The influences of a liquid storage tanks and soil characteristics under seismic loads

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KEYWORDS: Liquid storage tank, foundation, seismic behavior, wave propagation

ABSTRACT: The different seismic behavior of liquid storage tanks rather than conventional structures make their responses more complicated. The tank seismic behavior can be improved by modifying dynamic characteristic of tank with verifying seismic loads as well as retrofitting and improving base ground. As a matter of fact, uses of liquid storage tanks because of the simple construction on compact layer of soil as a foundation are very conventional. This paper focuses on a typical steel tank on medium, loose and stiff soil and describes an evaluation of displacement of the tank when the depth of the tank is constant. Because of the assessment of earthquake response of such structures, finite element methods are indispensable tools since they offer a concise way of accurately considering all these nonlinearities in the model. Three dimensional tank was modelled by software of ABAQUS.The compact layer of soil, as the tank base, has been modelled and the influences of tank and soil characteristics that are effective on tank seismic behavior have been considered. The results shows that, by increasing shear strength parameter of soil, the performance of the liquid storage tank under the case of seismic load was improved and necessity of retrofitting tank decrease.

1 INTRODUCTION

Due to the requirement of remaining functional after a major earthquake event, the seismic performance of liquid storage tanks has been a matter of special importance .The most common type of tank is the vertical cylindrical tank. Damages to liquid storage tanks in past earthquakes motivated several experimental and analytical investigations of the seismic response of vertical cylindrical tanks. Some simplified Mass Spring Model (MSM) has been proposed for predicting tank responses, such as base shear force and overturning moment. The most frequent failures of the steel tanks are related to shell buckling near the bottom of the tank wall, where large compressive membrane stresses are induced to resist the overturning moment from the earthquake shaking of the system. If the sloshing freeboard is not properly accounted in the design procedure, sloshing of the contained liquid can also cause yielding in the connection of the tank roof and its wall. Other types of damage, including failure of the piping system connected to the tank (due to its inability to follow the shell movement and rupture at the junction of the tank wall and the base plate) may appear due to excessive plastic conditions. Nearly all the models used until recently in seismology for predicting ground motion induced by earthquakes have been based on the assumption of linear elastic behavior of the soil. On the other hand, for a number of years nonlinear soil implication has been routinely taken into consideration in geotechnical engineering practice (Seed & Idriss, 1984). The main reason seismologists had in the past ignored the possibility that nonlinear phenomena could play an important role in earthquake ground motion was that compelling evidence for nonlinear effects in the observed motion, other than in liquefiable sites, was scarce. In the last decade, however, a number of accelerograms have been recorded during strong earthquakes that have made it possible to infer nonlinear response. The most common manifestations of inelastic soil behavior involve the reduction in shear wave velocity and the increase in soil damping with increasing load (Hardin & Drnevich, 1972).In general, investigations on the seismic response of liquid storage tanks have been conducted over the past 30 years. Housner (1954, 1957) proposed a simple MSM for computing the seismic response of liquid storage tanks which is still widely used with certain modifications for the analysis of rectangular and cylindrical tanks. His simplified MSM is a two degree-of freedom (DOF) system for a rigid tank; one DOF accounting for the motion of the tank-liquid system, in which a part of the contained fluid being rigidly attached to the tank wall (impulsive mode) and the other DOF for the motion of the sloshing fluid effect on the tank wall (convective mode).In further studies, Housner's simplified MSM has been modified to account for the flexibility of the tank wall. Veletsos and Yang (1976) used one mass for the impulsive component and two convective mass in their simplified MSM .Haroun and Housner (1981) divided the impulsive mass into two parts; one part rigidly connected to the ground and one part representing the mass participating in the relative movement due to the deformation of the tank shell. Malhotra et al. (2000) modified the properties of the simplified MSM proposed by Veletsos and Yang (1976) using one convective mode .Uplifting of unanchored tanks, as well as soil structure interaction effects, has been also extensively studied by several researchers (Natsiavas;1988, El-zeiny;1998,2003, Fisher;1979).Some of above mentioned works have constituted the basis for the seismic design provisions for vertical cylindrical tanks in Euro code 8-part 4.3 and American Petroleum Institute (API). In this study a typical steel tank on loose, medium and dense sandy soil was analyzed and settlement, sliding and amplification effect for all three types of soil were illustrated.

