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Design and feasibility study of underground water tanks by different ground conditions and earthquake loads

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Abstract. This study comprises the design of rectangular underground water tanks under different ground conditions and the strength analysis of slab floor, walls, and foundation of rectangular underground water tanks. The importance and sustainability of water storage and management for humans is a very important and detailed issue. In this research, the design and analysis of rectangular water tanks to be constructed in ZA and ZE ground classes classified according to the Turkish earthquake regulation (TBDY 2018) were made using the IdeCAD program. The results of the stress, moment and deformation analyzes according to the design made with the design parameters used in this research showed that the rectangular water tanks to be built in the ZA ground class have structural strength against the stresses arising from soil, water and earthquake loads without suffering any significant deformation. The design values obtained using stress, deformation, and structure overturning moment analyses were found to be with in the limits of structural safety confirming the reliability of the design parameters. On the other hand, it has been found that underground water tanks to be built in the ZE soil class could also successfully resist to the lateral overburden and earthquake loads. However, it was determined that the deformations in the tank structure in ZE class soil were found higher than in the ZA class soil due to th e loose, weathered, and low bearing strength of the ZE class soils. This study also emphasizes the importance of using raft foundations under underground water tanks to be built on ZE class grounds to increase safety and prevent increasing deformations over time, such as creep.

Keywords: IDECAD; underground water tanks; ZA and ZE class soils and rectangular water tanks

1. Introduction

People have tried to retain underground and surface water and have searched for ways to deliver the stored water to the necessary places and facilities for centuries. Various shapes and sizes of water retaining structures have been constructed to retain water economically and conveniently in the locations where it is needed. Water tanks, both in industrial and domestic settings, are crucial for storing and maintaining water quality. Despite Turkey's rich water resources, with a potential of 95 billion m³, the utilization of these resources is not adequate (Akın and Akın 2007). These tanks are categorized into two ma in types: underground and aboveground, with a distribution in Turkey of 82.6% aboveground and 17.4% underground (Kolaylı *et al*. 2019).

The determination of the location and construction of water tanks involves factors such as protection from sunlight and the necessity of being constructed at least 60 cm below the surface, which plays a significant role in preventing water from gett ing warm and bacterial contamination (World Health Organization 2014, Yavuz and Koşar 2020)

As human needs diversify, different storage solutions have been developed, including tanks for water, fuel, gas, and wastewater treatment facilities (Kasper and Schramm 2023, Ward 2003). The presence of disease-causing bacteria in water tanks often originates from the water being previously exposed to contaminants like human or animal waste (Akyıldız *et al*. 2021). Liquid storage systems are essential not only for water shortages but also for various purposes such as water storage for buildings with low pressure, storage of utility waters, accumulation of wastewater, provision of fire extinguishing water, purposes fo r livestock, chemical production, food preparation, and storage and storing petroleum, etc. Storage systems are classified based on their intended use as water tanks, fuel and gas tanks, and wastewater treatment tanks. Moreover, these systems are also classified according to the type of construction material used such as reinforced concrete tanks, prestressed tanks, masonry concrete tanks, and steel tanks. Besides these classifications, liquid storage systems are also classified in terms of their shapes as mostly circular, rectangular cross- section tanks, and trapezoidal cross-section tanks (Fawell and Nieuwenhuijsen 2003). The materials used in the construction of water tanks must possess various properties and meet legal requirements. For example, the necessity of using concrete class C25 or higher is emphasized for reinforced concrete rectangular and cylindrical water tanks. The tank slab floor should be at least 30 cm thick, and types CEM I, CEM II, and CEM III types of cement should be used; aggregates must comply with TS706 EN 12620 standards (Singh *et al*. 2017, Drinking-water 2023). The design of the tank geometries depends on factors suchas statics, impermeability, location,

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economy, and operational factors.

Underground water tanks have several advantages, including requiring less space need for construction compared to cylindrical tanks, no noise issues from pumps, no negative impact on aesthetics, less solar ray effect from sunlight, keeping chemicals away from the public, providing durability through internal and external insulation, and prevents bacterial growth by blocking the harmful solar rays. Since the filled water applies pressure to the tank walls, both compressive and indirect tensile forces and moments occur on the tank walls. Any water tank sections must have dimensions and reinforcement to absorb the normal force, moment, and cracking, as the section effect must also be considered. When it comes to resistance to section effects in water tanks, circular sections are seen to be superior to other tank sections in terms of statics, as the sections where the bending moment occurs are less than other angular sections. However, cylindrical water tanks require more space and have no cost advantage, as molds with curved surfaces must be used. Considering the cross-sectional effects, square and rectangular cross-sections are preferred because the distribution of the effects is more balanced, and they are more economical as well as being superior in terms of statics (Dogagun and Livaen 2004, Demirören 2005, Anirutha *et al*. 2016, Wang 2022).

While designing the tanks, the dead loads are considered first and the water load to be stored is considered second in the construction stage. Not only the weight of the water but also the water pressure on the walls of the tank must be considered, which is the most important problem, to minimize the dead water weight. Water pressure is effective in sizing the side walls where water comes into contact. Water pressure acts as a triangular normal force with an intensity equal to the elevation difference between the water surface and the point on the surface it affects, multiplied by the specific gravity of the water. More specifically, the following loads and effects must be considered during the design of water tanks: The weight of the tank and equipment, the weight of the stored water, operational loads, effects of temperature changes, creep and shrinkage effects, snow and wind loads, earthquake impact and dynamic loading, soil and water pressure, uplift force from groundwater (Fawell and Nieuwenhuijsen 2003). The following aspects should also be considered during the water tank design: The presence and functionality of remote monitoring systems, the ratio of the maximum hourly flow rate to the average flow rate, the effects of pump failures and power outages, availability of alternative water sources, time required to repair distribution line faults, allocation of water for industrial needs, fire flow, and other special circumstances. Pedestal and other water tanks should be designed and constructed with safety issues to prevent changes in water quality (Drinking-water 2023).

1.1 Earthquake effect on underground water tanks

An earthquake is a natural disaster in which vibrations occur suddenly due to fractures in the earth's crust, spreading as waves and shaking the environment and the earth's surface. Calculations for earthquakes in buried water retaining structures differ from those for aboveground structures and tanks, and it is necessary to consider the effects of dynamic ground pressure in underground tanks when analyzing earthquake effects. A significant part of the vibration energy occurs in underground and aboveground structures is damped by the damping in the ground and the irreversible diffusion effect on the ground, but this mechanism is not expected in underground structures if there is a rigid foundation. For this reason, different settlements may occur in the load-bearing systems of buildings during an earthquake due to the ground effect (Gu 2015, Farajin *et al*. 2017, Sonmezer and Celiker 2020, Soltani and Bagheripour 2022, Yoo *et al.* 2022). Earthquake calculations for liquid storage structures are generally done according to the Hausner method, EUROCODE, and ACI in the literature (Eurocode 8 2006 a, b, ACI 2007, Livaoğlu 2008, Sonmezer and Celiker, 2020). During an earthquake, the part of aboveground structures within the ground oscillates with the ground, and these oscillations affect the superstructure, causing internal forces to occur (Chen *et al*. 2016, Çelik and Köse 2020, Yoo *et al*. 2022). Since the superstructure tries to resist these movements that occur with the ground using its mass, there is a directly proportional relationship between the earthquake force and the mass of the superstructure. However, when considering underground structures such as underground water tanks, the entire structure oscillates with the ground, and therefore, especially in underground structures with small volumes, significant stresses are not observed during the earthquake.

