SEISMIC DESIGN CONSIDERATIONS FOR UPLIFTED TANKS

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ABSTRACT

An evaluation of the most commonly used seismic design procedures for unanchored tanks is presented. It is noted that current standards are inconsistent in predicting the behavior of unanchored tanks. In general, the estimation of liquid-exerted overturning moments lacks explicit consideration of the support effects, and may not even include shell flexibility and site conditions. The capacity of the bottom plate to resist uplifting forces is generally underestimated because membrane forces are neglected. However, current design procedures are in most cases conservative partly because the allowable stress is significantly reduced by a large knock-down factor. The use of more elaborate analyses, which are increasingly becoming available, is recommended to complement current design standards.

INTRODUCTION

Unanchored, cylindrical, thin-walled, steel liquid storage tanks are susceptible to buckling when subjected to seismic excitations. The overturning moment caused by the hydrodynamic pressure tends to lift the shell off its foundation, thus developing highly-concentrated compressive stresses which may cause buckling of the shell. A literature review of available design standards shows that the API 650 standard [1] for oil tanks (or alternatively, the AWWA standard [2] for water tanks) have been the most commonly used standards for seismic design of tanks. In recent years, the New Zealand recommendations for seismic design of storage tanks [5] have gained wide acceptance internationally. A comparison between the analysis procedures for unanchored tanks in these standards and guidelines is presented, and a critical evaluation of their accuracy is made. It should be noted that the performance of tanks during past earthquakes has revealed a much more complex behavior than is implied by current design procedures and continually demonstrates the need for more reliable analyses to assess their seismic safety. Specific areas targeted for improvements are related to:

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- Estimation of the loads exerted on unanchored tanks, particularly the overturning moment.
- Estimation of the compressive stress at the shell bottom (demand).
- Estimation of the allowable shell buckling stress (capacity).

Note that the uplifting problem is nonlinear in nature because of the successive separation and contact of the bottom plate with its foundation.

CURRENT METHODS FOR SEISMIC DESIGN

Recommended seismic design provisions for flat bottom storage tanks have been developed to assure the stability of the tank shell against overturning and to preclude buckling of the shell due to the axial compressive stress.

Overturning Moment: Design bending and overturning moments in the API standard [1] as applied to the bottom of the shell and to the foundation, respectively, are determined using the simplified procedure developed by Housner [4] for rigid tanks. A lateral force coefficient, equals to 0.24, is specified to represent the amplified tank acceleration as a ratio of the acceleration of gravity; it does not take into account explicitly the effects of shell flexibility, site conditions, or support conditions (anchored vs. unanchored). Each of these factor may amplify the tank acceleration, for example, soil-tank interaction and associated rocking motion could, under horizontal excitation, amplify the tank acceleration as high as 200% or more for soft soil.

The New Zealand recommendations provide normalized response spectra for soil and rock, recommended geographic coefficient for the design according to tank location zone, and a recommended peak ground acceleration of 0.35 g. A mechanical analog [3], which takes into account the deformability of tank wall, is used to reduce the tank and its content to equivalent masses and springs at different heights. A correction formula is used to modify the frequencies of the mechanical analog and the corresponding damping ratios depending on the soil type and its mechanical properties. It should be noted that this mechanical analog was developed for tanks anchored at their base. However, due to the lack of readily available methods, the recommendations include this model for calculating the amplified overturning moments in unanchored tanks!

