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# Buckling behavior of floating-roof steel tanks under measured differential settlement

Yang Zhao*, Xiang Lei, Zhen Wang, Qing-shuai Cao

*Space Structures Research Center, Zhejiang University, Hangzhou 310058, China*

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ABSTRACT

Large vertical cylindrical steel tanks constructed on soft foundations may bring forth various types of settlement, which is well known as the uniform settlement, the planar tilt and the differential settlement. Measured settlements of steel tanks in several practical projects are first summarized according to the in-site surveying data, and two kinds of settlement patterns are clearly defined, which are referred to as the global differential settlement and the localized differential settlement. Two practical floating-roof steel tanks are taken as the illustrative examples of large steel tanks, which are marked TK-2020 with the height-to-radius ratio of 0.35 as the representatives of large volume tanks and TK-2090 with the height-to-radius ratio of 0.7 as representatives of smaller volume tanks in this paper. Buckling behaviors of the two illustrative tanks under the global and localized differential settlement are investigated using the general-purpose finite element computer package ABAQUS by means of the geometrical nonlinearity algorithm. It is shown that for tanks under global differential settlement, local buckling occurs first at the eave wind girder, followed by a stable post-buckling behavior, so that the local buckling of the wind girder can be taken as the serviceability limit state and the post-buckling strength can be utilized in structural design of tanks. Moreover, the behavior of tanks under localized differential settlement is related to the degree of localization. The buckling behavior in the case of a large circumferential central angle for localized settlement is similar to that under global differential settlement, while the effect of the localized settlement with a relatively small central angle is more obvious than that of the global differential settlement, and the snap-through buckling induced by localized settlement would govern the design.



## 1. Introduction

Large vertical cylindrical steel tanks employed in various industries for bulk and fluid storage normally consist of a thin bottom plate, a cylindrical shell with uniform or stepped wall thickness, and a fixed or floating roof. As a typical kind of thin-walled structure, these tanks are frequently constructed in coastal regions for economic reasons where foundation settlements arise due to soil depositing. The settlements beneath the tank can be described in terms of several components: dishing settlement of the bottom plate, uniform settlement, planar tilt and circumferential differential settlement of the tank wall. The dishing and uniform settlements, which have little effect on the safety of the structures, can be predicted by applying the theory of soil mechanics [1] and compression test on site borings [2], respectively. Whilst the planar tilt and circumferential differential settlement are the principal potential sources of overstress and distortion resulting in significant damage to the tank [1,3,4], many disastrous accidents have been reported in the literatures[1,5–7]. Concerns related to the differential component are summarized as follows: (a) Jamming of the floating roof and buckling of the shell on the top course on account of tank top ovalization [1,8–10]; (b) Significant overstress occurring at the base caused by the meridional compression and at the top as circumferential stresses, which may lead to buckling near the tank bottom and of the primary wind girder; (c) Overstresses developing in the tank bottom that induce fracture of welds in the bottom plate; (d) Plasticity may occur in parts of the tank wall [11].

In order to evaluate the settlements beneath the tank wall, several methods have been recommended: a graphical procedure proposed by DeBeer [2], and the Fourier decomposition method initially proposed by Kamyab and Palmer [9]. A fold-line method to determine the pattern of wall settlements was also introduced by D'Orazio [7]. However, the circumferential settlements beneath the tank wall are typically described in terms of a truncated Fourier series [9,12–14]:

$$u = u_0 + \sum_{n=1}^{k} u_n \cos(n\varphi + \varphi_n)(0 \le \varphi < 2\pi) \quad (1)$$

* Corresponding author. Tel.: +86 571 88208752.
*E-mail address:* ceyzhao@zju.edu.cn (Y. Zhao).

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where, $n$ is the wave number, $u_n$ is the amplitude of the $n$th harmonic settlement, $u_0$ is the uniform settlement and $\varphi n$ is the relative phase angle of each component.

Meanwhile, various approaches have been proposed to evaluate the effect of differential settlement on the tank shell. The inextensional theory estimating the radial displacement at top of the shell was first reported by Malik et al. [8], in which the bending stiffness of the shell and the effect of the wind girders were neglected, and consequently it was accurate only for low-order harmonic settlement. To extend the range of the solution to be applicable to the larger wave numbers, other analytical solution, the membrane theory and the modified Donnell equation, were proposed by Kamyab and Palmer [9,12], in the presence of a primary wind girder. The limits of above three solutions were evaluated in the literatures, and three critical harmonic wave numbers were presented to distinguish different valid ranges of these three solutions. Besides the distortion, the occurrence of high axial compressive stresses at the bottom of the shell and circumferential stresses in the primary wind girder of the tank were also received much attention, and analytical solutions of these effects were also derived [9,12,14]. Finally, the approach was extended by Hornung and Saal [15,16] to shell wall of varying thickness and the phenomenon of "bridging" of unanchored tanks was also discussed [14,16].

