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Foundation Retrofitting of Storage Tank under Seismic Load

Seyed Abolhasan Naeini, Mohammad Hossein Zade, E. Izadi, M. Hossein Zade

***Abstract*—**The different seismic behavior of liquid storage tanks rather than conventional structures makes their responses more complicated. Uplifting and excessive settlement due to liquid sloshing are the most frequent damages in cylindrical liquid tanks after shell bucking failure modes. 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, but in some cases need to retrofit are essential. 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. This paper focuses on a typical steel tank on loose, medium and stiff sandy soil and describes an evaluation of displacement of the tank before and after retrofitting. The Abaqus program was selected for its ability to include shell and structural steel elements, soil-structure interaction, and geometrical nonlinearities and contact type elements. The result shows considerable decreasing in settlement and uplifting in the case of retrofitted tank. Also, by increasing shear strength parameter of soil, the performance of the liquid storage tank under the case of seismic load increased.

***Keywords*—**Steel tank, soil-structure, sandy soil, seismic load.

I. Introduction

THE dynamic responses of a liquid storage tank to a seismic motion differ from those of general structures such as buildings or bridges. It is well known that these differences mainly come from the effect of hydrodynamic pressure on structures. This effect has been examined by numerous studies that focus on the interaction between a flexible wall and liquid [1]-[4]. Veletsos [5] gave a detailed account of these efforts and Rammerstrofer et al. [6] summarized various treatments of earthquake-loaded liquid storage tanks. Those studies usually concentrated only on the structural system, even though the effect of soil– structure interaction is important. Some exploratory studies on coupling effects between a liquid tank and a flexibly supported foundation have already been performed [7]-[9]. Recently, many liquid storage tanks are constructed with concrete ring foundation system to reduce damages due to seismic motion [10]. In such cases, it is essentially needed to consider a whole system that contains a three-dimensional fluid–structure–soil interacting with the concrete ring foundation system for precise analysis. Many of these factors have been studied by several researchers since early 1930's. Hopkins and Jacobsen [11] have worked on water pressure in tanks. Jacobsen [12] also studied the hydrodynamic pressure in tanks. Several studies have been performed on tanks, including hydrodynamic pressure by Housner [13] as well as vibration tests and analysis by Housner and Haroun [14], [15]. Epstein [16] has worked on the seismic design of liquid storage tanks. Haroun and Ellaithy [17], and Veletsos and Tang [18] have studied the rocking motion of flexible tanks during earthquake. Barton and Parker [19] have studied the effect of anchorage conditions on the seismic response of tanks. In recent years the soil-structure interaction effect has been one of the most attractive subjects for many researchers. Velestos and Tang [20] have studied comprehensively the effect of soil-structure interaction on the tank seismic response. James and Raba [21] have studied the behavior of steel tanks from various aspects, including soil-structure interaction. Liquid-structure interactions as well as sloshing phenomenon have been also matters of interest for several researchers in recent years. Lay [22] has studied the modeling of axisymmetric tanks by taking into account the liquid-structure interaction. The sloshing phenomenon has been studied by Veletsos and Shivakumar [23] in the case of rigid tanks. Large amplitude sloshing has been also studied by Chen and his colleagues [24] for tanks subjected to sever earthquakes. Soil-structure interaction has been taken into consideration again in a recent work by Malhotra [25] for unanchored tanks. Most of the aforementioned studies have been performed for the anchored tanks. Nevertheless, some research has been also conducted for unanchored tanks, especially in recent years. In addition to studies of Malhotra [25], some other researchers such as Haroun [26] have been also worked on the behavior of unanchored tanks subjected to lateral or seismic loads. The use of unanchored tanks has not been recommended for seismic areas as the separation of tank walls and bottom from the foundation usually leads to heavy damages to the system in addition to the loss of content and environment pollution. More recently the soil-structure interaction has been a matter of interest for some researchers. Zou and Kong [27] have suggested a simplified method for seismic analysis of cylindrical tanks, in which the geometric parameters of tanks have been taken into consideration.

