

Analytical assessment of elevated tank natural period considering soil effects

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Abstract. The main purpose of current study is to find the soil effects on natural period of elevated tank. The coupled analytical method is used to assess in this study. The current study presented models which are capable to consider the soil dynamic stiffness changes and fluid- structure interaction effects on natural period of elevated tanks. The basic of mentioned models is extracted from elastic beam and lumped mass theory. The finite element is used to verify the results. It is observed that, external excitation can change the natural period of elevated tanks. Considering the increase of excitation frequency, the natural period will be decreased. The concluded values of natural period in case of soft and very soft soil are more affected from excitation frequency values. The high range of excitation frequency may reduce the natural period values. In addition it is observed that the excitation frequency has no significant effect on convective period compare with impulsive period.

Keywords: ground excitation; analytical model; natural period; elevated tank; impulsive; convective

1. Introduction

The elevated tanks are the most important and necessary structures which used in water distribution, Water storage system, oil storage system and firefighting (ACI 350 2006, ACI-317 2008, Dutta 1995, 2004). They are also working as a life line structures. They should be stable during and after the earthquake and natural disasters (Livaoglu and Dogangum 2006, Ghanbari and Maedeh 2015). To design these sensitive structures, the role of natural period is one of more necessary parameters to consider the dynamic behavior of elevated tanks (Housner 1963, Haroun and Temraz 1992, Livaoglu and Dogangum 2006, Livaoglu and Dogangum 2007). One of the major topics in natural period determination is to consider the effects of soil and fluid on the body of structure (Livaoglu and Dogangum 2006).

The method which consider both fluid and soil effects on natural period is called as fluid-structure- soil interaction (Livaoglu and Dogangum 2006, Ghanbari and Maedeh 2015). Most of

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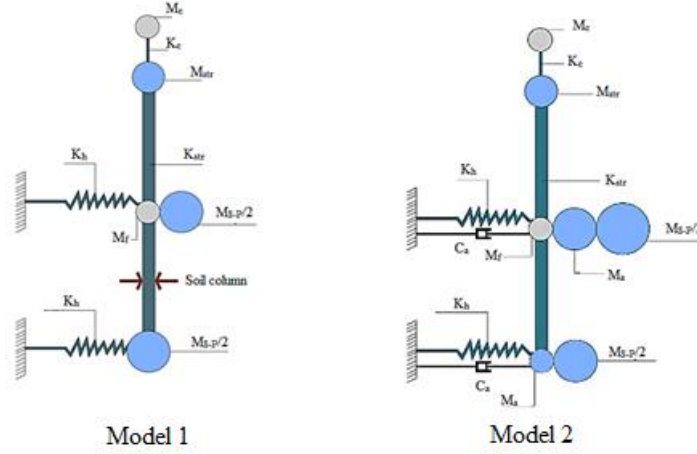


Fig. 1 Schematics of current study analytical models

disc) is given by the following Eq. (1) (Pacheco 2008, Shirgir *et al.* 2015)

$$K_h = G\pi f(a_0, \nu, D) = G\pi \{ \text{Real}[f(a_0, \nu, D)] + i \text{Imag}[f(a_0, \nu, D)] \} \quad (1)$$

Where G is the shear modulus of soil and the $f(a_0, \nu, D)$ is a dynamic variable which calculated by using the Bessel function (Novak and Abloul-Ella 1978, Novak *et al.* 1978, Pacheco 2008). a_0 is a dimensionless frequency $= \omega r_o / V_s$, ω is the vibration frequency in rad/sec, r_o is the pile (foundation) radius, V_s is the shear wave velocity of the soil; ν is the Poisson's ratio of the soil and also D is the damping ratio of the soil. Basic information of this method is reported in pervious and original literature (Novak *et al.* 1978, Novak 1974).

The coefficients α_k , α_m , and α_c were determined by pervious researcher (Novak and Abloul-Ella 1978, Novak *et al.* 1978, Pacheco 2007, 2008). In this study the natural period considering dynamic excitation will be evaluated with and without considering the dynamic damping (Pacheco 2008, Shirgir 2015). The schematic picture of presented analytical models is shown in Fig. 1. Regarding the schematic the superstructure part assumption is constant in both recommended models. The analytical soil modeling of model 1 just considers the real part of Eq. (1) and it is neglected from dynamic damping. Model 2 will consider both the real and imaginary parts of the Eq. (1).

