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Large Amplitude Settlements of Oil Storage Tanks

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Large Amplitude Settlements of Oil Storage Tanks

Paper No. 5.44

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SYNOPSIS The measured profile of large-amplitude settlements of an oil storage tank was analyzed by the finite element method. Both geometric and material nonlinearities were included in the finite element analysis. Stresses and deformations, based on available qualification criteria, were examined. The results showed that most criteria in use today for the tank shell and the bottom plate are overly conservative. The calculated response of the existing operational tank under the measured large-amplitude settlements confirmed such an observation.

INTRODUCTION

In general, steel tanks are flexible structures which are capable of adjusting to relatively large foundation movements and of tolerating large differential settlements. Their tolerance for settlement and distortion [2, 6, 7, 8], however, is not without limits. Foundation settlements have caused severe distortions, and even complete rupture of steel liquid storage tanks [2, 6]. Many of these incidents were followed by rapid spilling of the tank content causing pollution of the environment, destructive fires and loss of human life. To prevent these damages and potential tank failure, performance criteria for the settlement of large steel tanks have been proposed. These present the upper limit of settlements that a steel tank can withstand without affecting its operation.

The principal criteria in use today relate to the two major components of the tank: the shell and the bottom plate. A relatively large number of criteria has been suggested regarding the tolerable settlement of large oil tanks; however, a few of them vary considerably. Differential shell settlements are primarily analyzed in terms of planar tilt and non-planar settlements. Planar tilt is a rigid-body tilt on a plane whereas non-planar settlements involve bending of the tank floor. A practical method by Sullivan and Nowicki [9] is generally used to evaluate non-planar settlements. For the settlements of the tank bottom plate, two important deformation modes exist: dish-type settlement and localized depressions. In 1982, Marr, Ramos and Lambe [6] proposed a criterion for dish-type settlement of the bottom plate which considers the initial maximum camber of the bottom plate, the ultimate stress of the particular weld used to construct the bottom plate, the factor of safety and Young's modulus of steel. For local depressions, Guber [4] proposed criteria for localized settlement of the bottom plate which distinguish between localized settlement remote from the shell and localized settlement adjacent to the shell.

Because the principal criteria is use today were developed through approximate analyses, many tend to be overly conservative. In this study, an advanced finite element program is used to evaluate the stress level in each of the tank components when a few of current criteria are adopted. Further, the measured profile of large-amplitude settlements of an existing operational tank was used to confirm that these criteria are generally conservative. This article presents a summary of the findings and representative charts.

TANK DIMENSIONS AND PROPERTIES

The tank under consideration is a circular cylindrical tank of radius R = 68.9 ft (21.0 m) and height H = 35.0 ft (10.7 m). Other tank dimensions and shell thicknesses are presented in Fig. (1) and Table 1.

Table 1. Height and Thickness of Shell Rings

Shell Rings	Height		Thickness	
	ft	m	in	mm
1	5.84	1.78	0.65	16.00
2	5.84	1.78	0.53	13.00
3	5.84	1.78	0.41	10.00
4	5.84	1.78	0.28	7.00
5	5.84	1.78	0.24	6.00
6	5.84	1.78	0.24	6.00

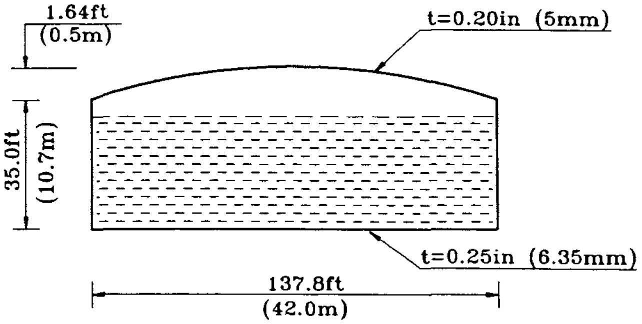

Figure 1: Tank Dimensions and Properties.

The material properties used in the analysis are: Young's modulus of steel, E = 30 $\times 10^6$ psi (2.1 $\times 10^{11}$ Pa); yield stress of steel, σ_{yield} = 36 ksi (2.5 $\times 10^8$ Pa); unit weight of steel, γ_{steel} = 486.72 lb/ft^3 (76,440 N/m^3); and unit weight of oil, γ_{oil} = 49.92 lb/ft^3 (7840 N/m^3).

