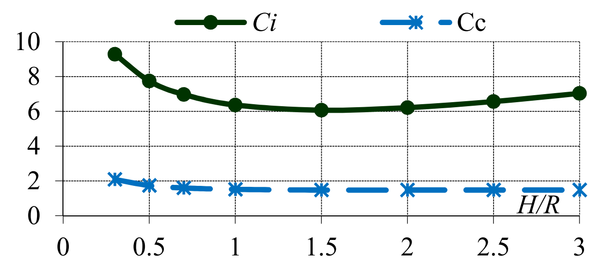

Fig. 2: Coefficients C_i [dimensionless] and C_c [$\mathrm{m \cdot s^{-\frac{1}{2}}}$], as function of the tank slenderness parameter γ [dimensionless].

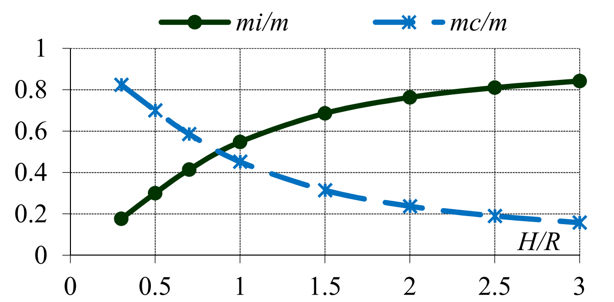

Fig. 3: Ratios m_i/m [dimensionless] as function of the tank slenderness parameter γ [dimensionless].

Fig. 4 and Fig. 5 are documented the responding of masses heights above the tank bottom h_i [m], h_c [m], h_i^* [m], and h_c^*[m] as fraction of the total tank fluid filling H [m] as function of the dimensionless tank slenderness parameter γ that γ is taken as $\gamma = H/R$, Table in [17] and [18].

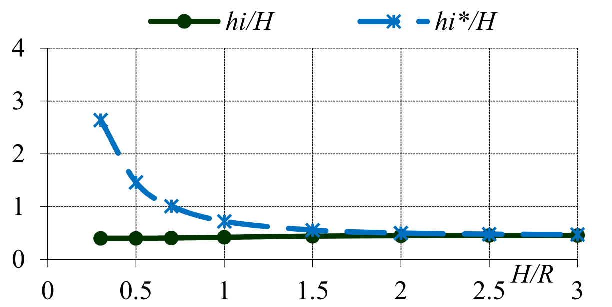

Fig. 4: Ratios h_i/H [dimensionless]and h_i^*/H [dimensionless]as functions of the parameter tank slenderness γ [dimensionless].

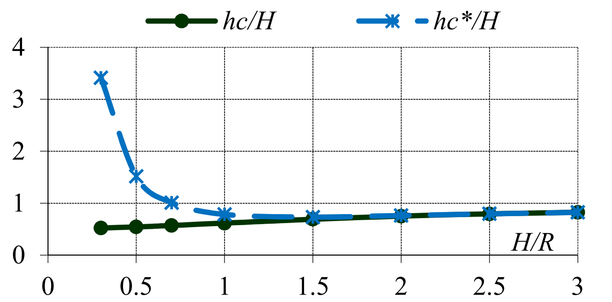

Fig. 5: Ratios h_c/H [dimensionless] and h_c^*/H [dimensionless] as functions of the tank slenderness parameter γ [dimensionless].

3. Numerical Solution of Fluid – Structure – Soil Interaction

The shallow founded cylindrical storage container with inner diameter $D = 14$ m and wall height $H_w = 7.25$ m, without a roof, was analysed in this study. The circular tank wall has the uniform thickness 0.25 m and tank base 0.4 m. The material characteristics of solid domain of liquid storage tank are: Young's modulus E = 35 GPa, Poisson ratio $\nu = 0.18$ and density $\rho = 2550\ \mathrm{kg \cdot m^{-3}}$. The maximum fluid filling with water (H_2O) of density $\rho_w = 1\,000\ \mathrm{kg \cdot m^{-3}}$ is 7 m. The cylindrical tank was founded at depth of 0.5 m below the surface on the circular foundation with diameter of 7.8 m with a thickness of 0.5 m. The water filled tank is grounded on gravel and cohesive subsoil. As the seismic excitation we consider the earthquake Loma Prieta, California (18.10.1989) in only horizontal direction, see Fig. 6. The elastic response spectra for damping 5%, 2% and 0.5% acquired for the considered accelerogram Loma Prieta in California are shown in Fig. 7.

