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STRUCTURAL BEHAVIOUR OF LIQUID FILLED STORAGE TANKS OF LARGE CAPACITY PLACED IN SEISMIC ZONES OF HIGH RISK IN MEXICO

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SUMMARY

This research has focused on the behavior, under seismic conditions, of already existing steel storage tanks of large capacity, located in high risk zones. From the revision of analysis and design criteria concerned with thin walls structures, it has been prepared a procedure based on a numeric modeling where the mechanic characteristics of the materials and the real geometrical measures have been considered. Numeric analysis by FEM have been used in different conditions: empty tanks vibration, full tanks where fluid-structure interaction is considered to the case of flexible walls, in order to take into account the pressure distribution of the liquid. To estimate the response, real seismic records originated in the Mexican Region, have been used. Finally the numerical results obtained of the empty tanks with those calculated analytically are compared and it is observed that a good correlation between both approaches. For the results obtained of the fluid-structure interaction models with the selected seismic registry is observed that given its great dimensions and the rigidity that provides the ring to them in the top part of the tanks, the effect of the surge is not very significant due to the fluid system - structure is excited in the first seconds, reason why the action of the hydrostatic pressure on the walls of these is sample to be dominant.

INTRODUCTION

The growing need to satisfy the national oil industry demand has recently required the evaluation and retrofit of the existing structures, in addition to create new oil terminals for distribution and oil products. As a consequence, some storage tanks have been placed in high seismic risk areas. Therefore, this

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research has focused on the behavior, under seismic conditions, of already existing steel storage tanks of large capacity, of 500 and 200 thousands barrels, located in high risk zones.

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 these 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.

Thin cylindrical shells may vibrate in a variety of ways depending on the particular effort involved. The present work is focused to study of the vibration of the shell. Some of the vibration forms, which are possible under such conditions, are illustrated in figure 1.a and b. For sections perpendicular to the axis of the cylinder, the vibration consists of both radial and tangential movement, a number of stationary waves being formed around the circumference. The form of vibration increases in complexity with the number of modes, but theoretically there is no limit to the number, which may be present. Further complication, however, may result due to the superposition of waves in the axial direction. Some examples of this are given in figure 1.b for the case in which the ends of the cylinder are maintained circular and no directional restraint is imposed, a condition which will be termed freely supported.

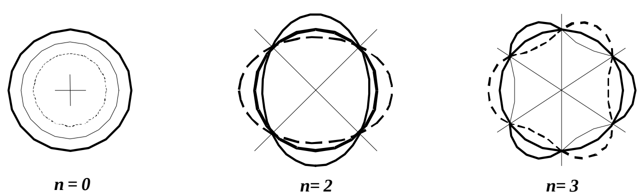


Figure 1.a – Circumferential mode shapes

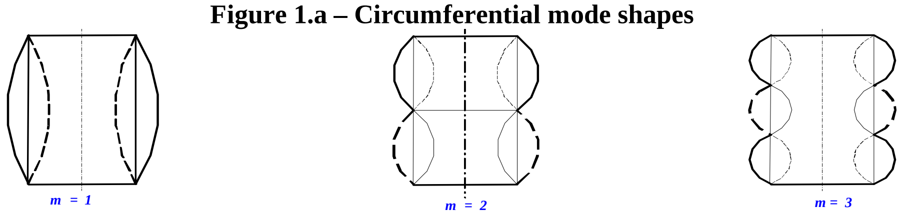
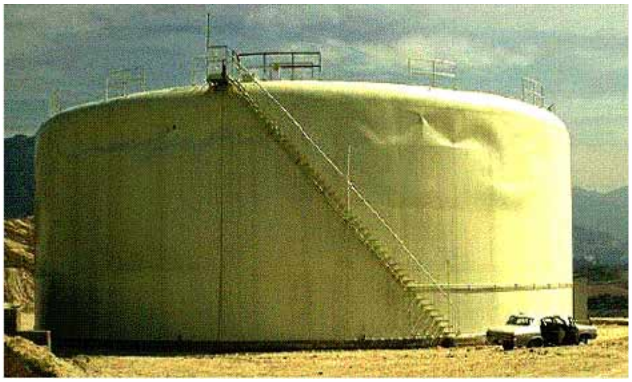
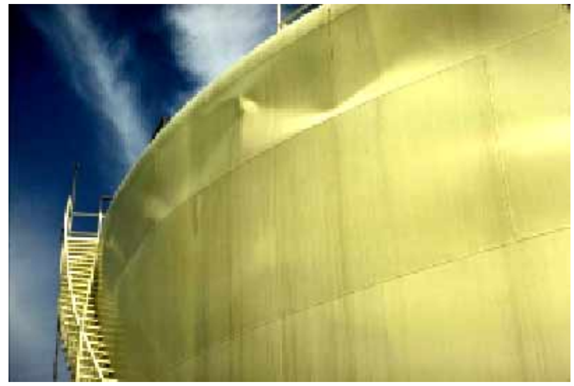


