EFFECTS OF DIFFERENT BACKFILL SOIL TYPES ON DYNAMIC BEHAVIOR OF RECTANGULAR TANK WALL CONSIDERING BACKFILL-WALL-FLUID INTERACTION

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ABSTRACT

This study focused on the effects of backfill soil types variation on seismic response of rectangular storage tanks. However, only the exterior wall of the rectangular tank interacts with both backfill and fluid is tackled since each part of the structure shows considerable differences in terms of the loads subjected to along with geometrical and positional differences. Hence, the objectives of this study are to develop a model to determine the response of tank wall under dynamic loading and to examine the commonly encountered backfill effects on dynamic response of rectangular tank wall. Three different backfill soil types, which are classified by Unified Soil Classification System, were chosen to represent the soil properties in the analyses. These are poorly graded gravels (GP), silty gravels (GM) and poorly graded sands (SP). Drucker-Prager material approach is used for elasto-plastic soil behavior, and also nonlinear wall-soil interface behavior including seperation is considered. Fluid-rectangular tank wall-backfill system is modeled with the finite element method considering wall-backfill interaction. In addition to this, the fluid-wall interaction is taken into account using Lagrangian approach. The findings obtained from the study showed that maximum vertical displacements of backfill, lateral and roof displacements, stress responses generally decreased with increasing backfill soil stiffness. However, sloshing displacement is not affected by backfill-wall interaction.

KEYWORDS: rectangular tank, wall-backfill interaction, fluid-structure interaction

1. INTRODUCTION

Liquid storage tanks are becoming more and more prevalent in the modern world due to fast growing population and industry. As an integral part of the infrastructure of modern society, these structures are used for a wide range of goals, i.e to store water for drinking and fire fighting, chemicals, petroleum, and liquefied gas, etc. Therefore, the liquid storage tanks should remain functional in the post-earthquake period to ensure water supply in earthquake-affected regions. In some cases, however, these structures have collapsed during earthquakes with disastrous physical and economical consequences. Thus, to ensure the safety of liquid storage tanks, the seismic behavior of them has been studied for many years.

Depending on design conditions and load bearing mechanisms, the tanks are classified into different categories, e.g. rectangular tanks, elevated tanks, underground tanks, ground-level cylindrical tanks, etc. Numerous studies have been carried out for seismic behavior of liquid storage tanks, however, most of these studies have concentrated on the ground-level cylindrical tanks.

The effect of soil pressure is important in a number of problems, such as retaining and sheet pile walls, basement walls, bridge abutments, tunnel walls and many other structures. Earthquakes have unfavorable effects on lateral soil pressures acting on retaining walls. Hence, the assessment of seismic lateral soil pressures is of practical significance in most seismic designs of retaining walls. Discussion of the all the research work on the seismic soil pressure is extensive and is beyond the scope of this study. Rather, only some milestones that have influenced the design practice are described below. The pioneering work, currently known as the Mononobe-

Okabe method (M-O), is developed by Okabe (1924) and Mononobe and Matsuo (1929). Since then, a great deal of research has been performed to evaluate its adequacy and to improve it. Nazarian and Hadjian (1979) reported on a survey of the literature in the area of earthquake-induced lateral soil pressures and identified the shortcomings of different approaches. Seed and Whitman (1970) focused on limit-state design and they used modified Mononobe Okabe analysis, an extension of the Coulomb-Rankine sliding wedge theory. Also, a detailed summary of retaining wall damage during earthquakes was reported by Seed and Whitman (1970). The pseudo-static design and the plastic equilibrium mechanisms are adopted in these methods. However, displacements of the retaining walls may be induced during earthquakes. Therefore, a displacement-based design needs to be introduced. Thus, Richards and Elms (1979) proposed a procedure to design retaining walls taking into account the permissible displacements of the wall. Some researches focused on elastic or elasto-plastic approximations, i.e elastic solutions have been developed like Wood's solution which for a rigid wall fixed at its base lead to pseudo-static earth pressures hereby 2.5 times higher than Mononobe-Okabe (Gazetas et al., 2004). Furthermore, Veletsos and Younan (1994a, 1994b) developed a simple approximate expression for simulating the dynamic pressures, the associate forces, and the responses induced by ground shaking on a straight, vertical rigid wall retaining soil with a semi-infinite, uniform viscoelastic layer of constant thickness. The solutions for frequency-dependent and frequency-independent parameters were studied and compared with the results proposed by Scott (1973). The elastic constrained bars with distributed mass were used to represent the soil stratum in backfill. They concluded that Scott's (1973) model, which ignores radiational soil damping and considers the wall pressure to be proportional to the relative motions of the wall and the soil at the far field, does not adequately describe the action of the system and may lead to large errors.