2. FINITE ELEMENT MODEL (FEM)

2.1. MASS SPRING MODEL (MSM)

The simplified Mass Spring Model (MSM) proposed by Malhotra et al (2000) is illustrated in Figure 1. The procedure was based on the work of Veletsos and his co-workers with certain modifications including; i) Combining the higher impulsive modal mass with the first impulsive mode and combing the higher convective modal mass with the first convective mode. ii) Modifying modal heights of mass to account for the contribution of higher modes to the base overturning moment. iii) Generalizing the formula for the impulsive period so that it could be applied to tanks of various wall thicknesses. The effects of liquid-structure interaction and an uncoupled manner by dividing the hydrodynamic pressure acting on the shell into two components;

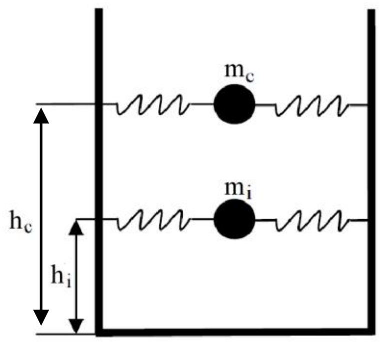

Figure 1. Simplified Mass Spring Model (MSM) proposed by Malhotra et al. (2000).

1) The impulsive pressure caused by the portion of the liquid, m_i, which is rigidly attached to the shell wall, and
2) The convective pressure caused by the portion of the liquid, m_c, sloshing in the tank.
These components were then modeled as single DOF oscillators. For very large values of fluid height to tank radius (*H/r*), the sloshing mass is only a small portion of the total mass. As *H /r* less than unity, more than half the total mass can participate in the convective mode. The values proposed by Malhotra for the parameters of the simplified model can be obtained from equations 1 and 2 as well as Table 1.Where m_l is the total mass of the liquid, *hi* and h_c are the respective heights of the resultant force of the hydrodynamic pressure due to the motion of the impulsive m_i and the convective m_c masses, respectively, ρ is the mass density of liquid, c_i and c_c are constant and related to the fluid height to tank radius.

$$T_{imp} = C_i \frac{H\sqrt{\rho}}{\sqrt{h/r} \times \sqrt{E}} \tag{1}$$

$$T_{con} = C_c \sqrt{r} \tag{2}$$

In equations 1 and 2, *h* is the wall thickness, *E* is the modulus of elasticity of the tank material, T_{imp} and T_{con} are the mass density of the liquid, the periods of the impulsive and convective modes, respectively,

Table 1. Parameters of the simplified MSM (Malhotra et al.2000)

H/r	C_i	C_c [s/$\sqrt{\text{m}}$]	m_i/m_l	m_c/m_l	h_i/H	h_c/H
0.3	9.28	2.09	0.176	0.824	0.400	0.521
0.5	7.74	1.74	0.300	0.700	0.400	0.543
0.7	6.97	1.60	0.414	0.586	0.401	0.571
1.0	6.36	1.52	0.548	0.452	0.419	0.616
1.5	6.06	1.48	0.686	0.314	0.439	0.690
2.0	6.21	1.48	0.763	0.237	0.448	0.751
2.5	6.56	1.48	0.810	0.190	0.452	0.794
3.0	7.03	1.48	0.842	0.158	0.453	0.825

In this research the tank was modeled from the Malhotra's assumptions, the radius of the tank is 2.5m and the height of the liquid is 6.5m, value of fluid Height to tank Radius (*H/r*) is 2.6 thus the parameters of the simplified MSM can be obtained from Table 1. The influences of the three types of sandy soil (dense, medium, and loose) as a foundation of the tank under the specific time history acceleration were aimed. The property of dense, medium and loose sand was illustrated in Table 2.

Table 2. Properties sands used for 3D finite element.

	dense	medium	loose
Young's modulus (MPa)	500	200	100
Poisson's ratio(υ)	0.35	0.35	0.4
Φ (deg)	38˚	30˚	25˚
Undrained shear strength C_u(Kpa)	10	7	5

2.2. FEM STRATEGY

The finite element software ABAQUS was used for describing the behavior of soil. Figure 2 shows 3D finite element mesh used in this analysis. Relatively fine mesh is occupied near the surface while a coarser mesh was used for further distance from the tank. Three types of soils were modeled by using Mohr-Coulomb criteria .For tank-soil contact, the modeling of the tank-soil interfaces is an important concern. Therefore one of the main issues is identifying interaction between soil and tank. When a compressive normal pressure (p) applied on the bottom plate of the tank, tank can only transfer shear forces along their lateral surfaces. When contact take places, according to modified Coulomb's friction theory, the relationship between shear force and normal pressure is shown in equation 3.

$$\tau = \mu \times p \tag{3}$$

Where μ is friction coefficient and p is normal pressure that varied in each level of soil. As reported by Jeong et al (2003) the interface friction coefficient (μ) for sand varies from 0.4 to 0.6. Therefore, in this study interface friction coefficient (μ) of 0.5 for all the types of sand was adopted.

