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Research Article

Vertical Water Silo Design and Analysis

Serap ÖZHAN DOĞAN[1*], Burak Galip ANIK[2], Umut GÖKTAŞ[3]

[1] Department of Mechanical Engineering, İstanbul Beykent University, İstanbul-Türkiye
***Corresponding Author Email:** serapdogan@beykent.edu.tr - **ORCID:** 0000-0001-5210-1549

[2] R&D Department, Tersan Shipyard, Yalova-Türkiye
Email: banik@tersan.com.tr - **ORCID:** 0000-0002-8315-9441

[3] R&D Department, Tersan Shipyard, Yalova-Türkiye
Email: ugoktas@tersan.com.tr - **ORCID:** 0009-0001-0243-8263

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Abstract:

This study covers the design of the 155 m^3 water tank, which is intended to be established in Tersan Shipyard and to be used for the treatment plant, to meet the needs, and the analysis and verification of the design. First of all, the needs were determined and then the solution steps to meet these determinations were determined. The three-dimensional design of the tank, whose material, dimensions and shape were determined, was carried out. In addition, the places where this tank will be fixed were selected and the analysis was carried out in this part by applying the necessary forces to the structure. It was designed using Rhinoceros, a design program, and then Autodesk Nastran finite element analysis program was used. In order for our water tank design to be considered safe, the result of the analysis should be below the maximum Von Mises Stress value occurring in the structure, below 241.68 MPa. Afterwards, the Nastran simulation module was run and as a result of the simulation, Von Mises Stress values of maximum 46.71 MPa and displacement values of maximum 2.136 mm were reached. According to the results obtained, it has been determined that the designed structure is safe.

1. Introduction

Materials are deposited vertically or horizontally in the silo tank and transported by gravity or mechanical force. The silo system is a widely used storage solution in industrial facilities. It plays a very important role in material management and operational efficiency.

Cylindrical steel liquid storage tanks are the most common among the steel tanks used for liquid storage. In the studies carried out to determine the damage types in these tanks during the earthquake and the factors causing these damages, it has been revealed that the liquid storage tanks perform very poorly in earthquakes and the need to develop new methods to increase their earthquake resistance. The complexity is due to the thin wall of the tank, the axial and circumferential stretching of the wall and the multiple dynamic responses of the agitated liquid, the non-linear behavior of the fluid contained and the vibrating wall, and the buckling-deformation difference of the tank wall [1].

Storage structures, which are frequently found in the industrial field, vary according to the liquid to be stored (water, chemical liquid products, oil), different geometry (rectangular, cylindrical, conical), carrier system (recessed, above ground, free standing) and building material (reinforced concrete, steel, wood), aluminum, fiberglass) and is called a silo/tank.

Water will be stored in the liquid storage silo, which is the subject of this study. The silo will be constructed of steel material with a cylindrical and footed structure. A structure to be built for liquid storage should be designed and constructed taking into account the stored substance, the height of the liquid, the wave force that may occur on the liquid surface, and the hydrostatic pressure that the liquid exerts on the silo wall.

Cylindrical steel water tanks are thin-walled structures that are exposed to the hydrostatic pressure of the stored liquid together with the axial pressure caused by the horizontal earthquake loads and the friction of the stored materials on the walls.

Under seismic loading, overturning and shearing moments occur due to axial stresses on the walls [2].

Silo design; It includes the size, shape, material, capacity, pressure requirements, discharge and filling mechanisms, safety precautions and other technical details of the tank. Factors such as the design process, engineering calculations, material selection, structural analysis and compliance with standards are taken into account.

The first studies on liquid storage tanks are related to the rigidity of the tank and the hydrodynamic effects of liquids. Studies by scientists such as Jacobsen (1949), Graham and Rodriguez (1952) and Housner (1957) focused on the seismic response analysis of liquid storage tanks, the solidity of the tank and the dynamic pressure it contains [3,4,5,6]. Hydrodynamic calculations in the later stages of this study are calculated based on the housner model.

To design a structure safely, its behavior under different loading conditions needs to be studied in detail. There are different theoretical, numerical and experimental methods for examining the stresses and displacements arising from different loadings [7].

The most intense earthquake belts in the world; Pacific Earthquake Belt, where 81% of the earthquakes on earth occur, is the Alpine-Himalaya Earthquake Belt, where 17% occurs. Turkey, on the other hand, is one of the countries with the highest seismicity in the world, as it is located in the Alpine-Himalayan Earthquake Belt, one of these earthquake belts. According to the Earthquake Zones Map, it is known that 92% of our country is in earthquake zones, 95% of our population lives under earthquake risk, and 98% of large industrial centers and 93% of our dams are located in earthquake zones [8].

