NONLINEAR ANALYSIS OF THIN-WALL CYLINDRICAL LIQUID STORAGE RESERVOIRS UNDER SEISMIC ACTION

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SUMMARY

This paper summarizes some of the results of a comprehensive theoretical investigation concerning the seismic response of ground supported liquid storage reservoirs. Dynamic properties of the fluid-shell interaction system with arbitrary boundary conditions were examined first. Evaluation of the results have shown that the variation of natural frequencies to the geometrical properties and filling ratio are highly dependent to the lateral and circumferential mode number. Finally, the accuracy of Code specified procedures for seismic design are examined and compared with the results obtained from the dynamic nonlinear finite element analysis.

INTRODUCTION

The circular cylindrical reservoirs, usually constructed in steel or prestrssed concrete have numerous structural applications, from simple reservoirs for storage of water to containments for highly inflammable and toxic petrochemical products. Investigations of structural damage due to earthquakes have shown various modes of failure of these structures. For cylindrical reservoirs made of steel the most common form of failure observed has been the buckling of shell walls due to the development of high compressive stresses or overturning of the structural system. Damage to prestressed concrete reservoirs is broad and ranges from partial cracking of concrete to total collapse of the shell structure. These observations concerning failure modes indicate that the seismic design procedures within most current design codes and standards which are generally given in terms of maximum design resultant lateral force and overturning moment may not be adequate.

Numerous studies have been conducted on the seismic response of cylindrical liquid storage reservoirs under seismic action. Initial studies [1], were concerned with the hydrodynamic effects of fluid in rigid reservoirs, whereas the latest investigations [2], [3], [4] explored the same effects of fluid-structure interaction taking into account the deformable response of shell structure. More recently, the research investigations have moved to more complex problems concerning the fluid-structure-foundation of anchored and unanchored reservoirs. Despite these recent developments of more refined mathematical models which increase the insight into the seismic response of cylindrical reservoirs, they have not yet found widespread applications in the field of seismic design of liquid-storage reservoirs. The main reasons are the complexities in evaluating the dynamic response of the reservoir-fluid-foundation system, and perhaps the insufficient experimental confirmations of theoretical concepts.

Among the various design methods and procedures currently available, three models for the seismic design of ground-supported flat bottom thin-walled cylindical liquid storage reservoirs are most dominant: design of rigid anchored reservoirs, design of flexible anchored reservoirs and design of flexible unanchored reservoirs. Most of national codes are based mainly on the simplest model of rigid anchored reservoirs whereas some simplified design provisions for the more compex models are specified in API[5] and AWWA[6] standards.

This paper summarizes the results of a comprenhensive numerical investigation of the seismic analysis of cylindrical liquid storage reservoirs. The main objective of this work was to examine the degree of validity and

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accuracy of various design methods adopted by National and several other design standards and compare these results with the results obtained from the nonlinear finite element time-history analysis.

NATURAL FREQUENCIES AND MODE SHAPES

The hydrodynamic pressures in a flexible liquid storage reservoir undergoing base accelerations can be separated into three components: impulsive pressure component associated with the flexible response, impulsive pressures associated with the rigid body motion of the reservoir and convective pressures due to the sloshing of the liquid inside reservoir. To determine the hydrodynamic forces in a flexible reservoir it is necessaray to obtain the dynamic properties (frequencies and mode shapes) of the fluid-shell interaction system. Free vibration characteristics were obtained using finite element method, and the relevant elements we used in our analysis were one-dimensional three noded axisymetric shell element, and general four noded shell element.

