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Soil interaction effects on sloshing response of the elevated tanks

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Abstract. The aim of this paper is to investigate how the soil-structure interaction affects sloshing response of the elevated tanks. For this purpose, the elevated tanks with two different types of supporting systems which are built on six different soil profiles are analyzed for both embedded and surface foundation cases. Thus, considering these six different profiles described in well-known earthquake codes as supporting medium, a series of transient analysis have been performed to assess the effect of both fluid sloshing and soil-structure interaction (SSI). Fluid-Elevated Tank-Soil/Foundation systems are modeled with the finite element (FE) technique. In these models fluid-structure interaction is taken into account by implementing Lagrangian fluid FE approximation into the general purpose structural analysis computer code ANSYS. A 3-D FE model with viscous boundary is used in the analyses of elevated tanks-soil/foundation interaction. Formed models are analyzed for embedment and no embedment cases. Finally results from analyses showed that the soil-structure interaction and the structural properties of supporting system for the elevated tanks affected the sloshing response of the fluid inside the vessel.

Keywords: elevated tank; sloshing; fluid-structure interaction; soil-structure interaction: supporting system

1. Introduction

The elevated tanks are critical and strategic structures and damage of these structures during earthquakes may endanger drinking water supply, cause to fail in preventing large fires and substantial economical loss. i.e., This type of upsetting experiences was shown by the damage to the staging of elevated tanks or failed fire resistance in Chile 1960 (Steinbrugge and Rodrigo 1963), 1978 İzu-Oshima and Miyagi earthquakes (Minowa 1980) and 1971 San Fernando, 1987 Whittier earthquakes (Knoy 1995). Since the elevated tanks are frequently used in seismically active regions, seismic behavior of them has to be investigated in depth. Historically, shear stress does not appear as a significant contribution to tank damage. In contrast, overturning moment appears to have been of critical importance in tanks damaged during earthquakes (Taniguchi 2004). Therefore, estimation of the structural response to lateral forces has been mainly investigated. Moreover, an excessive liquid sloshing may cause the structural failure or/and the manipulation loss, and which frequently leads to the tremendous loss of human, economic and environmental resources (Cho and Lee 2004). For this purpose, effects of the soil-structure interaction and fluid-structure interaction on the behavior are the issues that researcher should focus on.

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Numerous studies in the dynamic behavior of the fluid storage tanks have been carried out and most of them have a connection with the ground level cylindrical tanks. Contrary to this, very few studies are related to the underground (Goto and Shirasuna, 1980), the rectangular (Doğangün and Livaoğlu 2004) and the elevated tanks (Livaoğlu and Doğangün 2006) in which fixed-base assumption is mostly made. Therefore, concentration is focused on the dynamic behavior of the fluid and/or on the supporting structure. How the soil/foundation systems affect the sloshing response of the elevated tanks have not been generally discussed in these studies. Almost all studies about the seismic behavior of the elevated tanks may be summarized as follows;

Haroun and Ellaithy (1985) developed a model including an analysis of a variety of elevated rigid tanks undergoing translation and rotation. The model considers fluid sloshing modes; and it assesses the effect of tank wall flexibility on the earthquake response of the elevated tanks. Resheidat and Sunna (1986) investigated the behavior of a rectangular elevated tank considering the soil-foundation-structure interaction during earthquakes. They neglected the sloshing effects on the seismic behavior of the elevated tanks and on the radiation damping effect of soil. Haroun and Temraz (1992) analyzed models of two-dimensional X-braced elevated tanks supported on the isolated footings to investigate the effects of the dynamic interaction between the tower and the supporting soil-foundation system but they neglected the sloshing effects, too. Marashi and Shakib (1997) carried out an ambient vibration test for the evaluation of the dynamic characteristics of the elevated tanks. Dutta *et al*. (2000a, 2000b) studied on the comparisons of the supporting system of the elevated tanks with reduced torsional vulnerability and they suggested approximate empirical equations to evaluate lateral, horizontal and torsional stiffnesses for different frame supporting systems. Dutta *et al*. (2001) also investigated how the inelastic torsional behavior of the tank system with accidental eccentricity varies with the increasing number of panel and column. Livaoğlu and Doğangün (2004, 2005) proposed a simple analytical procedure for the seismic analysis of fluid-elevated tank-foundation/soil systems and they used this approximation in selected tanks considering fluid-elevated tank-soil/foundation system. Livaoğlu (2005) performed a comparative study of seismic behavior of the elevated tanks by taking both fluid and soil interaction effects on the elevated tanks into account. Finally Livaoğlu and Doğangün (2006) summarized simplified techniques simply to determine seismic response of the fluid-elevated tanks-soil/foundation system.

Sloshing effects were investigated from different point of views by many researchers. These investigations, especially, condense in cylindrical and annular type of tanks (Aslam and Godden, 1979; Fujita 1981). Horoun and Housner (1981) investigated the sloshing mode effect on shell modes in RC tanks and they indicated that the interaction between these modes is weak. Also Amabili (1996) investigated the steel cylindrical shells half-filled with fluid and this study indicates that the presence of a liquid in a shell structure has a great eject on its modal characteristics. Then Amabili *et al*. (1998) presented a new theory for the dynamics of cylindrical shell tanks with a flexible bottom and ring stiffeners using Winkler elastic springs. By using this theory free surface waves may be taken into account so that both bulging and sloshing modes of the system may be estimated. Cho and Lee (2004) carried out a parametric study in sloshing effects on baffled tanks. As can be seen from above studies any one does not include both sloshing and soil-structure effect on elevated tanks but Veletsos and Tang (1990) studied these effects on ground level cylindrical tank and pointed out that soil structure interaction does not considerably affect sloshing responses of these type of structures. Because of the indefiniteness on elevated tanks about this subject, this study aims at investigating whether the soil-structure interaction affects the fluid sloshing in these tanks or not.

