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Estimation of elevated tanks natural period considering fluid- structure- soil interaction by using new approaches

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Abstract. The analytical method is used to develop new models for an elevated tank to estimate its natural period. The equivalent mass- spring method is used to configure the developed analytical models. Also direct method is used for numerical verification. The current study shows that developed models can have a good estimation of natural period compared with concluded results of finite elements. Additional results show that, the dependency of impulsive period to soil stiffness condition is higher than convective period. Furthermore results show that considering the fluid- structure- soil interaction has remarkable effects on natural impulsive and convective periods in case of hard to very soft soil.

Keywords: elevated tanks; fluid- structure- soil interaction; analytical method; impulsive; convective

1. Introduction

The methods which can estimate the natural period of structures are classified in two groups: numerical and analytical (Ghanbari and Abbasi Maedeh 2015). Basically the analytical methods are used for solving the regular problems in structural and mechanical engineering (Shirgir *et al*. 2015). To simplify the analytical problems, a mass-spring method is used in vibration and mechanical engineering problems (Dutta *et al*. 2004, Ibrahim 2005, Livaoghlou and dogangun 2007). The most famous subcategory of mass- spring method is called “added mass” theory (Livaoghlou and dogangun 2007, Rai 2002). In this method, the geometry of the structure will be neglected and systems will be only composed of masses, springs and dampers (Livaoghlou and dogangun 2007, Ghanbari and Abbasi maedeh 2015, Shirgir *et al*. 2015).

The structure of elevated tank works as a mechanical system which is capable to be a model by using the mass-spring method (Livaoglu and Dogangun 2006). In addition its inside liquid will be assumed as a mechanical behavior system. The most famous and practical analytical method to find fluid- structure interaction effects was created by Westergard (1933). The mentioned model was modified and developed by Housner (1963) and Haroun and Ellaithy (1985). The most reliable international codes which consider the vessel designing such as Eurocode-8 (2006) and ACI 350 (2006) applied the Housner (1963) theory.

Regarding mechanical behavior of elevated tanks, the natural period of elevated tanks will be more significant for designing this complex system (Housner 1963, Ibrahim 2005, Livaoghlou and dogangun 2006, 2007). The remarkable problem of elevated tanks design is the soil effect on their dynamic behavior (Livaoglu and Dogangun 2006, Ghanbari and Abbasi 2015). Considering the recommended relations in international codes to estimate the natural period of elevated tanks, it is observed that a few international codes have directly paid attention to effects of soil- structure interaction (SSI) on the natural period of these specific structures.

The equivalent mass spring method is used to determine the effect of soil on superstructures dynamic behavior. It is a well-known method of analytical soil modeling (Wolf 1985, Kramer 1996). The soil stiffness matrix of the surrounding soil is represented as a 2×2 matrix (Lysmer 1979, Wolf 1985, Kramer 1996, Jahankhah *et al*. 2013). The formulas which are applicable to estimate the soil stiffness for a circular rigid foundations supported at the surface of a homogeneous half space are reported in literature and international codes (Lysmer 1979, Pais and Kausel 1985, 1988, FEMA 450 2003, Jahankhah *et al*. 2013).

Most analytical models which used for soil modeling have neglected the ground mass participation effects on dynamic behavior of elevated tanks and sloshing (Livaoglu and Dogangun 2006, Shirgir *et al*. 2015). Most advanced studies in soil structure interaction, such those on soil-pile interaction and soil dynamic stiffness, indicate that considering the soil mass and frequency dependence of soil stiffness are significant in dynamic response of structures (Novak and Abloul-Ella 1978, Novak *et al*. 1978, Shirgir *et al*. 2015). The ground mass participation is more effective in case of soft soils with high range of Poisson’s ratio soils (Pacheco 2008). It is recommended to consider the ground mass in dynamic behavior evaluation (Novak and Abloul-Ella 1978, Novak *et al*. 1978, Pacheco 2007, Pacheco 2008, Shirgir *et al*. 2015).

