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Effects of Shell Thickness on Directional Deformation and Buckling Behaviour Cylindrical Steel Water Tanks Subjected to the Kobe Earthquake

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Abstract

Cylindrical steel storage tanks are widely used for the storage of various liquids, industrial chemicals and firefighting waters. They have also been used for cooling purposes in nuclear power plants in recent years. Liquid-storage tanks have many different configurations; however, in this study, cylindrical ground-supported liquid steel tanks were preferred because of simplicity in their design and construction as well as their efficiency in resisting applied hydrostatic and hydrodynamic loads, when compared with other configurations. If liquid steel tanks are damaged in an earthquake, they can also cause great financial loss and environmental damage due to their hazardous chemical contents. These tanks may be exposed to several types of failures such as elephant-foot buckling, diamond-shape buckling, overturning and uplifting during earthquakes. The aim of this study is to compare the deformity states of cylindrical steel tanks with three different roof shapes. For this reason, dimensions of the cylindrical open-top, flat-closed and torispherical-closed top tanks were determined for 3D-finite element method (FEM) models in an ANSYS workbench software. This article focuses on the seismic-activity-resistant ground-supported cylindrical (vertical) steel liquid storage tanks. Seismic analyses were conducted under Kobe earthquake loads. The free vibration frequency values calculated using API 650 (American Petroleum Institutes) were verified with the FEM results. Directional deformation and buckling were presented for both impulsive and convective regions. According to API 650 standard, the tank shell thickness is 6 mm. Analyses were performed for tanks with 4 mm and 8 mm shell thickness. In this study, directional deformation and buckling were observed in models with shell thickness under the standard (4 mm) and above the standard (8 mm), unlike the earlier studies in the literature. It was also observed that increasing shell thickness above the specified code values the deformation in the flat-closed tank. In addition, torispherical dome-shaped tanks were observed to have smaller directional deformation and buckling in all cases considered.

Keywords: Cylindrical Storage Tank, API 650, FEM Analysis, Shell Thickness

1. INTRODUCTION

Cylindrical steel tanks are widely used for storing water and cooling in nuclear power plants. Due to their importance, they should not be damaged during earthquakes. The seismic behaviour of liquid storage tanks is very complicated due to the hydrodynamic pressures of the fluids in them. Several researches have been performed in the literature to determine the seismic performance of cylindrical liquid storage tanks, considering dynamic fluid-structure interaction (FSI)

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[1-6]. When a tank containing liquid is subjected to earthquake movement, the liquid is subjected to horizontal acceleration. In turn, the tank walls will be exposed to hydrodynamic pressure. The liquid at the bottom of the tank also behaves like a mass that is rigidly attached to the tank wall. The fluid mass moving along the wall is called as the “impulsive mass”. Impulsive hydrodynamic pressure acts on tank walls due to this impulsive liquid mass. The liquid mass in the upper part of the tank experiences a sloshing motion which is called as convective fluid. Thus, the hydrodynamic response of the took divided into impulsive and convective components to accurately investigate dynamic behaviour of tanks. The idea that the response of tank can be divided into a single impulsive and a number of convective modes was advocated to Housner [7]. Housner proposed two mass model for cylindrical tanks. Housner’s two mass model has been commonly used by many international codes such as API650, IITK-GSDMA Guidelines for Seismic Design of Liquid Storage Tanks [8,9].

Field investigations have been performed by various researchers to determine the type of damage that occurred in liquid tanks in earthquakes and the factor causing these damages. In the field surveys has revealed that most liquid tanks are performing poorly under the influence of earthquakes and that it is necessary to develop new methods for increased earthquake resistance. According to the Praveen et al, when subjected to strong shaking, tanks respond in a non-linear fashion and experience some damage [10]. However, no generally acceptable methods do not require non-linear seismic analysis of tanks. Therefore, the damage sustained by tanks under ground motions of different intensities cannot be quantified easily [11]. Because of the simplicity in design and low cost, very-thin-perimeter walls are commonly used in the construction of steel storage water tanks [1]. However, these thin-shelled cylindrical steel tanks subject to internal pressure from stored liquid besides lateral pressure that can arise from roof loads, horizontal loads such as earthquakes and frictional drag of stored materials on the walls [12]. There are two important factors that impact the steel tanks’ deformation after earthquake: the dynamic characteristics of the earthquake and the structure itself. Steel storage tanks are affected by ground components that comprise two lateral components, and a vertical component, and three tensional components which are around the structures coordinate axes [13]. Steel storage tanks take several deformations under earthquake loads. Large axial compressive stresses due to beam-like bending of the tank wall can cause elephant-foot buckling of the wall. The roof of the tanks can also be damaged due to the sloshing liquid [14].

There are various methods for seismic analysis of tanks such as API 650 formulation method, boundary conditions technique and finite element method [15]. API 650 guidelines for seismic design of tanks is developed mainly on Housner's work [8,9]. Housner found out a useful tool called spring-mass model to analyze the on-ground supported tanks that are experiencing seismic loads by separating the system into two main components. The boundary condition method is a numerical technique used to solve various engineering, scientific and mathematical problems. This technique is generally used in the analysis of simpler structures. Naghdali et al [15]. have investigated several existing tanks using both API650 rules and FEM model based on ANSYS software. Their study demonstrated that, in some cases, there are some imperfections in the API 650 requirements that need further investigations.

Spritzer and Guzey [16] compared the design provisions in Appendix E of API 650 with other well-known design documents throughout the world, including those used in New Zealand and Japan. In comparative study, damage and states such as hydrodynamic hoop stress, elevation and floor tensioning, freeboard stress and tipping are taken into account. Based on the results, that concluded that API 650 Annex E, compared to New Zealand and Japanese design documents, accounts for all major failure modes well enough [17].

In recent years, the tendency towards finite element analysis (FEA) of steel storage tanks involving tank wall and foundation flexibility issues have been increasing. One of these studies was about the modeling of partially filled steel liquid tanks. Nicolici and Bilegan [18] focused on computational fluid dynamics (CFD) analysis to estimate the effect of sloshing wave amplitude, convective mode frequency and the pressure applied to the walls. As a result of the analysis, it was found that the fluid structure interaction affected the sloshing effect and the wall elasticity strengthened the impulsive pressure.

Maheri and Karbaschi [19], examined three models with H/D of 0.40 (squat tank), H/D of 0.63 (medium tank) and H/D of 0.9 (thin tank) diameters to investigate the effect of tank geometric aspect ratios on structural responses. The results obtained using the proposed simplified mechanical model showed that the method could determine the frequency of sloshing of liquid filled tanks with acceptable accuracy. It was also observed that there was a substantial reduction in the initial natural frequency of the tank.

