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Seismic Behavior of Ground Rested Rectangular RC Tank Considering Fluid- Structure- Soil Interaction

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Abstract: *Many liquid storage tanks around the world have affected by earthquakes. Seismic analysis of such tanks is much complicated due the Fluid-Structure Interaction (FSI). Furthermore, when the soil properties are taken into consideration, the analysis with the Fluid-Soil-Structure Interaction (FSSI) becomes very complicated and tedious.*
In this paper, a 3-D Finite Element (FE) model for a shallow rectangular rested on soil Reinforced Concrete (RC) tank is constructed using the FE software; ANSYS. Furthermore, a nonlinear dynamic time history analysis is carried out to investigate the behavior of this type of tanks during earthquake considering the FSSI. The vertical and the horizontal components of three ground motion records are used in the study with different frequency contents. Moreover, two different soil types are considered. The effects of the FSSI and the ground motions on the straining actions at the tank's walls at the base, the sloshing and, the hydrodynamic pressure are obtained and discussed. It is concluded that the dynamic behavior of the rectangular tank system is sensitive to the frequency content of the ground motion. In addition, the FSSI has great effects on the seismic behavior of such type of tanks, which should be taken into account in the design.
Keywords*: Rectangular Tanks, Seismic, Fluid-Soil-Structure Interaction, Frequency Content, Time History Analysis*

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I. Introduction

Rectangular reinforced concrete tanks are widely used as engineering structures to store water, fuel or the other liquids. Earthquake behavior of storage tanks is very different to other structures. The dynamic interaction between fluid, structure and soil is of great concern in many engineering problems. Each of the soil-structure interaction and fluid-structure interaction is separately a complex phenomenon for structures. In fact, the dynamic characteristics of the tank and its response to transient excitations are governed by several factors such as earthquake characteristics, the interaction between the fluid and the structure, and the soil-structure interaction along with their boundaries.

Although, there was many researches on the fluid–structure interaction in liquid storage tanks, most of them are concerned with cylindrical tanks. There are very limited studies that were carried out on the Fluid-Structure-Soil Interaction (FSSI) effect on the seismic behavior of RC rectangular tanks. For rectangular tanks, **Haroun (1984)** proposed a very comprehensive model for analysis of the general system of loadings of tanks. The hydrodynamic pressures were computed by a classical potential flow method. The formulation of hydrodynamic pressures just considered the rigid wall condition. **Park et al. (1990)** studied the dynamic response of rectangular tanks using the boundary element method to calculate the hydrodynamic pressures and the finite element method to analyze the solid wall. The time history analysis was used to obtain the dynamic response of fluid storage tanks considering both impulsive and convective effects. **Dogangun et al. (1996)** presented the formulation of three-dimensional Lagrangian fluid finite element that includes the effects of compressibility and surface sloshing motion. The general-purpose structural analysis program SAPIV used this developed finite element and was employed for the static and dynamic behavior of rectangular liquid storage tanks.

Chen and Kianoush (2005) presented a procedure referred to as the sequential method to get hydrodynamic pressures based on a two-dimensional model for rectangular tanks considering the effect of flexibility of tank. **Livaoglu (2008)** investigated the dynamic behavior of fluid– rectangular tank foundation system with a simple seismic analysis procedure. In this procedure, Housner's two mass approximations for fluid and the cone model for soil foundation system used to present interaction effects. **Ming and Duan (2010)** proposed a new technique for numerical simulation of sloshing in the fluid-structure interaction problems based on the unstructured grids. **Livaoglu et al. (2011)** studied the dynamic behavior of the backfill on rectangular tanks using the finite element method. The study considered both the effects of liquid–structure and soil–structure interactions. **Naderi et al. (2011)** studied the effects of soil-buried tank-liquid interaction under several earthquake ground motions. ABAQUS software was used to analyze the buried rectangular concrete storage tanks. The results from the endurance time analysis were compared to nonlinear time history analysis and shows reasonable consistency.

Chen and Kianoush (2012) proposed a design procedure based on the structural model using the generalized single degree of freedom (SDOF) system for concrete rectangular tanks. The effect of tank wall flexibility on the hydrodynamic pressure was considered. The consistent mass approach in dynamic analysis was used. **Cakir and Livaoglu (2013)** investigated the seismic behavior of the rectangular tank considering the effects of Soil-Structure-Interaction (SSI) and verified the validity of FEM under fixed base assumption through the proposed analytical model. **Kotrasová (2014)** presented a theoretical background for analytical calculation of circular frequencies and hydrodynamic pressures developed in rectangular liquid storage tanks during an earthquake. Analytical results of natural frequency are compared with experimental ones. **Chen and Huang (2015)** used a time-independent finite difference method to solve for a fully nonlinear sloshing fluid in a tank mounted on a structure. The interaction between the sloshing fluid and the dynamic response of the structure was also investigated. The fourth-order Runge-Kutta method was used to calculate the dynamic response of the structure. **Faridkhouri and Elias (2015)** presented a simplified method to solve wall forces in rectangular storage tanks subjected to earthquake loading. The suggested procedure was compared with Housner's and ACI methods and it was observed that the results of these equations were accurate and reliable.

Yazdanian et al. (2016) explained that the natural frequencies obtained from modal analysis are a starting point for time history analysis and it is necessary to obtain the frequencies before any further analysis. Four different analyses including static, modal, response spectrum, and time history analyses were performed in order to make a comparative analysis on two rectangular concrete tanks. **Kotrasova and Kormanikova (2016**) presented a theoretical background for specification of hydrodynamic effect of fluid on solid of tank fixed to rigid foundation and numerical solution for Finite Element Method (FEM). **Toussi (2016)** conducted a series of experimental and numerical studies to find the effect of different types of base excitations on liquid surface in its container. **Elizabath and Janardhanan (2016)** investigated the dynamic effects of sloshing phenomenon by coupling computational fluid dynamics and structural solver. The use of baffles inside the tanks is also studied and compared with those tanks without baffles.

Yazdanian and Ghasemi (2017) investigated the dynamic behavior of concrete rectangular tanks using the FE method in three-dimensional space in which the coupled fluid–structure equations are solved. **Chougule et al. (2017)** investigated the seismic analysis of the ground supported water tank resting on soft soil consisting of mass of roof, mass of tank wall, mass of water and mass of base slab. In addition, a parametric study was carried out considering spring mass model, period in impulsive and convective mode, horizontal seismic design coefficients, base shear and, hydrodynamic pressure due to impulsive and convective mass of water. **Stranda and Faltinsen (2017)** investigated a 2D rectangular sloshing tank with a flexible sidewall analytically and numerically taking into account the coupling between sloshing and the flexible wall. This analysis presented new information about the effect of internal motions and flow in a membrane structure with a free surface. **Yazdanian and Fu (2017)** presented a comprehensive study for the dynamic response of rectangular storage tanks using Finite Element Method (FEM). Various parameters were investigated, such as; liquid height, density and, earthquake with different Peak Ground Acceleration (PGA). Modal and time history method is used to investigate these parameters. Six different ground motion records were used for time history analysis.

This research work aims to obtain a comprehensive understanding of the seismic behavior of the shallow rectangular RC ground rested tanks with [$(L/H_w) > 2$] during earthquakes. Accordingly, the effect of the Fluid-Soil-Structure Interaction (FSSI) on the seismic behavior of shallow rectangular RC tanks during earthquakes has been investigated. Moreover, the effect of the soil properties and the frequency content of the ground motion on the tank's seismic behavior have been investigated too. To get such understanding, the well-known ANSYS software has been used to construct a FE model for a shallow rectangular RC tank with its foundation system and subsoil conditions. A modal analysis has been carried out first for the tank with fixed base in order to verify the basic dynamic properties of the tank against the obtained analytical ones from other published researches and several design codes worldwide. After that, a parametric study using nonlinear dynamic time history analysis has been carried out using three ground motion records representing a wide range of frequency content. Furthermore, three different subsoil cases have been considered, the first is the tank with fixed base in which no subsoil has been considered and, the other two cases correspond to different soil properties representing hard and medium soils.