In this paper, a study has been performed on the effect of the tank concrete ring foundation on the modal properties of the tank-liquid-soil system for the case of anchored and unanchored cylindrical steel tanks in the case of different peak ground acceleration The simplified modeled that described by Malhotra [10] was used. Both liquid structure and soil-structure interactions have been taken into account. For this purpose a cylindrical steel tank with height over radius (H/R=0.66) that was settled on the loose, medium and stiff

Seyed Abolhassan Naeini, Associate Professor, and Mohammad Hossein Zade, Phd Candidate, are with the Civil Engineering Department, Imam Khomeini International University, Qazvin 34149-16818, Iran (e-mail: Naeini_h@ikiu.ac.ir, mohammad_lg12@yahoo.com).

sandy soil was selected. The property of dense, medium and loose sand illustrates in Table I. In the first case tank was unanchored and then the result compared with the case of anchored tank. As the results shows the retrofitting of the tank by anchoring the tank to ringing foundation can be assumed the effective way to decrease the settlement and uplifting. By Improving the soil strength parameter the settlement and uplifting of the tank decrease thus needed to retrofitting decrease under the seismic load.

TABLE I
SANDY SOIL MATERIAL PROPERTIES

Soil Properties	Dense	Medium	loose
Young's Modulus	100	70	40
Poisson's Ratio(υ)	0.28	0.33	0.35
φ (deg)	38˚	30˚	25
Undrained Shear	7	5	2

II. FINITE ELEMENT STRATEGY

The finite element software ABAQUS was used for describing the behavior of soil. Fig. 1 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. Friction plays an important role in the interaction effects between tank and soil. Sliding of the tank over its foundation which occurs when the lateral inertial force (base shear) exceeds the static friction force is prevented by friction. Friction is an integral part of the contact algorithms of ABAQUS and it is based on a Coulomb formulation, where the magnitude of the friction force is proportional to the normal force, but its direction is always opposite to that of the sliding velocity.

The Coulomb friction law neglects the elasticity between the particles and a rigid plastic contact behavior is assumed. 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 as (1):

$$\tau = \quad *p \tag{1}$$

where μ is friction coefficient and p is normal pressure that varied in each level of soil. As reported by Jeong et al [28] 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.

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. [29] for static response and of Lysmer et al. [30], 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 Fig. 1 in the seismic load direction infinite element was used. The time history that was used in this paper was shown in Fig. 2 and its peak ground acceleration was changed to show the relation of peak ground acceleration with settlement and uplifting.

