Non linear vibration analysis of liquid storage tank

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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, are considered. A linear three-dimensional finite element analysis is adopted to predict the natural frequencies. The 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. Tanks made from steel as well as from concrete are investigated. A general purpose finite element program **(ANSYS 12.0)** used to model the analysed system. The tank base and wall are modelled by plane strain shell elements. The contained liquid is represented by a special solid element. Finally, the soil is modelled by simple spring-damper elements. The soil medium is idealized by the elastic half space model, that is, linear springs are assumed to represent the structure-soil interface. Which is then modelled by two-node spring dashpot elements. Forced vibration analysis is conducted on above ground and buried concrete tank. This analysis is carried out by applying the records of the North-South component of the 1940 El Centro earthquake with peak acceleration of 0.32g. It is found that the bending stresses in above ground concrete tank is (74.167) % greater than the stresses in buried tank with the same dimensions.

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. أستخدمت طريقة العناصر المحددة للتحليل الخطي ثلاثي الابعاد وذلك لغّرض تحري علاقة كل من الأهتزاز الطبيعي ونسبة ارتفاع الجدران من حيث تغير نوع التربة وكمية الماء الموجودة بالخزان وكذلك علاقتة ايضا بأختلاف سمك الجدران.تم تحري نوعين من الخزانات احدهما حديد والاخر كونكريت بصورة عامة تم استخدام طريقة العناصر المحددة باستخدام برنامج **(ANSYS 12.0)** لغرض التحليل. كل من قاعدة وجدار الخزان مثلت باستخدام عنصر الطبقة القشرية. السائل داخل الخزان مثل باستخدام العنصر الخاص بالعناصر الصلبة. وأخيرا تم تمثيل التربة باستخدام العنصر البسيط (spring-damper). بحيث تم نمذجة الوسط الترابي اعتمادا على مبدأ نصف الفضاء المرن (Elastic Half Space) بفرض وجود نوابط خطية مرنة (Elastic Springs).تم حل معادلات الأتزان باستخدام طريقة التكامل المباشر وباعتماد طريقة (Newmark) لهذا الغرض. خصائص الأهتزاز الحر للخزان تم إثباتها مقارنةً مع نتائج نظرية سابقة. تم اجراء دراسة موسعة تأخذ بنظر الاعتبار اهم العوامل الموثر على التصرف الديناميكي للخزانات أثناء الاهتزاز الحر أو أثناء الزلزال. تحليل الاهتزاز القسري تتضمن حالات دراسة لخزان كونكريتي، فوق التربة ومدفونة كلياً. حيث تم ايجاد كل من الازاحة وقوى القص والعزم والأجهاد للخزان الكونكريتي. نوع الهزة الارضية التي استخدمت هي1940 (EL Centro) في كاليفورنيا. ان القيمه القصوى للتعجيل هو 0.32g. النتائج اظهرت بأن أجهاد الانحناء اكبر لحالة الخزان فوق التربة مما لو كان مدفوناً بنسبة %(74.167) لنفس ابعاد الخزان الكونريتي.

Introduction

Liquid storage tanks are important components of lifeline and industrial facilities. Behavior of large tanks during seismic events has implications far beyond the mere economic value of the tanks and their contents. Similarly, failure of tanks storing combustible materials, can lead to extensive uncontrolled fires. A study on the effect of the geometry of the tank foundation on the modal properties of the tank-liquid-soil system in which both fluid-structure and soil-structure interactions studied by **Hosseini and Mohajer [1] in (2000).** The free vibration analysis of circular cylindrical fully anchored ground supported steel liquid storage tanks studied by **Atalla [2] in (2008) and Saadi [3] in 2008. Malhotra ,Veletsos and Tang [4] in 1993** and **Malhotra and Veletsos [5] in 1994** investigated the principal effects of base uplifting on the seismic response of ground supported cylindrical steel tanks which were unanchored with their base. **JIN et al.[6] in 2004,** presented the earthquake response analysis of LNG storage tank by Simple beam-stick model. Also showed that the sloshing height could be underestimated when it is considered only one sloshing mode. The methods which used : the finite element method (FE), lumped mass and spring model. **Sanchez, Salas and Dominguez [7] in 2004,** investigated the behavior, under seismic conditions, of already existing steel storage tanks of large capacity, located in high risk zones with a strong ground motions (MEXICO). Dynamic analysis of cylindrical storage tanks anchored to rigid base, empty, filled and partially filled with liquid are considered studied by **Haroun[8] in (1980), Seyoum[9] in (2005), Lateef A. [10] in (2010) and Khtar [11] in 2012. Malhotra and Eeri M.[12] in 2005,** Presented a simple method to estimate the additional loads on tank's roof, wall and foundation due to impacts from the sloshing waves which caused by long-period ground motions. **O R Jaiswal et al. [13] in 2007** and **P. Pal [14] in 2009,** investigated the sloshing of liquid in partially filled container subjected to external excitation.

