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RESEARCH ARTICLE / ARAŞTIRMA MAKALESİ

Impact Analysis of Cylindrical Steel Water Storage Tanks Under the Seismic Action

Sismik Hareket Altında Silindirik Çelik Su Depolama Tanklarının Darbe Analizi

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Abstract
Cylindrical steel liquid tanks are widely used to store various liquids such as water, oil and industrial chemicals. They are used in nuclear power plants for cooling purposes in recent years. Petroleum or other hazardous chemicals in steel liquid tanks can cause large financial and environmental damage due to damages in tanks during the earthquake. The main goal of this paper is to reveal buckling shapes of cylindrical steel tanks with nonlinear seismic analysis according to different roof shapes. Tanks were designed as open-roof, flat-roofed, conical-roofed and torispherical-roofed tanks. For this aim, El-Centro earthquake recording of 0.22 seconds was used for determining the significant shell buckling events. In addition, this earthquake values are ideal for impact analysis because ANSYS Workbench “Explicit Dynamics” tool provides very good results in the dynamic analysis of structures under destructive and short-term forces. In order to provide the interaction between the water and the tank wall, for tank “Lagrangian” and for water "Eulerian Body" mesh technique is preferred in the “Explicit Dynamics” model. As a result of this study, many collapse events were determined due to seismic ground motion in cylindrical steel liquid storage tanks. If the tank was closed in the shape of a torispherical, less buckling would occur in the tank.
Keywords: Cylindrical Steel Tanks, Nonlinear Analysis, Impact Analysis, Seismic Analysis.

Öz
Silindirik çelik sıvı tankları, su, yağ ve endüstriyel kimyasallar gibi çeşitli sıvıları depolamak için yaygın olarak kullanılmaktadır. Son yıllarda nükleer santrallerde soğutma amaçlı kullanılmaktadırlar. Çelik sıvı tanklarındaki petrol veya diğer tehlikeli kimyasallar deprem sırasında tanklardaki hasarlar nedeniyle büyük mali ve çevresel hasara neden olabilir. Bu çalışmanın temel amacı, farklı çatı şekillerine göre doğrusal olmayan sismik analiz ile silindirik çelik tankların burkulma şekillerini ortaya çıkarmaktır. Tanklar açık çatılı, düz çatılı, konik çatılı ve kubbeli (torispherical) çatılı olarak tasarlanmıştır. Bu amaçla, önemli cidar burkulma şekillerini belirlemek için 0.22 saniyelik El-Centro deprem kaydı kullanılmıştır. Ayrıca bu deprem değerleri darbe analizi için idealdir çünkü ANSYS Workbench “Explicit Dynamics” aracı yapıların yıkıcı ve kısa süreli kuvvetler altında dinamik analizinde çok iyi sonuçlar verir. Su ve tank cidarı arasındaki etkileşimi sağlamak için, “Explicit Dynamics” modelinde tank için “Lagrange” ve su için “Eulerian Body” mesh tekniği tercih edilmiştir. Bu çalışma sonucunda, silindirik çelik sıvı depolama tanklarında sismik yer hareketinden kaynaklanan birçok çökme olayı tespit edilmiştir. Tankın çatısı kubbeli olduğunda, daha az burkulmanın meydana geldiği tespit edilmiştir.
Anahtar Kelimeler: Silindirik Çelik Tanklar, Doğrusal Olmayan Analiz, Etki Analizi, Sismik Analiz.

I. INTRODUCTION

Seismic behaviour of cylindrical steel storage tanks is very complicated due to hydrostatic and hydrodynamic pressure on the shell. This complex issue attracts the attention of researchers studying in the field of civil engineering. Researchers have been looking for solutions to prevent tanks from collapsing during an earthquake for years. However, they were damaged again in the last earthquakes, such as Van (2011) earthquake, Emila (2012) earthquake, South Napa (2014) earthquake. For this reason, comprehensive seismic analysis and efficient design of these structures are important. In fact, seismic ground motion causes hydrodynamic pressures of the fluids in them. There have been used different Seismic behaviour of cylindrical steel storage tanks is very complicated due to hydrostatic and hydrodynamic pressure on the shell. There have been used different technique for interaction between fluid and shell in the Finite Element Method (FEM) so far. Investigation behaviour of tanks and include fluids was carried out under seismic excitation by using FEM. More specifically, there are different paths within the commercial ANSYS program, which is widely used to simulate similar systems involving all solid analyses and solid mass interaction. ANSYS Workbench Explicit Dynamics tool is an excellent tool to perform many nonlinear structural mechanical analyses. For example, impact analysis from 1m/s up to 500 m/s, stress, high-frequency dynamic impact analysis, nonlinear large deformations, analysis of

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include complex contact conditions, simulation of complex material flows, buckling and failure analysis, fastener analysis, rigid and flexible many analysis can be done such as body analysis [1]. It is possible to predict exactly the reaction of flowing fluids by contacting rapidly changing surfaces and surfaces by using algorithms based on first principles during simulation of events occurring within a few milliseconds by means of Explicit Dynamics tool. Simulations with longer duration can also be performed with this tool, but a longer wait is required for the simulation to finish [2].

Some researches were determined the seismic performance of cylindrical liquid storage tanks, considering dynamic fluid-structure interaction (FSI). Very thin sheets are preferred in the design and manufacture of steel liquid storage tanks. This preference is mostly due to economic concerns and easy design. This situation increases the importance of seismic analysis of steel liquid tanks [3-8]. Veletsos and Yang (1977); Haroun and Housner (1981) investigated the effect of hydrodynamic fluid-structure interaction on seismic response [6, 9]. Many researchers have conducted research on the seismic response of ground-supported tanks over the long time and have shown hydrodynamic outcome of the isolated structure [10, 11].