Description of the model

In order to deal with such a complex problem, which is the fluid-soil-structure interaction (FSSI), a rested on soil, shallow rectangular RC tank with dimensions of 30.0 m length (L_y), 15.0 m width (L_x) and, 6.0 m wall height (H_w) has been used in this study. The walls' thickness of the tank (t_w) was 0.60 m and the height of the liquid inside the tank (H_L) was 5.50 m. It is worth to mention that this tank was previously used by several researchers such as **Kianoush and Chen (2006)**, **Chen and Kianoush (2005)**, **Kim et al. (1996)**, **Ivval (2012)** and, **Yazdanian and Ghasemi (2017)**. A schematic configuration of the tank is shown in **Fig.1.** The material properties for the concrete and the liquid are listed in **Table 1**.

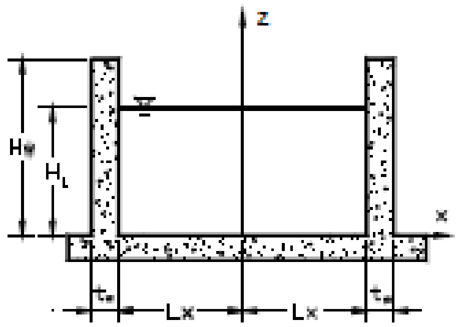


Figure 1 A schematic representation of the tank considered for analysis.

Table 1 Material properties of liquid and tank for concrete rectangular tank

concrete			liquid	
E_c (Pa)	ρ_c (kg/m^3)	υ	ρ_w (kg/m^3)	bulk modulus (Pa)
$2.644e^{10}$	2300	0.17	1000	$2.1e^{9}$

Where E_c, ρ_c, υ and ρ_w are the young modulus, density, poisson ratio of concrete and the density of liquid respectively.

Finite Element (FE) modeling

Before going through the tedious investigation and the complex parametric study, a verification process has been carried out in order to assess the reliability of the model and assumptions by comparing its results to the numerical findings available in the previous published researches and design codes. The verification process includes assessment of the suitability of the model to simulate the Fluid-Structure Interaction (FSI) behavior by carrying out a modal analysis for a fixed base tank and the tank's floor is fully anchored to the rigid ground.

For this purpose, the well-known FE software ANSYS has been used to simulate the behavior of the rectangular tank. The material models have been set using the material library in ANSYS for different linear, nonlinear and contact material for the fluid and structure. The tank structure has been modeled using plastic shell element, SHELL181, with eight nodes, which has three degrees of freedom (DOF) at each node. The fluid domain has been modeled using 3D brick-shaped fluid element, FLUID80, having three DOF at each of its eight nodes. The FE idealization of the tank with fixed base is shown in **Fig. 2**.

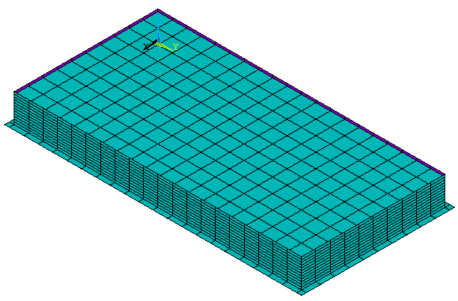


Figure 2 FE model of the rectangular tank fixed at its base

The fluid-structure interaction (FSI) has been considered by coupling the nodes at the interface of the fluid and the shell in order to get equal displacements in the perpendicular direction to the tank's walls. On the interface, each node of the fluid domain should coincide exactly with that of the corresponding shell element. Therefore, only normal pressure can be exerted to the tank's walls by the fluid and it can slip on the tank wall in the direction parallel to the wall. In vertical direction, all fluid nodes located at the interface with the tank floor must be restrained. Finally, it is worth to mention that the reduced method has been used in the modal analysis.

Verification of the model

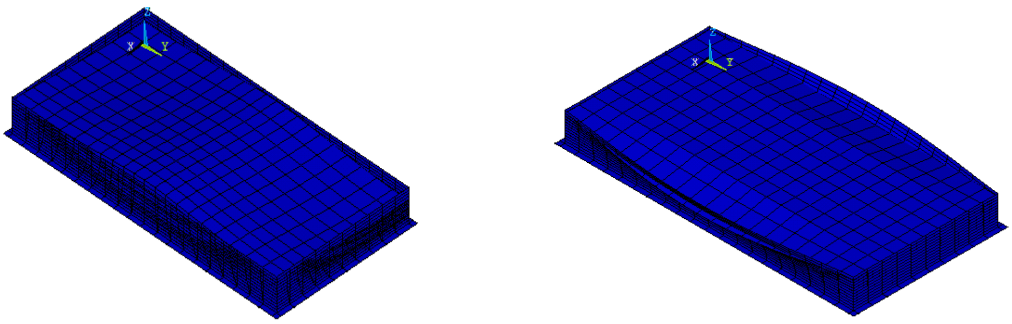
Natural frequencies and mode shapes of any tank are significant parameters in the analysis of the tank. The most important modes are the convective and the impulsive modes, which have the maximum effective mass. In addition, this analysis can be a starting point for other analyses, such as response spectrum analysis or time history analysis. Modal analysis is carried out using ANSYS program to get the free surface's natural frequencies and the corresponding mode shapes. The verification process includes comparing the obtained results to analytical results provided by other researchers and, comparing the results to different design codes' equations.

a- Verification with analytical results

To verify the proposed FE model, the fundamental periods of the impulsive and the convective modes of the shallow rectangular tank have been obtained and compared to the analytical solution proposed by **Haroun and Housner (1981)**. Accordingly, the modal analysis has been employed and the resulted natural frequencies for the impulsive (T_i) and the convective (T_c) modes have been listed in **Table 2** and compared with the analytical results. As shown in **Table 2**, the obtained FE results are in a good agreement with analytical results as minor differences have been noticed between the FE results and the analytical ones. Therefore, the results demonstrate the validity of the model. Furthermore, the fundamental mode shapes of the shallow rectangular tank are shown in **Fig.3.**

Table 2 Comparison between FE and analytical results

Fundamental period (sec)	FEM	Analytical	% Difference
T_i	0.154	0.15	-2.67
T_c	9.18	8.56	-7.24



(a) Convective mode shape
T_c = 0.154 sec

(b) Impulsive mode shape
T_i = 9.18 sec

Figure 3 The fundamental mode shapes of the tank.

b- Verification with different design codes

Great attention was paid by several design codes for the seismic design equations of the liquid storage tanks such as ASCE 7, Eurocode-8 (2008), ACI 350.3 (2001), ECP-201 (2012) and, IS 1893 (1984). The formula for calculating the convective and impulsive periods, which were provided by these design codes, are listed in **Table 3**. It can be noticed that the formula for calculating the convective period is the same in ACI 350.3 (2001), ECP-201 (2012) and, IS 1893 (1984). In addition, the formula of the impulsive period is the same in Eurocode-8, ECP-201 (2012) and, IS 1893 (1984). In ASCE 7, there is no expression for the impulsive period.

Table 3 Expressions for convective and impulsive time period given in different codes.

