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SEISMIC RESPONSE OF CYLINDRICAL TANKS FOR OIL STORAGE FOR CONDITIONS OF ANCHORED AND UNANCHORED

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ABSTRACT

Seismic response of storage tanks anchored and unanchored for oil, placed in high seismic risk zones in 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 tank vibration and full tanks with 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 from 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 Mexico.

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.

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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.

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.

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.

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.

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.

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.

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.

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 Figs. 1 and 2, and tables 1 and 2.

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

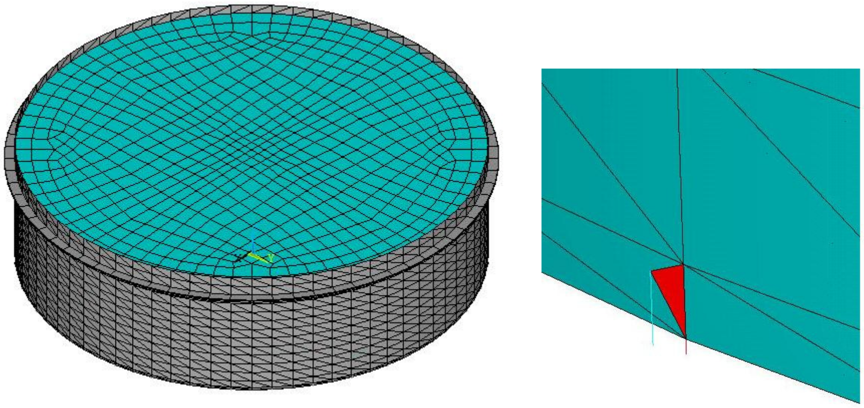


Figure 2. Numerical model of cylindrical steel storage tank of 200 thousands barrels.

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/m3
ρ_s	7840	Mass per unit volume of the steel (N/m3)/g
γ_l	9,810	Weight per unit volume of the liquid N/m3
ρ_l	1,000	Mass per unit volume of the liquid (N/m3)/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	
t_1 (mm)	25	32.16	12.7
t_2 (mm)	22	27.60	
t_3 (mm)	19	22.53	
t_4 (mm)	16	15.85	
t_5 (mm)	13	10.78	
t_6 (mm)	10	8.22	
t_7 (mm)	-	8.22	

Numerical Results

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.

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).

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.

Analytic and numerical results comparison

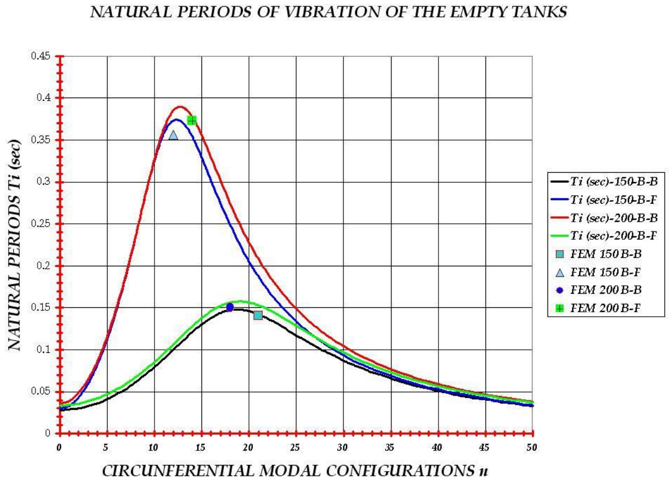


Figure 3. Natural periods of vibration.

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***

Fig. 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.

Hydrostatic analysis

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 γl the radial displacement *w(x)* given by Timoshenko.

$$w(x) = -\frac{\gamma h}{4D\beta^4}\left[1 - \frac{x}{h} - e^{-\beta x}\cos\beta x - e^{-\beta x}\left(1 - \frac{1}{\beta h}\right) sen\beta x\right] \qquad (1)$$

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

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.

