Seismic Response Analysis of an Unanchored Steel Tank under Horizontal Excitation

Zhang Rulin, Cheng Xudong and Guan Youhai
College of Pipeline and Civil Engineering, China University of Petroleum, Qingdao 266580, China
Email: zhangrulin@upc.edu.cn;

Abstract. The seismic performance of liquid storage tank affects the safety of people's life and property. A 3-D finite element method (FEM) model of storage tank is established, which considers the liquid-solid coupling effect. Then, the displacement and stress distribution along the tank wall is studied under El Centro earthquake. Results show that, large amplitude sloshing with long period appears on liquid surface. The elephant-foot deformation occurs near the tank bottom, and at the elephant-foot deformation position maximum hoop stress and axial stress appear. The maximum axial compressive stress is very close to the allowable critical stress calculated by the design code, and may be local buckling failure occurs. The research can provide some reference for the seismic design of storage tanks.

1. Introduction
With the increasing demand for soil energy in the world, the large storage tanks have become important foundation for the energy reserves. Storage steel tanks often store flammable and explosive liquid media, once suffered earthquake damage, a large number of flammable liquid leakage and burning, and even lead to devastating secondary disasters. So the seismic performance of steel tanks has attracted the attention of scholars all over the world. The research of storage tank often uses the classic Haroun-Housner model to simulate the coupling of tank and liquid [1], and different simplified mechanical models of tank are studied by literature [2-3]. Based on the mechanical model with fluid masses and convective spring stiffness given by Newmark and Rosenblueth [4], Seleemah A.A. and El-Sharkawy M. [5] investigated the seismic response of elevated broad and slender liquid storage tanks isolated by elastomeric or sliding bearings, and studied the accuracy of predictions of SAP2000 vs. 3DBASIS-ME programs.

However, the simplified model is difficult to get tank wall stress and displacement distribution. Actually, the seismic problem of tank belongs to a three-dimensional space problem, and the performance of tank is very complicated. Especially, it is difficult for the unanchored tank to apply the simplified method due to the nonlinear lift-off effect at the tank bottom. Bayraktar [6] studied the issue of the tank uplift and showed that the displacement and stress response became more obvious after uplift. ZHANG [7] studied the horizontal seismic response of unanchored tanks based on the numerical simulation method. Hosseinzadeh [8] compared the seismic assessment of existing steel oil storage tanks by API650-2008 provisions with FEM analyses, the results demonstrate there are some imperfections in the code requirements that require further investigation in some cases. In this paper, a 3-D FEM model of an unanchored tank is established based on the software ANSYS, in which it considers the large amplitude sloshing of liquid, liquid and tank coupling effect and contact characteristics between the tank bottom and concrete foundation, and the deformation and stress distribution along the height of tank under horizontal earthquake action has been studied.
2. FEM model of steel tank and input seismic wave

2.1. FEM Model and parameters
The studied tank is a steel tank, and the tank body part adopts Q235, the inside diameter is 18.9 m, high 14.5m, the tank wall is 12.30 m high, the vault height is 2.25m, the liquid level is 10.5m height. Tank wall thickness is divided into 4 sections, from the bottom are 12mm, 10mm, 8mm and 6mm. The vault thickness is 6mm. The material parameters of the tank are as flows: the elastic modulus is 206GPa, the poisson ratio is 0.3, the density is 7800kg/m³, and the coefficient of linear expansion is 1.0*10⁻⁵. The reinforcing ring uses angle steel 63*8*100. In this part of the research, steel storage tanks were analyzed using nonlinear FEM analysis using ANSYS software [9]. The FEM model of fluid-tank coupling system based on ANSYS is shown in figure 1.

In the FEM model, the tank wall, the bottom plate and the vault use the element of Shell181. Assuming that the fluid is incompressible and uses the element of Fluid80, which is well suitable for fluid-solid coupling analysis. The stiffening ring is made of Beam188 elements. The Beam188 and elements of Shell181 are used to share the node in the same joints, the FEM mesh is divided and the tank wall is coordinated.

This paper considers the coupling relationship between the liquid and the tank wall. The radial degrees of freedom are coupled between the liquid element and the tank wall element at the same location, and coupling the vertical degrees of freedom at the same locations at the bottom of the tank. In this case, along the height of the tank wall, the shell and fluid will keep the displacement coordination in the tangential direction, and no mutual penetration in the radial direction. At tank bottom the fluid is allowed the relative sliding along the horizontal direction, and also not allowed to penetrate in the vertical direction.