PERFORMANCE CRITERIA

To qualify the performance of a liquid storage tank, there are different criteria available for both the tank shell and the bottom plate. In this article, two of these criteria are thoroughly examined, namely, the planar tilt of shells and the dish type settlements of the bottom plate. For the evaluation of other criteria, refer to [10].

Shell (Planar Tilt)

As defined earlier, a shell may be governed by two criteria: planar tilt and non-planar settlements. A summary of the criteria pertaining to planar tilt of shells is listed in Table 2.

Table 2. Criteria for Planar Tilt of Shells

Langeveld (1974)	Greenwood (1974)	Japanese Fire Defense Agency	Marr, Ramos, Lambe (1982)
$\delta \leq 20.3$in (50cm) $\delta_{hor} \leq 12.2$in (30cm)	$\delta \leq D/200$	$\delta \leq D/100$	$\delta \leq 2\Delta h_d$ $\delta \leq 2\sqrt{R_{tol}D}$

where δ is the difference in settlement between diametrical points; δ_{hor} is the horizontal deformation at the top of the tank shell; Δh_d is the design freeboard; R_{tol} is the tolerance of the seal; and D is the diameter of the tank.

Bottom Plate (Dish-type Settlements)

Several criteria have also been proposed for dish-type settlements of the bottom plate (see Table 3).

Table 3. Criteria for Dish-type Settlements of Bottom Plate

Langeveld (1974)	Hayashi (1973) Guber (1974)	Japanese Fire Defense Agency	Marr, Ramos, Lambe (1982)
$w \leq D/100$	$w <$ $D/90$ to $D/50$	$w \leq D/100$	$w \leq \sqrt{w_0^2 + \frac{0.37 \cdot D^2 \cdot \sigma_f}{FS \cdot E}}$

where w is the camber or difference between the center and the edge elevation; w_0 is the initial camber of bottom plate; FS is a factor of safety = 4.0; and σ_f is the rupture stress of steel.

FINITE ELEMENT MODEL

The finite element mesh, shown in Figs. (2), (3) and (4), includes a total of 480 elements. Each of the roof and the bottom plate was subdivided into 120 elements and the shell was discretized to 240 elements. The element type used was a four-node shell element.

Numerical Examples

Because it is anticipated that the criteria in use today are conservative, one should select the least conservative criterion for the more elaborate finite element analysis. The finite element analysis calculates the maximum stress according to the Von Mises criterion.

Planar Tilt: Of the four criteria for planar tilt, the criterion proposed by Langeveld is the least conservative for the analyzed tank. This yields a value of δ = 1.64 ft (0.5 m).

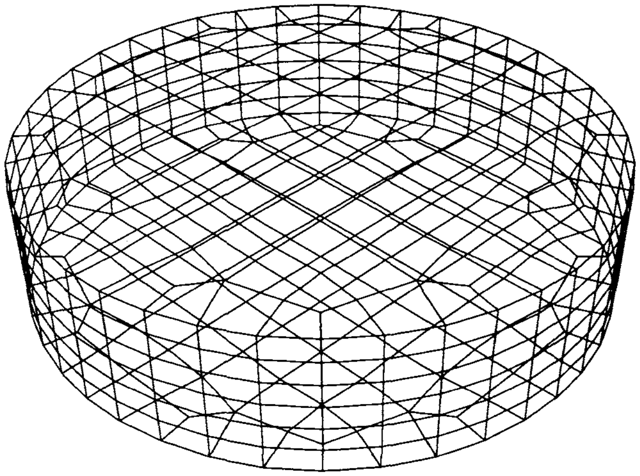

Figure 2: Finite Element Mesh.

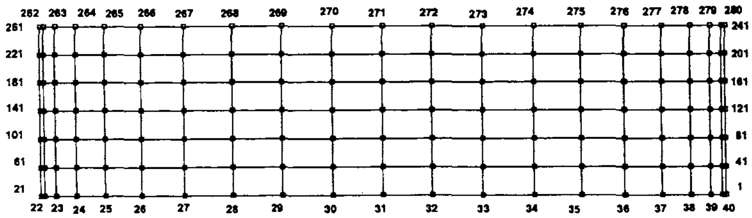

Figure 3: Elevation Mesh.

