05 Apr 1995, 1:30 pm - 3:30 pm

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Proceedings: Third International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, April 2–7, 1995, Volume I, St. Louis, Missouri

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Paper No. 5.43

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SYNOPSIS During seismic events, the overturning moment exerted by the hydrodynamic pressure of a liquid contained in an unanchored, thin-walled liquid storage tank tends to lift the tank base plate off its foundation. The nonlinear uplift and contact mechanism between the base plate and the underlying foundation is investigated in the present study. Nonlinearities due to base plate contact with foundation, large deflection and plastic hinge formation are examined.

INTRODUCTION

The seismic response of an unanchored liquid storage tank is governed primarily by the mechanism of base plate uplifting and its interaction with the underlying foundation. Numerous studies have dealt with the analysis of base plate uplifting over both elastic and rigid foundations in order to reach an understanding of the complex response of such structures. Clough [4] proposed a simplified model for uplifted unanchored tanks but the load carrying capacity of the bottom plate was ignored. Wozniak and Mitchell [9] suggested a more realistic model for uplifting by including the flexural stiffness of the bottom plate; however, the analysis assumed a small-deflection response, thereby neglecting the membrane effects in the bottom plate. Later, in 1986, Leon and Kausel [8] proposed a few modifications to this model. Auli, Fischer and Rammerstorfer [1] presented an analysis for the uplifting of unanchored tanks using the finite element method to solve an axisymmetric uplift problem of a base plate experiencing uniform uplift all around the circumference. Haroun and Badawi [2, 7] modeled the base plate in both its strip and circular configurations and investigated its nonlinear behavior under equivalent static uplifting forces using an approximate energy-based approach. The latter analysis differed from other available analyses in that the plate was modeled as a circular plate with an uplifted, crescent-shaped region rather than being modeled as a strip. A concurrent work was also performed by Haroun and Bains [3, 6] which sought the same characteristics of the base plate by a nonlinear finite element shell program developed by the authors. The program was extended to analyze the base plate and to assess the accuracy of the developed simplified energy-based models.

The "true" dynamic characteristics of the uplifting mechanism have not been evaluated yet. In this paper, the strip model is analyzed under both sinusoidal and transient dynamic uplifting forces. The analysis accounts for plasticity, contact as well as large-deformation nonlinearities. The nonlinear finite element code DYNAZ [5] is used in the analysis. Results were compared with those obtained from commercially available finite element software, such as COSMOS and MARC, and showed very close agreement in the response of the uplifted strip.

STRUCTURAL MODEL

In order to account for membrane effects induced by large uplifting displacement, the base plate is considered a strip modeled by a degenerated shell finite element [5]. The soil under the strip is modeled using Winkler type springs, Fig. (1). These springs are assumed to work only in compression. The stiffness of the foundation is superimposed to the shell stiffness only in contact condition.

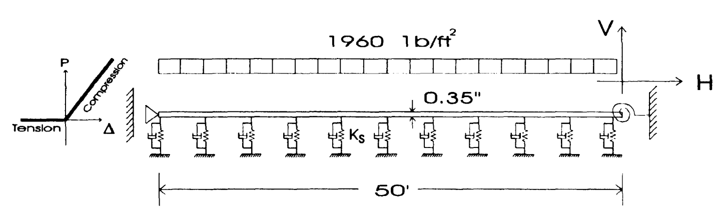
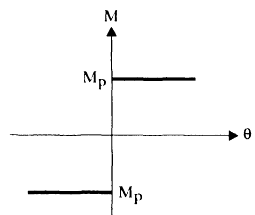
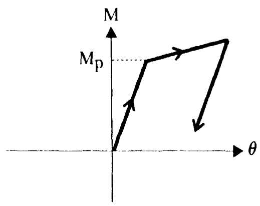


Figure 1: Structural Model of the Strip

Two types of geometric nonlinearities, namely large displacement and large rotation, may arise. When the structural element experiences large displacements as compared to its thickness, membrane stresses are developed due to midplane stretching. Large rotation is caused by a large change in the element slope which, in turn, causes the transformation matrix to change during the analysis. It also causes the relationship between the displacement field and the nodal rotation to be nonlinear.

Two approaches may be used to handle such nonlinearities: either by updating the geometry or by adding additional terms to the strain vector to account for large deformations. Geometric update is incrementally performed by superimposing the current time step incremental displacement vector to the previous time step geometry. This approach is general and suitable for both nonlinearities. In some cases, the deformed geometry does not show large change in slope but still indicates relatively large displacements. In such cases, it is desired to include the effect of large displacement into the strain displacement matrix and to use the original geometry to obtain faster convergence. This approach is adopted in the present analysis.

