AN INVESTIGATION ON SEISMIC RESPONSE OF THE R/C RECTANGULAR FLUID TANKS CONSIDERING FLUID-STRUCTURE-SOIL INTERACTION

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ABSTRACT

The coupled oscillations of partially filled reinforced concrete (R/C) rectangular tanks with fluid and soil interactions were studied in this study. Two different rectangular tanks having flat bottoms with 0.5 m and 1 m wall thicknesses are considered. It is assumed that the tanks are situated on six different soil types defined due to well-known earthquake codes. Fluid-Rectangular Tank-Soil/Foundation systems are modeled with the finite element (FE) technique and analyzed using full-transient analysis. In these models, a displacement based fluid FE approximation implemented for taking into account fluid-structure interaction by means of general purpose computer code ANSYS and 3D-Solid FE model with viscous boundary is used to consider soil/foundation interaction effects. Finally, deviations of the sloshing responses, displacement of the tank walls orthogonal to the excitation, and reaction forces obtained from the results are discussed at the end of the study. It is shown that when the soil-structure interaction is considered, the sloshing amplitude of the fluid and displacements of the wall are not affected on this type of tanks, however, the fluid–structure interaction are fairly effective on the seismic behavior of the tank wall orthogonal to the excitation.

1. INTRODUCTION

The motion of the fluid inside a tank and soil behind the tank can be rather violent. These have caused and will cause of different types of damages on various type of tanks. There is an obvious need for explaining what happens in seismic analysis of the tank, when the fluid-structure and soil-structure interaction are considered together. Currently few guidelines and standards include some approximate procedures that these try to consider soil-structure and fluid-structure interaction practically. Chen and Kianoush (2005), however, point out that lumped mass approximation, used generally in modeling the fluid-structure system on these guidelines and standards, fairly overestimates the seismic responses. Furthermore, Livaoğlu and Doğangün (2006) carried a similar study on elevated tanks expressing the soil-structure procedures defined in codes may yield different results from each other. For this purpose, an understanding of the earthquake damage or survived of water tanks requires an understanding of the dynamic force associated with the sloshing and soil-structure interaction by using more realistic assumptions.

Early investigation of dynamic analysis of rectangular tanks including Fluid interaction effects were carried out in 1934 by Hoskins and Jacobsen (1934). They gave the first report on analytical and experimental observations of rigid rectangular tanks under a simulated horizontal earthquake excitation. Then Graham and Rodriguez (1952) used spring-mass analogy for the fluid in a rectangular tank. Housner (1957; 1963) proposed a simple procedure for estimating the dynamic fluid effects of a rigid rectangular tank excited horizontally by an earthquake, and finally, Epstein (1976) extended Housner's procedures in the sense of practical design rule. Finally static and dynamic analysis of rectangular tanks are carried by using Lagrangian fluid finite element (Doğangün et al, 1996). The performance of the rectangular water tank during earthquakes is of much interest to engineers and scientists, because these tanks are commonly used type of tanks that can be used to store variety of liquids, e.g. water for drinking and fire fighting etc. So the seismic behavior of this type of tanks needs to be understood well, otherwise earthquake damage to tanks can take several forms and cause several unwanted events such as shortage of drinking, utilizing water, uncontrolled fires and spillage of dangerous chemical and liquefied gas. Hence understanding of behavior of tank due to cracking on the wall, Schnobrich (2000) underlined the importance of the membrane shear force system in carrying the base shear produced by hydrodynamic pressure on rectangular tank structures and than Chen and Kianoush (2005) conducted a parametric study stating that flexibility of tank wall should be considered in the calculation of the hydrodynamic pressure. Kianoush and Chen (2006) also studied the importance of the vertical component of ground motion on the overall seismic behavior of the rectangular tank and they are suggested that especially for the tank on near field zone, vertical component of the ground motion should be consider for not experiencing above mentioned- unwanted events. Otherwise, even uncontrolled fires and spillage of dangerous fluids subsequent to a major earthquake may cause substantially more damage than the earthquake itself (Priestley et al, 1986).