The assembled developed stiffness and mass matrix for an elevated tank system considering mentioned models show as following respectively

$$[K] = \begin{bmatrix} K_c & -K_c & 0 & 0 & 0 & 0 \\ -K_c & K_c + K_{str} & -K_{str} & 0 & 0 & 0 \\ 0 & -K_{str} & K_{str} + K_h + \frac{12EI}{L^3} & \frac{6EI}{L^2} & -\frac{12EI}{L^3} & \frac{6EI}{L^2} \\ 0 & 0 & \frac{6EI}{L^2} & \frac{4EI}{L} & -\frac{6EI}{L^2} & \frac{2EI}{L} \\ 0 & 0 & -\frac{12EI}{L^3} & \frac{6EI}{L^2} & \frac{12EI}{L^3} + K_h & -\frac{6EI}{L^2} \\ 0 & 0 & \frac{6EI}{L^2} & \frac{2EI}{L} & -\frac{6EI}{L^2} & \frac{4EI}{L} \end{bmatrix}$$

Table 1 Soil classification and general properties

Soil category	ν	$\gamma(\text{kN/m}^3)$	$G(\text{kN/m}^2)$	$V_s(\text{m/s})$
Very hard	0.2	19	2041667	1026.71
Hard	0.3	18	293461.5	399.92
Soft	0.35	17	35666.67	143.46
Very soft	0.4	13	11428.57	92.86

Different categories of current study soil properties show in Table 1.

4. Results and discussion

Considering the current study assumptions analytical and numerical models are made. The finite element model by using the direct method technique is made in general software ANSYS 15 (ANSYS 2015). The direct method estimation allows the performer to analyze the considered soil foundation- structure system as a complete system in a single step, in which the free field input motions are specified along the base and sides of the model (Livaoglu and Dogangun 2007, Torabi and Reyhani 2014). This method have been particularly employed for solution of the tank- soil system in this study, because it is the robust method that remains valid for all kinds of problems involving material linearity, contact problems, different loading cases and complex geometries (Preisig and Jeremic 2005, Li *et al.* 2014). The convective and impulsive mode in numerical model are shown in Fig. 3.

It is observe that there is no shaft deformation in case of convective mode and only the liquid has deformation. Both liquid and shaft will be deformed in impulsive mode. The shape of liquid deformation in impulsive mode is different compare with convective mode. Also, the maximum liquid wave height of impulsive mode is lower than convective mode.

To find the natural convective and impulsive period the Block Lanczos method (ANSYS 2015) was chosen. The pervious researcher recommended to find the convective period of liquid maximum mass participation of liquid should be considered (Moslemi *et al.* 2011). Results of numerical direct method considering different condition of soil cases are reported in Fig. 4.

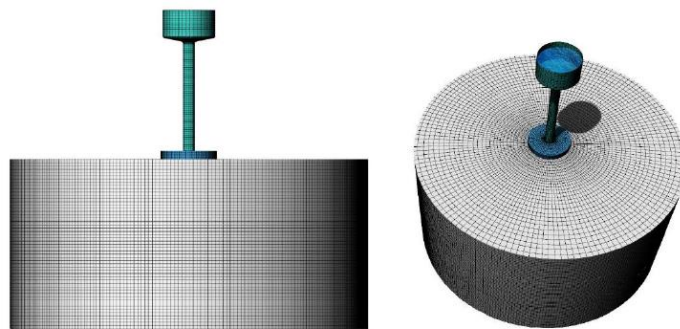


Fig. 3 The numerical model of elevated tank by using the 3D direct method

Table 2 Results of impulsive period concluded from model 1 and finite element

Soil	Model 1 (sec)	FEM (sec)	Error %
Very hard	0.55	0.51	7.84
Hard	1.088	1.02	6.67
Soft	3.01	2.94	2.38
Very soft	5.2	5.25	-0.95

