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Buckling strength of cylindrical steel tanks under measured differential settlement: Harmonic components needed for consideration and its effect

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A R T I C L E I N F O

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A B S T R A C T

In practical engineering, the measured differential settlement can be gained by monitoring the points beneath the tank wall and it can induce the buckling of the tank even with a small amplitude. In general, Fourier series is adopted to decompose the measured differential settlement into harmonic components with various wave numbers. However, the question that which harmonic components should be considered is a main challenge for buckling investigations of the tank under measured differential settlement. In this work, a recommendation for harmonic components needed for consideration was proposed when decomposing measured differential settlement into harmonic components in terms of Fourier series. Moreover, the effects of the harmonic components considered on buckling behavior of floating roof tanks and conical roof tanks were discussed. The results presented that three monitoring points can make a first estimate of ovalling and the harmonic components considered should be smaller than and equal to $[N]/3$ ([] is the rounding function and N is the number of the monitoring points). The introduction of the harmonic component with a high wave number can cause the change of the buckling modes of the tanks under differential settlement, including floating roof tanks and conical roof tanks. Meanwhile, it can decrease the buckling strength of the floating roof tank more significantly than that of the conical roof tank.

1. Introduction

Cylindrical steel tanks, mainly composed of a cylindrical shell, a top stiffening ring on the top, and a floating roof or a fixed roof [1], are widely employed for storing oil, chemical products and other mediums in many industrial areas. In general, the foundation settlement is observed beneath tank walls due to the unevenness of the soil conditions and the settlement can be resolved into three components: uniform settlement, tilt settlement and differential settlement. Among all these components, the differential settlement has a significant influence on the shell although its magnitude is usually the smallest of the three components [2]. It can cause a large radial displacement, buckling of the shell, and even the failure of the tank [3–6]. As stated above, it is essential to study the buckling behavior of cylindrical steel tanks under differential settlement.

In previous studies, the buckling behavior of cylindrical steel tanks under differential settlement has been reported. For instance, Jonaidi et al. [7,8] reported the linear buckling behavior of cylindrical shells under vertical edge settlement. Moreover, the combined internal pressure and vertical harmonic settlement were involved. Cao and Zhao [1] studied the buckling strength of fixed-roof tanks under harmonic settlement using the finite element computer package ANSYS. Gong et al. [6,9] analyzed the buckling performances of conical roof tanks and open top tanks subjected to the harmonic settlement, and the buckling behavior of both types of tanks is compared with each other. Nevertheless, the above works are mainly limited to harmonic settlement. In addition, the buckling behavior of tanks or cylindrical shells under the local settlement has been discussed by Godoy and Sosa [10–12], Holst and Rotter [13,14], and so on. In practical engineering, measured differential settlement is quite different from harmonic settlement and the local support settlement mentioned above. Recently, some works have reported the buckling analyses on the shell under measured differential settlement, such as the work of Zhao et al. [15,16]. In their work, the Fourier series was used for the decomposition of the differential settlement and then the buckling behavior of different steel tanks was conducted. It was stated that the wave number smaller than eight was assumed for analyses, mainly determined by experience and detailed evidence for this value was not provided. Other investigators also mentioned how to identify the highest wave number for numerical analyses. For instance, Holst and Rotter [2] recommended that five observations are needed for a first estimate of ovalling, implying that N monitoring observation stations are available