Since Turkey is located in an earthquake zone and the earthquake movement has a devastating effect on the structures, it is of great importance for the life safety of the society to calculate this effect with the closest possible form during the design of the structures and to make the design accordingly.

There are many methods for calculating the effect of earthquake motion on the structure. Among these methods, the simplest, most understandable and easiest to implement is the Equivalent Earthquake Load Method. The Equivalent Earthquake Load Method is generally based on the calculation of the load that will affect the structure during an earthquake with the help of certain coefficients. Some coefficients have been developed to simplify the complex behavior of structures during earthquakes. The coefficients used vary for each country.

2. Theoretical Calculations

For this study, first of all, loads acting on the structure were found according to 3 different situations. These situations are;

- When the water tank is full
- If the water tank is half full
- Empty water tank

It has been determined that the loads given below affect the structure and each one is calculated in turn.

- Hydrostatic pressure
- Wind load
- Earthquake load
- Weight of structure and water
- Hydrodynamic calculation

The data determined by calculating the above conditions for the silo are shared in Table 1 below.

Table 1. *Calculated data of the silo to be designed*

The volume of the silo	1.33E+09 (mm^3)
Mass of Silo	10450 (kg)
Liquid height when silo is full	13337 (mm)
Liquid mass when the silo is full	155000 (kg)
Liquid height when silo is half full	7428 (mm)
Liquid mass in the half state of the silo	81000 (kg)

2.1. Hydrostatic Pressure

Hydrostatic water pressure varies linearly with liquid depth and acts normal to the surface of the tank. Depending on the height and density from the top of the liquid to any point, the hydrostatic pressure can be calculated with $;p = \rho \times g \times h + p_0$ or simply. As seen in Figure 1, hydrostatic pressure increases linearly along the wall towards the bottom.

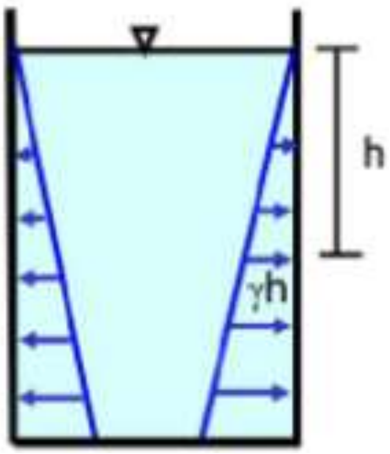

***Figure 1**. Hydrostatic pressure*

p = Hydrostatic pressure

ρ = Liquid density ($1000\,\mathrm{kg/m^3}$)

h = depth of fluid (mm)

g = Gravitational acceleration($9.81\ \mathrm{m/s^2}$)

$\mathrm{p_0} = 101325$ Pa

First case fluid height:13364 mm

Second case fluid height: 7428 mm

Third case fluid height:: 0 mm is found as.

2.2. Effect of Earthquake Load

Earthquake load calculation was calculated according to the rules and formulas of the Turkish Building Earthquake Code (2018). S_S ve S_1 değerleri yapının inşa edileceği yerin koordinat bilgileri girilerek AFAD'ın sitesinden öğrenilmiştir.

S_S: *Short period map spectral acceleration coefficient*

S_1: *Map spectral acceleration coefficient per second*

S_S =0.808

$S_1 = 0.228$

The S_S and S_1 coefficients defined above are converted to the design spectral acceleration coefficients S_{DS} and S_{D1} with the help of the following formulas.

$$S_{DS} = S_S \times F_S$$

$$S_{D1} = S_1 \times F_1$$

F_S and F_1 show the local ground effect coefficient and are found with the help of the table 2.

***Table 2**. Local Ground Effect Coefficients for the short period Region*

Yerel Zemin Sınıfı	Kısa periyot bölgesi için *Yerel Zemin Etki Katsayısı* F_S					
	$S_S \leq 0.25$	$S_S = 0.50$	$S_S = 0.75$	$S_S = 1.00$	$S_S = 1.25$	$S_S \geq 1.50$
ZA	0.8	0.8	0.8	0.8	0.8	0.8
ZB	0.9	0.9	0.9	0.9	0.9	0.9
ZC	1.3	1.3	1.2	1.2	1.2	1.2
ZD	1.6	1.4	1.2	1.1	1.0	1.0
ZE	2.4	1.7	1.3	1.1	0.9	0.8
ZF	*Sahaya özel zemin davranış analizi yapılacaktır* (**Bkz.16.5**).					