Figure 1.b - Axial mode shapes

The combination of both modal shapes lead to a multi-modal shapes which are consequences of different parameters such as: thickness ***t***, geometrical and mechanical characteristics, seismic and pressure efforts and boundary conditions. These modal shapes are solutions of theoretical problems of vibrations and they are employed to study the dynamic behaviour of real structures, see figures 2.a and b. Earthquake damage to steel storage tanks can take several forms. Large axial compressive stresses due to bending of the tank wall can cause “elephant-foot” buckling of the wall

Figures 2.a y 2.b - Earthquake damages of cylindrical storage tanks with flexible shell walls, collection Steinbrugge EERC, U.C Berkeley

MODEL AND ASSUMPTIONS

Statement of the problem

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.

The general hypothesis employed in the analysis are:

- the cylindrical steel tanks are constituted by different constant thickness ***t*** of the wall, that change along of the height ***H***
- the walls of the curve plates are thin, the thickness ***t*** of the shell is least than 10% of the radius ***R***
- the material is isotropic homogenous and elastic
- exist loads applied on the curve plates and it is considered also the own weight (mass)

Structures studied

To known the seismic behavior of the cylindrical storage tanks, was studied the cylindrical tanks geometry of **200** and **500** thousands barrels, metallic constituted by rings welded mutually of the shells, with variable thickness ***t*** along of the height ***H***, see figure 3, 4 and tables 1 and 2.

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**

Figure 3 – Circular cylindrical steel storage tanks of 200 thousands barrels

Steel storage tank (thousands barrels)	**Table 2 - Geometrical characteristics**									
	H ***(m)***	h ***(m)***	***R*** ***(m)***	t_1 ***(mm)***	t_2 ***(mm)***	t_3 ***(mm)***	t_4 ***(mm)***	t_5 ***(mm)***	t_6 ***(mm)***	t_7 ***(mm)***
200	15.79	14.63	27.42	32.16	27.60	22.53	15.85	10.78	8.22	8.22
500	15.79	14.63	42.68	38.36	34.75	25.48	21.02	14.50	9.47	9.47
Stiffness ring	1.2			12.7						

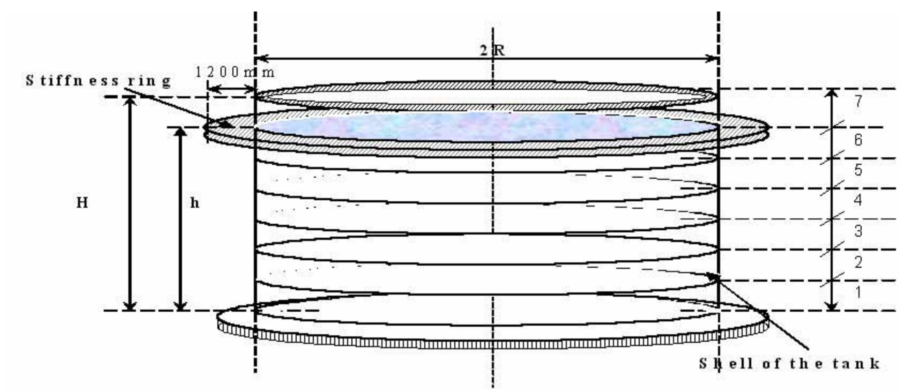


Figure 4 - Geometrical characteristics of the cylindrical storage tanks studied

ANALYSIS

Numerical modeling of analysis

Description of the model

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 7.0. These numerical models take into account the geometric and mechanic characteristics of the materials (steel and fluid), as soon as the large deformations, see tables 1, 2 and fig. 5.

Shell walls and base of tank

To study of the seismic behaviour of the shell walls and the base of the tanks, shell63 element was selected to analyze then. This element has 6 degree of freedom in each node, and it is 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-linearities such as large deformation assumptions are permit.

