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Research of Curve Fitting Method on the Measured Settlement of Tanks

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Abstract

The settlement data of oil storage tanks made of steel are measured by the measurement points located around the base of the tank wall. The measured settlement data need to be curve fitted in order to reflect the settlement distribution around the whole tank wall base. Considering about the disadvantage of measured settlement data treatment methods on tanks in current standards, an optimization method of curve fitting on the measured settlement data is presented. The Fourier series expansion is used to analyze the measured settlement data, the fitting curves and mean square error according to different order are obtained. The fitting curve with minimum mean square error is selected as the most appropriate one that reflects the actual displacement of the tank base. The optimization method of curve fitting present is applied to analyze the measured settlement data obtained from the floating roof tank and the fixed roof tank. Results show that different effects can be obtained with different order of the fitting curve. Curve fitting referring to different order is necessary to the measured settlement data in actual engineering in order to find the most appropriate one that reflects the real tank base displacement distribution.

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Keywords: curve fitting method; measured settlement; tank; order; mean square error

1. Introduction

Large vertical steel tanks are key equipment in national strategic oil reserves[1,2]. For the large oil tanks constructed on the coastal soft soil foundation, uneven soil deposition and non-uniform load distribution will lead to

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settlement of the tank base[3,4]. According to the effects on the tank wall of tank base settlement, the settlement beneath the tank can be described in terms of three components, i.e. uniform settlement, planar tilt and circumferential differential settlement[5]. The uniform settlement is the rigid sinking of the tank and has little effect on the safety of the structures. The planar tilt will lead to the rise of the liquid level, which makes the circumferential stress higher in the lower area of the tank wall. The seal and movement of the floating roof can also be affected because of the planar tilt. The circumferential differential settlement is the principal source leading to instability of the tank. Even the amplitude is relatively small compared to the uniform settlement and planar tilt, the circumferential differential settlement will result in distortion and overstress of the tank wall, ovalization on the top of the tank and jamming of the floating roof[6,7]. In actual engineering, the settlement data of the tank are obtained by the measurement points located evenly around the base of the tank. Thus the curve fitting needs to be applied to the discrete data of measured settlement in order to obtain the whole settlement distribution beneath the tank wall.

2. Brief of measured settlement analysis

The graphical representation method and the mathematic method are commonly used in current standards to obtain the harmonic curve to describe the settlement beneath the tank wall[6]. Although the most convenient method is by free hand drawing techniques, the mathematic method can get more accurate results and better fitting curve reflecting the real measured settlement data. Based on Eq. (1), the optimum constants *a*, *b* and *c* are calculated by the mathematical and graphical capabilities of a computer.

$$ELEV_{\mathrm{pred}} = a + b \times \left(\cos\theta + c\right) \tag{1}$$

where θ is the angle around the tank circumference; $ELEV_{\mathrm{pred}}$ is the predicted elevation at θ; *a*, *b* and *c* are the fitting coefficients. Eq. (2) is used to predict if the fitting curve obtained is valid.

$$R^2 = \frac{S_{yy} - SSE}{S_{yy}} \tag{2}$$

where the R^2 is determination coefficient; S_{yy} is sum of the squares of the differences between average measured settlement data and the measured settlement data; *SSE* is sum of the square of the differences between the measured data and predicted data obtained by Eq. (1). Only if the value R^2 is greater than or equal to 0.9, the curve is considered valid.

While in actual engineering, the settlement around the circumference may concentrate in one area or more. The difference between the predicted curve by Eq. (1) and the real measured settlement data may be too large. Kamyab et al[8-10] used Fourier series analysis to transform the measured settlement data in terms of superposition of several harmonic functions with different order as shown in Eq. (3)

$$u = u_0 + \sum_{i=1}^{\infty} u_i \cos\left(i\theta + \theta_i\right) \tag{3}$$

where *i* is the wave number, u_i is the amplitude of the *i*th harmonic settlement, u_0 is the uniform settlement and θ_i is the relative phase angle of each component. Rotter and Holst [11] pointed out that the circumferential differential settlement beneath the tank wall was represented by summation of components with order $i \geq 2$. Cao et al[12] considered that for the tank with *n* measured points, the expanded Fourier series with order [(*n*-1)/2] could be obtained and 16 measured points would provide relatively complete data to reflect the settlement beneath the tank wall.

