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# New coefficients to find natural period of elevated tanks considering fluid-structure-soil interaction effects

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**Abstract.** The main purpose of the current study is to develop the new coefficients for consideration of soil-structure interaction effects to find the elevated tank natural period. Most of the recommended relations to find the natural period just assumed the fixed base condition of elevated tank systems and the soil effects on the natural period are neglected. Two different analytical systems considering soil-structure- fluid interaction effects are recommended in the current study. Achieved results of natural impulsive and convective period, concluded from mentioned models are compared with the results of a numerical model. Two different sets of new coefficients for impulsive and convective periods are developed. The values of the developed coefficients directly depend to soil stiffness values. Additional results show that the soil stiffness not only has significant effects on natural period but also it is effective on liquid sloshing wave height. Both frequency content and soil stiffness have significant effects on the values of liquid wave height.

**Keywords:** coefficient; impulsive; convective; elevated tanks; soil effect

## 1. Introduction

Lots of elevated tanks damage or collapse experiences during past earthquakes occurrence around the world are reported. These inconvenient events show that in addition to vessel design of elevated tanks, staging structure system stability of the elevated tanks and also site effects on structural dynamic behavior are more important than the other structural types of liquid tanks (Dutta *et al*. 2004). Large numbers of storage tanks are used as water and oil storage facilities. They play an important role in urban water supply or firefighting systems. In order to provide the head of water required for a water supply process, water tanks are placed on a supporting shaft or braced columns, thereby instead of requiring heavy pumping facilities, the necessary pressure can be obtained by ground gravity.

For this super structure designing, as a complete recognition of dynamic liquid effects on this kind of vessels, the fluid-structure interaction (FSI) method (Housner 1963, Livaoghlou and Dogangun 2007) is recommended. During the responses of structure and soil under the dynamic

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loadings, the influence of soil due to structure, and the influence of structure due to soil are recognized as soil-structure interaction (SSI) (Kramer 1996, Shirgir *et al*. 2015, Wolf 1985). The most accurate method for liquid tanks modeling is fluid-structure-soil interaction (FSSI) (Livaoghlu *et al*. 2006).

Many international standards and codes such as ACI 350, ACI 371 and the Japan gas association (1981) have adapted Housner's (1963) to consider the liquid effects on structure, but there are no any references to consider the soil effects on liquid or body of the vessel directly. Various research methods have been applied to the study of elevated tanks in recent decades considering FSI and FSSI. Haroun and Ellaithy (1985), Resheidat and Sunna (1990), Haroun and Temraz (1992), Livaoglu and Dogangun (2006, 2007), Dutta *et al*. (2004), Goudarzi and Sabbagh Yazdi (2008), Marashi and Shakib (2008), Ghaemmaghami *et al*. (2010), Livaoglu *et al*. (2011), Livaoglu (2013) and Ghanbari and Abbasi Maedeh (2015) are assessed dynamic behavior of elevated tanks.

All of mentioned studies reported that the most accurate factor to design elevated tanks considering dynamic effects would be natural period. In addition, some of pervious research results show that the height of liquid wave displacement is affected from natural period. In those reasons, it is important to find soil effects on natural period, height of liquid wave effect and eventually invent a solution to consider the ground flexibility effects on dynamic behavior of elevated tanks.

In this study, two analytical models are suggested to consider the effects of soil on natural period. To consider the liquid effects, the international codes recommendations are used. For ground flexibility effects, the FEMA (Federal emergency management agency) recommendation is chosen. To verify the results, analytical system results would be compared with numerical modeling results and regular international code suggestions. The effects of natural period on elevated tanks considering soil-structure-fluid interaction will be evaluated in four different categories of soils. The soil and natural period effects on liquid wave sloshing are also will be evaluated. Four different frequency contents of recently earthquake were chosen as external excitations. Eventually considering current study results, two new sets of coefficient to find the soil effects on natural sloshing and impulsive period are developed.

## 2. Basic concept and assumptions

Regarding the main purpose of current study the analytical and numerical models are prepared. Two numerical models of fixed and flexible base for elevated tank are made in numerical software. For analytical liquid modeling, the ACI-350 (2006) and Eurocode-8 (2006) international codes recommendation are used. To consider the soil-structure, interaction effects in analytical model the mass spring theory from FEMA is used. The computer software ANSYS is chosen to model the FEM analyses (ANSYS 2015). A filled elevated tank is selected and FEM analyses are conducted using displacement-based (D-Fluid) Elements. D-Fluid elements use displacements as the variables in the liquid domain. These elements are considered as an extracted of structural solid elements in which the element shear modulus is set to zero and the liquid bulk modulus; $K$ is used to establish the elastic stress–strain relations. D-Fluid elements are particularly useful in modeling fluids contained within vessels having no net flow rate (ANSYS 2015, Ghaemmaghami *et al*. 2010, Moslemi *et al*. 2011). It can be employed for transient as well as free vibration analyses (Moslemi *et al*. 2011). The stress–strain relationship of the D-Fluid element is established using the stiffness matrix as Eq. (1).

$$\begin{bmatrix} \varepsilon_{bulk} \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{xz} \\ R_x \\ R_y \\ R_z \end{bmatrix} = \begin{bmatrix} 1/_k & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1/_S & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1/_S & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/_S & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/_B & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/_B & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1/_B \end{bmatrix} \times \begin{bmatrix} P \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{xz} \\ M_x \\ M_y \\ M_z \end{bmatrix} \tag{1}$$