In a study by Ormeno et al [20], reconducted the seismic response of steel tanks, it was shown that displacement and tank shell acceleration on the upper side increased as the tank ran up, while axial pressure stress decreased from 35% to 64% with tank elevation.

The finite element method FEM has advantages during solving general problems with a complex structure shape. In this paper, such as, were first calculated using API 650 standard, the Kobe earthquake data being used for the non-linear analyses are conducted using kobe earthquake.

Since cylindrical steel water tanks are thin-walled structures, the wall thickness and the tank roof significantly affect the deformation and buckling pattern in the tanks. Depending on the earthquake ground motion, it is not always possible to reduce the deformations and prevent buckling in the tanks only by increasing the shell thickness. In addition, improper design of the tank roof can increase the risk of buckling in tanks with increased shell thickness. Figure 1 and 2 show roof buckling and shell buckling respectively. In order to prevent buckling in the cylindrical steel liquid tanks, it is necessary to examine the relationship between shell thickness and roof shape.

Figure 1. Roof buckling [21]

Figure 2. Shell buckling [22]

The aim of this study is to consider the effects of shell thickness on seismic behaviour of open-top, flat-closed and torispherical-closed cylindrical steel water tanks using finite element method. Most researchers have studied the effects of seismic loads on storage tanks using time histories or some have used discrete fluid elements. However, this study reveals effects to different shell thickness for the impulsive and convective modes on the different roof types of tanks. Moreover, the FEMs representing of nonlinear flexible tank walls shapes are presented. For this reason, analyses were carried out by reducing shell thickness to 2 mm and increasing to 2 mm from the code defined values in tank models with open-top, flat-closed and torispherical dome-shaped.

2.SEISMIC ANALYSES OF CYLINDRICAL STEEL TANKS

Cylindrical steel storage tanks subjected to earthquake loads has several critical failure modes that are not observed under service loads. These risks involve buckling of the elephant-foot buckling or diamond-shape buckling, failure due to excessive hydrodynamic hoop stresses or convective forces. In the United States, these failure modes are generally explained using the design standard defined by the American Petroleum Institute (API650) [23]. This standard has been used worldwide for seismic- design of steel storage tanks. API 650 establishes minimum requirements for material, design, fabrication, erection and testing of vertical, cylindrical, above ground, open-top and closed-top tanks as well as steel storage tanks in various sizes and capacities provided that internal pressures do not exceed the weight of the roof plates. Higher internal pressure is permitted when additional requirements are met [24]. In this study, impulsive and convective components of the seismic load have been calculated via the API-650 as well as using finite element method.

The geometrical and material properties of the model tanks are given in Table 1.

Table 1. Geometrical and material properties of the models used in the study

Parameter unit	Open-top tank	Flat-closed tank	Torispherical-closed tank
Inner diameter of tank (m)	15.08	15.08	1508
Tank height without roof (m)	11.31	11.31	11.31
Tank height with roof (m)	11.31	11.31	11.31
Water height (m)	10	10	10
Shell thickness (m)	0.006	0.006	0.006
Bottom plate thickness (m)	0.006	0.006	0.006
Density of tank steel (kg/m^3)	7850	7850	7850
Density of water (kg/m^3)	1000	1000	1000
Young's modulus of tank wall (GPa)	200	200	200
Poisson's ratio of tank wall (*v*)	0.3	0.3	0.3
Bulk modulus of elasticity of water (GPa)	2.2	2.2	2.2

Housner's spring-mass model and the description of hydrodynamic pressure distribution on the tank wall are presented Figure 3 and 4 respectively.

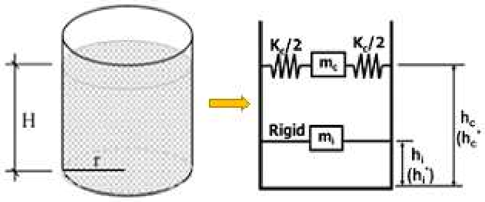


Figure 3. Housner's spring-mass model for the tank

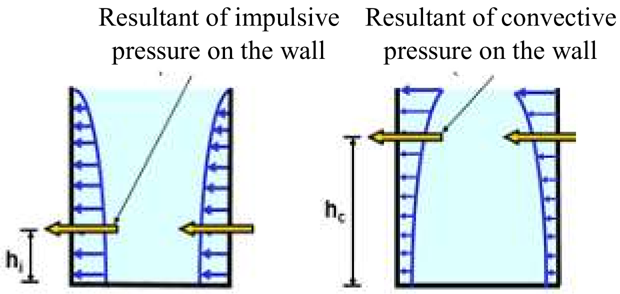


Figure 4. Impulsive and convective pressures [25]

2.1 Impulsive Period

The impulsive mode refers to the lateral mode of the tank–liquid system. The lateral seismic forces applied to the tank depend on the period of this mode. Contrary to the assumption made by Housner that because the tank is solid, the impulsive mode period is zero; the current design codes require the calculation of the period of the impulsive mode using of impulsive mass and rigidity of the tank shell, even though they use Housner's method (API 650). The mass density of the tank wall is not included in the impulsive period expressions instead; the mass density of liquid is used because the mass of the wall is usually quite small compared to the liquid mass for steel tanks. The first impulsive mode period of a flexible anchored tank is usually smaller than 0.5 sec [26].

2.2 Convective (Sloshing) Period

The period of the convective (sloshing) mode depends on the diameter of the tank and to a lesser extent on the depth of the liquid. The periods of convective mode are usual very long (up to 6–10 sec for large tanks) and are more influenced by the level of seismic ground displacements rather than ground accelerations. API 650 recommends the expression derived by Housner [7]. The convective mode is often referred to as the "sloshing" mode because of the liquid waves generated during earthquake movements. However, it is based on Jacobsen's work, in which impulsive fluid pressures applied to cylindrical tanks were considered as rigid base connection and non-deformed walls [27].

2.3 Spectral Acceleration and Design Loads

The impulsive mass, convective mass, base-shear, overturning moment and free board of water that a cylindrical tank is subjected to during seismic loading are seen in Figure 5.

