Stress analysis of large crude oil storage tank subjected to harmonic settlement

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Abstract. Differential settlement has a significant effect on the safe operation of tanks. In order to investigate the stress response of crude oil storage tank subjected to harmonic settlement. A numerical simulation model of the steel storage tank was developed in this study. Based on a validated finite element model, parametric analysis was conducted based on the main factors. The results show that the stress at the top of the tank wall is symmetrically distributed along the circumference of the tank. The stress result increases linearly with the increasing harmonic amplitude. The axial stress increases firstly, and then decreases for large wave number. Meanwhile, The stress value increases with the increment of the height-to-radius ratio, and decreases with the increment of the radius-to-thickness ratio. Especially, when the height-to-radius ratio ranging from 1.0 to 1.5 or the ratio r/t is more than 1500, the tendency of stress variation is slighter. This study could be referenced in strength or safety assessment of crude oil storage tank subjected to harmonic settlement.

1. Introduction

With the rapid growth of oil demand, the need of storage devices has increased. As important storage equipment, large scale oil tanks have been widely used in recent decades. Meanwhile, the steel tanks are usually constructed on coastal areas where large differential settlement may easily occur. And the failure behaviour caused by foundation settlement is an urgent problem. In order to ensure the safe operation of storage tanks, investigation on mechanical response of oil storage tank subjected to settlement is important and necessary.

In recent years, extensive experimental and numerical research has been conducted to analyze the performance of large scale steel tanks subjected to differential settlement. Gong et al. [1-4] adopted numerical simulation methods to buckling strength of the fixed-roof tank subjected to harmonic settlement. Based on the symmetrical finite element model of the tank shell, Ahmed et al. [5] investigated the effect of tank wall thickness on the buckling mode and the critical buckling settlement displacement. Shi et al. [6-7] studied the effect of wave number, harmonic amplitude and liquid level on the radial deformation of the tank wall. Full-scale model of tank was developed to simulate stress
state caused by differential settlement. Li et al. [8] studied the deformation and stress response of large oil storage tanks subjected to foundation settlement. Chen et al. [9-10] investigated the deformation behavior of steel tank wall under uneven foundation settlement, and proposed solution for predicting deformation of steel tank under differential settlement. Shang et al. [11] studied the stress distribution of storage tanks under harmonic settlement, and Fourier series was adopted to represent the measured settlement value. The strength evaluation of the tank wall and bottom was carried out. Yang [12] investigated structural response of thin-walled cylindrical shells under uneven settlement, based on the result of experimental research. He [13] developed the finite element method to obtain the deformation result and stress distribution of steel tanks subjected to uneven settlement.

As it can be seen from there view of previous literature, investigations on the mechanical response of large scale steel tank subjected to differential settlement. In this stage, parametric analysis was conducted based on the main factors that influence the buckling strength of storage tank. While the stress and deformation analysis of tanks is performed by 2D finite element method. Numerical simulation results can not accurately reflect the true service status of the storage tank. Meanwhile, influence factors of tank’s stress response were not sufficiently investigated. In this study, stress results of large crude oil storage tank was simulated by 3D model. The influence of the harmonic amplitude, wave number, height-to-radius ratio and radius-to-thickness ratio on the stress response of tank was studied.

2. Finite element model

2.1. Geometric model
In this study, a full 3D numerical simulation model of crude oil storage tank was developed. The radius and height of the model are R=40 m, h =22 m, respectively. The variations of wall thickness were considered. The shell and bottom plates of the tank were modeled by S4R. The elements modelling the shell-to-bottom fillet welds and tank foundation are C3D8R. Based on the results of a preliminary mesh sensitivity analysis, the finite element model was divided into 70671 elements as shown in Figure 1.

![Figure 1 Finite element model of tank](storage tank model)

![Figure 1 Finite element model of tank](Section in tank wall)

2.2. Material properties
The elastic modulus, the density and the Poisson ratio of the tank material are 206 GPa, 0.3 and 7850 Kg/ m³, respectively. The yield strength of Q235-B, 12MnNiVR and 16MnR adopted in the model are 235MPa, 490MPa and 345MPa. In order to estimate the mechanical response of steel tank subjected to measured differential settlement. The material nonlinearity was considered in the model. As shown in Figure 2, the well-recognized Ramberg-Osgood model was adopted to regress the true stress-strain curve of the tank materials.
2.3. Boundary conditions

The own-weight of the steel tank was calculated using the gravity constant $g = 9.81 \text{ m/s}$. Meanwhile, the effect of the hydrostatic pressure should be considered. The liquid pressure value decreases with the increasing height. The effect of the harmonic settlement was investigated by imposing axial displacement load to the circumference of the foundation, while the radial displacement and the circumferential displacement are constrained. The settlement value can be calculated as formula 1. The friction coefficient between tank foundation and bottom plate is 0.2 according to verification analysis.

$$u = u_n \cos (n\theta + \varphi_n)$$

Where $u_n$ stands for harmonic amplitude, $n$ represents wave number, and $\varphi_n$ is phase angle.