Finally it should be said here that Veletsos and Tang (1990) studied soil-structure interaction effects on ground level cylindrical tank and pointed out that soil structure interaction does not considerably affect sloshing responses of this type of structures also Livaoglu .and Dogangün (2006) conducted a study on elevated tanks and show that soil structure interaction play important role on this type of tank. Therefore, investigations including fluid-rectangular tank-soil/foundation interaction using 3D FE models have a vital importance on evaluations of seismic behavior of the rectangular tank. There is, however, not adequate number of studies about rectangular tank and not any study about seismic behavior of rectangular tank considering both fluid and soil interaction effects. So, taking into account both the interaction effects in this study, the sloshing, displacements and reaction force responses in seismically-excited rectangular tank are addressed to understate the seismic behavior of this type of tanks.

2. CONSIDERED SYSTEM MODEL AND FORMULATION

Each one of the soil-structure interaction and fluid-structure interaction is separately a complex phenomenon for structures. Especially, the fluid structure interaction needs to be taken into account when analyzing a seismically-excited tank system. In this context, the fluid structure interaction effects are considered by means of displacement based FE in this study. Furthermore, Veletsos and Tang (1990) showed that the effect of soil structure interaction on the impulsive component of response for cylindrical tanks may be substantial and should be considered in the design, also Livaoğlu and Doğangün (2005) expressed that elevated tanks are extremely affected by these interaction effects. So this study takes into account soil-structure interaction effects for seismically-excited rectangular tanks by means of solid FE with viscous boundary. The considered FE model including structure, soil, fluid and boundary elements is shown in Fig 1.

By using different approaches such as: the added mass, Lagrangian, Eulerian, Lagrangian-Eulerian with the finite element method (FEM), the Smoothed Particle Hydrodynamic (SPH) methods etc, fluid-structure interaction effect can be accounted for in determination of the seismic response of tank system. Addition to these approximations, there are some simplified approaches like Housner's two mass representation, Bauer's and Veletsos' multi-mass model for considering the interaction effect approximately. From all, displacement based Lagrangian approach is selected to model fluid-rectangular tank interaction in this study. The fluid finite element is defined by eight nodes having three degree-of-freedom at each node: translation in the nodal x, y, and z directions. Degrees-of-freedom of the element being interaction surface are coupled with the adjacent node-degree-of-freedom of tank wall in the direction normal to the tank wall. The 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. The positive spring stiffness can be expressed below (ANSYS, 1994).

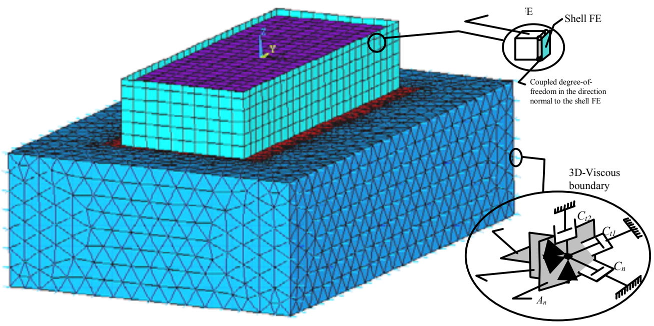

Figure 1: *Considered finite element model of the fluid-rectangular tank-soil/foundation system*

Modeling infinite medium with the numerical method such as FE or boundary element method etc, 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 1996).

To simulate the radiation condition, the "cut off" boundaries with numerical models must include normal and tangential energy absorption elements. These absorption elements are usually represented by springs and dashpots. The use of these dashpots is shown in Figure 1 and, by using this, the radiation condition can be easily achieved. Properly calibrated, these elements absorb the propagating waves in such a way that any incident waves produce zero energy being reflected back into the domain. Even though the energy absorption depends not only on material properties but also on frequency content, Lysmer and Kuhlmeyer (1969) showed that this viscous type of infinite element has enough validity to be used for modeling soil-structure interaction and also defined how the dashpot coefficients are determined in terms of the material properties of the semi-infinite domain. Other approximations as the artificial and/or transmitting boundaries can be classified according to specificness of the problem investigated. For example, there are different types of these boundaries in frequency or time domain with different sensitivities like Damping-Solvent Extraction Method (Song and Wolf 1994), Doubly-Asymptotic Multi Directional Transmitting Boundary (Wolf and Song 1995) etc. Finally, from all of above-mentioned boundaries, viscous boundaries for three dimensions are used to model infinite medium in this study (see Figure 1). Mathematical background of all above mentioned procedures can be viewed from the study by Livaoğlu and Doğangün (2007)