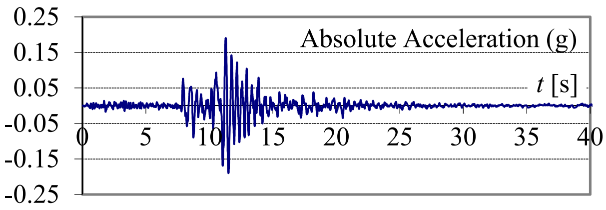

Fig. 6: Accelerogram Loma Prieta, California.

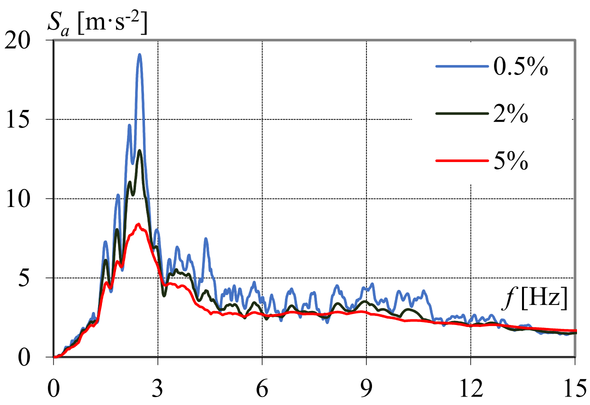

Fig. 7: Elastic response spectra for 0.5%, 2%, and 5% damping for the accelerogram Loma Prieta.

The concrete cylindrical tank - water reservoir - founded on gravel and fine subsoil was analysed. The seismic response of tank, the base shears and moments are calculated using the simplified procedure for seismic analysis of liquid-storage tanks with recommending of [17] and [18]. The 5% damped elastic response spectra is used for $S_e(T_i)$, i.e. impulsive response of fluid and for inertia effect of concrete tank wall, concrete tank bottom and concrete tank foundation. The 0.5% damped elastic response spectra is used for $S_e(T_c)$, i.e. convective response of fluid. The subsoil was modelled using 4 various types of subsoil - soil group G5 and S5 and cohesive subsoil – soil group F2 and F4. Geotechnical characteristics of soils are given in the Tab. 1.

The three load conditions were considered for modelling of this problem: 1. Empty tank, 2. Water filled tank (for static analysis), and 3. Water filled tank (for seismic analysis). The vertical and horizontal bearing capacity was computed for verification the ultimate limit state (ULS), and settlement and rotation of a foundation was computed for verification the serviceability limit state (SLS).

Tab. 1: Geotechnical characteristics of soils.

Characteristics of soils	Soil group			
	G5	S5	F2	F4
Unit weight γ (kN.m^{-3})	19.5	18.5	19.5	18.5
Angle of internal friction φ_{ef}(°)	30.0	27.0	27.0	24.5
Cohesion of soil c_{ef} (kPa)	6.0	8.0	10.0	14.0
Deformation modulus E_{def} (MPa)	50	8.0	11.0	5.0
Poisson's ratio ν	0.30	0.35	0.35	0.35

The resulting deformation depends on the deformation characteristics of the subsoil and on the size of the tensions in the foundation soil (original stress in soils σ_{or} and stress from the external load σ_z). The theory of elasticity (Boussinesq theory) was used for determined stresses in the soil.

Tab. 2: Results of the ultimate limit state (ULS).

The ultimate limit state	Load condition		
	1.	2.	3.
Subsoil formed of clayey gravel (GC) – soil group G5			
Design bearing capacity of foundation soil R_d (kPa)	971.24	971.24	796.21
Extreme contact stress σ (kPa)	34.40	91.10	96.11
Horizontal bearing capacity R_{dh} (kN)	3509.35	8396.43	8368.81
Extreme horizontal force H (kN)	0.0	0.0	1327.0
Subsoil formed of clayey sand (SC) – soil group S5			
Design bearing capacity of foundation soil R_d (kPa)	621.44	621.44	510.32
Extreme contact stress σ (kPa)	34.40	91.10	96.11
Horizontal bearing capacity R_{dh} (kN)	3302.00	7555.23	7518.41
Extreme horizontal force H (kN)	0.0	0.0	1327.0
Subsoil formed of gravelly clay (CG) – soil group F2			
Design bearing capacity of foundation soil R_d (kPa)	672.33	672.33	552.35
Extreme contact stress σ (kPa)	34.40	91.10	96.11
Horizontal bearing capacity R_{dh} (kN)	3479.50	7732.74	7686.71
Extreme horizontal force H (kN)	0.0	0.0	1327.0
Subsoil formed of sandy clay (CS) – soil group F4			
Design bearing capacity of foundation soil R_d (kPa)	492.82	492.86	405.92
Extreme contact stress σ (kPa)	34.40	91.10	96.11
Horizontal bearing capacity R_{dh} (kN)	3252.63	7271.95	7207.52
Extreme horizontal force H (kN)	0.0	0.0	1327.0