Factors affecting the damage to underground structures caused by ground deformations resulting from seismic waves in the earth's crust are as follows: shape, size, and depth of the structure; characteristics of the ground or rock environment in which the structure is located (apparent speed of the Vs/Cs wave, unit volume weight of the ground, Poisson ratio of the ground, and soil thickness on rigid rock); geometry characteristics of the structure; and the magnitude of the earthquake (Karasin *et al*. 2020). While the behavior of underground structures against earthquakes is examined and their designs are carried out, the interaction of the structure and the ground (SSI) is sometimes neglected and sometimes becomes important (Sisman and Ayvaz 2020, Zhao *et al*. 2017). For example, in underground structure designs to be made in regions where low vibrations are expected or on highly rigid soils such as rocks, the SSI is ignored by assuming that the structure directly changes into the deformation types in the ground. However, in soft soils, the structure-soil interaction is examined in cases where the structure is thought to resist the movements and displacements on the ground. In an underground structure such as a rectangular cross-section water tank, the deformations caused by earthquake waves perpendicular to the axis of the structure result in bending deformations (Dubey *et al*. 2021). However, almost all regulations, including EUROCODE, ACI, and Turkish Earthquake Regulation, recommend considering oscillation and impulse components in the dynamic analysis of tanks. Additionally, for the short -period special tank type, the base

Table 1 TBDY-2018 article 16.4.1. (Karasin *et al.* 2020)

Soil Class	Soil Type	Average in the upper 30 meters		
		(Vs)30 [m/s]	(N60)30 [blows/30 cm]	(Cu)30 [kPa]
ZA	Strong, hard rocks	>1500	-	-
ZB	Moderately weathered, relatively strong rocks	760-1500	-	-
ZC	Very dense layers of sand, gravel and hard clay or weathered, weak rocks with many cracks	360-760	>50	>250
ZD	Medium-tight sand, gravel or very solid clay layers	180-360	15-30	70-250
ZE	Profiles containing loose sand, gravel or soft-solid clay layers or a soft clay layer (cu < 25 kPa) with a total thickness of more than 3 meters that meets the conditions of Pl > 20 and w > 40%	< 180	< 15	< 70
ZF	Soils that require site-specific research and evaluation: 1) Soils with a risk of collapse and potential collapse under the influence of an earthquake (liquefiable soils, highly sensitive clays, collapsible weakly cemented soils, etc.) 2) Peat and/or clays with high organic content with a total thickness of more than 3 meters 3) High plasticity (Pl > 50) clays with a total thickness of more than 8 meters 4) Very thick (> 35 m) soft or medium solid clays.			

shear force ratio of the tank is almost the same in all codes (Dubey *et al.* 2021). Significant changes have been made to soil parameters and design spectra with the 2018 Turkey Building Earthquake Regulation (TBDY 2018). Soils are classified according to the TBDY 2018 as ZA, ZB, ZC, ZD, and ZE. The characteristics of these soil classes determined by TBDY 2018 are shown in Table 1.

Soil parameter calculations are made for the first 30 meters downwards from the base or pile cap of the soil profile. In profiles containing various soil and rock layers, these layers in the top 30 meters are subdivided and numbered from i = 1 to i = N. The average shear wave velocity (VS)30, the average standard penetration test blow count (N60)30, and the average undrained shear strength (CU)30 are calculated as follows

$$(VS)_{30} = \frac{30}{\sum_{i=1}^{N}\left(\frac{h_i}{VS_i}\right)}, \quad (N60)_{30} = \frac{30}{\sum_{i=1}^{N}\left(\frac{h_i}{N60_i}\right)}, \quad (CU)_{30} = \frac{30}{\sum_{i=1}^{N}\left(\frac{h_i}{CU}\right)} \tag{1}$$

Where, hi is the thickness [m] of the i-th sublayer, VSi, N60i, and CUi are the shear wave velocity [m/s], the number of blows from the standard penetration test [blows/30 cm], and the undrained shear strength [kPa] of the sublayer respectively (TBDY-2018, Article 16.4.2). The design will consider buried water tanks in ZA and ZE soil classes. (Songur and Dabanlı 2006, Bingöl and Kavvas 2011, Gorchev and Ozolins 1984, Sönmez and Çizmecioğlu 2007).

There are 4 types of earthquake ground motions: DD-1, DD-2, DD-3, DD-4. The largest earthquake motion is DD-1. The spectral magnitude with a 2% exceedance probability in 50 years and a return period of 2475 years characterizes the earthquake ground motion. DD-2 earthquake ground motion, the spectral magnitude with a 10% exceedance probability in 50 years and a return period of 475 years characterizes the earthquake ground motion. This earthquake ground motion is also called the standard design earthquake ground motion. There is approximately 1.5 times the difference between each earthquake level. (IdeCAD 2023). DD2 earthquake mentioned in TBDY2018 corresponds to the design earthquake in our earthquake regulation currently in force.

In this paper, the design and performance analyses of a rectangular water tank and its interaction with two soil classes ZA and ZE are studied. The effect of soil types on the seismic response of underground water tanks and durability is investigated under earthquake loading, as well as the impact of varying loadings on the walls and slab floor of a water tank depending on the soil type. The ZA class, classified by TBDY 2018, consists of robust and hard rocks, while the ZE class, also classified by TBDY 2018, includes loose sand, gravel, or soft-firm clay layers (TBDY 2018). And also DD-2 standard design earthquake ground motion is used. This region represents places with less seismicity than the 1st degree, but still at risk of serious earthquakes.

2. Analyses and research methodology of the study

In this study, soil-structure interactions of a rectangular shaped underground water tank constructed on ZA and ZE class soils with geotechnical reports and field data were analyzed with the IdeCAT program. IdeCAD program is widely used in civil engineering and architecture for the analysis and design of concrete, reinforced concrete and steel structures. It is able to ana lyze the systems using semi-rigid diaphragm, fully rigid diaphragm, or without diaphragm methods. The sofware allows to model the combined use of both frame and shell elements with multidisciplinary building information modeling software for architecture, structural analysis, design, reinforcement, visualization and drawings (Basov 2017, Systems 2011). It is possible to determine the vertical earthquake effect, an effect on the building behavior as a certain proportion of the horizontal

Table 2 Earthquake parameters in the analyses determined according to the TBDY2018 (Ozcebe *et al.* 2003)

Building Importance Coefficient (I):	1
Building Usage Class (BKS):	3
Carrier System Behavior Coefficient R (Entered) (X / Y):	6/6
Carrier System Behavior Coefficient R (Selected) (X / Y):	4.8. / 6
Strength Excess Coefficient (X / Y):	2.5. / 2.5
Eccentric Ratio:	0.05
Ductility Level:	High
Earthquake Ground Motion Level:	DD2
Earthquake Design Class (DTS):	1
Building Height Class (BYS):	8
Normal Performance Target:	Controlled Damage
Evaluation / Design Approach:	Design According to Strength

Table 3 Soil parameters used in the IdeCAD analyses

Soil Type	ZA
Spectrum Characteristic Periods:	Ta : 0.05, Tb : 0.24
Ground Bearing Strength	100.00 [tf/m^2]
Bearing coefficient	15000.00 [tf/m^3]
Short period map spectral acceleration coefficient (Ss):	1.111
Map spectral acceleration coefficient (S1) for a 1.0 second period:	0.262
Short period design spectral acceleration coefficient (SDs):	0.8888
Design spectral acceleration coefficient (SD1) for 1.0 second period:	0.2096
Maximum Ground Acceleration (g) (PGA):	0.453
Maximum Ground Velocity (PGV):	26.166

earthquake effect, on the movements of the underground structures under earthquakes loading.

2.1 Rectangular water tank design for ZA class soil

The local soil class effect may differ during an earthquake depending on the structure of the ground. In soft ground, the earthquake effect can reach the ground with higher acceleration. Different soil types produce growth in different periods within the earthquake response spectrum. If the natural period of structures is close to this growth range, damage to the structure would increase significantly. For this reason, local ground conditions are of great importance in the process of ground motion analysis and earthquake resistant structure design. Determining an earthquake acceleration spectrum appropriate to local ground conditions is the most used input parameter in dynamic structure analysis. This refers to a spectrum containing the highest peak acceleration value and period (PGA).

Dimensionless map spectral acceleration coefficients are defined within the scope of Turkey Earthquake Hazard Maps for four different earthquake ground motion levels:

(a) Short period map spectral acceleration coefficient SS

(b) Map spectral acceleration coefficient S1 for 1.0 second period

Map spectral acceleration coefficients corresponding to the geometric mean of earthquake effects in two horizontal directions perpendicular to each other are defined as dimensionless coefficients by dividing map spectral accelerations by gravity acceleration for a specific earthquake ground motion level for a 5% damping ratio based on the reference ground condition [(VS 30) = 760 m/s].

Short-period design spectral acceleration coefficient SDS, and 1-second period design spectral acceleration coefficient SD1 values are calculated with Eq. (2).

$$S_{DS} = S_S F_S \qquad S_{D1} = S_1 F_1 \tag{2}$$

Where, SS is the map spectral acceleration coefficient for the short period and S1 is the map spectral acceleration coefficient for the 1.0 second period. Fs and F1 are the ground effect coefficients for the short period, and F1 is the local ground effect coefficient for a period of 1.0 seconds respectively. These coefficients were obtained from the TDBY 2018 regulations.