From the above discussion, it can be stated that there is no literature about the analysis of backfill-rectangular drinking water storage tank wall- fluid system under the combined actions of forces induced by fluid and soil interactions. Literature investigations also show that relatively little work has been done on rectangular storage tanks. Moreover, different studies are extremely essential for the design purpose of the rectangular drinking water storage tanks. Therefore, the aims of this study are to appreciate the significance of the backfill effects and investigate how different backfill soil types affect the seismic behavior of rectangular tank wall. In order to achieve the objectives of this study, finite element analyses covering backfill-tank wall-fluid system have been performed considering both soil and fluid interactions.

2. DESCRIPTION OF THE CONSIDERED RECTANGULAR TANK SYSTEM

In this study, the structural properties of the prismatic reinforced concrete rectangular storage tank with a container capacity of 10000 m^3, which is frequently constructed in Turkey, were considered as shown in Fig. 1. For that purpose, Kökçüoğlu drinking water tank constructed in Samsun province in Turkey was selected as the reference structure. Considered rectangular tank has two main divisions. The length and the width of the structure are 61 m and 39.2 m, respectively. Total height of the reference tank is 7.4 m from the bottom of the foundation. The other characteristics like dimensions of the tank and the foundation system are shown in Fig.1. In the analyses, Young's Modulus, Poisson's ratio and the weight of concrete per unit volume are taken to be 28000 MPa and 0.2 and 25kN/m^3, respectively.

The container is filled of water with a density of 1000 kg/m^3. In such structures, the maximum service level (liquid level) is taken into account as 5.5 m. The exterior wall of the rectangular tank considered in this study interacts with various soil types encountered in practice. Many types of material can be used for backfill. Clean sands and gravels are the most suitable materials. They drain rapidly, are not susceptible to frost action, and remain stable. Silty sands, silts and coarse-grained soils containing some clay are less desirable since they drain slowly, are subjected to seasonal volume changes, and may lose much of their strength with time. But frequently in practice, the excavated soil materials are used as backfill. In the light of these explanations, dry-cohesionless poorly graded gravels (GP), silty gravels (GM) and poorly graded sands (SP) were taken into consideration as backfill materials. The soil properties used in the analyses are shown in Table 1.
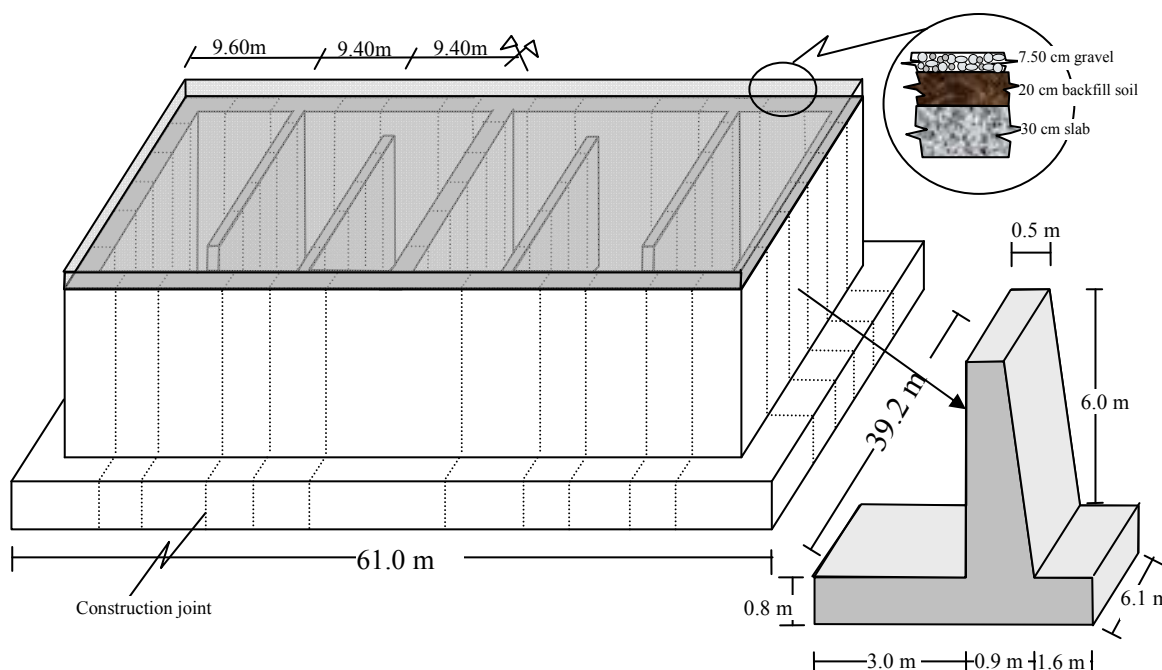
Figure 1 Considered tank and the exterior wall properties