3. NUMERICAL EXAMPLES

A reinforced concrete (R/C) rectangular storage tank shown in Figure 2 with two different wall thicknesses is considered in this study. First, one has the 0.5 wall thickness and second has 1 m, they are named 0.5 m-wall thickness tank and 1 m-wall thickness tank, respectively. These tanks are selected as the same tanks investigated by Koh, Kim and Park (1998). and Doğangün and Livaoğlu (2005). In the examples, Young's modulus, the weight of concrete per unit volume, bulk modulus and density of fluid are taken to be 28000 MPa and 25 kN/m3, 2070 MPa and 1000 kg/m3, respectively. The other characteristics like dimensions of the tank and the foundation system are as shown in Figure 2.

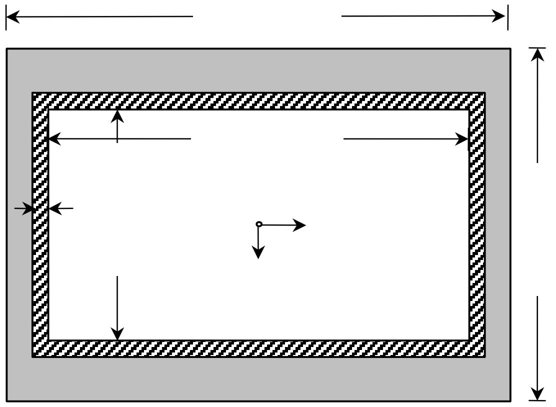

Figure 2: *Plan of the sample rectangular tank*

As an example, first twenty seconds part of North-South components of August 17, 1999 Kocaeli Earthquake in Turkey is applied simultaneously to the system along the y-direction. Both 0.5 m and 1m-wall-thickness-rectangular tanks are analyzed considering them situated on six different soil types given in Tab. 1. The systems are used for analyzing the empty tanks to evaluate the fluid interaction effect on displacement of tank wall. The soil medium beneath the structure foundation is modeled with 29,496 solid elements that the element has eight nodes with three degrees of freedom at each node. The viscous boundaries are modeled by using 760 elements for three dimensions per node.

	Soil Types					
	S1	S2	S3	S4	S5	S6
ζ_g	5.00	5.00	5.00	5.00	5.00	5.00
E (x10^4) (kN/m^2)	700	200	50	15	7.5	3.5
G (x10^4) (kN/m^2)	270	77	19	5.8	2.7	1.3
E_c (x10^4) (kN/m^3)	940	270	67	20	16	7.5
γ (kg/m^3)	2000	2000	1900	1900	1800	1800
υ	0.30	0.30	0.35	0.35	0.40	0.40
v_s (m/s)	1149.1	614.2	309.2	169.36	120.82	82.54
v_p (m/s)	2149.9	1149.2	643.7	352.6	295.9	202.2
E: Young modulus, , G : Shear Modulus, E_c : Bulk modulus υ: *Poisson's ratio* γ: unit density of the soil ζ_g: damping ratio						

Table 1: Properties of the considered soil types

4. DISCUSSION OF THE RESULTS

There are three parameters selected to investigate the seismic behavior of the rectangular tank system taking fluid-structure-soil/foundation interaction into account: (i) displacements of the walls orthogonal to the excitation, (ii) reaction forces along the excitation direction on same walls and (iii) sloshing displacement of fluid inside the tank. First, the maximum displacements responses at the selected node of the tank walls (Figure 3.) and its deviations with time are evaluated due to soil condition and in view of both partially filled and empty tank circumstances. Next using the reaction forces obtained at the base node of the wall shown in Figure 3, how the reaction forces are affected by interactions was tried to be clarified. Finally the response of sloshing displacement is discussed whether the soil-structure interaction changes it or not for the rectangular tanks accounted for this study.