2. Modelling of fluid-elevated tank-soil/foundations system

There are different methods and/or approaches in modeling the soil and fluid medium interacting with structures. In this paper the methods that can be implemented into FEM are selected. For this purpose the soil domain was discritized using 3-D finite elements with viscous boundaries in order to take soil-structure interaction effects into account and Lagrangian fluid finite elements are selected for the fluid-structure interaction. These approaches and the whole the Fluid-Elevated Tank-Soil/Foundation model are subtitled as follows.

2.1 Fluid-Structure Interaction

Fluid-structure interaction problems can be investigated by using different approaches such as added mass, Lagrangian, Eulerian, and Lagrangian-Eulerian in FEM and Smoothed Particle Hydrodynamic (SPH) methods (Anghileri et.al. 2005) or by using the analytical methods like Housner's two mass representations (Amabili 1996), multi mass presentations of Bauer (1964) and Eurocode 8 (2004) etc. Among these, displacement based Lagrangian approach is selected to model fluid-elevated tank interaction. The fluid elements are defined by eight nodes having three degree-of-freedom at each node; translation in the nodal x, y, and z directions. Brick fluid element also includes special surface effects, which may be thought as gravity springs used to hold the surface in place. This is performed by adding springs to each node, with the spring constants being positive on the top of the element. Gravity effects must be included if a free surface exists. For an interior node, the positive and negative effects cancel out (Ansys 1994). The positive spring stiffness can be expressed below

$$K_s = \rho A_f (g_x C_x + g_y C_y + g_z C_z) \tag{1}$$

where ρ is the mass density, A_f the area of the element face, g_i and C_i are the acceleration and damping in the i direction and i^{th} normal to the face component of the element, respectively. In addition expressions for mass and rigidity matrices for fluid element are given below

$$M_f = \rho \int_v Q^T Q dV \rightarrow M_f = \rho \sum_i \sum_j \sum_k \eta_i \eta_j \eta_k Q_{ijk}^T Q_{ijk} \det J_{ijk} \tag{2}$$

$$K_f = \int_v B^T EBdV \rightarrow K_f = \sum_i \sum_j \sum_k \eta_i \eta_j \eta_k B_{ijk}^T EB_{ijk} \det J_{ijk} \tag{3}$$

where J is the Jacobian matrix, Q_{ijk} is the interpolation function, η_i, η_j and η_k are weighting functions, B is the strain-displacement matrix obtained from $\varepsilon = B\,u$ expression. Where kinetic (T) and potential equations (U) can be written as below

$$U = \Pi_\varepsilon \rightarrow U = \frac{1}{2} u^T K_f u \tag{4}$$

$$T = \frac{1}{2} v^T M_f v \tag{5}$$

If the expressions for the kinetic and potential energies are substituted into Lagrange equation, which is

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{u}_j}\right)-\frac{\partial T}{\partial u_j}+\frac{\partial U}{\partial u_j}=F_j \tag{6}$$

where u_j is the j^{th} displacement component and F_j is the applied external load, the governing equation can be written as

$$M_f \ddot{u}+\left(K_f+K_s\right)u=R \tag{7}$$

where $\ddot{u}$ is the acceleration and R is a general time varying load vector.

2.2 Soil/foundation-structure interaction

The simulation of the infinite medium in the numerical method is a very important topic in the dynamic soil-structure interaction problems. The general method treating of this problem is to divide the infinite medium into the near field (truncated layer), which includes the irregularity as well as the non-homogeneity of the foundation, and the far field, which is simplified as an isotropic homogeneous elastic medium (Wolf and Song 1995). The near field is modeled using finite elements and the far field is treated by adding some special artificial boundaries or connecting some special elements. The soil is in most cases a semi-infinite medium, and this domain should be enlarged so extent that the simultaneous modeling together with the structure may be impractical. In a dynamic problem, it may be insufficient to prescribe a zero displacement at a large distance from the structure, as is routinely done in static (Nofal 1998). But sufficiently large soil model may prescribe the soil structure interaction as is performed in some studies (Livaoğlu 2005, Wilson 2002). The other and more appropriate approximations are the artificial and/or transmitting boundaries. Furthermore, reflecting and radiation effects of the propagating waves from the structure-foundation layer may be avoided by means of these types of boundaries. There are different types in frequency or time domain with different sensitivities. Firstly Lysmer and Kuhlmeyer (1969) developed viscous boundary using one-dimensional beam theory and this theory has been commonly used with the FEM. Then more complex boundary types are used and developed like Damping-Solvent Extraction Method (1994), Doubly-Asymptotic Multi Directional Transmitting Boundary (Wolf and Song 1995) and etc. In this study, viscous boundaries are used for three dimensions (Fig. 1).

