Abstract

This paper reports the influence of support settlements on the mechanical behavior of thin-walled cylindrical tanks with a fixed top roof. The shells considered are representative of steel tanks constructed in Puerto Rico, and have a ratio between diameter and height of the order of 5, with slenderness ratio (radius to thickness) of the order of 2,000. The tanks are discretized using the finite element computer package ABAQUS and a geometrically non-linear algorithm. Results are presented for two cases: a small-scale model and a steel tank built in Peñuelas, Puerto Rico. It is shown that the equilibrium path is non linear and the shell displays a stable symmetric bifurcation behavior.

1. INTRODUCTION

Large thin-walled steel tanks are employed in various industries to store water, oil, chemical and other fluids. The geometry of such cylindrical tanks is different from other structural shells such as silos or pressure vessels, and may be rather short (about 8 m height, 38 m diameter, and 1 cm thickness) leading to a ratio between the radius and the thickness between 1,000 and 2,000. In their most usual configuration, the tanks are clamped at the base and may have a fixed or a floating roof. This paper reports the computational modeling of localized settlements in the supports of the tank, which induce large geometric distortions in the cylindrical shape of the structure.

The settlement of the foundation in large, thin walled shells has been of great concern in the past. Studies on reinforced concrete cooling towers shells constructed in the form of hyperboloids of revolution indicate ratios of maximum amplitude of the out-of-plane displacement versus the vertical settlement of the support between 3.5 and 6.0 [1-4]. However, all the computer simulations carried out by those authors employed a geometric linear formulation in spite the fact that large amplitude displacement may have occurred. For tanks, Myers [5] indicates a possible mechanism of settlement at the base but does not provide data of actual displacements in the shell. For cylindrical barrel vaults, Rao and Rao [6] computed the influence of settlement of one column. But again, the computations were carried out using a linear model.

In the present investigation, the geometrical non-linear behavior of thin-walled tanks under support settlements is considered. The main questions addressed are: What is the displacement pattern of the shell? How can the non-linear equilibrium path help to classify the behavior of the structure? What are the levels of out-of-plane displacements compared with the linear solution?

2. COMPUTER MODEL

To simulate the response of the shell, a finite element model was constructed using the general-purpose finite element package ABAQUS [7]. To obtain a discretization of the structure, shell elements identified as S8R5 and STRI65 have been employed. Element S8R5 is an 8-node element with corner and midside nodes, and five degrees of freedom per node. The other element (STRI65) is a triangle with midside nodes similar to the previous one. For such elements the shear energy is neglected so that Kirchhoff hypothesis are satisfied. For a tank with or without a roof only one-half of the structure is discretized. For a tank with a conical roof the number of elements is 2,700 (about 50,000 degrees of freedom).

A static analysis is performed under displacements in the vertical direction at certain nodes. Several settlement configurations were studied in each case, including a linear variation of the vertical displacements up to a maximum value at the center of the zone of settlement, and a cosine variation. But the main parameters controlling the response are the
central angle of the zone of settlement and the maximum amplitude of the vertical displacement. Parametric studies were performed using a linear model to identify the worst angles. Then, geometrical non-linear analyses were done to obtain deflected shapes and equilibrium paths.

3. NUMERICAL RESULTS

Two typical cases are presented here because of limitations in space, and they include a small-scale model of a tank with a flat roof and a real-size tank with conical roof. The meshes of finite elements for both cases are shown in Figure 1.

![Figure 1](image1.jpg)

**Figure 1.** Finite element mesh for: a) a small-scale model, and b) a steel tank

The small-scale model was previously tested in a laboratory (Figure 2.a) and is about 135 times smaller than a real tank, but the material properties were not scaled using theories of similitude. The diameter of the cylinder is 226 mm, height 90 mm, and thickness 0.2 mm, with estimated values of E = 10 GPa and Poisson’s ratio ν = 0.3. First, a geometrically linear model was built, and the results showed a pattern of displacements which was not what was observed in the experiments; furthermore, the amplitude of the displacements were higher than in the model tank.

The non-linear studies allowed to obtain both modes of deflection and amplitude of the displacements closer to the experiments. A typical equilibrium path is shown in Figure 4 for a settlement with a central angle of θ = 30°.

Both linear and non-linear analyses are in close agreement for a small range of the vertical settlement (of the order of the shell thickness). However, as the settlement increased, the maximum out-of-plane displacements departed significantly from the linear solution. Such behavior is typical of buckling of a shell in a stable symmetric behavior. It is believed that the shell buckles under prescribed displacements, and deflects in a post-buckled configuration, which is reached for small values of the control parameter.

A linear study only increases proportionally the initial deflection and is representative of the fundamental equilibrium path. For increasing values of the settlement amplitude, Figure 3 shows a sequence of deformed shapes in the computational model. For different meridians (θ = 0° and θ = 15°) the equilibrium paths are shown in Figure 4.
The second case studied, a shell with the dimensions taken from a real tank in Peñuelas, Puerto Rico, was investigated. The deformed shape for this case is shown in Figure 5.

This tank was previously studied in reference [8] within the context of wind buckling during hurricanes. For this tank, the influence of the geometric non-linearity is not so significant as in the small-scale model, as shown in Figure 6.
4. CONCLUSIONS

The simulations carried out in this research show that the evaluation of deflection patterns in thin-walled shells due to localized settlements of foundations is a highly non-linear problem. For one shell problem studied, i.e. a small-scale model of a cylindrical tank with a flat roof, the behavior seems to be what is identified as a symmetric bifurcation in the theory of elastic stability [9].

A short fundamental equilibrium path is seen to occur, before buckling develops into a new shape for the shell. In the new stable configuration, the shell can withstand further vertical displacements with an increase in the amplitude of the post-buckling mode. This situation is less clear for steel tanks. Regarding the engineering importance of this effect, one has to look at the displacement amplitudes. The out-of-plane displacements computed are much larger than the vertical displacement due to the settlement. The parametric results show that the most damaging effects are associated to settlements with a small central angle, of the order of $\phi = 10^\circ$.

Further research in this area is needed to contribute to the understanding of the mechanics of behavior of the structure, and to include the influence of the liquid stored in the tank as stabilizing effect.

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REFERENCES