Where $\varepsilon_{bulk} = \dfrac{\partial u}{\partial x} + \dfrac{\partial v}{\partial y} + \dfrac{\partial w}{\partial z} = bulk\ strain$

K = Fluid elastic (bulk) modulus
P = Pressure
$\gamma$ = Shear strain
S = $K \times 10^{-9}$ arbitrary small number to give element some shear stability
$\tau$ = Shear stress
R = Rotation about axis *i*
B = $K \times 10^{-9}$ arbitary small number to give element some rotation stability
$M_i$ = Twisting force about axis *i*

The extracted results through free vibration analysis, including natural periods of vibration are compared with those obtained from analytical recommended and international code approximation. The equation of motion of the system can be solved by using the direct integration method. However, when the response of the structure is linear, more efficient analysis using the concept of modal superposition (Ghaemmaghami and Kiyanoush 2010). According to ACI 371R-08 for each model, a sufficient number of modes (both impulsive and convective) to obtain a combined modal mass participation of at least 90% of the actual mass of the structure in the direction under consideration were employed (Moslemi *et al*. 2011).

The ACI-350 and Eurocode-8 recommendation relations are used for fluid and the FEMA-450 recommendation (Table 1), to find soil equivalent stiffness values are considered. The lumped model of current study recommended models shown in Fig. 1.

To find natural periods and associated mode shapes of the structure considering analytical model solving the eigenvalue problem will be necessary. In general, for a system of *n* degree of freedom, the equation of motion is a set of second linear differential equation as given in Eq. (2) (Chopra 2000).

$$[K]\{U\} + [C]\{\dot{U}\} + [M]\{\ddot{U}\} = \{F\} \tag{2}$$

The vector $\{U\}$ function of time denotes the displacement response at all degrees of freedom. The matrices $[K], [C]$ and $[M]$ represent stiffness matrix, damping matrix and mass matrix respectively, which are constant for a linear system. The vector of $\{F\}$ denotes the prescribed loads at the corresponding degree of freedom as a function of time. In order to estimate the fundamental frequency of the system under harmonically varying load, Eq. (3) can be written by substituting the general mass and stiffness matrix in eigenvalue equation for the *n* degree of freedom system with an emphasis on soil and superstructure matrix (Jahankhah *et al*. 2013). The

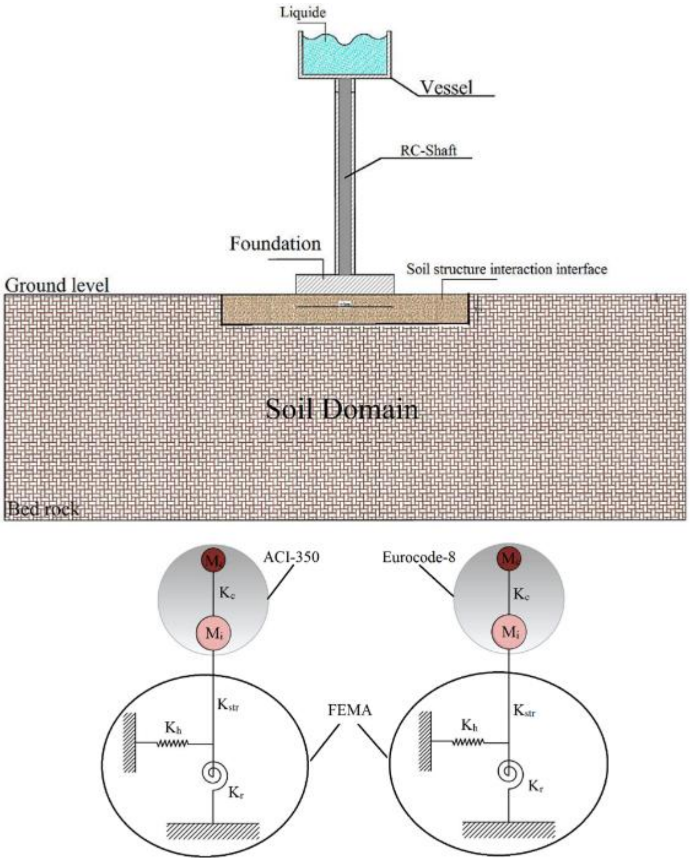


Fig. 1 Analytical recommended models considering fluid-structure-soil interaction

content of each stiffness and masses matrix are described in literature (Abbasi Maedeh *et al*. 2016).

$$\begin{bmatrix} [K_{Elevated\ \ tank}] & [K_{Soil-Elevated\ \ tank}] \\ [K_{Elevated\ \ tank-Soil}] & [K_{soil}] \end{bmatrix} - \{\omega^2\} \begin{bmatrix} [M_{Elevated\ \ tank}] & [M_{Elevated\ \ tank-Foundation}] \\ [M_{Foundation\ \ -Elevated\ \ tank}] & [M_{soil}] \end{bmatrix} = 0 \tag{3}$$

The soil stiffness matrix of the foundation surrounding soil is represented by a 2 × 2 matrix. Where $K_h$, $K_r$ and $K_{rh}$ are the Horizontal, rocking and Horizontal-rocking coupling terms of the corresponding static stiffness matrix, respectively (Wolf 1985).

$$\begin{bmatrix} K_h & K_{rh} \\ K_{rh} & K_r \end{bmatrix}$$

Soil stiffness (spring) is attached to the central point of the rigid circular foundation (Kramer 1996, Jahankhah *et al*. 2013). The explained soil stiffness for circular rigid foundations supported at the surface of a homogeneous half space formulas are presented in Table 1.

