

SEISMIC RESPONSE OF CYLINDRICAL TANKS FOR OIL

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ABSTRACT :

Seismic response of storage tanks storage anchored and unanchorage for oil, placed in high seismic risk zones of Mexico are studied. The growing need to satisfy the national oil industry has required the evaluation and retrofit of the existing structures, and new reservoirs for distribution of oil products.

Therefore, this research has focused on the behavior, under seismic conditions, of steel storage tanks of large capacity, of 150 and 200 thousands barrels. From the revision, analysis and design criteria concerned with thin walls structures, it has been proposed and applied in this study a procedure based on a numeric modeling where the mechanical characteristic of the materials has been considered. The FEM has been used to carry out such analysis.

Numeric analysis has been obtained for two conditions: empty tanks vibration and full tanks where fluid-structure interaction is employed to take into account the flexible walls; real seismic record of Subduction originated in the Mexican Pacific Ocean has been used by a time history analysis. Finally, the numerical and theoretical results obtained of the real structures are compared and it is considered to be used to determine new design of steel storage tanks, as well in the regulations environment in our country.

1. INTRODUCTION

The damages reported due to seismic actions in the past in unanchored aboveground storage tanks have been observed principally at the base in the fond and the walls. Then, these damages could be producing the structural loss of the tanks. It can be classified in four general categories:

- Buckling at the bottom plates of the wall tanks, where it is attending the maximal axial compression stresses due to overturning moment. In this zone the buckling of the plates appear with long deformations as elephant foot.
- Damage of the roof near to the end wall hoop and the internal columns is due to sloshing effect of the liquid.
- Damage in pipes and others accessories linking to the wall tanks during the seismic movement of the soil.
- Damage due to fails of the foundation or intense seismic loads.

As is known, the developments and early studies about the dynamic and seismic behavior in tanks have considered the rigid wall hypothesis. This hypothesis has been considered in the statements of Housner, however, experimental works and subsequent researchers have shown that the flexibility of the walls of the tanks has an important influence on response due to seismic excitations. That is seen represented by the multi - modal shapes and by the dynamic stresses which can be greater to those obtained from rigid tanks. Then, the objective of this work is to show through a numerical analysis of fluid- structure interaction, the structural behavior of this type tanks with flexible walls, that represent to the real structures selected for this investigation.

Consequently, it is studied the structural behavior of tanks through a seismic and dynamic analysis of the fluid - structure system. In the one which is identified the effect of the sloshing and its interaction with the walls (shell) of the tank, as well as its typical modal configurations of the axisymmetric structures of thin wall, whose behavior defers of those common and typical outlining.

KEYWORDS: Tank, flexible wall, subduction, cylindrical shell, elastic.

2 ANALYSIS CONSIDERATIONS

The structures selected are typical structures employed in oil industry; therefore they have been used real values of the geometric and mechanical properties that constitute it. The investigation is developed in the following way, the structure is modeling through a fine mesh composed by elements shells and fluid, and it is analyzed applying the method of the finite element (FEM), considering different thickness t of wall that contribute to modify the dynamic behavior. It is studied with detail the flexibility of the shell walls and the sloshing effect generated by the dynamic action in the fluid on the walls.

2.1. General considerations

The walls of the cylindrical shells are considered as thin curve surfaces with an elastic behavior. The vessels are submitted to vibrations due seismic excitations. The seismic behavior of these structures is studied by fluid – structure interaction system.

2.2. Numerical modeling of analysis

The development of this research was carried out by the construction of numerical modeling of the fluid – structure system of FEM analysis, with help of the computer program ANSYS 8.1. These numerical models take into account the geometric and mechanic characteristics of the materials (steel and fluid), as soon as the large deformations.

Then, the objective of this work is to show through a numerical analysis of fluid- structure interaction, the structural behavior of this type tanks with flexible walls, that represent to the real structures selected for this investigation. Consequently, it is studied the structural behavior of tanks through a seismic and dynamic analysis of the fluid - structure system, and it is identified the sloshing effects and its interaction on the system, also the behavior on the walls at the bottom of the anchorage tanks.