3. A new optimization method of curve fitting

For the decomposed Fourier series, the fitting curve corresponding to the highest order does not represent the optimum one. The local differential settlement according to the fitting curve will encounter a sudden change as the order increases. Since the tank wall has certain rigidity itself, the displacement of the tank wall bottom won't change rapidly as the soil foundation drops suddenly. The tank base may separate from the foundation because of sudden drop of the foundation[3,9]. In fact, the settlement data obtained from the measured points represent the displacement of the soil foundation. Separation between the tank base and the foundation needs to be considered in order to get the appropriate fitting curve reflecting the settlement displacement of the tank wall bottom. Exorbitant order is not recommended in order to avoid occurrence of over fitting which will result in higher calculated stress than the real stress in the tank wall and inaccurate results in actual engineering. Thus it is important to analyze different order of the fitting curves and select an optimum one to reflect the displacement beneath the tank wall.

Based on the above analysis and the current standards and research, a new optimization method of curve fitting on the measured settlement data is presented. First, the measured settlement data will be expanded by Fourier series analysis and the highest order needs to satisfy $i_{max} \leq 8$ or $i_{max} \leq$ (n-1)/2. Then the fitting curves corresponding to different order ($i = 1 \sim i_{max}$) will be obtained by computer program, and the mean square error between each fitting curve and measured settlement data is calculated. At last, the fitting curve with the minimum mean square error will be selected as the optimum one that reflects the real displacement of the tank wall bottom.

The program of curve fitting for the measured circumferential settlement is designed as following. The location of the measured point is recorded as X ($x_1, x_2 \ldots x_n$) and the corresponding measured settlement data are recorded as Y ($y_1, y_2 \ldots y_n$). The number of measured point n determines the highest order of the fitting curves, i.e. i_{max} = [(n-1)/2]. Considering that exorbitant order of the fitting curve will lead to the occurrence of over fitting, the highest order is restricted to be $i_{max} \leq 8$. For the Fourier series expanded from measured settlement data, the fitting curve of order one is derived and the mean square error MSE_1 between the fitting curve and measured settlement data is calculated and recorded as MSE_{min} firstly. Then the fitting curve and mean square error MSE_2 corresponding to order two are obtained in the same way. The value of MSE_2 will be compared to that of MSE_{min}, if $MSE_2 > MSE_{min}$, the MSE_{min} will remain unchanged; if $MSE_2 \leq MSE_{min}$, it will satisfy $MSE_{min} = MSE_2$. The program will be calculated as the above procedure until $i = i_{max}$ and the optimum fitting curve will obtained. The program procedure is shown as follows in Fig. 1. *a* and *b* in Fig. 1 are amplitude corresponding to each order of the fitting curve.

4. Application and analysis

Large oil storage steel tanks can be divided into two types according to the structure form of the roof, i.e. the floating roof tank and the fixed roof tank. Applications of the presented optimization method of curve fitting on the measured settlement data are introduced to this two kind tank.

4.1. Floating roof tank

The measured settlement data of G106# floating roof tank in one oil reserve base of China are shown in Fig. 2. The diameter and height of the tank are 80m and 21.8m respectively and 24 measured points are located around the tank base evenly.

The cylindrical coordinate system is used and point 1 is selected as the start point. The angle between adjacent points around circumferential direction is $\pi/12$. Fitting curves with different order and corresponding mean square error can be obtained by substituting the coordinate value and measured settlement data into the optimization program of curve fitting. The fitting curves of order 1 to order 8 are shown in Fig. 3 and the corresponding mean square error is shown in Fig. 4.

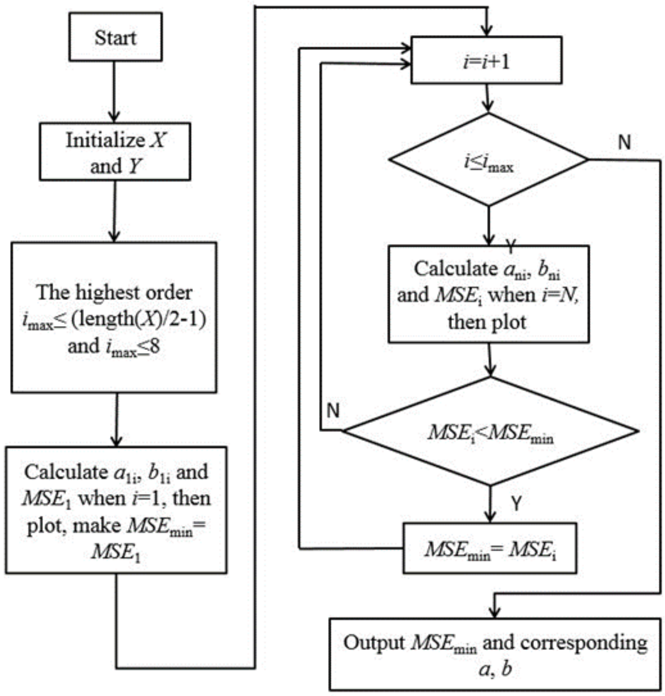

Fig. 1. Procedure diagram of fitting curve optimization program.