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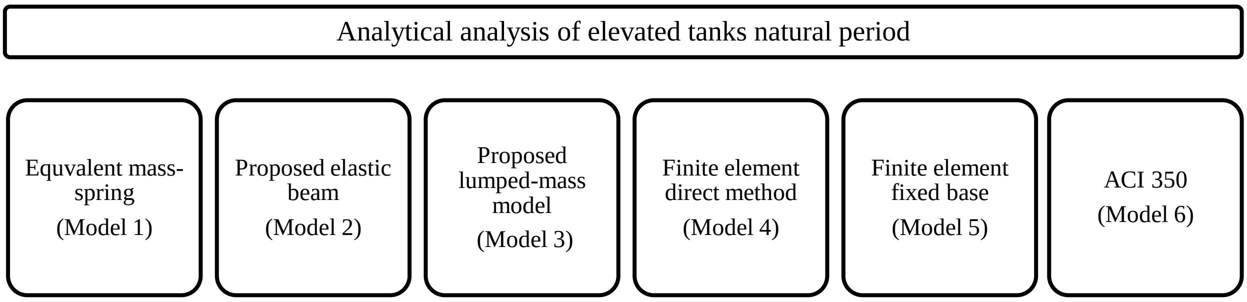

Fig. 1 Evaluated models of elevated tanks considering fluid- structure- soil inter action and ground mass participation

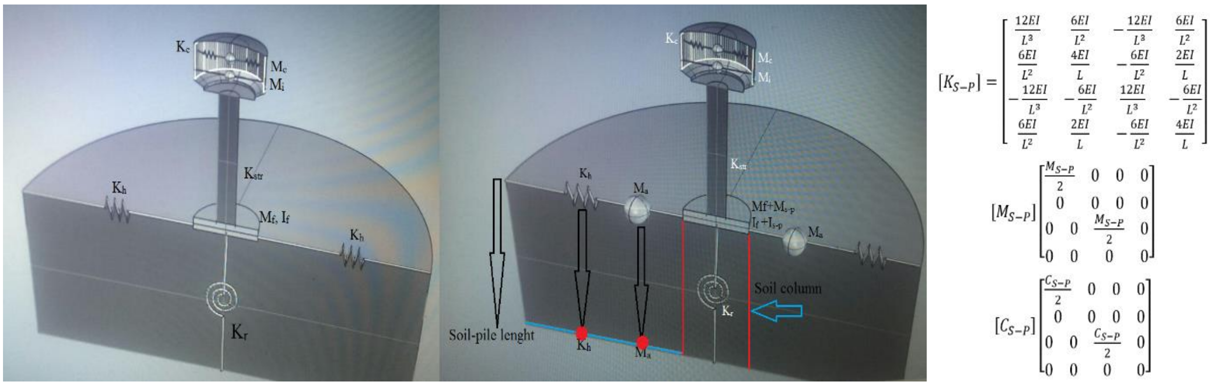

Fig. 2 Schematics of analytical models; Left: Equivalent mass spring model; Right: Proposed models 2 and 3 considering ground mass participation and its matrixes

Various research methods have been applied to study the elevated tanks in recent decades considering fluid- structure interaction (FSI) and fluid- structure- soil interaction (FSSI). Haroun and Temraz (1985), Resheidat and Sunna (1990), Haroun and Temraz (1992), Dutta *et al*. (2004), Livaoglu and Dogangun (2006), Livaoglu and Dogangun (2007), Goudarzi and Sabbagh Yazdi (2008), Marashi and Shakib (2008), Ghahramani *et al*. (2010), Livaoglu *et al*. (2011), Ghanbari and Abbasi Maedeh (2015) and Sorace *et al*. (2015) have assessed dynamic behavior of elevated tanks.

Mentioned studies reported that the most accurate factor to design elevated tanks considering dynamic behavior will be natural period. In current study new analytical models to estimate natural period of elevated tanks considering both fluid- structure-soil interaction and the ground mass participation effects will be developed. The basic of elastic beam theory and added mass are used in developing analytical models. To verify the proposed models results, they are compared with the concluded results of finite elements and the authentic international code ACI-350.

2. Principal equations and assumptions

To find the natural periods of a multi degree of freedom (MDOF) system, the following equation was defined (Chopra 2000)

$$\big[[K] - \omega^2 [M]\big] = \{0\} \tag{1}$$

Where $[K], [M]$ denotes the stiffness, and mass matrices, respectively, which are constant for a linear system.

