SEISMIC ANALYSIS OF LIQUID STORAGE TANKS

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ABSTRACT

This study presents an idealization scheme for the analysis of rectangular storage tanks acted upon by earthquake excitations. Above and below ground tank, uses have been considered. A linear three-dimensional finite element analysis has been used to predict the natural frequencies. Analysis parameters are the ratio of height to length of the tank, the type of soil, level of water in the tank, and also the wall thickness. The results for top displacement and axial force components for a full tankabove ground case have values greater than those in half- full (31%) and empty tank cases (75%). At the opposite of that, the underground tank demonstrates that top displacement and axial force components for an empty tank case have values greater than those in half- full (19%) and full tank cases (40%). The base shear for above ground tank case has values greater than those in underground tank cases (19% to 37%). The shear base for soil type 2 is greater than those in soil type 1(17% to 28%).

Key words: Seismic analysis, viscous dampers, rectangular tanks, finite element models, fluid-structure-soil interaction, time history, free vibration, ANSYS.

الخلاصة

تتضمن الدراسة تحليل الخزانات المستطيلة المعرضة الى هزات أرضية بحالتين، الأولى تكون فيها الخزانات مدفونة بشكل كامل تحت الارض والحالة الثانية تكون الخزانات فيها فوق مستوى سطح الارض.أستخدم التحليل الخطي ثلاثي الابعاد بطريقة العناصر المحددة لغرض تحري علاقة كل من الأهتزاز الطبيعي ونسبة ارتفاع الجدران من حيث تغير نوع التربة وكمية الماء الموجودة بالخزان وكذلك علاقتة ايضا بأختلاف سمك الجدران والأزاحة العليا والقوه المحورية لحالة الخزان فوق الارض وهو مملؤ، لها قيم اعظم من الحالة النصف مملؤه بنسبة 31% وبنسبة 75% اعظم من الحالة الفارغة. بعكس ذلك تكون الأزاحة العليا والقوة المحورية لحالة الخزان المدفون اعظم وهو فارغ من ماهو نصف مملؤ بنسبة 19% وبنسبة 40% أعظم من الحاله المملؤه. قوة القص عند الاساس لحالة الخزان فوق سطح الارض لها قيم اعظم من حالة الخزان تحت الارض بنسبة (19% الى 37%). قوة القص عند الاساس في حالة التربة رقم 2 (التربة الضعيفة) تكون اعظم من حالة التربة رقم1 بنسبة (17% الى 28%).

1. INTRODUCTION

Damages of storage tanks due to recent earthquakes have been extensively studied by (Jennings 1971, Hanson 1973, and Monos and Clough 1985). These tanks are mainly steel tanks whose failure modes are edge effects in the form of elephant foot buckling at the base. (Housner 1957) is the first who considered the hydrodynamic pressure distribution developed in rigid tanks during horizontal base excitation. He formulated a dynamic model for estimating the liquid response in seismically excited rigid, rectangular and circular tanks. The effect due to shell flexibility is later incorporated in the model by (Veletsos and Yang 1976), (Nash et al. 1978), (Haroun and Housner 1980). (Haroun and Tayel 1984) have investigated the effect of soil-structure interaction. (Veletsos and Tang 1986) and (Luft 1984) have considered the effect of vertical excitation on the hydrodynamic pressures. (Haroun and Chen 1989) have investigated the nonlinear sloshing behavior in rectangular tanks by considering large amplitude sloshing. The finite element analysis of the liquid-tank system is studied by (Haroun and Housner 1981). Several studies were also carried out to investigate that dynamic interaction between deformable wall of the tank and the liquid using finite element analysis. (ASCE 1984) comprehensively discusses the effect of fluid-structure interaction on the hydrodynamic pressures and (ASCE 1981) provides excellent guidelines for the analysis and design of liquid storage structures.

2. BASIC ASSUMPTIONS

The assumptions introduced in the present analysis are as follows:

a. The tank is symmetric about x-axis and z-axis in terms of geometry.
b. The material of the tank is linearly elastic, isotropic and homogeneous.
c. The contained liquid is inviscid, incompressible and in a non-rotational motion, within vessels having no net flow rate
d. The base is connected rigidly to the tank wall.
e. The soil medium is represented as a system of closely spaced independent linear springs, masses and dashpots.
f. The seismic effect is parallel to the z-axis and perpendicular to the x-axis