1. 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.

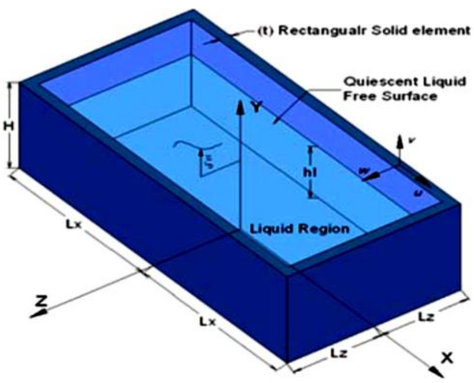

Plate (1) Rectangular storage tank and Coordinate system

2. Parametric Studies for Rectangular Concrete Tanks

To study the effect of tank geometry on natural frequencies, an examination of the above ground and buried tanks, is conducted. The properties of material used in all cases of the parametric study are as follows:

a) Concrete is used for base and walls of the tank whose properties are: E_c= $20x10^6$ kN/m^2, υ_c= 0.15 and ρ_c= 2400 kg/m^3.
b) Water is used as a contained liquid of the tank having density of 1000kg/m^3, E_w= 2.0684 x10^9 kN/m^2 and υ_w= 0.19 [ANSYS 2012].
c) Three different models of soil types are carried out. The three types of soil are listed in table (1).[SOIL PROPERTIES(LPILE&COM624P)]

Table (4.5) Soil properties of all concrete models considered in the analysis

Soil Type	Modulus of subgrade reaction (kN/m^3)		Winkler Spring Stiffness Ks (N/m)	
	Vertical	Horiz-ontal	Vertical	Horiz-ontal
Dense	33900	22600	6864750	4576500
Medium	27150	18100	5497875	3665250
Soft	8140	5426.7	1648350	1098900

3. SEISMIC GROUND EXCITATION

The structure is assumed to be acted upon by a seismic ground motion. 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).

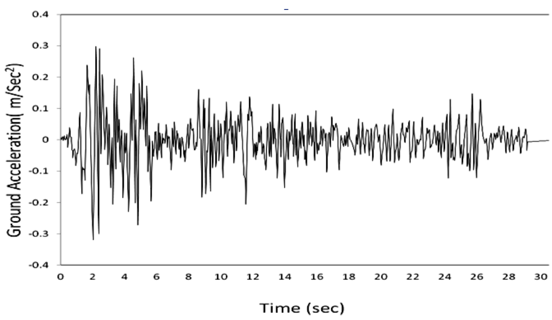

Figure (1): Accelerogram N-S El Centro earthquake, 18-May-1940

4. 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 2012). The rectangular storage tank is modeled for the two cases of tank considered in this work, i.e. the underground tank and the tank above ground. 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. 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. 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):

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F_{(t)}\}$$

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

5. 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.

6.1 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.

6.1.1 Effect of Tank Height to Length Ratio Variation

For this purpose, two cases of storage tanks are considered, the tank above ground and buried tank, for each empty and completely liquid filled tanks are examined. Tank length, L=9.9m, tank width B=6.3m and the tank height, H_t, are varied from 1.8m to 12.6m at 1.8m increments to accommodate the aspect ratio (H_t/l_x) range of 0.2 to 1.4. I_x= Clear length=9m. The results of natural frequencies are plots of Figures.(2) to (5) for empty and completely liquid fill tanks, for the three different types of soil. It is observed that the natural frequency for all modes decreases as the strength of supporting soil decrease. This can be justified due to the lowering of the stiffness of the system. And it has been noticed that the natural frequencies decreased when the ratio (H_t/l_x) increased because of the increasing of the tanks mass. In comparing the results between the two cases of the tanks (the tank 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 and that will make the natural frequencies getting less. It is also noticed by examining these tables and plots, that the natural frequencies of the empty tank are much larger than those of the full tanks regardless of the type of soil.