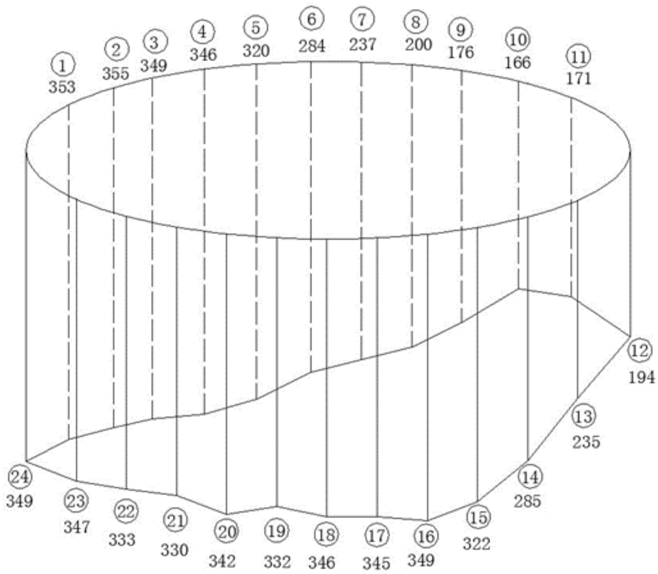

Fig. 2. Measured settlement data of G106# tank.

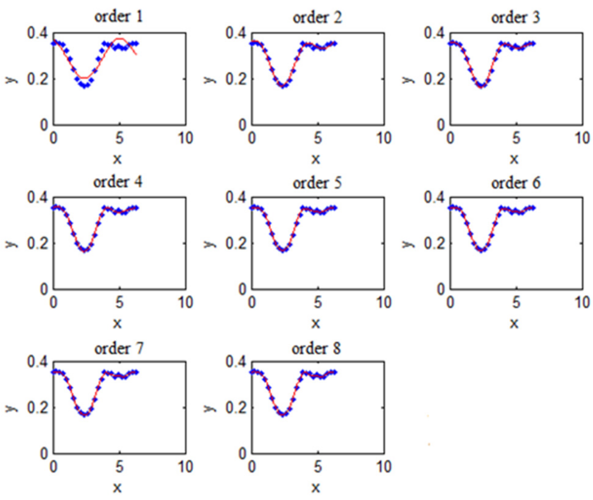

Fig. 3. Fitting curves with different order.

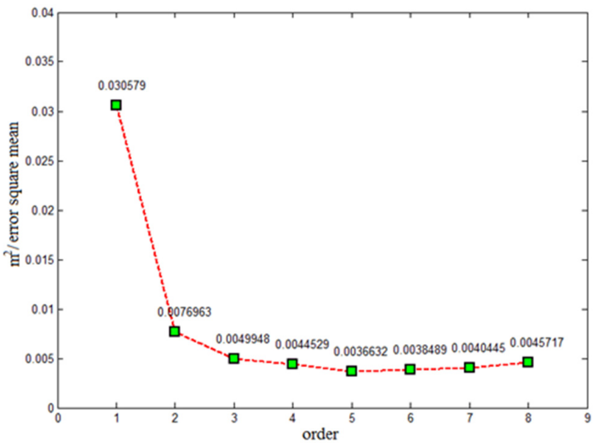

Fig. 4. mean square error of different fitting curves

In Fig. 3, x is circumference coordinate, rad; y is settlement, m.

As we can see in Fig. 3, results of fitting curves with order 2 to order 8 are better while the result of order 1 seems not ideal. In Fig. 5, the mean square error of the fitting curves reaches minimum, $0.0036632 m^2$, when the order is 5. While when the order is 1, the mean square error is 8.35 times to the minimum one. Thus the fitting curve with order 5 is selected as the optimum one for this floating roof tank and the expression is shown as Eq. (4)

$$\begin{aligned} y = {} & 0.2944 + 0.05932\cos x - 0.05531\sin x + 0.003084\cos 2x + 0.04656\sin 2x - 0.00208\cos 3x \\ & - 0.007505\sin 3x - 0.003335\cos 4x + 0.0002165\sin 4x + 0.002143\cos 5x - 0.002431\sin 5x \end{aligned} \tag{4}$$

4.2. Fixed roof tank

The measured settlement data of V2213# fixed roof tank in one oil reserve base of China are shown in Fig. 5. The diameter and height of the tank are both 18.8m and 12 measured points are located around the tank base evenly.