Table 1 FEMA recommendation relations for soil stiffness

| Soil stiffness mode | Relation |
|---|---|
| Horizontal stiffness (kN/m) | $K_h = \frac{8GR}{2-\upsilon}\left(1+\frac{e}{r}\right)$ |
| Rocking stiffness (kN.m) | $K_r = \frac{8GR^3}{3(1-\upsilon)}\left(1+2.3\left(\frac{e}{r}\right)+0.58\left(\frac{e}{r}\right)\right)^3$ |
| Horizontal-rocking stiffness (kN/m) | $K_{hr} = K_{rh} = \frac{e}{3}(k_h)$ |

Where, $G$, $R$, $e$ and $\upsilon$ are shear modulus, Poisson's ratio of soil, foundation embedment ratio (Abbasi Maedeh *et al*. 2016, Jahankhah *et al*. 2013) and radius of equivalent circular foundation. The foundation radiuses for translational and rotational degree of freedom are also calculated (Gazetas and Stoke 1991, Gazetas 1991). By solving Eq. (3), $n$ vibration frequencies corresponding to n degrees of freedom will be concluded. The natural frequency equation for a multi mass assumption considering impulsive and convective mass separately (Housner 1963), with an emphasis on soil effects are written as Eq. (4)

$$\begin{bmatrix} K_c & -K_c & 0 & 0 \\ -K_c & K_c + K_{str} & -K_{str} & 0 \\ 0 & -K_{str} & K_{str} + K_h & K_{rh} \\ 0 & 0 & K_{rh} & K_r \end{bmatrix} - \{\omega^2\} \begin{bmatrix} M_c & 0 & 0 & M_{ch} \\ 0 & M_{str} & 0 & M_{sh} \\ 0 & 0 & M_f & 0 \\ M_{ch} & M_{sh} & 0 & I_f + {M_{sh}}^2 + {M_{ch}}^2 \end{bmatrix} = 0 \quad (4)$$

Where

$M_c$ : mass of convective liquid
$M_{str}$ : mass of impulsive liquid+ mass of vessel + 66% of shaft structure
$M_f$ : mass of foundation
$M_{ch}$ : $M_c(h_c + h_{str})$
$M_{sh}$ : $M_{str}(h_i + h_{str})$
$I_f$ : moment inertia of foundation
$K_c$ : convective liquid stiffness
$K_{str}$ : stiffness of structure

The references of above values are described in literature (Housner 1963, ACI-350 2006). To sloshing wave height of inlet liquid assessment considering analytical technique, the Japan Gas Association (1981) recommendation is used as Eq. (5).

$$\mu_c = 0.00245. T_c. \tanh\left(\frac{1.84H}{R}\right). S_v(T, h) \quad (5)$$

Where $T_c$ is convective period, of the storage tank, and the sloshing wave height, $\mu_c$. H is the liquid level, $R$ is the tank radius, $g$ is the gravitational acceleration, and $S_v$ ($T$, $h$) is the velocity response spectrum value for the period $T_{(s)}$ and damping ratio $h$. in current study the 5% damping ratio is assumed for assessed sited soil.

## 3. Geometry of case study and properties of seismic excitation

The particular tank configuration considered is that of regular storage tank which constructed in the developed country. It is assumed that the vessel is full of liquid and its capacity of 486 $m^3$. Regarding international codes (ACI-350 2006), it is neglected from the effects of tank wall's flexibility.

To find analytical impulsive and convective period considering FSSI theory the developed matrixes in basic and assumption part are used. The SSI analysis through the direct method configuration (Preisig and Jeremic 2005, Yoo 2013, Li *et al*. 2014) is used for numerical method in this paper (Fig. 5). The direct method estimation allow 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

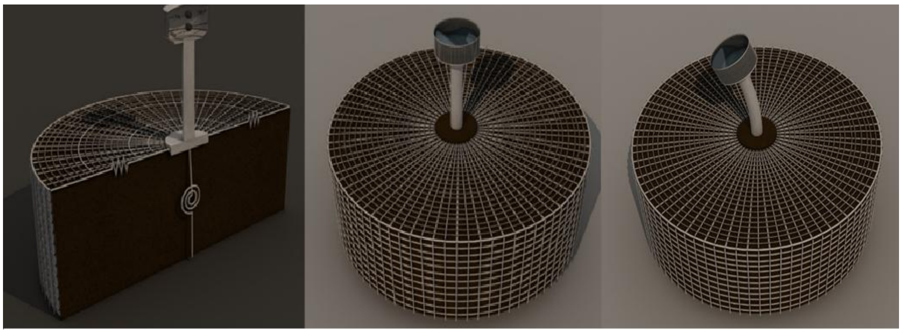

Fig. 2 Analytical and finite element direct method model of soil-structure-fluid interaction