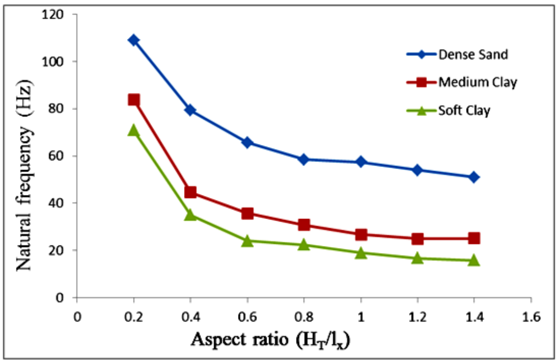

Figure (2):Fundamental natural frequencies versus aspect ratio (H_t/l_x) variation of empty tank above the ground

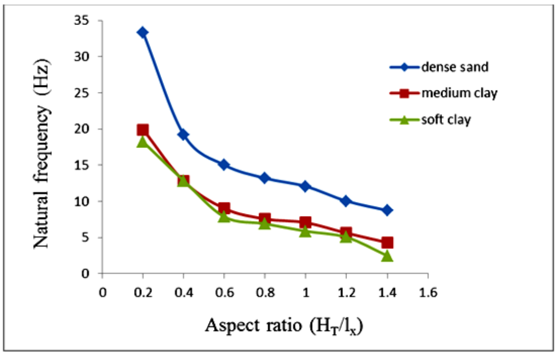

Figure (3):Fundamental natural frequencies versus aspect ratio (H_t/l_x) variation of full tank the above ground

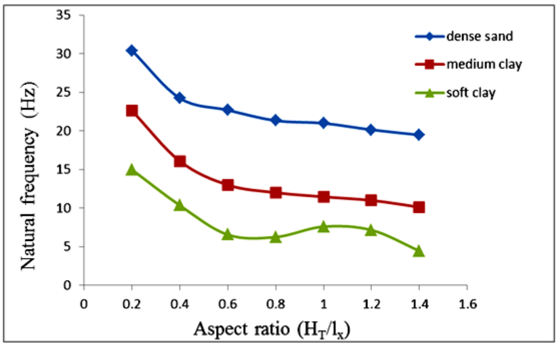

Figure (4):Fundamental natural frequencies versus aspect ratio (H_t/l_x) variation of empty buried tank

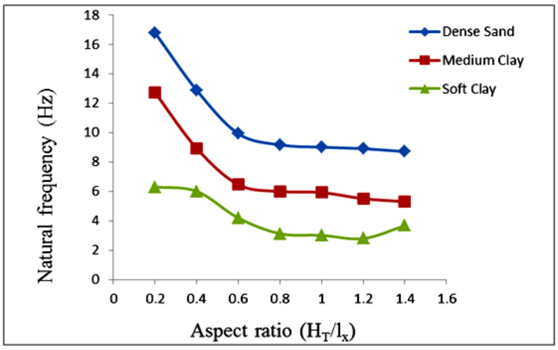

Figure (5):Fundamental natural frequencies versus aspect ratio (H_t/l_x) variation of full buried tank

6.1.2 Effect of Liquid Height to Tank Height 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. Tank length, L=9.9m, tank width B=6.3m and the tank height, H_t =5.4m. Different values of liquid depths for the same three types of the soil were carried out to demonstrate the influence of liquid height on the dynamic characteristics. The resulting natural frequencies shown at Fig.(6) and (7) for above ground and buried tanks respectively. It can be observed from these plots that, as the level of fluid in the tank increases, the natural frequencies decrease for both cases of tanks and for all three types of the soil. This behavior is obvious since the mass of the structure system increases with the level of fluid.

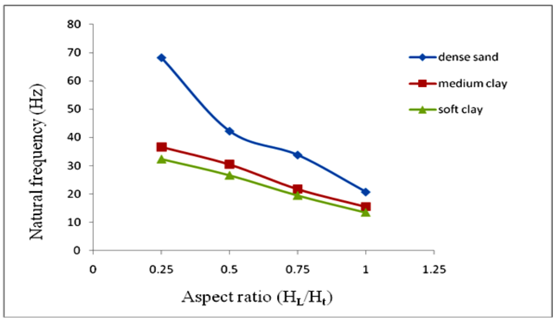

Figure (6):Fundamental natural frequencies versus filling ratio (H_L/H_t) of tank above ground