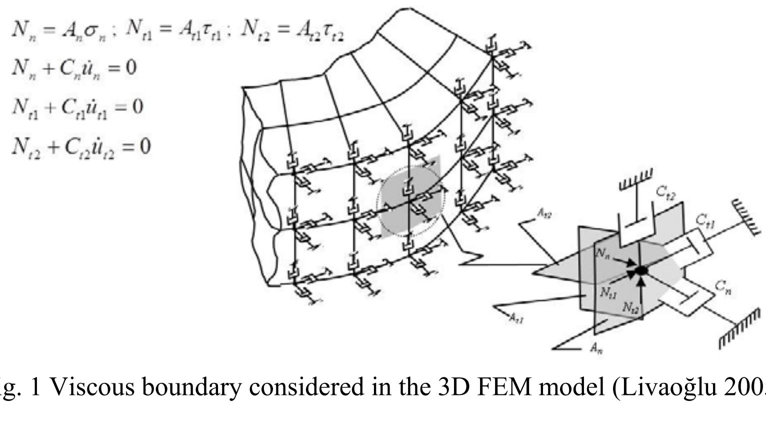

Fig. 1 Viscous boundary considered in the 3D FEM model (Livaoğlu 2005)

To calculate the properties of this boundary condition, it is considered a plane wave propagating in the x-direction. The one dimensional equilibrium equation in the x-direction is

$$\rho \frac{d^2 u}{dt^2} - \frac{d\sigma_x}{dx} = 0 \tag{8}$$

One-dimensional partial differential equation is written in the classical wave propagation form

$$\frac{d^2 u}{dt^2} - v_p^2 \frac{d^2 u_x}{dx^2} = 0 \tag{9}$$

where v_p is the wave propagation velocity of the material and is given by $v_p = \sqrt{E_c / \rho}$ in which ρ is the mass density and E_c is the constrained modulus. The solution of the equation for the harmonic wave propagation in the positive x-direction is a displacement $u\,(t, x)$ and velocity $\dot{u}\,(t, x)$ of the following form

$$u(t,x) = U\left[\sin\left(\omega t - \frac{\omega x}{v_p}\right) + \cos\left(\omega t - \frac{\omega x}{v_p}\right)\right] \quad \dot{u}(t,x) = U\omega\left[\cos\left(\omega t - \frac{\omega x}{v_p}\right) - \sin\left(\omega t - \frac{\omega x}{v_p}\right)\right] \tag{10}$$

The strain in the same direction and the corresponding stress can be expressed in the following simplified form as can be seen same results in the study carried out by Lysmer and Kuhlmeyer (1969)

$$\varepsilon(t,x) = \frac{du}{dx} = -\frac{\dot{u}(x,t)}{v_p} \qquad \sigma_x = E_c \varepsilon(t,x) = -\rho v_p \dot{u}(x,t) \tag{11}$$

where ρ, v_p and v_s are mass density, dilatational and shear wave velocity of the considered medium, respectively. Finally these viscous boundaries can be used with the FE mesh as shown in Fig. 1. In this figure A_n, A_{t1} and A_{t2} are the fields that controlled viscous dampers, σ and τ are the normal and shear stresses occurred in the boundaries of the medium and n and t are the subscripts represent normal and tangent directions in the boundary. It is worth mentioning here that the most important action in this boundary is shear motions along perpendicular two directions because of the dynamic nature of soil. For this purpose the derivatives may also written by using shear wave velocity (v_s) of the soil then three dimensional boundary condition can be used as shown Fig. 1.

When the viscous boundaries are taken into consideration, well-known equation of motion can be written as below

$$[M_{ss}]\{\ddot{u}(t)\} + [C_{ss}]\{\dot{u}(t)\} + [C_i^*]\{\dot{u}(t)\} + [K_{ss}]\{u(t)\} = \{R(t)\} \tag{12}$$

where C^*_i is the special damping matrix and that is

$$[C_i^*] = \begin{bmatrix} A_n \rho v_p & 0 & 0 \\ 0 & A_{t1} \rho v_s & 0 \\ 0 & 0 & A_{t2} \rho v_s \end{bmatrix} \tag{13}$$

Finally equation of the motion concerning the fluid-elevated tank-soil/foundations system is

$$\left(\left[M_{ss}\right]+\left[M_f\right]\right)\{\ddot{u}(t)\}+\left(\left[C_f\right]+\left[C_{ss}\right]+\left[C_i^*\right]\right)\{\dot{u}(t)\}+\left(\left[K_f\right]+\left[K_s\right]+\left[K_{ss}\right]\right)\{u(t)\}=\{R(t)\} \tag{14}$$

Where M, K and $\boldsymbol{C}$ are the mass, stiffness and damping matrix, subscript of ss, f, i and s indicate the soil-structure, fluid, boundary surface and fluid surface of the fluid-structure – soil/foundation system, respectively.

2.3 Fluid-structure soil/foundation interaction model

To model the fluid-elevated tanks-soil/foundation system, finite element method is used as shown in Fig. 2. Columns and beams are modeled with frame elements (six degree-of-freedom per node) container walls and truncated cone with quadrilateral shell element (four-node six degree-of-freedom per node). For the shaft supporting system, shaft is modeled with quadrilateral four node-shell elements. It has to be acknowledged that, because of lack of a geometrical capability in considered Lagrangian FEM (brick shaped), intze-type is idealized as a cylindrical vessel that has same capacity with it.