Table 4 Material characteristics used in the analyses

Curtains:	C25 B420C
Floors:	C25 B420C
Foundation	C25 B420C
Static Material Name:	C25 B420C
Characteristic Compressive Strength of Concrete:	25 Mpa
Characteristic Tensile Strength of Concrete:	178.45 tf/m^2
Concrete Safety Coefficient:	1.5
k1 Constant:	0.85
Flexural Reinforcement Yield Strength:	420 Mpa
Stirrup Reinforcement Yield Strength:	420 Mpa
Steel Safety Coefficient:	1.15
Elasticity Modulus:	3084641.544 tf/m^2
Slip Module:	1285267.31 tf/m^2
Poisson's Ratio:	0.2
Unit weight:	2.5 tf/m3
Coefficient of Thermal Expansion:	1.00E-05

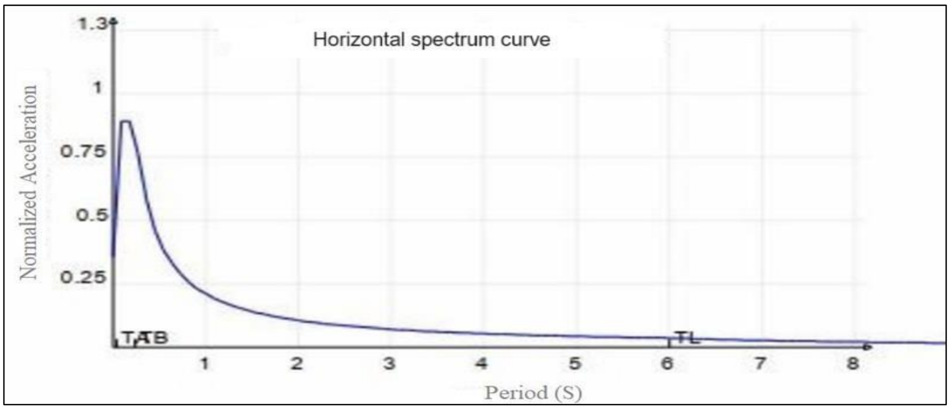


Fig. 1 Horizontal spectrum curve

In this study, static and dynamic analyses were performed using IdeCAD software on a rectangular water tank with a length of 8 meters, a width of 5 meters, a height of 5 m, and a total capacity of 200m3. The earthquake parameters, soil parameters, and construction material properties in the analyses are given in Tables 2 -4, respectively

The normalized acceleration value reaches 0.85 at 1 second as shown in Fig. 1. This indicates that the acceleration of ground motion reaches 85% of its expected maximum value during an earthquake load with 1 second period. This short period spectral acceleration coefficient SDs value obtained is very important for use in the design of structures and seismic analyses. This value makes it easier for designers to understand how a structure will respond during a seismic event with the characteristics that engineers have determined.

2.2 Loading and moment analyses of the water tank for ZA class soil

In this study, a rectangular water tank constructed in ZA class soil was analyzed using the IdeCAD program with a semi- rigid diaphragm model. There are two different types of slab floor floor modeling in structural analysis with IdeCAD: Fully rigid diaphragm and Semi-rigid diaphragm. The Semi-Rigid Diaphragm is an acceptance in which in-plane stresses and movements can occur by modeling the slab floor with shell finite elements, considering the slab floor stiffness in the analys is model, and based on slab floor thicknesses, dimensions, and construction material properties. In the Full Rigid Diaphra gm model, it is assumed that the in-plane stiffness of the slab floor is very large, and the in-plane movement is neglected. Thus, the semi-rigid diaphragm model uses shell finite elements to simulate in-plane and out-of-plane stresses and deflections of the slab floor to reflect the most realistic behavior of the floor in the structural analysis model. Additionally, the analysis with t he fully rigid diaphragm is based on the assumption that there is little to no in -plane deformation in the slab floors under the earthquake effect. Since this deformation does not occur, in-plane stresses will not appear in the analysis model. On the other hand, it is an analytical model that represents situations where the stiffness of the slab floor is close to or equal to the

Table 5 Loading symbols and notations

	Loading type	Loading combinations in the analyses
G	Constant Load	6G+1.4Q+1.6H 0.9G+1.6H
Q	Moving Load	1.4G+1.6Q G+Q
G'	Dead load (Effective section stiffnesses were used)	G+Q G'+Q'+Ex-
Q'	Live load (Effective section stiffnesses were used)	0.3Ey+0.3Ez G'+Q'+Ex+0.3Ey+0.3
Ez(G)	Vertical earthquake (4.4.3.2)	Ez G'+Q'-Ex- 0.3Ey+0.3Ez G'+Q'-
HX1	Earth thrust loading in X direction	Ex+0.3Ey+0.3Ez
HY1	Earth thrust loading in Y direction	G'+Q'+Ey- 0.3Ex+0.3Ez
S	FULL WATER LOAD	G'+Q'+Ey+0.3Ex+0.3 Ez G'+Q'-Ey-
H	SOIL LOAD	0.3Ex+0.3Ez G'+Q'- Ey+0.3Ex+0.3Ez
Ex	Additional eccentric earthquake loading in X direction (Full rigid diaphragm solution)	0.9G'+Ex-0.3Ey- 0.3Ez
Ey	Additional eccentric earthquake loading in Y direction (Full rigid diaphragm solution)	0.9G'+Ex+0.3Ey-0.3Ez 0.9G'-Ey-0.3Ex-0.3Ez 0.9G'-Ey+0.3Ex-0.3Ez

stiffness of the system. The stiffness calculation depends on the thickness, dimensions, and material parameters of the slab floor. The acceptance of a semi-rigid diaphragm reflects the behavior of the slab floor in the structure analysis model that is closest to reality. In the semi- rigid diaphragm model, floors are modeled using two-dimensional finite elements (shell). These elements create stresses on the shell by moving in-plane and out-of-plane. The design of reinforced concrete slab floors is based on this stress distribution. The reason for considering the diaphragm stiffness in the analysis is that the semi-rigid diaphragm acceptance most accurately represents the behavior of the slab floor in the models. It provides a close approximation of the real behavior in structures with irregular or large spaces in the plan. However, the analysis time is longer compared to the rigid diaphragm because the analysis is not simplified. According to TBDY 2018, it is mandatory to accept the semi-rigid diaphragm, especially in beamless floor structures and buildings with defined irregularities. The loading configurations and relative notations in the loading and moment analysis are provided in Table 5.