2.4. FE model verification

The FE model established in this study is validated by a stress result based on field tests [6]. The liquid level of the storage tank is set to 19.76m. The axial stress of the tank wall is plotted against the distance from bottom plate in Figure 3(a). It can be observed from the figure that the trends of the numerical simulation results of axial stress in this study and field test result are basically identical. The maximum of axial stress is mainly located at the shell-to-bottom Fillet Welds. As can be seen from the figure 3(b), the simulation result of radial stress and test result are highly similar. Comparing the finite element analysis (FEA) results with the existing research results, we can find that the maximum relative error of the model in this paper is 9.15%.
3. Parametric study

3.1. Effect of the harmonic amplitude ($u$)
Harmonic amplitude has a significant effect on the stress response of the tank subjected to harmonic settlement. As the amplitude increases, a large radial displacement, buckling of the shell, and even the failure of the tank may occur. In order to investigate the stress result of tank under differential settlement, the harmonic amplitude varies from 20 mm to 100 mm, and the Wave number is set as 3. Axial stress and hoop stress are calculated. The stress response result at the top of the tank wall are plotted against the harmonic amplitude in Figure 4. As observed in the figures, the stress is symmetrically distributed along the circumference of the tank. The axial stress and hoop stress presents a similar trend as follow: The stress result increases linearly with the increasing harmonic amplitude.

![Figure 4](image.png)

Figure 4 The stress response results versus circumferential angle of tank wall for various harmonic amplitude

3.2. Effect of the height-to-radius ratio ($h/r$)
The height-to-radius ratio ($h/r$) of large crude oil storage tanks varies. As the ratio $h/r$ of tank increases, the stability of the shell will significantly change under the foundation settlement. In order to obtain the effect of the $h/r$ on the stress response of tank wall, the axial stress results at the top of the tank wall with different height-to-radius ratio are displayed together in Figure 5 (a). It can be clearly noticed that the axial stress is monotonically increasing. The value of axial stress increases more slightly, when the height-to-radius ratio ranging from 1.0 to 1.5.

3.3. Effect of the radius-to-thickness ratio ($r/t$)
The wall thickness design of large scale storage tank follows the equal strength design criterion. The value of tank wall thickness in the numerical model varies. Keeping the average wall thickness constant at 18 mm, the stress response of tank wall are obtained when radius-to-thickness ratios ranging from 500 to 2000. Figure 5(b) illustrates the effect of the ratio $r/t$ on the axial stress. The plots in the figure show that the axial stress decreases significantly as the radius-to-thickness ratio increases. Meanwhile, as for large ratio (e.g. the ratio $r/t$ is more than 1500), the stress decreases slightly with increasing the ratio. The anti-deformation capacity of tank wall with larger radius-to-thickness ratio will be weaken.
3.4. Effect of the wave number (n)
As the most dangerous settlement type, differential settlement can be simplified as the harmonic forms. The harmonic settlement with wave number varying from 2 to 6 can more accurately reflect the real state of the foundation settlement. In this section, effect of the wave number was investigated by varying n from 2 to 6 while keeping the harmonic amplitude constant at 40 mm. Figure 6 present axial stress of tank wall versus wave number. It clearly shows that the wave number has a significant effect on the stress response. The axial stress increases firstly, and then decreases for wave number n=6. This is due to the separation between the tank bottom plate and foundation becomes more obvious, as the wave number increases. The effect of foundation settlement on the tank wall stress is weakened.

4. Conclusions
A comprehensive investigation on stress response of large steel storage tank subjected to harmonic settlement has been performed throughout this paper. A numerical model was established by nonlinear finite element software ABAQUS. Based on the numerical model verified by existing research results, parametric analyses were conducted to derive how the parameters influence the mechanical response of large scale tank. Some remarkable conclusions can be drawn as follows:

(1) The stress value is symmetrically distributed along the circumference direction of the tank. The axial stress and hoop stress presents a similar trend. The stress result increases linearly with the increasing harmonic settlement amplitude.
(2) The axial stress increases firstly, and then decreases for large wave number (e.g. when the wave number is more than 6). This may be due to the separation between the tank bottom plate and foundation becomes more obvious, as the wave number increases.

(3) When height-to-radius ratio ranges from 0.5 to 2.0. The axial stress increases monotonically. The axial stress decreases with the increasing radius-to-thickness ratio. As for large ratio (e.g. the ratio r/t is more than 1500), the stress decreases slightly with increasing the ratio.

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