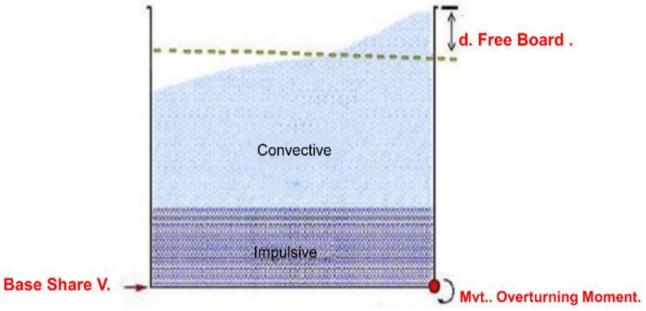


Figure 5. Seismic diagram of tank [25]

There are several analytical and theoretical methods for the seismic analysis of liquid cylindrical tanks. One of this method is the API 650 formulation method developed by the American Petroleum Institute. The basic API 650 formulation is presented below.

The total volume of water = $\pi R^2 h = \pi \times 7.54^2 \times 10$ (1)

$R/h = 7.54/10 = 0.754$ (2)

$h/R = 10/7.54 = 1.32$ (3)

Mass of impulsive equation $m_i = m_w \frac{\tanh(1.74\frac{R}{h})}{(1.74\frac{R}{h})}$ (4)

Mass of convective equatio m_c

$$m_c = 0.455 * \pi * \rho_l * R^3 * \tanh\left(1.84\frac{h}{R}\right) \tag{5}$$

Convective spring stiffness equation

$$k_c = m_c \frac{g}{R}\, 1.84 \tanh\frac{1.84h}{R} \tag{6}$$

Location of convective the centroid of mass equation

$$h_c = \left[1 - \frac{\cosh\left(1.84\frac{h}{R}\right)}{1.84\frac{h}{R}\sinh\left(1.84\frac{h}{R}\right)}\right] h \tag{7}$$

Location of impulsive the centroid of mass equation

$$h_i = 3/8h \tag{8}$$

$$\omega_i = \frac{2\pi}{Ci*hi} * \sqrt{\frac{E*t}{p*r}}$$

(9)

$$\omega_c = \frac{2\pi}{Cc*\sqrt{r}} \tag{10}$$

The impulsive period equation

$$Ti = \left(\frac{1}{\sqrt{2000}} * \left(\frac{Ci*H}{\sqrt{\frac{tu}{D}}}\right) * \left(\frac{\sqrt{p}}{\sqrt{E}}\right)\right. \tag{11}$$

The convective period equation

$$Tc = 1.8 * Ks * \sqrt{D} \tag{12}$$

Sloshing height equation d=$0.84R\frac{S_c(T_{con})}{g}$ (13)

The impulsive spectral acceleration parameter

$$A_i = S_{DS}\left(\frac{I}{R_{wi}}\right) \tag{14}$$

$$A_c = KS_{D1}\left(\frac{1}{T_c}\right)\left(\frac{I}{R_{wc}}\right) \tag{15}$$

$$V_i = A_i\left(m_S + m_r + m_f + m_i\right) \tag{16}$$

$$V_c = A_c W_c \tag{17}$$

$$V = \sqrt{{V_i}^2 + {V_c}^2} \tag{18}$$

$$M_{rw} = \sqrt{[A_i(m_S * h_s + m_i * h_i)]^2 + A_c(m_c * h_c)]^2} \tag{19}$$

Some seismic analysis results obtained for this study according to API 650 are presented in Table 2.

Table 2. Results calculated for cylindrical model tank using API 650 formulation.

Title	**Value**
The total volume of water (m^3)	1780.4
Total mass of water in the tank (Kg)	1780400
Ratio of radius to water height	0.754
Ratio of height to radius	1.32
Impulsive mass (Kg)	1173539.90
Convective mass (Kg)	603291.22
Location of the centroid of impulsive mass (m)	3.75
Location of the centroid of convective mass (m)	7.60
The natural frequency of impulsive mass (Hz)	3.26
The natural frequency of convective(sloshing) mass (Hz)	0.246
The impulsive period ($\boldsymbol{Ti}$, **sec**)	0.29
The convective period ($\boldsymbol{Tc}$, sec)	3.29
Mass of shell (Kg)	5939.14
Weight of fixed roof (Kg)	1146.58
Location of system ($h_{s,\,m}$)	5.08
Sloshing height of water (d,m)	0.96

Calculating the base shear ($\boldsymbol{V}$, N)	3613896.79
The seismic overturning moment(Nm)	21875380.59
Minimum yield strength of shell (MPa)	345
Minimum tensile strength (MPa)	485
Design Stress (S_d, MPa)	194
Hydrostatic Stress(S_t, MPa)	208

3. SEISMIC ANALYSIS WITH FINITE ELEMENT METHOD

This section deals with seismic analysis of three different types of ground-supported cylindrical steel water tanks; open-top, flat-closed and torispherical tanks. The main parameters of studied tanks are listed n Table 1. The results of the dynamic analysis of each tank under Kobe Earthquake is presented in the following paragraphs.

3.1. Modal Analysis

The vibration characteristics (natural frequencies and mode shapes) of a structure or a machine component determine with modal analysis. It can be also served as a starting point for a more detailed dynamic analysis such as transient dynamic analysis, harmonic analysis or spectrum analysis. In the design of a structure, natural frequencies and mode shapes play an important role in dynamic loading conditions [25].

Any non-linearity in material behaviour is disregard, because of the nature of the modal analysis. Orthotropic and temperature dependent material properties can be optionally used. Stiffness and mass are defined in some form by the critical requirement. The hardness can be determined by using isotropic and orthotropic elastic material models such as, elasticity module and poison's ratio, using hyperplastic material models (linearized to an equivalent combination of initial bulk and shear modules) or spring constants. The mass may be obtained from density of material or from distant masses [26].

Three cylindrical steel tanks with different roofs, representative of three classes of tanks namely 'open top', 'flat tank' and 'torispherical tank' are considered for 3D-FEM analysis throughout this section. In this study, the effect of the soil–structure interaction is not included. Since only ground-supported tanks are considered, the ground under the tank is not included in the FEM model. The tank walls and base are considered to be of the same thickness. Dimensions of tanks and are shown below in Figure 6.