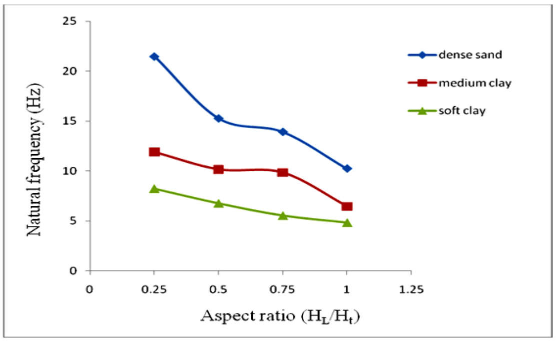

Figure (7):Fundamental natural frequencies versus filling ratio (H_L/H_t) of buried tank

6.1.3 Effect of Wall Thickness Variation.

To demonstrate the effect of wall thickness variation, empty tank and completely full tank, having dimensions 3.6m height, 9.9m length and 6.3m width is studied for the free vibration characteristics when its wall thickness varies from 450mm to 1350mm with one type of the surrounding soil (dense sand), and also for two cases (above ground and buried tank). The resulting natural frequencies are plots at Figs.(8) to (11). It can be seen clearly from these results that, the natural frequencies increases when the thickness of the wall increases without changing the height of the tank (the wall stiffness increases with increasing its thickness).

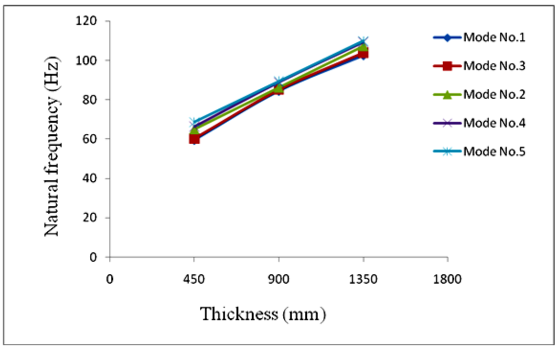

Figure (8): Effect of thickness variation on natural frequencies of empty tank above ground

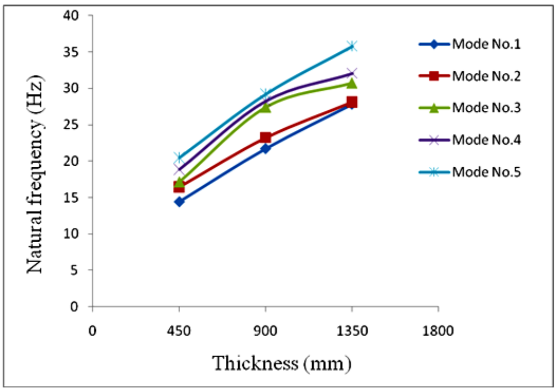

Figure (9): Effect of thickness variation on natural frequencies of full tank above ground

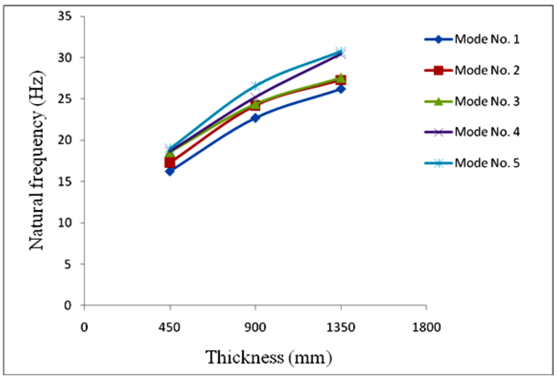

Fig. (10): Effect of thickness variation on natural frequencies of empty buried tank

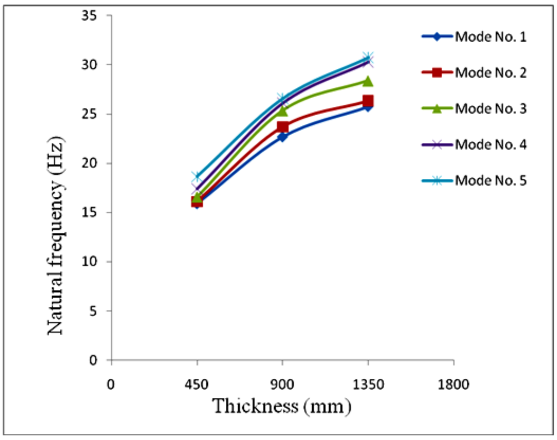

Figure (11): Effect of thickness variation on natural frequencies of full buried tank

6.2 Time Domain Analysis

A time domain analysis using 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. These studies depend on two cases, the first case, is for an above ground tank and case two is for the tank underground (buried tank). The results are compared for each case for variant effects including (soil type and location of the tank). The damping ratio (ζ) is taken equal to 5% of the critical damping ratio and the acceleration duration is divided into several step with Δt=0.02 sec.