The finite element method can be applied on fluid-shell interaction problems in three ways: added mass approach, Lagrangian and Eulerian approach. The essential of the added mass method lies in the fact that the mass which will create the hydrodynamic pressure is added to a shell structure mass at the interface of the fluid-shell structure. The neglection of fluid on the overall rigidity and ignoration of the fluid oscillations are the major shortcomings of this method. In Lagrangian method, the behaviour of the fluid and the structure are expressed by the terms of the displacement unknowns at the finite element nodes. As a consequence, the equilibrium and compatibility conditions are satisfied at the nodes of the fluid-structure interface. The most important fact is that the fluid element is genarally considered to be an elastic solid element with a negligible shear modulus and whose volumetric modulus is equal to the bulk modulus of the fluid. This method complicates the dynamic analysis, since zero energy modes are generated by assuming that shear modulus is equal to zero. There are different ways in eliminating these zero energy modes. One approach is by assuming that the shear modulus of the fluid is numerically very small, or more often this is achieved by assuming that the fluid is irrotational and inviscid. In Eulerian method, the behaviour of the fluid is formulated in terms of pressure potential. Mathematical model of the fluid can be expressed by analytical functions for some specific geometric situtions or by finite elements with the nodal pressures as the unknowns. An incompatibility occurs as an consequence of the upper assumptions.

The natural frequencies and mode shapes were obtained using the following generalized eigenvalue problem:

$$K\Phi = \lambda M\Phi \tag{1}$$

where K and M are, respectively, the stiffness and mass matrix of the finite element fluid-structure assemblage. The eigenvalues λ_i and eigenvectors Φ_i are the free vibration frequencies and corresponding mode shape vectors, respectively. For the Eulerian formulation we used the one dimensional two-noded axisymetric shell element and two-dimensional fluid elements with the following assumptions:

1. nonviscous, incompressible and homogeneus fluid ,
2. small displacements, and velocities ,
3. irrotational flow field.

The cylindrical shell was modeled as a thin shell, for which the Kirchhoff-Love assumptions were adopted. The fluid region was devided into a number of identical fluid elements with four nodes. The fluid boundary conditions at the bottom of the shell have zero displacement and rotation. The number of fluidelements was proportionally increased according to the amount of liquid. The nodes connected entirely by fluid elements were free to move arbitrarily in 3-D space with the exception of those which were restricted to motion at the center line. The radial displacement of the nodes of fluid elements for r=0 was constrained, and the bottom surface was considered fixed in axial direction. The radial velocity of the fluid nodes along the interface are equal to the shell velocities.

For the added mass and Lagrangian method the general four noded shell element was used. In Lagrangian approach the three-dimensional fluid-solid element with eight nodes was used assuming that the fluid is elastic, irrotational and inviscid in obtaining the governing equations. The mass matrix is given as

$$M_f = \rho \int_V N^T N dV = \sum_i \sum_j \sum_k \eta_i \eta_j \eta_k N_{ijk}^T N_{ijk} \det J_{ijk} \qquad (2)$$

where J is the Jacobian matrix, N_{ijk} are the interpolation functions and $\eta_{i,}\eta_j, \eta_k$ are the weighting functions. The stiffness matrix of the fluid element is given as

$$K_f = \int_V B^T CBdV = \sum_i \sum_j \sum_k \eta_i \eta_j \eta_k B_{ijk}^T CB_{ijk} \det J_{ijk} \qquad (3)$$

where B is strain-displacement matrix and C is the constraint matrix. The stiffness matrix for the shell element is given as follows:

$$K_f = \rho g \int_A N_s{}^T N_s dA = \sum_i \sum_j \eta_i \eta_j \rho g N_{sij}{}^T N_{sij} \det J_{ij} \qquad (4)$$

where N_s are the interpolation functions for shell elements.

To compare the effects of the fluid-shell structure interaction the parametric study was performed. The dynamic properties of the system were investigated as a function of four parameters: $H_l / R, t / R, \rho_l / \rho_c$, and ν (Figure 1).