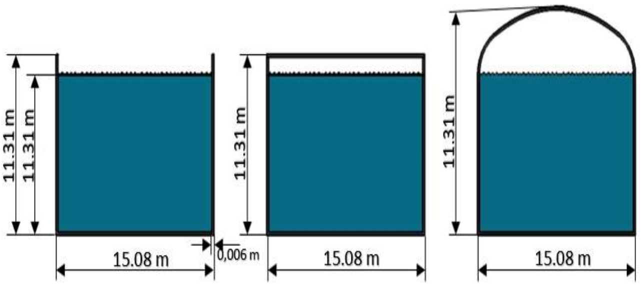
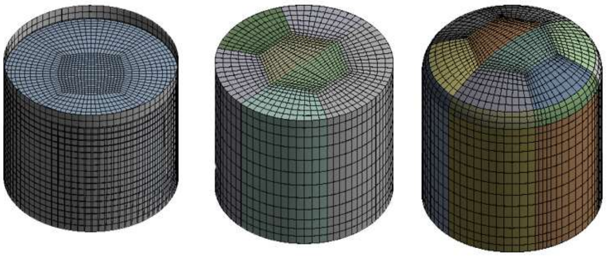


Figure 6. Three configurations of tanks

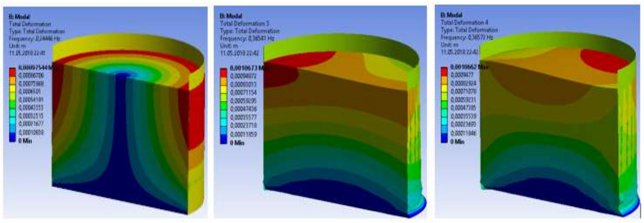
Numerical verification is necessary to show that numerical models can predict responses with reasonable accuracy and precision. For this reason, a static and dynamic modal analysis of the sample tank model was performed. Modal analysis is used to understand the behaviour of a structure. The cylindrical steel storage tank and fluid body were modelled with ANSYS Workbench. The materials used to model the water storage tank are the structural steel and water element. The density of structural steel was 7850 kg/m3, its Young Modulus 210 GPa and Poisson was ratio 0.3. density and bulk modulus of water were taken as 1000 kg/m3 0.3, respectively.

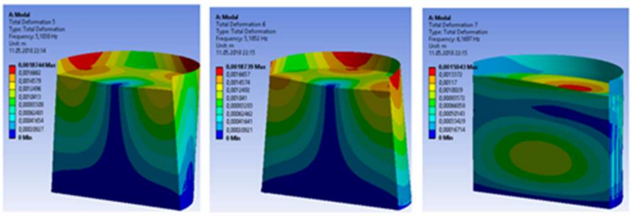


a) Open b) Flat c) Torispherical

Figure 7. Meshed view of tanks

Modal analysis was performed for all tank models. This analysis performed with water levels of 10 m. The problem of the interaction between the shell and the liquid is modelled using Shell 281, Solid 186, Contact 174 and Target 170 elements. The mesh models of tanks are shown in Figure 7.





f1=3.231 Hz f2=3.383 Hz f3=3.385 Hz

f4=5.183 Hz f5=5.185 Hz f6=6.169 Hz

Figure 8. Impulsive modal analysis results and frequencies for open-top tank model.

Generation and meshing of the finite elements for the shell of the tanks are based on the width of the plates used to form them in order to calculate the damping effects of viscous fluids in liquid storage tank subjected to earthquakes, it is assumed that the damping factor is 2%. The first 6 modes and related frequency values for the open tank model are shown in Figure 8.

The motion of contained fluid in cylindrical may be expressed as the sum of two separate contributions, called 'impulsive' and 'convective', respectively. When the tank is accelerated under seismic conditions, a part of the liquid mass moves simultaneous with the tank. This part of the liquid mass is known as the impulsive mass. The vibration modes set up by this mass are called the impulsive modes. Other parts of the liquid mass may be exposed vibration due to inertial properties and cause sloshing. This part of the liquid mass is called the convective mass and the vibration modes set up by this mass are called the convective modes.

The convective mass is located at the position indicated by h_c in the upper part of tank as shown in figure 9, and represents the liquid mass causing the liquid face sloshing. The mass moved with the liquid mass and the tank was exposed to the sloshing the face of water. Distribution of convective mass and sloshing of water are shown in Figure 9.

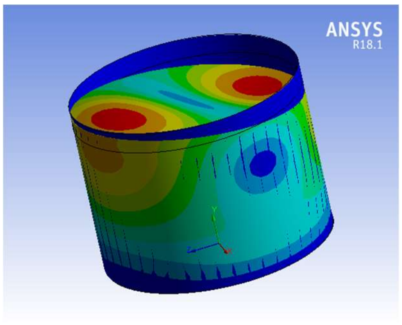
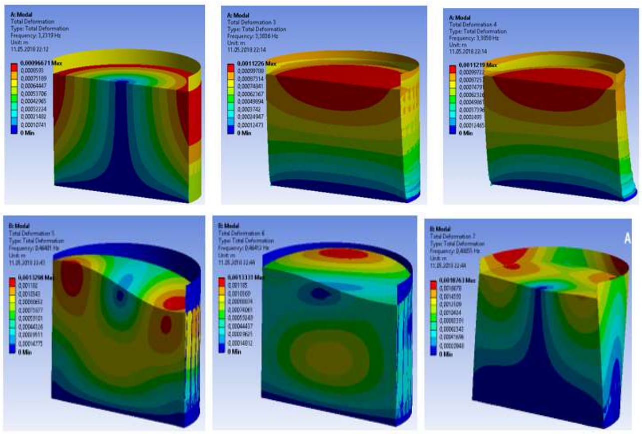


Figure 9. Convective (Sloshing) effect

The interaction between structure and liquid has vital importance. Great effort was made to accurately model the interaction between the shell and the liquid. The results of the modal analysis performed in the ANSYS workbench software using the finite element method were verified using API 650 formulation method. The first 6 convective modes are shown in Figure 10.



f1 = 0.24446 f2 = 0.36541 f3 = 0.36572

f4 = 0.46401 f5 = 0.46412 f6 = 0.48855

Figure 10. Convective modal analysis results and frequencies for open-top tank model

Table 3 compares the results obtained using the FEM analysis and API 650 formulation for the first frequency values.

Table 3. Modal analysis results of the open-top tank model

Mode Number	Impulsive Frequency (Hz)		Convective Frequency (Hz)	
	FEM	API650	FEM	API650
1	3.2319	3.26	0.24446	0.246
2	3.3836	NA	0.36541	NA
3	3.3858	NA	0.36572	NA
4	5.1838	NA	046401	NA
5	5.1852	NA	0.46412	NA
6	6.1697	NA	0.48855	NA

Modal analysis was repeated for flat-closed and torispherical-closed tanks. In addition, frequency modes were compared to determine the presence of a roof in impulsive and convective mass. These comparisons are shown with graphs in Figure 11 and Figure 12. In Figure 11, the flat-closed-top tank model in the impulsive model attracts attention with its low frequency values and low deformation values.