Axial Shell Compressive Stress: The resistance to overturning is provided by the weight of the tank shell and by the weight of a portion of the tank content which depends on the width of a bottom annular ring that lifts off the foundation. To determine this width, an elemental strip of the bottom plate perpendicular to the shell which can be lifted off the ground is considered in the API standard. The content weight which may be utilized to resist overturning is based on calculated reaction at the tank shell of this strip. It is assumed that two hinges are developed in the bottom plate, one at the junction of shell and bottom plate, and the other at some distance inward from shell. Neglecting hydrodynamic pressure on tank bottom plate, the equilibrium of the strip leads to the unknown value of the compressive stress. It is noted that neither the deformability of the tank wall nor the flexibility of the underlying soil are considered in the model. In addition, only small deformation behavior of the bottom plate is taken into account. At higher levels of ground excitation, the capability of the plate to resist the applied loads would not be fully accounted for, leading to conclusions of global instability (overturning). One other discrepancy noted in the API procedure is that the overturning moment at tank base and the uplift force are independent of each other which is unrealistic as the overturning moment produces the uplift force! It is noted that the API standard restricts the maximum value of uplift width of the bottom annular ring to 0.035 of tank diameter, otherwise, the tank must be anchored.

In the New Zealand recommendations, the stress in the tank shell is calculated using global equilibrium of the shell and its base. It is assumed that the bottom plate remains in contact with the foundation on a circular area of a radius slightly less than the radius of the tank, and that the edge of shell rests on an arc of the tank's perimeter of unknown central angle. The two unknowns of the problem, the maximum compressive stress in tank shell and the central angle of contact arc, are found by solving two nonlinear algebraic equations which govern both global vertical force equilibrium and global moment equilibrium. One disadvantage of this model is that it does not take into account the deformation behavior of either the tank wall or the bottom plate. Furthermore, it neglects the variation of dynamic pressure on bottom plate and uses a constant value equal to the static pressure.

Allowable Stress: The allowable buckling stress in the API standard is based on the classical value of buckling under axial load, significantly reduced by a large knock down factor due to shell imperfections and also increased to account for the effects of the internal liquid pressure. In the New Zealand recommendations, the classical buckling stress in membrane compression is calculated, then corrected according to the imperfection amplitude and the internal pressure. In addition, an elastic-plastic collapse stress is also calculated. The lower of the two stresses is used in the calculation of the factor of safety.

COMPARISON BETWEEN SEISMIC STANDARDS

The overturning moment calculated according to the New Zealand recommendations with and without soil effects, and that computed according to the API standard is displayed in Fig. (1) versus the tank aspect ratio (H/R). The former overturning moment was developed for a peak ground acceleration of 0.35 g, 10% damping ratio, rigid foundation on rock, 1% probability of exceedence and geographic coefficient of 1.0. The latter moment was computed for an importance factor of 1.0 and a soil magnification factor of 1.0. The 10% damping ratio is recommended by the New Zealand guidelines for the case of unanchored

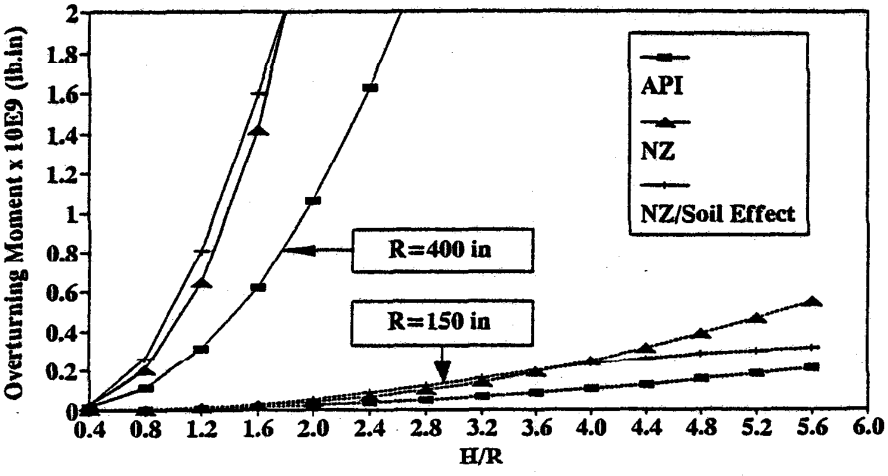

Figure 1: Seismic Overturning Moment.

