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Research Article

DIRECTIONAL-DEFORMATION ANALYSIS OF CYLINDRICAL STEEL WATER TANKS SUBJECTED TO EL-CENTRO EARTHQUAKE LOADING

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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 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 due to their simplicity design and performance of resistances against seismic loads, when compared with other configurations. Earthquakes are a natural occurrence and are unpredictable and complex; thus, the steel storage liquid tanks are expected to withstand earthquake-related loads. These tanks may be exposed to some damages such as elephant-foot buckling, diamond-shape buckling, overturning and uplifting during earthquakes. They can also cause great financial and environmental damage with their hazardous chemical contents. Dimensions of 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 storage liquid tanks. Seismic analyses were conducted under El-Centro earthquake loads. Directional deformation, equivalent stress and acceleration results were presented for both impulsive and convective regions. In this study, directional deformations of the tanks with the same diameter and three different roofs (open-top, flat-closed and torispherical-closed) were compared after the seismic analysis. The results show that if the cylindrical steel water tank roof is closed in a torispherical dome shaped, the directional deformation will decrease. Hence, torispherial roof shape of tank is recommended.
Keywords: Cylindrical storage tank, API 650, FEM analysis, seismic analysis.

1. INTRODUCTION

Cylindrical steel tanks are widely used for storing water and cooling in nuclear power plants. Because of their importance, they should not be damaged during earthquakes. Contrary to other constructions, these structures are in contact with the liquid and their response under a seismic load is quite different. Due to the fluid–structure interaction, the behaviours of storage tanks are extremely complicated during earthquakes, which leads to a tedious design process [1]. When a

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tank containing liq uid is subjected to earthquake movement, the liquid is subjected to horizontal acceleration. The tank walls will be exposed to hydrodynamic pressure. The fluid at the bottom of the tank moves a mass which 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 idea of the separation of the response to the contribution of a single impulsive mode and a number of convective modes are followed belong to Housner [2]. The liquid mass in the upper part of the tank experiences a sloshing motion which is called as convective fluid. Thus, the hydrodynamic response is divided into impulsive and convective components to accurately investigate dynamic behaviour of tanks. Housner proposed a two mass model for a cylindrical tank. 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 [3,4].

Field investigations have been performed by various researchers to determine the type of damage that occurred in liquid in earthquakes and the factor causing these damages. In the field surveys, it has been revealed that liquid tanks are performing poorly under the influence of earthquakes and it has become necessary to develop new methods for increasing earthquake resistance. According to Preveen et al., When the liquid storage tanks are subjected to strong shaking, they react non-linearly and suffered some damage. However, it does not perform non-linear seismic analysis of tanks with generally acceptable methods. Therefore, the damage sustained by tanks seismic excitation of different intensities cannot be easily determined [5]. Generally, very thin peripheral walls are used in the construction of steel storage reservoirs for a simplicity and low cost. However, these cylindrical steel tanks are thin-shelled structures that are subject to internal pressure from stored liquid alongside lateral pressure that can arise from roof loads, horizontal loads such as earthquakes and the frictional drag of stored materials on the walls [6]. There are two important factors that impact the steel tanks' deformation after earthquake: the characteristics of the earthquake's force and the dynamic characteristics of the structure. Steel structure is affected by ground components that comprise two lateral components, a vertical component and three tensional components [7]. Steel storage tanks take several deforms under the earthquake loads. Large axial compressive stresses due to beam-like bending of the tank wall can cause elephant-foot buckling of the wall. Their roof and top can be damaged due to the sloshing liquid [8].

There are various methods for the seismic analysis of tanks, such as the API 650 formulation method, boundary conditions technique and finite element method. API 650 design code is based primarily on the Housner's study [3,4]. In order to perform the seismic analysis of steel storage tanks, Housner developed a useful tool called the spring mass analogy that experienced seismic forces 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., researched existing tanks using the API650 code standard and the numerical finite element model based on ANSYS engineering software. The results show that in some cases there are some flaws in API 650 requirements that require further investigation [9].

