Deformation of Large Steel Tank under Uneven Foundation Settlement

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Abstract. In this paper, the deformation behaviour of the large steel tank under uneven foundation settlement is investigated. The finite element model of the tank is firstly established, the finite element analysis of the large steel tank under the harmonic settlement conditions is carried out consequently, the influence of height-diameter ratio, diameter-thickness ratio and wind girder stiffness on the deformation behaviour of the tank top is studied. Based on the finite element results, regression equation for predicting maximum radial displacement of the tank is proposed. Furthermore, the accuracy of proposed solution is validated.

1. Introduction

The steel tank is an important infrastructure in oil & gas industry. Uneven foundation settlement may cause the excessive deformation of the tank wall affecting the operation of the tank. In other words, floating roof of the tank may be stuck due to excessive deformation of the tank wall. Therefore, the accurate prediction of the tank deformation of large steel tanks under uneven foundation settlement is of practice importance.

A number of researchers focused on the failure and safety evaluation of large steel tanks under uneven foundation settlement. DeBeer[1] proposed the control standard of the tank foundation settlement considering the measuring point distribution of tank. Malik[2] proposed the more accurate control standard of the tank foundation settlement by conducting experimental test. Kamyab[3-4] proposed the relationship between the radial displacement of the tank top and the harmonic settlement using the modified Donnell solution. Jonaidi[5] proved that the wind girder stiffness should be considered in the safety evaluation of the large steel tank. Qingshuai Cao[6] proposed a new solution for maximum radial displacement of the large steel tank. However, these methods have certain limitations in practice. On the basis of finite element results, the deformation behavior of steel tank wall under uneven foundation settlement is studied. Furthermore, solution for predicting deformation of steel tank under uneven foundation settlement is proposed, which can be referred in structural integrity of oil steel tank.
2. Finite element model and validation

The finite element model established is shown in the Figure 1, the foundation settlement is simulated by applying vertical displacement at the bottom of the tank bottom plate. The stress contour of the tank is illustrated in the Figure 2. To validate the finite element result, the experimental results provided by Malik et al. [2] are adopted in this paper. It is noted that relative errors are less than 10%. It is demonstrated that finite element model build in this paper can give reasonable and accurate results, which can be used for subsequent parametrical analysis and research.

![Figure 1. Finite element model of the tank](image1)

![Figure 2. Stress contour of steel tank](image2)

Table 1. Comparison the finite element results with experimental results

| Harmonic settlement order | Experiment results (mm) | Finite element results (mm) | Relative error (%) |
|---------------------------|-------------------------|----------------------------|-------------------|
| 2                         | 1.92                    | 1.9889                     | 3.59              |
| 3                         | 4.0                     | 4.3448                     | 8.62              |

3. Comparisons with available methods

The maximum radial displacements of the steel tank can be obtained using the modified Donnell solution, the membrane theory and the solution proposed by Cao [5], as shown in Eq. (1) - (3). The finite element model of the tank was applied to $2^{nd}$-$12^{th}$ harmonic settlement order. The maximum radial displacement of the tank calculated using FEM are compared with other solutions available, the comparison is illustrated in the Figure 3. The membrane theory solution and the modified Donnell solution can give yet accurate prediction, however, it is complicated to solve. Furthermore, the solution proposed by Cao can only give reasonably results for $2^{nd}$-$6^{th}$ order.

\[
[w]_{x=b} = -(n^2 h / r) u_n \cos \theta / [1 + n^2 (n^2 - 1)^2 (2 + \nu) I_e h / (r^4 t) + n^4 (n^2 - 1)^2 I_e h^3 / (3 r^4 t)]
\]

\[
[w]_{z=b} = \left( \frac{n^2 h}{r} \right) u_n \left( \frac{1}{a_3 + a_4 \frac{I_{\text{ratio}}}{I_e}} \right) \cos \theta
\]

\[
\frac{W_s}{u_s} = 9(1 - \nu^2) e^{-0.075 \nu^2 + 0.76 \nu} \left( \frac{h}{r} \right)^{0.5} \left( \frac{I_{e}}{r} \right)^{0.15} \left( \frac{1}{1 + 0.02 \frac{I_{\text{ratio}}}{I_e}} \right)
\]
Figure 3. Prediction of maximum radial displacements of steel tank