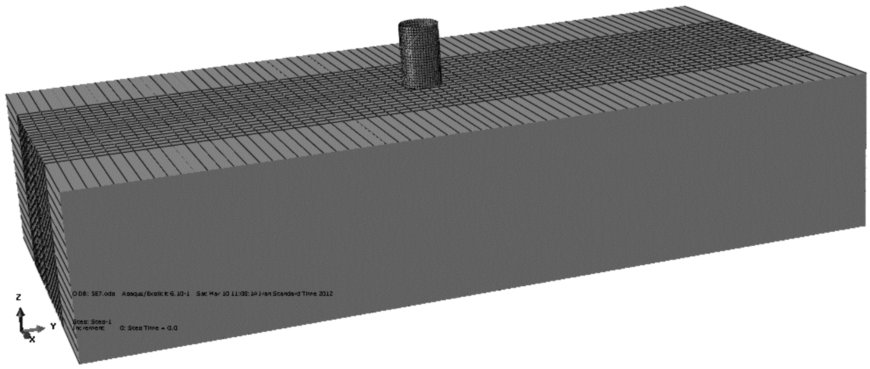

Figure 2. 3D finite element model

In order to represent the half-space soil medium with explicit finite elements, the near field is expected is modeled with explicit 3-D brick type elements. The lateral boundary of the near field model should be extended sufficiently far such that the outgoing wave due to the structural vibration diminishes drastically at the boundary. To prevent any reflection of outgoing waves at the boundary, a series of artificial viscous dampers are attached to the boundary. In ABAQUS, the approach developed by Lysmer and Kuhlemeyer (1969) was implemented, in which viscous normal and shear stresses are applied to the boundaries in a manner as defined in the following equations:

$$\sigma_{normal} = -\rho c_d V_{normal} \tag{4}$$
$$\sigma_{shear} = -\rho c_s V_{tangential} \tag{5}$$

Where ρ, c_d, and c_s are the material density, material longitudinal and shear wave velocities of the transmitting media. These equations reveal that the magnitude of these stresses at the boundaries is proportional to the particle velocities in the normal (V_{normal}) and in the tangential ($V_{tangential}$) directions.

The Lysmer's dampers placed on the artificial boundary are effective in reducing unwanted wave reflections if the boundary of the finite element mesh is sufficiently far outward. However, in doing so, the size of the near field finite element mesh is increased significantly and so is the cost of running the dynamic analysis. As it was mentioned the unbounded or infinite medium can be approximated by extending the finite element mesh to a far distance, where the influence of the surrounding medium on the region of interest is considered small enough to be neglected. This approach calls for experimentation with mesh sizes and assumed boundary conditions at the truncated edges of the mesh and is not always reliable. It is particularly of concern in dynamic analysis, when the boundary of the mesh may reflect energy back into the region being modeled. A better approach is to use "infinite elements": elements defined over semi-infinite domains with suitably chosen decay functions. Abaqus provides first- and second-order infinite elements that are based on the work of Zienkiewicz et al. (1983) for static response and of Lysmer et al. (1969) for dynamic response. The elements are used in conjunction with standard finite elements, which model the area around the region of interest, with the infinite elements modeling the far-field region. As it was shown in Figure.2 in the seismic load direction infinite element was used.

3 RESULTS AND DISCUSSION

Liquid storage tanks are important elements of lifeline and industrial facilities. The evolution of codes and standards for the seismic design of these structures has relied greatly on observations of tank damages during past earthquakes, yet the time lag between acquiring the information and implementing the findings in practice has remained relatively long. Even though, current codes and standards reflect a mature state of knowledge for tank design, recent earthquakes as well as advanced state-of-the-art analyses continued to point out to a few overlooked issues. Both failure of the tank and failure of the foundation of the tank were caused the necessity of tank retrofitting.

In this study, a nonlinear numerical technique based on finite element method is employed for the seismic analysis of unanchored steel liquid storage tanks by focusing on the tank foundation. Large differential settlement and sliding of the tank caused considerable damage and made the tank out of work. If the estimated differential settlements are large enough to cause problems, measures can be taken to reduce their magnitudes through treatment of the foundation. In marginal cases, it may be more desirable to measure settlements carefully during first filling of the tank, and then institute mitigative measures only if the predicted potentially damaging settlements are confirmed by field observations Abaqus procedure is utilized to consider the interaction forces between tank and soil. The complex interaction mechanism of unanchored tank base plate and soil is taken into account with contact algorithm including friction forces.