Virella et al., investigated the dynamic buckling of anchored cylindrical steel liquid tanks due to horizontal earthquake excitation. In their study, they found that buckling at the top of the cylindrical tank wall showed negative (inward) pressure in the area where the impulsive hydrodynamic pressure caused by the earthquake excitation exceeded the hydrostatic pressure [12]. Maekawa and Fujita proposed a nonlinear dynamic analysis method for the combined vibration between fluid and structure. They used a shell element which takes into account the geometry non-linear characteristics and a solid element following the Euler equation. ALE method was used in the analysis between fluid and structure and Explicit time integration method was used for time-history analysis [13]. Mittal et al, using the coupled Euler - Langrange formulation, investigated the maximum hoop stress and shear stresses occurring in the cylindrical steel tank wall under blasting. They observed that the stresses in the tank and the liquid sloshing heights increased with the decreasing distance of the explosive material and the increased aspect ratio from the height to the radius ratio [14]. One of the FEM studies about the steel liquid storage tanks involving the tank wall and tank-ground flexibility is performed by Nicolici and Bilegan, is a study of the modeling of fluid-structure interaction (FSI) of partially filled steel liquid tanks. In the modeling, they focused on computational fluid dynamics (CFD) analysis to estimate the effect of the amplitude wave amplitude, convective mode frequency, pressure applied to walls, and sloshing. As a result of the analysis, it was determined that fluid structure interaction affected the sloshing effect and wall elasticity strengthened impulsive pressure [15]. Çelik et al. (2020), preferred the "Eulerian Body" mesh technique in “Explicit Dynamics” model to provide the interaction between the water and the tank wall. They made successful observations about the tank roof deformation as a result of the analysis [16].

According to the results obtained by Kamyar at al., (2018) working on how the method can be protective to determine the behavior of the tank under earthquake ground motion. It can be extended to other target spectra since the period change interval for steel tanks is not very wide and is always in the constant acceleration region of the spectrum. Buckling analysis plays an important role in the design of steel tanks due to their thin shell [17]. In the study by Buratti and Tavano (2014), in order to investigate various aspects of dynamic buckling, in the FEM model of the tank, mass addition method was used to model liquid. In particular, peak displacement and maximum relative displacement of the tank walls were considered in the study [18]. Djermane et al (2014), tried to compare the results of numerical analysis with tanks with different geometric parameters under three earthquake recordings with the dynamic buckling results obtained with two design standards in order to increase dynamic buckling resistance. In their comparison of large and long tanks, they stated that design standards need to be revised in order to determine dynamic buckling criteria [19].

Generally, there are four types of water storage tanks such as open-roof, flat-roofed, conical-roofed and torispherical-roofed tanks. Figure 1 shows the four tank types and some types of damage belonging to them.

In this study, deformations and buckles due to hydrodynamic pressures of four types of vertical cylindrical steel tanks filled with water observed under the seismic loading. Numerical simulations and analyses were performed with the “Explicit Dynamics” tool in ANSYS Workbench. In recent years, "Explicit Dynamics" FEM method is widely used in collision experiments and provides advantages in dealing with large-scale contact problems. Workbench Explicit Dynamics can solve a variety of non-linear problems, such as high-speed collisions in the three-dimensional non-linear structure, explosions and non-linear contact of metal formation and the effect of the load. The FEM method used in the aforementioned studies have not accurate the interaction between tank wall and water, contains deficiencies in nonlinear analysis. By using the "Explicit Dynamics" analysis method, ideal results can be obtained for the interaction between the tank wall and the liquid. This method was used by some researchers for analysis of tanks which have been exposed to explosion from outside or are damaged due to explosions due to gas pressure. However, Explicit Dynamic method gave very good results in determining buckling shapes in tanks with under the seismic loading. The analyses were carried out in three different thicknesses with four cylindrical tanks such as open-roof, flat-roofed, conical-roofed and torispherical-roofed. Directional deformation and buckling results of the tank were observed under the El-Centro earthquake loading of 0.22 seconds. The El-Centro earthquake was preferred because it is one of a major earthquake commonly used in similar analyses.

It is possible to obtain the desirable performance and result in the analysis by using safe and reasonable values without spending much time. In this way, great advantages are provided in terms of cost and optimization. The natural vibration periods of these tanks are between 0.1 sec and 0.5 sec, so they may be damaged due to the maximum earthquake energy. In this study, the damage status of the tanks is examined directly. Tank wall thickness was determined according to API650 design code (2013) [19]. In the Explicit Dynamics simulation method, the Eulerian Body mesh structure for the liquid, the Lagrangian mesh structure technique for the wall, the friction and dynamic interaction between the two are modeled accurately the liquid and tank wall movements are observed together. The types of damage occurring during the earthquakes and the buckling shapes obtained by this modeling technique of Explicit Dynamics show very similarities. In this way, simulations can be continued and many real damage shapes that can be obtained. Therefore, many damages of cylindrical tanks may be prevented by means of accurate simulation of collapse events. In the result of his paper, include suggestions to improve seismic performance of tanks and reduce the level of risk.

a) Open-roof b) Flat-roofed c) Conical-roofed d) Torispherical-roofed

e) Collapse of open-roof f) Collapse of flat-roofed g) Collapse of conical h) Collapse of torispherical

Figure 1. Types of cylindrical steel water tanks and their collapse

II. EXPLICIT AND IMPLICIT FEM APPROACH

Explicit and implicit FEM analysis methods are used in analysis to obtain solutions of time-dependent ordinary and partial differential equations that require computer-based simulations in physical processes of products, and to obtain numerical approximations [20]. For all nonlinear and dynamic analyzes, both "implicit" and "explicit" methods are used to solve the problems when the forces applied in the boundary conditions need to be applied incrementally/gradually. Explicit methods go to the solution by considering the state of the system at a certain time after the current state of the system, implicit methods find a solution by using an equation that includes both the current state of the system and the next state. Using very small-time steps without the need for convergence controls, the explicit method performs high-energy dynamic analysis by exceeding most of the limitations of the implicit method. It accurately simulates the propagation and interaction of stress waves due to sudden impacts or easily solves nonlinear structural problems due to impacts [21].

In linear problems, partial differential equations simplify the matrix equation as follows:

$$[K]\ \{x\}=\{f\} \tag{1}$$

k = hardness matrix

x = displacement/deviation

F = force

For nonlinear static problems:

[K (x)] {x} = {f} → [k0 + k1.x + k2.x2 +…] {x} = {f} (2)

Matrix equations for dynamic problems would be:

[M] {x´´} + [C] {x´} + [K] {x} = {f} (3)

x´ = velocity

x´´ = acceleration

C = damping matrix

M = mass matrix

If the strain rate/rate is equal to 10 units/second or more, the explicit method can be used. In this case, ballistic explosions, sudden hits, automotive accidents as well as sudden displacement simulations due to seismic movement can be performed. Earthquakes can sometimes extend for 45-60 seconds, but much more acceleration occurs in the first few seconds. Since the actual destructions and deformations occur in this range, so constructions can be simulated with short-term data.

As can be seen from Figure 2, it is seen that plasticity, buckling and acceleration increase depending on the stability, dynamism and gradually increasing speed. In the region where this increase is present, it seems more logical to make Explicit Dynamics analysis. Thus, it will be possible to capture the real damage situations of the structures.