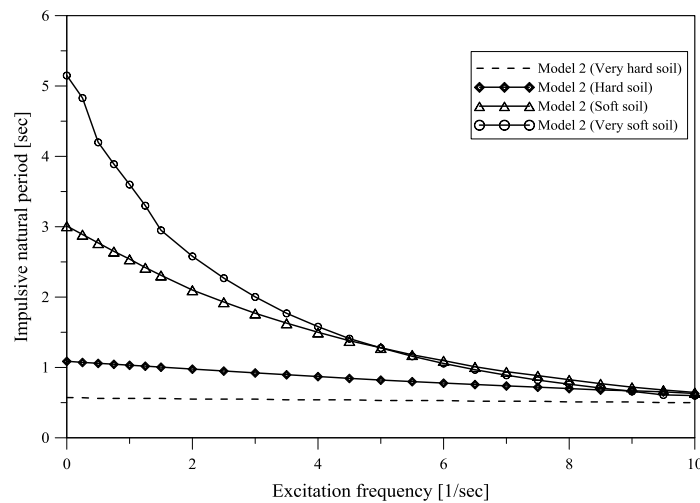


Fig. 6 Results of impulsive period by using model 2 considering different soil category and excitation frequency

The analytical model results are given by substituting the assembled mass and stiffness matrix in eigenvalue equation (Chopra 2000). To consider the ground mass participation, regarding empirical experiences (Pacheco 2008, Shirgir *et al.* 2015) the suggested soil pile length for the case of hard and very hard soils is recommended 30 meters. The recommended value in case of soft and very soft soil is changed to 25 meters. It is observe that the mass participation for hard and very hard soil is higher that soft and very soft soil.

The excitation frequency domain is chosen from 0 to 10 (1/sec). The normal range of construction natural frequency is from 0.1 to 3 (1/sec) (Kramer 1996), but the frequency content of excitation is included more different frequency values. The bed rock material properties, depth of failure occurrence and many other reasons (Kramer 1996) can take effects on earthquake frequency content. Regarding to frequency excitation changes, the value of a_0 will be changed (Pacheco 2008, Shirgir *et al.* 2015). In this reason the values of mass and stiffness matrix would change considering different frequency of excitation (Pacheco 2008, Shirgir *et al.* 2015).

Results of impulsive period extracted from model 1 considering different case of soil properties and excitation frequency values are plotted in Fig. 5. It is observed that by increasing the excitation frequency the impulsive natural period of elevated tank will be decreased. Results show that the dependency of natural period to excitation frequency in case of hard and very hard is not significant compare with the results of soft and very soft soil cases.

The low range of excitation frequency (Less than four 1/sec) is more effective on impulsive

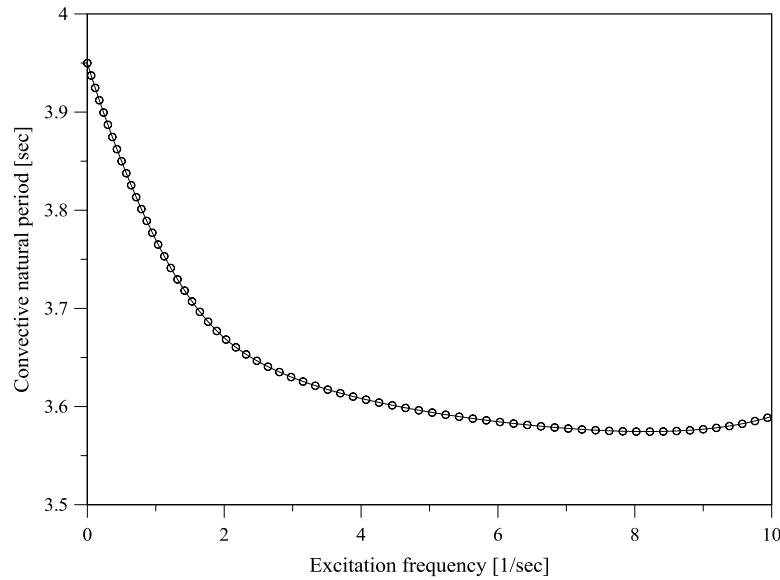


Fig. 8 Results of convective period with an emphasis on very soft soil case

The compared results of model 2 and FEM are reported in Table 3. It is observed that the model 2 have less error compare to results of model 1. Considering the dynamic damping in this model is the cause of fewer error compare with results of model 1.