The tank dimensions for this model having length 9.9m, width 6.3m, height 12.6m, thickness of wall 45cm. The analysis shown the relationships between the displacement ,shear force ,bending moment , stresses and the time and also for the two cases (above ground and underground) are presented. In this case found the displacement (1.9 mm) for empty tank above ground as shown in the figure (12) ,greater than the displacement (0.032 mm) for tank underground as shown in figure(13) , the shear force is (2500 kN) for empty above ground tank as shown in the figure (14) greater than (2000 kN) for underground tank as shown in figure (15) , and the bending moment for empty tank above ground as shown in the figure (16) is (13000 kN.m) greater than (4500 kN.m) for underground tank as shown in figure (17).The maximum stresses for empty tank above ground as shown in figure (18) is (24 MPa)greater than (6.2 MPa) for underground tank as shown in figure (19).

The results for empty tank above ground appearance largest than underground due to the confined from soil also for the fixed support the displacement ,shear and bending moment less than simply support and the bending stresses according to maximum bending moment value.

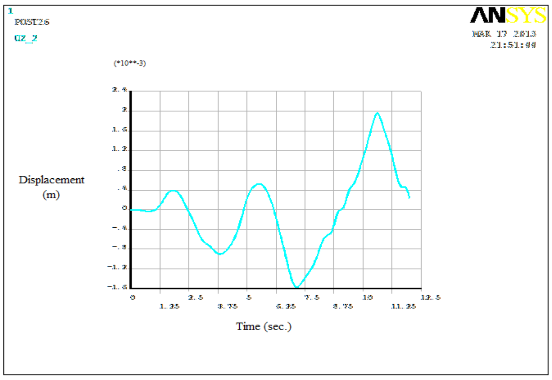

Fig. (12): The displacement for empty tank above ground

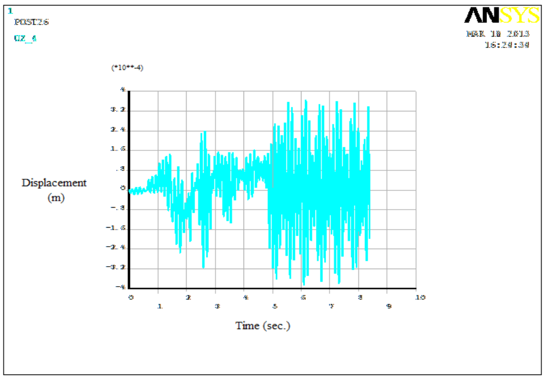

Fig. (13): The Displacement for empty tank under ground

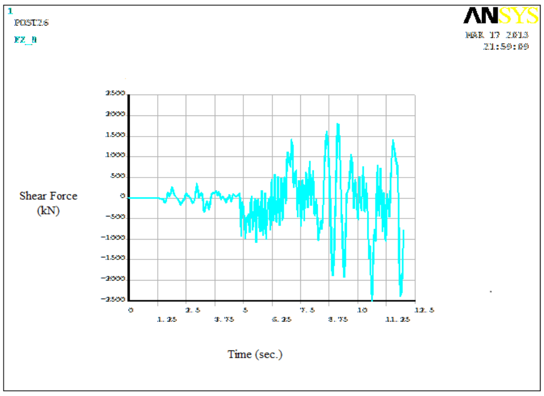

Fig. (14): Shear force for empty tank above ground

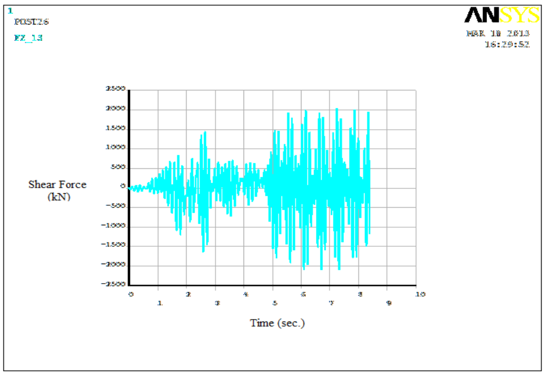

Fig.(15): Shear force for empty tank under ground

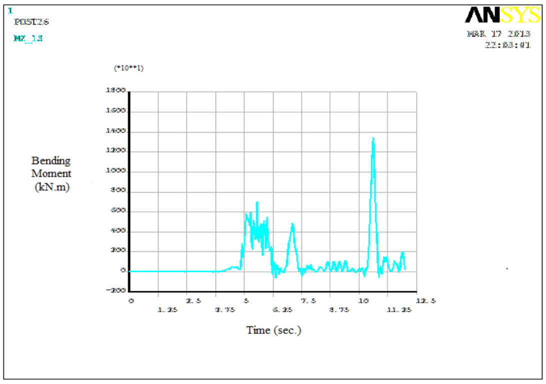