Torispherical-closed-top tank has maximum frequencies and deformation values.

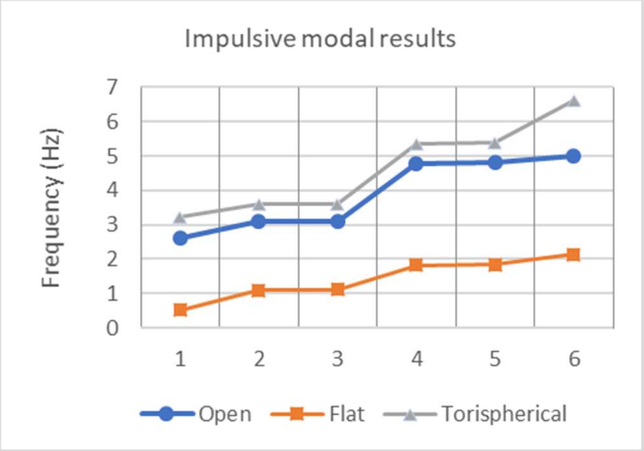


Figure 11. Impulsive modal analysis results and frequencies

Figure 12 shows very different results in convective mode, with the open-top tank and the values in the flat-closed tank overlapping, the torispherical tank has the lowest frequency and deformation.

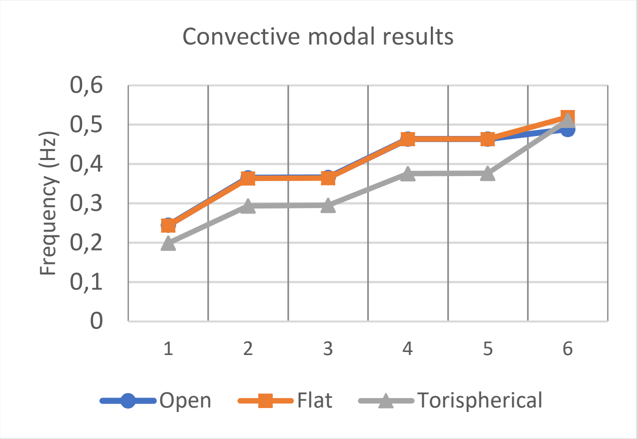


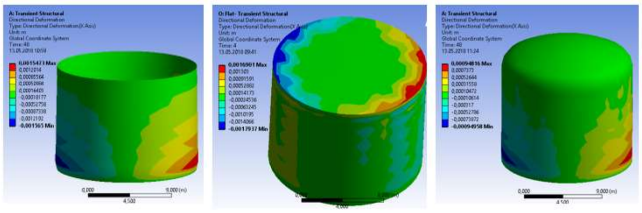
Figure 12. Convective Modal Analysis Results and Frequencies

4. TIME-HISTORY ANALYSIS AND DIRECTIONAL DEFORMATION

Time-history analysis is used to determine the dynamic response of a structure to on arbitrary loading. Displacements, accelerations and speeds will depend on ground motion, if the load includes ground acceleration. This analysis is a step-by-step analysis of a dynamic response to a given load, which can vary with time. Any number of time-history analysis cases can be defined. The time history analysis results may differ according to the load applied and the type of analysis to be performed. In this study time-history analysis using the Kobe earthquake (The Great Hanshin earthquake-1995 with a magnitude scale of 7 in Japan) was performed. The time history response of the tanks are separated into impulsive and convective components in order to perform the time-varying response characteristics of the tank models.

4.1 Impulsive Directional Deformation Under Kobe Earthquake

The transient behaviour of the contained water for Kobe earthquake is shown in Figure 13 and the results are compared with that of impulsive directional deformation. The directional deformation occurs when the horizontal directional motion of the storage tank. These analyses were conducted using ANSYS transient structural tools. Figure 13 shows impulsive directional deformation for open, flat and torispherical tank models. Directional deformation of the open-top and torispherical-shaped tanks occurs at the bottom of the tank, whereas the top is seen to slide upward in the flat-closed model. Red colours show maximum deformation. While the maximum directional deformation was 0.0015473 m in open-top tank, the highest deformation was 0.0016901 m in flat-closed model and the lowest deformation is found in the 00094816 m torispherical-closed model.



a) Open-top b) Flat c) Torispherical

Figure 13. Impulsive Directional Deformations

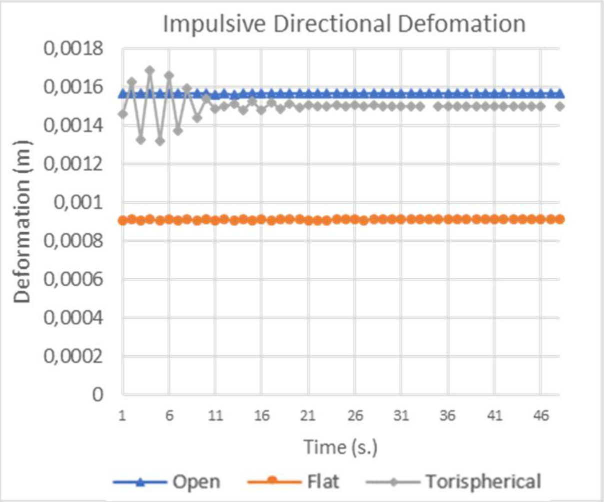
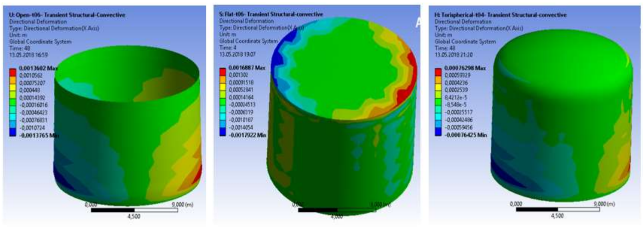


Figure 14. Impulsive directional deformation

From Figure 14 the maximum directional deformation in the impulsive mode is seen. The maximum deformation is 0,001690 m at approximately 4 sec for the flat-closed tank model. The open-top tank model and the torispherical-closed tank model have very low linear deformation values.