Considering the literature (Chopra 2000) the system damping coefficients are neglected. The *n* DOF general system eigenvalue equation with an emphasis on soil and superstructure effects matrix can be substituted into Eq. (1) as following (Wolf 1988, Jahankhah *et al.* 2013)

$$\begin{bmatrix} [K_s] & [K_{sf}] \\ [K_{fs}] & [K_{soil}] \end{bmatrix} - \{\omega^2\} \begin{bmatrix} [M_s] & [M_{sf}] \\ [M_{fs}] & [M_{soil}] \end{bmatrix} = 0 \tag{2}$$

Six different models are evaluated in current study (Fig. 1). Model 1 is developed regarding equivalent mass- spring and the recommended Housner (1963) FSI relation. Models 2 and 3 are developed to consider the ground mass participation effects on natural period in both convective and impulsive parts. To verify the results of mentioned models, two different conditions of finite elements model are used. Model 4 by considering the fixed base condition and model 5 with a special emphasis on flexible base are evaluated. Model 6 is extracted from international code ACI-350.

The Schematics of equivalent mass- spring analytical models which presented in this study are shown in Fig. 2.

Where the values of M_c is convective mass of liquid, M_{str} is impulsive mass of liquid plus mass of vessel and 66 percent of shaft mass, K_{str} represent the lateral stiffness of the structure, Kc is the liquid dynamic stiffness and M_f is the mass of foundation. The values of $M_{S\text{-}P}$, C_a, K_h and M_a will be explained in next models introduction. Extra information for mentioned parameters are discussed in literature (Housner 1963, ACI-350 2006, Ghanbari and Abbasi 2015). Regarding the equivalent mass spring, the developed mass and stiffness matrixes of model (1) were inserted into Eq. (1) as follows

$$\begin{bmatrix} K_c & -K_c & 0 & 0 \\ -K_c & K_c + K_{str} & -K_{str} & 0 \\ 0 & -K_{str} & K_{str} + K_x & K_{x\theta} \\ 0 & 0 & K_{x\theta} & K_\theta \end{bmatrix} - \{\omega^2\} \begin{bmatrix} m_c & 0 & 0 & mc(e + hc + hstr) \\ 0 & m_{str} & 0 & mstr(e + hi + hstr) \\ 0 & 0 & m_f & m_f(\frac{e}{2}) \\ m_c(e + h_c + h_{str}) & m_{str}(e + h_i + h_{str}) & m_f(\frac{e}{2}) & I_f + m_f\left(\frac{e}{2}\right) + m_{str}(e + h_i + h_{str})^2 + m_c(e + h_c + h_{str})^2 \end{bmatrix} = 0 \quad (3)$$

Where e is depth of foundation, h_i is impulsive height, h_{str} is height of shaft, h_c is convective height and K_x, K_Θ and $K_{x\Theta}$ are the sway, rocking and sway-rocking coupling terms of the corresponding static stiffness matrix, respectively.

Model 2 is extracted from the theory of elastic beams (Novak 1974). In this model, it is assumed that the area below foundation and the foundation layer of soil behave as a continuous pile (Fig. 2). It is also assumed that the soil is composed of a set of independent, infinitely thin horizontal layers in the plane strain state that extend laterally to infinity and experience small displacements. The soil layers are considered homogeneous, isotropic, and linear-elastic. The soil-pile is assumed to be vertical and cylindrical and to move as a rigid body (a hypothesis that is consistent with the Naiver- Bernoulli beam theory) (Novak and Abloul-Ella 1978, Novak *et al.* 1978). No separation is allowed between the rigid cylinder and the soil medium. More information about theory of elastic beams and its basics has been discussed in literature (Novak *et al.* 1978, Novak 1974, Pacheco 2007, Pacheco 2008). The main relation to calculate the horizontal soil stiffness in this model is defined as following Eq. (4)

$$\mathrm{K}_h = \mathrm{G}\pi\mathrm{f}(\mathrm{a}_{0,}\nu, \mathrm{D}) \quad (4)$$

Where the $f(a_{0,}\nu, D)$ is the dynamic factor of soil stiffness is a modified Bessel function of the second kind of order n, a_o is a dimensionless frequency = $\omega r_o/V_S$, ω is the vibration frequency in rad/sec, r_o is the pile and foundation radius, V_s is the shear wave velocity of the soil; and ν is the Poisson's ratio of the soil. Basic information of this method is reported in pervious and original literature (Novak *et al.* 1978, Novak 1974).