Table 2 Shaft, vessel, and foundation geometry and material properties

| | | | |
|---|---|---|---|
| Mass | Convective mass [kg] | Impulsive mass [kg] | |
| | 18500 | 190000 | |
| Mechanical properties | Elastic modulus [kN/$m^2$] | Density [kN/$m^3$] | |
| | 2.23E+10 | 25 | |
| Tank geometry | Thickness of shaft and vessel [mm] | Vessel diameter [mm] | Water height [mm] |
| | 200 | 9500 | 4100 |
| Foundation geometry | Slab height [mm] | Slab diameter [mm] | Density [kN/$m^3$] |
| | 2000 | 10000 | 25 |

Table 3 Current study soil classification and mechanical properties

| Soil category | $\gamma$ [kN/$m^3$] | $E$ [kN/$m^2$] | $G$ [kN/$m^2$] | $Vs$ [m/s] |
|---|---|---|---|---|
| Very hard | 19 | 4.90E+06 | 2041667 | 1026.71 |
| Hard | 18 | 7.63E+05 | 293461 | 399.92 |
| Soft | 17 | 9.63E+04 | 35666 | 143.46 |
| Very soft | 14 | 3.20E+04 | 11428 | 92.86 |

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 (Hacıefendioğlu 2012, Preisig and Jeremic 2005).

Table 4 Properties of selected earthquakes excitations

| No. | Event | Station | PGA [$g$] | Magnitude [$M_w$] |
|---|---|---|---|---|
| 1 | San Fernando | Lake Hughes | 0.38 | 6.6 |
| 2 | Chuetsu-Oki, Japan | Yamakoshi Takezawa Nagaoka | 0.35 | 6.8 |
| 3 | Loma Perieta | San Jose-Santa Teresa Hills | 0.26 | 6.9 |
| 4 | Hector Mine | Hector | 0.32 | 7.1 |