On the soil-structure interaction surface, foundation is also modeled using shell elements. For no-embedded case, in other words ratio of embedment height to foundation radius is zero, foundation is set up to solid soil model, but embedded cases, it is modeled using very stiff elements, by means of that, flexible motion is ignored for foundation's itself and foundation embedment ratio is selected as 1, which means that foundation embedment (e) is equal to foundation radius (r_0). In order to realize fluid-elevated tank-soil/foundation model and

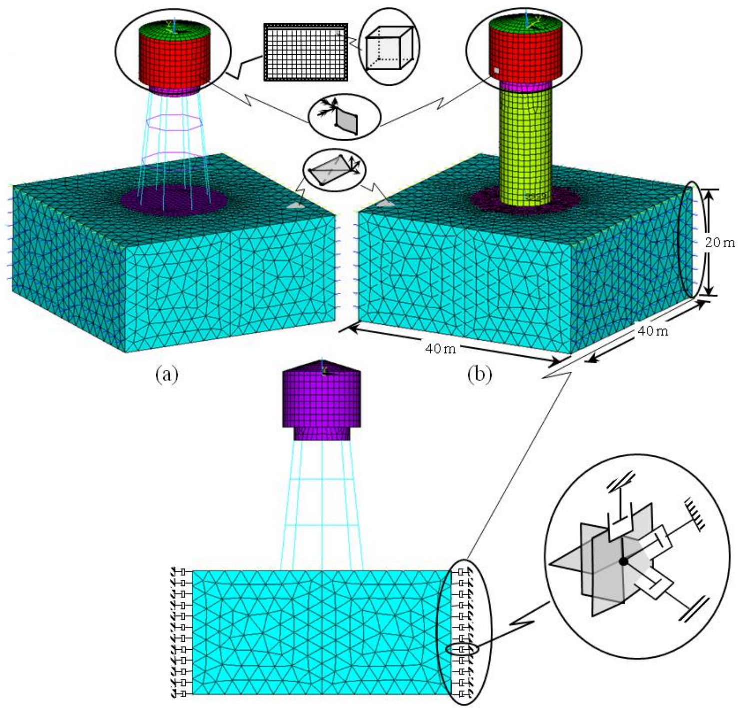

Fig. 2 Considered FE model of the fluid-elevated tank-soil/foundations in this study

characterize the seismic behavior of the systems, transient dynamic analyses were carried out using the ANSYS. All elements mentioned above are available in ANSYS. Fluid elements particularly formulated to model fluid contained within vessel having no net flow rate. Modeling details of fluid and the soil/foundation system are explained under the following title.

2.4 Details of analyzed models

Two reinforced concrete elevated tanks on six different soil types with a container capacity of 900 m^3 are considered in seismic analyses (Fig. 3). One of them has frame supporting system whereas the others have the shaft supporting system. The elevated tanks with a frame supporting system in which columns are connected by the circumferential beams at regular interval at 7 m and 14 m elevations. Since the intze type tank container has an optimal load balancing shape, it is widely preferred (Rai 2002). It is also used in the tanks modeled in this study. The elevated tanks with frame supporting structure have been used as a typical project in Turkey up to recent years. Young's modulus and the weight of concrete per unit volume are selected as 32,000 MPa and 25 kN/m^3, respectively. The container is also filled with the water density of 1,000 kg/m^3 and as seen from Fig. 3.

A destructive seismic event, August 17, 1999 Kocaeli Earthquake in Turkey, was considered in the time domain transient analyses. Izmit-Yarimca station N-S component was selected for use in the analyses. Fig. 4 depicts this acceleration time history of the ground motion. The horizontal