The basic of model 3 is extracted from lumped mass theory. This theory is a modified version of elastic beam theory (Pacheco 2007, Pacheco 2008). By grouping the real and imaginary parts, the Novak's soil dynamic stiffness k_h becomes

$$\mathrm{K}_h = \mathrm{G}\pi\mathrm{f}(\mathrm{a}_{0,}\nu, \mathrm{D}) = \mathrm{G}\pi\{\mathrm{Real}[\mathrm{f}(\mathrm{a}_{0,}\nu, \mathrm{D})] + \mathrm{i}\ \ \mathrm{Imag}[\mathrm{f}(\mathrm{a}_{0,}\nu, \mathrm{D})]\} \quad (5)$$

In Model 3, k_h is approximated as a quadratic polynomial in a_o. In this way, k_h is equivalent to the dynamic stiffness of a SDOF system. This is done by introducing the following approximations into the real and imaginary parts of the complex function $f(a_{0,}\nu, D)$

$$K = k_h - m_a\omega^2 + ic_a\omega \quad (6)$$

$$k_h = G\pi a_k \quad (7)$$

$$m_a = \pi r^2 \rho a_m \quad (8)$$

$$c_a = \pi r_0 V_s \rho a_c \quad (9)$$

The coefficients α_k, α_m, and α_c were determined as dynamic coefficients literature (Novak *et al.* 1978, Novak 1974, Pacheco 2007, Pacheco 2008, Shirgir *et al.* 2015). The developed mass and stiffness matrixes for model 2 and 3 considering both FSSI and ground mass participation which substituted in Eq. (1) are shown as following Eq. (10)

$$\begin{bmatrix} K_c & -K_c & 0 & 0 & 0 & 0 \\ -K_c & K_c + K_{str} & -K_{str} & 0 & 0 & 0 \\ 0 & -K_{str} & K_{str} + K_h + \frac{12EI}{L^3} & \frac{6EI}{L^2} & -\frac{12EI}{L^3} & \frac{6EI}{L^2} \\ 0 & 0 & \frac{6EI}{L^2} & \frac{4EI}{L} & -\frac{6EI}{L^2} & \frac{2EI}{L} \\ 0 & 0 & -\frac{12EI}{L^3} & -\frac{6EI}{L^2} & \frac{12EI}{L^3} + K_h & -\frac{6EI}{L^2} \\ 0 & 0 & \frac{6EI}{L^2} & \frac{2EI}{L} & -\frac{6EI}{L^2} & \frac{4EI}{L} \end{bmatrix} - \{\omega^2\} \begin{bmatrix} m_c & 0 & 0 & 0 & 0 & 0 \\ 0 & m_{str} & 0 & 0 & 0 & 0 \\ 0 & 0 & m_a + m_f + \frac{m_{S-P}}{2} & 0 & 0 & 0 \\ 0 & 0 & 0 & I_f + m_{str}(h_i + h_{str})^2 + m_c(h_c + h_{str})^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & m_a + m_{S-P} & 0 \\ 0 & 0 & 0 & 0 & 0 & I_s \end{bmatrix} = 0 \quad (10)$$

The first estimate of soil pile length participation regard to pervious experiences will be near the height of superstructure. The numerical model to verify the results was created in an advance FEM software. The direct method was chosen in the numerical model to emphasize the effects of SSI (Preisig and Jeremic 2005, Hacıefendioğlu 2012, Yoo 2013, Li *et al.* 2014). Considering just natural time period analysis, the elastic model is chosen for the soil domain (Livaoglu and Dogangun 2007, Casciati and Borja 2004, Torabi and Reyhani 2014). Plain and fluid elements were used for the soil, structure and the liquid, respectively (Goudarzi and Sabbagh-Yazdi 2008, 2009, Moslemi *et al.* 2011). Similar studies approved that, this method of numerical modeling may have a good estimate of liquid and structure behavior (Goudarzi and Sabbagh-Yazdi 2008, 2009, Ghahramnai and Kianoush 2013). The basic concept of numerical direct method is shown in Fig. 5.