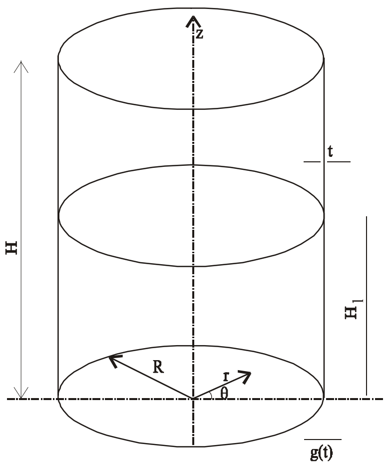


Figure 1. Reservoir geometry and coordinate system

The reservoir under consideration is ground-supported, vertical circular cylindrical thin-walled container of radius R, height H, and thickness t, filled with liquid of mass density ρ_l to hight H_l and subjected to horizontal ground acceleration g(t). A cylindrical coordinate system (r, ϑ, z) is used with the origin located at the center of the base, as shown in Figure 1. The radial displacement of a point on cylindrical shell middle surface is denoted as w(z). Several sizes of reservoirs (short to long) were investigated whose height to radius ratio falls within range 0.2 to 4.0. The representive cylindrical shell was of the radious R=7.0 m and the thickness to radius ratio of 0.001. The mass density of the steel cylindrical shell was $\rho_c = 77kN / m^2$, the Young's modulus was E=200 GPa and the Poissons ratio was taken as ν=0.3.

The first three natural frequencies for the class of short to tall steel cylindrical reservoirs are presented in Figures 2-6. Variation in circumferential mode shapes due to contained water are shown in Figure . The influence of the shell thickness on natural frequencies of the reservoir are presented in Figures 7-10. It can be concluded that the natural frequencies of the liquid filled reservoirs are not independent of their wall thickness and for the lower circumferential wave number are smaller than those of higher for the identical axial number.