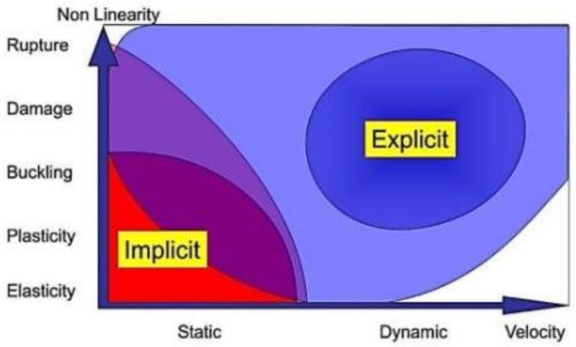


Figure 2. Definition of Implicit and Explicit analysis [21]

In Explicit dynamics analysis, depending on the rapidly changing time, the stress wave and loads spread immediately, and a dynamic response occurs from the structure. Momentum change has a significant effect between the moving object and the inertia, according to the analysis types. Nonlinear dynamic analysis can thus be simulated effectively. Explicit Dynamics tool contains menus in the form of a step-by-step one after the other. The menus are expanded at different stages of the analysis, offering specific specifications for making various adjustments about objects, such as environmental factors, predicates, and contact surfaces [20].

2.1. Design Method

The diameter of the analyzed tank is 15.08 m, its height is 11.31 m, the height of the conical and tprispherical roof is 2.96 m, the height of the water in the tank is 10 m, the tank wall thicknesses are 4, 6 and 8 mm, the tank steel density is 7850 kg/m3, the elastic modulus is 200 GPa, the density of water was determined as 1000 kg/m3, the poisson ratio of steel was 0.3, the poisson ratio of water was 0.5 and finally the bulk modulus of water was 44229 GPa. These values were determined by considering design codes of the American Petroleum Institute (API 650 (2013) for steel cylindrical water tanks [22].

Under dynamic seismic loading, impulsive mass occurs near the bottom of cylindrical steel liquid tanks and convective mass that gradually rises towards the top as shown in Figure 3. Impulsive and convective masses were calculated using the design standard developed for cylindrical and ground-supported vertical liquid tanks by API650. Model validation was performed by performing modal analysis of the calculated masses in FEM. The seismic analysis of the tanks was continued with geometric designs verified by modal analysis.

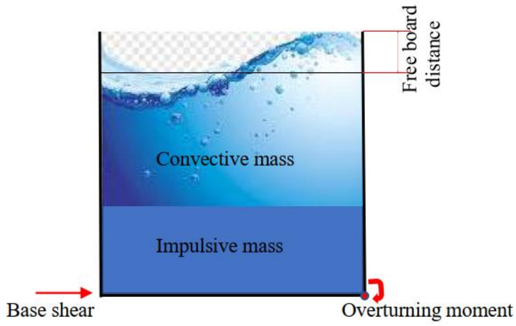


Figure 3. Representations dynamic behaviour of full tank

Results of the the API 650 formulation are shown below.

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

$= m_w = 1000 \times 1780.4 = 1780400Kg$ (2)

Mass of impulsive equation $m_i = m_w = \frac{tanh*(0.866*\frac{D}{H})}{(0.866*\frac{D}{H})}$

m_i =1176875.813 Kg

Mass of convective equation

$$mc = 0.455 * \pi * \rho l * R3 * \tanh(1.84\frac{H}{R}) \quad (3)$$

m_c =603291,22 Kg

The natural frequency of impulsive mass 3.26 Hz

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 hs 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

After the analytical calculation, modal analysis was performed with FEM. The results of the convective modal analysis performed using the FEM method in the ANSYS workbench software are shown in Figure 4. Both impulsive and convective frequency results are listed in Table 1 as comparison of API 650 and FEM [23].

The natural frequency results according to FEM modal analysis with API 650 analytical calculation are shown in Table 1.

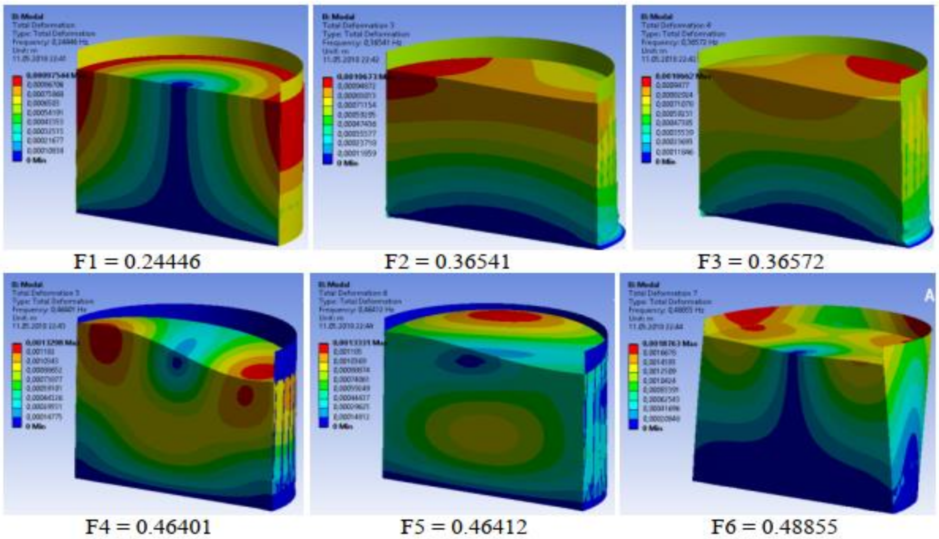


Figure 4. Modal analysis of convective mass

Table 1. The natural frequency results according to FEM modal analysis with API 650 analytical calculation

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

According to the model verified by analytical and modal analysis, four different tank models were designed for numerical simulation. The diameter of the tanks, shell thickness and the water levels they contain are the same. The most important feature that distinguishes Explicit Dynamics FEM analysis from other FEM techniques is the Lagrangian mesh structure for the steel body to use the Eulerian body mesh structure technique to model the water to provide interaction between the steel body and water.

The most important feature that distinguishes "Explicit Dynamics" finite element analysis from other finite element techniques is that it uses the Lagrangian network structure for the steel body to provide the interaction between the steel body and the water, and the Eularian body network structure technique to model the water. In the model whose cross-section is seen in Figure 5, 24712 nodes and 22570 elements are used for a smooth network structure.