The compared results of model 1 and model 2 are shown in Fig. 7. It is observed that generally model 2 has a lower estimation of natural impulsive period in case of very soft soil. Additional results show that there are negligible differences according to results of model 1 and model 2 in case of soft to very hard soil. According to extracted results of impulsive natural period in case of soft and very soft soils, it is observed that, the results values are located on the region of displacement sensitive in response spectrum. The displacement controlling in this area will be necessary for superstructure designing. Also in case of hard and very hard soils the natural impulsive period values are located in acceleration sensitive part of response spectrum. It is observed that the statically condition of soil have a higher estimation of natural impulsive period compare with the high frequency excitation condition. It means the high frequency excitation is capable to change the dynamic soil stiffness and decrease the impulsive natural period.

The natural convective period results show that the excitation frequency effects in convective period is not significant. Maximum variation of convective period in different case of soil and excitation frequency reported less than 6 percent. The value of convective period changes in case of very soft soil are shown in Fig. 8.

Complimentary evaluation on the concluded results show that, the dependency of impulsive period to soil category, ground mass participation and excitation frequency will be more important than convective period. Also results show that regarding to decrease the natural period considering excitation frequency the base shear and over turning moment can be increase. Also results of natural impulsive period show that, its value is place on acceleration sensitive part in response spectrum in case of hard and very hard soil but also the values will be moved to displacement sensitive part in case of soft and very soft soils. The high frequency excitation will be changed the sensitive part of impulsive period in case of soft and very soft soil. Generally the convective period

- Eurocode 8 (2006), *Design of Structures for Earthquake Resistance-Part 4: Silos, Tanks and Pipeline*, Brussels, Belgium.
- Gazetas, G. (1991), "Formulas and charts for impedances of surface and embedded foundations", *J. Geotech. Eng.*, **117**(9), 1363-1381.
- Gazetas, G. and Stokoe, K.H. (1991), "Free vibration of embedded foundations: Theory versus experiment", *J. Geotech. Eng.*, **117**(9), 1382-1401.
- Ghaemmaghami, A.R., Moslemi, M. and Kianoush, M.R. (2010), "Dynamic behavior of concrete liquid tanks under horizontal and vertical ground motions using finite element method", *Proceedings of the 9th US National and 10th Canadian Conference on Earthquake Engineering*, Toronto, Canada, July.
- Ghaemmaghami, A., Kianoush, R. and Yuan, X.X. (2013), "Numerical modeling of dynamic behavior of annular tuned liquid dampers for applications in wind towers", *Comput.-Aided Civil Infrastruct. Eng.*, **28**(1), 38-51.
- Ghanbari, A. and Maedeh, A.P. (2015), "Dynamic behavior of ground-supported tanks considering fluid-soil-structure interaction (case study: southern parts of Tehran)", *Pollution*, **1**(1), 103-116.
- Goudarzi, M.A. and Sabbagh-Yazdi, S.R. (2009), "Numerical investigation on accuracy of mass spring models for cylindrical tanks under seismic excitation", *J. Civil Eng.*, **7**(3), 190-202.
- Goudarzi, M.A. and Sabbagh-Yazdi, S.R. (2008), "Evaluating 3D earthquake effects on sloshing wave height of liquid storage tanks using finite element method", *J. Seismol. Earthq. Eng.*, **10**(3), 123.
- Hacıfendioğlu, K. (2012), "Stochastic seismic response analysis of offshore wind turbine including fluid-structure-soil interaction", *Struct. Des. Tall Spec. Build.*, **21**(12), 867-878.
- Haroun, M.A. and Ellaithy, H.M. (1985), "Seismically induced fluid forces on elevated tanks", *J. Technol. Topic Civil Eng.*, **111**(1), 1-15.
- Haroun, M.A. and Temraz, M.K. (1992), "Effects of soil-structure interaction on seismic response of elevated tanks", *Soil Dyn. Earthq. Eng.*, **11**(2), 73-86.
- Housner, G.W. (1963), "The dynamic behavior of water tanks", *Bull. Seismol. Soc. Am.*, **53**(2), 381-387.
- Jahankhah, H., Ghannad, M.A. and Rahmani, M.T. (2013), "Alternative solution for kinematic interaction problem of soil-structure systems with embedded foundation", *Struct. Des. Tall Spec. Build.*, **22**(3), 251-266.
- Kramer, S.L. (1996), *Geotechnical Earthquake Engineering*, Prentice-Hall, New Jersey, U.S.A.
- Li, M., Lu, X., Lu, X. and Ye, L. (2014), "Influence of soil-structure interaction on seismic collapse resistance of super-tall buildings", *J. Rock Mech. Geotech. Eng.*, **6**(5), 477-485.
- Livaoglu, R. (2013), "Soil interaction effects on sloshing response of the elevated tanks", *Geomech. Eng.*, **5**(4), 283-297.
- Livaoglu, R., Cakir, T., Dogangun, A. and Aytakin, M. (2011), "Effects of backfill on seismic behavior of rectangular tanks", *Ocean Eng.*, **38**(10), 1161-1173.
- Livaoglu, R. and Dogangun, A. (2006), "Simplified seismic analysis procedures for elevated tanks considering fluid-structure-soil interaction", *J. Fluid. Struct.*, **22**(3), 421-439.
- Livaoglu, R. and Dogangun, A. (2007), "Effect of foundation embedment on seismic behavior of elevated tanks considering fluid-structure-soil interaction", *Soil Dyn. Earthq. Eng.*, **27**(9), 855-863.
- Lysmer, J. (1979), "Finite element analysis of soil-structure interaction", Appendix to "Analysis for soil-structure interaction effects for nuclear power plants", Report by the Ad Hoc Group on Soil-Structure Interaction, Nuclear Structures and Materials Committee of the Structural Division of ASCE.
- Marashi, E.S. and Shakib, H. (2008), "Evaluations of dynamic characteristics of elevated water tanks by ambient vibration tests", *Proceedings of the 4th International Conference on Civil Engineering*, Tehran, Iran.
- Moeindarbari, H., Malekzadeh, M. and Taghikhany, T. (2014), "Probabilistic analysis of seismically isolated elevated liquid storage tank using multi-phase friction bearing", *Earthq. Struct.*, **6**(1), 111-125.
- Moslemi, M., Kianoush, M.R. and Pogorzelski, W. (2011), "Seismic response of liquid-filled elevated tanks", *Eng. Struct.*, **33**(6), 2074-2084.
- Novak, M. (1974), "Dynamic stiffness and damping of piles", *Can. Geotech. J.*, **11**(4), 574-598.
- Novak, M. and Aboul-Ella, F. (1978), "Impedance functions of piles in layered media", *J. Eng. Mech. Div.*,