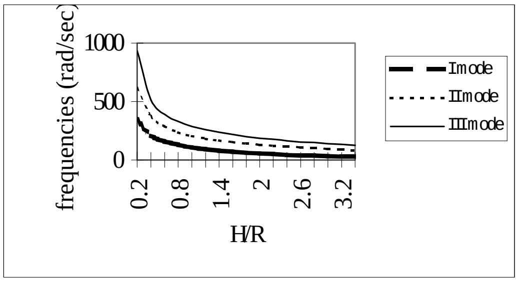


Figure 2. Completely filled reservoir

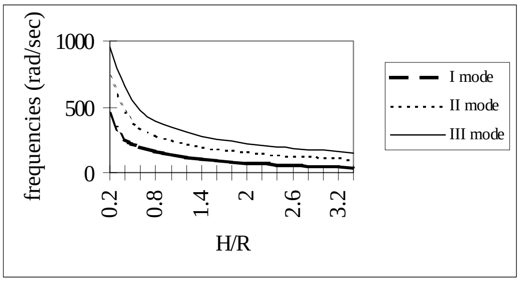


Figure 3. 75% filled reservoir

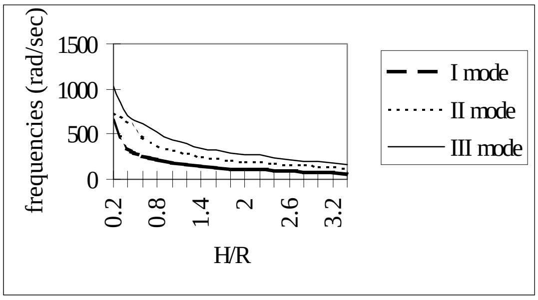


Figure 4. 50% filled reservoir

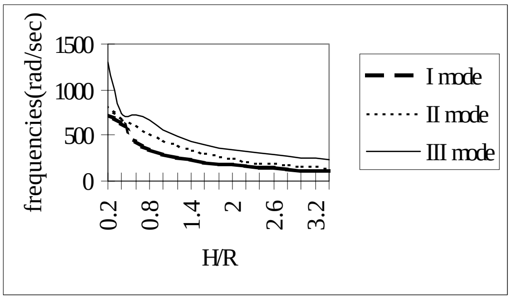


Figure 5. 25% filled reservoir

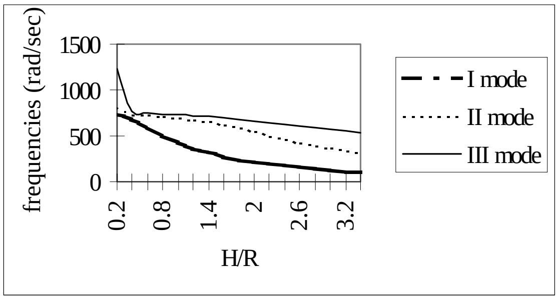


Figure 6. Empty reservoir

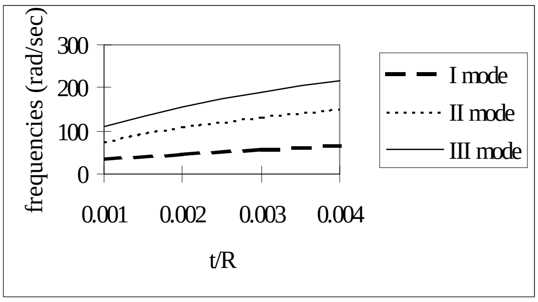


Figure 7. Completely filled reservoir

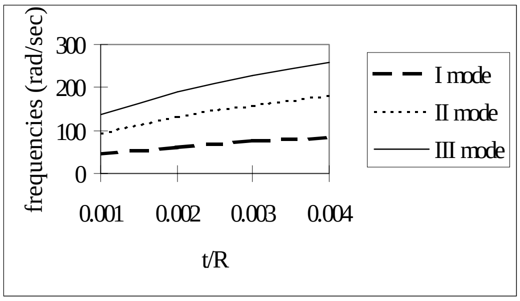


Figure 8. 75% filled reservoir

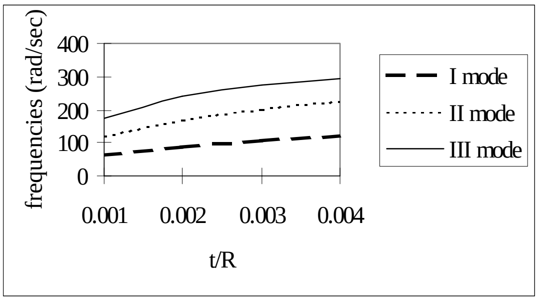


Figure 9. 50% filled reservoir

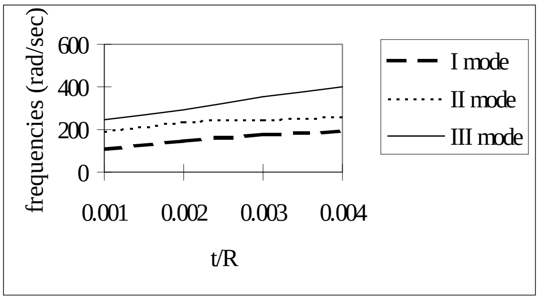


Figure 10. 25% filled reservoir

NONLINEAR ANALYSIS

In order to ensure the structural behaviour of cylindrical liquid storage reservoirs subjected to seismic action, either in strength or in its ability to sustain certain structural deformations without significant loss of load carrying capacity, nonlinear analysis is recomended. Particularly important for the design purpose is the dynamic buckling capacity of the cylindrical shell, which is highly influenced by the presence of the geometric imperfections of the shell, internal fluid pressure and the degree of concentration in the axial, circumferential and bending stresses from the overturning moment. It must also be noted that the boundary conditions concerning the reservoir foundation are also very important parameters for the appearance of buckling in cylindrical shells.