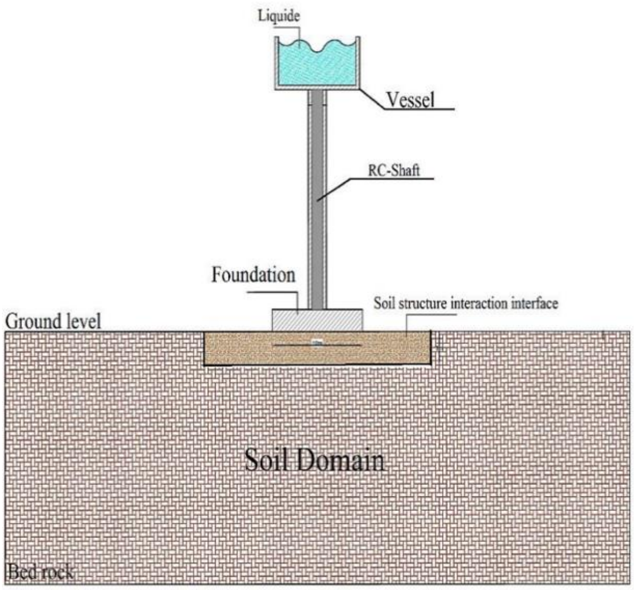

Fig. 3 The numerical direct method model for a Fluid-structure- soil interaction system of an elevated tank

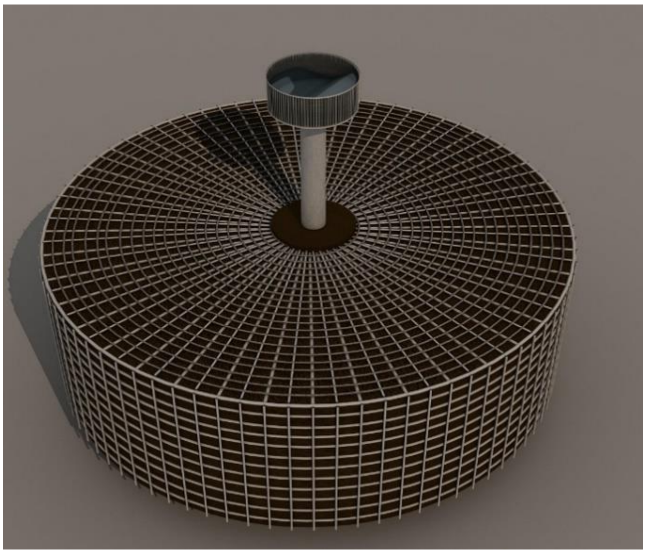

Fig. 3 Continued

3. Geometry of the case study

A reinforced concrete elevated tank with a capacity of 486 m^3 was considered in current study. The elevated tank has a structure supported with shafts with a total height of 20 meters from the surface. This form of container and support structure is typical for water supplies in developed and developing countries (Livaoghlou 2006). The container was assumed to a depth of 4 meters as the final safe capacity with a density of 1000 kg/m^3. Additional information of shaft supporting, vessel and foundation geometry are shown in Table 2.

In the current study it is assumed that the elevated tank was built on a dry and non-saturated soil with different mechanical properties. The stiffness of the equivalent springs for different types of soil were obtained from shear modulus "G" of the soil. Table 3 shows the soil classification and general soil properties used in the study.

Table 2 Shaft, vessel and foundation properties of the elevated tank

Mass (Kg)		Material properties (kPa)		Tank geometry (mm)		Foundation geometry (mm)	
Convective mass	18518	Elastic modulus	2.24E+7	Thickness of shaft and vessel	200	Slab height	2000
Impulsive mass	191541	density	25 kN/m^3	Vessel diameter	9000	Slab diameter	10000

Table 3 Current study soil classification and their mechanical properties

Soil category	ν	γ (kN/m^3)	E (kN/m^2)	G (kN/m^2)	Vs (m/s)
Very hard	0.2	19	4.90E+06	2041667	1026.71
Hard	0.3	18	7.63E+05	293461.5	399.92
Soft	0.35	17	9.63E+04	35666.67	143.46
Very soft	0.4	13	3.20E+04	11428.57	92.86

3. Results and discussion

Achieved results from different models are evaluated and compared. Results of the first model are reported in Table 4. It is observed that he impulsive period will be 9 times larger considering soil softening in this study. Furthermore it is observed that there is only near 10% increase in convective period considering soil type softening. Concluded results show that in the case of very soft soil, the impulsive period has higher amounts comparing with convective period. Generally in range of very hard to hard soil, the value of impulsive period is about 80 to 100 percent lower than convective period. In addition, no significant variation in the convective part considering soil stiffness will be occurred in comparison with impulsive part. Maximum 8 percent increasing is observed in convective period considering current study soil type change.