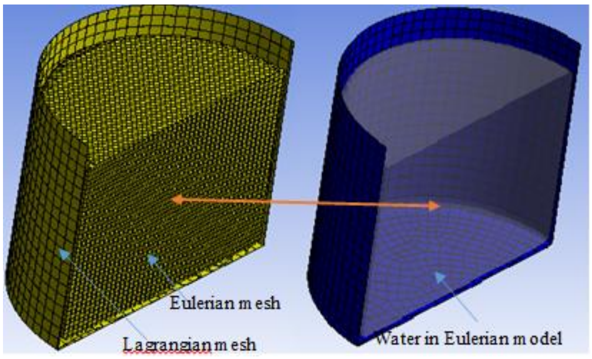


Figure 5. Shell and Water mesh model [16]

2.2. Theory of Dynamic Behaviour of Cylindrical Steel Tank

If there is no dynamic movement, the hydrostatic pressure acts on the cylindrical tank in the form of an increasing mass towards the bottom. However, when there is an earthquake that impulsive and convective dynamic water pressures occur as well as hydrostatic fluid pressure. When the tank moves, approximately one-third of the total liquid moves in the same direction with the tank, while the remaining water mass in the upper part shows the effect of convective sloshing in the opposite direction with the tank (Housner 1957) [24]. Since the hydrodynamic pressure moves in the same direction, it can cause damage to both the wall and the bottom of the tank. Liquid sloshing of upper side causes deformation in the upper areas of the tank. Static liquid pressure is effective only at the base (Figure 6 (a)), the effect on the walls is equal to both sides of the axis, so the value is zero. The hydrodynamic pressures originating from impulsive (rigid) and convective bodies, defined by Housner (1954) for the first time, are shown in Figure 6 ((b) and (c)) [22, 25].

With Explicit Dynamics analysis, events with a time scale of less than 1 second (usually 1 millisecond) can be simulated with geometric deformations such as hyperlastisite, plastic flows, faults and collapse [26]. Therefore, in order to observe plastic deformations caused by time-dependent short-term and rapidly changing loads in cylindrical steel tanks, Explicit Dynamics analysis was preferred.

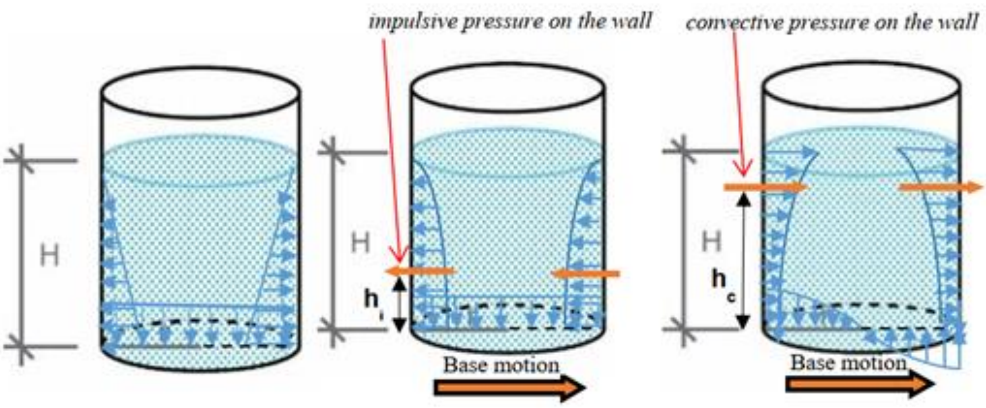


Figure 6. Theory of dynamics behaviour of cylindrical steel tank

2.3. Lagrangian and Eulerian References Frame

Lagrangian and Euler reference frames are utilized for modeling a unit operation. Euler Reference frames are preferred due to capability of more efficiently computational [26]. Control volumes fixed in space can be used by the Euler Reference frame. Mathematically, the derivation of the basic equations of fluid mechanics is carried out with a simple approach. It allows frequent changes of direction within the fluid control volume within the reference frame [27]. Different eulerian references frame and lagrangian are shown in Figure 7a) The position vector in the Euler reference frame is not a function of time. Instead, the position vector s1 'is identically located in s0. The grid divided into cells in the Eulerian reference frame remains constant until the simulation ends. Thanks to this feature, large deformation problems can be simulated. The Lagrange reference frame, whose details are shown in Figure 7b), moves with the flow field. Initially, the control volume of T0 has the velocity of the flow field v0 at position s0. At T1, the control volume will have gone to s1 when it has the velocity of the flow field v1. In the Lagrangian reference frame, the position vector is a function of time in contrast to the Eulerian reference frame. Connecting each position vector over time allows the particle trajectory to be reconstructed [26].

Particle trajectories are used to visualize the flow field. Different sA, 0, sB, 0, sC, 0, etc. indicated by seeding small particles towards the flow field at their initial positions. The stream area is then recorded with a camera with very long exposure settings. The recorded image will highlight the movement of the particles in the form of trajectory lines as the particles move across the flow field. Naturally, the same is true for control volumes moved in the flow field.

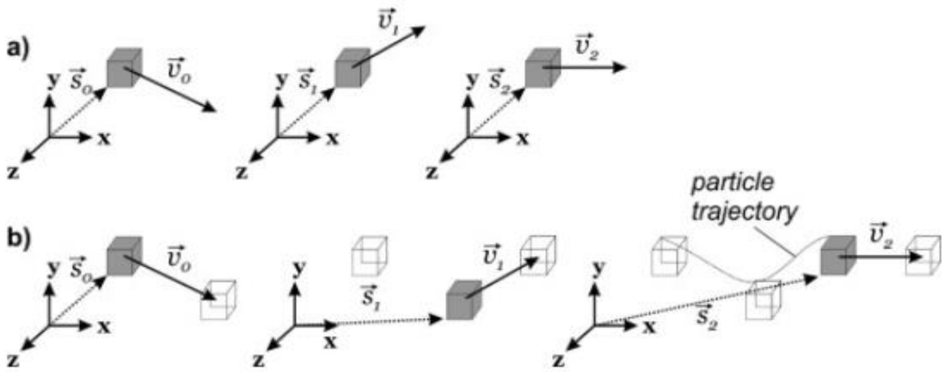


Figure 7. a) Eulerian frame of reference: fixed in space b) Lagrangian frames of reference: moving in space [27].