2.3 Loading and moment analyses of the water tank for ZA class soil

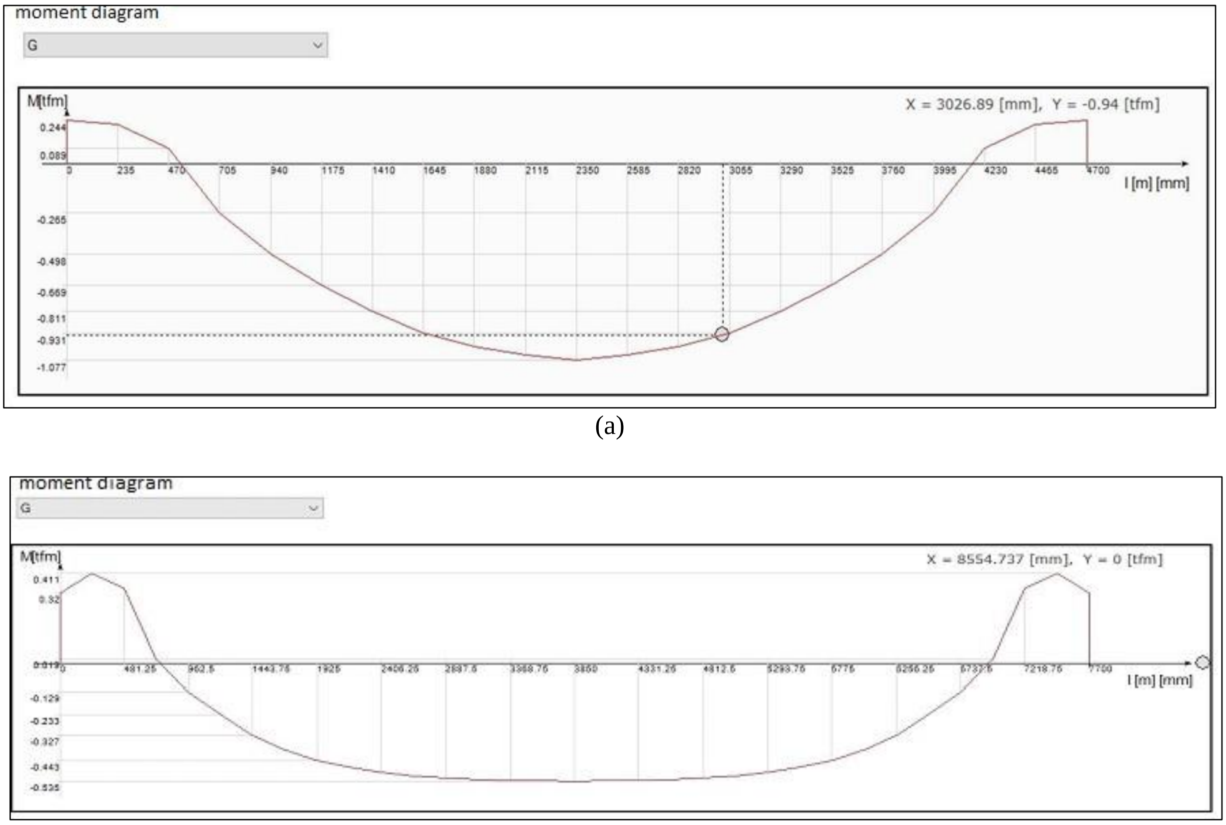
In this study, a rectangular water tank constructed in ZA class soil was analyzed using the IdeCAD program with a semi- rigid diaphragm model. There are two different types of slab floor floor modeling in structural analysis with IdeCAD: Fully rigid diaphragm and Semi-rigid diaphragm. The Semi-Rigid Diaphragm is an acceptance in which in-plane stresses and movements can occur by modeling the slab floor with shell finite elements, considering the slab floor stiffness in the analysis model, and based on slab floor thicknesses, dimensions, and construction material properties. In the Full Rigid Diaphragm model, it is assumed that the in-plane stiffness of the slab floor is very large, and the in-plane movement is neglected. Thus, the semi-rigid diaphragm model uses shell finite elements to simulate in-plane and out-of-plane stresses and deflections of the slab floor to reflect the most realistic behavior of the floor in the structural analysis model. Additionally, the analysis with the fully rigid diaphragm is based on the assumption that there is little to no in-plane deformation in the slab floors under the earthquake effect. Since this deformation does not occur, in-plane stresses will not appear in the analysis model. On the other hand, it is an analytical model that represents situations where the stiffness of the slab floor is close to or equal to the

stiffness of the system. The stiffness calculation depends on the thickness, dimensions, and material parameters of the slab floor. The acceptance of a semi-rigid diaphragm reflects the behavior of the slab floor in the structure analysis model that is closest to reality. In the semi- rigid diaphragm model, floors are modeled using two-dimensional finite elements (shell). These elements create stresses on the shell by moving in-plane and out-of-plane. The design of reinforced concrete slab floors is based on this stress distribution. The reason for considering the diaphragm stiffness in the analysis is that the semi-rigid diaphragm acceptance most accurately represents the behavior of the slab floor in the models. It provides a close approximation of the real behavior in structures with irregular or large spaces in the plan. However, the analysis time is longer compared to the rigid diaphragm because the analysis is not simplified. According to TBDY 2018, it is mandatory to accept the semi-rigid diaphragm, especially in beamless floor structures and buildings with defined irregularities. The loading configurations and relative notations in the loading and moment analysis are provided in Table 5.

The tank was positioned at a depth of -5m below ground level and supported with a 30 cm thick raft foundation in the designs. The water pressure (Q) for the tank was determined to be 5 tf/m2, obtained by dividing the 200 m 3 volume by the 40

Table 6 Earthquake loading and other relative parameters used in design

Total Mass of the Structure	124.84 t
Live load coefficient =	0.3000
Total Earthquake Load (X)	Vt = 22.69 [tf] - (Dynamic Method)
Total Earthquake Load (Y)	Vt = 22.33 [tf] - (Dynamic Method)
Structure Natural Vibration Period (X - Modal E1)	Ta = 0.05 ≤ Tr = 0.09 ≤ Tb = 0.24 [s]
Structure Natural Vibration Period (X - Modal E2)	Ta = 0.05 ≤ Tr = 0.09 ≤ Tb = 0.24 [s]
Structure Natural Vibration Period (Y - Modal E3)	Ta = 0.05 ≤ Tr = 0.09 ≤ Tb = 0.24 [s]
Structure Natural Vibration Period (Y - Modal E4)	Ta = 0.05 ≤ Tr = 0.09 ≤ Tb = 0.24 [s]
Spectrum Coefficient	S(T) = 0.89



(a)

(b)

Fig. 2 (a) and (b) Slab floor moment and required reinforced area of the water tank constructed in ZA soil class

m2 base area. The tank walls were designed with a thickness of 30 cm and a height of 8m, with a soil pressure of 1 tf/m2 applied. The top slab floor was designed with a thickness of 30 cm and can resist a dead load of 0.5 tf/m 2. The concrete cover thickness was set at 6 cm. The minimum reinforcement spacing was determined to be 8 cm, and the maximum reinforcement spacing was set at 10 cm to minimize deformation and permeability in water tanks. The earthquake loading and related components used in the designs are given in the Table 6.

Fig. 2 shows the moment distributions and corresponding reinforcement areas required for the slab floors in a water tank constructed in a ZA soil class for two different section plans within the slab floor of the water tank. Fig. 2 shows the bend ing moments in tf-m and the required reinforcement areas in cm2 for the left, middle, and right sections of the slab floor. The load combination "1.6G+1.4Q+1.6H" used in this analysis is specially chosen to evaluate the slab floor's performance under permanent, live, and horizontal loads (earth pressure).

The strength properties of concrete and reinforcement steel are considered to ensure the slab floor's design provides sufficient safety and durability. The moment diagram illustrates the variation of moments along the length of the slab floor and identifies the locations and magnitudes of the tensile and compressive moments. This information is important for structural designers to determine the desired locations and the

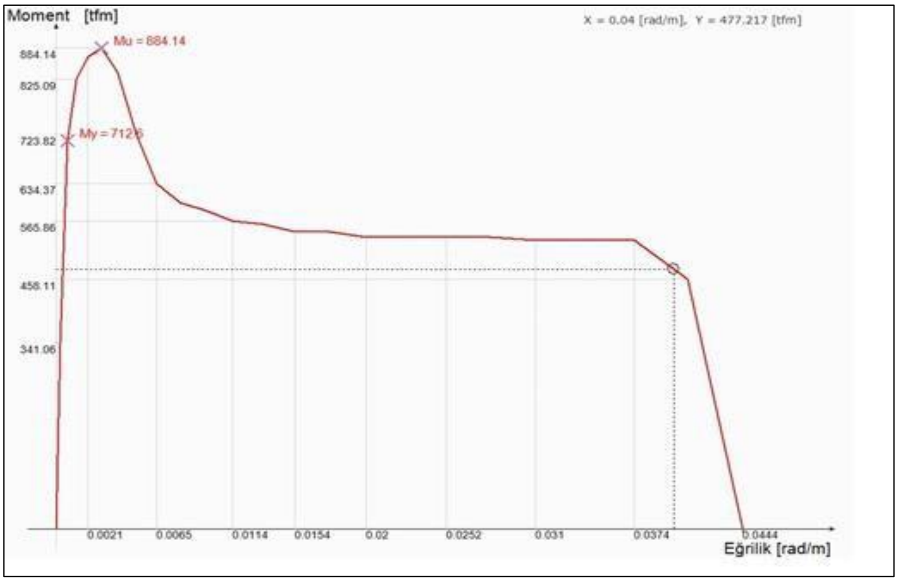


Fig. 3 Wall moment-curvature graph of the water tank constructed in ZA soil class