Under strong earthquake nonlinear lift-off may appear between the foundation and the tank bottom. Face-to-face contact is adopted between the tank bottom and the base of the platform, and the contact element and the target element which are matched with the shell element and the solid element are selected. Goal element is set at the tank bottom, and surface contact element is set on the cap.

2.2. Seismic wave input
When the seismic wave is input, the bottom of the concrete platform is fixed with three directions. In this paper, the tank is located in the seismic fortification area of 8 degree, which belongs to class III site. According to site condition and requirements of code for design of vertical cylindrical welded steel oil tanks, El Centro (North-South direction) earthquake is selected as the horizontal input excitation. The peak acceleration of seismic wave is adjusted to 0.4g according to Chinese seismic code, and the duration of seismic wave is 30s. The time history curve and the corresponding Fourier spectra of seismic wave are shown in figure 2 and figure 3.
3. Analysis of seismic response results

3.1. Modal analysis results
Modal analysis is the basis of dynamic analysis, and it is also a means to check whether the finite element model is established and the parameters of model calculation are correct or not. According to the FEM model of tank liquid system established in this paper, and modal analysis is carried out. The liquid sloshing frequency and liquid tank coupled vibration fundamental frequency are 0.23 Hz and 7.05 Hz respectively, which is very close to the calculation results by the formula in the latest National Standards of the People's Republic of China, "Code for design of vertical cylindrical welded steel oil tanks" (GB50341-2014) [10] are respectively 0.22 Hz and 7.19 Hz. That is to say, the finite element analysis model of the tank-liquid system in this paper is reasonable and can be used for dynamic analysis.

3.2. Sloshing displacement of liquid
Choose the left and the right position on the free liquid surface near the tank wall, along the input direction of seismic wave, and denoted as “LEFT” and “RIGHT”, and the time history curve of vertical sloshing displacement is shown in Figure 4.

It can be seen from the Figure 4, on both sides of the tank liquid surface, it occurs large amplitude sloshing with long period under the horizontal seismic wave excitation, and sloshing history time curves of the two ends are basically symmetrical. Among them, the maximum sloshing height at the
left end reaches 0.409m, the maximum sloshing height of the right end reaches 0.515m, but both do not exceed the maximum height of the tank wall. In addition, due to the difference of stiffness between the liquid and the tank body is great, and the maximum shaking height value appears at 3.98s(RIGHT), which is later than peak value time of the input seismic wave, which is at 2.14s.

3.3. Displacement analysis of tank
Select the feature point’s location on the tank section along the input direction of seismic wave, and study the displacement distribution along the height of tank wall, which are shown in figure 5. The horizontal displacement on the left side and right side appeared maximum response at 2.44s and 2.30s respectively, and it is later than seismic wave peak value time 2.14s. Figure 6 is the maximum horizontal displacement the distribution along the tank wall at 2.44s (LEFT) and 2.30s (RIGHT).

![Figure 6. The horizontal displacement distribution along the tank wall height](image)

From the Figure 6, the tank wall near the bottom appears to be a certain elephant-foot deformation, and the largest displacement is 6.97mm (LEFT) at the height of 1.2m from the bottom of the tank. At the height of 1.8m from the bottom of the tank, due to the interaction of both axial compressive stress and hoop tensile stress, the tank wall has a larger shrinkage deformation. At the same time, the horizontal displacement distribution at 8.5m from the bottom of the tank is reduced due to the constraint of the stiffening steel ring.

3.4. Stress results of tank
Select the same location points as shown in figure 5. As the radial stress distribution along the height of the tank wall is very small, it is not listed here, and the hoop stress and the axial stress distribution along the height direction of the tank wall are given in figure 7 and figure 8.