4.1 Displacements of the wall orthogonal to the excitation

As a scope of this study, partially filled rectangular tanks were selected (Fig 3.a), but to investigate the seismic behavior of superstructure, empty tank-soil/foundation system is also analyzed considering soil-structure interaction effect (Figure 3b.). It can be clearly seen from the illustration that displacements occurred in the tank wall are quite different from each other. While walls of partially-filled tank vibrate outside from the fluid domain and never move to the interior of the fluid domain, oscillations of empty tank walls have standard characteristics. It is also worthy to state here that the left side and right side wall vibration characteristics and maximum displacement values and their occurring times are not same whereas for the empty tank these are same as expected. These results conclude that the fluid play an important role on dynamic behavior of the rectangular tank walls.

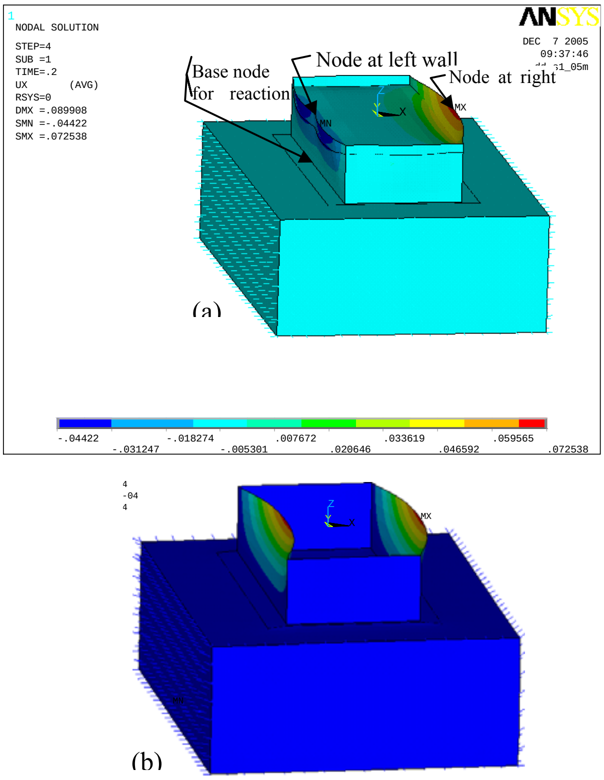

Figure 3: *Displacement shape of tank walls (a) for partially-filled tank (b) for empty tank*

When lateral wall displacement histories are compared for the empty tank, as seen from the Figure 4., the maximum lateral displacement takes place approximately at 5 second. Maximum displacement of the walls obtained for tank in S6 soil type is 0.011 m and roughly six times greater than the displacement obtained for S1 soil type. It is also meanly seen from this comparison that soil structure interactions affects the wall displacement histories for the empty tank.

The displacement histories for partially-filled tanks are not same with the displacement histories' estimated for empty tank in character. As seen from Figure 5., the displacement histories for these tanks are differently occurred not only in view of empty or filled circumstances but also oscillations shapes of left and right side wall.

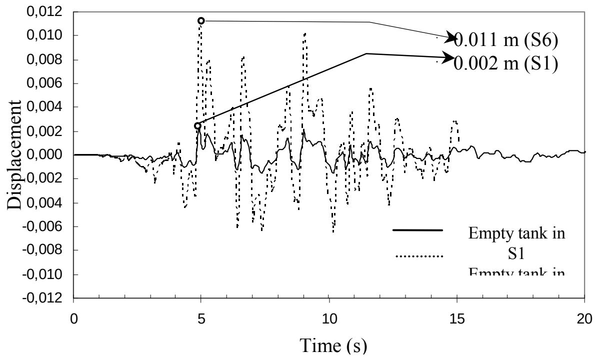

Figure 4: *Comparison of displacements histories between 0.5 m-wall-thickness empty tanks situated on S1 and S6 soil type*

