Thin-Walled Structures 106 (2016) 284–293

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

Buckling of steel tanks under measured settlement based on Poisson curve prediction model

Haigui Fan [a], Zhiping Chen [a,*], Jianmin Shen [b], Jian Cheng [a], Dingyue Chen [b], Peng Jiao [a]

[a] Institute of Process Equipment, Department of Chemical and Biological Engineering, Zhejiang University, 38 Zheda Road, Hangzhou, Zhejiang 310027, PR China

[b] Ningbo Institute of Special Equipment Inspection, Ningbo 315048, PR China

ARTICLE INFO

Article history:
Received 14 January 2016
Received in revised form
18 April 2016
Accepted 16 May 2016

Keywords:
Tanks
Measured settlement
Settlement prediction model
Buckling
Geometrical nonlinearity

ABSTRACT

Buckling behavior of large steel tanks under measured settlement has been researched and analyzed in this paper. The settlement prediction model based on Poisson curve is established by applying least square principle and Lagrange quadratic interpolation. Settlement of each measuring point at any time can be obtained applying this prediction model. The discrete settlement data at any time beneath the tank wall is transformed into global settlement expression distributed in the circumferential direction by using the method of Fourier series expansion. Settlement variation with time beneath the tank wall is predicted accurately then. Based on the predicted settlement beneath the tank wall at any time, bucking behavior of the tank is researched by numerical simulation method and the critical buckling time of the tank is predicted. Hydrostatic pressures are applied to inner surface of the tank wall to research the buckling behavior of the tank with different liquid storage. The present method is applied to a fixed roof tank and result shows that the tank wall presents stable linear variation under settlement in initial stage. As time and settlement increase, a typical snap-through buckling occurs to the tank wall, which indicates that the buckling analysis method presented in this paper can be used to predict the buckling behavior of the tank effectively. Buckling behavior analysis of a floating roof tank with the same size and under the same settlement with the fixed roof tank is also made. It indicates that compared to the buckling of fixed roof tanks, the radial displacement on the top of the floating roof tank wall is regarded as the controlling factor to determine the tank failure.

1. Introduction

Large vertical cylindrical steel tanks are widely employed in various industries. The tank wall is welded using several cylindrical shells with the same or different thickness. Since the thickness to diameter ratio is very small, the tanks are regarded as a typical kind of thin-walled structure [1–4]. As key equipment in national strategic oil reserves, large vertical steel tanks are mostly constructed on the coastal soft soil foundation. Uneven soil deposition and non-uniform load distribution will lead to settlement of the tank base [5]. Stress redistribution and deformation will occur in tank wall because of settlement, which may make the tank unable to continue work as usual and occurrence of buckling leading to instability of the tank.

Buckling behavior of tanks has attracted attention of some researchers in recent years. Zhao et al. [6,7] researched buckling behavior of floating roof tanks and fixed roof tanks under harmonic settlement. Effects of tank geometric parameters on the static and buckling behavior were researched by parametric analysis method and the settlement criterion was presented. Based on this, Zhao et al. [8,9] researched buckling behavior of floating roof tanks under global differential settlement and localized differential settlement. Result showed that local buckling occurred at the eave wind girder under global differential settlement, which could be taken as the serviceability limit state of the tanks; for short tanks with a relatively small height to radius ratio, the maximum radial displacement of the tank wall was regarded as the ultimate limit state, for tall tanks with a large height to radius ratio, the snap-through buckling of the tank wall should be considered as the ultimate limit state; tanks under localized differential settlement were more likely to suffer snap-through buckling, which was related to the degree of localization. Buckling of the tanks with a floating roof and a conical roof subjected to harmonic settlement was researched by Gong et al. [10–12]. The critical harmonic settlement for different wave numbers was obtained and parametric study was applied to analyze the relations between critical harmonic settlement and structure parameters. Godoy et al. [13,14] applied experimental testing to study fixed

* Corresponding author.
E-mail address: zhiping@zju.edu.cn (Z. Chen).

http://dx.doi.org/10.1016/j.tws.2016.05.009
0263-8231/

roof tanks under localized support settlement. Result was obtained combining finite element simulation analysis, which showed that the equilibrium path of the tank was highly nonlinear. Jonaidi et al. [15] combined theoretical derivation, finite element analysis and laboratory test to analyze the displacement and stress distribution of floating roof tanks with a constant thickness and a variable thickness under harmonic settlement. Structural parametric study was done and the settlement criteria was presented based on that. In addition, static behavior of tanks under different settlement, including displacement and stress of tank wall, had also been analyzed by some researchers [16–23].