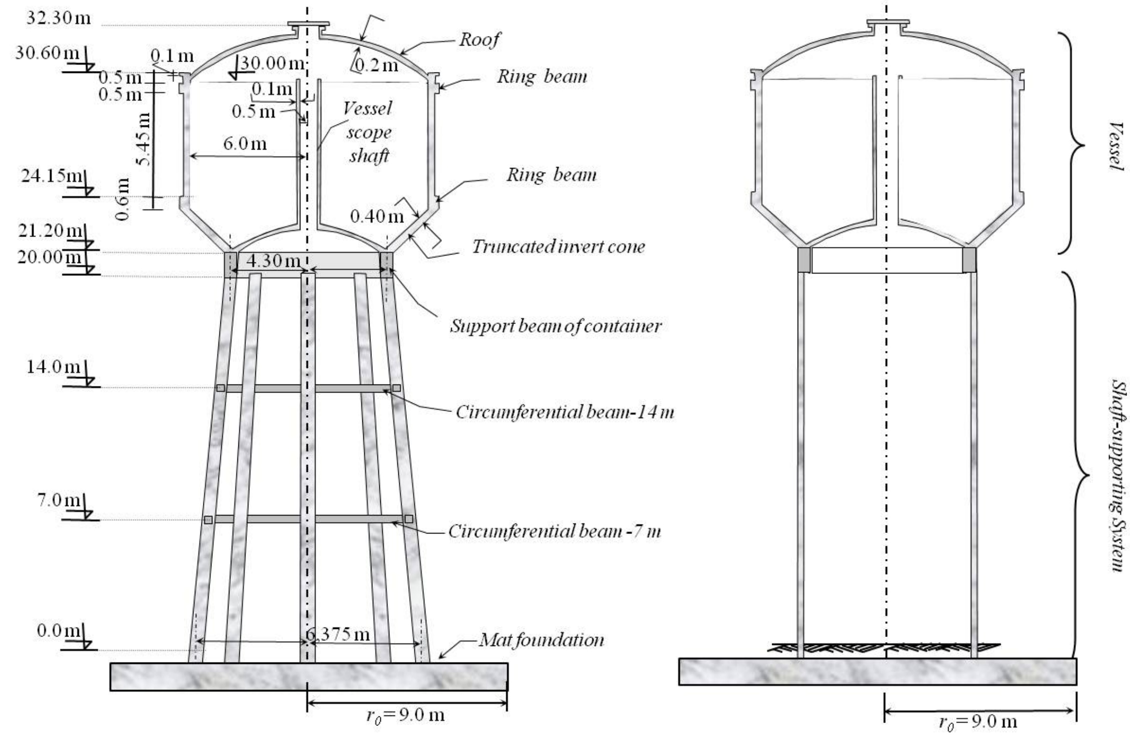

Fig. 3 Vertical cross section of the reinforced concrete elevated tanks considered for the seismic analysis

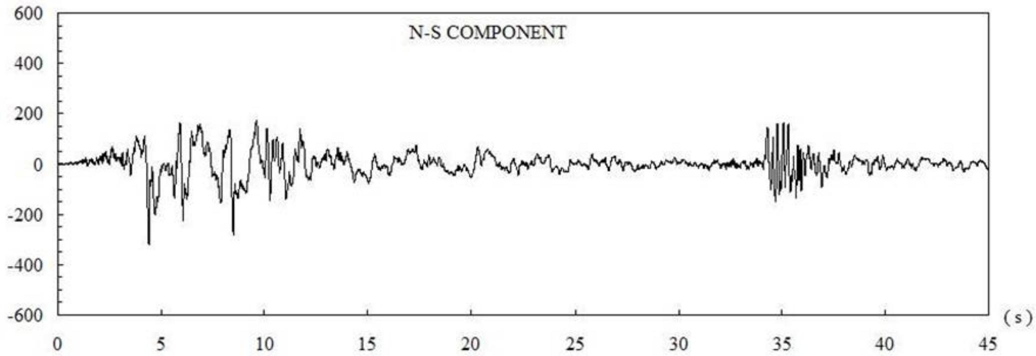

Fig. 4 Considered ground motions N-S component of Yarımca Station – 1999 Kocaeli Earthquake

earthquake time history is applied to the base of model shown in Fig. 2. The vertical components are neglected in the analyses. The consideration of vertical earthquake components may be necessary in certain case where they are larger than their horizontal counterparts. However, the vertical components of the earthquakes considered in this study were lower than the horizontal components. Thus, the consideration of only horizontal earthquake components in the analyses is a valid approach given the tall and slender nature of structure.

To evaluate variations of the dynamic parameters in the elevated tanks depending on different soil conditions, six soil types as shown in Table 1 were considered. Soil conditions recommended in the literature are taken into account in the selection of the soil types and their properties (Bardet 1997, Coduto 2001). For two different supporting structures and six different soil types, seismic analysis of the elevated tank and soil systems were carried out in cases of no embedment ($e/r_o = 0$) and embedment ($e/r_o = 1$).

3. Discussion of the analysis results

The obtained peak values and their times of the maximum sloshing displacements (u_{smax}), according to the soil condition, embedment and supporting system from the different 24 models are given in Table 2 respectively. As can be seen from the table, these maximum responses of the

Table 1 Properties of the considered soil types

Soil types	ζ_g	E (kN/m^2)	G (kN/m^2)	E_c (kN/m^3)	γ (kg/m^3)	υ	v_s (m/s)	v_p (m/s)
S1	5.00	7000000	2692310	9423077	2000	0.30	1149.1	2149.89
S2	5.00	2000000	769230	2692308	2000	0.30	614.25	1149.16
S3	5.00	500000	192310	673077	1900	0.35	309.22	643.68
S4	5.00	150000	57690	201923	1900	0.35	169.36	352.56
S5	5.00	75000	26790	160714	1800	0.40	120.82	295.95
S6	5.00	35000	12500	75000	1800	0.40	82.54	202.18

Table 2 Results of sloshing displacement of the fluid obtained from all seismic analysis

Frame Supporting System												
Soil Type	S1		S2		S3		S4		S5		S6	
	t (s)	u_s(m)	t (s)	u_s(m)	t (s)	u_s(m)	t (s)	u_s(m)	t (s)	u_s(m)	t (s)	u_s(m)
$e/r_0=0$	10.10	-1.96	10.10	-1.98	10.15	-2.02	10.15	-2.14	10.20	-2.26	10.35	-2.42
$e/r_0=1$	10.10	-1.96	10.10	-1.97	10.10	-1.99	10.15	-2.08	10.15	-2.15	10.25	-2.31
Shaft Supporting System												
Soil Type	S1		S2		S3		S4		S5		S6	
	t (s)	u_s(m)	t (s)	u_s(m)	t (s)	u_s(m)	t (s)	u_s(m)	t (s)	u_s(m)	t (s)	u_s(m)
$e/r_0=0$	10.10	-1.74	10.10	-1.77	10.10	-1.80	10.10	1.94	10.15	2.10	10.20	-2.32
$e/r_0=1$	10.05	-1.73	10.05	-1.74	10.05	-1.75	10.10	1.82	10.10	1.95	10.15	-1.98

systems obtained about 10.1 to 10.35 seconds and maximum responses are calculated for the systems in S6 soil type for frame supporting system.