While maximum displacement calculated for the right side wall (see Figure 3.) occurs at 6.75 s as 0.11 m, for the left side wall maximum displacement occur differently at 8.85 s as 0.034 m. It is clearly seen from this comparison that numerical modeling of fluid inside a tank can provide to determine changes of the seismic behavior of wall. Therefore, the hydrostatic and hydrodynamic pressure of fluid must be included for the dynamic analysis of the fluid-rectangular tank system. Otherwise the model may not represent behavior of the system. Differently from the empty circumstance, histories obtained for the partially-filled tanks show the soil condition does not change the deviations. So the deviations of histories, maximum displacement occurred time and values indicates that fluid-structure interaction has the most important parameter on the seismic behavior of the rectangular tanks. Finally, figure 5. shows that how the impulsive and convective parts representing the motion of the fluid are effective on the seismic response of the tank. For example the maximum displacement obtained partially filled tank are ten times greater than the empty tank in S6 soil type. Simply, this result exhibits the fluid interaction effects on seismic response of rectangular tanks.

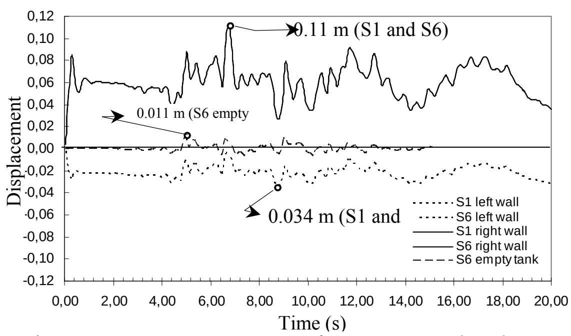

Figure 5: *Comparisons of maximum displacement histories of the walls orthogonal to the excitation for 0.5 m-wall-thickness tanks*

Figure 6. shows good comparison for the tanks in S1 soil type and expresses such a wall flexibility that has an effect on displacement. When the evaluations are made for 1 m-wall-thickness tanks, the all fact obtained above are also found to be same. Also, it should be explained that the wall flexibility play an important role on the changes of fluid interaction effect. i.e the maximum displacement occurred on the fluid-structure-soil/foundations system realized as 0.013 for the right wall of the tank (t_w=1.0 m), in other words, the maximum displacement due to wall thickness reduces from 0.11 m to 0.013 m. Finally, it is easily said that considering the comparisons on the Figure 6., when the wall gets more flexible, the fluid structure interaction effect on displacement appears more clearly, whereas any changing does not appear due to the soil-structure interaction effects.

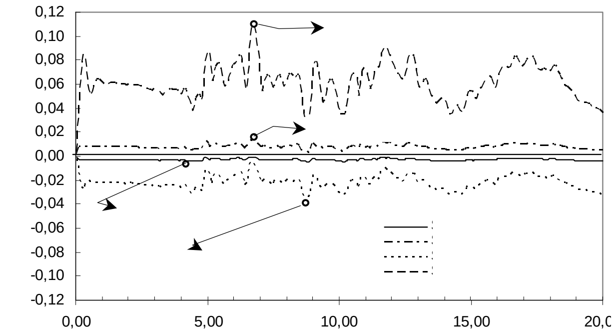

Figure 6: *The comparative deviations of the displacement values of the walls for 0.5 m and 1 m-wall-thickness-tanks orthogonal to the excitation*

4.2 Reaction Forces

To see the effects of soil-structure interaction on the maximum values and time histories of resultant force due to soil type, figure 7 for (a) 0.5m-wall-thickness tank, (b) for 1 m-wall-thickness and figure 8 for comparison of time histories of the resultant forces between S1 and S6 soil types are illustrated. The comparisons given in figure 7 prove the soil type may have some effect on changing the reaction forces. For example the reaction decreased value of $2.46x10^6$ to $2.33x10^6$ between 0.5 m-wall-thickness tank situated on S1 and S6 soil types. It is worthy here to note that even in the case 1 m-wall-thickness tank, similarly maximum reaction forces may be affected by the soil conditions as depicted in Figure 7. These decreases in some cases may reach 7% for 0.5 m-wall-thickness tanks and 9% for 1 m-wall-thickness tanks. Figure 8 illustrates a comparison on the response histories of the reaction forces acting on bottom-node at the middle of the long side wall between the tanks situated on S1 and S6 soil type. It may be concluded from the illustration that the flexible soil conditions change the response of the system, but the question "does this interaction effect have to be included in design of the tank or not" is vital for the earthquake resistant of this structure. The analyses realized and considered soil condition show that this effect can be ignored. However the special soil condition, not studied in this study, may increase the effects on behavior of the rectangular tanks, because the illustration of the comparison of the histories show that the interaction effect cause to begin the system seismic response changing for the tank situated on S6 soil type.