Reference	Expression	
	convective	impulsive
ACI 350.3	$T_c = \dfrac{2\pi\sqrt{L}}{\sqrt{3.16\, g \tanh\left(3.16\left(\frac{H}{L}\right)\right)}}$	$T_i = 2\pi\sqrt{(W_i + W_w)/(gk)}$ k = flexural stiffness of tank wall

Eurocode 8	$T_c = \dfrac{2\pi\sqrt{L/g}}{\sqrt{\frac{\pi}{2}tanh\left(\frac{\pi}{2}\left(\frac{H}{L}\right)\right)}}$	$T_i = 2\pi\sqrt{d/g}$ d = deflection of wall due to a uniformly distributed load of magnitude q = m_f g/4Bh
IS (1893-1984)	$T_c = \dfrac{2\pi\sqrt{L/g}}{\sqrt{3.16\tanh\left(3.16\left(\frac{H}{L}\right)\right)}}$	$T_i = 2\pi\sqrt{d/g}$
ECP-201		
ASCE 7	$T_c = 2\pi\sqrt{\dfrac{D}{3.68\,g\tanh\left(3.68\frac{H}{D}\right)}}$ Replace D with L	No expressions are given

To verify the FE results with these design codes, the obtained convective period from the FE model has been compared to those obtained by the formerly mentioned codes' formula as listed in **Table 4**. The comparison shows that minor differences have been found; about 9.04%, when comparing the FE result with the ACI 350.3, ECP-201and, IS 1893 (1984). On the other hand, the difference has been increased to reach 9.83% due to Eurocode-8. ASCE 7 Code gives the greatest difference, which reaches 18.66%.

Table 4 Comparison between FEM and different seismic design codes for the convective mode.

Fundamental period (sec)	ACI 350.3	Eurocode 8	IS 1893 (1984)	ASCE 7	ECP-201
T_c	8.55	8.277	8.55	7.467	8.55
% Difference	9.04	9.83	9.04	18.66	9.04

Parametric study

After verifying the ability of the FE model to simulate the rectangular tank and the FSI, the seismic response of partially filled rectangular shallow RC tank under ground motion excitations in both horizontal and vertical directions has been studied. The rectangular concrete tank dimensions used in the parametric study are listed in **Table 5** and the material properties are the same as listed in **Table 1**. Furthermore, and in order to account for the soil-structure interaction, two types of soil have been used to investigate the effect of soil structure interaction (SSI) on the dynamic response of liquid storage tanks. The first soil has been chosen to represent hard soils, referred to by S1 and, the second one represents medium soils, and has been referred to by S2. The nonlinear parameters of the studied types of soil are listed in **Table 6** where ρ is the soil density and υ is Poisson's ratio of the soil.

Table 5 Rectangular tank dimensions

Lx (m)	Ly (m)	H_w (m)	t_w (m)	H_L (m)
10	20	6	0.5	5.5

Table 6 Characteristics of soil used in the analysis

Soil type	ρ (kg/m^3)	υ	E (MPa)	Cohesion (C) N/m^2	Dilation angle ψ
Hard (S1)	2000	0.25	260	20000	10
Medium (S2)	1900	0.3	90	10000	4

Generally, two methods were followed by the researchers to model the soil-structure interaction (SSI) problems, the direct method and the substructure method. In the direct method, the superstructure, the foundation system and, the unbounded soil mass are modeled with a suitable interface element. On the other hand, in the substructure method, the superstructure and the foundation system are modeled separately with a convenient consideration of load transfer from superstructure to the foundation system. In this paper, the soil structure interaction (SSI) has been modeled with the concept of elastic half space theory and the superstructure and the foundation system have been presented by direct method.

As mentioned before, the tank walls and floor were generated using SHELL181. In this part, the concrete nonlinear behavior was considered on the model using a multi-linear stress strain curve. To perform this in ANSYS, MISO (Multilinear Isotropic Hardening) option is used to describe the stress-strain diagram. MISO option is preferred to use for non-cyclic load histories and for large strain cycling. In addition, the 3D model of the subsoil has been created using the SOLID45 element and the Drucker–Prager nonlinear material model has been employed to model the soil behavior. The Drucker–Prager material model describes the nonlinear behavior of the material plasticity, which depends on the engineering properties of soil that have been input. The contact between the structure and the soil has been presented by contact pair TARGE170 and CONTA173 elements. The effect of friction between the tank floor and the subsoil was neglected at the contact area so the coefficient of friction has been set to zero. Furthermore, the nonlinearity of the soil within the soil medium and at the interface between the foundation and the subsoil has been employed using the Dracker-Prager material model and a default contact function for the foundation-subsoil interaction.

Nonlinear Time History Analysis

The nonlinear dynamic time history analysis was proven to be the most powerful analysis type in predicting the behavior of the structures under the seismic loads. This is because it takes into account the material, as well as, the geometrical nonlinearities. Due to its powerful capabilities and its reliability, this type of analysis was dealt with as the reference solution by which any other type of analysis is compared for validation. However, this type of analysis is not preferred in the design process due to its complexity and the high requirement of hardware resources and running time. In this research work, the dynamic time history analysis has been employed to obtain more realistic results and reliable conclusions. Both material inelasticity and geometrical nonlinearity have been employed.

In order to cover a wide range of the expected ground motions, three different ground motion records which have different frequency contents; Low Frequency Content (LFC), Medium Frequency Content (MFC) and, High Frequency Content (HFC), have been selected to perform the dynamic time history analysis. The three records are Kobe (1995), Northridge (1994) and, Duzce (1999) representing LFC, MFC and, HFC, respectively. It is worth to mention that, the frequency content of a ground motion is the ratio between the normalized Peak Ground-Acceleration (PGA) and the normalized Peak Ground-Velocity (PGV). The frequency content can be classified into three categories as follows (Hodhod and Wilson, 1992):

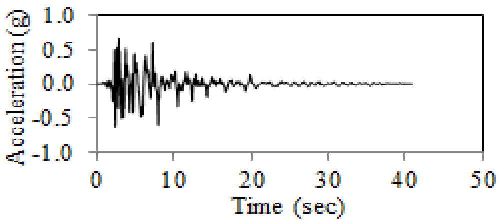
1. Low frequency ground motion: (LFC) for [(A/V) < 0.8 g/ms-1].
2. Medium frequency ground motion: (MFC) for [0.8 g/ms-1 ≤ (A/V) ≤ 1.2 g/ ms-1].
3. High frequency ground motion: (HFC) for [(A/V) > 1.2 g/ms-1].

Moreover, Rayleigh damping has been considered in the analysis. The damping value for both structure and the soil has been set to be 5% and for the fluid was 1%. The characteristics of the selected ground motion records are listed in **Table 7**. The ground accelerations for the horizontal components are shown in **Fig.4**. Furthermore, the ground acceleration of the vertical components can be found on the https://peer.berkeley.edu

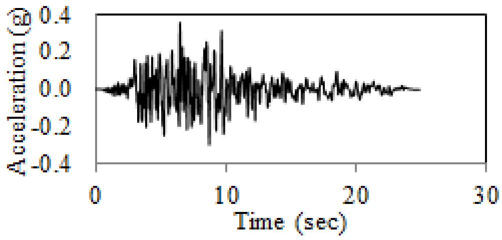
The seismic excitation has been applied at the base of the structure as an acceleration time history in both horizontal and vertical directions and the structure responses have been obtained at each time step. As the sloshing height variation has a great concern in the design of rectangular tanks, its values have been detected at three different locations (points A, B and C in **Fig.5.a**). Points A, B and C are located at the free surface of the liquid at the mid-span of the walls in X and Y directions and at the corner of the tank, respectively.

Table 7 Characteristics of the selected ground motions.