Yerel Zemin Sınıfı	1.0 saniye periyot için *Yerel Zemin Etki Katsayısı* F_1					
	$S_1 \leq 0.10$	$S_1 = 0.20$	$S_1 = 0.30$	$S_1 = 0.40$	$S_1 = 0.50$	$S_1 \geq 0.60$
ZA	0.8	0.8	0.8	0.8	0.8	0.8
ZB	0.8	0.8	0.8	0.8	0.8	0.8
ZC	1.5	1.5	1.5	1.5	1.5	1.4
ZD	2.4	2.2	2.0	1.9	1.8	1.7
ZE	4.2	3.3	2.8	2.4	2.2	2.0
ZF	*Sahaya özel zemin davranış analizi yapılacaktır* (**Bkz.16.5**).					

As a result of the researches, the ground class on which the building will be built was chosen as ZC and accordingly $\mathrm{F_S} =$ 1.2 ve $\mathrm{F_1}$ = 1.5 are chosen.

Using the above formulas, $\mathrm{S_{DS}} = 0.9696$ ve $\mathrm{S_{D1}} = 0.342$ values are found. As the next step, corner periods $\mathrm{T_A}$ and $\mathrm{T_B}$ values are calculated with the help of the following formulas.

Using the above formulas, the values of $\mathrm{S_{DS}} = 0.9696$ and $\mathrm{S_{D1}} = 0.342$ are found. As a next step, the corner periods $\mathrm{T_A}$ and $\mathrm{T_B}$ values are calculated with the help of the following formulas.

$$\mathrm{T_A} = 0.2 \times \frac{\mathrm{S_{D1}}}{\mathrm{D_S}}$$

$$\mathrm{T_B} = \frac{\mathrm{S_{D1}}}{\mathrm{D_S}}$$

$$\mathrm{T_A} = 0.0705\ \mathrm{sn}$$

$$\mathrm{T_B} = 0.35\ \mathrm{sn}$$

Natural vibration period: $\mathrm{T} = \mathrm{C_t} \times \mathrm{H_N}^{3/4}$

It is found as T=0.59

Since the T value found is between 0.35s ($\mathrm{T_B}$) and 1s, the design spectral acceleration is calculated as 0.58g with the formula $\mathrm{S_{ae}(T)} = \frac{\mathrm{S_{D1}}}{\mathrm{T}}$

The horizontal elastic design acceleration spectrum graph used is shared in Figure 2.

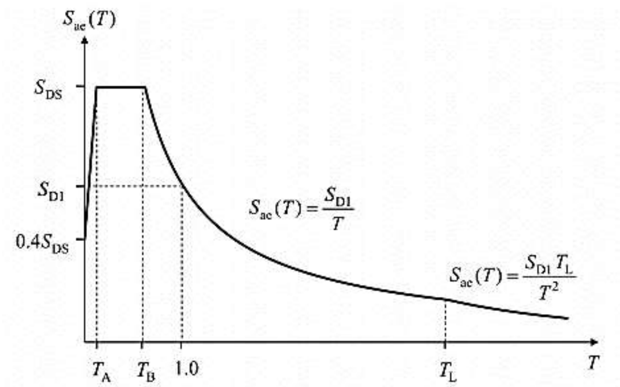

***Figure 2.** Horizontal elastic design acceleration spectrum graph*

The earthquake reduction coefficient is found with the help of the following formula.$T > T_B$ için $R_a(T) = \frac{R}{I}$

In the above formula, I building importance coefficient and R structural system behavior coefficient are taken as 1 and 4, respectively, according to TBDY-2018, and in the case $R_a(T) = 4$

The reduced design acceleration spectrum with the $S_{aR}(T) = \frac{S_{ae}(T)}{R_a(T)}$ formula was found to be 0.0725g.

As the final calculation; Equivalent earthquake load was calculated with the formula $V_t = m \times S_{aR}(T)$.

With the help of the above formula;

For the first case: equivalent earthquake load 11995,125 kg

For the second case: equivalent earthquake load 6630,125 kg

For the third case: the equivalent earthquake load was found to be 757,625 kg.