The analytical methods presented above provide insight into the behavior of tanks suffering harmonic settlements, whilst numerical approaches based on the finite element computer packages and experiments on small scale models were employed to valuate the analytical solutions [7,9,15,16]. Parametric study on fixed-roof tanks with uniform and tapered shell thickness was first performed by Jonaidi and Ansourian with the linear elastic FE analysis [17]. Similar investigation was also carried out for floating-roof tanks by Jonaidi and Ansourian [18] and Zhao et al. [19].

In addition, nonlinear behaviors of floating-roof tanks under large amplitude harmonic settlements were also explored [17], and some useful conclusions were derived that markedly nonlinear effects began at small settlement amplitudes and the circumferential stresses at the top wind girder were more critical comparing with the axial compressive stresses near the base. The behavior of fixed-roof tanks with a saddle settlement ($n=2$) was described by Jonaidi et al. [18]: linear buckling mode presented a shearing deformation throughout the height of uniform shell or at the top course for tapered shell, and elephant-foot failure was observed at the base when considering the internal pressure and geometric nonlinearity. Cao and Zhao [20] investigated the buckling strength of fixed-roof tank under harmonic settlement considering the influences of harmonic wave number, the radius-to-thickness ratio, the height-to-radius ratio, and the geometric imperfection. Gong et al. [21] also carried out buckling analysis on large oil tanks with a conical roof subjected to harmonic settlement. According to researches of Godoy and Sosa [11], the nonlinear equilibrium path of a conical-roof tank, which suffering linear-variation local settlement, showed a stable and stiffening configuration with a V-shape deflection on the shell, and radial displacements of shell derived from the nonlinear theory were much larger than that from the linear theory. It was concluded that the tolerance criterion for settlements based on linear elastic shell model were not acceptable and the results restricted to the linear analysis were questionable to some extent. In addition, the nonlinear behavior of a thin cylindrical shell under axial compression and localized differential settlement, investigated by Holst and Rotter [22,23], indicated that even a very small local uplift displacement beneath the shell could induce a snap-through buckling which would lead to a dimple deformation at the base, and the geometric imperfections affected the buckling strength markedly. However, it was argued that the failure criterion provided by European standard for shell structures [24], which indicated that a snap-through buckling event corresponds to the attainment of the ultimate limit state, was too restrictive considering the post-buckling strength of the structures.

Most previous studies were based on idealized harmonic settlement. However, for thin shell structures of high nonlinear behavior, it is obviously inappropriate to obtain the results under real settlement by simple summation of harmonic solutions. Hence, the conclusions derived from the previous studies should be treated with caution. In this paper, full settlement distribution along the circumference of tank bottom are obtained using Fourier decomposition, based on the measured data for settlements of eight in-site tanks. It is found that measured settlements of large steel tanks can be grouped into two types: the global differential settlement and the localized differential settlement. Two practical floating-roof steel tanks with typical dimensions are then taken as the illustrative examples of large steel tanks, and the buckling behaviors of the two illustrative tanks under both types settlements are investigated by geometrically nonlinear analysis.

## 2. Analysis of measured settlements

In recent several decades, tanks with large content for liquid or bulk storage are widely used in petrochemical industry and agriculture. Theses tanks in China are frequently constructed at ports in coastal regions, such as Shanghai, Guangdong Province, etc. It was indicated from the reports about tank failure of practical engineering that differential settlement of the tank was one of the most serious causes to tank failure. In order to obtain first-hand data about tank settlement, Institute of Geotechnical Engineering of Zhejiang University has been performing the settlement observation of many large steel tanks in recent several decades, such as 10,000 $m^3$ tanks of Shanghai Jinshan Petrochemical Company, 125,000 $m^3$ tanks of Guangdong Maoming Petrochemical Company, tanks of Baosteel Group Corporation in Shanghai and tanks in Zhapu Harbour of Zhejiang Province, et al. By setting measuring stations along circumference beneath the tank wall, mass data from settlement observation have been obtained. As this kind of settlement is difficult to be predicted by the theory of soil mechanics, results from measured settlement are particularly valuable for understanding full distribution of settlement of tanks. In this paper, eight in-site tanks (referred to as G1–G8, respectively) which have full settlement data records are chosen as representatives, as are shown in Fig. 1. These tanks are surveyed by setting 16 or 18 measuring points along circumference beneath each tank wall.

Measured settlements of each tank can be considered as the linear combination of harmonic settlements with different orders (different wave number $n$) by using Fourier decomposition method. The approach of data processing aims to investigate the component parts and their characteristics of differential settlements on the one hand, and on the other hand obtain full distribution of settlements along circumference beneath the tank wall so that settlements could be introduced into the following finite element model. For a cylindrical tank, the settlement $u$ beneath the tank wall is decomposed as a Fourier series in harmonics, as described by Eq. (1).

The measured settlement results of eight in-site tanks are decomposed according to Eq. (1), and the amplitude and initial phase angle of each component are shown in Table 1, in which the measuring point 1 is considered as the start point ($\varphi=0$). It is found that the Fourier coefficients of the eight tanks can be classified into two groups. The first group includes G1–G7 tanks. For this group, the coefficient for zero harmonic item corresponding to the uniform settlement is much larger than other items,