4. Parametrical sensitivity analysis

The influence of tank's height-diameter ratio, diameter-thickness ratio and wind girder stiffness on maximum radial displacement of the tank is investigated using finite element analysis. The computed results are illustrated in the Figure 4. It is noted that those parameters will affect the radial deformation of the tank to a certain extent.

Figure 4. Maximum radial displacement of the tank under various parameters

5. Solution for prediction the radial displacement of the steel tank

Based on the finite element results, the regression equation for predicting radial displacement of the steel tank under harmonic subsidence can be obtained as:
\[
\frac{w_{\text{max}}}{u_n} = \frac{H}{R} n^2 \left( 1 + \frac{1}{1.334 \times (\frac{H}{R})^{0.025} (\frac{R}{t})^{0.049} (n^2 - 1)^{0.028} + 2.391 \times (\frac{H}{R})^{4.783} (\frac{R}{t})^{2.704} n(n^2 - 1)^{0.674} \times I_{\text{ratio}}^{0.736}}{1} \right)
\]

(4)

Where, \( w_{\text{max}} \) is the maximum radial displacement of the steel tank under the \( n \)-order harmonic settlement condition, \( u_n \) is the amplitude of \( n \)-order harmonic settlement, \( H/R \) is the height-diameter ratio of the tank, and \( R/t \) is the diameter-thickness ratio of the tank, and \( I_{\text{ratio}} \) is the wind girder stiffness of the tank.

Figure 5 (a)-(f) compare the prediction of maximum radial displacement of the example tank using the proposed solution and finite element method. It is noted that the results calculated using the proposed equation agree quite well with the finite element results. In other words, the proposed regression equation can give relatively accurate prediction of radial displacement of the steel tank.

By overlaying the tank-top radial displacement formula under each order harmonic settlement, the prediction value of tank top radial displacement under uneven foundation settlement can be obtained as shown in the Eq. (5). Where \( w \) is the predicted value of the tank top radial displacement, and \( N \) is the number of foundation settlement monitoring sites. According to API 650 specification, the tank wall radial displacement should be less than 100 mm. The predicted maximum value of tank wall radial displacement appears at the top of the tank. Therefore, under the condition of tank foundation settlement, the prediction value of large tank top radial displacement should be less than 100 mm to ensure the structural integrity of the tank, as shown in the Eq. (6).

\[
w = \left[ \frac{w}{3} \right]
\]

(5)

\[
w \leq \left[ w \right] = 100 \text{ mm}
\]

(6)
6. Conclusions
To guarantee the structural integrity of oil steel tank, the accurate radial deformation of the large tank is important in engineering practice. The deformation behavior of large steel tank is investigated using finite element method. Parameters such as high-diameter ratio, diameter-thickness ratio and wind girder stiffness have certain effect on tanks’ deformation under harmonic settlement conditions. On the basis of finite element results, a regression equation for predicting the maximum radial displacement of large tanks under uneven foundation settlement is proposed, which can be referred for the safety evaluation of large steel tank.

Acknowledgements
The work was financially supported by: National Key R&D Program of China (Grant No. 2016YFC0802100 and No. 2017YFC0805800), National Science Foundation of China (Grant No. 51779265), Open Project Program of State Key Laboratory of Structural Analysis for Industrial Equipment (Grant No. GZ19119), Science Foundation of China University of Petroleum, Beijing (Grant No. 2462017BJB10), Open Project Program of Beijing Key Laboratory of Pipeline Critical Technology and Equipment for Deepwater Oil & Gas Development (BIPT2018002).

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