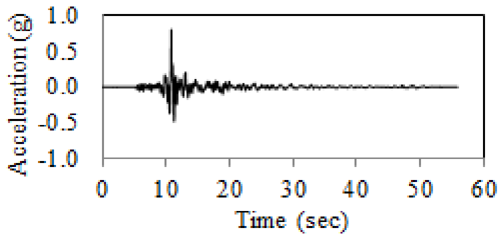
Class	Earthquake	Record	Station	Mw	PGA (g)	PGV (cm/s)	(A/V)
LFC	Kobe 1995/01/16 20:46	TAK-090	Takatori	6.9	0.616	120.73	0.510
MFC	Northridge 1994/01/17 12:31	CNP-106	90053 Canoga Park - Topanga Can	6.6	0.356	32.08	1.110
HFC	Duzce, Turkey 1999/11/12	BOL090	Bolu	7.1	0.822	62.10	1.324



(a) Kobe, 1995 (LFC)

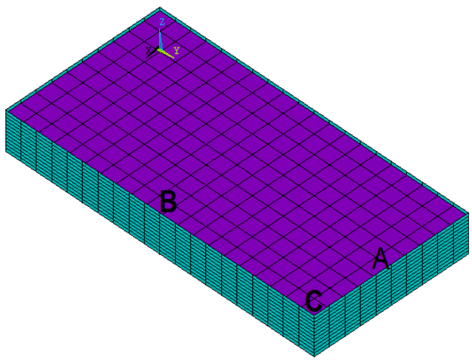


(b) Northridge, 1994 (MFC)

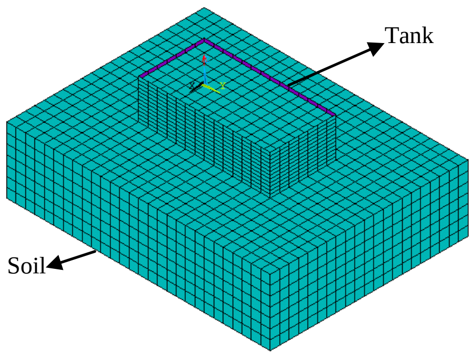


(C) Duzce, 1999 (HFC)

Figure 4 Horizontal components of the selected ground motion records



(a) Fixed base tank



(b) Tank with flexible soil

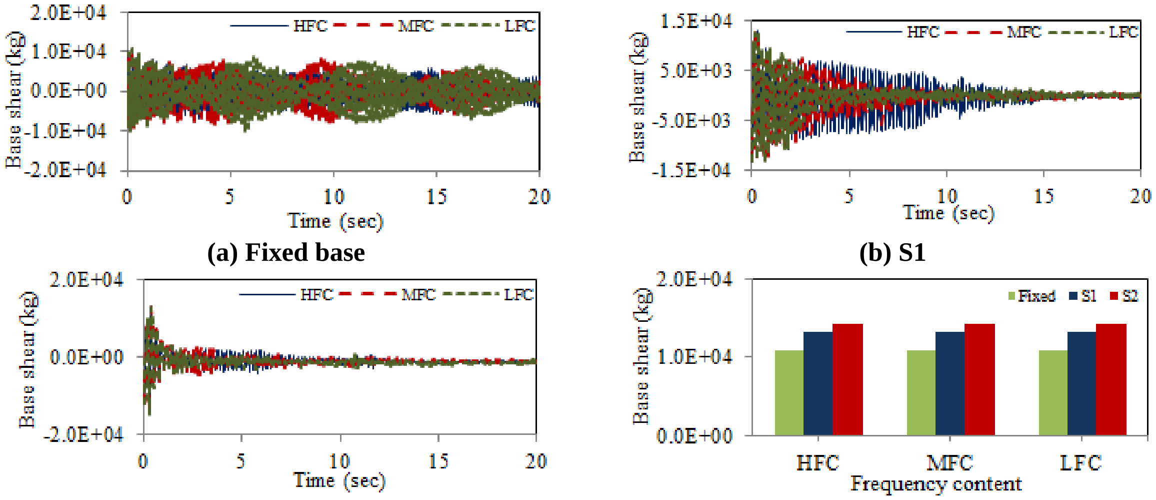
Figure 5 FE model of considered rectangular concrete tank

II. Results and discussion

The nonlinear dynamic time history analysis has been carried out in order to investigate the seismic behavior of shallow rectangular RC tanks when the FSSI is considered. Three cases have been studied, the first is the tank with fixed base in which no subsoil has been considered and, the soil has been considered in the other two cases with two different soil properties representing hard and medium soils. The resulting transient base shear (V), base moment (M), sloshing displacements and the hydrodynamic pressure on the tank's wall due to combined effects of horizontal and vertical components of earthquake records have been studied and a comparison between the different three subsoil cases has been constructed.

Base shears and base moment responses

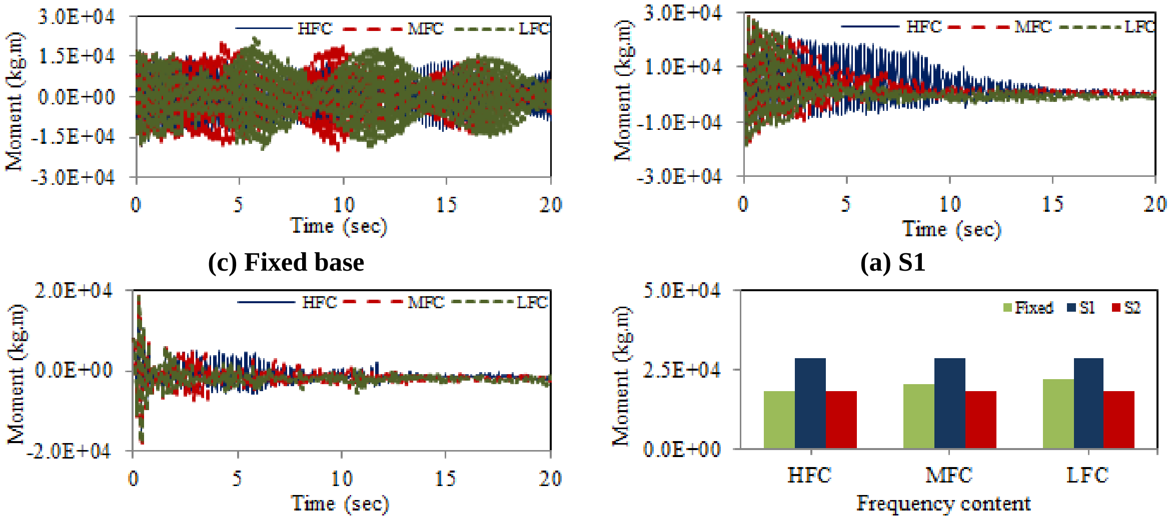
The time histories of walls' base shear and walls' base moment due to different ground motion records and different subsoil cases have been obtained at the middle strip of the tank wall for its long and short directions as shown in **Fig. 6** to **Fig. 9**.