Spritzer and Guzey reviewed the design provisions in Annex E of API 650, comparing with well-known design documents throughout the world, including New Zealand and Japan. The liquid in the tank accelerates horizontally and compel forces on the tank wall during the earthquake. In addition, in the standards they are compared, damage situations such as hydrodynamic hoop stress, uplift, base buckling, freeboard, stress and overturning were taken into consideration. when compared to New Zealand and Japanese design documents, API 650 Annex E can be considered to take sufficient account of all major error situations [10].

In recent years, the tendency towards finite element modeling (FEM) 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 Bilan focused on the computational fluid dynamics (CFD) analysis to estimate the effect of sloshing wave amplitude, convective mode frequency, pressure applied to 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 [11].

Maheri et al, 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 show that the method can determine the frequency of sloshing of liquid filled tanks with acceptable accuracy. It has also been observed that there is a substantial reduction in the initial natural frequency of the tank [12].

In a study by Ormeno et al, to evaluate the seismic response of steel tanks, 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 [13].

The finite element method has advantages during solving general problems with a complex structure shape. In this article, some basic seismic values were calculated by the API 650 standard, followed by the El-Centro earthquake data being used for the non-linear analysis. Unlike previous studies, the top of the tank in this study was flat-closed and torispherical-closed, for the directional-deformation analysis. The most important goal of this work is to protect the existing tanks from seismic damage by closing them in the shape of a torispherical dome.

2. SEISMIC ANALYSIS OF CYLINDRICAL STEEL TANK

Seismic behaviour of cylindrical steel storage tanks under seismic loading include several critical failures to the structure that are not exhibited during normal operating levels. There are main risks such as, the hydrodynamic-hoop stresses, sloshing forces and uplift, elephant-foot buckling or the diamond-shaped buckling. These failure criteria are generally calculated using the design standard developed by the American Petroleum Institute in the United States (API650) [14]. This standard has been used worldwide for a seismic-friendly design of steel storage tanks. API 650 code standard determines the minimum requirements for material, design, manufacturing, assembly and testing for vertical, cylindrical, aboveground, open top and closed top tanks as well as steel storage tanks of various sizes and capacities (internal pressures not exceeding the weight of the roof plates), but a higher internal pressure is permitted when additional requirements are met [15]. Impulsive and convective components of the seismic load have been calculated via the API-650 as well as the finite element method. The values of the model tanks were specified in Table 1.

Table 1. Model Parameters of Tanks and Material

Parameter and unit	Open-top tank parameter value	Flat-closed tank parameter value	Torispherical-closed tank parameter value
Inner diameter of tank m.	15.08	15.08	15.08
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 modulus of tank GPa.	200	200	200
Poisson ratio of tank ***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 description of hydrodynamic pressure distribution on tank wall are presented Figure 1.

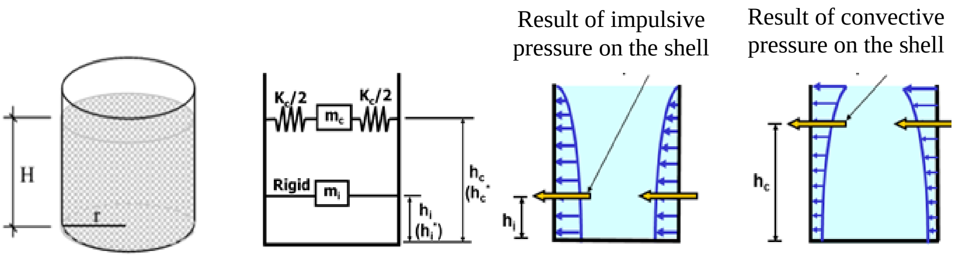


Figure 1. Spring-mass model of tank and the hydrodynamic pressure distribution on the wall [2].

2.1. Impulsive Natural Period

The impulse mode refers to the lateral mode of the tank–liquid system, and the lateral seismic forces applied to the tank depend on the period of this mode. Contrary to the assumption initially made by Housner that because the tank is solid, the impulsive mode period is zero; the current design practice calculates the impulse mode depending on the value of the impulsive mass and the rigidity of the tank shell, but uses the code used in Housner's method (API 650). The mass density of the tank wall is not included in the impulse period expressions given in the codes; instead, the mass density of liquid is used because the mass of the wall is usually quite small compared with the liquid mass for steel tanks. The first impulsive mode period of a flexible anchored tank is ≤0.5 s [16].