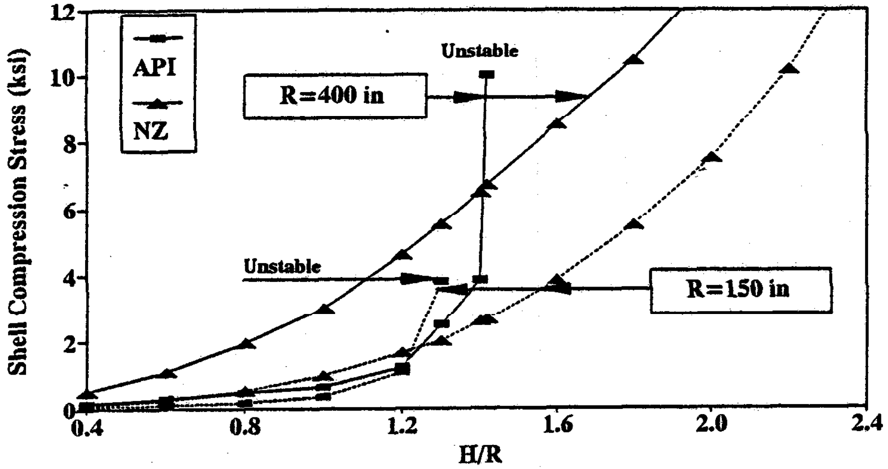

Figure 2: Shell Axial Compressive Stress.

tank under significant horizontal excitation. A soil of a shear modulus of 2.8 ksi and a Poisson's ratio of 0.3 was considered to investigate the effects of soil on the overturning moment calculated using the New Zealand recommendations. The significant difference noted in the figure is attributed to the difference in the spectrum used and to the effect of the impulsive-flexible mode. The response spectrum adopted in the New Zealand recommendations has relatively steep slopes that lead to a rapid change in the spectral acceleration due to a slight change in the periods of vibration. It should be noted that the thickness of all tanks was calculated from the magnified static hoop stress using the relation $t = \gamma_{liquid} H R A^* / 1.33 \sigma_{all}$, with a minimum thickness of 0.25 inch and a maximum thickness of 1.2 inch. The factor A^* represents the expected ratio of the maximum combined pressure to the hydrostatic pressure.

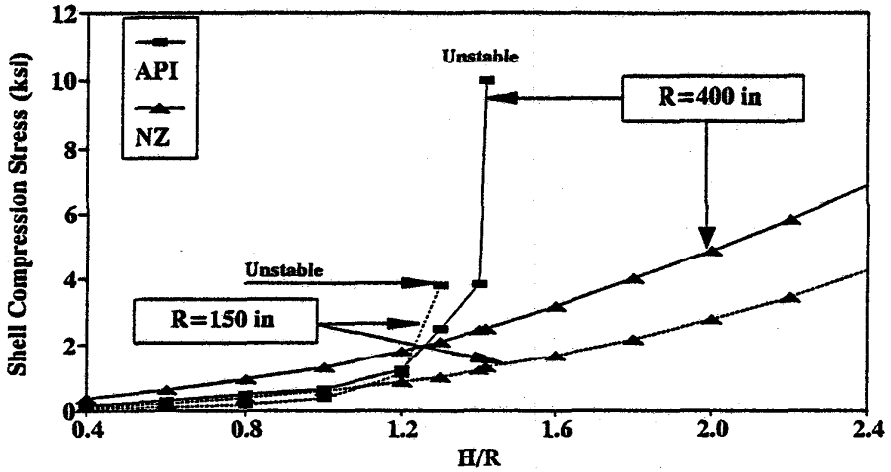

Figure 3: Shell Axial Compressive Stress Using API 650 Overturning Moment.