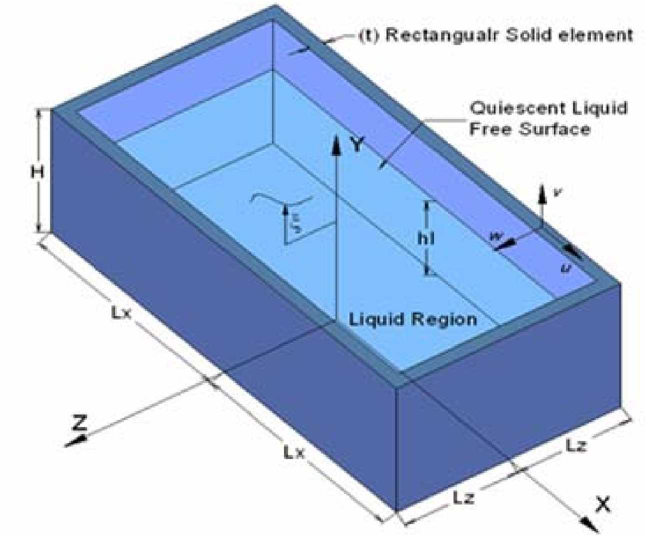


Plate (1) Rectangular storage tank and coordinate system

3. DESCRIPTION OF STRUCTURE

The structure analyzed in the present study, shown in Plate (1), is a typical rectangular storage tank with a volume of 767.6m3. The contained liquid is assumed to be water with the density of 10kN/m3, Ew= 2.0684 x109 kN/m2 and Viscosity = 1.2379 x10-12kN/m.s, υw= 0.19. The tank has a length of 12.6m, a width 6.3m, a height 12.6m and a shell thickness of 0.45m and is constructed using concrete with Ec= 20x 106kN/m2, υc= 0.15 and ρc= 24kN/m3. The damping coefficient of the overall structure has been assumed equal to 5%. The soil has been chosen, according to (Prakash 1981) classification, four different models of soil types are considered. The four types of soil are classified in Table (1).

Table (1) Parametric studies of soil type

No.	Soil type	Mass density (ρ_s)kN.s^2/m^4	Shear modules (G_s) kN /m^2
1	Loess at natural moisture	1.67	112892
2	Medium-sized gravel	1.8	58320
3	Medium-grained sand	1.65	42240
4	Fine-grained sand	1.65	19965

4. SEISMIC GROUND EXCITATION

The structure is assumed to be acted upon by a seismic ground motion, represented by acceleration whose duration is 31.18sec. A peak ground acceleration (PGA) of 0.318g have been used. A rectangular concrete tank has been analyzed due to north-south component El-Centro earthquake of Fig. (1), the first five seconds were considered for analyzing the tanks

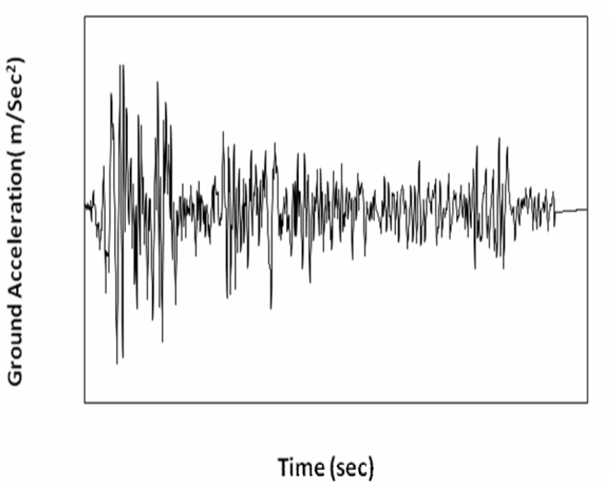


Figure (1) Accelerogram N-S El Centro earthquake, 18-May-1940

5 .SOIL-STRUCTURE INTERACTION

According to (Clough 2003), the soil-structure interaction (SSI) effects on the dynamic response of a rectangular tank can be taken into account by modeling each of the physical degrees-of freedom, i.e .horizontal and vertical, of the surrounding soil system as discrete system with six degrees-of-freedom. The constants of all the discrete elements are computed as listed in Table(2)