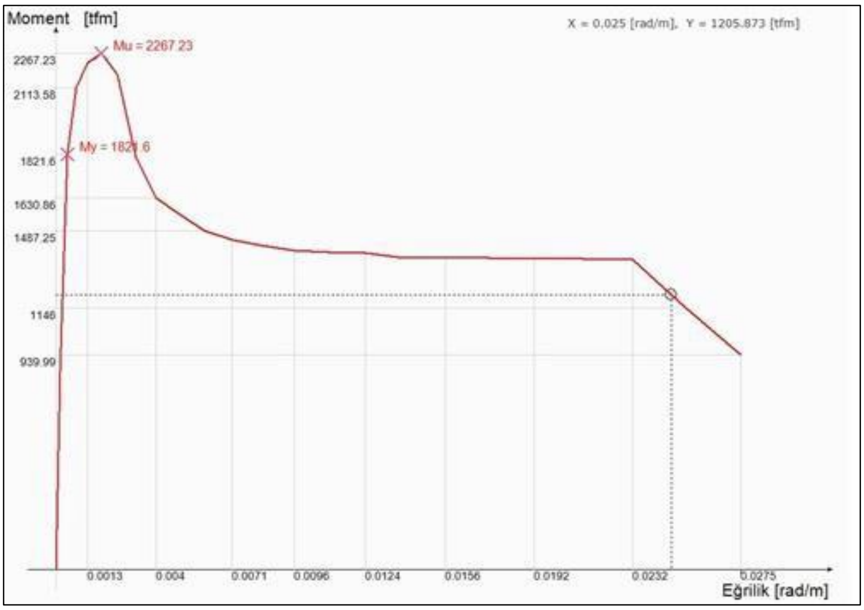
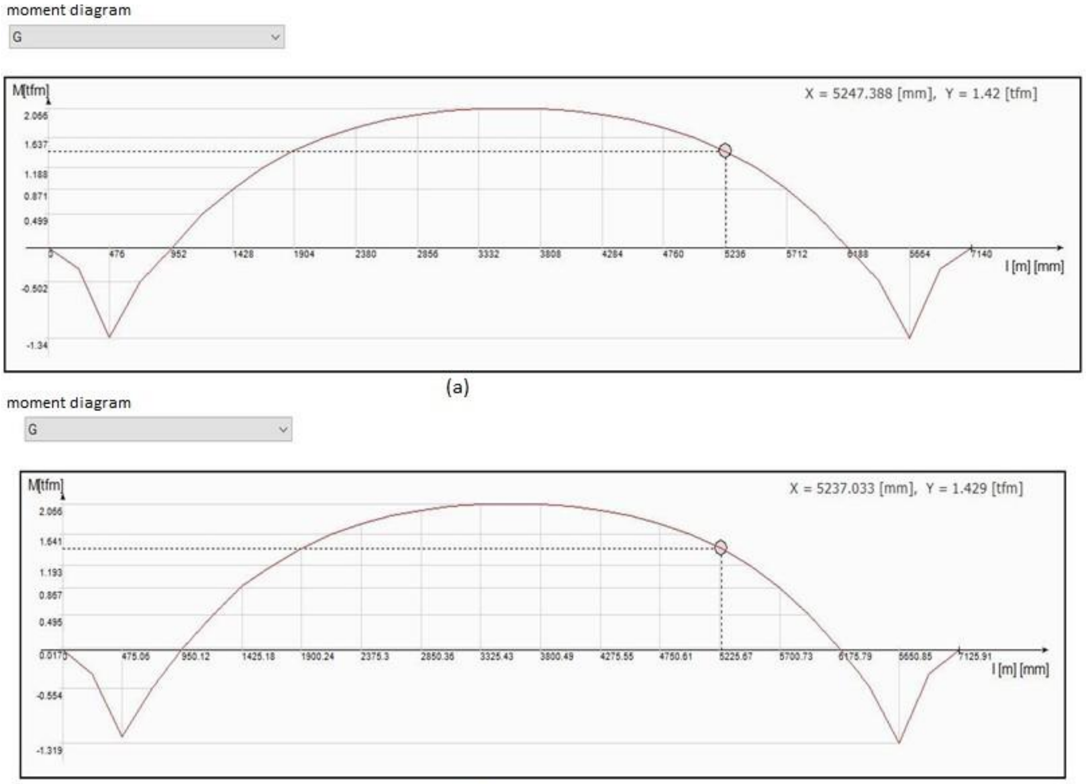


Fig. 4 Wall moment-curvature graph of the water tank constructed in ZA soil class

required reinforcement parameters within the slab floor. These moment calculations using earth pressure, permanent, and live loading give essential data on how to calculate compressive and tensile bending moments in various sections of a water tank slab floor and determine the required reinforcements for the service life of an underground water tank.

The interior walls of rectangular tanks resist fluid pressure with both vertical and horizontal bending moments. Necessary calculations must be made about the ratio of the pressure resisted by the bending moments in the vertical and horizontal planes. The direct horizontal stress caused by direct tension due to water pressure at the end walls must be added to the indirect stress caused by horizontal bending moments. Fig. 4 and 5 present the relationship between moment and curvature in the walls of water tanks located in the ZA soil class and show how the structural wall elements develop moments at the cross-sectional level. The unit deformation demands of concrete and reinforcement steel are compared with limit values and the performance of the carrier system at the cross-sectional level is determined by using the IdeCAD program easily. When the non-linear earthquake calculation is included in the IdeCAD analysis, the unit deformation demands obtained according to the proposal of TBDY 2018/15.6.2 are compared with the unit



moment diagram: G

(a)

moment diagram: G

(b)

Fig. 5 Raft foundation moment and required reinforcement areas of the water tank constructed in ZA soil class

deformation capacities and the load-bearing system performance at the cross- section level.

The high initial moment value in Fig. 4 represents the wall's maximum load -bearing capacity. The subsequent decrease in moment values indicates the wall's transition into plastic deformation, leading to a reduction in its load -bearing capacity. The point where the reinforcement reaches the yield stress and the moment value at this point was found to be 723.82 tfm with the moment-curvature analysis, and this moment is named as the flow moment (My). The smooth part of the graph, where the moment remains constant or decreases despite increasing curvature, shows that the wall has reached its maximum plastic deformation capacity. After this point, plastic deformations occur in the cross-section. This point is also the failure point of the section, and the moment at this point is the failure moment or moment capacity Mu. After this point, the cross-section loses its load-carrying capacity and plastic deformation capability and collapses. Similarly, Fig. 5 illustrates the wall's elastic limit and maximum load-bearing capacity at an initial moment value, followed by a transition to plastic behavior. The graph's end, where the moment stabilizes or remains constant, demonstrates the limit of the wall's energy absorption capacity.

If the tank is constructed directly on the ground, it must be able to support the load without significant collapse of any part of the floor, and the concrete floor must be poured in panels. When the underground tank is supported by walls, the floor sla b shall be designed like flooring in buildings to resist bending moments due to the water load and its weight. When floors are rigidly attached to walls, bending moments at the junction between walls and floors must be considered in the design of the floor, along with direct forces transferred from the walls or floor to the floor. In this study, analyses were made assuming that the underground water tank was built on a raft foundation, and the load and moment calculations on the raft foundation are shown in Fig. 5. As shown in Fig. 5 , the bending moments at various sections of the foundation and the corresponding required reinforcement, the moment distributions, and the required reinforcement areas for the raft foundation of a water tank planned to be constructed in ZA soil class.

The applied load combination is "1.6G+1.4Q+1.6H," which indicates the most unfavorable loading conditions on the foundation, including permanent loads (G), live loads (Q), and horizontal loads (H). As seen from the moment graphs, it has been determined that tensile stress moments occur in a wide area of the raft foundation, and compressive moments occur close to the junctions with the walls. Considering that the tensile strength of the concrete used is 1.7 N/m2, the required minimum raft foundation thickness was found to be 153 mm by equating the moment resistance to the maximum bending moment. In this design, since a 300 mm raft foundation is designed, it is concluded that the foundation design of the tank is very reliable.