Table 1 Data for considered backfill soil types

Name of the model		BF35_SP	BF33_GM	BF34_GP
Soil Properties	ϕ	35	33	34
	E (MPa)	20	75	125
	Y	0.3	0.3	0.3
	γ (kN/m³)	19	22	20.5

E :Young Modulus ; ϕ : Internal friction angle ; υ : Poisson ratio ; γ: unit weight of soil

3. BACKFILL-EXTERIOR WALL-FLUID INTERACTION MODEL

As shown in Fig. 2, in order to model the backfill-structure-fluid system, finite element method is used. The considered system is assumed as to be built in rock foundation. Structural wall is modeled with solid elements having six degrees-of-freedom per node, for roof system with quadrilateral shell element (four node six degrees-of-freedom per node) and also with additional mass of cover. To model backfill-wall interaction, unidirectional element with nonlinear generalized force-deflection capabilities is used in the analysis. The element has longitudinal or torsional capability in 1-D, 2-D, or 3-D applications. The longitudinal option is a uniaxial tension-compression element with up to three degrees of freedom at each node: translations in the nodal x, y, and z directions (ANSYS, 1994). Naturally backfill behind the exterior wall of the structure interacts with wall in compression; however, in tension it is assumed that there is no interaction. Therefore, this interaction is tried to model in this scope through the study. Then the unidirectional nonlinear element is used having very rigid compression characteristics with tensionless in interaction face of backfill-wall system. No bending or torsion is also considered. It must be emphasized here that the vertical friction between the wall and backfill is ignored. In order to characterize fluid-rectangular tank wall-backfill model and determine the seismic behavior of the systems, transient dynamic analysis was carried out by mean of ANSYS commercial package program. Elements all mentioned above are available in ANSYS; especially fluid elements are specially formulated to model fluid contained within container having no net flow rate. Mathematical details in modeling the fluid and the bounded media can be found on the other study of the second and third authors (Livaoğlu and Doğangün, 2007).