Tab. 3: Results of the serviceability limit state (SLS).

The serviceability limit state	Load condition		
	1.	2.	3.
Subsoil formed of clayey gravel (GC) – soil group G5			
Foundation settlement (mm)	2.2	10.7	10.7
Depth of influence zone (m)	7.22	13.16	13.16
Max. rotation of foundation (-)	0.0	0.0	0.097
Max. compress. foundation edge settlement (mm)	0.8	5.3	6.1
Min. compress. foundation edge settlement (mm)	0.8	5.3	4.6
Subsoil formed of clayey sand (SC) – soil group S5			
Foundation settlement (mm)	12.0	57.5	57.5
Depth of influence zone (m)	7.53	13.48	13.48
Max. rotation of foundation (-)	0.0	0.0	0.486
Max. compress. foundation edge settlement (mm)	4.5	29.3	32.5
Min. compress. foundation edge settlement (mm)	4.5	29.3	25.2
Subsoil formed of gravelly clay (CG) – soil group F2			
Foundation settlement (mm)	8.2	40.8	40.8
Depth of influence zone (m)	7.22	13.16	13.16
Max. rotation of foundation (-)	0.0	0.0	0.372
Max. compress. foundation edge settlement (mm)	3.0	20.4	23.3
Min. compress. foundation edge settlement (mm)	3.0	20.4	17.8
Subsoil formed of sandy clay (CS) – soil group F4			
Foundation settlement (mm)	19.2	92.0	92.0
Depth of influence zone (m)	7.53	13.48	13.48
Max. rotation of foundation (-)	0.0	0.0	0.778
Max. compress. foundation edge settlement (mm)	7.2	46.8	52.0
Min. compress. foundation edge settlement (mm)	7.2	46.8	40.3

The stress in the foundation bottom was calculated as first and then was determined the overall settlement and rotation of foundation for computing the settlement below the foundation bottom [1], [5], [9] and [17]. The subsoil was subdividing into layers of a different appropriate thickness. The vertical deformation of each layer was then computed - the overall settlement is defined as a sum of partial settlements of individual layers within the influence zone (deformations below the influence zone are either zero or neglected). The equation to compute compression of i^{th} soil layer below foundation having thickness h is from the definition of oedometric modulus E_{oed}. The results of the ultimate limit state (ULS) are presented in Tab. 2, and the results of the serviceability limit state (SLS) in Tab. 3.

4. Conclusion

The shallow founded cylindrical fluid filled container was analysed by considering of the earthquake Loma Prieta, California (18.10.1989) as ground motion in horizontal direction. The Fluid-Structure-Soil interaction of shallow founded tank was analysed according to theories of I. Limit States - the ultimate limit state (ULS) and II. Limit States - the serviceability limit state (SLS) under EN 1997-1 [19]. It was computed vertical and horizontal bearing capacity, settlement and rotation of a foundation. We can summarize results of the seismic analysis of FSSI problem of fluid filled tank:

- it is seen from comparison of the results for Ultimate Limit State (ULS) that the biggest value of bearing capacity of foundation soil has soil group G5 and the lowest value of bearing capacity of foundation soil have soil group F4 (Tab.2),
- by comparing of the results for Serviceability Limit State (SLS), the greater settlement is for soil group F4 and the lowest settlement is for soil group G5 (Tab.3),
- the settlement of the circular slab calculated for 2. load condition is 4 - 5 times higher than for 1. load condition for all types of soils,
- if 2. and 3. load condition is compared, it can be seen than the torque effect of seismic loading may cause to "lifting" of the tank edge,
- the maximum rotation of foundation is growing with the reduction of the stiffness of the subsoil,
- the resulting vertical and horizontal bearing capacity (Tab.2) depends on the strength properties (φ_{ef}, c_{ef}) of the subsoil.