2.2. Convective Sloshing Period

The period of convective (sloshing) mode depends on the diameter of the tank and to a lesser extent on the depth of liquid. The periods of convective mode are very long (up to 6–10 s 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 (1954). Convective mode is often referred to as "sloshing" mode due to fluid waves created during seismic events. However, the model developed by Housner, is based on the studies of Jacobsen, who developed expressions for impulsive fluid pressures on cylindrical tanks with a rigid foundation connection and non-deformable walls [17].

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 2.

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 total volume of water = $\pi R^2 h = \pi \times 7.54^2 \times 10 = 1780.4\ m^3$ (1)

Mass Density of Water = 1000 kg/m^3

Thus, the total mass of water in the tank = m_w = 1000 x 1780.4 = 1780400Kg

Mass of impulsive equation $$m_i = m_w \frac{\tanh(0{,}866\frac{D}{H})}{(0{,}866\frac{D}{H})} \quad (2)$$

m_i =1176875.813 Kg

Mass of convective equation $m_c = 0.455 * \pi * \rho_l * R^3 * \tanh\left(1.84\frac{H}{R}\right)$ (3)

m_c =603291,22 Kg

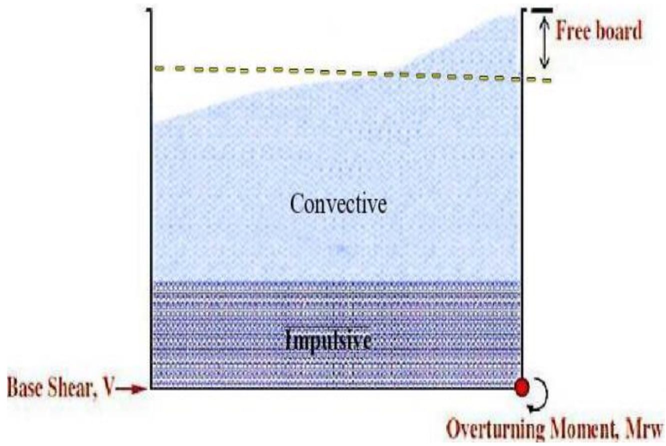


Figure 2. Seismic diagram of tank [18].

The total fluid mass may be slightly larger than the sum of the impulsive and convective masses [15]. Some seismic analysis results obtained for this study according to API 650 are presented in Table 2.

Table 2. Results calculated of cylindrical model tank according the API 650 formulation.

Title	Value
The total volume of water	1780.4 m^3
Total mass of water in the tank	1780400 Kg
Ratio of radius to water height	0.754
Ratio of height to radius	1.32
Mass of impulsive	1176875.813 Kg
Mass of convective	603291,22 Kg
Location of impulsive mass	3.75 m
Location of convective mass	7.60 m
The natural frequency of impulsive mass	3.26 Hz
The natural frequency of convective(sloshing)	0.246 Hz
The impulsive period $\boldsymbol{Ti}$	0.29 sec
The convective period $\boldsymbol{Tc}$	3.29 sec
Mass of Shell	5939.14 Kg
Weight of Fixed Roof	1146.58 Kg
Location of System $\mathbf{h_s}$	5.08 m
Sloshing height of Water **d**	0.96 m
Calculating the base shear $\boldsymbol{V}$	3613896.79 N
The Seismic Overturning Moment	21875380.59 N
Minimum yield Strength	345 MPa
Min. Tensile Strength	485 MPa
Design Stress (S_d)	194 MPa
Hydrostatic Stress(S_t)	208 MPa

3. SEISMIC ANALYSIS WITH FINITE ELEMENT METHOD

This section deals with the seismic analysis of ground-supported cylindrical steel water tanks. In this study, the dynamic results of the finite element method are presented for open-top, flat-closed and torispherical tanks.

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 [18].

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 poisson'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 [19].

Three cylindrical steel tank models with different aspect ratios, 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. Design of tanks and their size are shown below in figure 3.