a. variable t unachorage

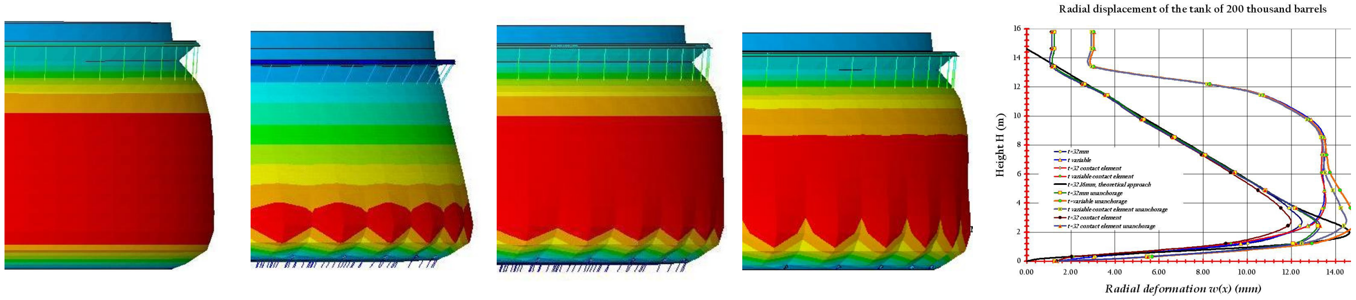
b. constant t

c. constant t

d. variable t

e. Radial displacement

Radial displacements *w* of the wall to the 150Tb tank



f. variable t unachorage

g. constant t

h. constant t

i. variable t

j. Radial displacement

Radial displacements *w* of the wall to the 200 Tb tank

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

Seismic Analysis

The seismic analysis were carried out employing a seismic record at Minatitlán, Veracruz, obtained of the earthquake originated at the Subduction zone of Mexican Pacific Coast, in 1978 (see Fig. 5); the longitudinal component of this register was applied at the base of the structures, in the horizontal direction x.

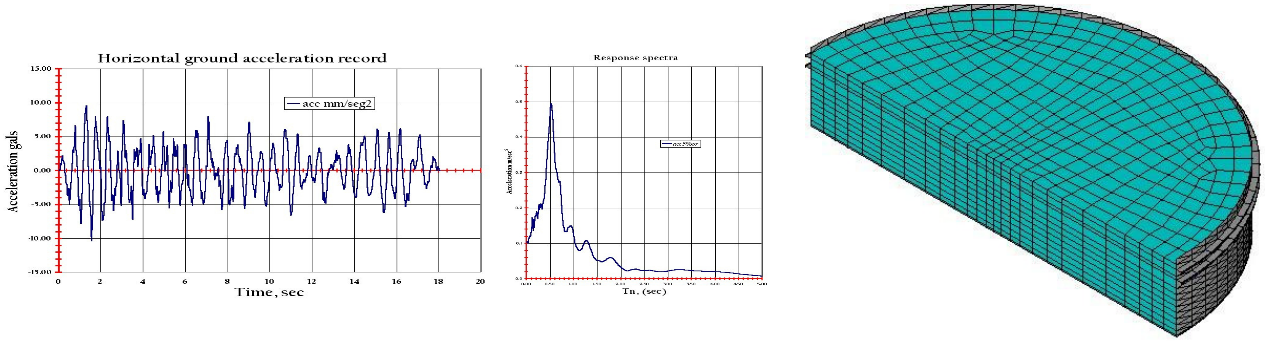


Figure 5. Input horizontal ground acceleration record and response spectra, Minatitlán, Veracruz.

Time History Analysis and Results

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.

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 90mm and 30mm for two tanks,

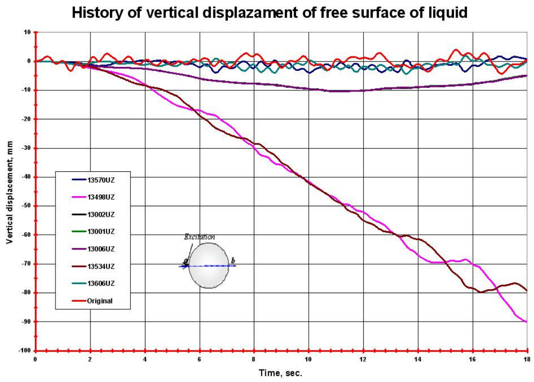


Figure 6a. Tanks of 150 thousand barrels.

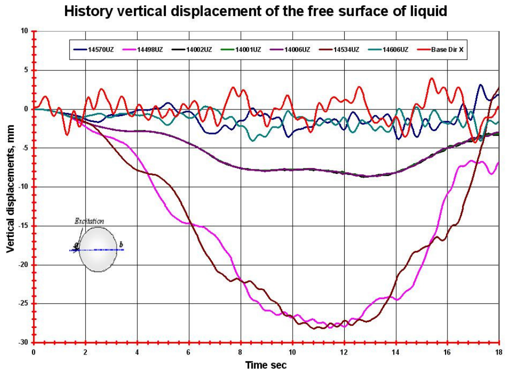


Figure 6b. Tanks of 200 thousand barrels.

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

Fig 7a and b show 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 25 and 20mm for two tanks 150 and 200 thousand barrel respectively.

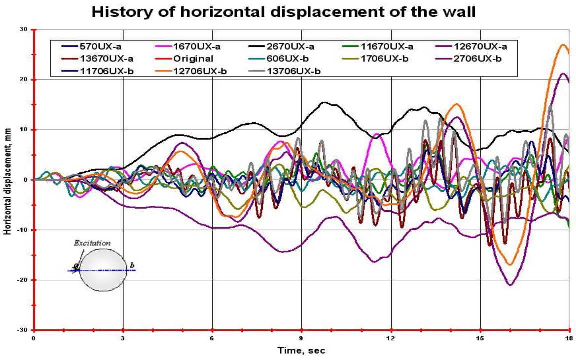


Figure 7a. Tanks of 150 thousand barrels.