Table 7 ZE class soil parameters used in the analysis

Soil Type	ZE
Spectrum Characteristic Periods:	Ta: 0.14, Tb : 0.70
Ground Bearing Strength	10.00 [tf/m2]
Bearing coefficient	1000.00 [tf/m3]
Short period map spectral acceleration coefficient (Ss):	1.111
Map spectral acceleration coefficient (S1) for a 1.0 second period:	0.262
Short period design spectral acceleration coefficient (SDs):	1.123.443
Design spectral acceleration coefficient (SD1) for 1.0 second period:	0.78338
Maximum Ground Acceleration (g) (PGA):	0.453
Maximum Ground Velocity (PGV):	26.166

Table 8 Earthquake loading and other relative parameters used in design

Total Mass of the structure	124.84 t
Live load coefficient =	0.3000
Total Earthquake Load (X)	Vt = 38.38 [tf] - (Dynamic Method)
Total Earthquake Load (Y)	Vt = 34.17 [tf] - (Dynamic Method)
Structure Natural Vibration Period (X - Modal E1)	$Ta = 0.14 \leq Tr = 0.17 \leq Tb = 0.70$ [s]
Structure Natural Vibration Period (X - Modal E2)	$Ta = 0.14 \leq Tr = 0.17 \leq Tb = 0.70$ [s]
Structure Natural Vibration Period (Y - Modal E3)	$Ta = 0.14 \leq Tr = 0.17 \leq Tb = 0.70$ [s]
Structure Natural Vibration Period (Y - Modal E4)	$Ta = 0.14 \leq Tr = 0.17 \leq Tb = 0.70$ [s]
Spectrum Coefficient	S(T) = 1.17

The material properties in both Figs. 5 and 6 are the characteristic and design strengths of concrete (fck and fcd) and the yield and design yield strengths of reinforcement steel (fyk and fyd). The moment diagrams in Figs. 5 and 6 show the relationship between the bending increase and bending moments of the foundation. They also demonstrate the elastoplastic bearing capacity limit of the foundation and its bending behavior under the applied loading. Critical points in the diagrams (indicated by X and Y coordinates) highlight areas where the foundation experiences support or where the moments are ineffective.

2.4 Rectangular water tank design for ZE soil class

The design processes of a rectangular water tank constructed to be in ZE soil class with a storage capacity of 200 m^3 are analyzed in this study. The tank has been designed with dimensions of 8 m in length, 5 m in width, and 5 m in height. The design takes into account the coordinates and earthquake design parameters as per the TBDY 2018 guidelines. The material properties and load combinations used are consistent with those applied in the ZA soil class. The soil parameters for the ZE class are given in Table 7.

The design of the rectangular water tank in soil class ZE was restructured following the existing soil properties and load - carrying capacity. In the initial design, under a full water load of 5 t/m^2, excessive stresses appeared in the raft foundation, which posed a risk of collapse. To solve this problem, the new design increased the base area of the foundation by 1 meter at each corner to 70 m^2, reducing the stresses in the foundation. In addition, the raft foundation thickness was revised to 50 cm, and the stresses and safety margins in the ground were minimized and the foundation structure was strengthened. These improvements are recommended to be simple, effective and the first to be made to increase the durability and reliability of the water tank designed in the ZE soil class. Earthquake loads and other relevant parameters used in the design are given in Table 8.

Fig. 7 shows the moment distributions and corresponding reinforcement areas required for the slab floors in a water tank constructed in a ZE soil class for two different section plans within the slab floor. The bending moments in different sectio ns of the slab floor and the corresponding required reinforcement areas are specified in ton -meters and square centimeters, respectively. The load combinations are given as "1.4G+1.6Q", representing the slab floor's performance under permanent and live loads. The material properties include the strength values of concrete and reinforcing steel, which have been considered as fundamental parameters in the design of the slab floor. Both moment diagrams given in Fig. 7 indicate the bending behavior of the slab floor under loads and highlight critical areas that need to be more carefully designed. The most significant values in Fig. 7 are the regions near the joints where the slab floor is subjected to high tensile moments requiring appropriate reinforcement. This data is very important information for structural engineers in evaluating the

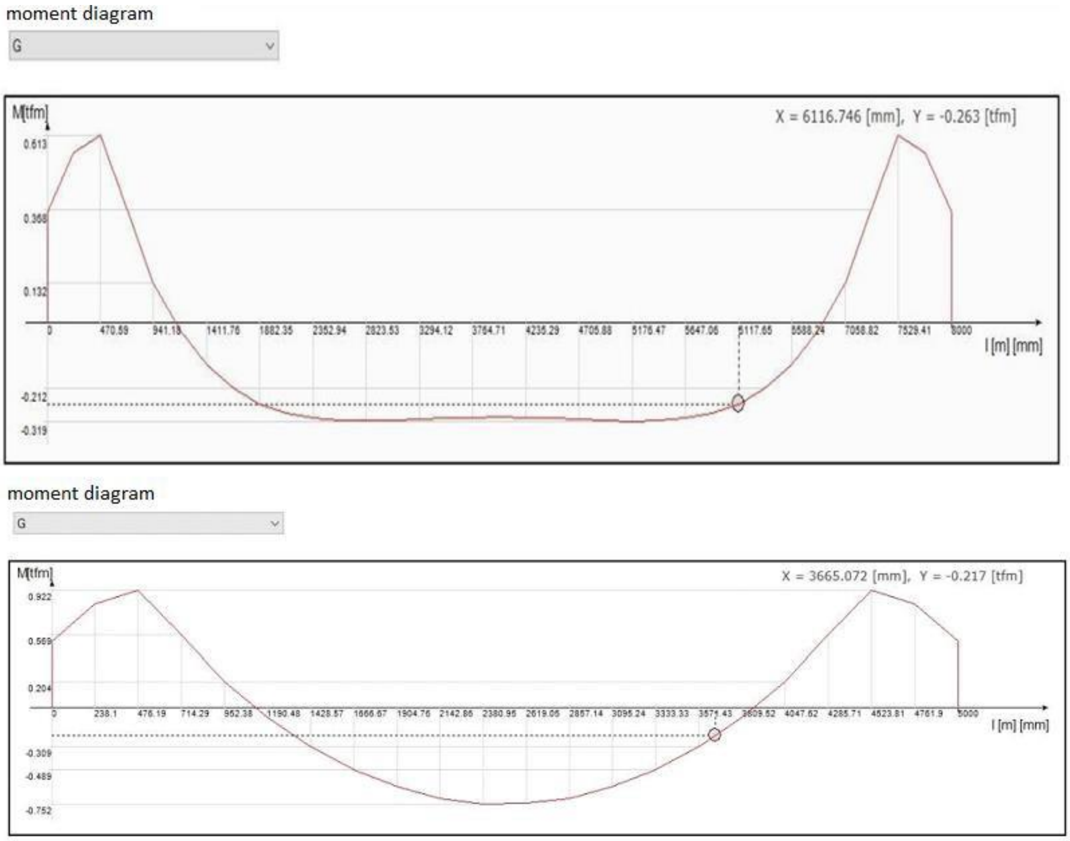


Fig. 6 Slab floor moment and required reinforcement area in slab floor of water tank in ZE class soil

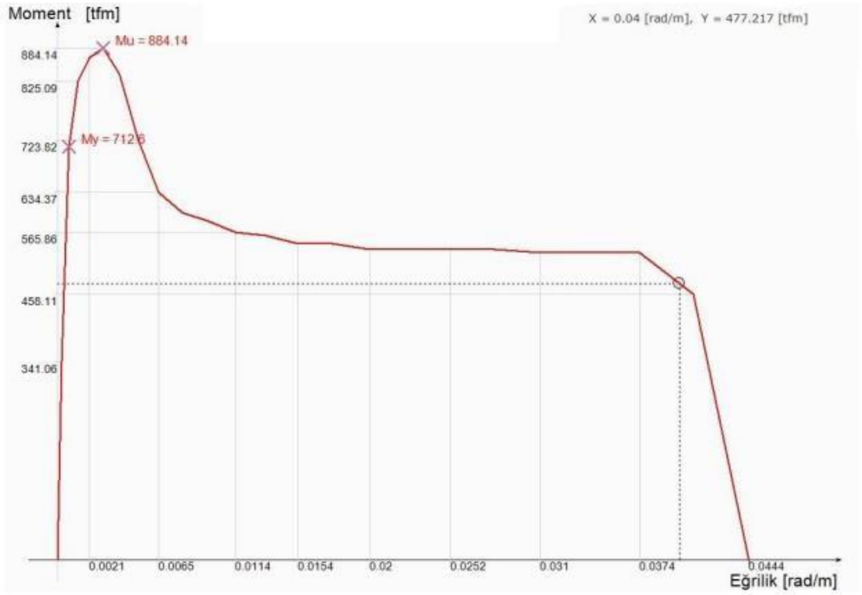


Fig. 7 Wall moment-curvature graph of the water tank constructed in ZE soil class

strength and durability of the slab floor and determining the amount of reinforcement required to safely carry the expected loads.