2.3. Shell walls and base of tank

To study of the seismic behavior of the shell walls and the base of the tanks, the shell element used is an element well suited to take into account the membrane and bending effects, allowing to apply normal pressures on internal surface, normal loads in its plane, as soon as efforts on theirs nodes. This element includes within the law of behavior of the material the hardening capacity and the non-linearity such as large deformation.

2.4. Fluid element

Fluid of the vessel was modeled by fluid 80 with eight nodes having three degrees of freedom at each node; this element is particularly well suited for calculating hydrostatic pressures, fluid-solid interaction and accelerations effects, such as sloshing problem.

2.5. Boundary conditions at the base of the tanks

- base of the tanks is modeled considering contact elements 52, to represent unanchored tanks
- rigid base is considered by simple supported (anchorage tanks) on the soil.

2.6. Structures studied

In order to known the seismic behavior of the cylindrical storage tanks, it were studied two metallic cylindrical tanks, constituted by rings welded mutually of the shells, with variable thickness t along of the height H , see figures 1 and 2, and tables 1 and 2.

3. Numerical Results

3.1. Empty condition

In this part, it carried out the dynamic analysis considering the empty condition of the tanks; one of the goals was to calibrate the numerical analysis of FEM vs the classical theory of vibration of thin cylindrical shells. Dynamic characteristic such as natural periods, frequencies and modal shapes of the tanks were calculated by a theoretical

vibration approach of the cylindrical shell structures, for different boundary conditions (built – free and built – simply supported), besides the numerical model of FEM.



Figure 1. Circular cylindrical steel storage tanks of 200 thousands barrels

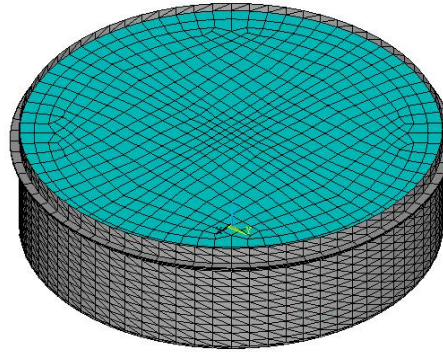


Figure 2. Numerical model of cylindrical steel storage tank of 200 thousands barrels

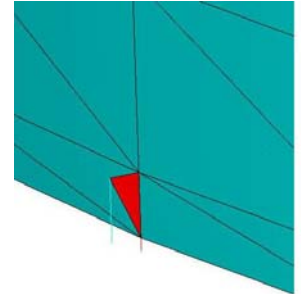


Table 1. Mechanical characteristics of materials of circular cylindrical steel storage tanks

E_s	206,000	Young modulus of steel Mpa
ν	0.3	Poisson's ratio of material
γ_s	76,910.4	Weight per unit volume of the steel N/m ³
ρ_s	7840	Mass per unit volume of the steel (N/m ³)/g
γ_l	9,810	Weight per unit volume of the liquid N/m ³
ρ_l	1,000	Mass per unit volume of the liquid (N/m ³)/g
γ	2,206	Bulk of compressibility of the fluid Mpa

Table 2. Geometrical characteristics of the circular cylindrical steel storage tanks

Geometrical characteristics	Tank (thousands barrels)		Stiffening ring t (mm)
	150	200	
H (m)	14.630	15.79	1.2
h (m)	13.563	14.63	
R (m)	22.847	27.42	
t1 (mm)	25	32.16	12.7
t2 (mm)	22	27.60	
t3 (mm)	19	22.53	
t4 (mm)	16	15.85	
t5 (mm)	13	10.78	
t6 (mm)	10	8.22	
t7 (mm)		8.22	

3.2 Solution derived of the classical theory

The expression to determine the dynamic characteristics of the cylindrical storage tanks is the cubic equation of the frequency in Δ , non-dimensional factor, (Warburton, 1976, and Sánchez et al, 2001).

3.3 Dynamic Analysis

Thin cylindrical shells may vibrate in a variety of ways depending on the particular stress involved. The present work is focused to study of the vibration of the shell.