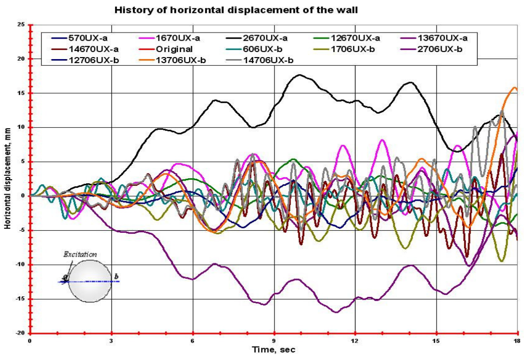


Figure 7b. Tanks of 200 thousand barrels.

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

Fig. 8a and b show the level of the Von Mises stresses during the time; the maximal values are about 65 and 83 Kg/cm^2, for the two tanks repetitively.

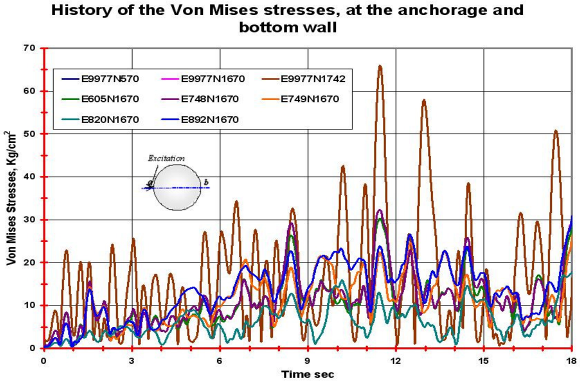


Figure 8a. Tanks of 150 thousand barrels.

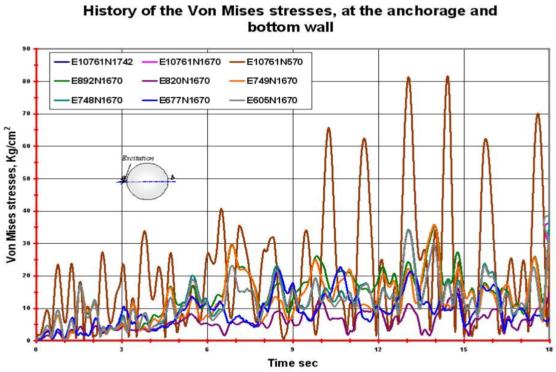


Figure 8b. Tanks of 200 thousand barrels.

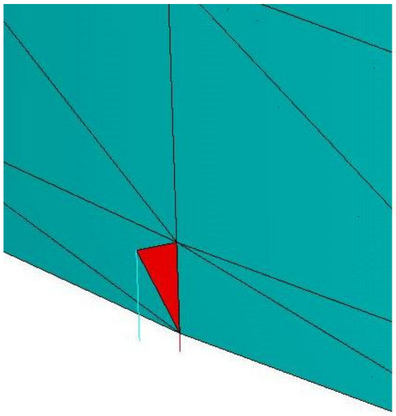


Figure 8c. Detail of the anchorage model of the Tanks.

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

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

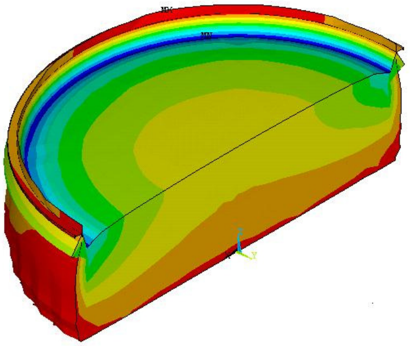


Figure 9a. Tanks of 150 thousand barrels.

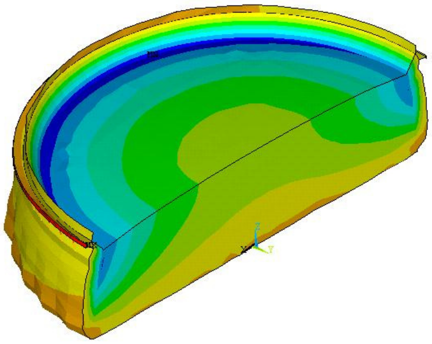


Figure 9b. Tanks of 200 thousand barrels.

Conclusions

The purpose of this work was to evaluate the structural behavior and response of cylindrical steel anchored storage tanks, with flexible thin walls, subjected to seismic action.

- The numerical results obtained from the empty tanks are compared with those estimated analytically and they observe a good correlation in the majority of the cases between both approaches. This represents a tool for revision and new designs to improve the present criteria of design.
- From the obtained results of the fluid-structure interaction models, with the selected seismic record for different boundary conditions at the bottom of the tank; it is observed that in all cases when the structures are horizontally excited, a mode one occurs at the 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 increases and produces a major uplift effect at the base of the anchorage tank and the sloshing effect of the liquid at the free surface exceeds the height of the tank. As a consequence of this behavior, axial stresses are increased the 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 the 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 research is necessary to continue the study of the seismic behavior of storage tanks of large capacity placed in regions of strong ground motions, while 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.

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