(a) Fixed base (b) S1

(c) S2 (d) Extreme values

Figure 6 Time history of base shear response of long wall under HL &VL excitation for the 3 earthquake records



(c) Fixed base (a) S1

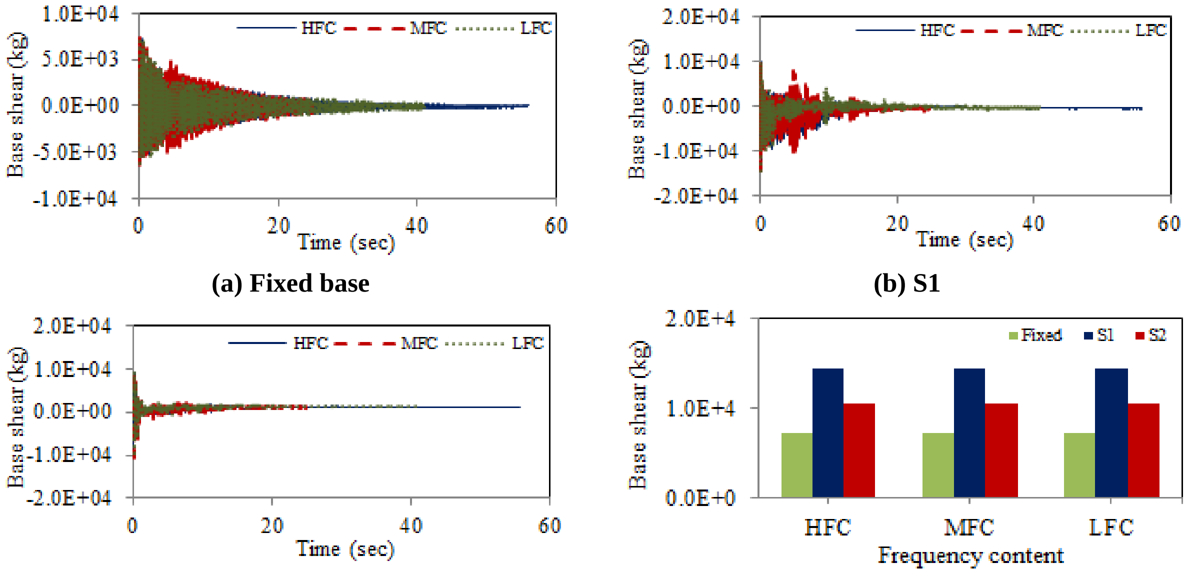
(b) S2 (d) Extreme values

Figure 7 Time history of base moment response of long wall tank model under HL &VL excitation for the 3 earthquake records.

The responses of the base shear forces of the wall in the longitudinal direction ranged from 1.09E+04 to 1.44E+04 kg. **Fig.6** shows that the absolute extreme values of base shear due to all ground motions at the same base conditions are approximately equal. S1 has led to an increase of about 21% in the base shear response comparing to the fixed base condition under all cases of frequency contents. On the other hand, S2 has led to an increase of about 32.1% in the base shear response comparing to the fixed base condition. It is worth to say that the fixed base condition gives underestimated values of the walls' base shear response compared to S1 and S2. The fixed base condition gives the minimum base shear response of the tank's walls, while the medium subsoil S2 gives the maximum response value. In addition, the figure shows that the frequency content has a minor effect on the base shear responses of the shallow rectangular RC tank. Finally, **Fig.6** shows that the base shear response of the rectangular tank has been affected by SSI, which is clearly noticed from the increase of the base shear response when the soil type has changed from hard to medium soil.

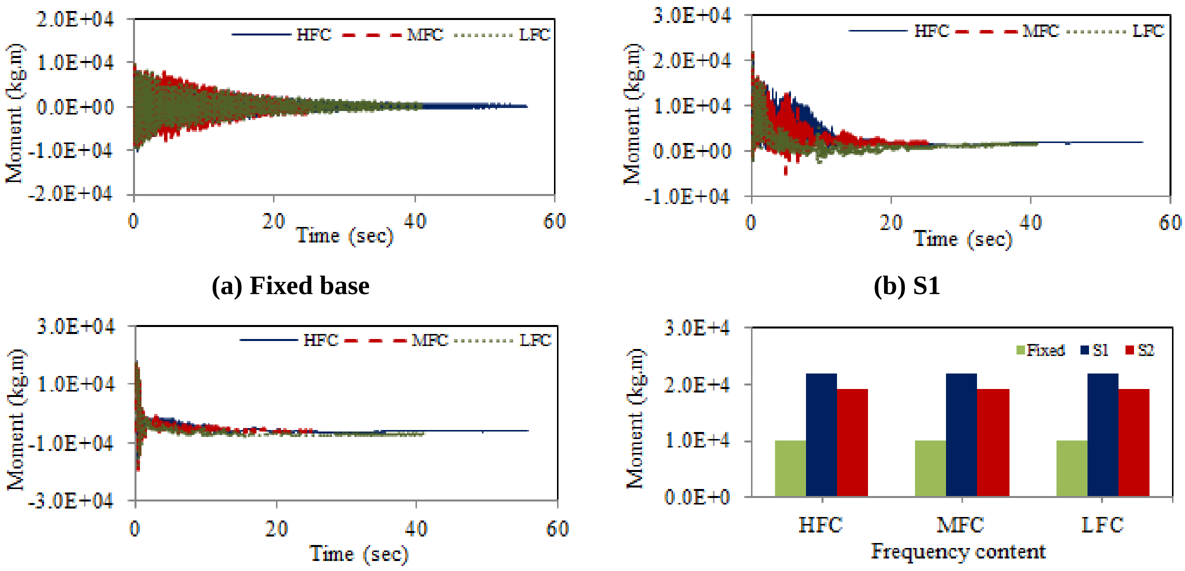
From **Fig.7**, the responses of the base moment of the wall in the longitudinal direction have a range from 1.82E+04 to 2.87E+04 kg.m. In the case of fixed base, the earthquake record with HFC gives the minimum response of base moment while, the earthquake record with LFC gives the maximum base moment response as shown in **Fig.7.** In addition, the base moment resulted from MFC and LFC comparing to HFC have an increase about 10.6% and 20.1%; respectively. On the other hand, for HFC case, S1 and S2 have led to an increase of about 58% and 1% in base moment response in comparison with fixed base condition; respectively.

Furthermore, S1 has led to an increase of about 42.8% and 31.5% in base moment response comparing to the fixed base condition for MFC and LFC; respectively. Moreover, S2 has led to a decrease of about 8.7% and 15.9% in comparison with fixed base condition for MFC and LFC respectively. It can be clearly noticed that, the base moment has been greatly affected by the frequency content of the applied ground motions.



(a) Fixed base **(b) S1** **(c) S2** **(d) Maximum values**

Figure 8 Time history of base shear response of short wall tank model under HL &VL excitation for the 3 earthquake records.



(a) Fixed base **(b) S1** **(c) S2** **(d) Maximum values**

Figure 9 Time history of base moment response of short wall tank model under HL &VL excitation for the 3 earthquake records.