As it can be seen from the review of previous literature, researches about buckling of tanks under settlement are mainly concentrated on harmonic settlement and the settlement that data of each measuring point increases in equal proportion. However, in the actual engineering, settlement does not satisfy the specific modes like harmonic settlement, and the settlement characteristic of each tank is different from each other. A new analysis method is presented in this paper in order to obtain actual settlement variation beneath the tank wall. The relationship between settlement data and time for each measuring point has been obtained by analyzing the settlement data variation and the settlement prediction models for each measuring point are established. The discrete settlement data at any time beneath the tank wall can be transformed into settlement expression continuously distributed along circumferential direction. Based on this, buckling behavior of the tank under the settlement at any time has been analyzed. The analysis method presented in this paper can truly reflect buckling behavior of tanks under measured settlement and predict operation life and buckling strength capacity of in-service tanks. Remediation treatment to the foundation can be conducted in advance if necessary according to the analysis result in order to prolong the service time of tanks.

2. Settlement prediction model

2.1. Model selection

Large steel tanks always have big diameters and the capabilities of the foundation around circumferential direction beneath the tank wall are not identical. That differences, including non-uniform load distribution and effects of liquid filling and discharge on the tanks in service, make the settlement amount and velocity different around circumferential direction during the tank base settlement. In order to analyze the settlement variation with time of the tank wall bottom reasonably, the measuring points evenly located around circumferential direction of the tank wall bottom should be taken as the research object and the settlement variation with time for each measuring point needs to be researched respectively. The settlement prediction model can be established based on the measured settlement data and the relation between settlement and time for each measuring point will be obtained to predict settlement variation. This analysis method can reflect the complete settlement process of the tank wall bottom with time comprehensively.

The settlement characteristic of tank wall bottom corresponds to deformation characteristic of tank foundation subjected to loading. When the tanks are putted into operation, relatively small displacement will appear to the tank foundation in the initial stage, leading to slow settlement of the tank wall bottom. As time and load increase, elastic deformation in some regions of the tank foundation changes into plastic deformation and the settlement amount and velocity will become larger. As time increases continuously, if the load does not exceed the critical bearing capacity of the tank foundation, the settlement of foundation and tank wall bottom will become smaller and smaller, until tends to stable gradually.

Although for different tanks, the loads as well as the corresponding settlements caused by specific liquid filling, discharge and other operations will be different from each other. From the macroscopic perspective, settlement of the tank wall bottom satisfies a general trend, which can be described that in the initial stage the settlement increases slowly as time increases, as time and load increase and variation of foundation property, the settlement amount and velocity will become larger gradually, while when it's up to a certain degree, the settlement increase will become smaller, until to zero approximately.

Considering about the above settlement characteristic of tank wall bottom, the Poisson curve is selected as the settlement prediction model for each measuring point. Poisson curve is generally used to describe the complete process of things from occurrence to development, until to stabilization, and the expression is shown as follows

$$S_t = \frac{k}{1 + ae^{-bt}} \tag{1}$$

where t is time, S_t represents the predicted settlement at time t, a, b, k are positive undetermined parameters, which can be solved by the known settlement data obtained from the measuring points.

2.2. Solution of the settlement prediction model

Based on the measured settlement data of different measuring points at different times in actual engineering, the three-stage method will be used to determine the parameters unknown in the Poisson curve prediction model. The settlement data S_1 to S_n, total n values, corresponding to different time are assumed to be measured at any measuring point. The undetermined parameters in Poisson curve prediction model will be solved using these n settlement data. The parameter n needs to be multiple of three, if not, the obtained settlement data needs to be appropriately selected to ensure that.

The factor r is defined as r=n/3 and the following ones are defined as

$$S1 = \sum_{t=1}^{r} \frac{1}{S_t}\ ; \qquad S2 = \sum_{t=r+1}^{2r} \frac{1}{S_t}\ ; \qquad S3 = \sum_{t=2r+1}^{3r} \frac{1}{S_t} \tag{2}$$

Substituting Eq. (1) into Eq. (2), one obtains

$$S1 = \frac{r}{k} + \frac{ae^{-b}\left(1 - e^{-rb}\right)}{k\left(1 - e^{-b}\right)} \tag{3a}$$

$$S2 = \frac{r}{k} + \frac{ae^{-(r+1)b}\left(1 - e^{-rb}\right)}{k\left(1 - e^{-b}\right)} \tag{3b}$$

$$S3 = \frac{r}{k} + \frac{ae^{-(2r+1)b}\left(1 - e^{-rb}\right)}{k\left(1 - e^{-b}\right)} \tag{3c}$$

The parameter expressions can be obtained as follows by combining Eqs. (3a), (3b) and (3c)

$$a = \frac{(S1 - S2)^2\left(1 - e^{-b}\right)k}{(S1 + S3 - 2S2)e^{-b}\left(1 - e^{-rb}\right)} \tag{4a}$$

$$b = \frac{\ln \frac{S1 - S2}{S2 - S3}}{r} \tag{4b}$$