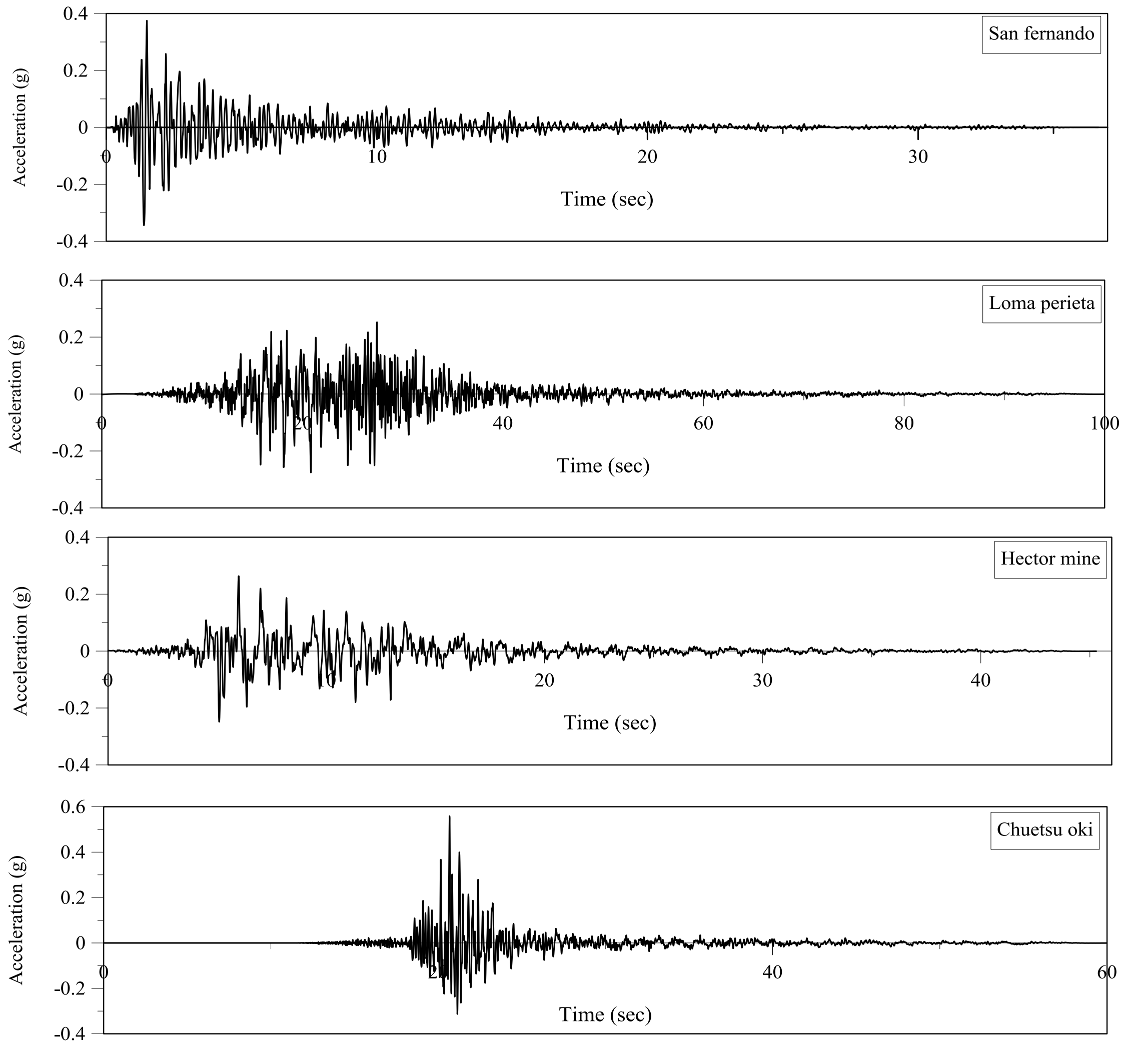


Fig. 3 Time history graphs for selected earthquakes excitations

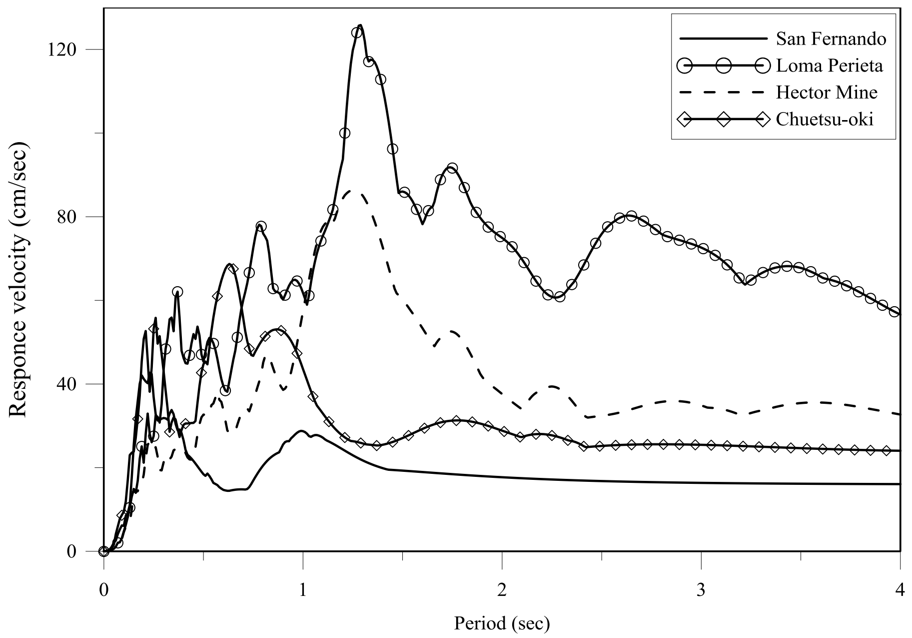


Fig. 4 Response velocity spectra of selected earthquakes excitations

The properties of the fundamental impulsive mode are mainly dependent on the geometry and stiffness properties of the supporting shaft (Goudarzi and Sabbagh-Yazdi 2008, 2009, Moslemi *et al*. 2011). D-Fluid elements are used for liquid and shell elements were used for modeling the tank. Fluid and shell domain should be meshed in such a way that the location of each node of the fluid domain on the interface coincides exactly with that of the corresponding shell element. selected earthquake excitations is reported in Table 4.

The time history of each selected excitation is shown in Fig. 3. In current study tried to choose different frequency content and acceleration content for the excitation.

The response velocity spectrums of selected earthquake considering regular calculated method are shown in Fig. 4.

Fluid nodes should be coupled at all interfaces with a containing shell. As a result, all fluid nodes located at the interface with the tank’s floor should be restrained in vertical direction. The shell element has six degrees of freedom (translations and rotations) at each node and both bending and membrane behaviors are permitted. The finite element configuration of the elevated tank model is indicated in Fig. 2.

Complementary information of elevated tank system and its foundation geometry is reported in Table 2.

Four different mechanical properties of seedbed soils are used to evaluate in current study, which show in Table 3. It is assumed that the elevated tank is established on dry and non-saturated soil. The stiffness of the equivalent springs for various varieties of soil has been obtained from values of shear modulus G of soil and substituting in Table 1 relations.

Four different horizontal excitation, which recently occurred are evaluated to components excitation. Current study neglected from site effects on selected excitation. General information of selected earthquake excitations is reported in Table 4.

## 4. Results and discussion

The numerical models of elevated tank considering both fixed and flexible base condition are made. The finite element method is used for direct method theory. It is observed that considering the increase of soil stiffness the natural impulsive period will be decreased. Numerical results of impulsive natural period considering base condition (fix and flexible) are plotted in Fig. 5. Results of fixed base condition are shown as a horizontal line in all range of soil stiffness. It is observed that, there are no values changes by changing the soil stiffness condition. Results show that there are significant variations between results of FSSI and FSI condition in case of hard to very soft soil. This variation would be clearer in soft and very soft soil range.

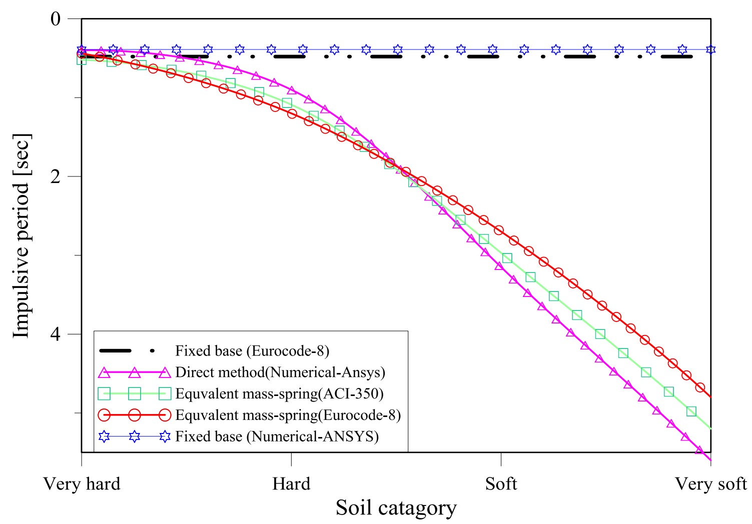


Fig. 5 Values of impulsive period considering numerical, analytical and international code