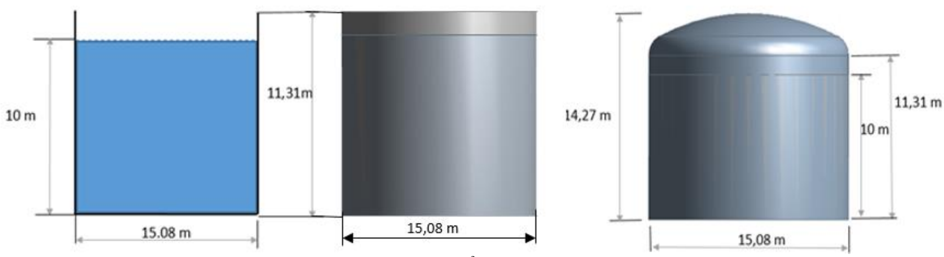
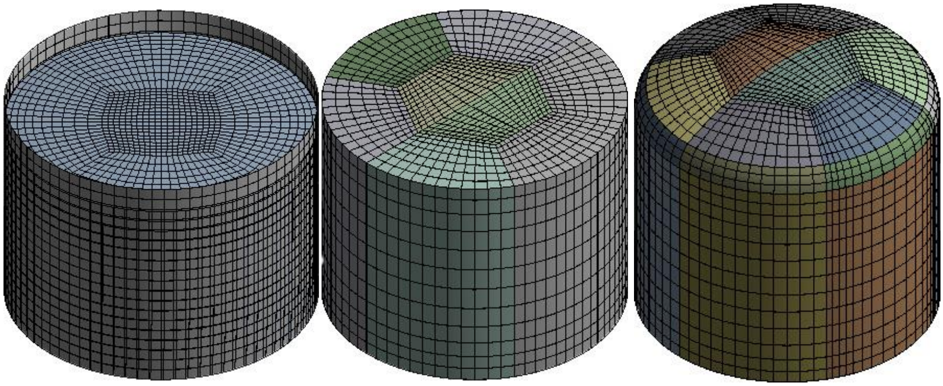


Figure 3. Three configurations of tank

3.1.1. Verification of Model

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/m^3, Young Module 210 GPa and Poisson Ratio 0.3. Water density of water 1000 kg/m^3 and bulk module 2.2 GPa were determined.

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 4.



a) Open-top tank b)Flat-closed tank c) Torispherical-closed tank

Figure 4. Meshed view of tanks

3.1.2. Modal Analysis of Open Tank Model

In designing a structure that is exposed to a dynamic load, the natural frequencies and mode shapes of a structure are very important. They can be considered as a starting point for a transient analysis. These modes are also excited, when the response of a structure can be evaluated. Modal analysis was performed in ANSYS Workbench software.

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. It is assumed that the damping factor is 2% for both tanks. The first 6 mode and frequency values of the open tank model are shown in Figure 5.