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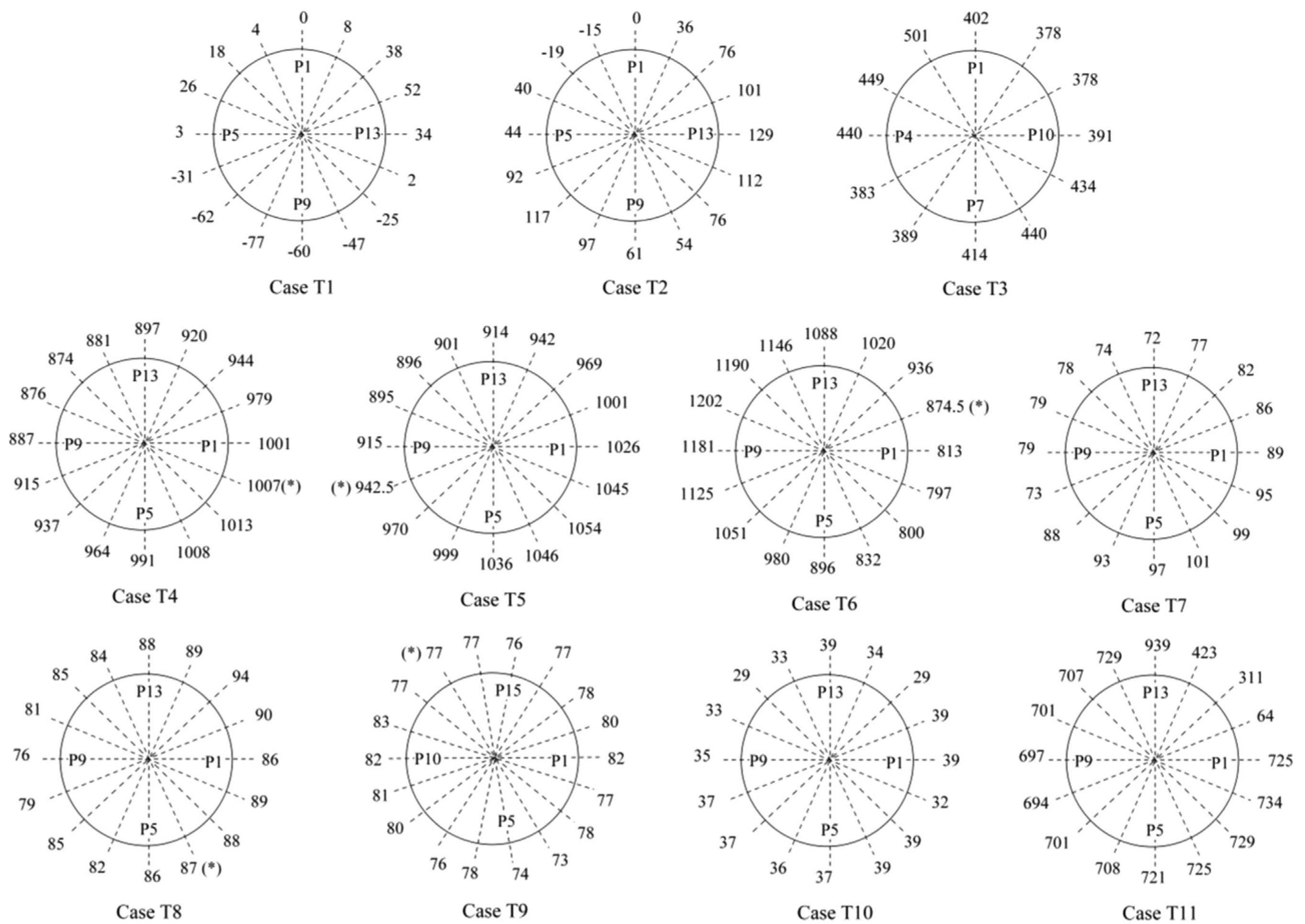

Fig. 1. Settlement patterns of tanks (settlement data from Refs. [5,15,20]).

Table 1
Decomposed components of several settlement patterns.

Case	Parameters	0	1	2	3	4	5	6	R^2 ($n \le 4$)
T1	u_n (mm)	−7.31	44.49	26.83	11.22	2.58	0.71	2.25	0.999
	φ_n (rad)	/	0.40	−2.95	2.94	−1.17	−0.08	−0.36	
T2	u_n (mm)	62.56	45.29	41.17	10.35	6.92	4.42	5.23	0.989
	φ_n (rad)	/	2.55	2.36	−1.02	1.86	0.72	−1.32	
T3	u_n (mm)	416.58	18.09	42.82	5.30	8.93	14.05	13.17	0.943
	φ_n (rad)	/	−1.23	−1.50	−2.33	−2.14	−2.21	−3.14	
T4	u_n (mm)	943.38	70.91	0.42	1.21	2.24	1.64	1.33	0.999
	φ_n (rad)	/	−0.71	−0.56	0.45	1.11	0.22	1.84	
T5	u_n (mm)	971.97	79.94	2.21	0.35	1.21	2.11	1.36	0.999
	φ_n (rad)	/	−0.79	−2.33	2.15	1.36	−1.48	2.13	
T6	u_n (mm)	995.72	203.78	3.46	1.62	2.69	1.76	2.42	0.999
	φ_n (rad)	/	2.65	0.49	2.30	−1.52	2.79	1.80	
T7	u_n (mm)	85.125	12.43	2.90	2.45	1.77	0.99	1.29	0.986
	φ_n (rad)	/	−1.02	−1.99	1.55	−2.36	1.77	−0.76	
T8	u_n (mm)	85.56	5.17	1.89	0.44	2.00	0.45	1.49	0.959
	φ_n (rad)	/	0.27	2.78	1.70	−3.08	−0.28	−2.55	
T9	u_n (mm)	78.11	1.22	3.01	0.29	0.91	0.43	0.29	0.899
	φ_n (rad)	/	2.66	0.27	0.33	−0.31	2.52	2.81	
T10	u_n (mm)	35.44	2.34	0.64	1.12	2.58	2.67	1.06	0.782
	φ_n (rad)	/	−1.14	2.13	−1.65	0.68	1.29	1.72	
T11	u_n (mm)	644.25	133.70	155.36	133.21	90.77	31.21	35.73	0.919
	φ_n (rad)	/	−2.56	−2.00	−1.26	−0.51	0.017	−1.43	

for an approximation of harmonic component of wave number n = $[N]/4$. Cao [17] concluded that the highest wave number in terms of Fourier series should follow the rule: $i_{max} < (n-1)/2.0$, but detailed demonstration on this recommended value was not provided. Based on the work of Cao [17], Chen et al. [18] claimed that the highest wave number (i_{max}) for settlement decomposition should satisfy two limitations: $i_{max} < 8$ and $i_{max} < (n-1)/2.0$. Meanwhile, the fitting curve with the minimum mean square error was selected as the optimum variable. As a whole, the above recommended rules are based on the experience. Regarding the measured differential settlement, the decomposition of