As seen from figure 7, the hoop tensile stress increases rapidly at the beginning and then decreases from the bottom of the tank. Due to the effect of stiffening ring, the hoop tensile stress at 8.5m premises decreases. The maximum tensile stress appears in the pot at 1.2m from the tank bottom, which is also in the neighborhood of the elephant-foot deformation. The maximum hoop tensile stress is 103.92MPa (RIGHT). The peak hoop stress is smaller than the yield stress of steel tank, which is 235 MPa. That is, the maximum deformation of the tank does not reach the yield limit state of the steel material.
From figure 8, the axial compressive distribution appears the mutation step shape, and the peak value occur at position slightly higher than the peak hoop stress location (i.e. elephant-foot position), that is at 1.8m from the bottom. Moreover, the distribution of axial compressive stress on the tank wall is larger than that of the base plate, and the upper part of the axial compressive stress decreases sharply, and the maximum value is far lower than that of the hoop stress. The maximum axial compressive stress of the tank wall is 23.23MPa (RIGHT), 24.26 MPa (LEFT). According to the latest National Standards of the People's Republic of China, "Code for design of vertical cylindrical welded steel oil tanks"(GB50341-2014)[10], the critical stress of tank wall under earthquake is calculated by the following equation,

$$[\sigma_{cr}] = 0.22E_t / D$$  \hspace{1cm} (1)$$

where $[\sigma_{cr}]$ is the allowable critical stress for the tank wall, MPa; $E$ is the elastic modulus of the bottom shell material at the design temperature, MPa; $t$ is effective thickness of bottom shell, m; and $D$ is the inner diameter of the tank, m.

According to the equation (1), the allowable critical stress of the tank is 28.77MPa. From the figure 8, the maximum axial pressure value along the whole tank is 24.26 MPa, and it is very close to the allowable compressive stress value 28.77MPa. Therefore, in this case, there may be local buckling failure occurs near the tank wall bottom under the input El Centro earthquake with PGA=0.4g.

4. Conclusions
By using the El Centro seismic wave as input, the results of liquid sloshing, the displacement and stress distribution along tank wall are analysed, and the following conclusions can be obtained,

(1) The liquid surface in the tank occurs large amplitude vertical sloshing with long period characteristic, and the sloshing time history curve at the two end points on the surface is basically symmetrical. The maximum sloshing height reaches 0.515m, and does not exceed the height of tank wall under earthquake.

(2) The elephant-foot deformation occurs at 1.2m height form the tank bottom. Due to the volume of the tank is relatively small, and the biggest elephant-foot deformation does not reach the material yield limit state. The peak axial compressive stress does is very close to the allowable compressive stress value in code, so there maybe local yield instability destruction near the bottom of the tank wall.

(3) It is suggested that the soil-structure dynamic interaction is considered in the future study because the foundation effect may have a great influence on the dynamic response of the tank.

5. Acknowledgments
The authors appreciate the support of National Natural Science Foundation of China (Grant No. 51408609) and Shandong Province Higher Educational Science and Technology Program (Grant No. J14LG51).
6. References

[1] Haroun, M A 1983 Vibration studies and tests of liquid storage tanks. *Earthq Eng Struct D*. 11 179-206.

[2] Goudarzi M A and Sabbaghi-Yazdi S R 2009 Numerical investigation on accuracy of mass spring models for cylindrical tanks under seismic excitation. *Int J Civ Eng*. 7 190-202.

[3] Sun J, Cui L, Hao J, and Wang, Z 2013 The simplified mechanical model and the seismic response for isolation tank with floating roof. *J Harbin Inst Tech*. 45 118-22.

[4] Newmark N M and Rosenblueth E, 1971 Fundamentals of earthquake engineering, Prentice-Hall, Englewood Cliffs, N.J.

[5] Seleemāh A A and Mohamed E S 2011 Seismic analysis and modelling of isolated elevated liquid storage tanks *Earthq. Struct*. 2 397-412.

[6] Bayraktar A, Sevim B, Altunışık A C, and Türker T 2010 Effect of the model updating on the earthquake behavior of steel storage tanks. *J Constr Steel Res*. 66 462-69

[7] Zhang X C, Cai Y Q, 2013 Horizontal seismic response numerical analysis of large unanchored storage tank, *J Wuhan Univ Tech*. 35 94-7

[8] Hosseinzadeh N, Kazem H, Ghahremannejad M, Ahmadi E, and Kazem N 2013 Comparison of api650-2008 provisions with fem analyses for seismic assessment of existing steel oil storage tanks. *J Loss Prevent Proc*. 26 666-75.

[9] ANSYS software. Engineering simulation software, 2007 version 14. Pennsylvania, United States: Canonsburg.

[10] National Standards of the People's Republic of China 2014 *Code for design of vertical cylindrical welded steel oil tanks*(Beijing: China Planning Press)