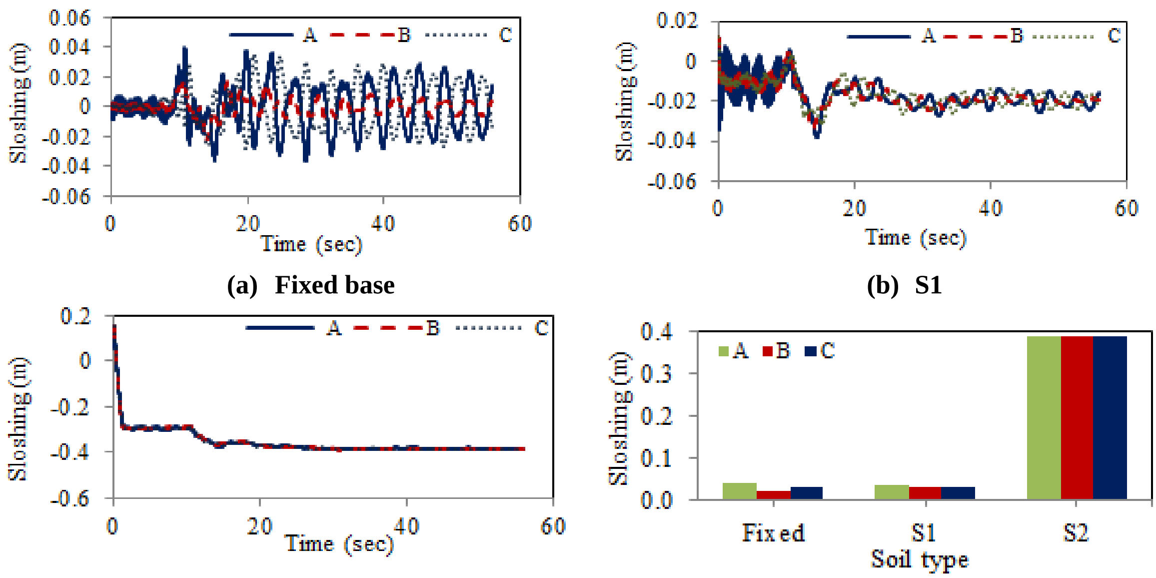
The estimated base shear and base moment of short wall of the wall in the short direction for the rectangular tank with fixed base and the other subsoils are illustrated in **Fig.8** and **Fig.9**. As can be seen from **Fig.8**, different responses have been obtained for different soil types. The tank with fixed base gives the minimum value of base shear response and the tank with hard soil S1 gives the maximum values. S1 and S2 have led to an increase of about 98.3% and 44.7% in base shear response in comparison with fixed base condition under all ground earthquakes respectively. In addition, the base shear response has not been affected by the frequency content of the applied ground motions. On the other hand, the base shear response is sensitive to the subsoil type as the base shear response increases with changing the soil type from fixed base to hard and medium soil.

Fig.9 shows that, the tank with fixed base gives the minimum value of base moment and the tank with S1 gives the maximum values. S1 and S2 have led to an increase of about 114.5% and 87.1% in base moment response comparing to the fixed base condition under all records respectively. In addition, the base moment response has not been affected by the frequency content of the applied ground motions. On the other hand, the base moment response has been greatly affected by the SSI as the base shear response increases with changing the soil type from fixed base to hard and medium soil.

Sloshing responses

The sloshing height at the corner of the tank (point C) is compared to the sloshing height at the middle cross section of the walls, in both X and Y directions (points A and B). In addition to the structural response, the fluid dynamic behavior has been investigated. The time history diagrams of water sloshing height for Duzce earthquake (HFC) are shown in **Fig. 10**.

For points A and C, S1 has led to a decrease of about 3.97% and 7.8% comparing to the fixed base condition respectively. Moreover, S1 has led to an increase of about 51.67% of sloshing height at point B in comparison with fixed base condition. In addition and as seen from **Fig.10**, the medium soil S2 with the HFC ground motion gives very large values of sloshing displacement at all points. This can be resulted from shear failure in the subsoil under the tank. Furthermore, no oscillation occurred in this case due to the high damping that took place due to the nonlinear properties of the soil and its failure. The results show that, the SSI has a great effect on the sloshing height response of the RC rectangular tank.



(a) Fixed base **(b) S1**

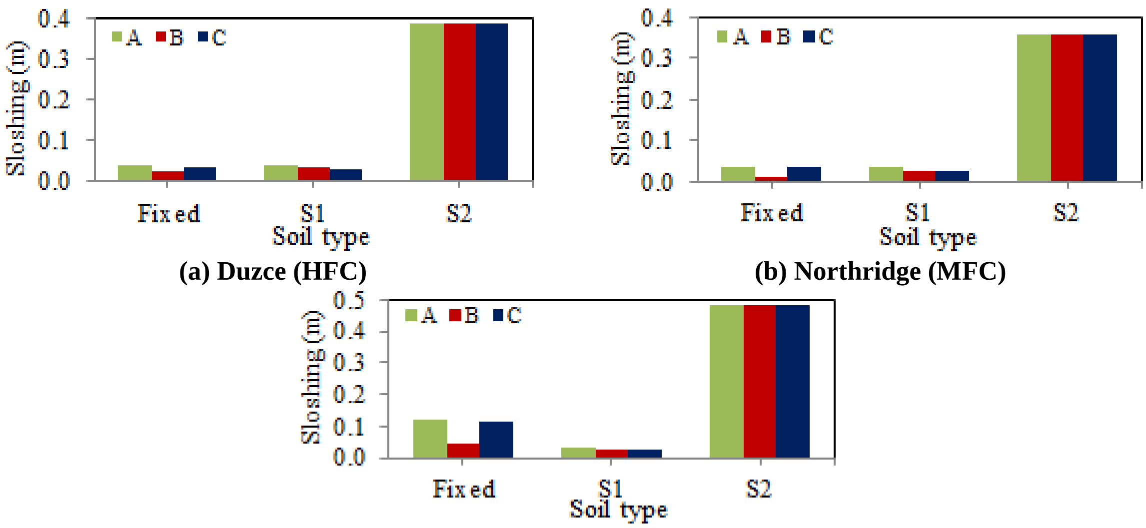
(c) S2 **(d) Extreme values**

Figure 10 Sloshing at points A, B, and C due to Duzce earthquake (HFC) at different soil types

A comparison between the extreme values of the sloshing height at the selected points A, B and C under the applied ground motion records for all the subsoil conditions are shown in **Fig.11** and their values are listed in **Table 8**. From **Fig.11** and **Table 8** it can be seen that for MFC, the hard soil S1 has led to a decrease in the sloshing height of about 5.2% and 29.6% for points A and C comparing to the fixed base conditions; respectively. However, this type of soil has led to an increase of about 78.3% for point B comparing to the fixed base condition. Finally and for the LFC record, the hard soil S1 has led to a decrease of about 71.7%, 41.4% and 75.3 % for points A, B and C comparing to the fixed base conditions; respectively. While in case of the medium subsoil S2, very large values for sloshing displacement for points A, B and C for all ground motion records have been noticed due to the shear failure, which occurs in the soil system under the tank.

Table 8 Sloshing Extreme values at points A, B, and C for three earthquakes

Ground motion	Duzce (HFC)			Northridge (MFC)			Kobe (LFC)		
Point	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Fixed (m)	0.0397	0.0223	0.0345	0.0362	0.0134	0.0358	0.1212	0.0464	0.1150
Time (s)	15.13	13.91	20.94	7.11	9.83	8.39	10.69	8.89	10.66
S1 (m)	0.0381	0.0338	0.0318	0.0343	0.0239	0.0252	0.0343	0.0272	0.0284
Time (s)	14.46	13.86	15.22	0.14	16.56	17.28	0.14	13.32	22.46
S2 (m)	0.3888	0.3892	0.3882	0.3582	0.3563	0.3565	0.4859	0.4849	0.4854
Time (s)	32.12	30.81	34.47	22.11	23.66	22.26	34.86	30.88	32.08