Because of complex interacting phenomena and the inherent variability and uncertainty of soil properties, it is not currently possible to analyze all aspects of the seismic response of backfill-wall-fluid system. Furthermore, it is well known fact that generally, soil is very sensitive in character when exposed the earthquake-induced motion, so elasto-plastic and/or perfectly plastic behavior of the backfill soil, in the soil-structure interaction especially for the system subjected to the lateral force or system excited by seismic actions, are frequently observed. Lateral responses are generally the most important parts of the SSI interaction. In view of all reason mentioned above Drucker-Prager material model is used in modeling the backfill soil medium in this study. In the seismic analyses, it is assumed that the tank is subjected to North-South component of the ground motion recorded at the Yarımca station during the August 17, 1999 Kocaeli earthquake in Turkey. The peak horizontal ground acceleration at the YPT station was 0.32g.
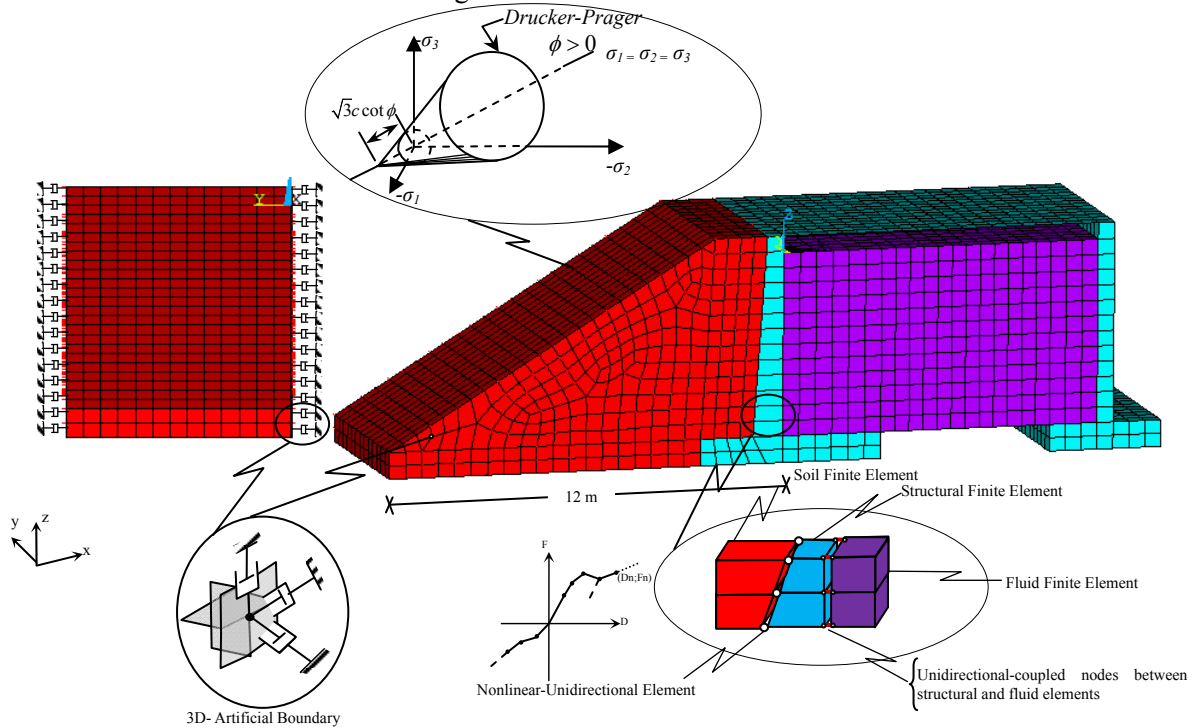

Figure 2 Considered Backfill-Structure-Fluid interaction model

4. DISCUSSION OF THE ANALYSIS RESULTS

Table 2 The obtained peak responses and their occurrence times for full of fluid systems

Model Name	BF35_SP		BF33_GM		BF34_GP	
	t(s)	value	t(s)	value	t(s)	value
u_{vi} (m)	16.0	-0.2654	16.0	-0.2047	16.0	-0.2513
u_{ve} (m)	16.0	-0.2277	16.0	-0.1909	16.0	-0.2001
u_r (m)	4.95	0.0079	4.9	0.0071	4.9	0.0031
u_{sl} (m)	9.95	-1.2613	9.9	-1.2605	9.9	-1.2588
u_{sr} (m)	9.95	1.2630	9.9	1.2622	9.9	1.2603
S_{ze} (MPa)	4.95	5.2890	4.9	4.3655	8.8	-1.8265
S_{zi} (MPa)	4.95	-5.6167	4.9	-4.8253	4.9	-1.7589
S_{xe} (MPa)	4.95	0.0461	7.4	-0.0362	8.8	-0.0537
S_{xi} (MPa)	7.45	-0.0424	7.4	-0.0435	8.8	-0.0506

u_{vi}: Maximum vertical displacements at top of backfill adjacent point on wall face ; u_{ve}: Maximum vertical displacements at outer point of top of backfill u_r: Maximum horizontal roof displacement of wall; S_{ze} : Maximum calculated stress in z direction of exterior face (backfill side) of the wall ; S_{zi} : Maximum calculated stress in z direction of interior face (fluid side) of the wall S_{xe} : Maximum calculated stress in x direction of exterior face (backfill side) of the wall ; S_{xi} : Maximum calculated stress in x direction of interior face (fluid side) of the wall ; u_{sl} and u_{sr} : Maximum sloshing vertical displacements at left and right side of the fluid medium

Table 2 reports the maximum vertical displacements, roof displacements and stress values at both the exterior and interior face of the rectangular tank wall and their occurrence times obtained from the analyses for full container system considering different backfill soil properties. For the tanks which are full of water at service level, the maximum sloshing vertical displacements and their occurrence times are given for both the left and right side. Their implications are discussed below.