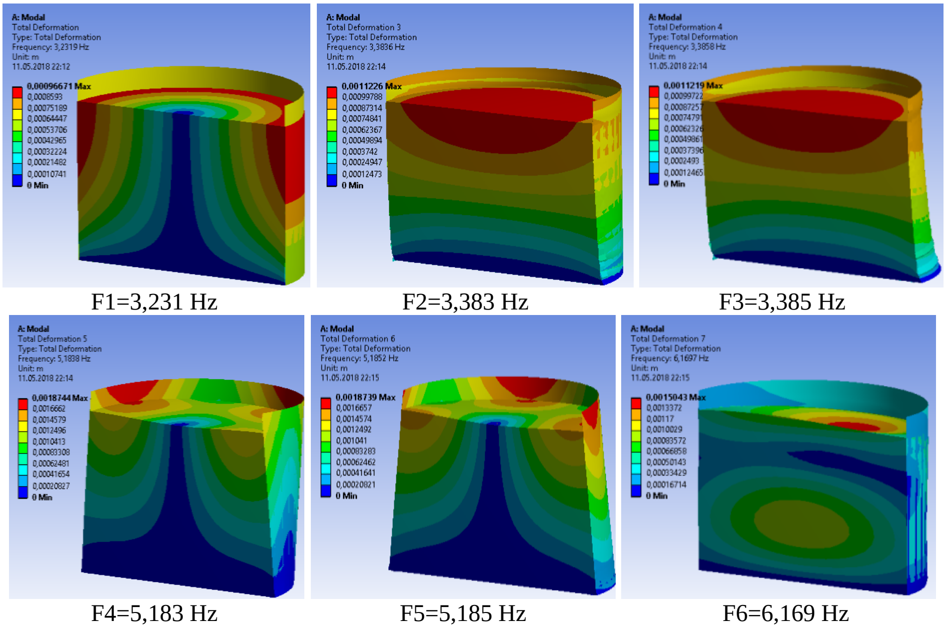


Figure 5. Impulsive Modal Analysis Results and Frequencies

The motion of contained fluid in vertical cylindrical tanks on ground, fixed under the base of tank may be expressed as the sum of two separate contributions, called ‘impulsive’ and ‘convective’, respectively. When the water tank is accelerated under seismic conditions, a part of the liquid mass moves in unison with the tank. This liquid mass is known as the impulsive mass. 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, and represents the liquid mass causing the liquid face sloshing. The point 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 6.

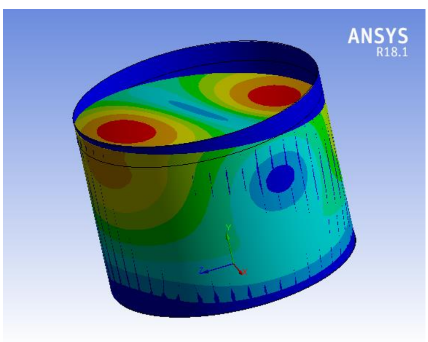


Figure 6. Convective (Sloshing) Effect

The interaction between structure and liquid has vital importance. Great effort was made to accurate 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 compared with the analytically calculated method. The first 6 convective modes are shown in figure 7.

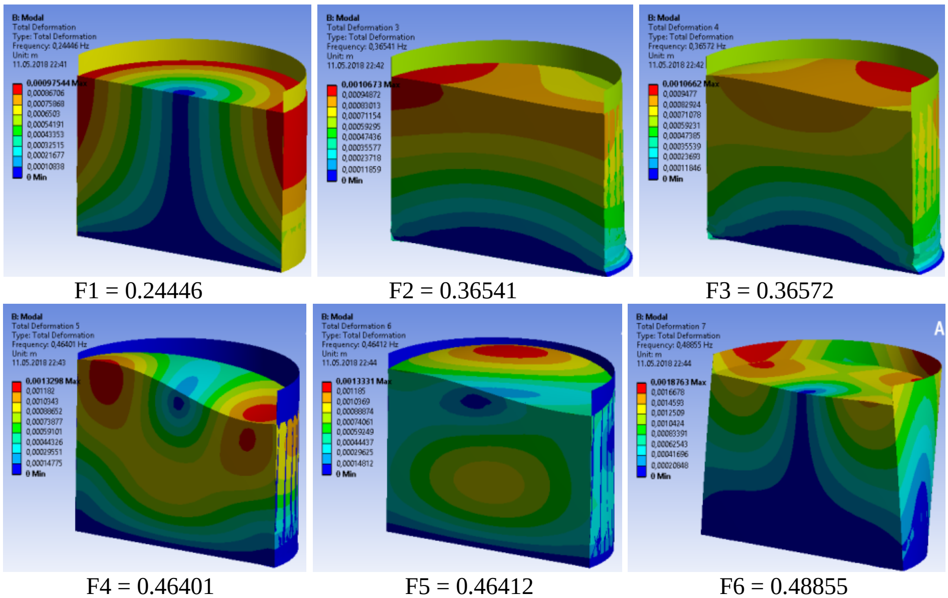


Figure 7. Convective Modal Analysis Results and Frequencies

Table 3 compares the results between the FEM analysis frequencies and the API 650 formulation calculated first frequency values respectively.

Table 3. Modal Analysis Results of the circular steel water tank

Mod.	Impulsive Frequency (Hz)		Convective Frequency (Hz)	
No	FEM Model	API650	FEM Model	API650
1	3.2319 Hz	3.26 Hz	0.24446 Hz	0.246 Hz
2	3.3836 Hz	NA	0.36541 Hz	NA
3	3.3858 Hz	NA	0.36572 Hz	NA
4	5.1838 Hz	NA	0.46401 Hz	NA
5	5.1852 Hz	NA	0.46412 Hz	NA
6	6.1697 Hz	NA	0.48855 Hz	NA

Modal analysis was performed for three different roof-type tanks, which are the open-top, flat-closed and torispherical-closed tanks. Furthermore, frequency modes have also been compared to determine presence of a roof on the impulsive and convective periods. These comparisons are shown with graphs in the figure 8 and figure 9. In figure 8, the flat-closed-top tank model in the impulsive period attracts attention with its low frequency values and low deformation values. Torispherical-closed-top tank has maximum frequencies and deformation values.