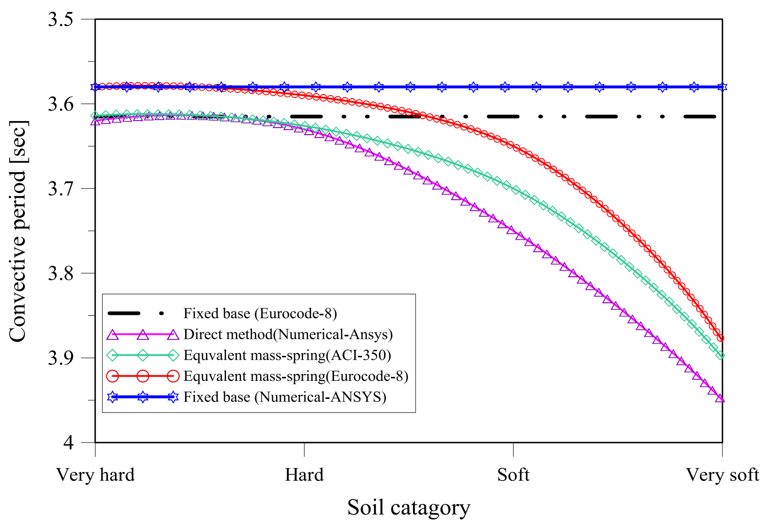


Fig. 6 Values of convective period considering numerical, analytical and international code

Results of analytical models show that the impulsive period estimation in very hard soil was higher than numerical FSSI model. Moreover, in very soft soil condition the analytical models value of impulsive period was lower than numerical model extracted values. It observed that in general the estimated values from FSSI and FSI from Eurocode-8 are lower than ACI-350 model.

The Convective period results of mentioned models are shown in Fig. 6. There are maximum 10 percent increases in convective period values considering soil stiffness effects. Numerical model extracted results have a higher estimate of convective period with an emphasis on different case of soil. Both of recommended analytical models have a lower estimate of convective natural period in compare with numerical analysis. Maximum difference of convective period in case of very hard to very soft soil is observed in numerical method model. Current study recommended analysis results show that, the rate of soil stiffness effects on impulsive period is more influential than soil stiffness effects on convective period. Moreover, results show that there are no significant differences of convective period in hard and very hard soil regarding current study recommended analysis.

As liquid displacement evaluating, the sloshing liquid wave height (LWH) spectra considering both soil stiffness and earthquake excitation are plotted in Figs. 7 to 9. Very hard soil results of LWH regarding selected earthquake show in Fig. 7. It is observed that a result of FSSI and FSI theory modeling has no remarkable change. Maximum LWH was occurred on the point of characteristic period regarding response velocity spectrum. In fact in hard and very hard soil the maximum range of frequency content have remarkable effect on sloshing wave height.

The results of hard soil reported that there are no any remarkable differences in results of hard and very hard soil. There are nearly 7 percent increasing in concluded values of LWH considering soft soil in compare with hard and very hard soil. In addition, results show that there are around 3 percent difference between the values of LWH, which extracted from fixed base condition and numerical method (FSSI) theory. The results of LWH considering soft soil base show in Fig. 8.