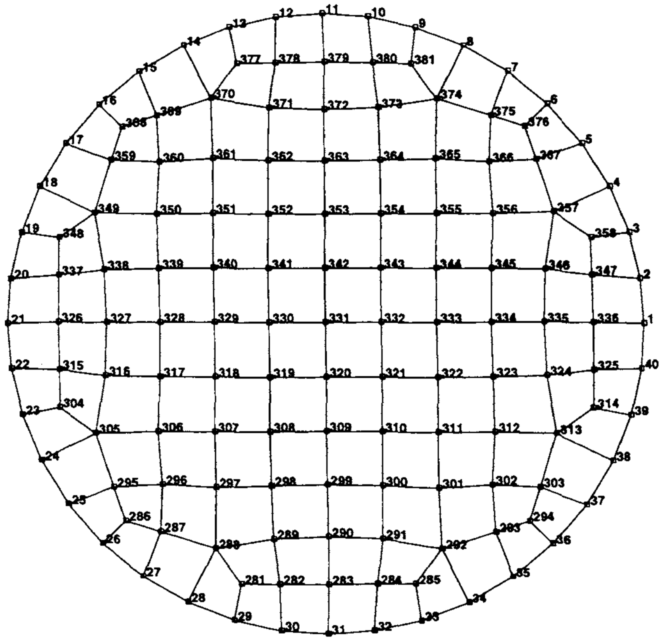

Figure 4: Finite Element Mesh of Tank Bottom Plate.

Figure (5) shows the shell radial displacements along the shell height which have a maximum value of 0.13m, significantly less than the value specified by the criterion. The maximum stress variation along the shell height is shown in Fig. (6); it indicates marginal variation

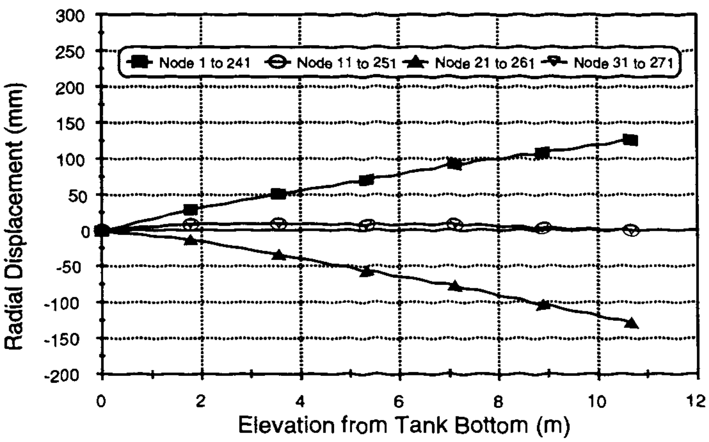

Figure 5: Shell Radial Displacement.

in the stresses at different points of the same elevation. The maximum stress in the tank occurred at the lower part of the shell with a maximum value $\sigma_{max} = 15.9 \times 10^3$ psi (1.1×10^8 Pa) which is significantly below the yield stress. This clearly shows that the chosen criterion is conservative.

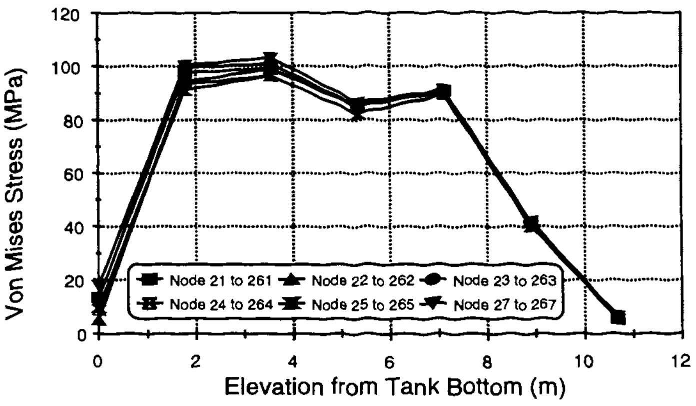

Figure 6: Variation of Shell Stress.

Dish-type Settlements: Of the four criteria for dish-type settlements, the criterion proposed by Hayashi and Guber is the least conservative; it yields a value of w = 2.76 ft (0.84 m). Figure (7) shows the bottom plate vertical displacements along any diameter (axisymmetric settlement) whereas Fig. (8) presents the maximum plate stress along the principal diameter which shows that the location of the maximum stress is at the connection with the shell. Again, it is demonstrated that even the least conservative criterion produces stresses well below the yield stress.