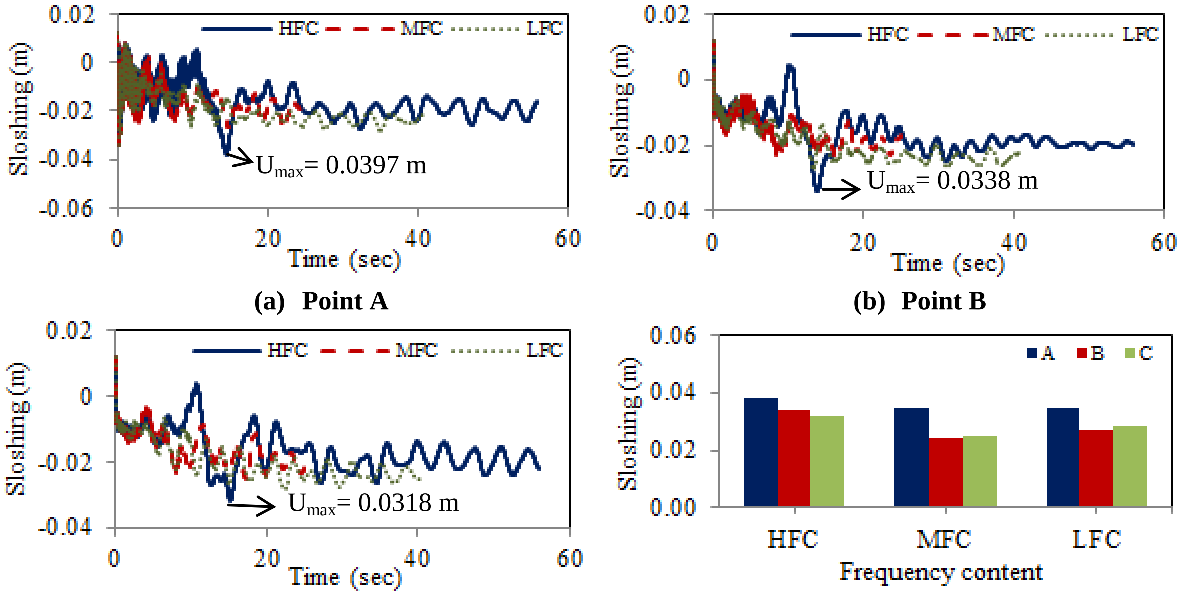


(a) Duzce (HFC) **(b) Northridge (MFC)**

(c) Kobe (LFC)

Figure 11 Sloshing Extreme values at points A,B,and C for different earthquakes

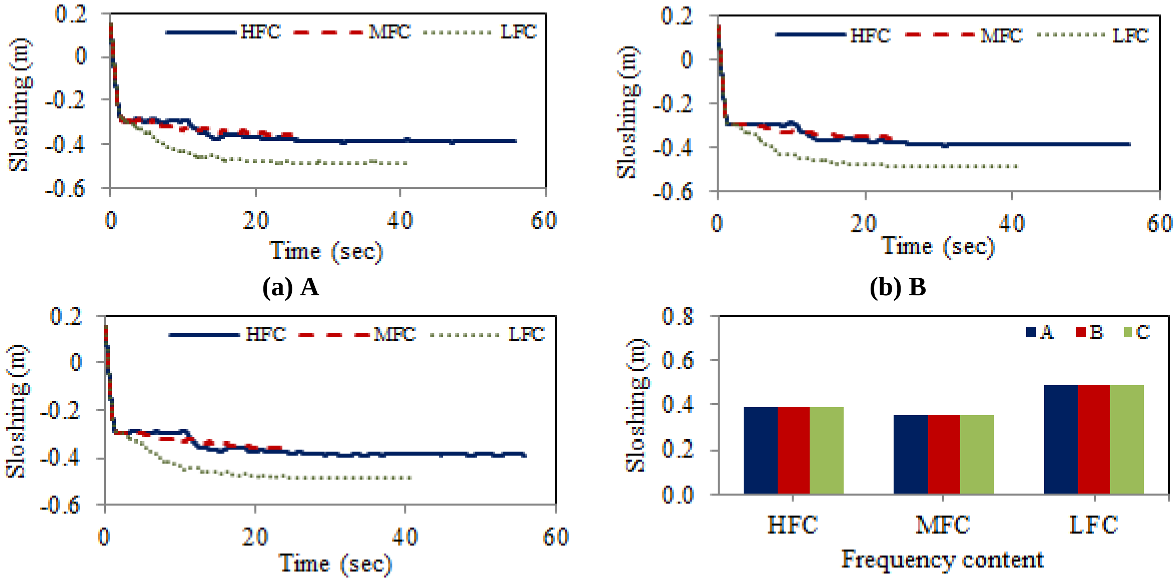
The sloshing height responses for the points A, B and C resulted from the three earthquakes for S1 are shown in **Fig.12**. It is worth to mention that the maximum values of the sloshing height for points A, B and C resulted from HFC earthquake for S1. In addition, sloshing height at point A, which is located at the top of the wall parallel to the direction of the applied ground motion, decreases with decreasing of the frequency content but at points B and C, the sloshing height decreases at MFC and increases again in case of LFC earthquake. **Fig.13** shows the sloshing height response for the points A, B and C resulted from the three earthquakes for S2. As mentioned before, S2 gives very large values of sloshing displacement for all applied ground motions for points A, B and C.



(a) Point A **(b) Point B**

(c) Point C **(d) Extreme values**

Figure 12 Sloshing response at points A, B and C for S1

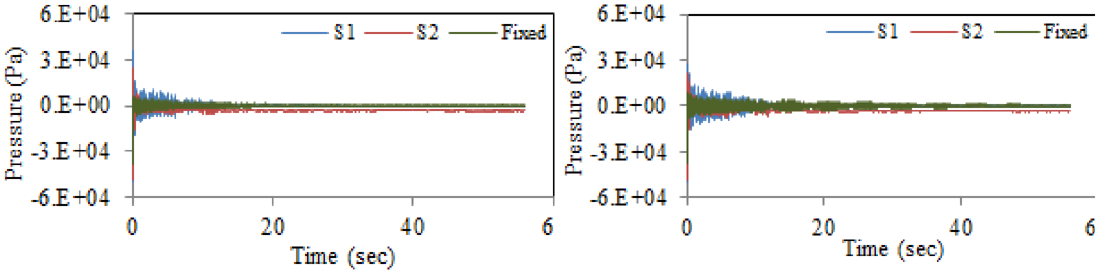


(a) A
(b) B
(c) C
(d) Maximum values

Figure 13 Sloshing at points A,B,and C for S2

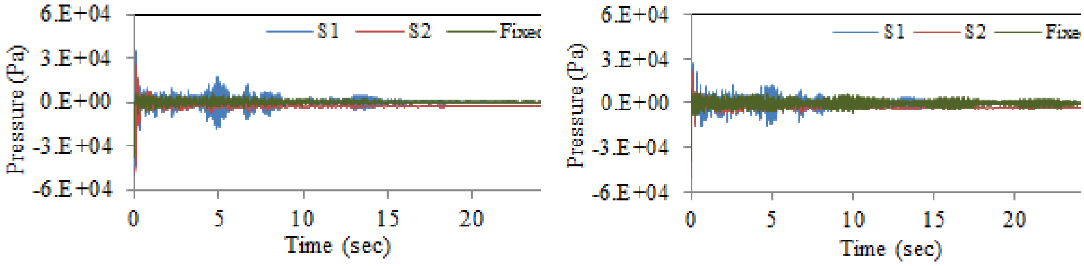
According to all of the formerly mentioned notices, it can be concluded that the sloshing response is very sensitive to SSI more than the frequency content of the applied ground motion.

Hydrodynamic pressure



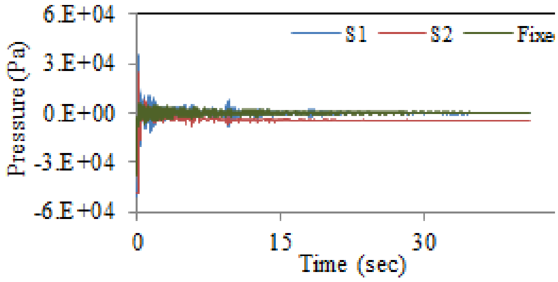
(a) short wall **(b) long wall**

Figure 14 Pressure response of the tank wall due to Duzce earthquake (HFC).