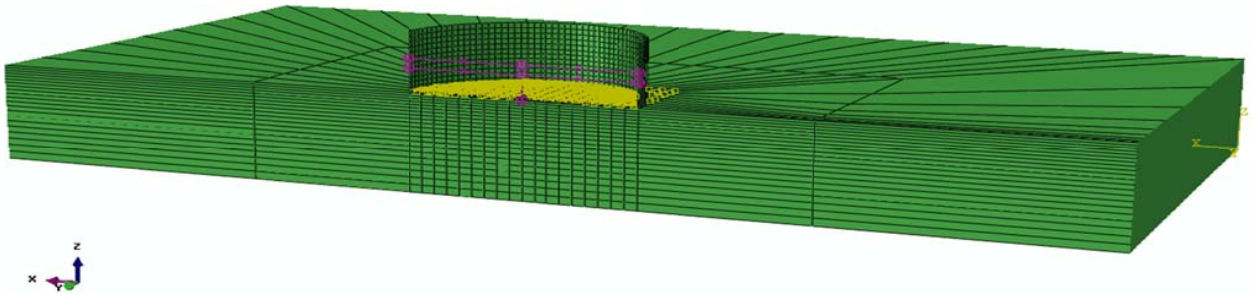

Fig. 1 3D finite element model

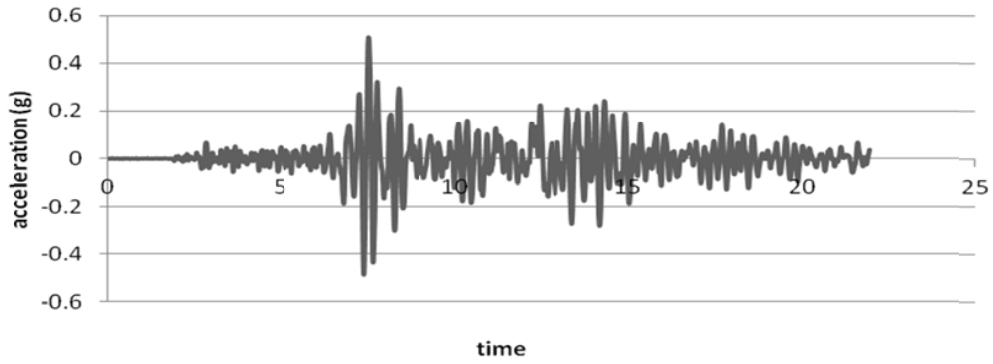

Fig. 2 Time history acceleration

III. Result and Discussion

Seismic tank design codes are used to limit the possibility of the damage of tanks during earthquakes depending on the performance criteria selected. There are various national and international codes for seismic design of steel vertical cylindrical liquid storage tanks. The common feature of all these codes is that the hydrodynamic forces in a liquid-tank system exerted by seismic loads are converted into equivalent mass spring system which develops the same forces and moments on tank when subjected to same ground motion.

In this study, a nonlinear numerical technique based on finite element method is employed for the seismic analysis of unanchored and anchored steel liquid storage tanks by focusing on the tank foundation. For this purpose three types of soil was selected and peak ground acceleration varied. A portion of the settlement occurs immediately upon application of the load, even though the foundation soils may be saturated and may drain slowly. The magnitudes of these immediate settlements, which occur due to distortion in the foundation soils, may be estimated using elastic theory.

Excessive settlement and uplifting of the tank caused considerable damage and made the tank out of work. If the settlements and uplifting are large enough to cause problems, measures can be taken to reduce their magnitudes through treatment of the foundation. Abaqus procedure is utilized to consider the interaction forces between tank and soil. The complex interaction mechanism of unanchored and anchored tank base plate and soil is taken into account with contact algorithm including friction forces.