Lagrange and Eulerian reference frames can be converted to each other. The position of s1 in the Lagrangian reference frame depends on s0. That is, the position vector appears as a function of the previous position. In the Eulerian frame of reference, the velocity and acceleration do not change, so the position vector appears only as a function of time.

$$\text{Position} = s(t) \tag{4}$$

$$\text{Veolocity} = \vartheta(t) = \frac{ds(t)}{dt} \tag{5}$$

$$\text{Acceleration} = a(t) = \frac{d\vartheta(t)}{dt} = \frac{d^2s(t)}{dt^2} \tag{6}$$

Velocity and velocity-dependent lagrange terms appear as derivatives of time in the eulerian frame of reference. The convective contribution of the moving fluid field can be expressed in these terms. In other words, when the fluid velocity is low, the importance of terms related to particle motion increases, while as the fluid velocity increases, the importance of terms related to particle motion decreases. This situation can be explained in the following way, the speed of the boat moving in the river depends firstly on the movement from the boat engine, secondly on the movement of the water in the river. If the engine of the boat is stopped, the motion will proceed only at the speed of movement of the water[27].

Analysis of liquid substances is used in Explicit Dynamics with the Euler frame of reference. Euler references framework can be used to observe large defects that may occur in structures such as water tanks, considering the calculation cost and material interface approach. During the simulation, the material flows from one cell to another. In some stages of the calculation, it is possible that a particular cell contains more than one material. Space is also considered a material in this sense; Figure 8 shows the flow of a material onto another material.

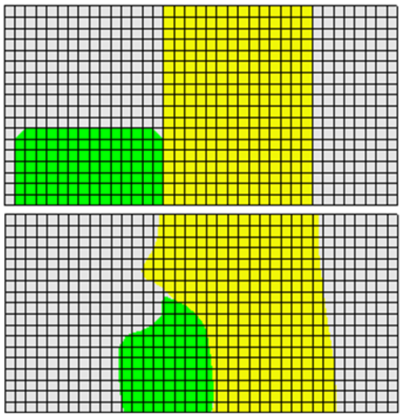


Figure 8. Flow of material in Eulerian references frame [28].

The liquid volume method is used to represent the material flow in each cell modeled in the eulerian reference frame. The sum of the volume of material flow occurring in a cell and the volume of the idle part is equal to 1. The calculation of this is shown in the formula below.

$$\sum_{i=1}^{i=nmat} \boldsymbol{F_i} + \boldsymbol{F_{void}} = \mathbf{1} \tag{7}$$

Thanks to the eulerin reference frame, the stress, pressure and ratios of the material in a cell can be calculated, and a special process is used to calculate the resulting tensile tensor for the mass transfer and momentum transfer calculations of the cell surfaces [26].

2.4. Explicit Liquid-Structure Interaction

Reference frames in the Explicit Dynamics system can act together simultaneously to combine each material in the analysis result. The organs in two different reference frames act as a whole by interacting with each other during the simulation. For example, when modeling water tanks containing liquid, the steel body can be modeled as a lagrangian body and the water inside as an eulerian body. The two of them use different meshing techniques, but the frames of reference allow them to interact and move together as a result of the analysis. Thanks to the interaction between eulerian and lagrangian bodies, high performance can be obtained, especially in bi-directional fluid structure[20].

When there is intersection between two bodies, the updated control volume emerges by solving the equations of the law of conservation of energy and the momentum of mass. The two-way fluid interaction occurs here depending on each other. The lagrangian body can be deformed by changing shape during simulation. Visible large deformations occur by causing wear on lagrangian body elements. As a result of these deformations, there is an update in the fasteners. During analysis the dominant eulerian cell size must remain at a minimum distance across the thickness of lagrangian objects. Otherwise, material leakage, ie irregular material flows, can be seen in the lagrange structure and eulerian region [20].

The Explicit Dynamics setup process consists of three consecutive steps, called preliminary, execution, and results. In the first step, the geometry is created using the Explicit Dynamics tool. Then characteristics of the water such as density and isotropic physical properties are defined via engineering data. The Poisson ratio value must have written as 0.49999999 because the water is not compressed.

III. RESULTS AND DISCUSSIONS

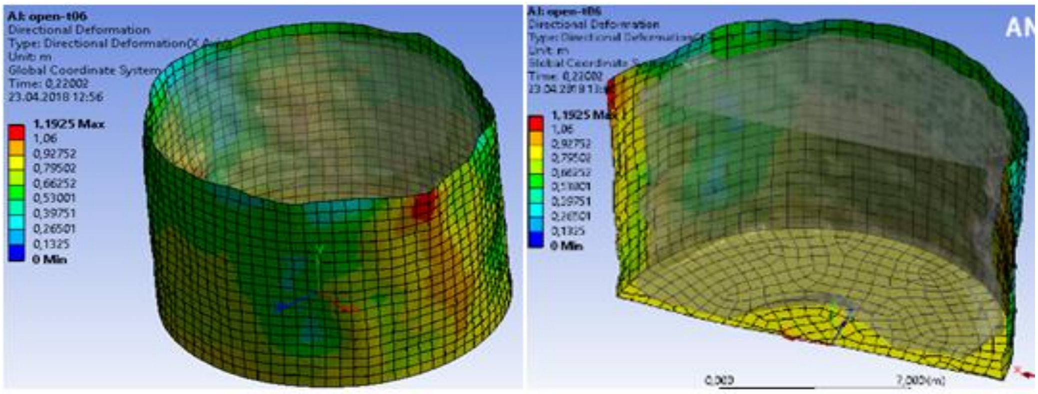
3.1. Observation of Axial Displacement

Axial displacement results are shown in Figures 9, 10, 11 and 12. As a result of the analysis, the simultaneous movement of the tank body, which is defined as the lagrangian body and the water body, which is defined as the eulerian body, shows that the Explicit Dynamics analysis results in success. Analysis results are observed on tank body, both full and half-sectioned. The churning due to the convective dynamic mass occurring in the upper part of the tanks is clearly visible. This situation can be explained with an example: If a bucket filled with water is dropped hard on the ground, the bucket oscillates a few times and stops, but with the dynamic mass effect that occurs, the convective sloshing at the top side continues for a while. The situation of tanks damaged in the earthquake is somewhat similar to this example. Even if the tank oscillation due to ground shock stops, the water agitation due to the convective mass at the top continues for a while. In the open-roofed tank model shown in Figure 9, the maximum axial displacement was 1.19 m. Sivy and Musil,2017 obtained a convective sloshing height of 0.75 m in their analysis with an open-roofed tank [29]. The deformation convective that occurs towards the upper edges of the tank clearly shows the shaking effect.