Table (2) Soil properties of all concrete models considered in the analysis

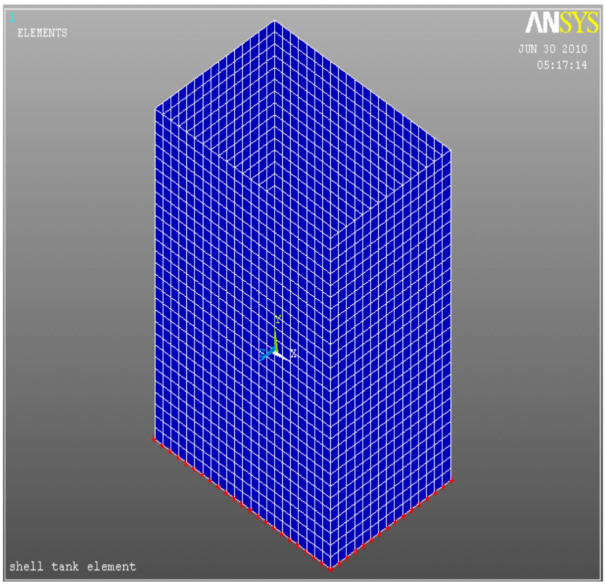
Soil type		unit	soil type 1	soil type 2	soil type 3	soil type 4
Directions	**r**	m	0.5085	0.5085	0.5085	0.5085
	G_s	kN/m	112892	58320	42240	19965
	ν_s	-	0.45	0.2	0.3	0.35
Vertical	**K_s**	kN/m^2	417495	148278	122737	62475
	C_s	kN.s/m	542.0	335.3	305.1	208.4
	m_s	kN.s^2/m	0.33	0.36	0.36	0.33
Horizontal	**K_s**	kN/m	346811	159921	123092	59554
	C_s	kN.s/m	298.0	210.1	184.3	122.8
	m_s	kN.s^2/m	0.06	0.07	0.07	0.06

6. FINIT ELEMENT MODEL

The numerical analysis of the rectangular storage tank structure is performed on the basis of detailed FE model implemented with the help of the routines available in the ANSYS Finite Element program (ANSYS 2008), as shown in Plate (2). The rectangular storage tank is modeled using 26485 or 19093 element, for the two cases of tank considered in this work, i.e. the underground tank and the tank above ground respectively. Four-noded shell elements (SHELL63) with six DOFs per node are used. The eight node solid fluid element (FLUID80), with three DOFs per node, has been chosen to model the incompressible fluid content. A total of 4368 or 8736 FLUID80 elements are used, respectively, for the three levels of water tank is considered in this work, i.e. empty, half full and full. In order to satisfy the continuity conditions between the fluid and solid media at the rectangular tank boundary, the coincident nodes of the fluid and shell elements are constrained to be coupled in the direction normal to the interface, while relative movements are allowed to occur in the tangential directions. The uniaxial "tension only" behavior of the braces is simulated by means of the 3-D spar elements LINK10, which feature a bilinear stiffness matrix, i.e. the stiffness is removed if the element goes into compression. The viscous fluid damper devices are modeled using the 1-D non-linear damper elements COMBIN37. Finally, concentrated mass elements (MASS21) and linear spring-damper elements (COMBIN14) are used to model the discrete elements for the simulation of soil-structure interaction. The above FEM rectangular tank model is numerically analyzed by means of a full transient linear analysis. The governing equations of motion can be expressed in matrix form as (Chopra 1996)

$$[M]\{\ddot{U}\} + [C]\{\dot{U}\} + [K]\{U\} = -[M]\{R\}\ddot{U}_g \quad (1)$$

with $[M]$, $[C]\{\ddot{U}\}$and $[K]\{U\}$ being the mass, damping and stiffness matrices of the structure, respectively, $\{R\}$ an influence coefficient matrix, and$\ddot{U}_g$ the ground acceleration. Eq. (1) is integrated directly in time using the Newmark-β method.



Plat (2) Finite element rectangular tank model

7 .NUMERICAL STUDY

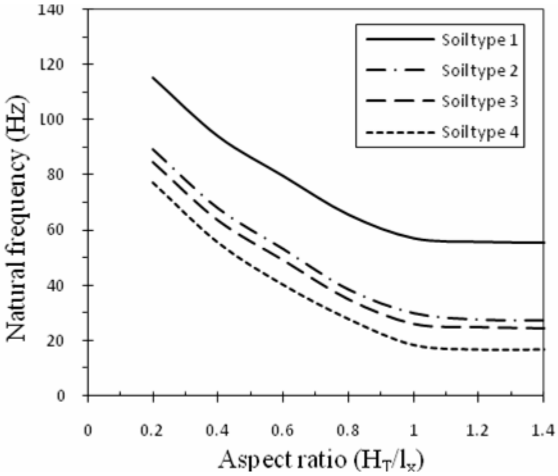
Seismic response of the rectangular liquid storage tank above ground and underground is investigated by performing two types of analyses: (i) modal analysis and (ii) time domain analysis. The problem is solved for four types of soil.