Fluid element

Fluid of the vessel was modeled with fluid 80 (3D) 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 and simple supported base, considering the stiffness of the soil (see fig.5).

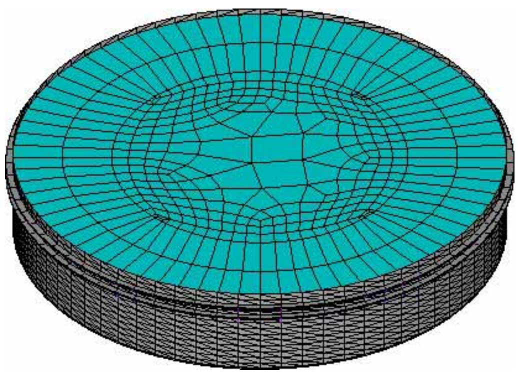


Figure 5 - Model of cylindrical steel storage tanks of 500 thousands barrels

Dynamic analysis

Empty condition

In this first part, it carried out the dynamic analysis considering the empty condition of the tanks; the meaning is to calibrate the numerical analysis of **FEM** vs. the classical theory of vibration of thin cylindrical shells. Dynamic characteristic such as periods, frequencies and modal shapes of the tanks were calculated by a theoretical vibration approach of the cylindrical shell structures, Sanchez [10], 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 [14].

RESULTS

Analytic and numerical results comparison

The dynamic analytical and numerical results of the two vessels 200 y 500 thousands barrels with uniform thickness ***t*** obtained of the both approaches; are shown in tables 3 and 4 for two boundary conditions.

(clamped – free and clamped – simply supported), that represents the follow conditions: a. tank without stiffness ring and b. tank with stiffness ring at the top of the tank.

Table 3 - Natural frequencies and periods of vibration of the empty tank of 200 thousands barrels

n	*f (hertz)*	*Periods (sec)*	*Boundary conditions*	$t_{cte} - mm$
13	2.5691	0.3892	Built – free	32.16
14	2.68	0.3731	FEM tank without stiffening ring	32.16
19	6.347	0.1576	Built – simply supported	32.16
18	6.648	0.1504	FEM tank with stiffening ring	32.16

Tank of 200 thousands barrels, with uniform thickness $t_c = 32.16\ mm$, $H / R = 0.5759$, $R / t_c = 852.488$, $m = 1$ (axial semi-wave), $n = 1$ a 50 (circumferential waves).

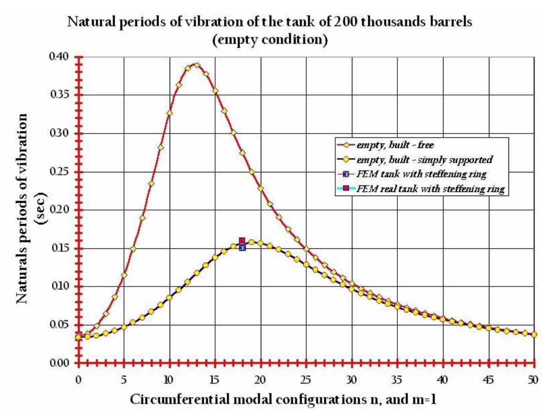
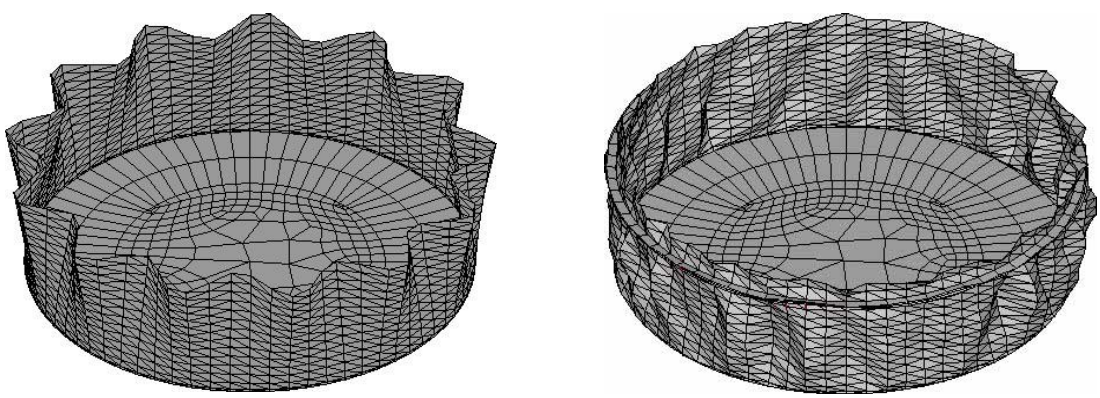


Figure 6 - Natural periods of the tank of 200 thousands barrels (empty condition).