a) Open b) Flat c) Torispherical

Figure 15. Convective Directional Deformation

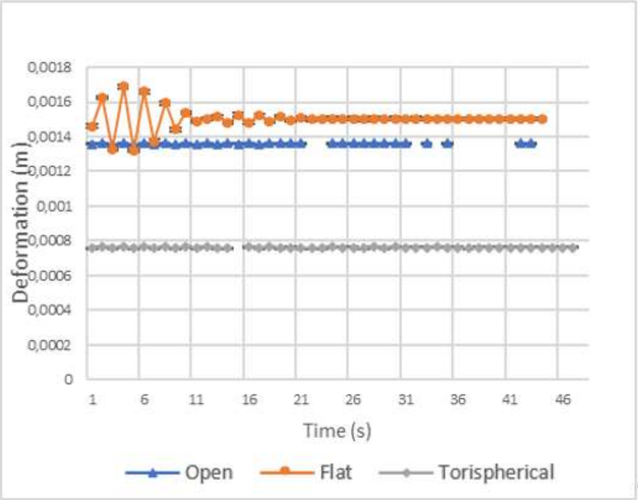
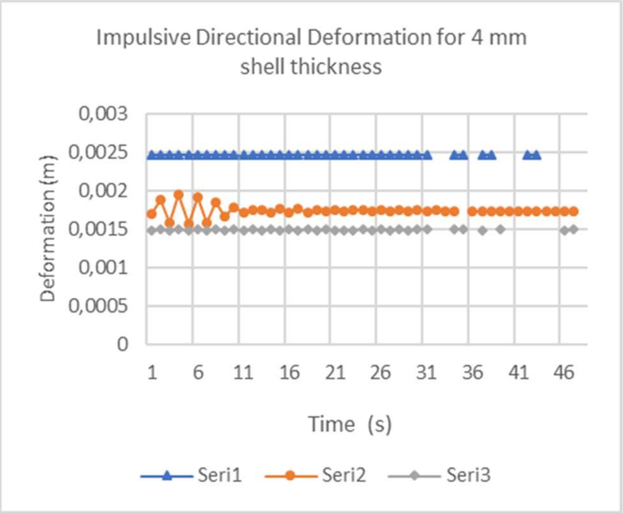
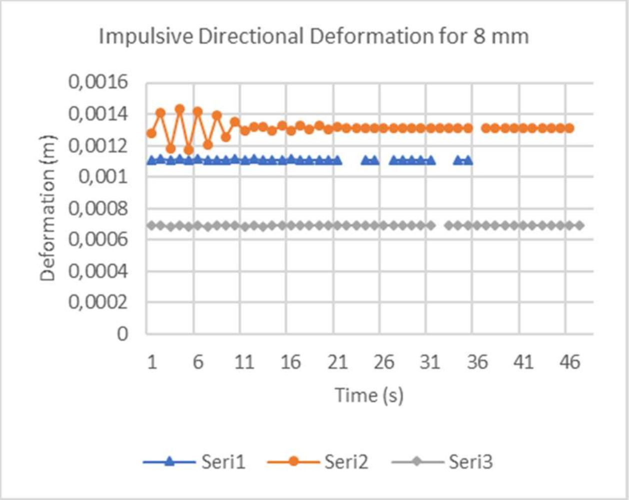


Figure 16. Impulsive directional deformation



a) Directional deformation for 4 mm shell thickness



b) Directional deformation for 8 mm shell thickness

Figure 17. Impulsive directional deformation for (a) 4 mm and (b) 8 mm shell thickness

4.2. Convective Directional Deformation Under Kobe Earthquake

In this section, the seismic analysis was performed for all tanks in the convective period. In Figure 15 the convective maximum directional deformation is 0.001142 m for the flat tank model whereas convective maximum directional deformation is 0.000804439 m for the open-top model and remains 0.00047955 m for the torispherical tank.

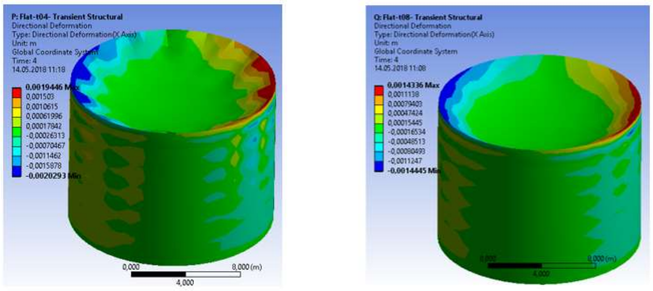
In Figure 16, open-top, flat and torispherical-closed-top models are compared. It is apparent that torispherial top model has lower deformation than open-top model.

Maximum deformation occurs in the flat-closed tank during at approximately 4 sec. The flat-closed tank does not provide any advantage in terms of directional deformation. It can be said that for studied cylindrical steel water tanks, when their tops are closed in a torispherical shape, they undergo less deformation under earthquake loads.

4.3. Buckling and Directional Deformation Analysis with Different Shell Thickness

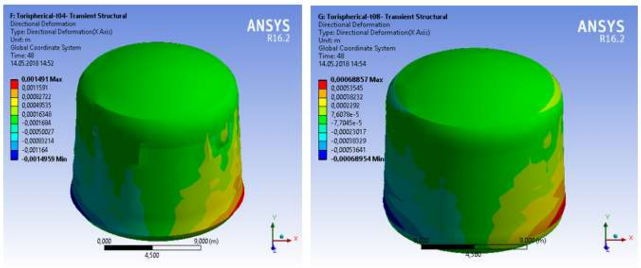
The shell thickness of the model tanks should be 6 mm according to API 650 standard. In order to be able to see the buckling in the shell, analyses were repeated for 4 mm and for 8 mm shell thickness. These thickness measurements are 2 mm lower and 2 mm higher than that given in the standard. In Figure 17 (a), directional deformation is decreased with flat-closed and torispherical-closed tank, but Figure 17 (b) flat-closed tank has maximum deformation.

Figures 18 (a) and 18 (b) show deformation and buckling in the flat-closed tank roof. In Figure 18 (a), the reduction of the shell thickness to 4 mm caused the buckling of the roof to increase. In Figure 18 (b), it is observed that buckling was decreased with shell thickness was 8 mm, but the center of the pressure was changing and more deformation occurs because the roof is flat.