7.1 Modal Analysis

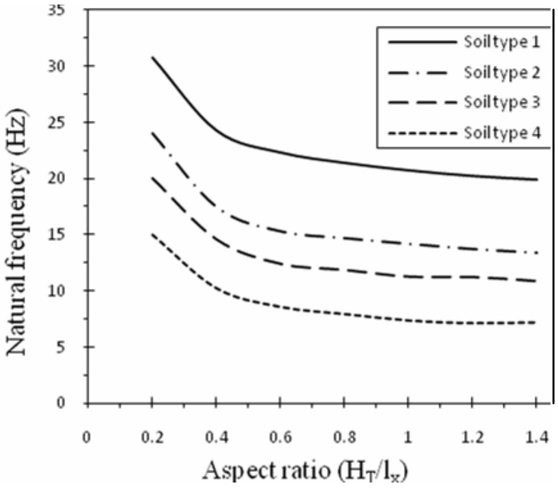
The first step in the dynamic analysis of any structural system is to determine the free vibration characteristic natural frequencies and mode shapes, which are important in calculating the seismic response of the liquid storage tanks. The Block Lanczos method is used in ANSYS for the Eigenvalue and Eigenvector extractions tocalculate natural frequencies including the fluid modes (Hallquist 1998).

7.1.1 Effect of Tank Height to Length Ratio Variation

For this purpose, two cases of storage tanks are considered, above ground tank and buried tank, for each case, both empty and completely full tanks. The results of natural frequencies are given in Fig.(2) and (3) for empty and completely full tanks, resting on four different types of soil. It is observed that as the soil becomes weaker (having low shear modules (Gs)), natural frequencies become less (soil type No.4).

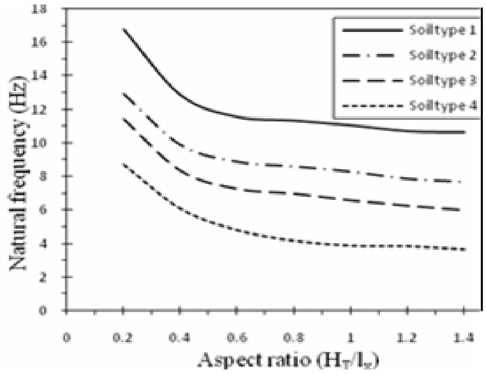


Above ground

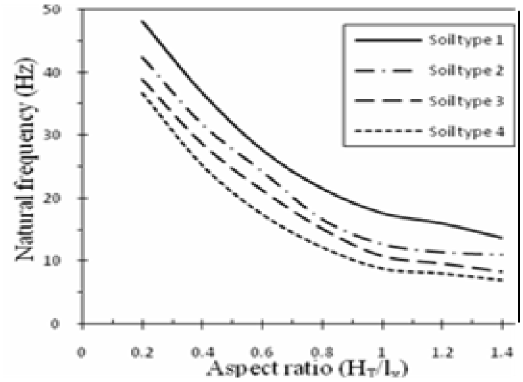


Underground

Figure (2) Fundamental natural frequencies versus aspect ratio (H_t/l_x) variation of empty tank



Above ground



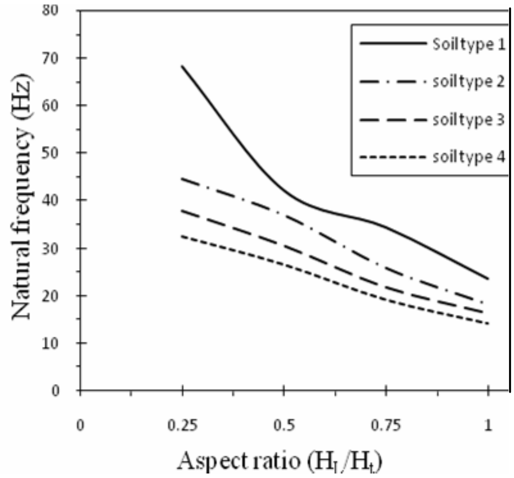
Underground

Figure (3) Fundamental natural frequencies versus aspect ratio (H_t/l_x) variation of full tank

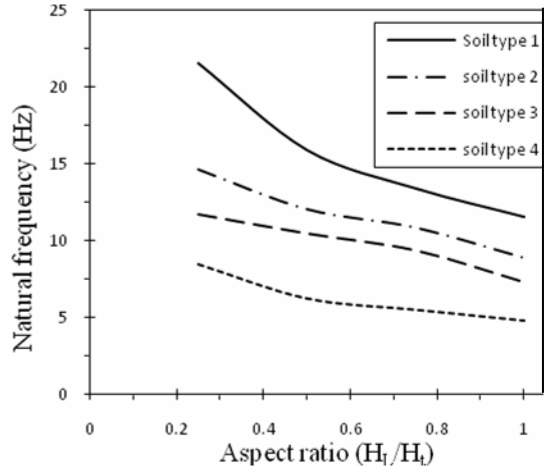
Comparing the results between the two cases of tanks (above ground and buried tank), it has been found that the buried tank has natural frequencies less than the tank above ground, because the mass of the tank will increase causing reduction in the natural frequencies. It is also noticed, that the natural frequencies of the empty tank are much larger than those of the full tanks regardless of the type of soil.