Figs. 8 and 9 illustrate the relationship between moment curvature plots of the walls of designed water tanks located in ZE soil class. It shows how the structural wall elements develop moments at the cross-sectional level. Moment rotation and total curvature values are calculated using the yield moment, yield curvature, crushing moment, and crushing curvature values obtained from the moment-curvature analysis. The moment curvature analysis is carried out to determine the earthquake performance of

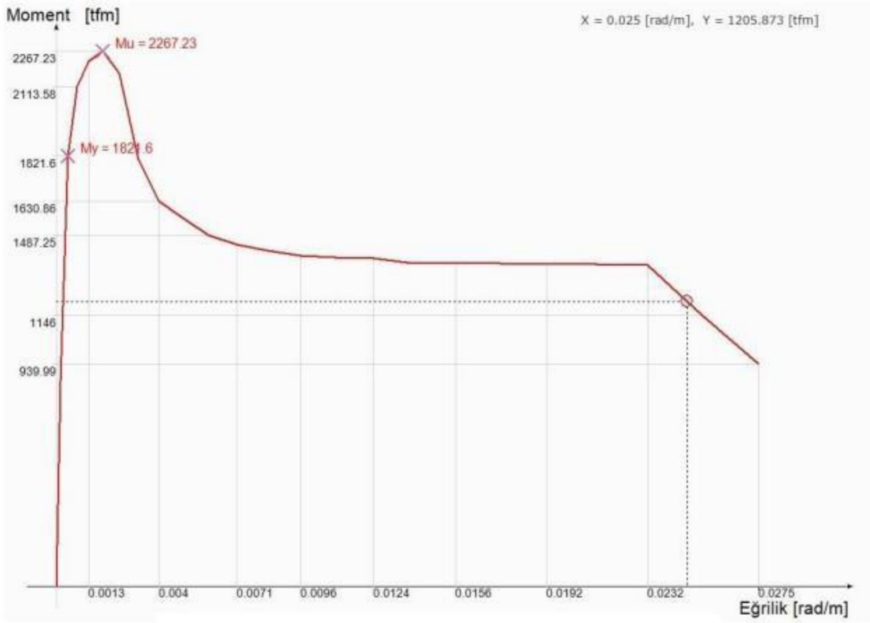


Fig. 8 Wall moment-curvature graph of the water tank constructed in ZE soil class

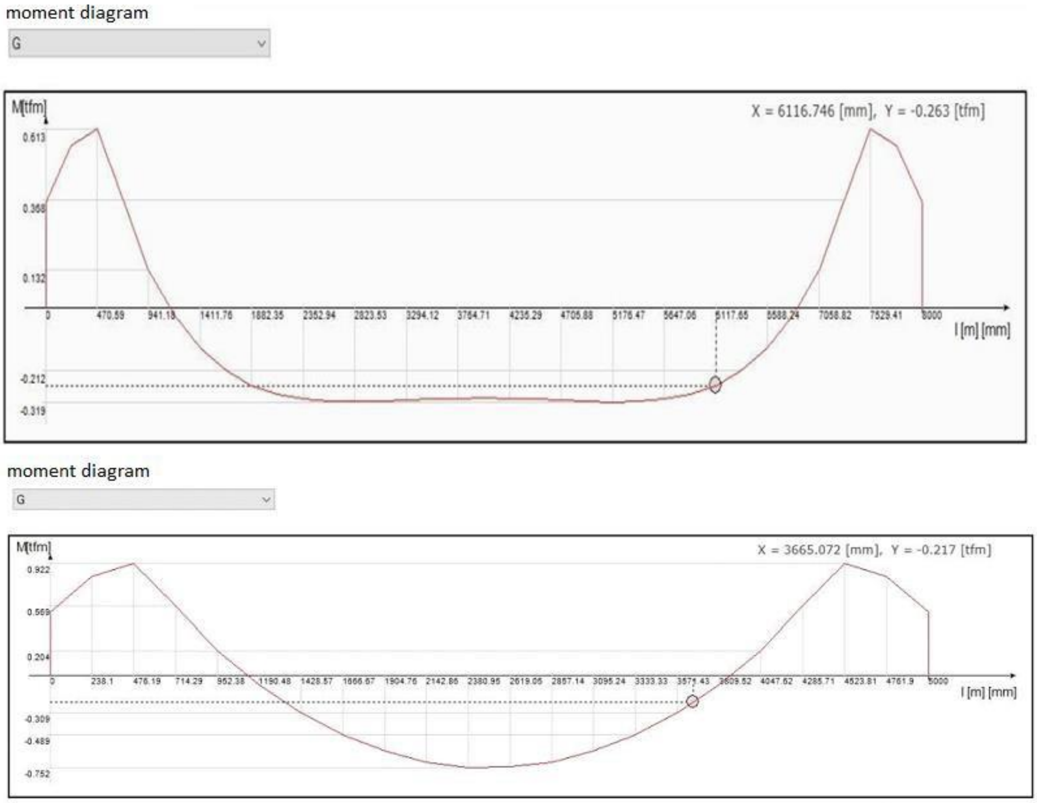


Fig. 9 Raft foundation moment and reinforcement areas in the Water Tank in ZE Floor Class

existing structures using the Deformation Based Evaluation and Design (SDDT) approach with IdeCad. Material models are used, taking into account the 'TDBY 2018 Information Level Coefficient and Existing Material Strengths'.

When the non-linear earthquake calculation is included in the IdeCAD analysis, the unit deformation demands obtained according to the proposal of TBDY 2018/15.6.2 are compared with the unit deformation capacities and the load -bearing system performance at the cross-section level. In both graphs, high moment

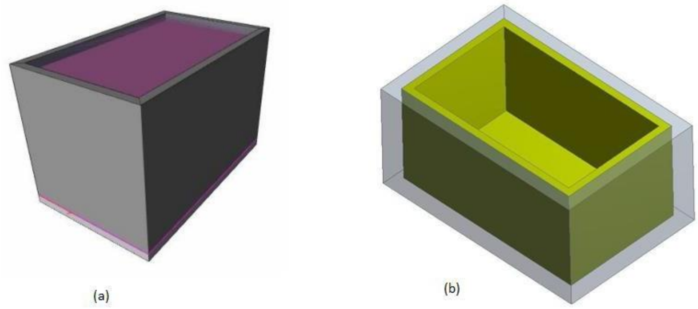


Fig. 10 (a) Water tank solid model, (b) solid model of the water tank with modeled ground

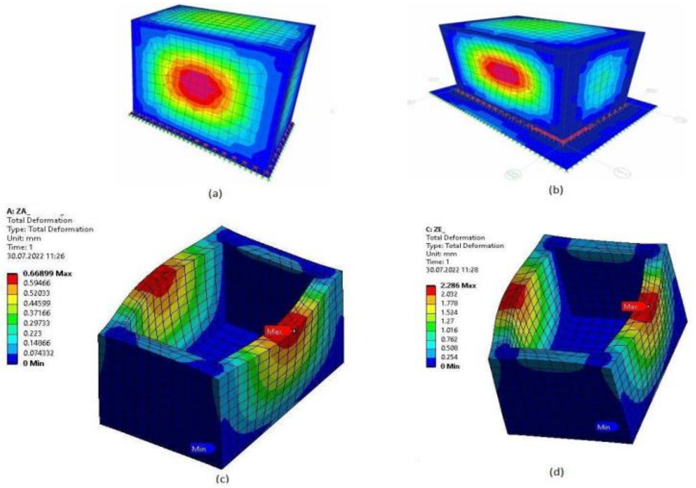


Fig. 11 Deformations at the walls of the water tank in (a) ZA class soil and (b) ZE class soil

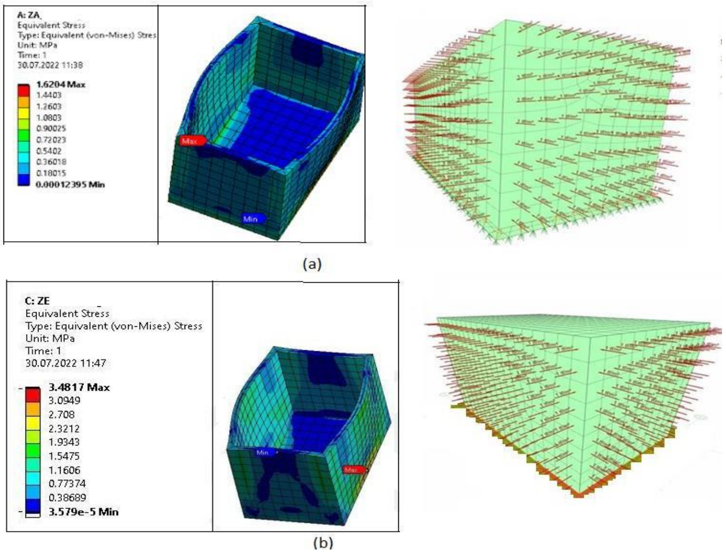
values (Mu) are observed and show the maximum walls' elastoplastic behavior and maximum load-bearing capacity. The graphs also indicate the regions where the moment values decrease and then smooth, indicating the transition of deformations from elastic to plastic deformation.