The first estimate of soil-pile length (to determine the mass participation) in model 2 and 3 was chosen as the elevated tank height. Lower and higher values of soil-pile length are checked to determine the variation in the effects of soil-pile length on the natural period and then compared with the results of FEM and the equivalent mass-spring model. It is observed that, by increasing the soil-pile length in different case of soil, the impulsive period values will be changed to decreases. Increasing the soil-pile length in each case of soil had no significant effect of the fluctuation of the convective period were evaluated.

The results of FEM considering FSSI effects with an emphasis on soil category stiffness is reported in Table 5. It is observed that in this method the impulsive period will increase until 11 times in comparison with very hard soil results. Also maximum difference in convective period is reported 9 percent considering different soil categories.

The most reason of difference between numerical and mass spring method results is the geometry neglecting. Considering equivalent mass spring theory, the geometry will be ignored and the system characteristic will be changed to the masses, stiffness and damping. In numerical models all of geometry properties will be effected on dynamic behavior response. The next reason of this difference event may be the ground mass participation. The new developed analytical models can determine the natural period of elevated tanks considering ground mass participation.

Table 4 Values of impulsive and convective natural period archived from model 1

Soil category	Impulsive period (sec)	Convective period (sec)
Very hard	0.448	3.614
Hard	1.06	3.626
Soft	2.9709	3.7
Very soft	5.15	3.9

Table 5 Values of impulsive and convective natural period archived from model 4

Soil category	Impulsive period (sec)	Convective period (sec)
Very hard	0.51	3.614
Hard	1.02	3.72
Soft	2.94	3.9
Very soft	5.25	3.97

The results for the fixed-base condition of numerical model (Model 5) show that the convective period for liquid was 3.615 second and the impulsive period of the combined mass of the liquid and vessel was 0.406 second. Results of American concrete institute (ACI-350, Model 6) shows that the value of convective period was 3.614 second and value of impulsive period was 0.40 second.

Fig. 4 and Fig. 5 show the results of different presented models versus other models. Note that there is a specific relationship between all the FEM, the proposed models and also Model 1 results for hard and very hard soils. In soft and very soft soils, the soil-pile length effected the response for the impulsive natural period. To understand the effects of soil-pile length and its mass participation in the natural period response, the impulsive period results were evaluated considering two soil categories. Each model was evaluated first for very hard and hard soils and then was investigated for soft and very soft soil.

The results for hard and very hard soils for proposed model 3 showed a good estimation of natural period using a 30 m soil-pile length (Fig. 4). Decreasing the soil-pile length in case of hard and very hard soil will be incurred the increase of impulsive period. The FEM method gave the highest estimate of the impulsive natural period for current study range of soil. Impulsive periods for 25 m soil-pile length have a good estimation in compared with those for the equivalent mass-spring and FEM analysis in case of soft and very soft soils.

As the soil-pile length increased, the impulsive period values were decreased. The difference between the results for the FEM and other soil-pile lengths of model 3 are remarkable. The maximum difference between Model 3, FEM and equivalent mass spring in soft soil was negligible and in very soft soil was 0.2 second. The results of this model show that, considering the ground mass participation and also the dynamic stiffness of soil can have a good estimation of impulsive period compare with equivalent mass spring analytical models. The dynamic soil stiffness and ground mass participation can help to improve the concluded results of this model. In addition the dynamic damping effects have a significant effects on results of model 2.

Model 2 results for soil-pile length in hard and very hard soil are shown in Fig. 5. The best estimate for the impulsive period occurred for the 30 m soil-pile length in case of hard and very hard soils, when compared to FEM and the equivalent mass-spring method. Generally, in hard and very hard soil, the model 2 estimates were higher than those of the FEM and analytical methods. The maximum difference among results of Model 3 (25 m), FEM and equivalent