7.1.2 Effect of Liquid Height to Tank Length Ratio Variation

To demonstrate the effect of liquid height variation (H_L/H_t), two cases of the tanks (the tank above ground and buried tank) were considered for this purpose. The resulting natural frequencies are given in Fig.(4) for above ground and buried tanks respectively.



Above ground



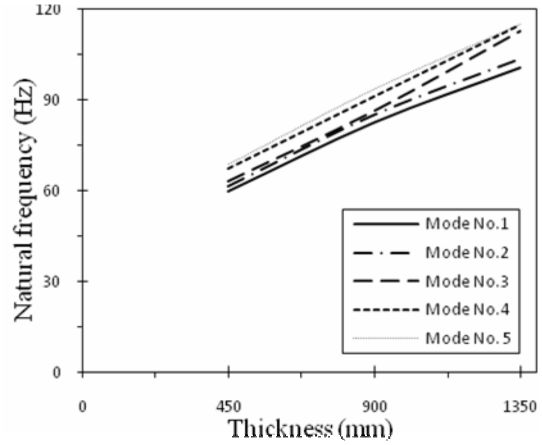
Underground

Figure (4) Fundamental natural frequencies versus height of fluid ratio (H_L/H_t)

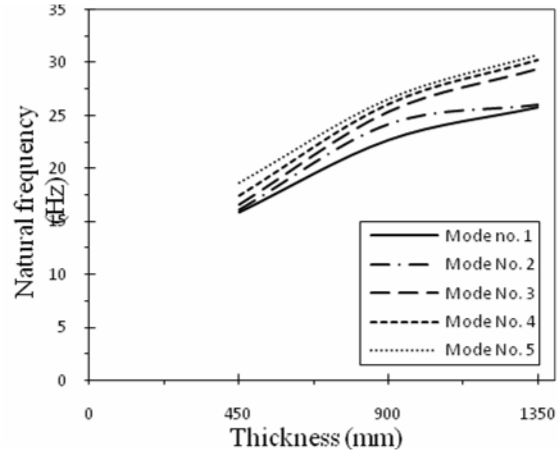
It can be observed from these tables and plots that, as the level of fluid in the tank increases, the natural frequencies decrease for both cases of tanks and for all four types of the soil. This behavior is obvious since the mass of the structure system increases with the level of fluid.

7.1.3 Effect of Wall Thickness Variation

To demonstrate the effect of wall thickness variation, empty tank and completely full tank, are studied for the free vibration characteristics with wall thickness varies from 450mm to 1350mm for a tank resting on soil type 1, and also for two cases (above ground and buried tank).