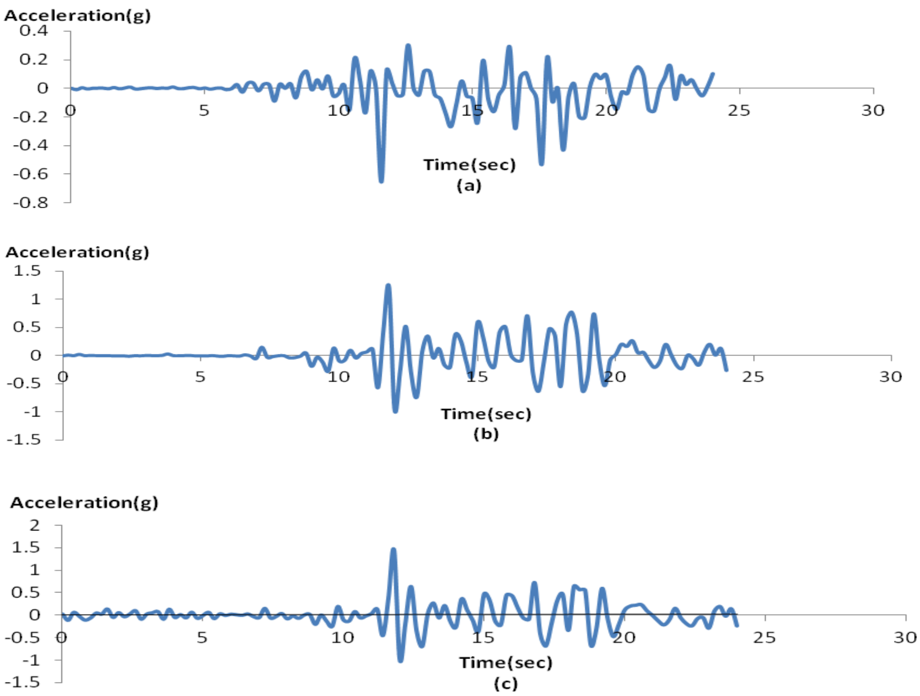

Figure 3. Time-acceleration on the ground: (a) dense, (b) medium and (c) loose sand