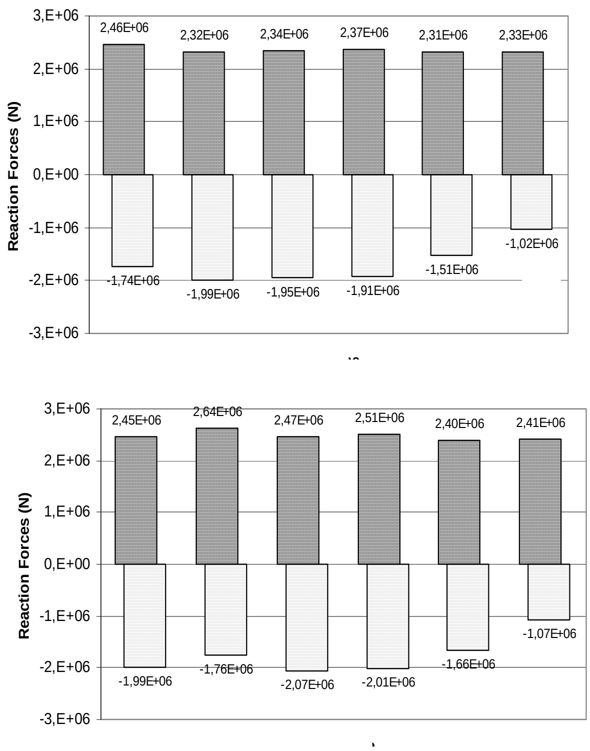

Figure 7: *Max and minum reaction forces at the mid-node of the bottom of (a) 0.5 m-wall-thickness tank wall (b) 1 m-wall-thickness tank*

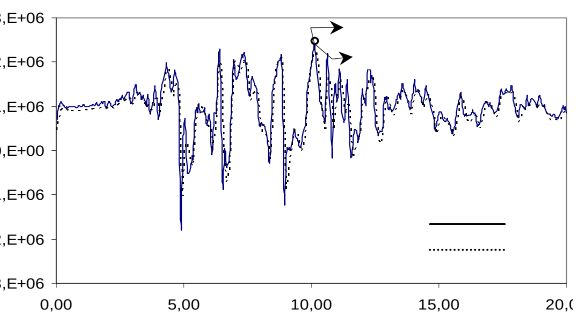

Figure 8: *A comparison of histories of reaction forces at the mid-node of the bottom of 0.5 m-wall-thickness tank between the tank on S1 and S6*

5. CONCLUSION

The conclusions drawn from the study may be summarized as follows:

Soil-structure interaction plays an important role to increase the displacement of the wall orthogonal to the excitation for the empty tanks investigated in this study, whereas it is observed that soil interactions effects are almost zero when the fluid inside the vessel considered numerically. After all it can be stated that the added mass and/or similar approximation trying to consider fluid structure interaction effects may cause the misleading results on behavior of the rectangular tank.

Histories obtained for the partially-filled tanks show that the soil condition does not been changed due to soil-structure interaction, contrary to the empty tank. So inferences from the deviations of histories and their comparisons between the empty and filled tank circumstances indicate that fluid-structure interaction has a pronounced influence upon the rectangular tanks than the soil-structure interaction.

From the results obtained reaction forces, it is concluded that flexible soil condition changes the response of the system, but the analyses realized for the considered soil condition in this study show that this effect can be ignored. However the special soil condition, not studied in this study, may increase the effects on behavior of the rectangular tank. As a recommendation, these investigations, thus, should be widen for the special conditions of soil medium.

For transient excitations the maximum water surface amplitude observed after the motion ceased, for this purpose correctly to determine the sloshing response amplitude of the fluid for the transient analyses, the analyze should be continued after the action ceased.

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