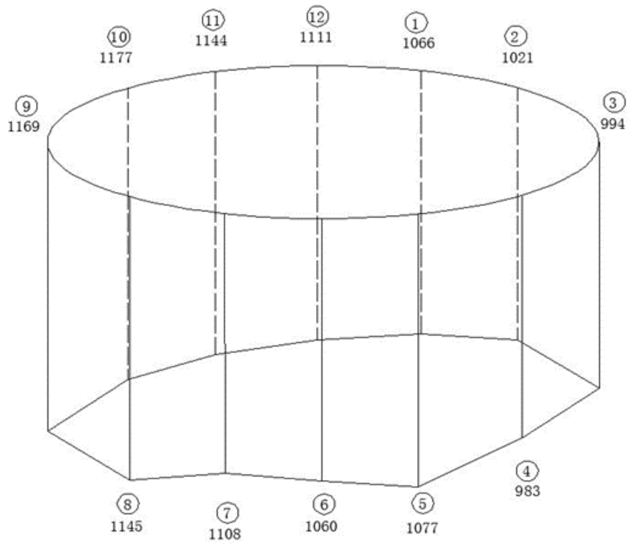

Fig. 5. Measured settlement data of V2213# tank.

Similarly, the presented optimization method of curve fitting is applied to the fixed roof tank. The number of the measured points is 12, so the highest order of the Fourier series satisfies i_{max} = [(12-1)/2]=5. The fitting curves of order 1 to order 5 are shown in Fig. 6 and the corresponding mean square error is shown in Fig. 7.

As we can see in Fig. 7, the mean square error of the fitting curves reaches minimum, 0.0018775m^2, when the order is 5. While when the order is 1, the mean square error is 2.87 times to the minimum one. Thus the fitting curve with order 5 is selected as the optimum one for this fixed roof tank and the expression is shown as Eq. (5)

$$\begin{aligned} y = 1.082 - 0.02076\cos x - 0.09195\sin x + 0.004196\cos 2x + 0.00101\sin 2x - 0.0007207\cos 3x \\ + 0.003167\sin 3x + 0.001363\cos 4x - 0.002454\sin 4x + 0.000316\cos 5x - 0.001883\sin 5x \end{aligned} \quad (5)$$

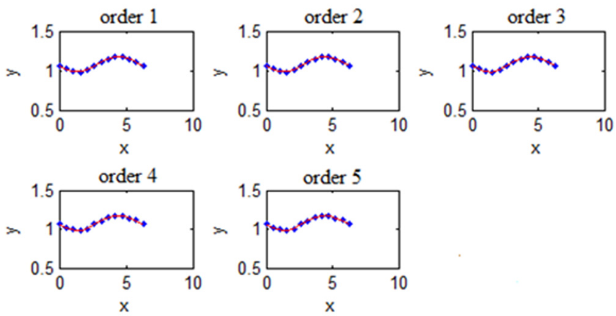

Fig. 6. Fitting curves with different order.

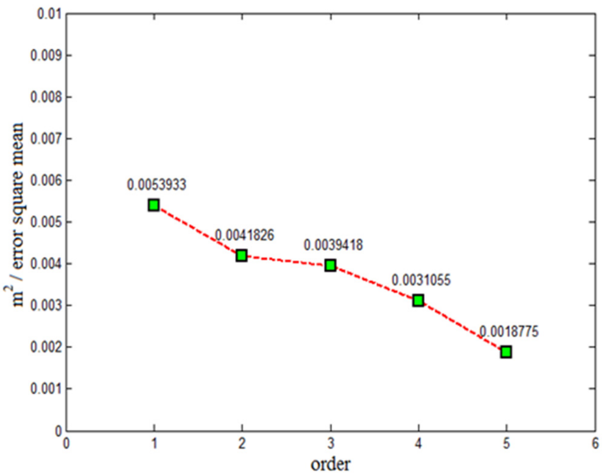

Fig. 7. Mean square error of different fitting curves.

5. Conclusions

(1) A new optimization method of curve fitting on the measured settlement data is presented considering about the disadvantage of current standards and research. The measured settlement data will be expanded through Fourier series analysis. The fitting curves with different order will be obtained by computer program, and the mean square error between each fitting curve and measured settlement data is calculated. The fitting curve with the minimum mean square error will be selected as the optimum one that reflects the real displacement of the tank wall bottom.

(2) The optimization method of curve fitting presented in this paper is applied to the measured settlement data of floating roof tank and fixed roof tank respectively. Results show that different effects can be obtained with different order of the fitting curve and highest order of the fitting curve doesn't mean the optimum one that reflects the tank wall bottom displacement. In actual engineering, curve fitting referring to different order is necessary to the measured settlement data in actual engineering in order to find the most appropriate one that reflects the real tank base displacement distribution.

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