2.3. Effects of wind load

Wind is a natural phenomenon that has a complex structure that is difficult to predict and its effect is irregular, that is, random. Due to this strong effect of the wind, its effect must be taken into consideration during design and application. Since the wind is located in the lower part of the atmospheric boundary layer where wind turbulence and wind speed gradient dominate, the wind pressures acting on the buildings fluctuate considerably. The loading effects of natural wind on buildings are a highly complex interactive process between wind flow and various components of the building [9,10].

In this study, the wind load calculation was calculated according to the Turkish standard, the calculation values of the loads to be taken in the dimensioning of the building elements;

$$W = C_f \times 0.8q \times A$$

Here;

C_f= Aerodynamic load coefficient

q = Suction (speed pressure), $q = \frac{v^2}{1600}$

$$q = \frac{25^2}{1600} = 0.390625\ {}^{kN}/_{m^2}$$

A = Impacting surface area

$$A = 4 \times 11.8 = 47.4\ m^2$$

$W = 1.6 \times 0.8 \times 0.390625 \times 47.4 = 23.7\ kN$ is found as.

2.4. Hydrodynamic calculation

For the first time, Housner (1957) modeled the hydrodynamic effect of water in cylindrical steel liquid tanks as two separate masses, impulsive and convective. According to Housner's spring mass model, in steel tanks standing on rigid foundations, some of the liquid moves in the long-term convective (agitation) mode, while the rest moves impulsive (rigid) together with the tank wall [4]. The dynamic model of the cylindrical steel liquid tank is shared in Figure 3.

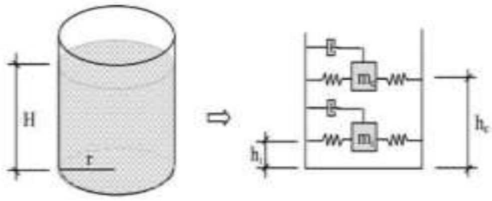

Figure 3. *Dynamic model of cylindrical steel liquid tank*

Bending and shear moments can be calculated by finding the m_i, m_c, h_i *and* h_c values in the dynamic model shown in Figure 4. The following calculations are made according to the ACI 350 standards based on the Housner model.

$$Impulse\ mass\ ratio\ (m_i) = m_t \times \frac{\tanh(0.866\left(\frac{D}{h}\right))}{0.866(\frac{D}{h})}$$

$$Oscillation\ mass\ ratio(m_c) = m_t \times 0.230 \times (\frac{D}{h}) \times \tanh(3.68\frac{h}{D})$$

$$Impulse\ mass\ impact\ height = \frac{D}{h} \geq 1.333$$

$$\rightarrow \frac{h_i}{h} = 0.375, \quad If\ \frac{D}{h} < 1.333\ \rightarrow$$

$$\frac{h_i}{h} = 0.5 - 0.09375(\frac{h}{D})$$

First case;

$m = 10450kg\ (curb\ weight\ of\ water\ tank)$

$h_0 = 8.469\ m\ (center\ of\ mass)$

$m_i = 151.500\ kg$

$m_c = 10627\ kg$

$h_i = 2.49\ m$

$h_c = 12.27\ m$

$h_i^L = 6.01\ m$

$h_c^L = 12.27\ m$ is found as.

Second case;

$m = 10450kg\ (curb\ weight\ of\ water\ tank)$

$h_0 = 8.469\ m\ (center\ of\ mass)$

$m_i = 75500\ kg$

$m_c = 10022\ kg$

$h_i = 2.42\ m$

$h_c = 6.34\ m$

$h_i^L = 3.34\ m$

$h_c^L = 6.30\ m$ is found as.

Third case;

In case 3, the calculation was not made because there is no liquid in the tank.

Since the highest values are in the 1st state, the moment calculations according to the 1st state are made, the superposed moments and the environmental loads are respectively;

$XR = 3.491E + 09\ Nmm$

$YR = 2.203E + 10\ Nmm$

$ZR = 4.752E + 07\ Nmm$

$XT = 8455\ N$

$YT = -6955\ N$

$ZT = -2.612E + 06\ N$ is found as.

3. Analysis Verification of Design

Static analysis is a type of analysis widely used in many industrial areas such as aviation, robotics, vehicle, construction, machinery and shipbuilding industries to determine whether it is safe or not, allowing us to examine the load on the structure or the effect of any external effect on the structure [9].

This silo, which will be installed in Tersan Shipyard and used in the treatment plant, are made by using Rhinoceros and AutoDesk Nastran Workbench analysis program in design verification studies.

Static structural analysis of the water tank designed with Rhinoceros is also used to determine the displacements in the water tank, stresses due to gravity and external loading, and hence the factor of safety, using AutoDesk Nastran Workbench.