3.4 Analytic and numerical results comparison

Figure 3 shows the natural periods of vibration of the empty tanks for all boundary conditions obtained by theoretical and numerical approaches; this comparison is good agreed between two them.

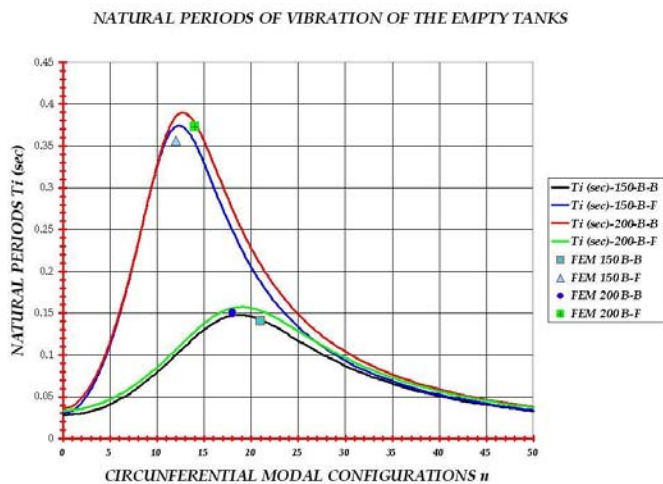


Figure 3. Natural periods of vibration

Natural periods of vibration T_i (sec) of the empty tanks					
* Built - Built, ** Built - Free					
Approach	n	150 B-B*	150 B-F**	200 B-B	200 B-F
Theoretical FEM	19 21	0.1408 0.14062			
Theoretical FEM	12 12		0.3730 0.3564		
Analytical FEM	19 18			0.1576 0.1504	
Analytical FEM	13 14				0.3812 0.3731

4. Hydrostatic analysis

4.1. Cylindrical tanks with uniform wall thickness

The numerical hydrostatic analysis of the tanks was compared with the analytical solution when the vessels are submitted to the action of a liquid pressure. For a vertical, cylindrical shell completely full of liquid, with uniform thickness t , radius R , heights h , and weight per unit volume of the liquid γ_l the radial displacement $w(x)$ given by Timoshenko.

$$w(x) = -\frac{\gamma_l h}{4D\beta^4} \left[1 - \frac{x}{h} - e^{-\beta x} \cos \beta x - e^{-\beta x} \left(1 - \frac{1}{\beta h} \right) \sin \beta x \right] \quad (1)$$

$$\text{Where: } \beta^4 = \left[\frac{Et}{4DR^2} \right] = \left[\frac{3(1-\nu^2)}{R^2 t^2} \right] \text{ and } D = \frac{Et^3}{12(1-\nu^2)} \text{ (flexural rigidity of the shell)}$$

4.2 Analytical and numerical results comparison of the hydrostatic radial displacement $w(x)$

Figures 4.a to 4.j show numerical vs analytical results of the radial displacement $w(x)$ due to hydrostatic pressure of the two steel storage tanks studied (150 and 200 thousand barrels respectively). It can see that both approaches are good agreed between them, the maximum values of displacement at the base of tanks of about 12 and 15mm and occurs about 2.0m of the height H respectively.

5 Seismic analysis

The seismic analysis were carried out employing a seismic record at Mexico City, obtained of the earthquake originated at the Subduction zone of Mexican Pacific Coast, in 1985 (see figure 5); the longitudinal component of this register was applied at the base of the structures, in the horizontal direction x.