Tank built – free   Tank with stiffening ring

Figure 7 – Mode shapes results of the empty tank of 200 thousands barrels, *t=32.16mm*

Table 4 - Natural frequencies and periods of vibration of the empty tank of 500 thousands barrels

n	*f (hertz)*	*Periods (sec)*	*Boundary conditions*	$t_{cte} - mm$
17	2.2526	0.4439	built – free	38.36
24	5.507	0.182	built – simply supported	38.36
25	5.585	0.1791	FEM tank with two stiffening ring	38.36

Hydrostatic analysis

Cylindrical tanks with uniform wall thickness.

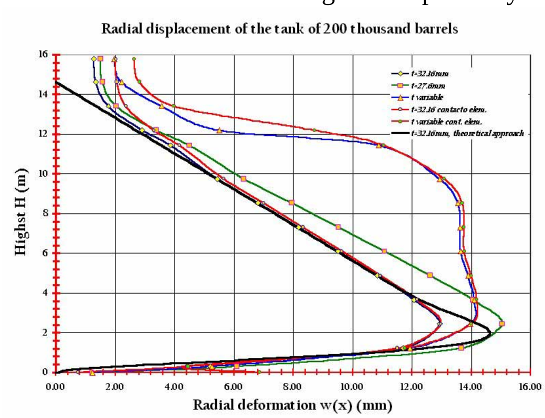
The numerical hydrostatic analysis of the tanks was compared with the analytical solution when the vessels are submitted to the action of a liquid pressure. For a vertical, cylindrical shell completely full of liquid, with uniform thickness ***t***, radius ***R***, heights ***h***, and weight per unit volume of the liquid γ_l the radial displacement **w(x)** is given by Timoshenko [12]

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

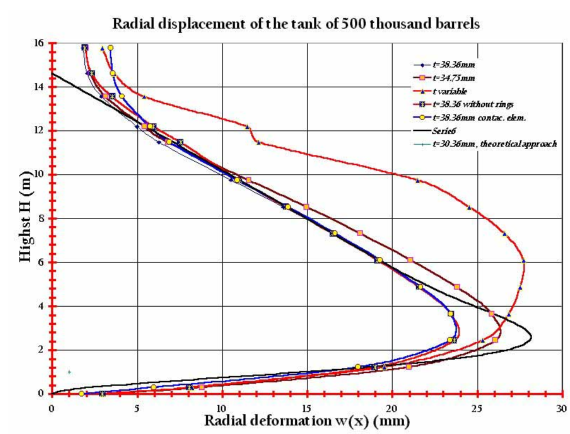
where: $\beta^4 = \left[\frac{Et}{4DR^2}\right] = \left[\frac{3(1-\nu^2)}{R^2 t^2}\right]$ and $D = \frac{Et^3}{12(1-\nu^2)}$ (flexural rigidity of the shell)

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

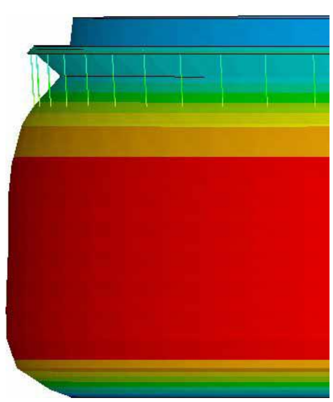
Figures 8.a, b, c and d, show numerical and analytical results of the radial displacement **w** due to hydrostatic pressure of the two steel storage tanks studied (200 and 500 thousand barrels), in these figures are compared numerical results for different thickness vs. analytical displacement. It can see that both approaches are good agreed between them, the maximum values of displacement at the base of tanks of 15 and 28 mm occurs about 2.1m of the height **H** respectively.