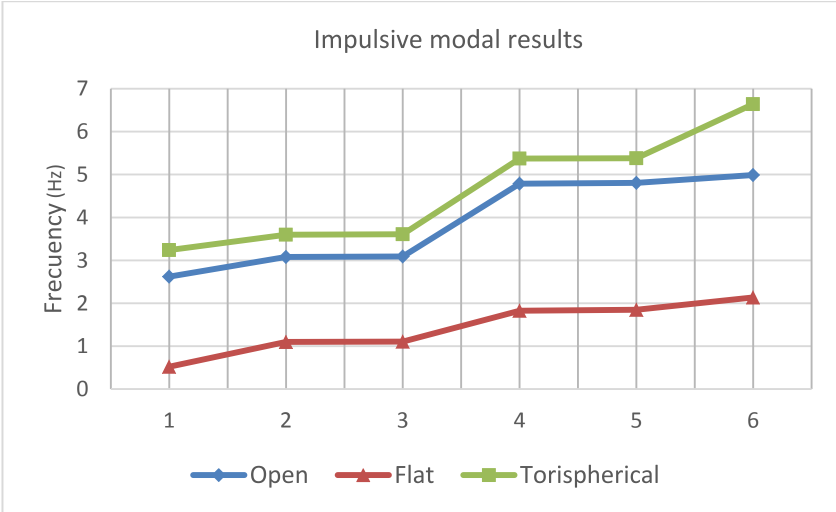


Figure 8. Impulsive Modal Analysis Results and Frequencies

Figure 9 shows very different results in convective period, with the open tank and the values in the flat-closed tank overlapping at the same time, the torispherical tank has the lowest frequency and deformation.

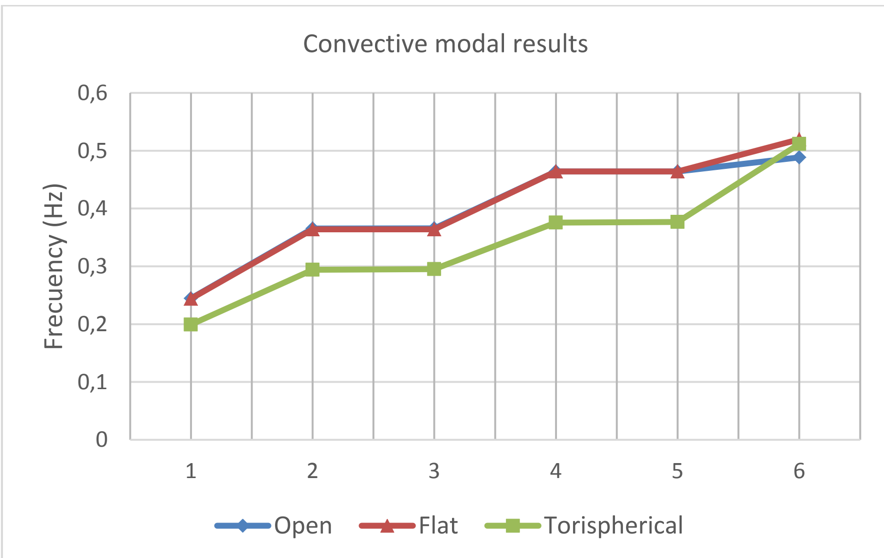


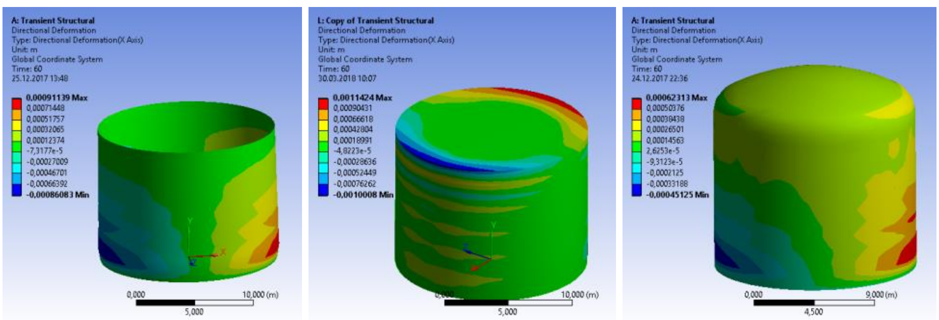
Figure 9. Convective Modal Analysis Results and Frequencies