As seen from this table sloshing response obtained for different soil types, supporting system and embedment condition are almost same, in character. Their occurrence time of maximum sloshing is in the vicinity of 10.20 second. For rigid soil conditions the embedment seems not effective on response. On the other hand increasing softness on the soil condition is different. For example maximum displacement reaches 2.42 m in 10,20 s for the no-embedded system in S6 while for embedded system this value can only reaches 2.31 for frame supporting system. This comparison for shaft supporting system are approximately same but the deviation is much bigger. However, as mentioned above, It is seen that approximately the maximum displacement practically occurs at the same time (t =10 s~10,2 s) for all systems. From these models the most decrease in deviation because of the embedment is 4.5% for frame supporting systems situated in S6 and this value reaches %17 for shaft supporting system. When this deviation is investigated for the other systems deviations are less with increasing soil/foundation systems and for this reason it is seen that embedment is not effective on sloshing displacement on the contrary the soft soil conditions. All obtained values and their deviations are discussed and some of them and their deviations in time are illustrated under following titles.

4. Effects of the soil/foundation condition

From analyses of twenty four different models, almost same result are obtained that Soil/foundation system changes the maximum sloshing response of the fluid inside the vessel of the elevated tanks. From all, results of maximum sloshing displacement obtained from the elevated tanks with frame supporting system in case of embedded and no embedment cases are illustrated in Fig. 5. This illustration supports that the interaction is effective on the sloshing in the elevated tank. When the soil gets softer, increases in the maximum sloshing response can be seen in the figure. This increase, especially, became more visible for the configuration with frame supporting system than that with shaft supporting system. Similarly this increase is more severe for no embedment cases than embedded case. For example, sloshing response for frame supporting

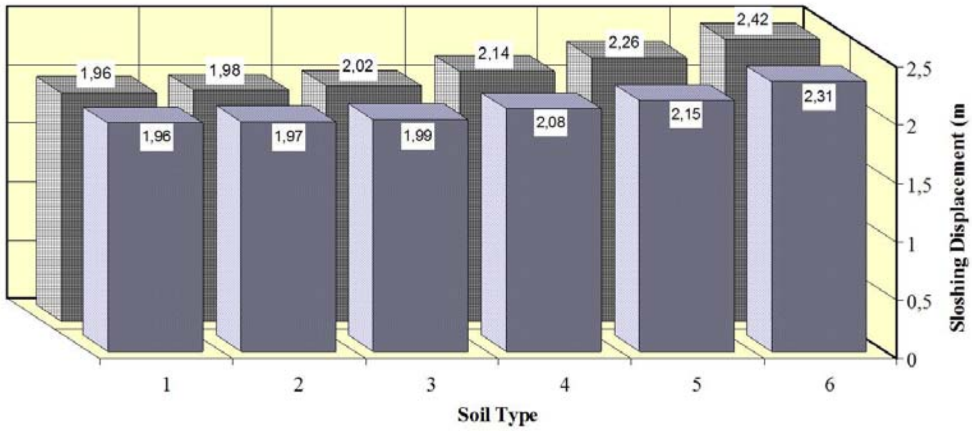

Fig. 5 According to the soil type the deviations of the maximum sloshing displacement obtained from the elevated tanks with frame supporting system in case of embedment and no embedment

system reach 2.42 m for S6 soil type in case of no embedment but for the shaft supporting system this can only reach 2.32 m. When same comparisons are made for the effect of embedment it can be seen that the maximum fall in the value of sloshing displacement is 0.34 m in S6 soil type underlying the tank with shaft supporting system.

The calculated sloshing displacements variation in time for S1 to S3 soils were illustrated in Fig. 6 indicating the case of embedment (a) and no-embedment (b). Similar comparisons between S1 to S6 were given in Fig. 7. It is seen that the maximum displacement practically occurs at the same time (t =10,1 s~10,3 s) for all systems. Comparing Fig. 6 with Fig. 7 and also Fig. 5, it is seen that the variation in the sloshing for stiff soil type like S1 to S3 is small. But for softer soil type variations is comparatively larger. Since the soil type deviations are investigated, the

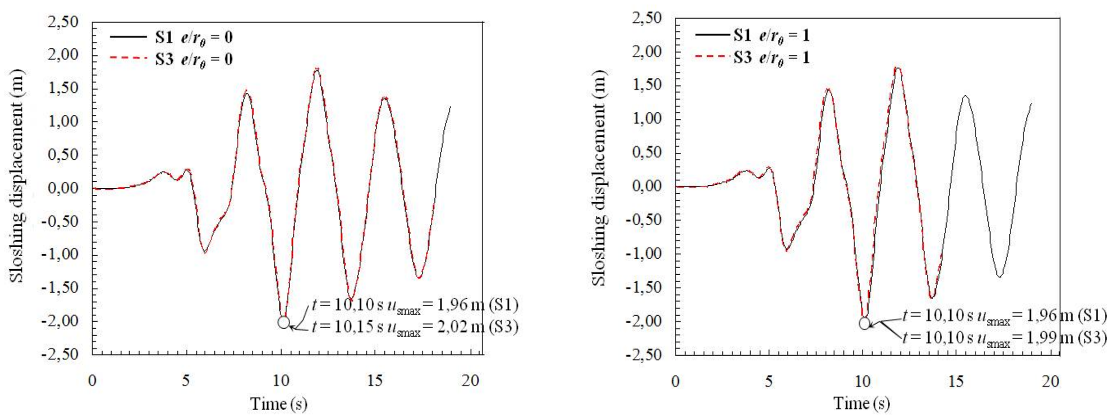

Fig. 6 Deviations of the sloshing displacements in time between S1 to S3: (a) in case of no embedment; and (b) in case of embedment