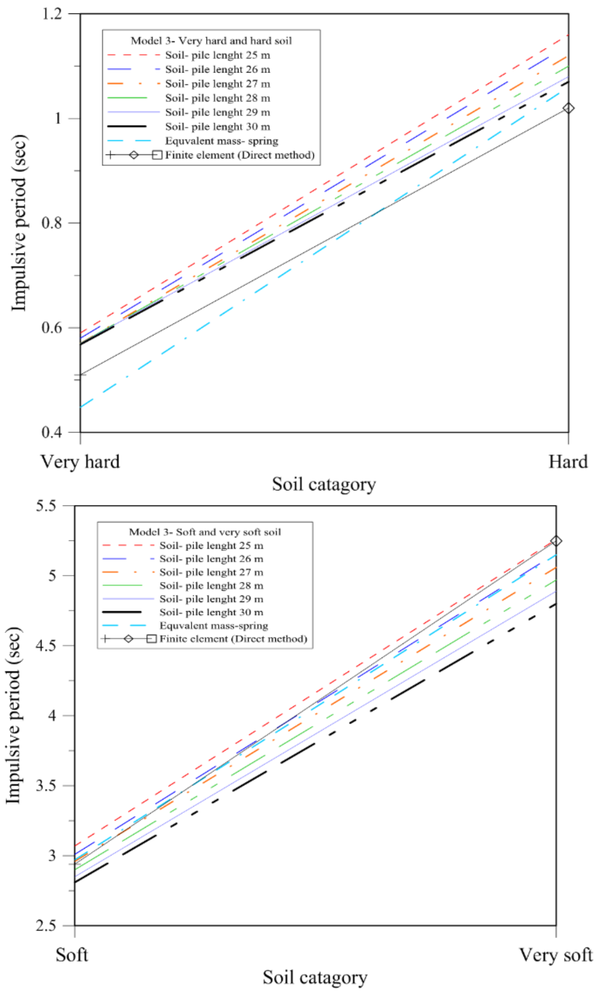

Fig. 4 Impulsive period from model 3 compared with those of numerical and equivalent mass spring methods

mass-spring methods occurred in very hard soil. There was significant difference between the results of the equivalent mass-spring method and Model 2 in very hard soil. This difference decreased as the soil category changed to hard. The soil participation range will be most reason for this event.

The impulsive period for Model 3 using the 25 m of soil-pile length in soft and very soft soil was significantly different from those of the FEM and equivalent mass-spring method. Increasing the soil-pile length decreased the impulsive period. The higher difference is observed in concluded results of model 2 compared with results of model 3. The dynamic damping and dynamic masse effects on natural period response are two most important reasons of this evidence. Also the geometry ignoring will be a general reason of finite element and developed models results difference.

Fig. 6 shows the convective period considering soil category. There was no significant variation in convective period in hard and very hard soil. The maximum value of convective period for the proposed models occurred in very soft soil. Regarding pervious study results, increasing the natural convective period decreased the sloshing height of liquid and increasing the convective natural period