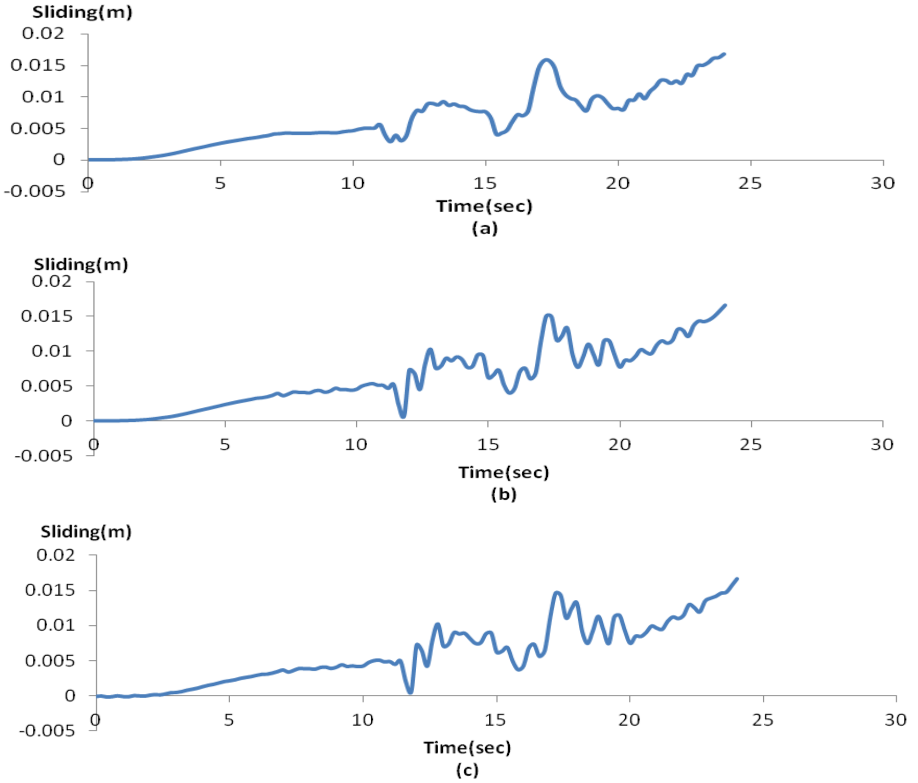

Figure 4. Sliding of the tank in: (a) dense, (b) medium and (c) loose sand

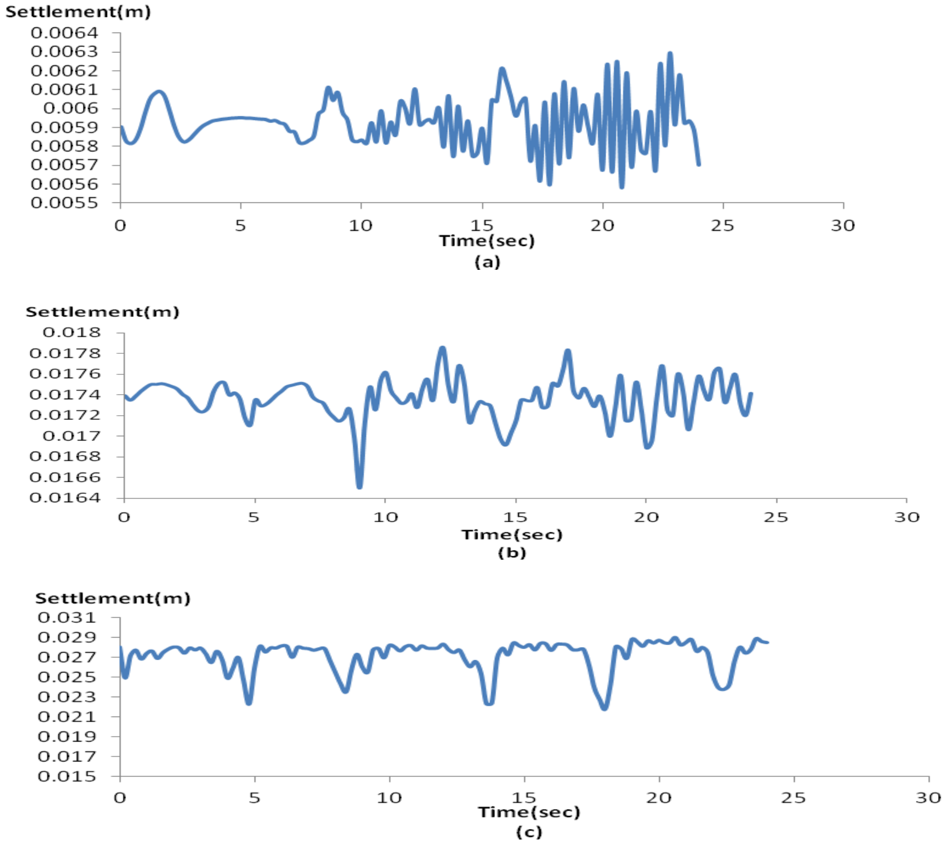

Figure 5. Settlement of the tank in: (a) dense, (b) medium and (c) loose sand

As it was shown in Figure 3, 4 and 5 by increasing module of elasticity and soil strength parameters, the measured acceleration on the ground was decreased. It means by improving the soil strength parameters the amplification effect was reduced (Table 3).All three types of the soil couldn't resist the tank from sliding. This point revealed that tall tank was recommended to build as an anchored tank. On the other hands increasing the soil strength parameters had a neglect able effect on sliding resistance, it was also reasonable because friction coefficient is constant, thus resistance force was nearly constant. By considering the rate of settlement during the earthquake (Figure 5), although reducing soil strength parameters caused increasing settlement of the tank, the rate of settlement couldn't make the tank out of work.

Table 3.Maximum acceleration, sliding and settlement

	dense	medium	loose
Acceleration (g)	0.8	1.1	1.5
Sliding (m)	0.0165	0.0165	0.016
Settlement (m)	0.0063	0.018	0.0285

4 CONCLUSIONS

Liquid storage tanks are vital construction that studying the behavior of them during the seismic load is essential. As well as the behavior of soil under the tank is important, because by decreasing the soil strength parameter the amplification effect and the settlement of the tank increase.

According to the result increasing the sliding resistance force for the tall tank is necessary and retrofitting of the tank foundation for this case could be a solution. However it should be better constructed tall tank as an anchored tank.

Also in this study there is no focus on the differential settlement, but for decreasing the sliding movement of the tank some strategies necessary. To clarify retrofitting of the tank foundation, more study is necessary.

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