Finite element incremental nonlinear formulation, involving load-deformation path is used for finding the corresponding collapse load for the fluid-shell system. General isoparametric four node element is used for the approximation of the cylindrical shell, [9]. The element behaviour is based on the following assumptions: straight lines defined, which are normal to the midsurface of the shell, remain straight during the shell deformation and no transverse normal stress is developed in that direction. Using the total Lagrangian formulation and the dynamic analysis the following equation are solved:

$$M \; {}^{t+\Delta t}\ddot{q} + \left({}^{t}_{o}K_L + {}^{t}_{o}K_{NL}\right)\ddot{q} = -M \; {}^{t+\Delta t}\ddot{x}_g - {}^{t}_{o}F \qquad (5)$$

where M is time independent mass matrix, ${}^{t}_{o}K_L$ is linear strain incremental stiffness matrix, ${}^{t}_{o}K_{NL}$ is nonlinear strain incremental stiffness matrix, q is the incremental vector of nodal point displacements and ${}^{t+\Delta t}\ddot{q}$ is the incremental vector of nodal accelerations and ${}^{t+\Delta t}\ddot{x}_g$ is the incremental ground acceleration vector. The damping effects were assumed to be neglegible.

The behaviour of the steel cylindrical shell was described by the elastoplastic material model, assuming that the strain and stress increment are given by the following relations:

$$de_{ij} = d\varepsilon_{ij}^{EL} + d\varepsilon_{ij}^{PL}$$

$$d\sigma_{ij} = C_{ijrs}^{E}\left(d\varepsilon_{rs} - d\varepsilon_{rs}^{PL}\right),$$

where C_{ijrs}^{E} is the elastic constitutive matrix and $d\varepsilon_{ij}, d\varepsilon_{ij}^{EL}, d\varepsilon_{ij}^{PL}$ are the total, elastic and plastic strain increment. The plastic strains were calculated adopting the von Mises criterion with isotropic hardening. The model was first subjected to a constant acceleration of 1g, and then to time scalled acceleration histories similar to 1979 Montenegro earthquake (Petrovac and Ulcinj accelerograms). It is assumed that the ground motion acts along the line θ=0. Besides the influence of earthquake ground motions we examined the influence of the bottom and top boundary conditions. We assumed only the rigid type of foundation condition. Typical time histories of the base accelerations and the accelerations above 0.5H above the base are shown in Figures 12-13.Very high axial membrane sresses developed only in the narow band along the reservoir base and produced the formation of plastic zones, Figures 14-15. The peak acceleration values ranged from 0.125g to 0.5g for both acceleration histories. Figures 16-17 represent different methods of seismic load evaluations in terms of lateral force and overturning moment as a function of the ratio H/R.

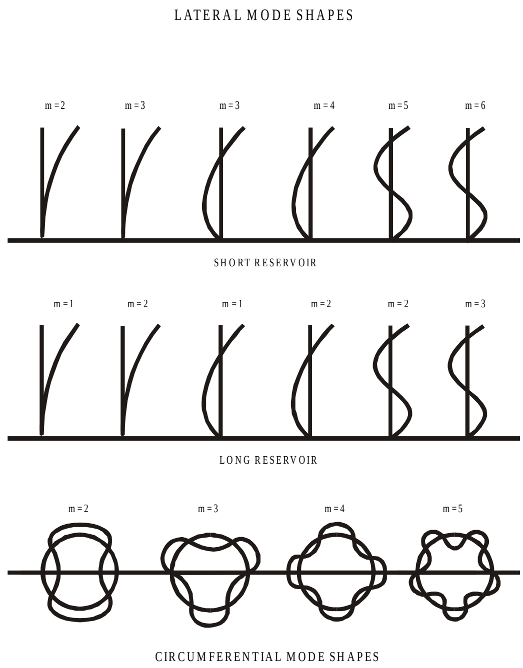


Figure 11.