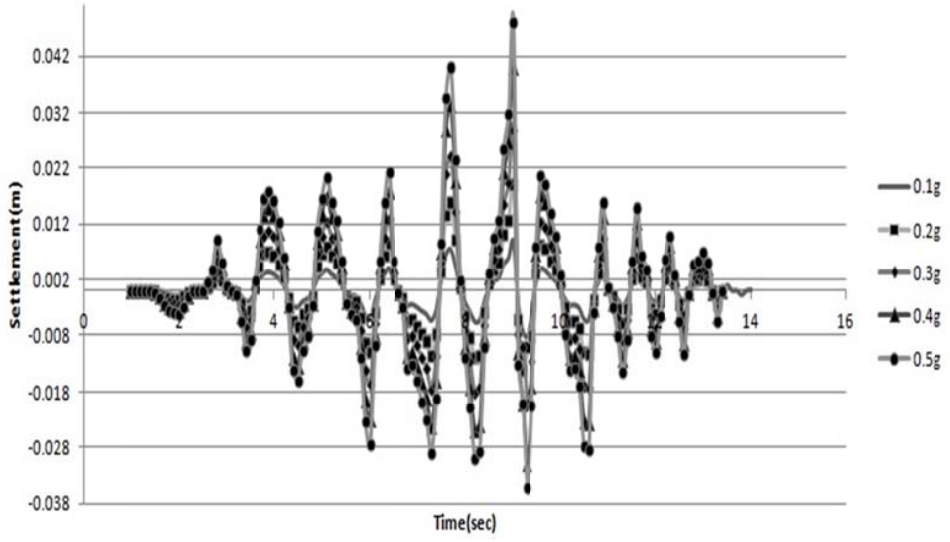

Fig. 3 Settlement and uplifting for unanchored tank in dense soil

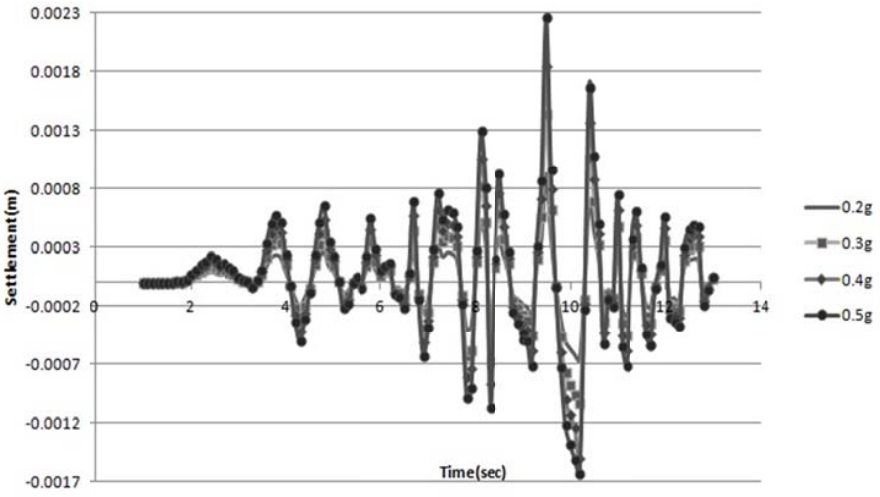

Fig. 4 Settlement and uplifting for anchored tank in dense soil

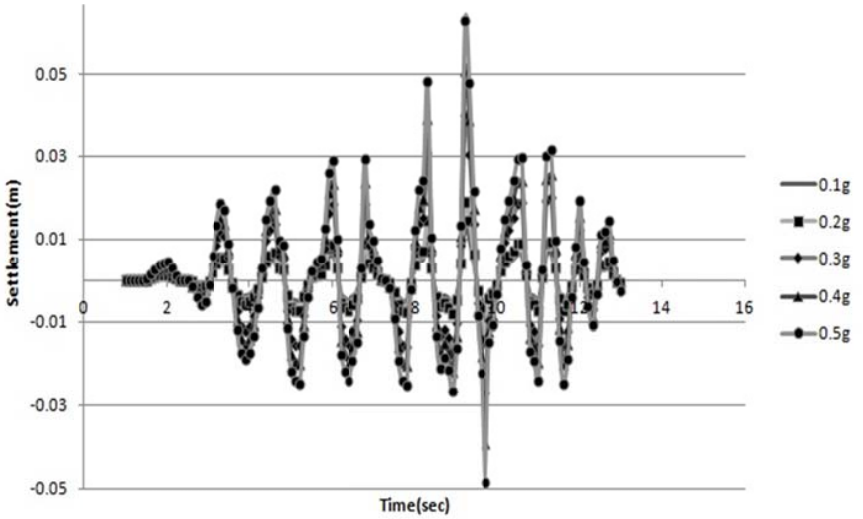

Fig. 5 Settlement and uplifting for unanchored tank in medium soil

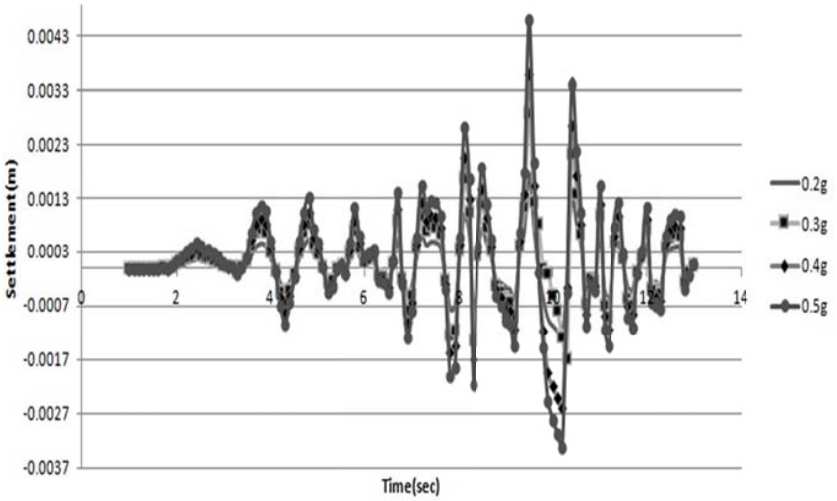

Fig. 6 Settlement and uplifting for anchored tank in medium soil

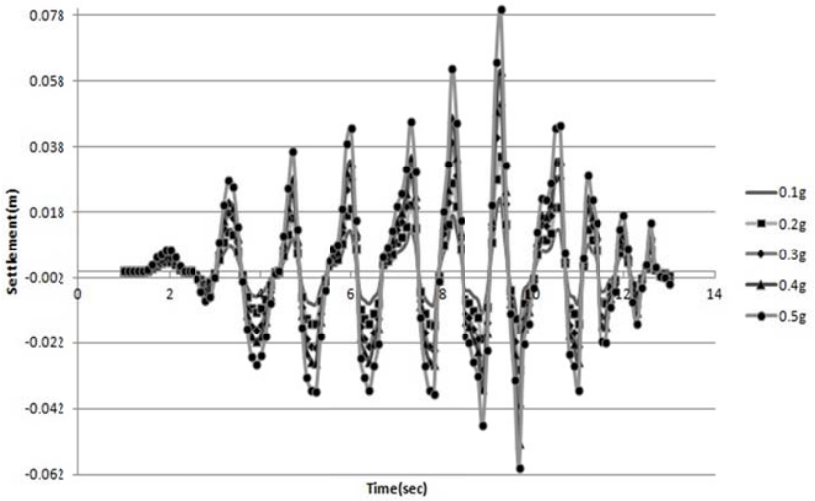

Fig. 7 Settlement and uplifting for unanchored tank in loose soil

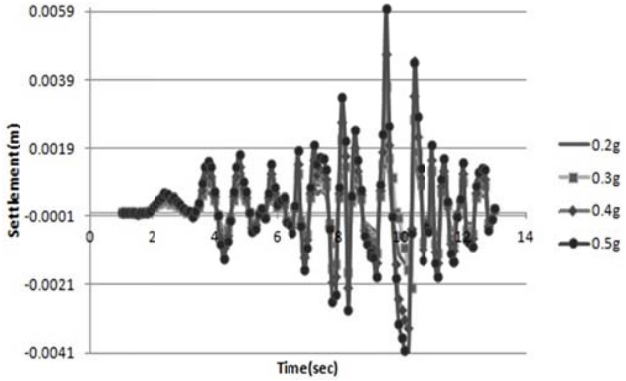

Fig. 8 Settlement and uplifting for anchored tank in loose soil

As it was shown in Figs. 3-8, by increasing the peak ground acceleration, settlement and uplifting increased and as the soil strength parameters increased, the settlement and uplifting decreased. It means that by improving the soil strength parameters the amplification effect was reduced, thus the rate of settlement and uplifting decreased. In the case of unanchored tank the settlement and uplifting was large. This point revealed that if tank was located in area with high peak ground acceleration, it was recommended to build it as an anchored tank. As it was shown in the case of anchored tank the settlement and uplifting of the tank decreased, it was reasonable, because the concrete ring foundation increased the stiffness of soil-structure system and it cause the resistance force for uplifting increased, thus the uplifting and settlement that caused from uplifting decreased.

IV. Conclusion

The developed program studied the effects of three types of soil on the behavior of an anchored and unanchored liquid storage tank. The seismic structure–soil interaction analysis is performed to evaluate the effect of the flexible soil and concrete ring foundation on the dynamic responses of a liquid storage tank. According to the result increasing the peak ground acceleration caused the rate of settlement and uplifting increased. As the uplifting and settlement of the tank increased, the improvement of the foundation is necessary and retrofitting of the tank foundation for this case could be a solution. One way for retrofitting is using concrete ring wall and anchoring tank to the ring. Also, results showed that by increasing the soil strength parameter, the rate of settlement and uplifting decreased. In the case of anchored tank the concrete ring increased the stiffness of soil-structure system and it cause reduction in the rate of settlement and uplifting.

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