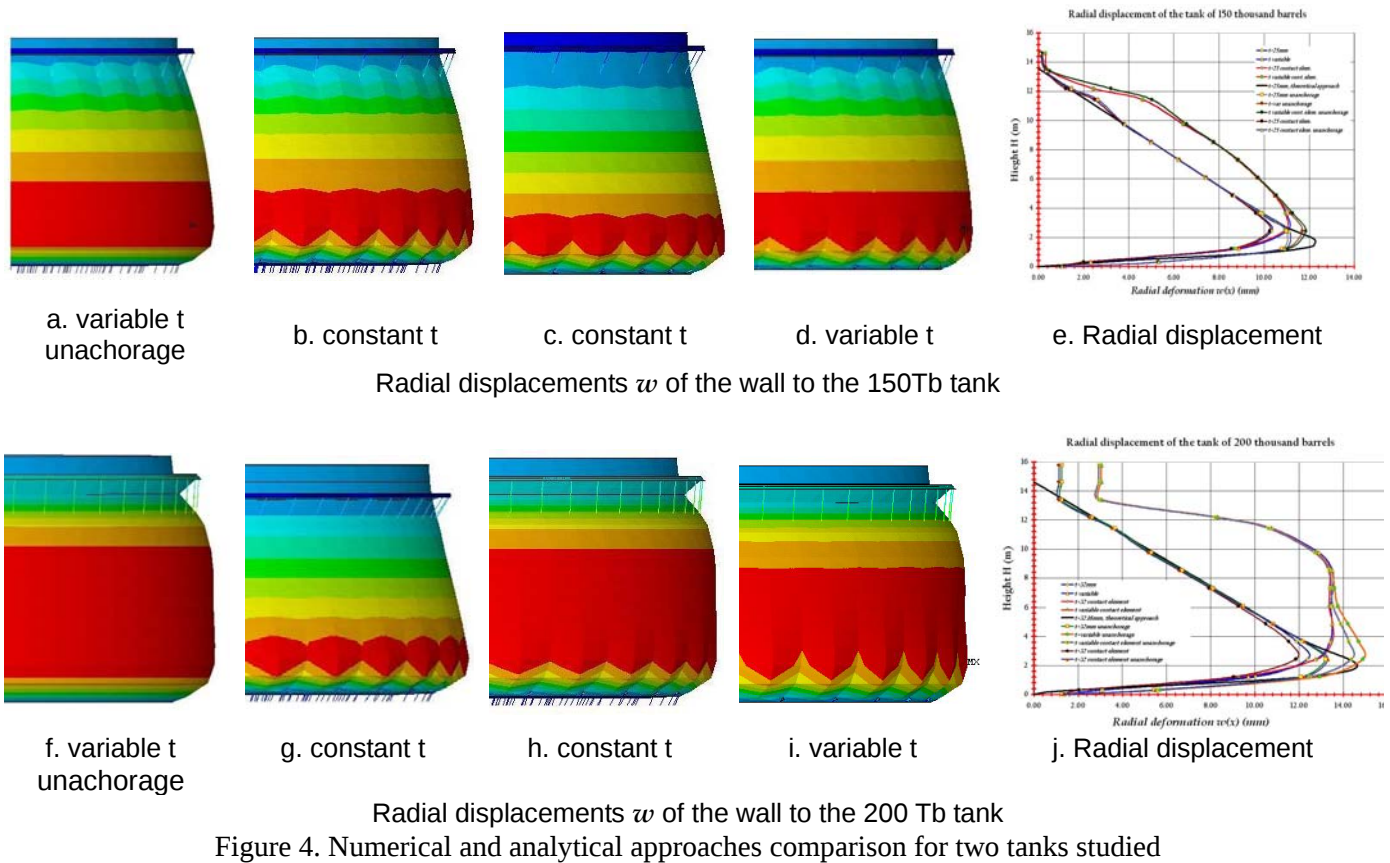


Figure 4. Numerical and analytical approaches comparison for two tanks studied

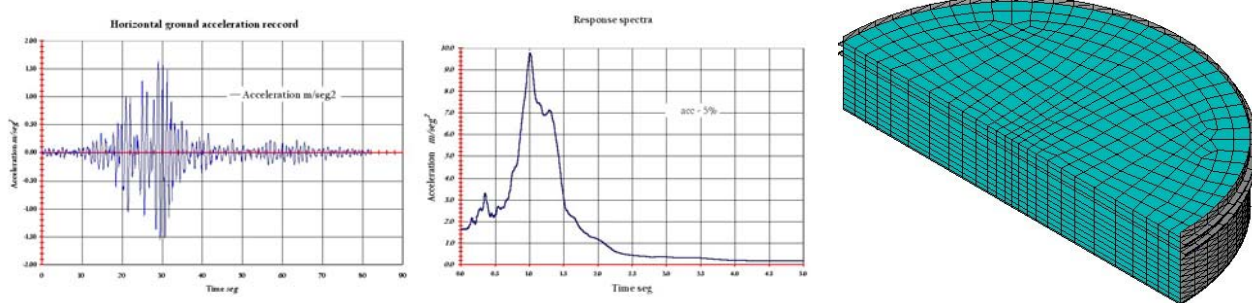


Figure 5. Input horizontal ground acceleration record and response spectra, Mexico City.