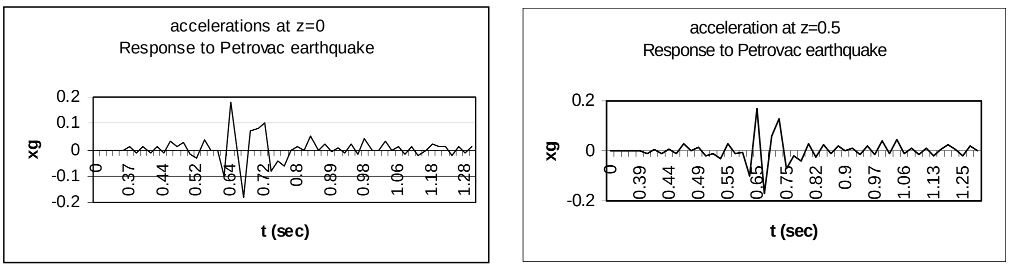


Figure 12.

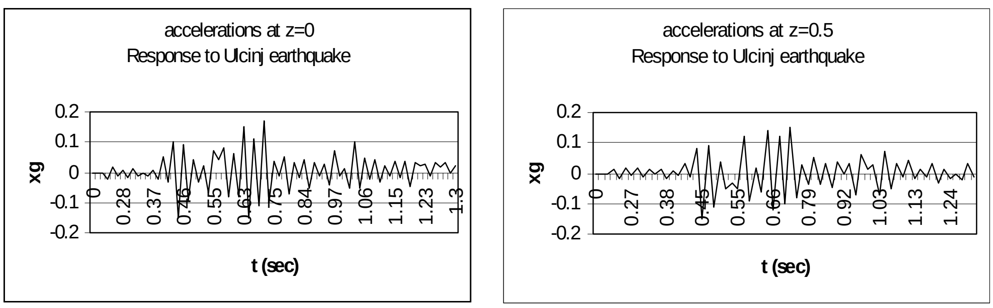


Figure 13.

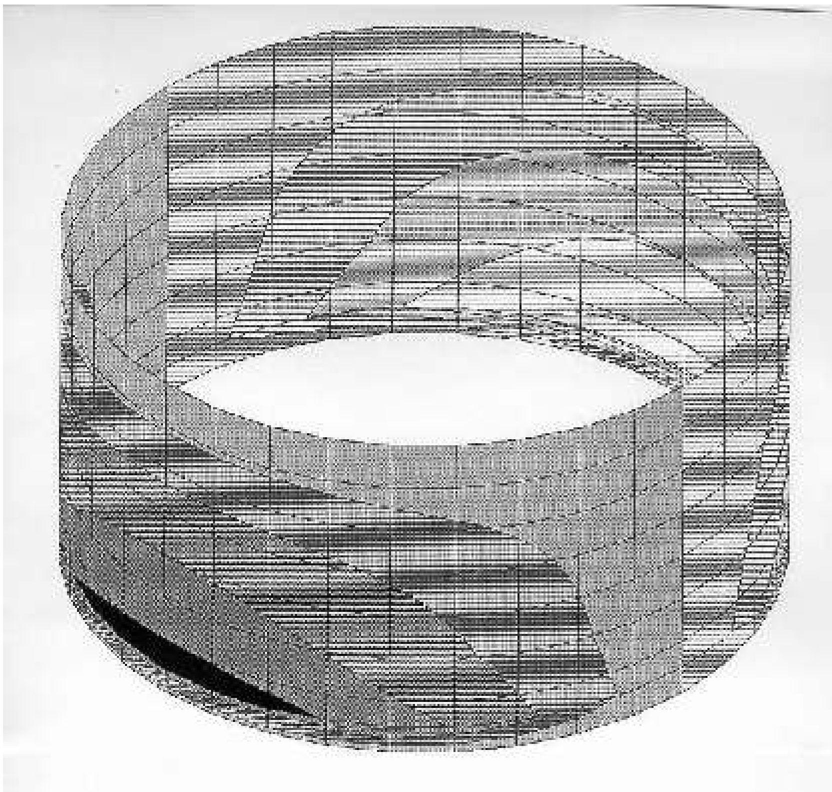


Figure 14.