4. TIME-HISTORY ANALYSIS AND DIRECTIONAL DEFORMATION

Time-history analysis is a step-by-step analysis of the dynamic response of a structure to a specific load that may vary with time. Time-history analysis generally is used to determine the dynamic response of a structure under arbitrary loading. In time-history analysis, the analysis may not be linear or nonlinear. Load, ground acceleration, displacements, speeds and accelerations vary according to ground motion. Any number of time-history analysis cases can be defined. The time history can always differ according to analysis and load applied to be performed. Time-history analysis using the north–south component of the 1940 El-Centro (Magnitude: 6.9) earthquake was performed. The time history of the tanks is 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 El-Centro Earthquake

The transient behaviour of the contained water for El-Centro earthquake is shown in figure 10 and the results are compared with that of impulsive directional deformation. These analyses were conducted using ANSYS transient structural tools. Figure 10 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.



a) Open-top tank   b) Flat-closed tank   c) Torispherical-closed tank

Figure 10. Impulsive Directional Deformation

From figure 11 the maximum directional deformation of the impulsive deformation is seen. The maximum deformation is 2,5 X 10^{-3} m at ≈8 s for the flat tank model.

4.2. Convective Directional Deformation Under the El-Centro Earthquake

In this section, the analyses were repeated according to the convective region. The seismic analysis was performed for all tanks in the convective period. In figure 12 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. Here, in the flat-sealed tank, the maximum deformations occurring on the cover edges with the sloshing effect are clearly seen.

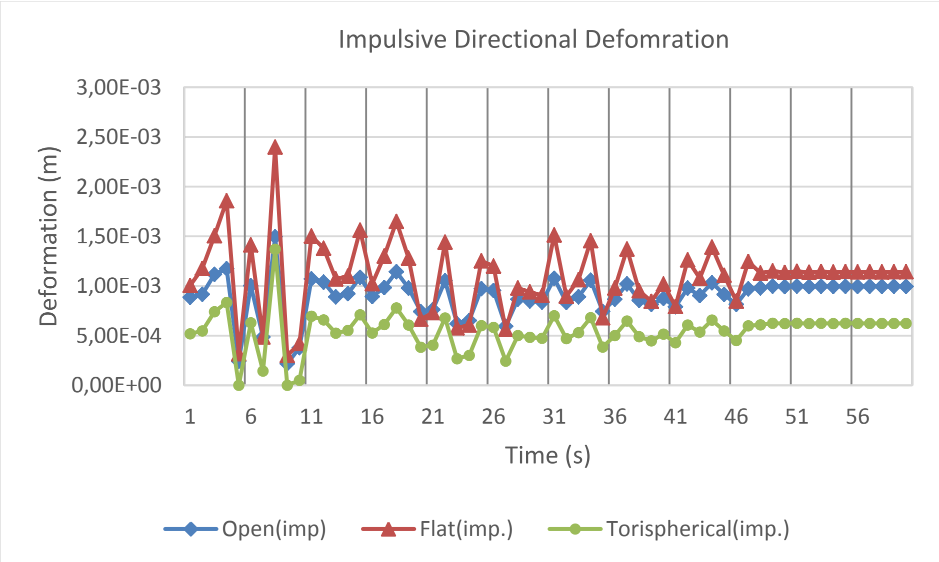
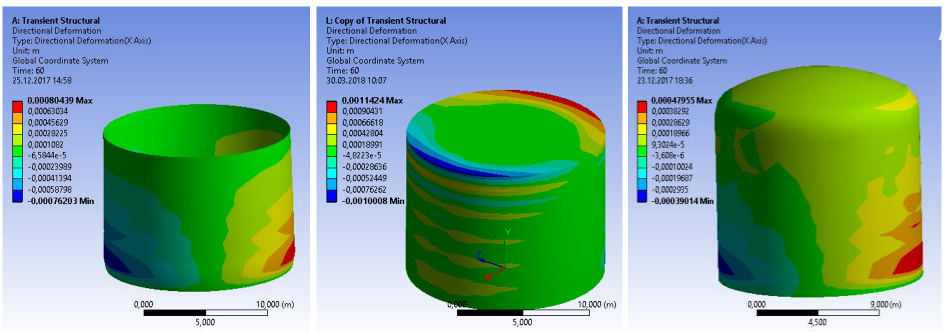