Fig. (16): Bending Moment for empty tank above ground

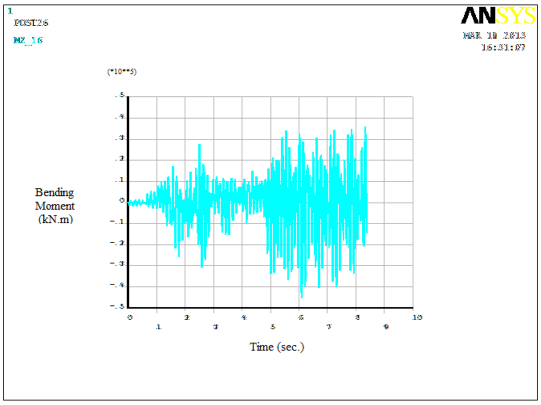

Fig. (17): Bending Moment for empty tank under ground

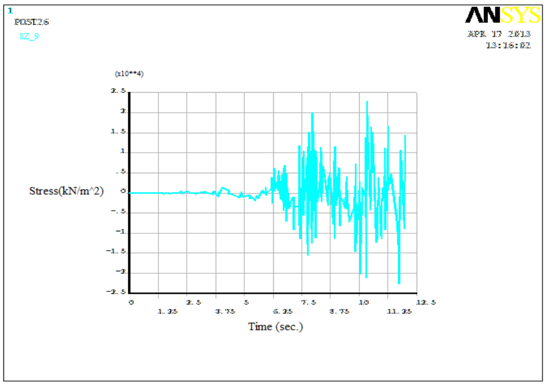

Fig. (18): Bending Stress for empty tank above ground

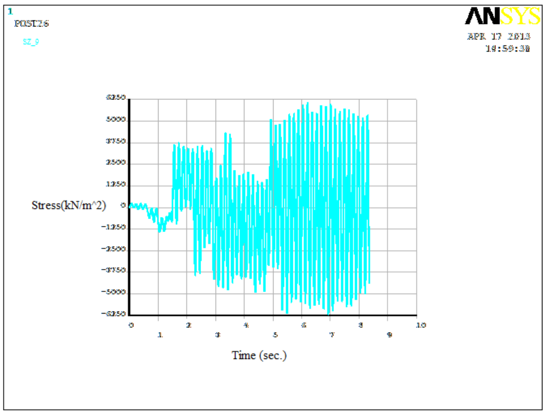

Fig. (19): Bending Stress for empty tank under ground

6. CONCLUSIONS

1. The wall and base of the tanks are modelled using four-node shell elements (**SHELL63** element).The fluid is modelled by using the eight-node brick elements (**FLUID80** element).The soil is modelled using two-node spring-dashpot element (**COMBIN14** element).
2. Buried tanks are found to have lower natural frequencies than comparable above ground tanks.
3. The natural frequency is found to decrease as the contained liquid level increases.
4. From seismic analysis it is found that the maximum displacement of above ground tanks is 1.9 mm while it is 0.032 mm for buried tank of similar dimension and subjected to the same earthquake loading.
5. Variations of the properties of surrounding soil medium are found to have an important influence on the free and forced vibrational response (seismic excitation) for the storage tanks.
6. The base shear for above ground tank have values (2500kN) greater than those in underground tank (2000kN).
7. The bending moment for above ground tank have values (13000kN.m) greater than those (4500kN.m) in underground tank.
8. The maximum bending stress for above ground tanks is found to be (24 MPa) and for underground tank is (6.2 MPa) when the two tanks are subjected to El Centro earthquake.

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