4.1. Vertical Displacements of the Backfill

In order to evaluate the vertical displacements of backfill, which represents the soil behavior during seismic action, three different analyses considering different backfill soil types were analyzed in case of full of fluid tanks. Figure 3 illustrates that the displacement responses of backfill increase with time and all the maximum responses were obtained at the end of the duration of seismic action as expected.
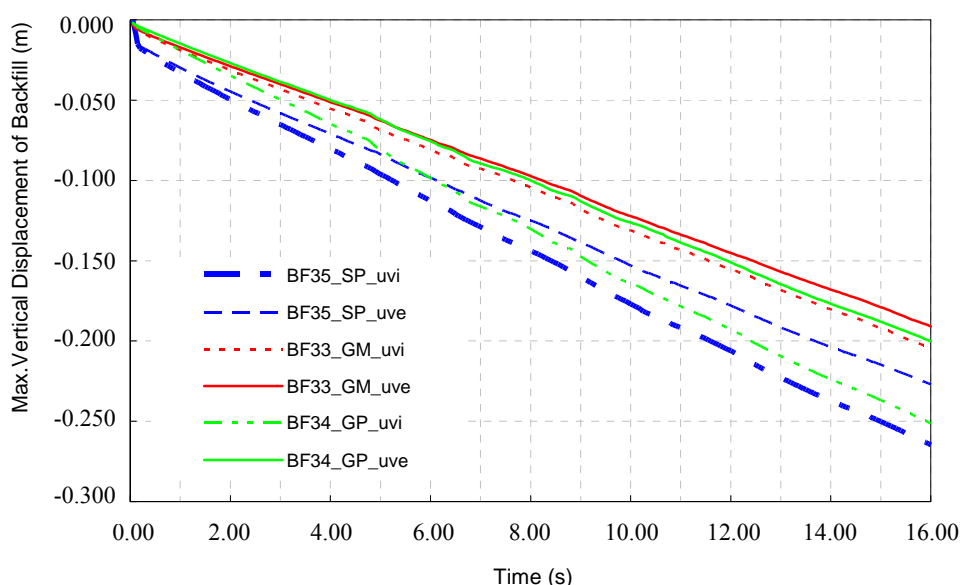
Figure 3 Calculated maximum vertical displacement time histories at backfill top

As can be shown in Figure 3, for the BF33_GM model, the value of maximum displacement is -0.2047 m and -0.1909 m at the adjacent node to the wall of backfill top and outer node to the wall of backfill top, respectively. Same quantities were calculated as -0.2654 m and -0.2277 m for the BF35_SP model. The results stated that maximum value of the vertical displacement response changed with changing backfill soil conditions and this response increases with decreasing the stiffness of the backfill soil between BF33_GM and BF35_SP models. But, the BF34_GP system behaves differently from the others. When the plastic stress intensities are investigated, it is observed that about 6 sec., plastic strain reaches the greater level in comparison with the other systems, and the system behaves like brittle material, so sliding surface appears clearly.

4.2. Lateral and Roof Displacements

The maximum calculated displacements along the height of the exterior wall of tank are shown in Figure 4. The most significant point from the comparison is that variation of backfill soil properties (relatively stiff or relatively soft) affects notably the displacement response of the system. For example; while the maximum roof displacement was estimated as 0.0079 m for the BF35_SP model, the same quantity was calculated as 0.0031 m for the BF34_GP model. As can be understood from this comparison, not to take into account the accurate backfill properties causes underestimation or overestimation of the displacement responses. Similarly, the variations of roof displacements as a function of time are shown in Figure 5. Time history responses of the