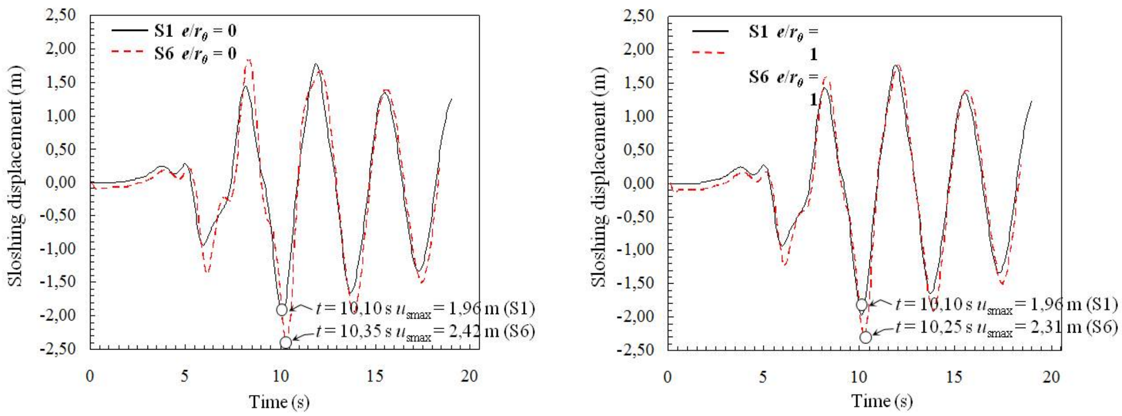

Fig. 7 Deviations of the sloshing displacements in time between S1 to S6: (a) in case of no embedment; and (b) in case of embedment

tendency between S1 to S3 is almost same for both embedment and no embedment (Fig. 6). This phenomenon is different for the Fig. 7. So the sloshing displacement increases 18% between S1 to S6 in embedded case and no embedment for frame supporting system. Furthermore, this variation is noted as 33% in case of no embedment whereas it remained 14% in case of embedment for the shaft supporting system (see Table 2).

Amplitude wise, sloshing deviations between S1 to S6 show that response is different from each other (Fig. 7). Especially, soil/foundation interaction effects on sloshing response are shown clearly from the result of all analyses. Negligible effects of foundation embedment on the results for frame supporting system, in which the value of fall reaches 5% maximally for S6. But for the shaft supporting system embedment cause 15% of decrease for S6.

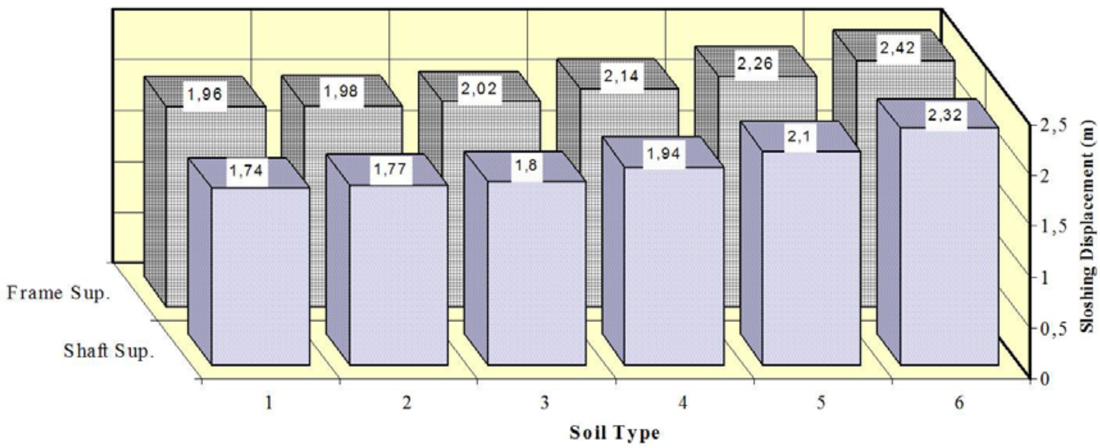

Fig. 8 According to the supporting systems, a comparisons of the sloshing displacements of the elevated tanks in six different soil types

5. Effects of the Supporting System

Fig. 8 shows the comparisons of the sloshing response of both the frame and shaft supporting system with soil types. Maximum sloshing amplitude obtained for all soil types is not close to each other whereas the tendency of the increase in sloshing response with getting smaller stiffness of the soil/foundations is same for investigated models. Also for stiff soil type supporting system for the elevated tanks is more effective than the elevated tank in the soft soil type can be seen from the from the Fig. 8. i.e., for the S1 soil type shaft supporting system causes to decrease on the sloshing displacement as 11%, on the other hand for the S6 soil type this decrease is only 4%.