Figure 10. shows axial displacement of flat-roofed. Compared to the flat-roofed tank model with the open-top, there doesn't seem to be much difference in terms of displacement. Thus, it can be concluded that roofing a cylindrical tank flat will not provide much benefit in terms of deformations that may occur. The biggest reason for this may be the changing pressure center due to the flatness on the tank. In Figure 10 maximum displacement occurred as 1.08 m. Flat roof tanks have been manufactured extensively in the past, Bayraktar et al, (2010). achieved a displacement of around 0.8 m in the 8 m height flat-roof tank, which their results were very close to each other. Modeling the water in the 11.31 m flat-roofed tank with the eulerian mesh also makes the numerical modeling of the tank special [8]. This causes them to take more damage. In other words, while the flat cover protects the water body from the open atmosphere pressure, it becomes the pressure center itself. In general, it is seen that convective sloshing is low and buckling occurs in the middle parts of the tank shell.

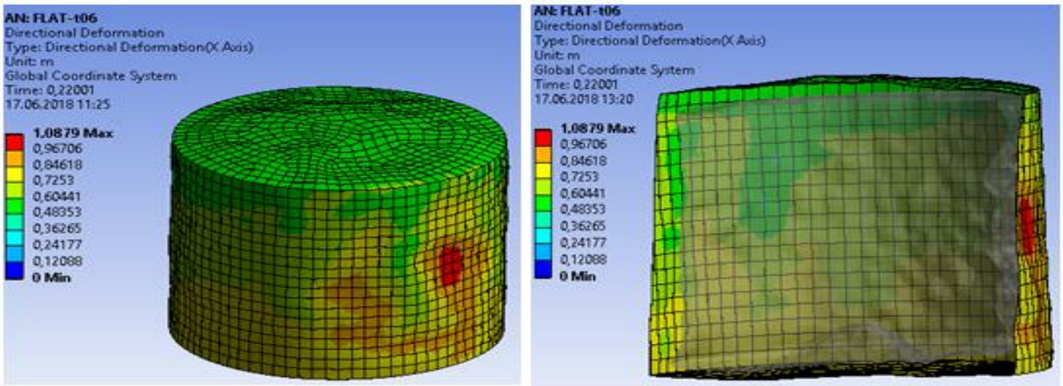
Figure 11. shows the conical-roofed tank model. With an axial displacement of 0.711 m, the conical-roofed tank may have better seismic performance than the open-roofed and flat-roofed models. Djermane et al., (1014) achieved a displacement of around 0.90 m in a conical-roof tank with similar characteristics [19]. The result obtained thanks to the Eularian mesh technique can guide designers with more specific visuals effects. Hence, it was seen that the stresses were spread on the roof thanks to the conical roof geometry. This protects the tank body against deformations.

Finally, the torisphericall-roofed tank is shown in Figure 12. The fact that the roof is torispherical, the stresses reduce. With a maximum displacement of 0.94 m, it contains less deformation than open and flat-roofed tanks. Nicolici and Bilegan. Nicolici and Bilegan, (2013) achieved 0.25 m of liquid sloshing with a smaller torisphercial-roofed tank with an internal diameter of 3200 mm, a height of 3294 mm and a shell thickness of 10 mm [15]. Considering the tank size, the wave height in the water shows similarities. In addition, the visual result obtained in the Figure 12. is more realistic.



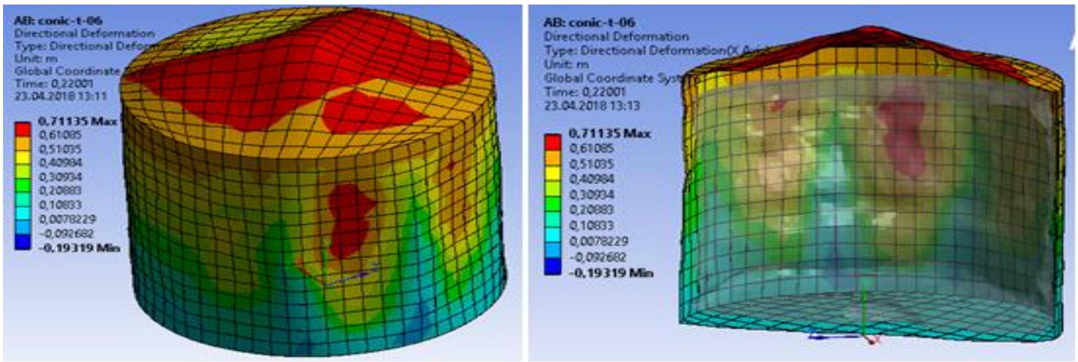
a) Axial displacement b) Cross section of Axial displacement

Figure 9. Axial displacement of open-roofed tank



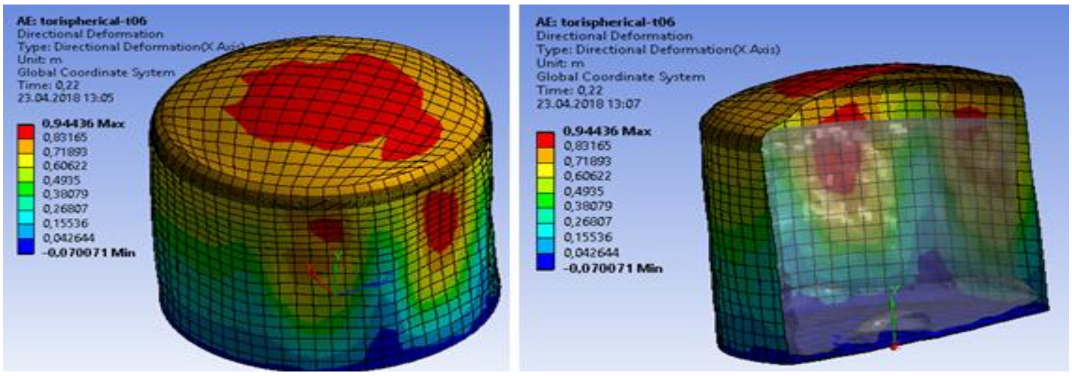
a) Axial displacement of flat-roofed b) Cross section of flat-roofed tank

Figure 10. Axial displacement of flat-roofed tank



a)Axial displacement of conical-roofed b) Cross section of conical-roofed tank

Figure 11. Axial displacement of conical-roofed tank



a) Axial displacement of torispherical-roofed b) Cross section of torispherical-roofed tank

Figure 12. Axial displacement of torispherical-roofed tank

Nonlinear axial displacement started around 0.012 seconds in all tanks. The axial-displacement reached 1.233 m in 0.12 seconds while it was 1.19 m in the open-roofed tank model, and 1.15 m in the torispherical-roofed model. The convective sloshing effect is more pronounced on the upper side of the models with open-roof and flat-roofed.