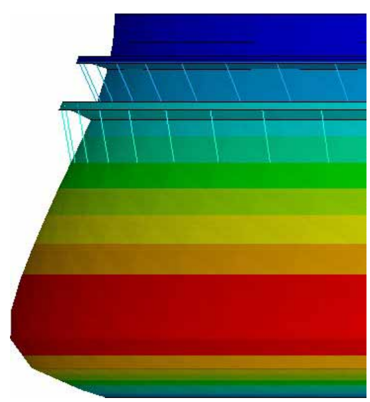
a. radial displacements



b. radial displacements



c. wall deformation of 200 thousands barrels



d. wall deformation of 500 thousands barrels

Figure 8 - Comparison of both numerical and analytical approaches hydrostatic radial displacement results for the two tanks studied

Fluid – structure system seismic analysis and results

Figure 9 shows the numerical model fluid - structure system employed to carry out the seismic analysis of the two storage tanks.

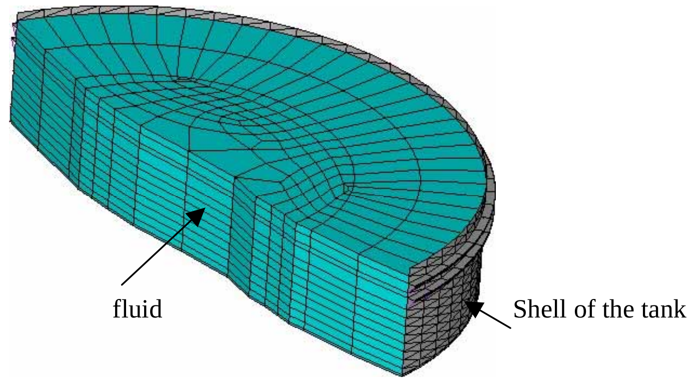


Figure 9 – Model of analysis of the fluid – structure interaction system

Figure 10 shows modal shapes of the full tank of the 500 thousand barrel with a natural period of vibration T=11.79 seconds obtained of the dynamic analysis.

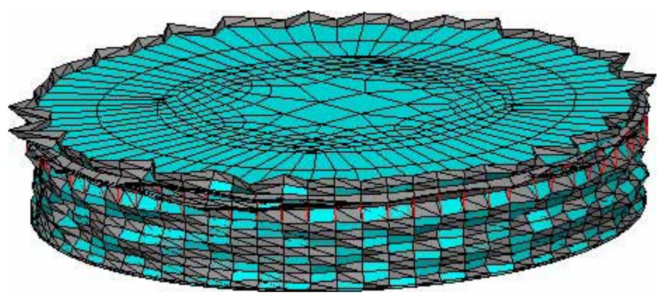


Figure 10 – Modal shapes of the tank of the 500 Tb with a natural period of vibration.

Seismic analysis

The seismic analysis were carried out employing seismic records of soil obtain of the earthquakes originated at central region of Mexico with 60 at 250 Km of deeper (see figure 11), the longitudinal component of these register was applied at the base of two structures, in the horizontal direction **x**.