While calculating the loads acting on the structure, 3 cases are considered, but the analysis is carried out according to this situation, since the 1st case (the state of which the entire structure is filled with liquid) is the most critical case when the analysis is performed.

The material chosen as the first step of the analysis, St37, is defined in the water tank. The next step is networking. To solve the mathematical model, the geometry must be extracted. The meshing tool divides the geometry into finite elements. The nodes in the structure are connected by lines, the water tank is divided into 1290909 elements and the network structure of complex geometry is formed by connecting with 2568251 nodes. At the next stage, the points where the water tank will be fixed, the forces to be applied and the direction of the forces are selected. Force and force direction are applied according to the worst case scenario. The points where the structure will be fixed and the force will be applied are shared in Figure 4.

Table 3. *Data on the material used*

Material used	St37
Density	7.8E-09 (Mg/mm^3)
Poisson ratio	0.3
Tensile yield strength	241.68 (MPa)
Elastic modulus	200000 (MPa)

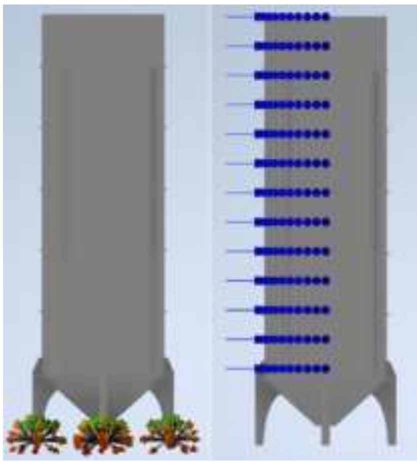

Figure 4. *Points where the structure will be fixed and force will be applied*

4. Results

4.1. Displacement

Displacement is the change in position of a particle or object. The first position of the particle or the object is accepted as a reference, and it is found by measuring the distance between the first and last position.

As can be seen in the first picture in Figure 2, the forces in the "loads acting on the structure" section were applied to the water tank after the water tank is fixed at the specified points. This resulted in a maximum displacement of 2,136 mm. The image of the displacement resulting from the analysis is shared in Figure 5.

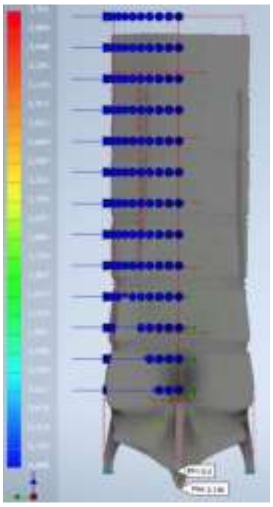

Figure 5. *Displacement in the building*

4.2. Stress-Strain

Stress - strain analysis is the response of a particle or object under certain loads. In Figure 6, the stresses that occur in the water tank after the loads we found in the "loads acting on the structure" section are shown on the water tank. The maximum Von Mises Stress value in the water tank is found to be 46.71 MPa. The image obtained as a result of the Von Mises Stress analysis is shared in Figure 6.

5. Conclusions

It should not be forgotten that the analyzes are an iterative process. In other words, the water tank design is changed many times until the design is deemed safe. For example, brackets and lama reinforcements are made to the skeleton that will carry the water tank.

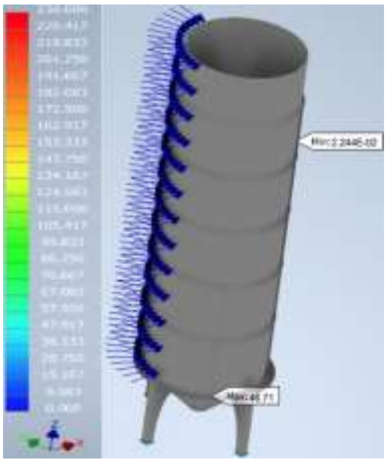

Figure 6. *Von Mises stress value in the structure*

It is seen from table c that the yield strength (tensile yield stress) of the material used in the design of the water tank is 241.68 MPa, and 241.68 MPa has been accepted as the upper limit in the analysis study carried out in order for our water tank design to be considered safe.

In order for our water tank design to be considered safe, the maximum Von Mises Stress value occurring in our structure as a result of the analysis should be below 241.68 MPa. In the light of this information; Since the maximum Von Mises Stess value in our structure is 46.71 MPa, it is decided that our water tank is safe for use.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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- **Author contributions:** The authors declare that they have equal right on this paper.

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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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