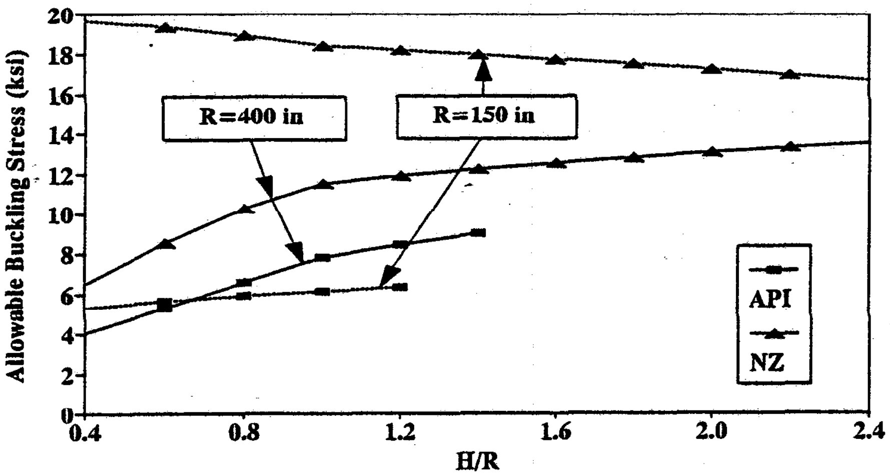

Figure 4: Allowable Buckling Stress.

A comparison between the shell axial compressive stress calculated based on the API standard and the New Zealand recommendations is shown in Fig. (2). To isolate the difference due to the method of calculation of the stress, the same value of the API overturning moment was employed with both methods for calculating the axial compressive stress and the results are displayed in Fig. (3). It shows that the New Zealand method of stress analysis leads to a higher stress level than that computed by the API method. Allowable buckling stresses are plotted in Fig. (4) while Fig. (5) displays the factor of safety against buckling.

The stability of the tank against overturning is checked by comparing the overturning moment with the stabilizing moment due to the weight of tank and content. The vertical acceleration due to vertical excitation is ignored which is not conservative if the direction of the ground motion is upward.

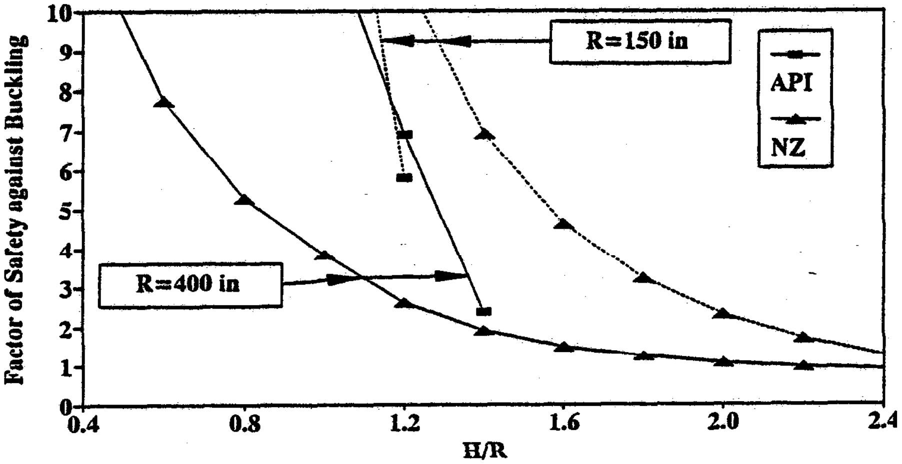

Figure 5: Factor of Safety Against Buckling.

CONCLUSION

A significant difference was found in the values of the seismic demand and the seismic capacity of unanchored liquid storage tanks, computed according to the API standard and the New Zealand recommendations. The intermediate steps in the simplified design procedures of both the API standard and the New Zealand recommendations differ significantly in approach and values. Further, according to the API procedure, tanks with aspect ratios (H/R) larger than about 1.2 would be required to be anchored due to overturning instability. The need for an accurate method for the computation of the seismic forces exerted on unanchored tanks is apparent. Furthermore, the uplift mechanism and the method for computing the stresses need major refinements.

REFERENCES

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