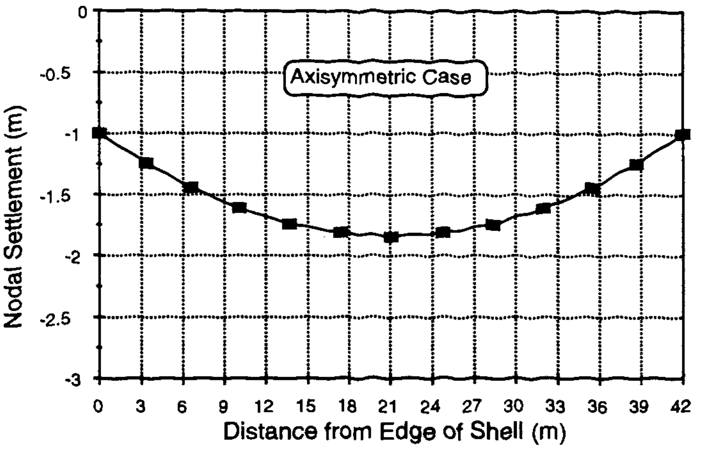

Figure 7: Vertical Displacement of Bottom Plate.

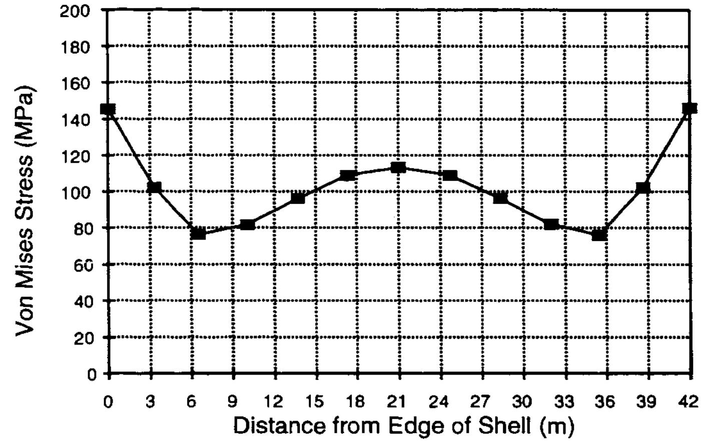

Figure 8: Variation of Plate Stress.

MEASURED SETTLEMENT OF EXISTING TANK

Having checked the criteria in use, the settlement data of an existing tank were introduced in the computer model. A total of 141 measurements of the vertical displacements of the bottom plate had been obtained. Settlement values varied from 1.42 to 1.64 m. A surface fitting was performed both in a rectangular coordinate system (x, y) and in a cylindrical coordinate system (r, θ). The mean square error for surface fitting in the cylindrical coordinate system with 50-term expansion was 0.0007 m whereas the same for a 25-term expansion was 0.00084 m. Because there was little difference in the mean square errors using the 50-term and the 25-term expansion, the latter was used in the analysis. Figure (9) displays the fitted settled surface of the bottom plate.

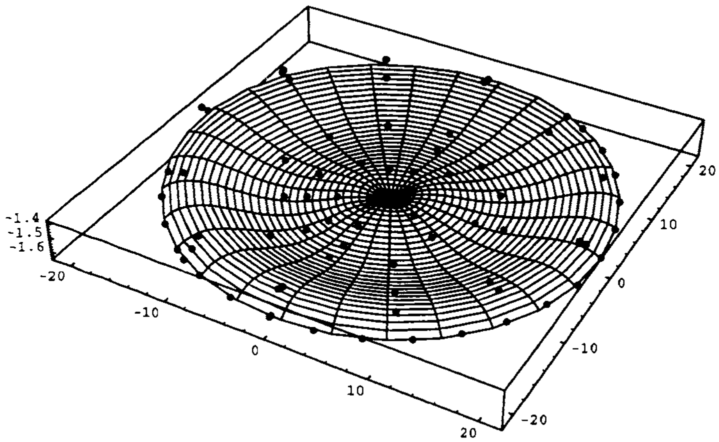

Figure 9: Fitted Settlements of Tank Bottom Plate.

The data provided included only the settlements of the bottom plate. No data were provided as to the imperfection of the shell. Accordingly, the analysis was performed by specifying the bottom plate deflection, and subsequently, calculating the shell displacements and both the bottom plate and shell stresses. The effect of shell distortions due to construction was not taken into consideration.