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References

[1] GHANBARI, A. and P. ABBASI MAEDEH. Dynamic behaviour of shallow founded tanks considering fluid-soil-structure interaction (Case study: southern parts of Tehran). *Pollution*, vol. 1, pp. 103-116.

[2] KOTRASOVA, K. and I. GRAJCIAR. Dynamic analysis of liquid storage cylindrical tanks due to earthquake. *Advanced Materials Research*. 2014, vol. 969, pp. 119-124. ISSN 1022-6680.

[3] JENDZELOVSKY, N. and L. BALAZ. Modeling of a gravel base under the cylindrical tank. *Advanced Material Research. 2014,* vol. 969, pp. 249-252. ISSN 1022-6680.

[4] MOCILAN, M., M. ZMINDAK and P. PASTOREK. Dynamic analysis of fuel tank. *Procedia Engineering*. 2016, vol. 136, pp. 45-49. ISSN 1877-7058.

[5] KRALIK, J. and J. KRALIK, JR. Probability assessment of analysis of high-rise buildings seismic resistance. *Advanced Materials Research*. 2013, vol. 712-715, pp. 929-936.

[6] KUKLIK, P. Preconsolidation, Structural Strength of soil, and its effect on subsoil upper structure interaction. *Engineering Structures*. 2011, no. 33, pp. 1195-1204. ISSN 0141-0296.

[7] TVRDÁ, K. Optimization and safety desing of the foundation plate. In: *Modelování v mechanice 2015. Proceedings of scientific conference*. Ostrava, 2015, pp. 1-10. ISBN 978-80-248-3756-7.

[8] KREJSA, M., P. JANAS and V. KREJSA. Software application of the DOProC method. *International Journal of Mathematics and Computers in Simulation.* 2014, vol. 8, no. 1, pp. 121-126. ISSN 1998-0159.

[9] LAJCAKOVA, G. and J. MELCER. Dynamic Effect of Moving Vehicles on the Road Concrete Slabs. *Comunications.* 2011, vol. 13, iss. 3, pp. 14-18 ISSN: 1335-4205.

[10] MICHALCOVA, V. and L. LAUSOVA. Numerical approach to determination of equivalent aerodynamic roughness of Industrial chimneys. *Computers and Structures*. 2018, vol. 207, pp. 187-193. ISSN 0045-7949. DOI: 10.1016/j.compstruc.2017.03.013.

[11] MAJOR, M. and I. MAJOR. Modelling of wave phenomena in the Zahorski material based on modified library for ADINA software. *Applied Mathematical Modelling*. 2017, no. 46, pp. 727-735 ISSN: 0307-904X.

[12] SUCHARDA, O. and J. BROZOVSKY. Bearing capacity analysis of reinforced concrete beams. *International Journal of Mechanics*. 2013, vol. 7, iss. 3, pp. 192-200.

[13] BAUMANN, T. and J. BÖHLER. Seismic Design of Base-Isolated LNG-Storage-Tanks. *Structural Engineering International*. 2011, vol. 11, no. 2, pp 139-144.

[14] KOTRASOVA, K., I. GRAJCIAR and E. KORMANIKOVA. A Case Study on the Seismic Behaviour of Tanks Considering Soil-Structure-Fluid Interaction. *Journal of Vibration Engineering and Technologies*. 2015, vol. 3, no. 3, pp. 315-330. ISSN 2321-3558.

[15] LIVAOGLU, R. and A. DOGANGUN. Simplified seismic analysis procedures for elevated tanks considering fluid-structure-soil interaction. *Journal of Fluid and Structures.* 2006, pp.421-439.

[16] VANDEN BERGHE, G. and M. VAN DAELE. Exponentially-fitted Störmer/Verlet methods, *Journal of Numerical Analysis, Industrial and Applied Mathematics (JNAIAM)*. 2006, vol. 1, no.3, pp. 241-255.

[17] MALHOTRA, P.K., T. WENK and M. WIELAND. Simple procedure for seismic analysis of liquid-storage tanks, *Structural Engineering International*. 2000, no. 3, pp. 197-201.

[18] EN 1998-4. Design of structures for earthquake resistance - Part 4: Silos, tanks and pipelines. European Committee for Standardization, Brussels ref. number EN 1998-4:2006 E.

[19] EN 1997-1. Geotechnical design - Part 1: General rules. European Committee for Standardization, Brussels ref. number EN 1997-1:2004 E.

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