6. Time history analysis and results

6.1. Response history of full tanks

It was obtaining the history analysis of the two full cylindrical tanks using the seismic record, with the goals to know the seismic response of the structures such as: the flexible walls, hydrodynamic behavior of the liquid and the level of the stresses.

6.2. History of vertical displacements of the two models of the tank at free surface of the liquid

The figures 6.a and b show vertical displacement history results at free surface of the liquid, for the two models of the tanks, 150 and 200 thousand barrels respectively. Maximum values of vertical displacement are about 1000mm and 900mm for two tanks.

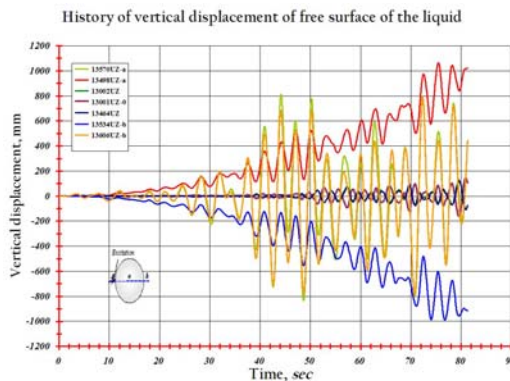


Figure 6.a. Tanks of 150 thousand barrels

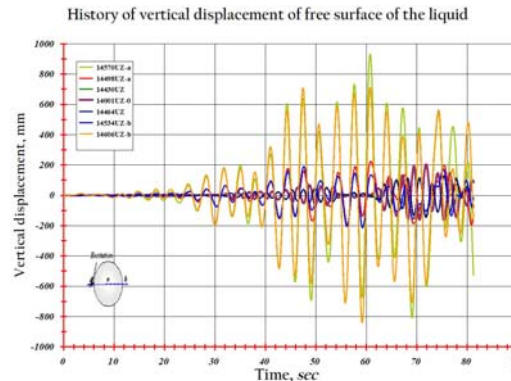


Figure 6.b. Tanks of 200 thousand barrels

6.3. History of horizontal displacements of the two models of the tank at two opposite walls a, b.

In figures 7.a and b, are showing horizontal displacement history results at two opposite walls a, b for the two models of the tank submitted to seismic excitation. The maximum values of horizontal displacement are about of 800 and 900mm for two tanks 150 and 200 thousand barrel respectively.

6.4 History of the Von Mises stresses, at the anchorage and bottom wall, for the two models of the tanks at point a

Figure 8.a and b, can see the level of the Von Mises stresses during the time, the maximal values are about 35000 and 25000 N/mm², for the two tanks repetitively.

6.5 Configurations of seismic response of the 150 and 200 thousand barrels tanks

Figure 9.a and b, show the seismic response configuration for two tanks.

7. Conclusions

The purpose of this work was evaluated the structural behavior and response of the cylindrical steel anchored an anchorage storage tanks with flexible thin wall submitted to the seismic action.

- The numerical results obtained of the empty tanks with those estimated analytically are compared and they observe a good correlation in the majority of the cases between both approaches, this represents a tool for the revision and new designs and to improve the present criteria of design.