- 104**(3), 643-661.
- Novak, M., Aboul-Ella, F. and Nogami, T. (1978), "Dynamic soil reactions for plane strain case", *J. Eng. Mech. Div.*, **104**(4), 953-959.
- Pacheco-Crosetti, G.E. (2007), "Dynamic lateral response of single piles considering soil inertia contribution", Ph.D. Dissertation, University of Puerto Rico, Puerto Rico.
- Pacheco, G., Suarez, L. and Pando, M. (2008), "Dynamic lateral response of single pile considering soil inertia contributions", *Proceedings of the 14th World Conference on Earthquake Engineering*, Beijing, China, October.
- Preisig, M. and Jeremic, B. (2005), "Nonlinear finite element analysis of dynamic soil-foundation-structure interaction", Ph.D. Dissertation, University of California, U.S.A.
- Resheidat, R.M. and Sunna, H. (1990), "Behavior of elevated storage tanks during earthquakes", *Proceedings of the 3rd World Conference on Earthquake Engineering*, Moscow, Russia.
- Shirgir, V., Ghanbari, A. and Shahrouzi, M. (2015), "Natural frequency of single pier bridges considering soil-structure interaction", *J. Earthq. Eng.*, **20**(4), 611-632.
- Sorace, S., Terenzi, G. and Mori, C. (2015), "Analysis of an elevated water storage tank with R/C frame staging structure", *Proceedings of the 14th World Conference on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures*, California, U.S.A., December.
- Torabi, H. and Rayhani, M.T. (2014). "Three-dimensional finite element modeling of seismic soil-structure interaction in soft soil", *Comput. Geotech.*, **60**, 9-19.
- Westergaard, H.M. (1933), "Water pressures on dams during earthquakes", *Trans. Am. Soc. Civil Eng.*, **98**, 418-433.
- Wolf, J.P. (1985), *Dynamic Soil-Structure Interaction*, Prentice-Hall, New Jersey, U.S.A.