Table 1: Different Models for the Strip Boundary Condition

Model Label	Description	$M-\theta$ diagram
A	Fixed	$\theta=0$
B	Perfectly rigid - perfectly plastic	
C	Bilinear	

PSEUDO SEISMIC ANALYSIS

The uplifting model presented by Wozniak and Mitchel [9] assumed that the contact area of the bottom plate with the foundation is a segment of an unknown central angle. The relevant uplift region was considered an annular ring of a width small in comparison with the radius of the tank, and the tank wall flexibility was ignored. Based on these assumptions, the tank base plate was represented by a strip of a unit width in the circumfrential direction. The strip acts as a beam resting on a rigid foundation subjected to the liquid pressure and lifted up by a vertical force at the plate-shell connection. When two plastic hinges were formed, one of which is at the shell-plate connection, the beam was deemed to have failed. In a further refinement of this particular model, Haroun and Badawi [2, 7] considered in addition to plastic hinge formations, the contact with an elastic foundation and the large deformation nonlinearities of the model. The seismic effects on the base plate was modeled by considering the equilibrium of the tank wall under the hydrodynamic pressure and the two edge forces transmitted to the base plate, the horizontal force H and the vertical force V, which yield the following relations

$$H = C_1 R\gamma_l H_l - \frac{1}{2}\gamma_l H_l^2 \tag{1}$$

$$V = \frac{C_1\gamma_l H_l^2}{3.75} \tag{2}$$

where H_l is the liquid height, γ_l is the unit weight of the liquid, R is the tank radius and C_1 is the lateral earthquake force coefficient. Neglecting the hydrodynamic pressure on the tank bottom plate, the uniformly distributed pressure over the beam length is given by

$$p = \gamma_l H_l \tag{3}$$

In the present study, three different models of the boundary condition at the connection of the base plate with the tank wall are considered, as shown in Table (1). Model A, which assumes fixed conditions, is used to investigate the behavior of the strip assuming elastic material and to check the model validity through a comparison with other commercially available software. Model B is good for a static analysis but is not recommended for a time history analysis because of the sudden formation of the plastic hinge. Model C alleviates this effect, adds the effect of wall flexibility to the model and introduces the energy dissipation due to plastic hysteresis loops. The initial slope is related to the wall stiffness and the strain hardening of the shell is assumed to be 10%. The plastic moment is given by

$$M_p = \frac{\sigma_y t^2}{4} \tag{4}$$

where t is the base plate thickness.

Numerical Examples

The analysis is applied to the strip shown in Fig (1). It has a total length of 50 ft and a thickness of 0.35 inch. The water depth is assumed 25 ft, and accordingly, the distributed load on the beam is 1960 lb/ft^2. Different values of the modulus of subgrade reaction K_s were implemented and the results are compared to those reported in reference [2]. The analysis was performed under static loads and assumes model B for the end boundary condition. The results presented in Table (2), Fig. (2) and Fig. (3) confirm those presented in [2], as they predict an increase in the uplift displacement as the soil gets softer. They also show that, ignoring membrane stresses induced by large uplifting displacement, produces a very conservative estimation of the uplift displacement.

Table 2: Static Analysis: Maximum Uplift Displacement

Case	$K_s \times 10^2$ lb/ft^3			
	Rigid	1728	172.8	17.28
Small Deflection	4.2177	4.2475	4.3972	5.3924
Large Deflection	0.8384	0.8455	0.8977	1.374

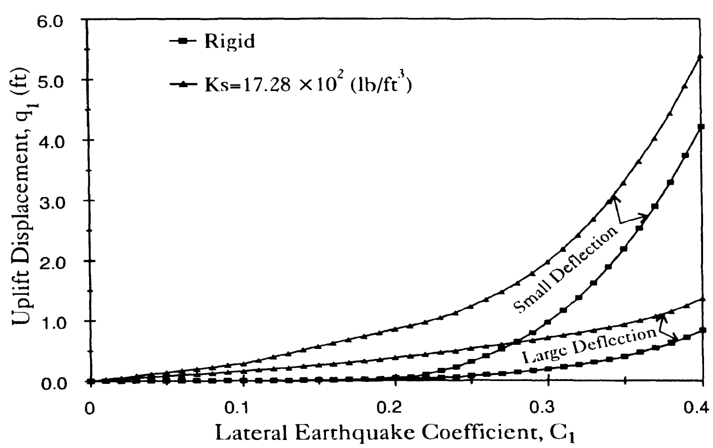


Figure 2: Static Analysis: Uplift Displacement

TRANSIENT ANALYSIS

The program DYNAZ is enhanced with a line search technique which makes it able to capture the time history of the uplifting mechanism and to account for material plasticity using various models of the plastic behavior. Two cases of uplifting forces are considered. The first case is due to sinusoidal seismic load given by