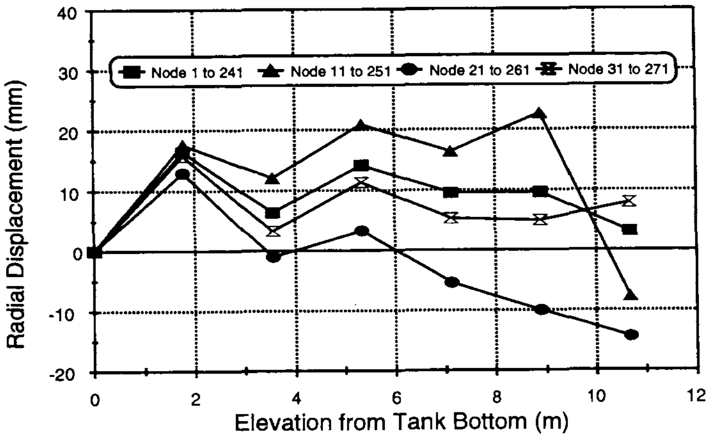

Figure 10: Shell Radial Displacement.

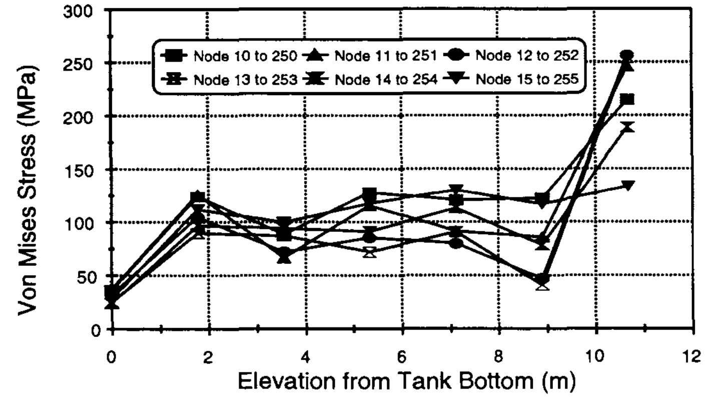

Figure 11: Variation of Shell Stress.

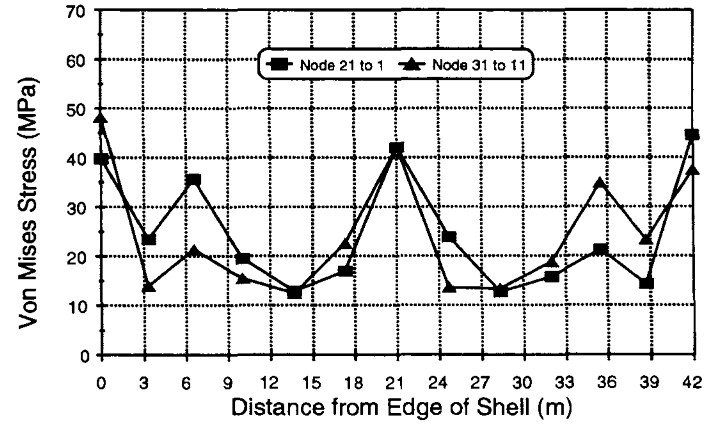

Figure 12: Variation of Plate Stress.

Because the analysis is nonlinear, the solution is obtained through a number of iterations until convergence is achieved. The maximum stress σ_{max} approached the yield stress during the last iteration, and only in the tank shell near its connection with the roof. Figure (10) shows the shell radial displacements along the shell height whereas Figs. (11) and (12) show the variation of Von Mises stress in the shell and the bottom plate, respectively. Even though the measured settlements exceeded those allowed by the design criteria, the nonlinear analysis showed that the tank is safe, a fact physically observed since the tank has been operational without incidents of malfunction.

CONCLUSIONS

Criteria for planar tilt and dish-type settlements were examined by an advanced nonlinear finite element program which takes both geometric and material nonlinearities into consideration. It was shown that qualification criteria in use today are generally conservative. Measured tank settlements of an existing operational tank were used to confirm this observation. Even though the values of the observed settlements were significant, it was found that the maximum shell and plate stresses were well below the yield stress except at a small region near the shell-roof connection. It should be noted, however, that no shell out-of-round distortion due to construction were measured, and this factor is likely to increase the computed stresses. Nonetheless, it has been noted that the physical tank has performed satisfactorily under the present environment without the need for further actions.

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