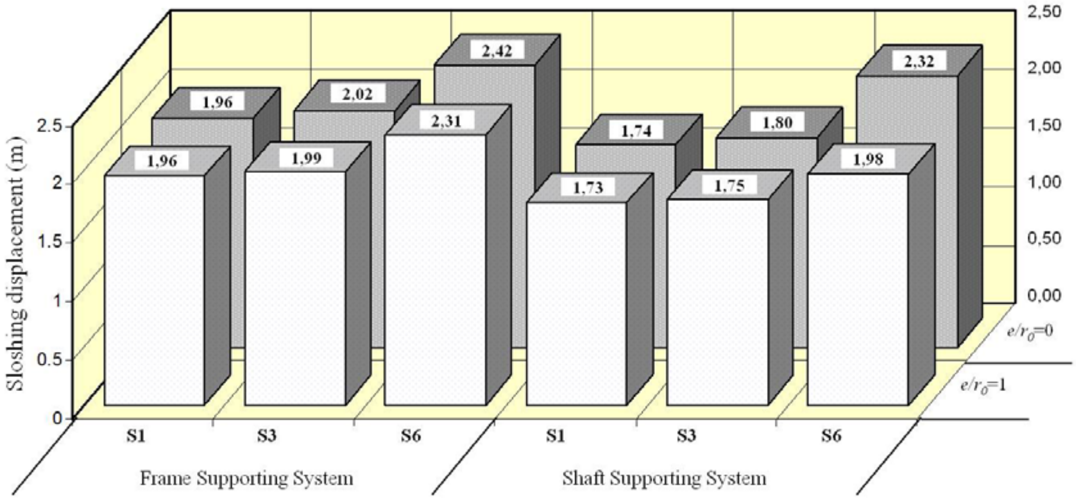

Fig. 9 For two different supporting systems, a comparison of the sloshing displacements of the elevated tanks in three different soil that includes cases of embedment (e/r_0=1) and no embedment (e/r_0=0)

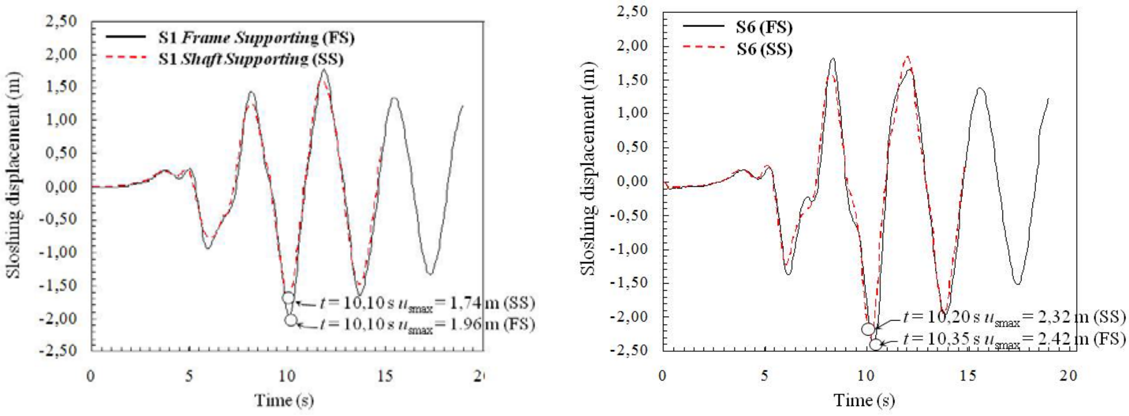

Fig. 10 Deviations of the sloshing displacements in time between frame supporting system to shaft supporting system for (a) S1 soil type and (b) S6 soil type

The comparisons of both supporting system with the case of the embedment are relatively seen from Fig. 9 that provides a summary of the comparison in supporting system according to the embedment. Same effects of the embedment are shown for both supporting system in this Fig. 9. On top of this similar effects the effects are similar, the results illustrated in Fig. 9 imply that embedment affect the sloshing response for the shaft supporting system more then the one with frame supporting system. For example, the decrease in the sloshing displacement due to embedment is 15% in elevated tanks in S6 soil type with shaft supporting system whereas this rate is 5% for the frame supporting in S6 soil type.

As can be seen in Fig. 10 the variations of the sloshing displacement with time almost the same tendency display same behavior for two different supporting systems. As such, the time of maximum reaction of the system nearly coincide for the stiff soil type (Fig. 10(a)). But the behavior differs with the stiffness of the soil type. i.e., as can be seen from the Fig.10.b the maximum reaction occurred in different time for different supporting system for soft soil.

6. Conclusions

Following conclusions are drawn from the performed study.

Although, it is stated in the literature that soil-structure interaction can not considerably affect the sloshing response of the ground level cylindrical tanks, as a consequence of this study it is found out that the sloshing response of the elevated tanks is affected by the soil-structure interaction. But this interaction effect should be taken in design of the elevated tanks into consideration in the design especially these effects should be encountered in the roof design of of the elevated tanks.

The sloshing response of the elevated tanks changes according to both supporting system and the case of the embedment. It seen from the results of the analysis that, the shaft supporting system and embedment results in a decline in the sloshing displacement. It should be stated here that embedment is more pronounced in elevated tanks with shaft supporting than the frame supporting.

The other conclusion can be drawn from the study is that the sloshing response is affected from the embedment more in case of soft soil than the stiff soil. In other words, when the soil gets softer, the effect of the embedment on sloshing response becomes more visible. This effect plays an important role to decrease the sloshing displacement value for the elevated tank with shaft supporting system. But for the frame supporting system this is not so effective and this can be ignored.

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