$$C_1 = 0.2(1 - \cos\frac{2\pi t}{T}) \tag{5}$$

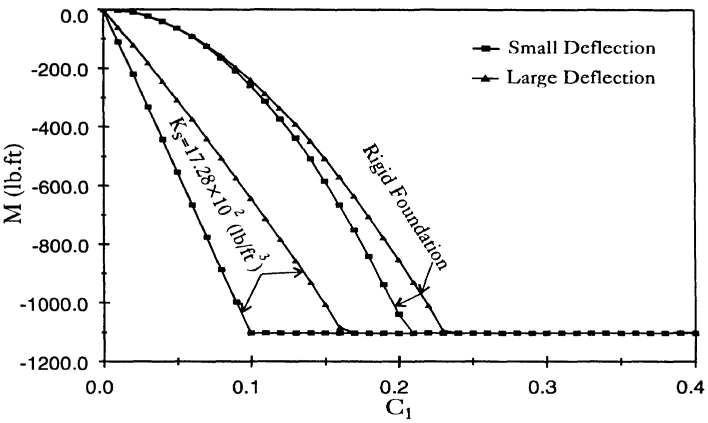


Figure 3: Static Analysis: Bending Moment at Plastic Hinge

where T is the period of the uplifting force. In order to assess the response of the model to different earthquake components, T was changed from 10 sec (extreme long-period sloshing effect) to 0.1 sec (short period impulsive effect). In addition, the effect of the fluid hydrodynamic pressure was taken into consideration by adding the mass of the fluid column above the strip to the strip's mass to yield

$$\rho_{eff} = \rho_s + \rho_f \frac{H_l}{t} = 0.0813 \text{ lb.sec}^2/\text{in}^4 \tag{6}$$

where ρ_s and ρ_f are the strip and the fluid mass densities, respectively. In order to assess the characteristics of the uplifting model, the results obtained from the program DYNAZ, for the case when $K_s = 17.28 \times 10^3$ lb/ft^3, are compared to the results obtained from COSMOS and MARC. Figure (4) shows the time history response for this case when the material is considered elastic, the period of the uplifting force is 1.0 sec, and geometric nonlinearity included. When the material plasticity was taken into consideration, both COSMOS and MARC showed convergence problems in the early stages of the time history analysis due to numerical sensitivity of the problem.

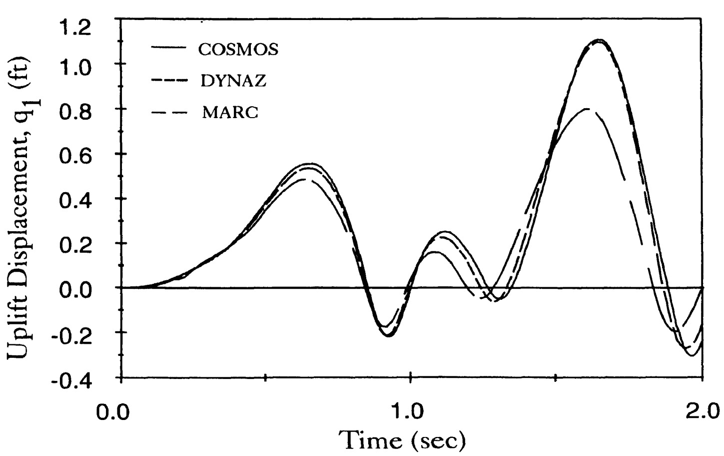


Figure 4: Dynamic Analysis: Uplift Displacement, Model A

Several other cases were implemented considering model C for the strip boundary condition. Figure (5) shows the time history response of the strip uplift displacement when supported on a foundation with stiffness of $K_s = 17.28 \times 10^3$ lb/ft^3 and subjected to a sinusoidal uplifting force of 1.0 sec period. Table (3) shows the maximum

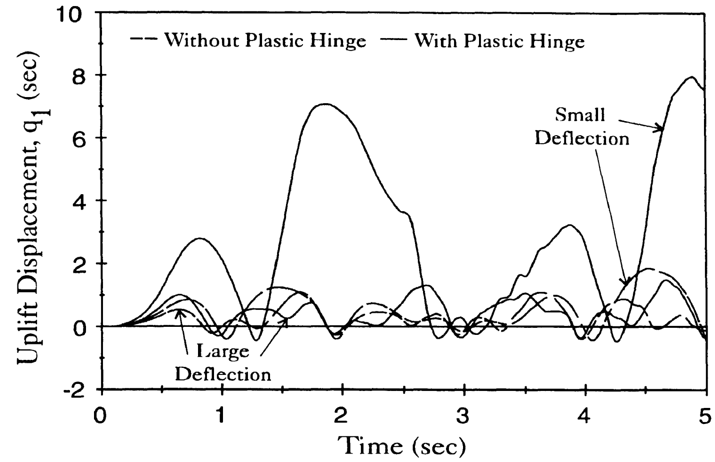


Figure 5: Sinusoidal Excitation: Uplift Displacement

uplift displacements for different values of the foundation stiffness. The results indicate that, as the foundation gets softer, the response considering plasticity gets closer to that considering elastic material. This is attributed to the postulation that the uplift displacement of a strip supported on soft foundation is caused mainly by strip penetration into the underlying soil than strip bending. It should be