displacement show that relatively softer backfill soil condition increases the displacement response, and one can be said that the backfill-wall interaction affects the system behavior so that, decrease in the displacement response is almost at a level of 60% between BF35_SP and BF34_GP models. Moreover, their deviations in time differ significantly.
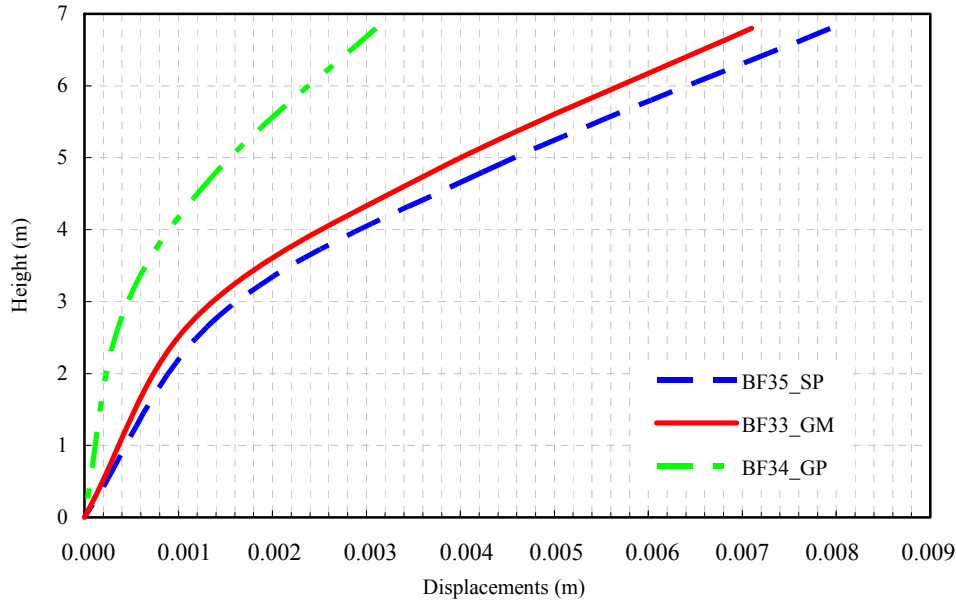

Figure 4 Heightwise variation of maximum calculated displacements of the exterior wall of the rectangular tank
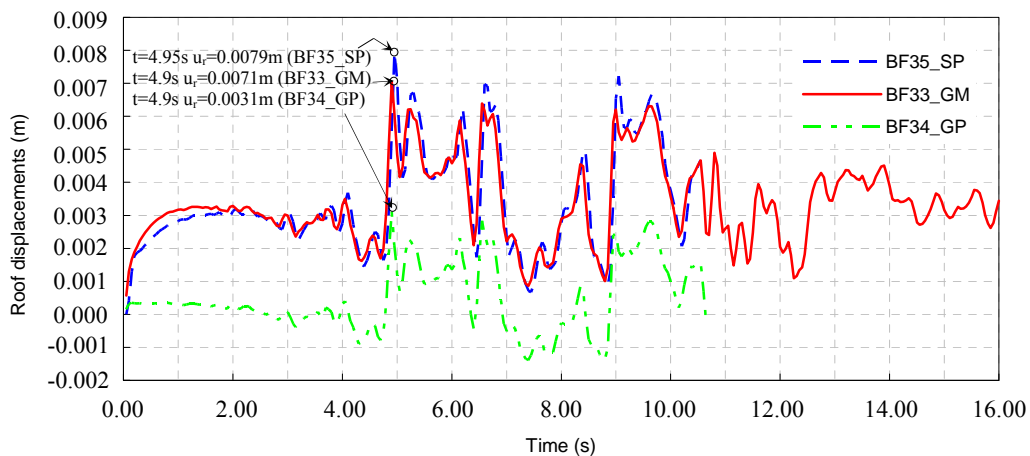

Figure 5 Variation of the roof displacements as a function time

4.3. Sloshing Displacements

The results of estimated sloshing displacement obtained in this study showed that neither maximum sloshing displacement nor their occurrence times are considerably changed for the investigated rectangular tank. From the results it is concluded that the maximum sloshing occurs approximately as 1.26 m in 9.9-9.95 s for all models. In addition, when the sloshing responses compared with the displacement responses, it is clearly shown that deviations are very small. So, it can be concluded that the backfill interaction does not affect the sloshing displacement response.