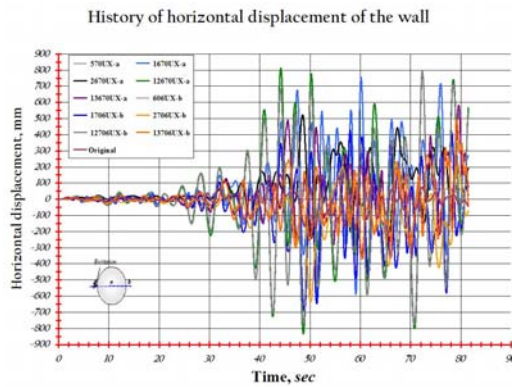


Figure 7.a. Tanks of 150 thousand barrels

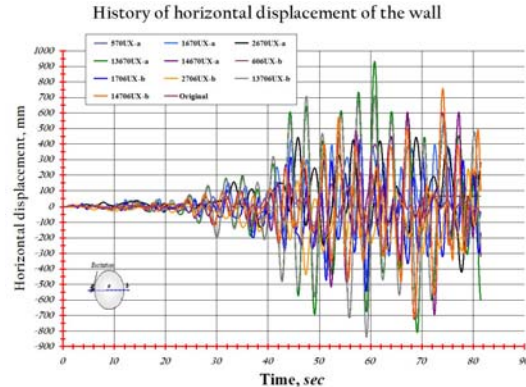


Figure 7.b. Tanks of 200 thousand barrels

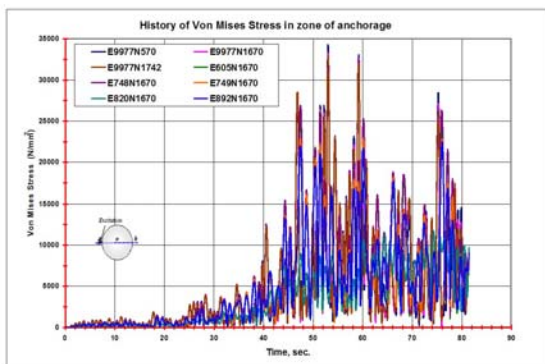


Figure 8.a. Tanks of 150 thousand barrels

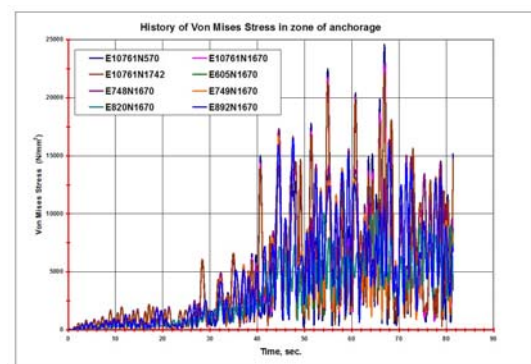


Figure 8.b. Tanks of 200 thousand barrels

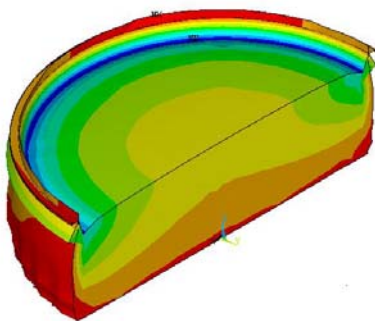


Figure 9.a. Tanks of 150 thousand barrels

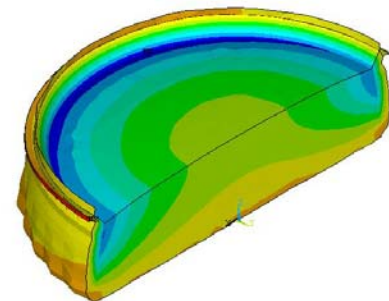


Figure 9.b. Tanks of 200 thousand barrels

- From the obtained results of the fluid-structure interaction models with the selected seismic record for different boundary conditions at bottom of the tank; is observed that in all cases when the structures are horizontally excited, occurs a mode one at free surface of the liquid associated to sloshing effect, simultaneously with a maximal radial deformation on the shell walls in mode one (*elephant foot*), in the vicinity of to the base of the tank. It is exposed also modal configuration on the all surface of the shells, deformation on the stiffed rings and uplift of the base due to overturning seismic moment.
- The general behavior observed in all tanks studied demonstrate that when the diameter D is minor, the overturning moment increase and produce a major uplift effect at the base of the anchorage tank and sloshing effect of the liquid at the free surface exceed the height of the tank. As consequence of this behavior, it is increased the axial stresses in tension and compression that could cause damage on the thin wall of the tanks.
- Finally, when the anchorage tank is subjected to horizontal ground excitation, the inertia effects of the fluid-structure interaction cause a change in the magnitude and distribution of hydrodynamic pressure exerted

by the liquid on the wall. This pressure distribution depends of the characteristics of the input excitation, the geometrical characteristics (thin walls) and foundations.