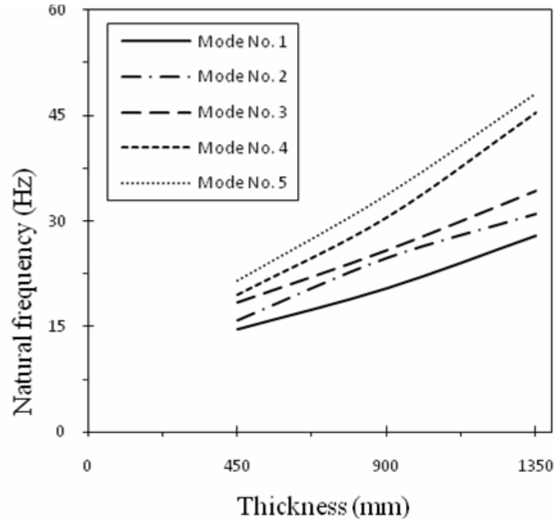


Above ground

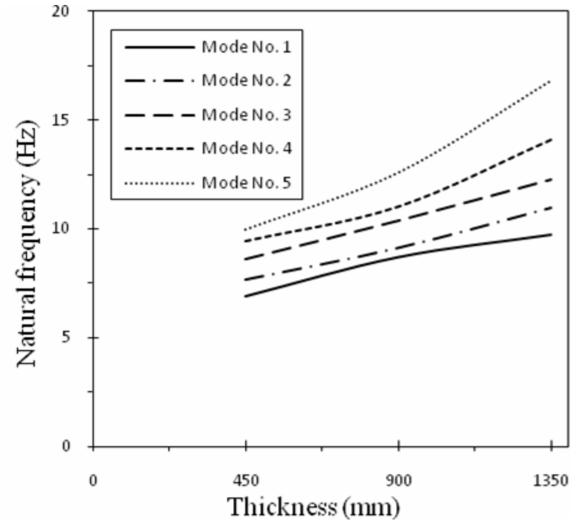


Underground

Figure (5) Effect of thickness variation on natural frequencies of empty tank



Above ground



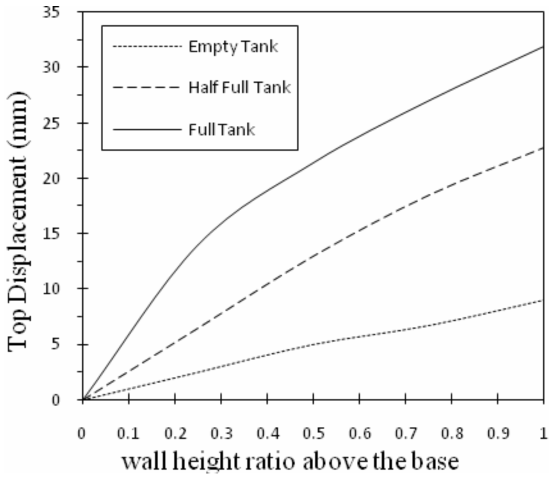
Underground

Figure (6) Effect of thickness variation on natural frequencies of full tank

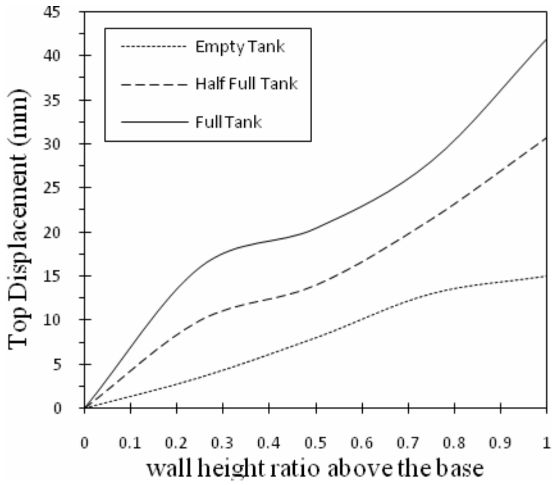
The resulting natural frequencies are given in Fig.(5) and (6). It can be seen clearly from these results that, the natural frequencies increase when the thickness of the wall increases without changing the height of the tank (the wall stiffness increases with increasing its thickness

7.2 Time Domain Analysis

A time domain analysis using the first five seconds of the north-south component of the 1940 El Centro earthquake was used for the linear elastic model. Peak ground acceleration values were adjusted to 0.318g. Model time history analysis under linear elastic, small deformation assumptions included evaluation of water surface profiles top displacements, axial force, and resulting base shear. The following sections summarize results.The four sets of figures drawn for the different two types of surrounding soil are assumed (soil type 1, and 2), with different levels of water (full, half –full, and empty tank) are considered, as shown in Figs.((7) – (10)). The plots are presented for earthquake response of the rectangular tank above ground demonstrate that top displacement and axial force components for a full tank case have values greater than those in half- full (31%) and empty tank cases (75%). While the case of underground rectangular tank demonstrate that top displacement and axial force components for an empty tank case have values greater than those in half- full (19%) and full tank cases (40%).It is also interesting to notice that the base shear for the above the ground tank case have values greater than those in underground tank cases (19% to 37%). The shear base for soil type 2 is greater than those in soil type 1(17% to 28%). It is found that the surrounding soil type has a significant influence on the tank response, as shown in Fig.(11) and (12).