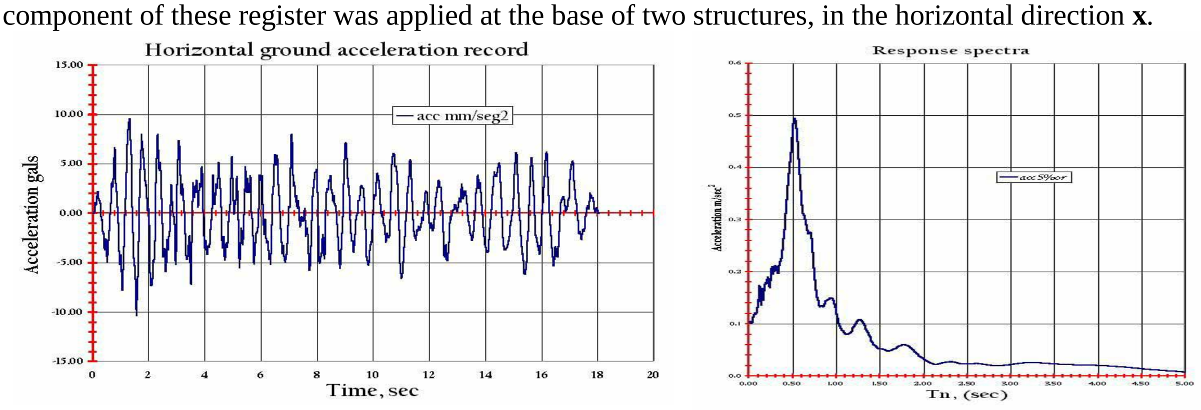
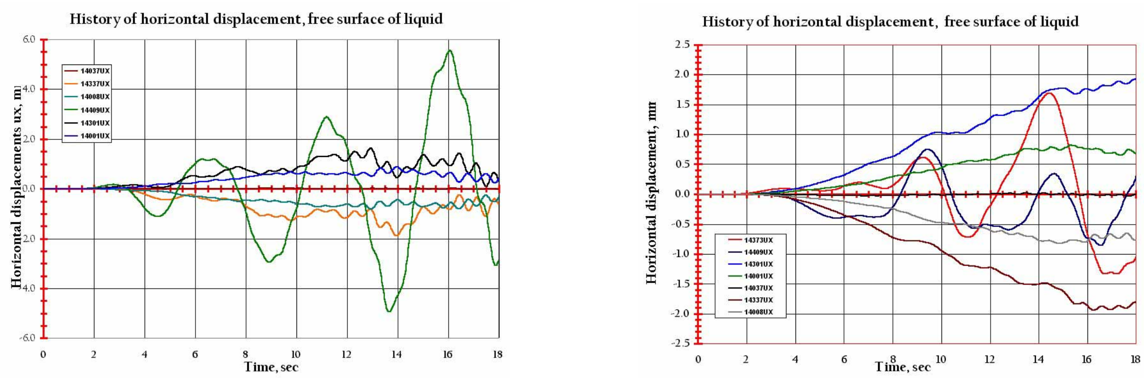


Figure 11 – Horizontal ground acceleration recorded at Minatitlan, Veracruz

Time history analysis and results

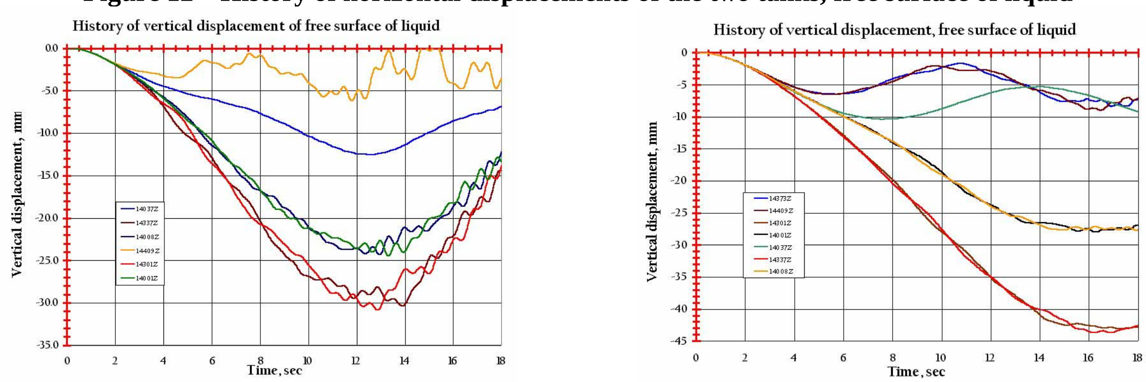
Response history of full tanks

Figures 12 and 13 show horizontal and vertical displacement history results at free surface of liquid for the two tank models submitted to seismic excitation. The maximum values of horizontal displacement of 5.7 and 2 mm occurs at about 16 and 18 seconds respectively. For vertical displacement the maximum values (-30 and 44 mm) occurs at 14 and 16 seconds respectively.



a. Tanks of 200 Tb b. Tanks of 500 Tb

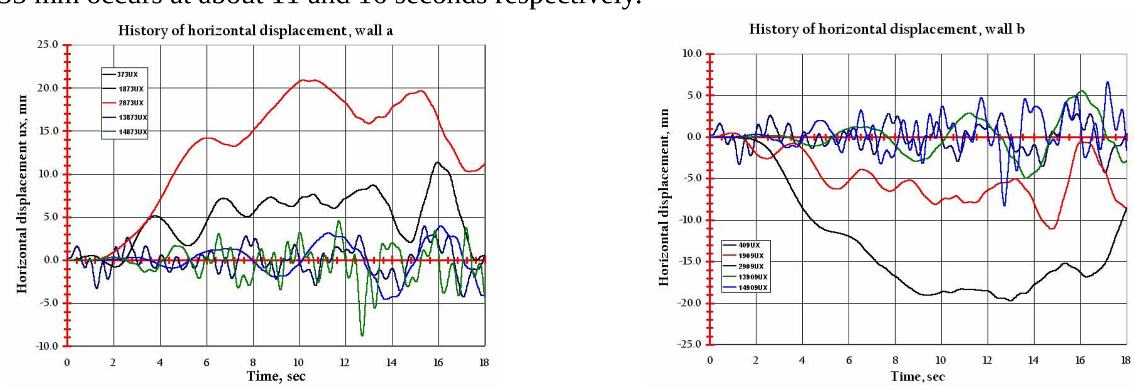
Figure 12 – History of horizontal displacements of the two tanks, free surface of liquid