a) For shell thickness of 4mm b) For shell thickness of for 8mm

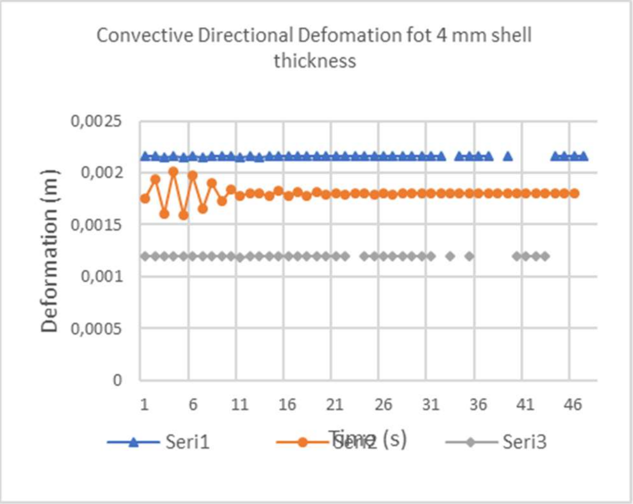
Figure 18. (a and b) Buckling of roof in flat-closed tank for 4 mm and 8 mm shell thickness



a) Buckling of flat tank for 4mm b) Buckling of flat tank for 8mm

Figure 19. (a and b) Buckling of roof in torispherical-closed tank for 4 mm and 8 mm shell thickness

a) Buckling of flat tank for 4mm shell thickness



b) Buckling of flat tank for 8mm shell thickness

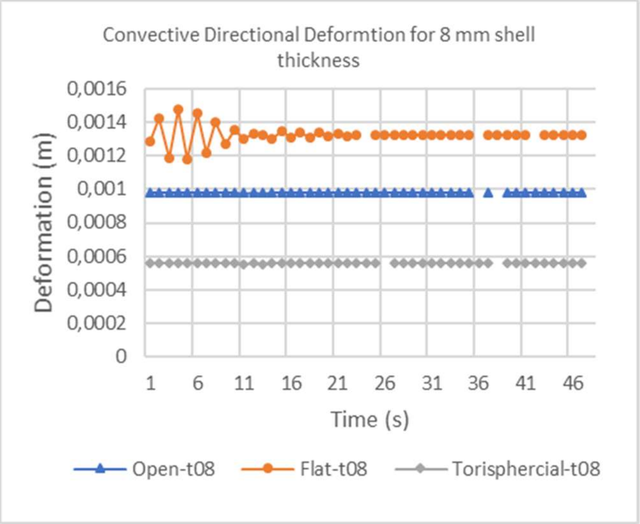


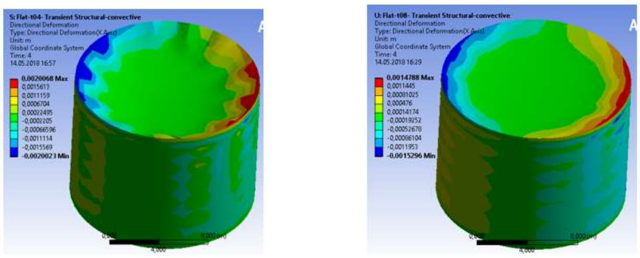
Figure 20. (a and b) Convective directional deformation of tanks for 4 mm and 8 mm shell thickness

As a result of the simulations made with 4 mm shell thickness in Figure 19(a) and 8 mm shell thickness in

Figure 19 (b), the torispherical-closed cylindrical tank shell was also buckled. 4 mm of crustal thickness causes both upper and lower surface of tank buckling of the tank. It is observed that buckling was decreased with 8 mm thickness and the buckling was occurred only on the upper side of tank in Figure 19(b).

Simulations and analyses were repeated within the convective region. Figure 20 (a and b) show the results of directional deformation for all tanks with 4 mm and 8 mm shell thickness. It appears that the flat-closed of the cylindrical steel tank roof, especially with increased shell thickness, does not provide an advantage here. In Figure 20 (b), it is observed that the directional deformation in the flat-closed tank is exerted by the effect of sloshing, while the deformation in the torispherical-closed tank is almost close to zero.

In Figure 21(a), the buckling seems to be excessive in flat closed tank, while in Figure 21 (b) the buckling is reduced by a shell thickness of 8 mm.



a) b)

Figure 21. (a and b) Convective buckling of roof in flat-closed tank for 4 mm and 8 mm shell thickness

Figure 22 (a) and (b) shows convective directional deformation and buckling deformations for 4 mm and 8 mm shell thickness. It seems that these two models have less buckling. Particularly when the crustal thickness is 8 mm, buckling was reduced.

a) b)

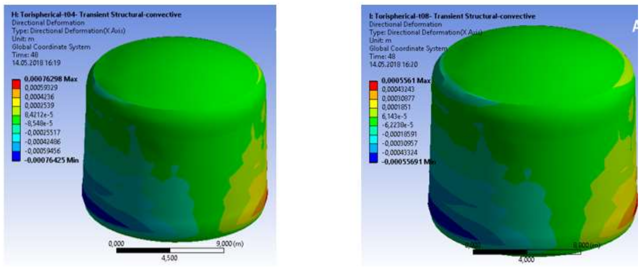


Figure 22. (a and b) Convective buckling of roof in torispherical-closed tank for 4 mm and 8 mm shell thickness

5. CONCLUSION

Many cylindrical steel tanks were damaged after earthquakes such as the 1940 El-Centro earthquake (or imperial valley earthquake) with a magnitude of 6.9 in Mexico USA, 1995 Kobe earthquake (or the Great Hanshin earthquake) with a magnitude of 7 in Japan and the 1999 İzmit earthquake (also known as the Kocaeli, Gölcük or Marmara earthquake), whose main shock had a moment magnitude of 7.6 (occurred on 17 August at 03:01:40 local time in north-western Turkey). Marina et al [28] reported that observations of damages after important earthquakes may provide insight into the various failure modes and possible areas where the design process may need more elaboration. Moreover, Priestley et al., Barros and the 2011 guidelines of the Petrochemical Committee of the Energy Division of the American Society of Civil Engineers [in ref. 27] investigated types of failures such as elephant-foot buckling, damage of the upper shell and weld failure between the bottom plate and the tank shell as a result of high-tension forces during the uplift.

This paper investigates effects of shell thickness under the Kobe earthquake of open-top, flat-closed and torispherical-closed cylindrical steel water tanks using finite element method. In order to obtain response parameters of interest as functions of time, the basic hydrodynamic equations (API 650) solutions are summarized.

Modal analysis was first performed. Impulsive and convective modal analysis results were obtained separately. The frequency values calculated using API 650 were verified with the FEM model results. Then, seismic analysis was performed with the FEM models to examine the time-dependent movements of the cylindrical steel water tank. Maximum directional deformations occurred in the flat-closed tank. The biggest buckling deformations occurred in flat-closed tank. One of the main reasons for this is that the center of pressure changes due to the flatness of the roof tank. The deformation calculation was performed via transient structural analysis which was not exceeding the limit of the tank, so that the tank can be safe under the analysis condition.