3.2. Observation of Buckling

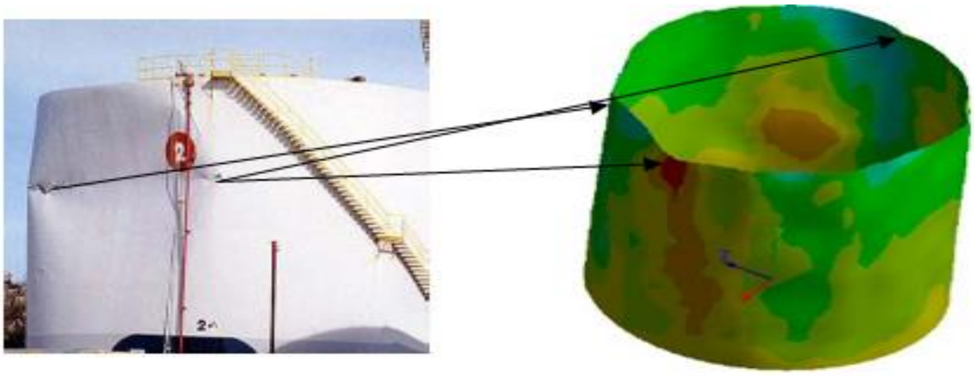
In steel liquid tanks, the convective sloshing effect due to seismic ground motion causes buckling, especially in the upper sides. One of the collapsed situations caused by convective sloshing is shown in Figure 13. Thanks to the Explicit Dynamics analysis, diamond-shaped buckling conditions were obtained.

As the earthquake duration increases, sprains may increase even more. But with the greatest acceleration in the first seconds, tanks can take great damage. These damage situations can be easily determined by the Explicit Dynamics analysis method and preventive measures can be taken. In a previous study, a protective system like seismic isolation in reinforced concrete structures was developed. [25]. Seismic isolation is placed under the bottom of the tank and damages that may occur during an earthquake are prevented by reducing the moment effect. The Explicit Dynamics analysis can serve for a guide before preventive measures are taken.

In Figure 14, images of a tank with a buckling shell and buckling obtained by Explicit Dynamics analysis are given. As can be seen in the figure, the effects of agitation on the upper parts of the shell are evident. The Explicit Dynamics FEM model is adept at capturing significant nonlinear changes. In terms of the accuracy of the analysis, it will be an important reference to obtain real and occurring buckling shapes with the Explicit Dynamics analysis.

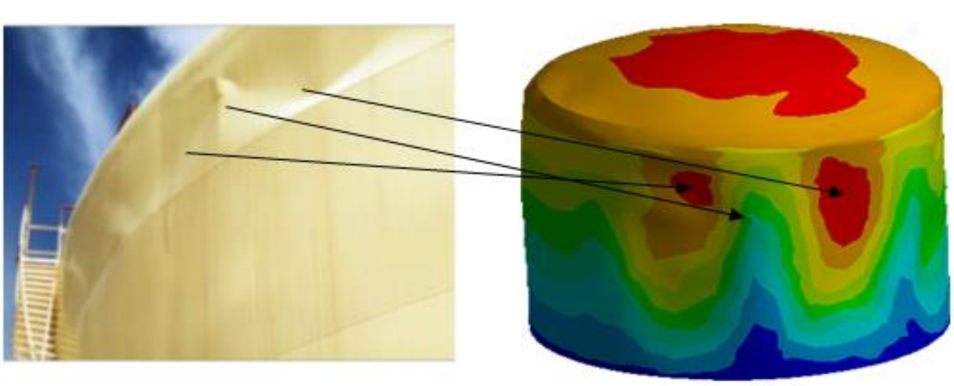
In fact, a good roof design protects the tank body from damage. Considering the buckling conditions in Figure 15, some stress and buckling occurred in the conical and torispherical roofs, but there was not much damage to the tank body. The tank body is only slightly damaged from one side. This situation can be explained as follows, especially the conical and torispherical roof shape distributes the stresses properly and reduces the agitation effect of the liquid in the tank. This results in less buckling of the shell.

The axial displacement graph of all tanks is shown in Figure 16. The nonlinear deformation started after 0.02 seconds. Maximum displacement is 1.23 m in the conical-roofed version and 1.15 m in the torispherical-roofed version. With the convective sloshing effect, it showed itself with buckling in the shell in open and flat roofed models. Conical and torispherical roof models also contain less buckling of the tank body.



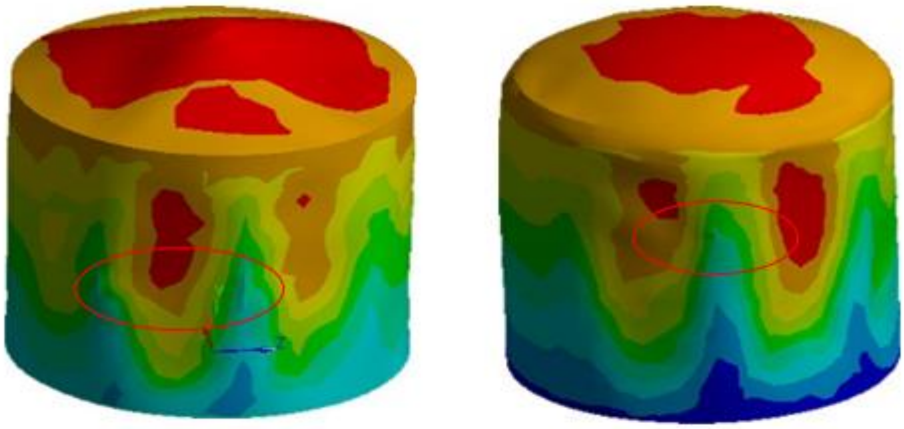
a) Crack of shell b) Fractured cracks with FEM

Figure 13. Shell buckling



a) Shell crack b) Obtained cracks shape with FEM

Figure 14. Cracks of shell



a) Shell buckles in conical-roofed tank b) Shell buckles in torispherical-roofed tank