a. Tanks of 200 Tb b. Tanks of 500 Tb

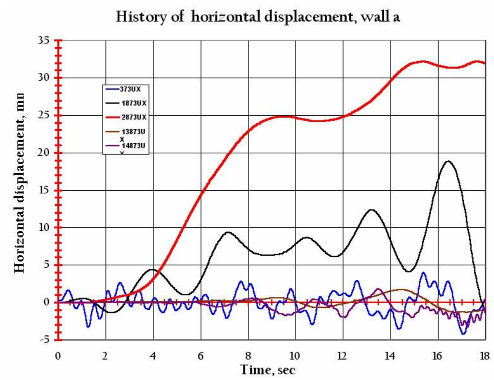
Figure 13 – History of vertical displacements of the two tanks, free surface of liquid

Figures 14.a, b and 15.a, b show horizontal displacement history results at two opposite walls a, b, for the two tank models submitted to seismic excitation. The maximum values of horizontal displacement of 21 and 35 mm occurs at about 11 and 16 seconds respectively.

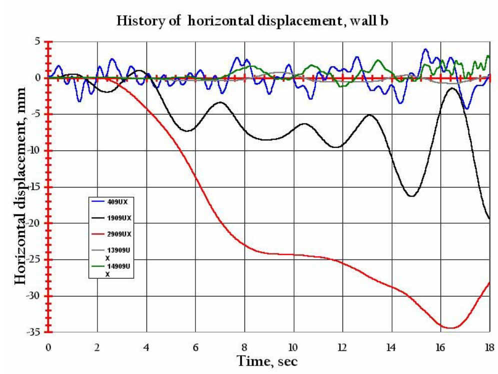


a. Tanks of 200 Tb b. Tanks of 500 Tb

Figure 14 – History of horizontal displacement of the tank of 200 thousand barrels



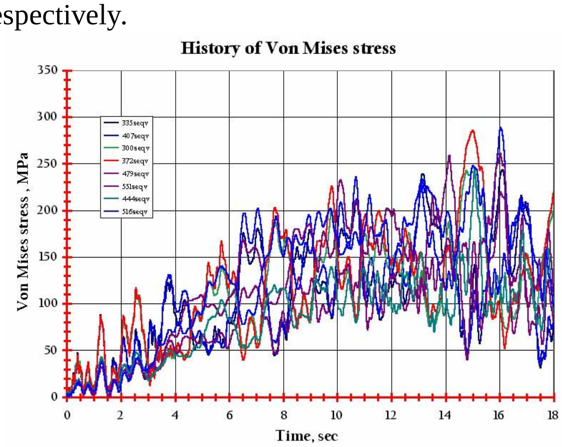
a. Tanks of 200 Tb



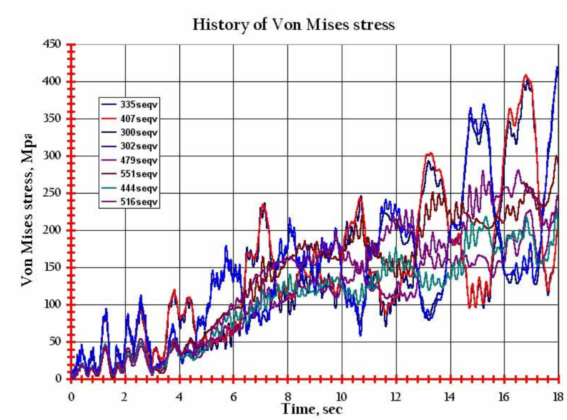
b. Tanks of 500 Tb

Figure 15 – History of horizontal displacement of the tank of 500 thousand barrels

Figures 16.a and b. show the results of maximum Von Mises stresses of the shell wall during the time history analysis. The maximum value of stresses of 300 and 410 Mpa occur at about 16 and 18 seconds respectively.