The most significant finding in this study is that if the top of the tank is in the shape of a torispherical dome, the deformation is majorly reduced. The flat-closed tank has a maximum directional deformation in both impulsive and convective modes. As a result, the flat-closed roof tank does not provide any advantage in directional deformation, if the tank is flat-closed, the deformations and buckling will be more likely to occur even if the shell thickness is increased. It can be concluded that the existing tanks may be prevented from being damaged by being closed in the shape of a torispherical dome so that they are not damaged by directional deformation during the earthquake.

REFERENCES

[1] Bayraktar A, Sevim B, Altunışık A C, Türker T. "Effect of the model updating on the earthquake behavior of steel storage tanks*." J Constr Steel* Res, 2010, 66: 462–468

[2] Veletsos, A.S., and Tang, Y. "Soil-structure interaction effects for laterally excited liquid storage tanks*", Journal of Earthquake Engineering and Structural Dynamics, Vol. 19, No. 4*, 1990: 473-496

[3] Lysmer, J., F. Ostadan, M. Tabatabaie, F. Tajirian, S. Vahdani*, "A System for Analysis of Soil-Structure Interaction" (SASSI2000)– User's and Theoretical Manual.* Thechnic, California: Department of Civil and Environmental Engineering, University of California, 1999.

[4] Haroun, M. A. and G. W. Housner. "Seismic Design of Liquid Storage Tanks" *Journal of the Technical Councils of ASCE*, April,1981-1.

[5] Y. Tang, "Dynamic-response of tank containing 2 liquids", *J. Eng. Mech*. ASCE 119 (3) (1993) 531–548.

[6] F.H. Hamdan, "Seismic behaviour of cylindrical steel liquid storage tanks", *J. Constr. Steel Res*. 53 (3) (2000) 307–333.

[7] Housner, G. W.,"Earthquake Pressures on Fluid Containers", *Eighth Technical Report under Office of Naval Research, Project Designation* No. 081 - 095, California Institute of Technology, Pasadena, California, pp. 02-16, Aug.-1954

[8] Housner G. W. "Dynamic pressures on accelerated fluid containers", *Bull Seismol Soc Am*, 1957, 47(1): 15–35

[9] Housner G W. "The Dynamic Behavior of Water Tanks", *Bull Seismol Soc Am*, 1963, 53(2): 381–387

[10] Praveen K., M. Thomas W., Martin W., "Simple Procedure for Seismic Analysis of Liquid-Storage Tanks", *Structural Engineering International* 10(3):197-201, 2000

[11] Malhotra P K, Wenk T, Wieland M. "Simple Procedure for Seismic Analysis of Liquid-Storage Tanks", *Struct Eng Int*, 2000, 10(3): 197–201

[12] Sunitha K R, Jacob B., "Dynamic Buckling of Steel Water Tank Under Seismic Loading", *International Journal of Civil Engineering* (IJCE), 2015, 4(6): 81–90

[13] Mohamadshahi M, Afrous A., "General considerations in the seismic analysis of steel storage tanks", *Journal of Scientific Research and Development,* 2015, 2(6): 151–156

[14] Brebbia C A, Popov V, Popov V. "Thirty-third international conference on Boundary Elements and Other Mesh Reduction Methods" *XXXIII. Southamption: Wit Press,* 2011,286, web link: https://books.google.com.tr/books?id=bOwoKUfWONIC&printsec=frontcover&hl=tr#v=onepage&q&f=false

[15] Naghdali H, Hamid K, Masoud G, Ehsan A, Navid K. "Comparison of API650-2008 provisions with FEM analyses for seismic assessment of existing steel oil storage tanks", *J Loss Prevent Proc Ind* 2013;26(4).

[16] J.M. Spritzer, S. Guzey, "Review of API 650 Annex E: Design of large steel welded abovegroun storage tanks excited by seismic loads", *Thin-Walled Structures*, vol 112, pp 41–65, 2017.

[17] J.M.Spritzer S.Guzey, "Nonlinear numerical evaluation of large open-top aboveground steel welded liquid storage tanks excited by seismic loads", *Thin-Walled Struct*., Volume 119, October 2017, Pages 662-676

[18] S. Nicolici, R.M. Bilegan, "Fluid structure interaction modeling of liquid sloshing phenomena in flexible tanks*", Nucl. Eng. Des*. 258 (2013) 51–56.

[19] M. R. Maheri, M. E. Karbaschi "Dynamic properties of unanchored circular ground-based steel tanks", *Thin-Walled Structures*, https://doi.org/10.1002/cepa.490 September 2017, Copenhagen, Denmark

[20] M. Ormeno, T. Larkin, N. Chouw, "The effect of seismic uplift on the shell stresses of liquid-storage tanks", *Earthq. Eng. Struct.* D 44 (12) (2015) 1979–1996.

[21] H. Nemati, G. Ghanbari, "Buckling Pressure In Double Wall Cryogenic Storage Tank By Fem", *Emirates Journal for Engineering Research*, 19 (1),43-48 (2014) (Regular Paper),

[22] Lindie Brewer. U.S. Geological Survey, Buckled Water Tank Lifted Off Base By Landers Earthquake,https://www.ngdc.noaa.gov/hazard/icons/med_res/17/17_344.jpg, available date: 15.05.2018

[23] A Guide to the American Petroleum Institute's 650 (API 650), "Welded steel tanks for oil storage", 12th Ed., *American Petroleum Institute*, 2013

[24] Ozdemir Z, "Interaction Fluide Structure et Analyse sismique pour les déformations non linéaires de réservoirs" *These pour obtenir le grade de, Université des* Sciences et Technologies de Lille Laboratoire de Mécanique de Lille (UMR CNRS 8107)

[25] Kuan, Siew Yeng. "Design, Construction and Operation of the Floating Roof Tank", Course ENG 4111 and ENG 4112 *Research Project*, University of Southern Queensland Faculty of Engineering and Surveying.

[26] Bedri R, Al-Nais M O. "Pre-stressed Modal Analysis Using Finite *Element", Package ANSYS' Lecture Notes in Computer Science*, 2005, 3401

[27] Jacobsen L S. "Impulsive hydrodynamics of fluid inside a cylindrical tank and of fluid surrounding a cylindrical pier" *Bull Seismol Soc Am*, 1949, 39(3): 189–204

[28] Marina E.Kalogerakoua Charilaos, A.Maniatakisa, Constantine C.Spyrakosa Prodromos N.Psarropoulosb, "Seismic response of liquid-containing tanks with emphasis on the hydrodynamic response and near-fault phenomena", *Engineering Structures* Volume 153, 15 December 2017, Pages 383-403

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