Future researches are necessary to continue the study of the seismic behavior of the storage tanks of large capacity placed in regions of strong ground motions, taking into account the flexibility of the foundation to evaluate the possible plastic rotation at the base and to insure stability of the tank shell.

8. Acknowledgments

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9. REFERENCES

- API STANDAR 650, 1998, Welded Steel Tanks for Oil Storage, Tenth Edition, API, Washington, D.C., USA.
- API STANDAR 653, 1995, Tank Inspection, Repair, Alteration, And Reconstruction, Second Edition, API, Environmental Mission and Guiding Environmental Principles, Washington, D.C., USA.
- Arnold, R.N. and G.B. Warburton, 1949, Flexural vibrations of the walls of thin cylindrical shells having freely supported ends, Department of Engineering, University of Edinburgh, Proc. Roy. Soc. London, Reprinted from, Ser. A, 238-256.
- CFE, 1993, Manual de Diseño de Obras Civiles - Diseño por Sismo, MDOC-DS, Comisión Federal de Electricidad, IIE, México D.F.
- Haroum, M.A., and Housner, W.G., 1981, Seismic design of liquid storage tanks, ASCE, Proceedings J. of Technical Councils, Vol. 107, No TC1, 191-345
- Haroum, M.A., 1983, Vibration studies and tests of liquid storage tanks, Earthquake Engineering and Structural Dynamics, Vol. II, 179-206
- Sanchez-Sanchez, H. y Vargas, O. S., 1999, Estudio del comportamiento sísmico de tanques de almacenamiento mediante diferentes métodos propuestos, Proceedings of the XII Congreso Nacional de Ingeniería Sísmica, Morelia, Mich.
- Sanchez-Sanchez, H. y Vargas, O. S, 2000, Análisis sísmico de tanques cilíndricos de almacenamiento, Proceedings of the XII Congreso Nacional de Ingeniería Estructural, León Gto.
- Sanchez-Sanchez, H. y Cortés S. C., 2000, Influencia de la rigidez de fondo en el comportamiento de estructuras cilíndricas de pared delgada, Proceedings of the XII Congreso Nacional de Ingeniería Estructural, León Gto.
- Sanchez-Sanchez, H., Urrutia, J. L., Minchaca, M, E. y Avelino, R. J., 2001, Comportamiento y Estabilidad en Estructuras Cilíndricas de Pared Delgada, Reporte del Proyecto de Investigación CGPI, Núm. 2000668, IPN, México.
- Sánchez Sánchez H., Vargas Ortega S., and Minchaca Montelongo E., 2001, Vibraciones Axisimétricas de Estructuras Cilíndricas de Pared Delgada, Proceedings of the XIII Congreso Nacional de Ingeniería Sísmica, Guadalajara, Jalisco
- Sanchez-Sanchez, H. y Cortés S. C., 2003, Comportamiento dinámico de tanques de almacenamiento con cubierta fija tipo cúpula, Proceedings of the XIV Congreso Nacional de Ingeniería Estructural, León Gto.
- Sanchez-Sanchez, H. y Cortes S.C., 2004, Structural Behaviour of Liquid Filled Storage Tanks of Large Capacity Placed in Seismic Zones of High Risk in Mexico, Proceedings of the 13th World Conference on Earthquake Engineering, Paper 2665, Vancouver, B.C., Canada.
- Warburton, G.B., 1976. The Dynamical Behavior of Structures, 2nd ed., Pergamon Press, Great Britain.
- Wozniak, R.S., and Mitchell, 1978, Basis of Seismic Design Provision for Welded Steel Oil Storage Tanks, Proceedings – Refining Department, Vol. 57, API, Washington, D.C., 485-501