Figure 15. Buckles of conical-roofed and torispherical-roofed tanks

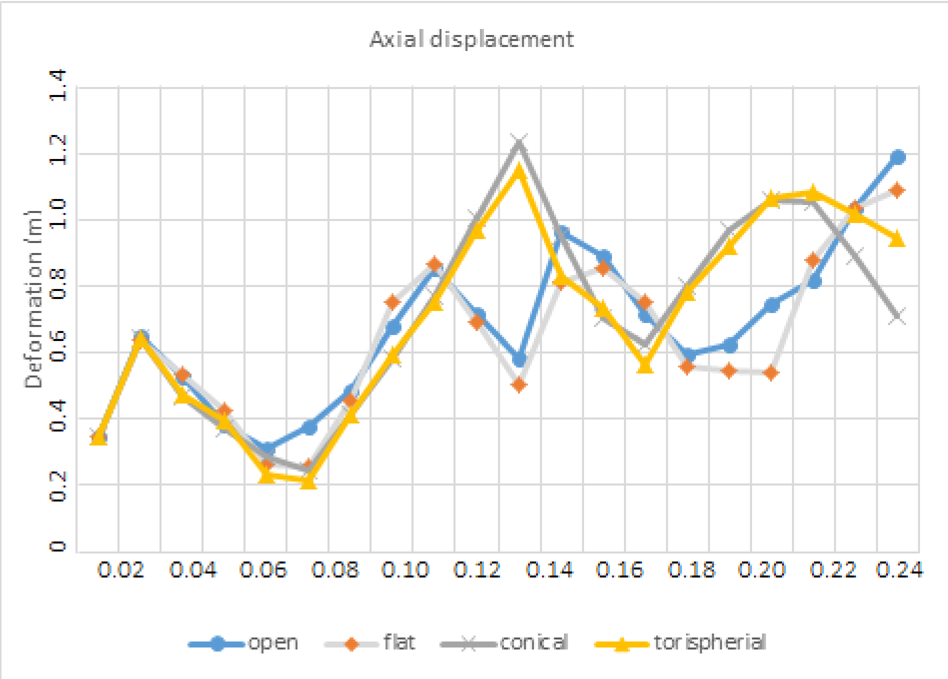
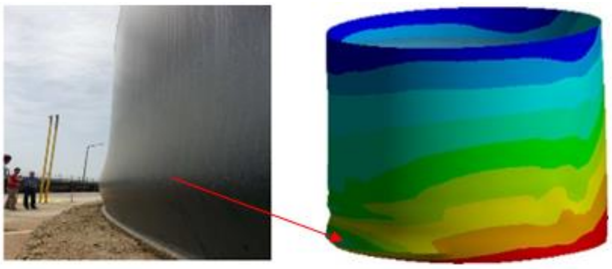


Figure 16. Axial displacement curve

3.2.1. Evaluation of buckling for different thicknesses

The above analysis results were performed according to API 650 tank design code for tanks with 6 mm thickness. Analyzes for tanks of 4 and 8 m thickness with the same specifications were mixed. The aim is here to measure the response of the roof type to nonlinear shape changes when the shell thickness decreases and loads. Firstly, the results obtained at 4 mm thickness were evaluated. The maximum displacement is 1.06 m in the open-roof model and 1.22 m in the flat-roof model. 1.05 m in conical-roof model, 0.98 m in torispherical-roofed model. axial displacement has occurred. Interestingly, the highest axial displacement occurred in the flat-roofed model. This result is that closing a cylindrical tank as flat does not cause any benefit in terms of damage that may occur. The biggest reason for this is that the flat roof becomes a pressure center and causes more damage. The best results were obtained from the torispherical model. This means that even if the thickness decreases, the shape of the roof is torispherical-shaped, which means that it can distribute the stresses and prevent possible damages.

Elephant foot buckling is the most common type of damage to cylindrical steel liquid tanks. Thanks to this analysis the elephant foot buckling that seen in Figure 17 for the 4 mm thick tank was also obtained in the FEM model. The buckling obtained in the FEM model (Figure 17b) is very similar to the elephant foot buckling (Figure 17a) that occurred during the 1999 TÜPRAŞ refinery's earthquake. In fact, the occurrence of elephant foot buckling in tanks means that the structure is damaged and not collapsed. This is a desirable situation in structures that are not very rigid. That is the structure will take some damage, but not be destroyed. However, thin-walled tanks that contain such dangerous liquids and hazardous substances must be rigidly designed. For a thin-walled steel structure, this does not cost much, and additional damages that fire and explosion are prevented. In summary, this buckling occurs when the crustal thickness decreases. Therefore, such damage can be prevented by preliminary studies.



a) Marmara earthquake (TÜPRAŞ 999) b) FEM model result

Figure 17. Elephant foot buckles of earthquake and FEM

IV. CONCLUSION

Seismic analysis of commonly used cylindrical liquid storage tanks and their protection against seismic effects are of direct interest to the field of civil engineering. It will be a good guide in terms of detecting the damages that may occur in these tanks in advance and taking measures against possible seismic effects. Many FEM analyzes have been made so far for cylindrical steel liquid tanks. Most of these analyzes have been carried out as static structures. In this study, the Explicit Dynamics analysis method, which is used in experiments such as sudden loading, explosion, slip and collision, is used in ANSYS Workbench. As a result of the analyzes obtained by the Explicit Dynamics tool, damage and buckling patterns of open-roof, flat-roofed, conical-roofed and torispherical-roofed tanks were obtained. These results give important clues about the damages that may occur during a possible earthquake. For the analysis, acceleration values of 0.22 seconds from the north-south composition of the el-Centro earthquake were used. In an earthquake, there can be many accelerated movements in a time period of 1 second. In addition, lagrangian and eulerian references were used together. The tank body modeled as lagrangian and the water body modeled as eulerian were allowed to move together in interaction during the analysis. In this way, the convective sloshing effect and buckling shapes formed by the water mass on the tank wall were obtained.

Tanks with 4 different roof types were analyzed first with 6 mm thickness and then with 4- and 8-mm shell thicknesses. In all analyses, axial displacement started to be evident after 0.02 seconds.

The results of the analysis existed, that is, it resulted in obtaining the buckling patterns of the tanks damaged in the earthquakes.

Depending on the earthquake ground motion, the liquid mass inside the tank gains dynamic motion along with the tank. This dynamic movement is defined as a convective liquid mass at the top of the tank. This mass continues the shaking effect even if the shaking stops. With this effect, it is more common especially in open-roof and flat-roofed models. In other words, sprains occur in the regions close to the upper edge with the effect of shaking.

Elephant foot and diamond-shaped buckling are common in cylindrical tanks containing liquids during earthquakes. Diamond shaped buckles were observed in the 6 mm thick tanks in the analysis made with Explicit Dynamics analysis. Elephant foot buckling was seen in 4 mm thickness. It is normal for elephant foot buckling to occur at low thickness, but diamond-shaped buckles at 6 mm thickness are not.

After this study, Explicit Dynamics analyzes can be made that simulates the discharge of water out of tanks containing liquid due to damage.

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