Table 3: Maximum Uplift Displacement (ft), Sinusoidal Excitation ($T = 1.0$ sec)

Case		$K_s \times 10^2$ lb/ft^3		
		1728	172.8	17.28
Small Deflection	Without Plastic Hinge	1.4597	1.8588	3.6302
	With Plastic Hinge	6.2849	7.9793	4.7230
Large Deflection	Without Plastic Hinge	0.6252	1.0962	2.6919
	With Plastic Hinge	1.8345	1.5010	2.8239

noted that if large deflection is ignored in this model, it is appropriate not to consider beam plasticity because this would produce excessive uplift displacement.

In order to assess the effects of the sinusoidal components of an earthquake motion on the strip response, the model was subjected to sinusoidal excitations of different periods. Table (4) shows that the model does not respond to high frequency components as much as it has responded to low frequency excitations.

Table 4: Maximum Uplift Displacement (ft), $K_s = 17.28 \times 10^3$ lb/ft^3

Case	Excitation Period (sec)				
	10.0	5.0	1.0	0.5	0.1
Small Deflection	5.2231	7.9780	7.9793	4.6493	0.7052
Large Deflection	0.9366	1.1509	1.5010	1.4688	0.3097

The response to transient excitations was conducted by subjecting the strip to the 1940 El Centro earthquake record, which was magnified for a maximum lateral earthquake coefficient of 0.4. Figures (6) and (7) show the uplift displacement response assuming model C for the plastic hinge and considering small and large deflection assumptions, respectively.

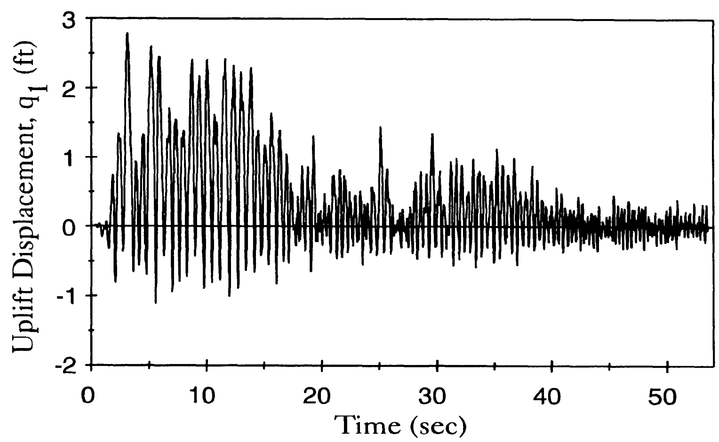


Figure 6: Earthquake Excitation: Uplift Displacement, Model C, Small Deflection

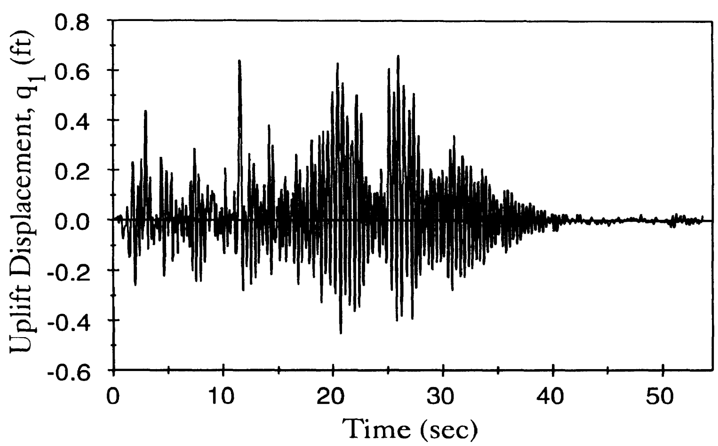


Figure 7: Earthquake Excitation: Uplift Displacement, Model C, Large Deflection

CONCLUSIONS

Numerical simulation of one-dimensional strip models undergoing uplifting showed that neglecting the membrane stresses induced by large displacement produced conservative estimates of the uplift displacement. It was also noted that the simultaneous exclusion of both the membrane stresses and the plastic hinges yielded reasonable values for the uplift displacement.

A "true" transient analysis has shown significant difference from a pseudo dynamic analysis. This is attributed to the liquid hydrodynamic pressure resulting from uplifting the water column above the strip.

The variables associated with the analysis render the problem to be highly nonlinear. In the dynamic analysis, this model suffers from numerical instability that caused both COSMOS and MARC to show convergence problems in the early stages of the time history analysis. The use of an efficient line search technique in the developed program overcame the convergence problem.

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