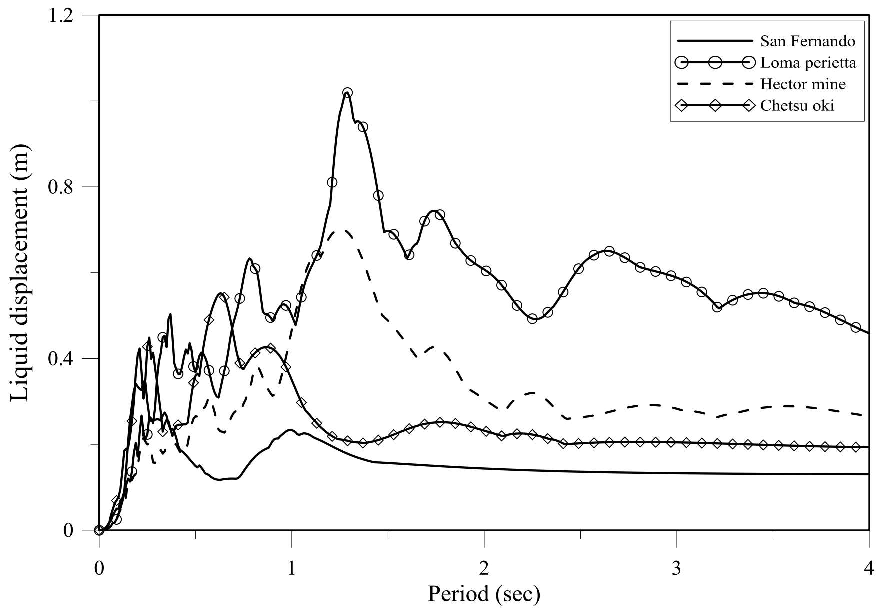


Fig. 7 Results of liquid displacement (LWH) in case of very hard soil

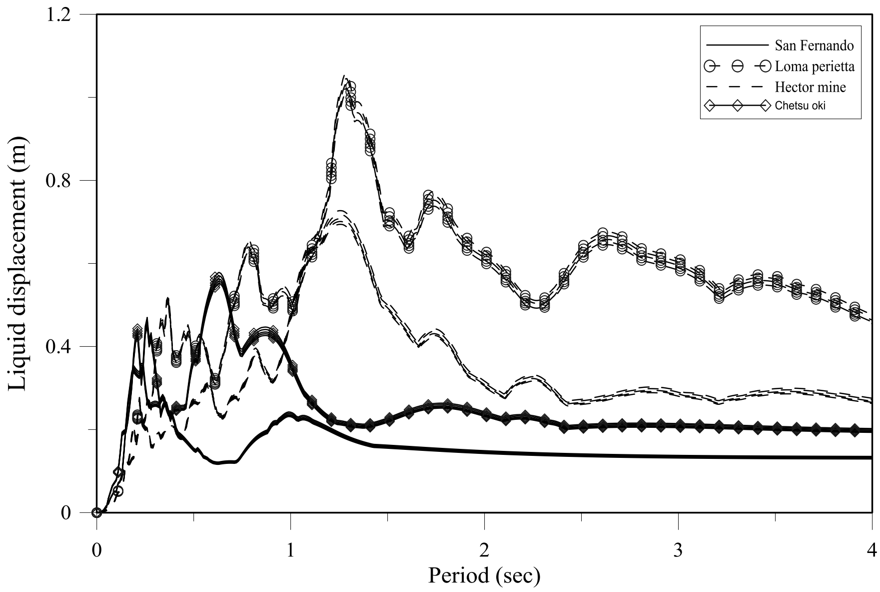


Fig. 8 Results of liquid displacement (LWH) in case of soft soil

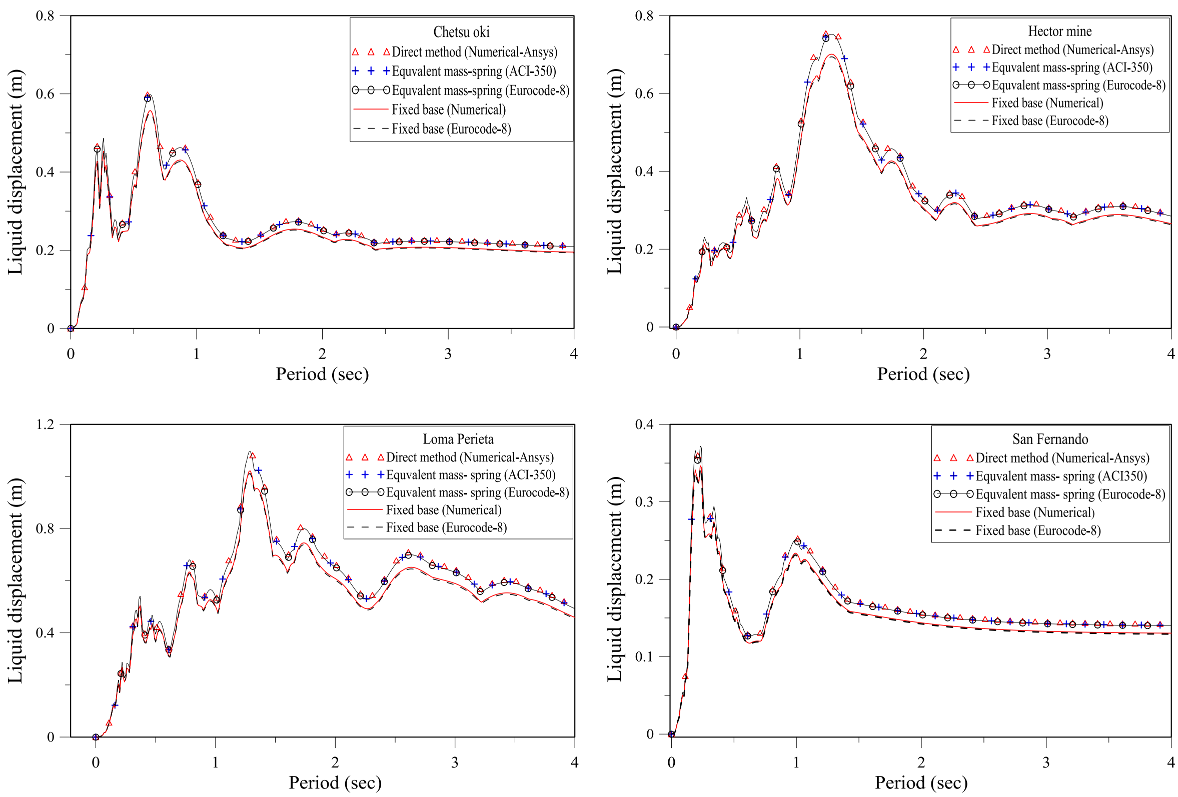


Fig. 9 Results of liquid displacement (LWH) in case of very soft soil

The maximum estimation of each analysis is reported from numerical direct method technique.