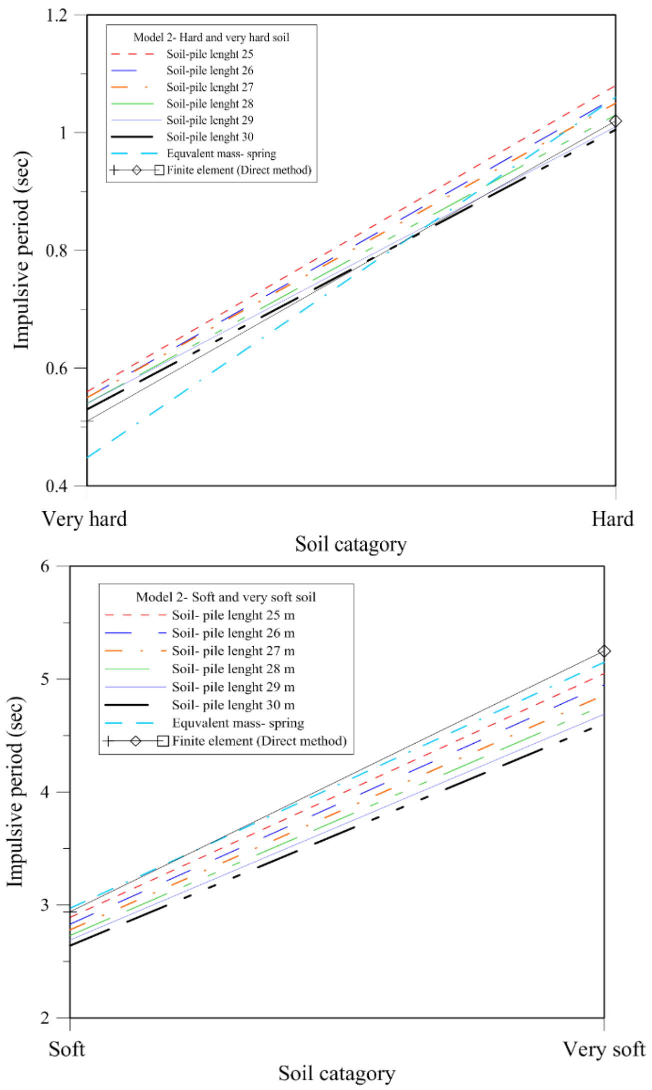

Fig. 5 Impulsive period results of model 2 vs. numerical and equivalent mass spring methods

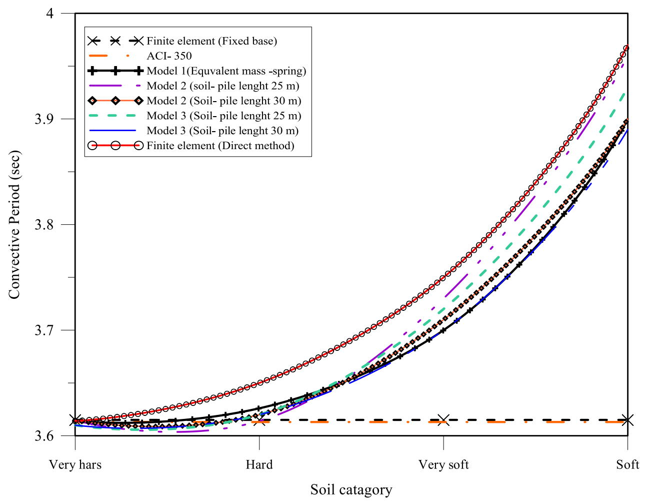

Fig. 6 Convective natural period from proposed models vs. FEM and equivalent mass-spring methods

decreased the convective base shear coefficient (Goudarzi and Sabbagh-Yazdi 2008, 2009).

Results of convective period show that the FEM method overestimates the convective period in comparison with analytical models. Complementary assessment shows that convective natural period extracted from developed models fall between the results for FEM and equivalent mass-spring methods. For the 25 m soil-pile length, convective period was nearer to the FEM results. The results also show that there was a significant difference between the equivalent mass-spring, Model 2 and Model 3 for the 30 m soil-pile length versus the FEM.

Complementary results of convective period assessment reported that the convective period is more affected from the geometry of vessel and its stiffness. The soil effects on convective period compare with the geometry effects will be negligible. Considering results evaluation, it is observe that the ground mass participation in case of convective period will be same as the ground mass participation in case of impulsive period assessment in soft soil range.

4. Conclusions

Estimation of elevated tanks natural period considering fluid- structure- soil interaction effects by using the new analytical models is presented in this study. In this case the impulsive and convective natural periods are evaluated considering different procedures of analytical models which are capable for modeling the soil and liquid. Both of massless foundation and ground mass participation methods are used in this study for model development models. The following conclusions can be drawn from this study:

- The proposed models were able to estimate the natural impulsive periods of a superstructure and the convective period of the inside liquid. They could also determine the natural periods of elevated tanks considering the soil effects.
- The ground mass participation models have a good estimation of natural period compared with mass less equivalent mass- spring model. Furthermore results show that both ground mass participation models have a good estimation in comparison with FEM model.
- The first estimate of soil-pile length participation was at 28 m. The 30 m soil-pile length gave good estimates of the natural period in hard and very hard soil and at 25 m soil-pile length for soft soil.
- There was no significant effect of soil stiffness on convective natural period of elevated tanks in hard soil. The impulsive period was more sensitive to soil stiffness. A maximum 10 percent increase in convective period was reported in very hard to very soft soil range. Furthermore, the shape of vessel and height of liquid are more significant than soil condition effects on convective period.
- International codes, such as ACI- 350 and Eurocode-8, provide no real estimate of convective and impulsive periods in case of soft and very soft soil. Concluded results show that Fluid- structure- soil interaction models are necessary to produce accurate estimates for the natural period. The ground mass participation models are strongly recommended to find the natural

period in case of soft and very soft soil.

• The proposed models results show that the impulsive period extracted from very soft and soft soil is 10 times more overestimate than results of hard soil. The finite elements results would be increased up to 10 times in range of soft and very soft soil.

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