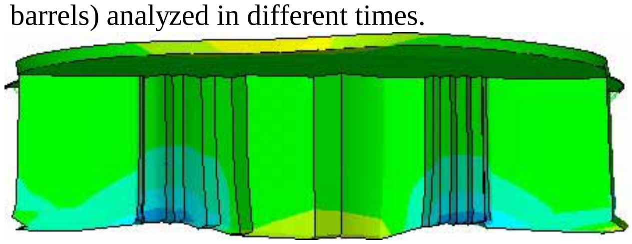
a. Tanks of 200 Tb



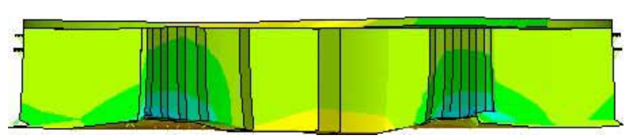
b. Tanks of 500 Tb

Figure 16 – Von Mises stress time history

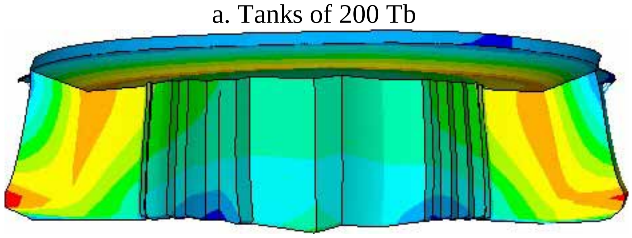
Figures 17.a to 17.f represent the seismic responses of the two storage tanks (200 and 500 thousand barrels) analyzed in different times.



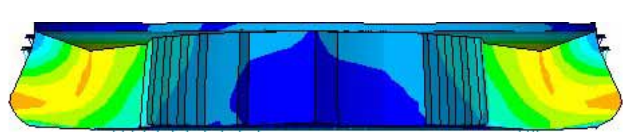
a. Tanks of 200 Tb



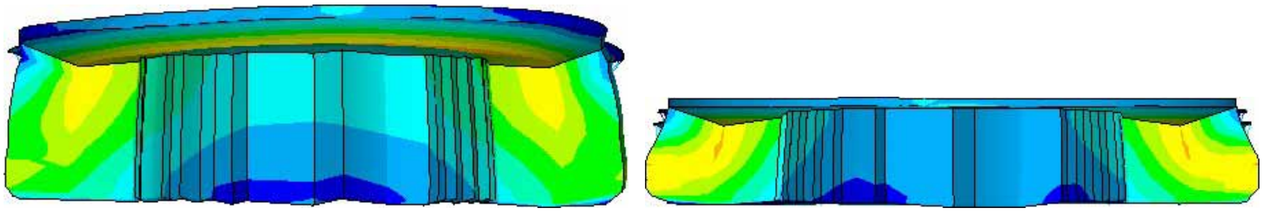
b. Tanks of 500 Tb



c. Tanks of 200 Tb



d. Tanks of 500 Tb



e. Tanks of 200 Tb f. Tanks of 500 Tb

Figure 17 – Configurations of seismic response of the two tanks studied

The figures 17.c to 17.d show the important configurations in the radial direction, being predominant in the average and bottom part of the both tanks after three seconds of history analysis.

SUMMARY AND CONCLUSIONS

The objective of this work was studied, the behavior and response of the cylindrical steel storage tanks with flexible thin wall submitted seismic actions. This work has attempted through numerical analysis through the technique of the finite element, to study the effect of the flowing interaction structure of cylindrical structures.

The numerical results obtained of the empty tanks with those estimated analytically are compared and it is observed that a good correlation between both approaches, this represents a tool for the revision of new designs, besides to lay the foundations to improve the present criteria of design in our country.

From the obtained results of the fluid-structure interaction models with the selected seismic record (see figures 12 to 15), is observed that given its great dimensions (54,84 and 85.36m of diameter), the rigidity that provides the ring to them in the top part of the tanks and the flexibility of the foundation, the effect of the surge is not very significant due to the fluid system - structure is excited in the first three second in way one, reason why the action of the hydrostatic pressure on the walls of these is sample to be dominant, being generated important configurations in the radial direction, being predominant in the average and low part of the tanks.

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.

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