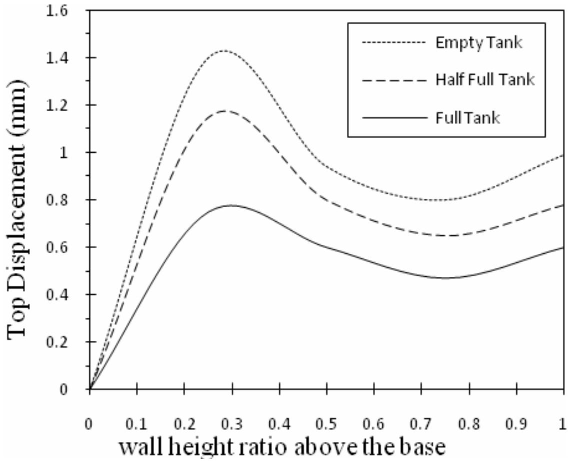


Soil type 1

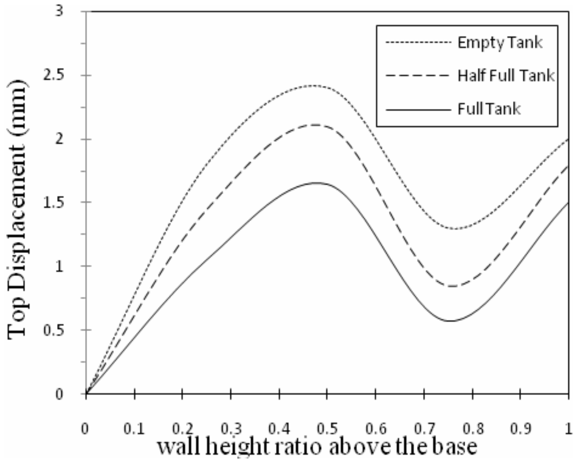


Soil type 2

Figure (7) Plots of the top displacement-versus wall height ratio above the base (tank above ground)

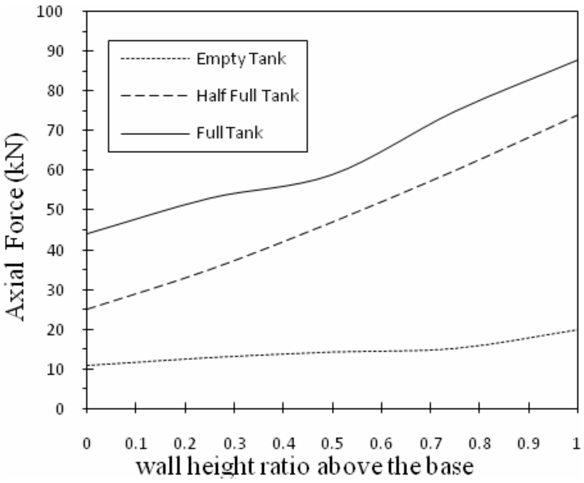


Soil type 1

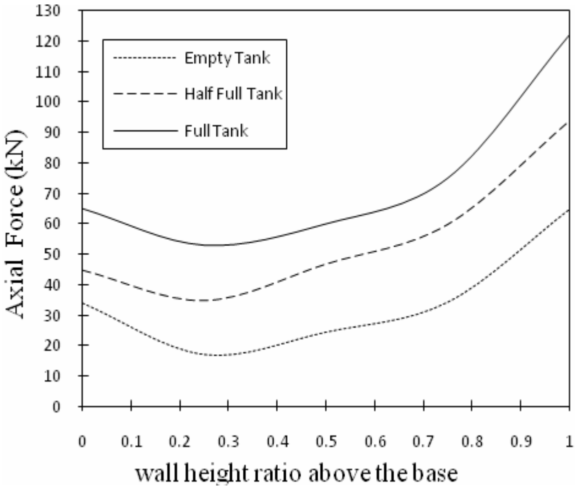


Soil type 2

Figure (8) Plots of the top displacement-versus wall height ratio above the base (buried tank)

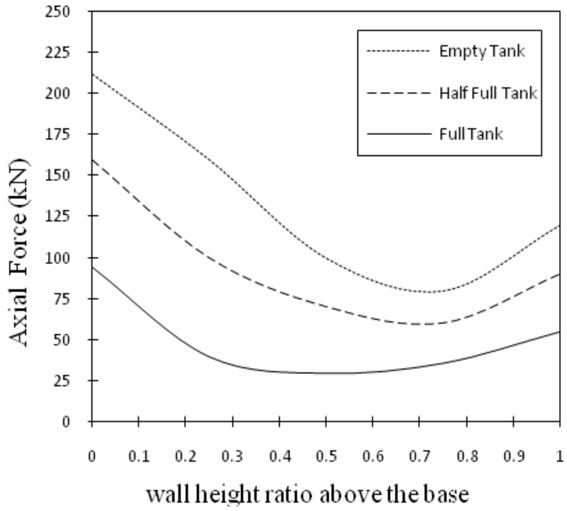


Soil type1

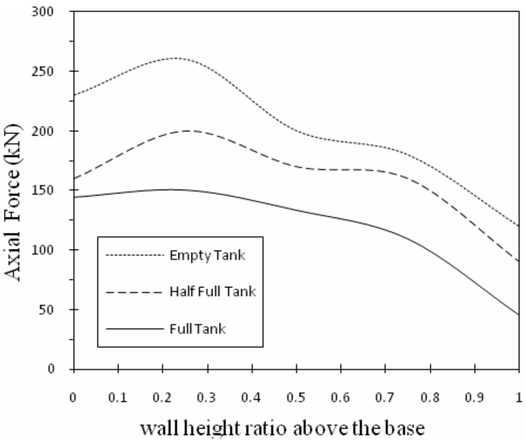


Soil type 2

Figure (9) Axial Force- wall height ratio for relationships above the base in long wall