Results of LWH, which extracted from very soft soil case show that there are about 10 to 12 percent difference between FSI model and FSSI model analysis. It is observed that the FEM modeling have over estimation of LWH for elevated tank considering very soft soil compared with analytical models and international code. The values of recommended analytical methods are filling between numerical finite element and FSI (Fig. 9). Regarding to results it is observed that the maximum response separation of LWH considering the different analyses are occurred between the ranges of 0.8 to 1.5 second.

It is observed that maximum estimation of natural period and LWH occurred in soft and very soft soil. Comparing the results of FSI and FSSI show that the international code suggested relations has no good estimation for convective and impulsive period in case of soft and very soft soil. Results of this study show that there is a meaningful relation between fixed bases, FSI and FSSI results such as Eq. (6).

$$FSSI = \{FSI \times \ Proposed\ FSSI\ coefficient\ \} \tag{6}$$

The new developed correction coefficient considering different soil stiffness is shown in Table 5. It is assumed that the poison ratio of soil would be constant on 0.3 as the normal of soil poison ratio. By multiplying, the proposed FSSI coefficient to fixed base concluded results of ACI-350 considering soil category the corrected estimation of natural period will be concluded. The values

Table 5 Suggested coefficients to find soil effects on natural period

| | Elastic modulus of soil | | | |
|---|---|---|---|---|
| Soil category | Minimum | Maximum | Convective FSSI coefficient | Impulsive FSSI coefficient |
| Very hard | 7.63E+05 | 4.90E+06 | 0.98 | 1.07 |
| Hard | 9.63E+04 | 7.63E+05 | 1 | 2.70 |
| Soft | 3.20E+04 | 9.63E+04 | 1.05 | 7.35 |
| Very soft | 3.20E+03 | 3.20E+04 | 1.10 | 12.95 |

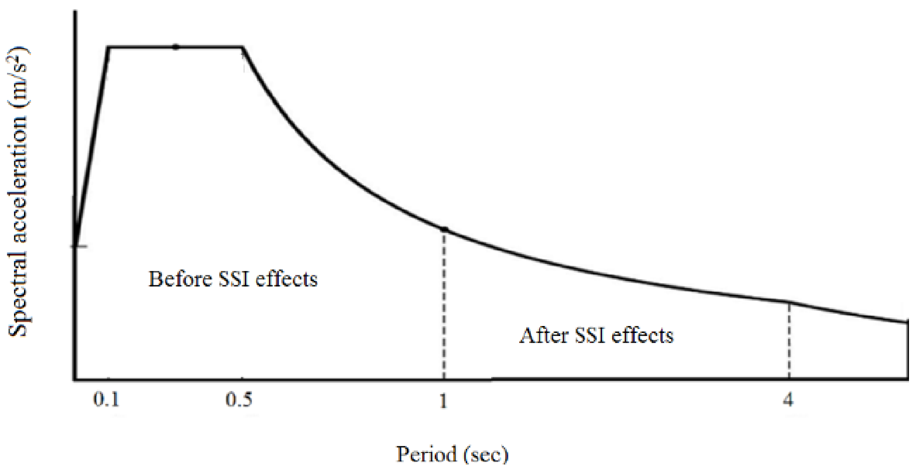


Fig. 10 Response spectrum considering the area of acceleration sensitive and velocity sensitive

of this correction are filled between the results of mass-spring method and FEM theory.

Suggested coefficient show that maximum effects of soil softening on convective period would be around 10 percent while this effect on the impulsive period would be near 12 times in very lose and soft soil. Results show that regarding to increase the natural period the base shear of elevated tank will be reduced, but the maximum displacement of structure will be greatly increased. Additionally results show that considering SSI effects on elevated tanks can be changed the affected of response in response spectrum (Fig. 10).

## 5. Conclusions

To find the effects of FSSI on natural period the analytical and numerical analysis are evaluated. Two new recommended analytical models considering FSSI effects to correct the international codes recommended relations are presented. To verify the results of mentioned models the numerical direct method analysis is chosen. Regarding to the evaluations of this study the following conclusions are reported:

- Equivalent mass spring-(ACI-350 2006) has over estimation of impulsive and convective period with and without emphasis on FSI in compare with equivalent mass spring-(Eurocode-8 2006) model.
- In range of very hard to hard soil the frequency content of excitation, has remarkable effects on LWH. However, in soft and very soft soil, the soil effects will be added to frequency content effects to find LWH.
- Results of LWH show that in all category of soils maximum difference to estimate the LWH will be occur in range of higher one second in period of excitation. It means the maximum error to determine the LWH will be occurring in high range period excitation.
- The maximum of LWH occurred in soft and very soft soil. There are 10 to 12 percent higher in compare with LWH, which concluded from very hard and hard soil.
- The recommended analytical models have good estimation of natural impulsive and convective natural period in case of soft and very soft soil compare with numerical direct method. In case of very hard soil, all of evaluated methods have good estimation in natural period. Current study recommended using presented models to find natural period in case of hard to very soft soils.
- By multiplying the proposed FSSI coefficient to results of international codes, the real natural period (impulsive and convective) considering FSSI effects would be reported. It is observed that the international code such as ACI-(2006) and Eurocode-8 (2006) has no good estimation of impulsive and convective period regarding soft soil effects.
- Considering The ACI-350 (2006) and Eurocode-8 extracted results are in the absence of safety results, compare with current study recommended models and the finite elements evaluation in case of flexible base.

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