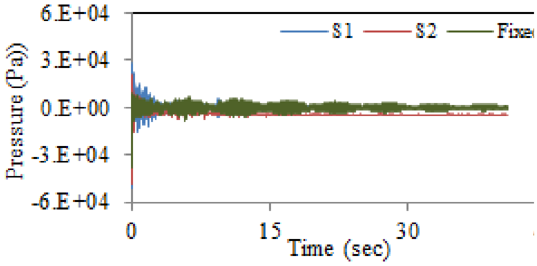


(a) short wall **(b) long wall**

Figure 15 Pressure response of the tank wall due to Northridge earthquake (MFC).



(a) short wall

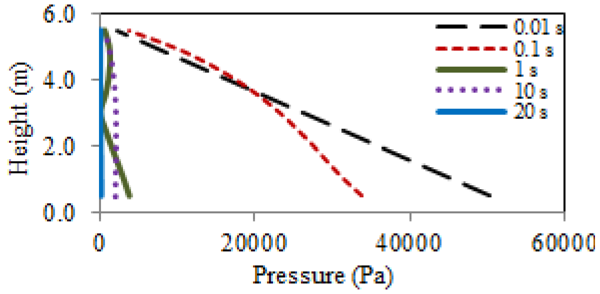


(b) long wall

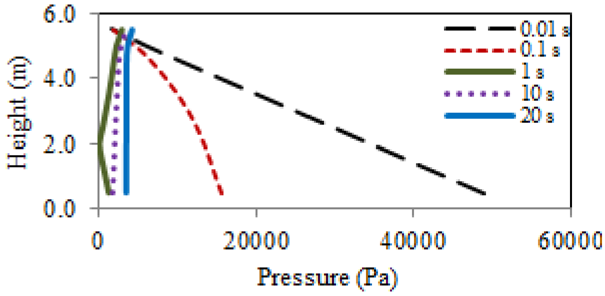
Figure 16 Pressure response of the tank wall due to Kobe earthquake (LFC).

The hydrodynamic pressure history at the base of the tank's walls measured at the middle strip of long and short walls are presented in **Fig. 14** to **Fig. 16** for all records under horizontal and vertical ground motions. It can be observed that, the resulting values of the hydrodynamic pressure on the short wall of the tank are generally less than that on the long wall for all ground motions, which is expected, as the long wall is perpendicular to the ground motion direction.

Fig. 17 shows the distribution of the hydrodynamic pressure along the tank wall height for S1 and S2 under Duzce (HFC) earthquake at different times. At the same time, the pressures resulted from S1 have different values from that for S2 which gives an evidence for the effect of the subsoil type on the resulted pressure on the tank's walls. Furthermore, **Fig.18** shows a comparison between the maximum absolute hydrodynamic pressure values on the tank's long wall due to all of the ground motion records for all the studied subsoil cases. From this figure, it can be seen that, higher values of hydrodynamic pressure are obtained due to subsoil S1 as compared to other base conditions. The maximum hydrodynamic pressure occurs at S1 is almost 32% higher than that resulted from the fixed base condition. Furthermore, for the medium soil case, S2; the pressure values are almost 28.5% higher than those of the fixed base conditions. Generally, the frequency content of the ground motion has a minor effect on the hydrodynamic pressure as noticed. On the other hand, the subsoil type has major effect on the pressure during earthquake.



(a) S1



(b) S2

Figure 17 Hydrodynamic pressure distribution along the height of the tank's long wall under Duzce earthquake at different times

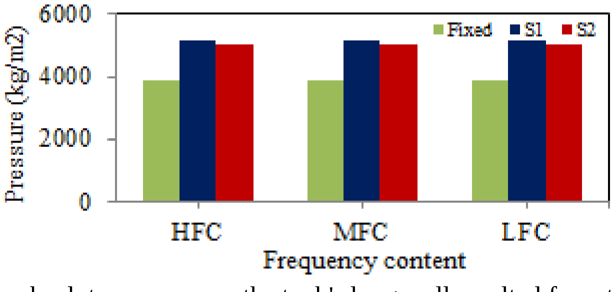


Figure 18 Maximum absolute pressure on the tank's long wall resulted from time history analysis

III. Conclusions

In this study, a dynamic time history analysis for a shallow rectangular rested on soil RC tank under horizontal and vertical ground excitations have been carried out. A 3-D Finite Element model for the tank has been constructed using the well-known FE software; ANSYS, to be employed in the study. In addition, this model used to investigate the effect of fluid-soil-structure interaction and the frequency content of the ground motion on the seismic behavior of the tank in time domain. Accordingly, three different ground motions with different frequency contents have been applied in this study. Moreover, two different soil types have been considered in the study representing medium and hard soils. The effects of the FSSI along with the ground motions on the straining actions at the tank's walls at the base, the sloshing and, the hydrodynamic pressure have been obtained and discussed.

The following conclusions can be derived according to the presented results in this paper:

1. For the long wall of the tank, considering the two soil types S1and S2 have led to an increase of about 21% and 32.1% in the base shear response comparing to the fixed base condition under all cases of frequency contents. In addition, the fixed base condition gives underestimated values of the walls' base shear response compared to S1 and S2.
2. The two soil types S1 and S2 have led to an increase of about 58% and 1% in base moment response in comparison with the fixed base condition; respectively for HFC case. S1 has led to an increase of about 42.8% and 31.5% in base moment response comparing to the fixed base condition but S2 has led to a decrease of about 8.7% and 15.9% in comparison with fixed base condition for MFC and LFC respectively.
3. The frequency content has a minor effect on the base shear responses of the shallow rectangular RC tank but it has a major effect in case of the base moment responses.
4. Considering the effect of SSI, the results show that the base shear and base moment responses of the considered tank model affected by changing of the soil properties
5. For the short wall of the tank, S1 and S2 have led to an increase of about 98.3% and 44.7% in base shear response in comparison with fixed base respectively. In addition, S1 and S2 have led to an increase of about 114.5% and 87.1% in base moment response comparing to the fixed base condition.
6. The base shear and the base moment responses have not been affected by the frequency content of the applied ground motions. On the other hand, SSI has a great effect on the base shear and the base moment responses, as the responses of the rested rectangular tank are sensitive to the subsoil type.
7. The soil structure interaction (SSI) has a great effect on the sloshing height response. As for MFC, the hard soil S1 has led to decrease the sloshing height by about 5.2% and 29.6% for points A and C comparing to the fixed base conditions; respectively. However, for point B, S1 has led to an increase of about 78.3% comparing to the fixed base condition. For the LFC record, S1 has led to a decrease of about 71.7%, 41.4% and 75.3 % for points A, B and C comparing to the fixed base conditions; respectively.
8. It is clear that the sloshing response is very sensitive to SSI more than the frequency content of the applied ground motion.
9. S1 has led to an increase of about 32% in the hydrodynamic pressure in comparison with fixed base condition. Furthermore, for the medium soil case, S2; the pressure values are almost 28.5% higher than those of the fixed base condition.
10. It is clearly noticed that, the frequency content of the ground motion has a minor effect on the hydrodynamic pressure. On the other hand, the subsoil type has major effect on the pressure during earthquake.
11. The intensity of hydrodynamic pressures responses on the short wall of the tank are generally less than that on the long wall for all ground motion excitations.
12. It is clearly noticed that the dynamic behavior of liquid concrete tanks depends on a wide range of parameters such as seismic properties of earthquake, tank dimensions, fluid–structure interaction (FSI) and soil structure interaction (SSI) which should be considered in current codes of practice. This study shows that the proposed FE method can be used in the time history analysis of rectangular liquid tanks.
13. The current study is done based on analysis of the 3D rectangular tanks in time domain using three different earthquake records and two different soil types. The current FE time history results that are more realistic can be used to study another cases of liquid storage tanks in future works

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