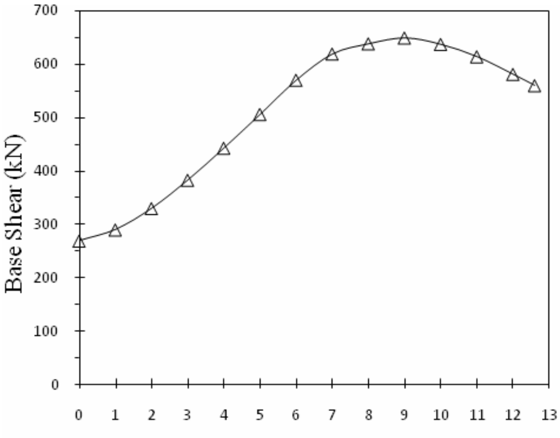


Soile type1

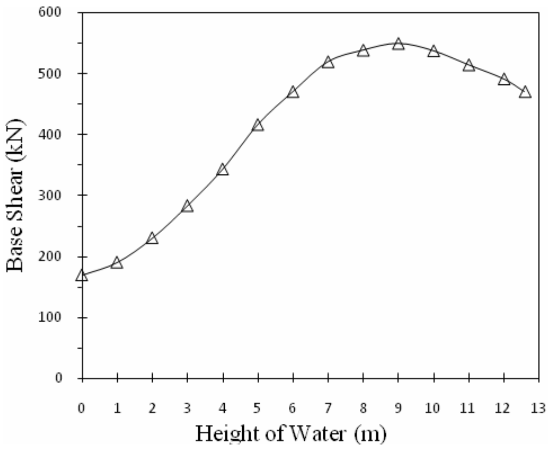


Soil type 2

Figure (10) Axial Force- wall height ratio for relationships above the base in long wall

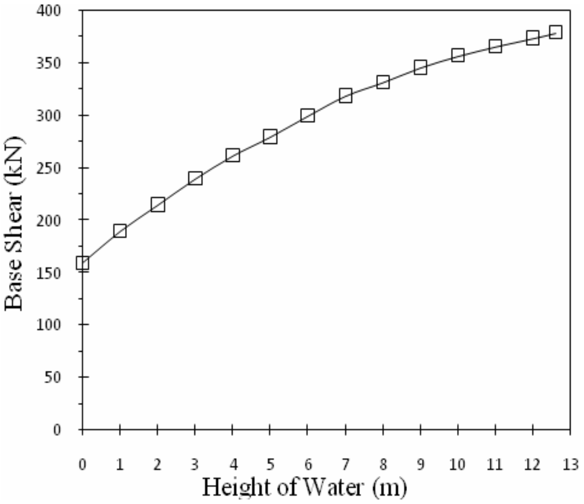


Soil type 1

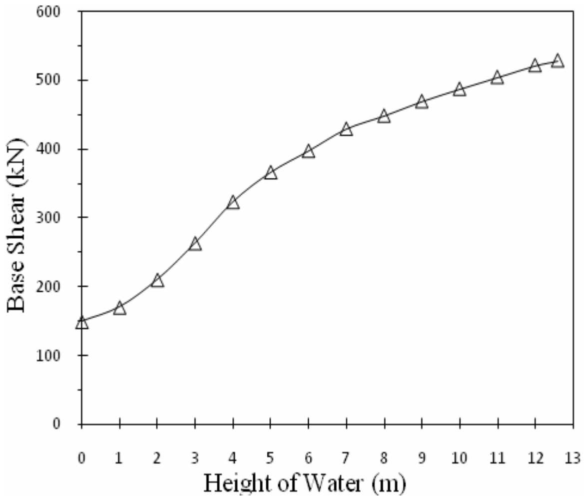


Soil type 2

Figure (11) Plots of base shear-height of water (tank above ground)



Soil type 1



Soil type 2

Figure (12) Plots of base shear-height of water (buried tank)

8. CONCLUSIONS

1- Variations of the properties of surrounding soil medium are found to have an important influence on the free and forced vibrational response (seismic excitation) of the storage tanks.

2- The frequencies in the above ground tank are greater than those for buried tank nearly (26% to 27%), and the frequencies in soil type 1 (stiff soil) case have values greater than those in type 2 (weaker soil) nearly (29% to 31%).

3- The shear base for above ground tank have values greater than those in underground tank by ratio ranging between 19% and 37%, The shear base for soil type 2 is greater than those in soil type 1 by a ratio ranging between 17% and 28%. It is found that the surrounding soil type has a significant influence on the tank response. It is also found that, the natural frequency is proportional to the wall thickness of the tank. This behavior is related to the fact that the stiffness of a tank is a function of its wall thickness

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