Figure 11. Impulsive directional deformation



a)Open tank b) Flat-closed tank c) Torispherical-closed tank

Figure 12. Convective Directional Deformation

In figure 13, 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 8 s. The flat-closed tank does not provide any advantage in terms of directional deformation. It can be said that for existing cylindrical steel water tanks, when their tops are closed in a torispherical shape, they will undergo less deformation under earthquake loads.

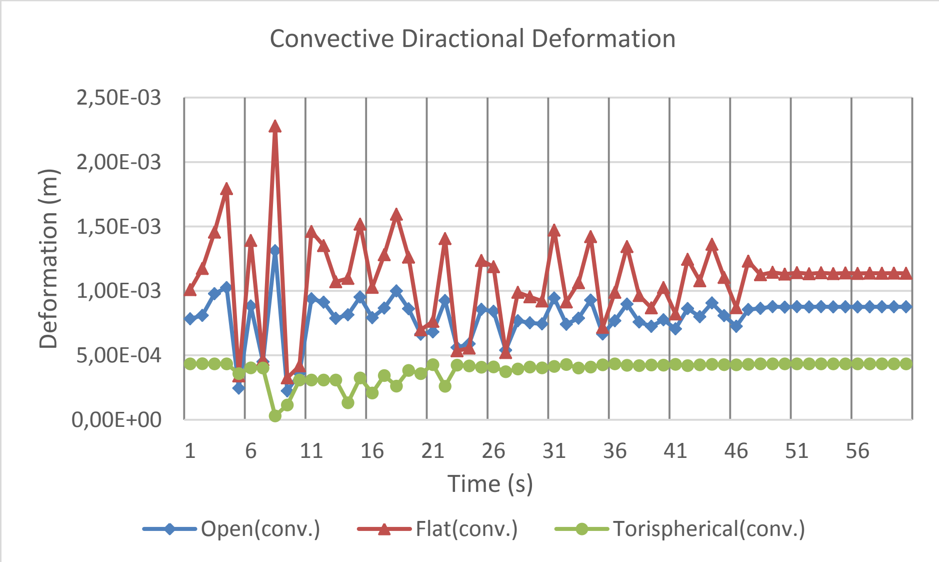


Figure 13. Convective directional deformation graph

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 scale of 7 in Japan and the 1999 Kocaeli, whose the shock had a moment magnitude of 7.6 (occurred on 17 August at 03:01:40 in Turkey). According to the report by Marina et al., observations on damage after major seismic events may provide insight into the various error modes and possible areas where the design process may need more detail [20]. Moreover, Priestley et al. [21], Barros [22], and the 2011 guidelines of the Petrochemical Committee of the Energy Division of the American Society of Civil Engineers [23] observed types of failures such as elephant-foot buckling which is buckle of tank wall above the tank base, damage of the upper shell of the tank wall and weld failure between the bottom plate and the tank shell as a result of high-stress forces during the uplift.

This study deals with the hydrodynamic pressure response of flexible cylindrical steel tanks under earthquake loads. The basic hydrodynamic equations (API 650) solutions are summarized in order to obtain response parameters of interest as functions of time.

Modal analysis was performed at the beginning of this study. Impulsive and convective modal analysis results were optioned separately. The frequency values calculated with API 650 were verified with the FEM model results. Then, seismic analysis was performed with the FEM model to examine the time-dependent movements of the cylindrical steel water tank. Maximum directional deformation occurred in the flat-closed 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 significant finding in this article 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 periods. As a result, the flat-closed roof tank does not provide any advantage in directional deformation, but the existing tanks can 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.

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