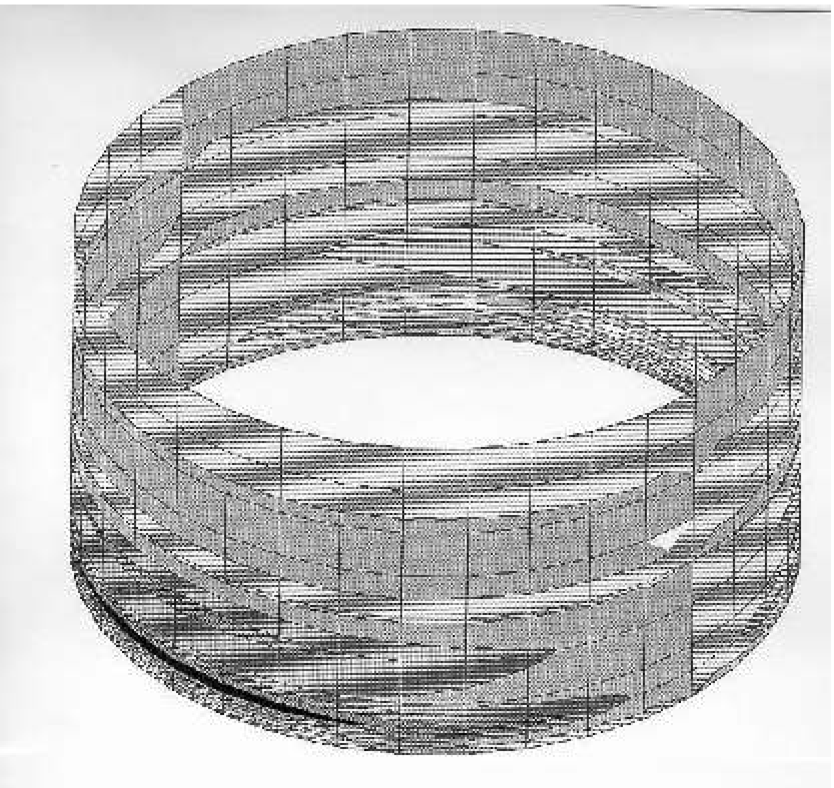
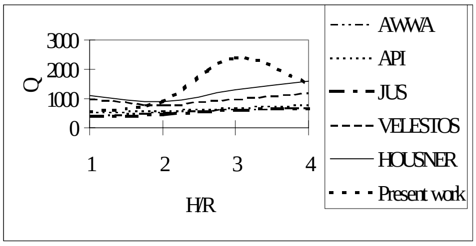


Figure 15.



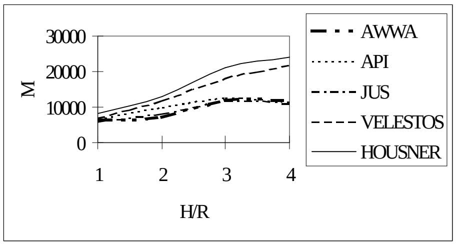


Figure 16. Lateral force

Figure 17. Overturning moment

CONCLUSION

The present analysis has demonstrated the relative importance of a number of parameters on the seismic response of liquid storage reservirs. Both in anchored and unanchored reservoirs the circumferential wave forms were significant and their influence on the overall dynamic behaviour must not be ignored.

The effects of the fluid on the dynamic properties of the reservoirs have shown that the main mode shapes of vibration are mostly unaffected by the presence of liquid.

The results of the nonlinear dynamic analysis of anchored reservoirs on rigid foundation have shown that the plastic strains due to very high axial membrane stresses developed only in a narrow band along the reservoir base. Based upon this study it might be concluded that the reservoir design procedures should incorporate more realistic predictions of the real physical problem.

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