4.4. Stresses in the wall

The computed stress responses and their variations in time at both the exterior and the interior face of the rectangular tank wall in z direction are shown in Figure 6. The maximum stress values obtained both exterior and interior face of the tank wall in z direction tend to decrease with increasing backfill soil stiffness.As shown in Figure 7, the maximum stress values at the exterior corner node of the wall in z direction are obtained as 5.2890 MPa at 4.95s for BF35_SP model and -1.8265 MPa at 8.8s for BF34_GP model. In other words, the stress response decreased almost 65%. Furthermore, time deviations of stresses are remarkably different from each other. When the comparisons are made at interior mid-node of the tank wall, it is observed that aforementioned decrease occurs at a level of 69%. Consequently, it is clearly said that the stress responses are significantly affected from backfill-wall interaction.
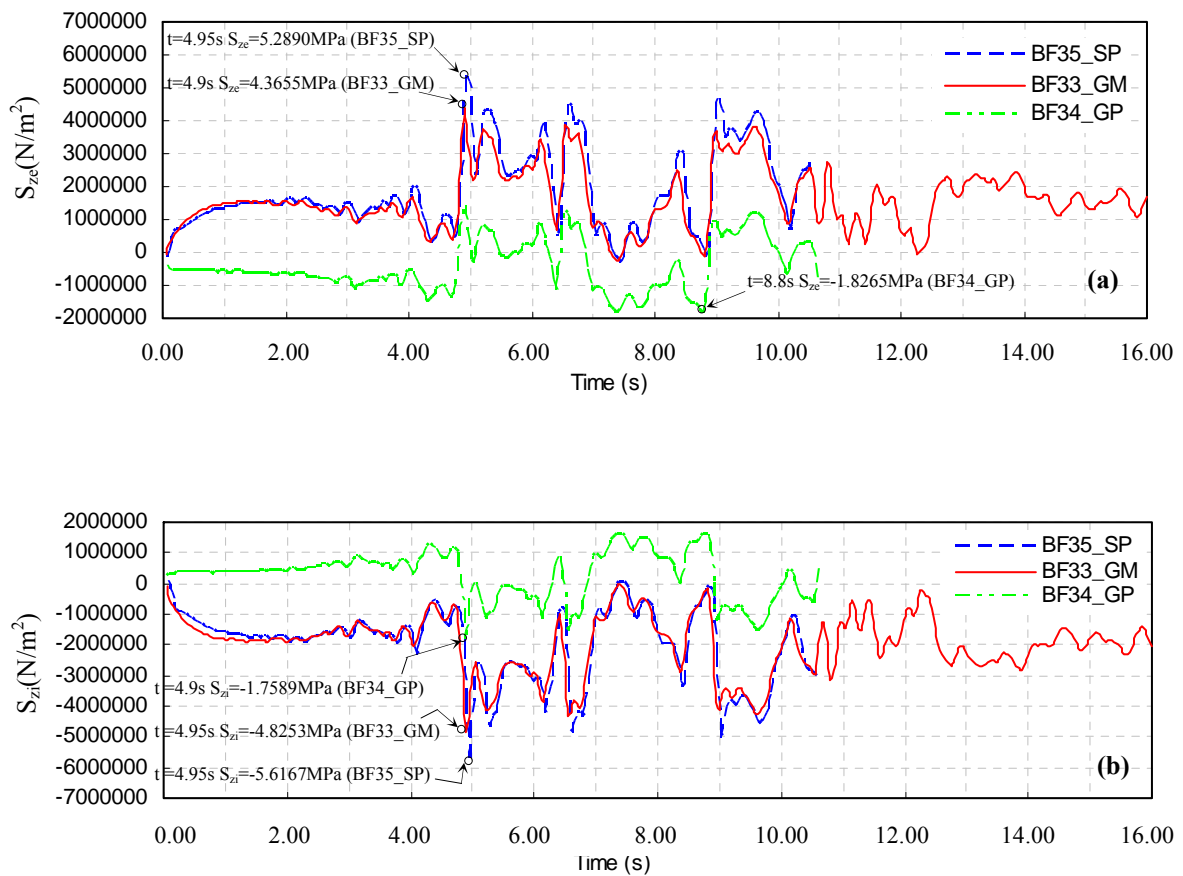

Figure 6 Comparative variations of the calculated stresses histories in z direction a)at exterior corner-node b)at interior mid-node of the tank wall

5. CONCLUSIONS

Considering the fluid and soil interactions, a finite element model is presented to investigate the effects of the backfill soil properties variation on the seismic response of rectangular tank wall. In general, the vertical displacements of backfill, lateral displacements over the height of the tank wall, roof displacements and stress responses significantly changed, when the backfill soil gets softer. So, one can be said that variation of backfill soil types may be more effective and influences the system behavior. However, the sloshing displacement response is not practically affected by backfill-wall interaction effects. So, these effects on the sloshing response of rectangular tanks can be ignored during design process.

The analyses can be extended considering the empty container situation. In this way, the fluid-wall interaction

effects are observed more sensitively comparing with the full of fluid situation. Furthermore, it is recommended that more numerical examples should be analyzed and evaluated for a wide range of backfill soil types so that the results presented here can be generalized.

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