Fig. 10 shows the structural analysis of the raft foundations under the designed water tank within the ZE soil class. Each chart includes details on the calculation of bending moments at various sections of the foundation and the corresponding required reinforcement areas. The load combinations indicate standard design scenarios for permanent loads (G), live loads (Earthquake) (Q), and lateral loads (H), and highlight the strength properties of concrete and reinforcement steel considered during the design and analysis process of the foundation. Both moment diagrams given in Fig. 10 illustrate the changes in bending moments along the length of the raft foundation under the applied loading type and highlight the distribution of moments and potential support points or sections where the moment becomes zero.

2.4.1 Stress distribution and deformation analyses of the rectangular water tank designed for ZA and ZE classes soils

In this study, rectangular underground concrete water tanks were designed, and stress deformation analyses were carried out due to their advantages such as widespread use around the world, ease of production, effective cost management, less space occupancy, and structural efficiency. In addition to determining the structural bending moments on the slab floor and raft foundation of the tank designed in the previous sections of this study and the locations requiring reinforcement, the yield moment and yield curvature values on the tank walls were calculated using the moment -curvature relation. Fig. 11(a) shows the solid model geometry of a rectangular water tank. In Fig. 11(b), the yellow part shows the water tank solid model, and the gray part shows the solid modeling of the ground surrounding the tank. The water tank is designed with dimensions of 5x8x 5.5 m, and the water storage height is 5 meters

As shown in Figs. 12, the central part of the wall of the rectangular-section water tank has undergone deformation. The most significant deformation occurs around the middle of the mass center (km) and the rigidity center (rm) of the water tank. The relatively more flexible nature of concrete compared to the surface contributes to this phenomenon. The internal fluid pressure, being less resistant in the central part, has caused a slight outward deflection and an increase in load in this area. As a result of the deformation analyses, as seen in Fig. 12, the middle region of the wall of the rectangular water tank was determined to be the region subject to the most deformation,



(a)

(b)

Fig. 12 Stress distribution at the walls of the water tank in (a) ZA class soil and (b) ZE class soil

and this is in agreement with the values obtained as a result of the moment analyses. This result can also be identified with the region where equivalent thrust pressure is received in retaining wall solutions. While the maximum displacement of the rectangular geometry designed in the ZE soil class is determined as 2.286 mm, this deviation is less in the ZA class soil and is 0.66 mm.

Following the deformation analyses, Von- Mises stresses occurring in reinforced concrete and soil for rectangular cross- section water tanks were determined separately for ZA and ZE soil classes with 1 tf/m2 soil thrust applied to all walls for every 1 m2 (Fig. 13). As seen from the analysis results given in Fig. 13, higher stresses occurred on the long side walls of a rectangular water tank to be built in ZE class soil than on the short side walls. In addition, the stress values calculated in the middle of the walls of a water tank to be designed for ZE class soil are almost twice the stresses that will occur on the walls of a tank to be built for ZA class soil

Another stress analysis is the horizontal earthquake loads and earthquake rollover control analyses on the water tank designed in ZA and ZE soil classes during earthquakes. These evaluations are compulsory for the structural design, safety, and standard practices in earthquake engineering and structural analysis in Turkey. The designed and expected earthquake loads that affect the water tank in ZA and ZE soil classes are presented in Table 9 for X and Y directions. Here, 'h' represents the height, 'ex' and 'ey' represent the interaction points of the horizontal components of the earthquake loads with axial loads, 'Fx' and 'Fy' represent the magnitudes of the earthquake loads, and 'T' represents the earthquake moments. The expected earthquake loads in both X and Y directions for the ZA soil class are found to be lower compared to those for the ZE soil class, which means the ZE class is less robust and probably results in more displacement during an earthquake. In Table 10, earthquake moments and vertical load moments are compared for both soil classes for overturn control. 'Structure Overturning Moment' is defined as the moment created by horizontal loads at the base. Structure Overturning Moment control is the control of ensuring that the ratio of the sum of the overturning moments of the structure to the total of the moments preventing the overturning is greater than 0.5. In the water tank structure overturning moment control analysis, overturning moments were controlled in both the X direction and the Y direction. Of course, in underground water tank design, a structure overturning moment analysis is not expected as above ground, but since these loads will cause changes in the pressures on the tank walls, slab floors and raft foundation, especially these overturning moment control analyzes have been carried out. The mentioned control ratios are for the X and Y directions of rollover in both ZA and ZE soil classes and being below 0.5 in both cases indicates that the risk of rollover is within acceptable limits.

In this case, when rollover controls are made in the X and Y directions for ZE class soil: X direction roll control 190.46/ 805.83 = 0.236< 0.5 Y direction tilt control 169.57 / 1151.44 = 0.147 < 0.5 are found.

It means that the design parameters obtained are quite safe.

3. Results and discussion

In this study, stress, moment, and deformation analyses were performed using the IdeCAD program to determine the effects on the walls, and upper and lower slab floors of underground rectangular water tanks if they were constructed in ZA and ZE soil classes. The design results in this study were found to be varied due to the differences in soil classes. While the behavior of underground structures against earthquakes is considered and their designs are carried out, the interaction of structure and ground is sometimes neglected. However, the interaction of ground and structure is very important and becomes important for large-scale underground structures (Kildashti *et al.* 2018, Sonmezer and Celiker 2020, Sisman and

Table 9 The designed and expected earthquake loads on the water Tank in ZA and ZE soil classes in soil classes in X and Y directions

EARTHQU.-X	Soil class	h [m]	ex [cm]	ey [cm]	Fx [tf]	Fy [tf]	T [tfm]	ex [cm]	ey [cm]	Fx [tf]	Fy [tf]	T [tfm]
WATER TANK	ZA	5.00	0	40	27.75	0	11.10	0	40	27.75	0	11.10
	ZE	5.00	0	40	38.09	0	15.23	0	40	38.09	0	15.23
EARTHQ.-Y	Soil class	h [m]	ex [cm]	ey [cm]	Fx [tf]	Fy [tf]	T [tfm]	ex [cm]	ey [cm]	Fx [tf]	Fy [tf]	T [tfm]
WATER TANK	ZA	5.00	25	0	0	27.36	6.84	25	0	0	27.36	6.841
	ZE	5.00	25	0	0	33.91	8.47	25	0	0	33.91	8.478

Table 10 Earthquake horizontal load moments

Earthquake moments	Soil class	h (m)	Fx (tf)	Fy (tf)	Mx (tf)	My (tf)
WATER TANK	ZA	5.00	27.75	27.36	138.77	136.82
	ZE	5.00	38.09	33.91	190.46	169.57
Earthquake vertical load moments						
Vertical load moments	Soil class	Soil weight (tf)	Dx (m)	Dy (m)	Mx (tf/m)	My (tf/m)
	ZA	168.34	2.50	4.00	420.59	673.17
	ZE	230.34	3.50	5.00	805.83	1151.44

Ayvaz 2020). According to TDBY 2018 in Turkey, if the underground structure is close to the surface, structure-soil interaction would be neglected in relatively soft soils exposed to earthquake loads (Korkmaz and Demir 2012, İnel and Tanık 2016, Eroglu and Ipek 2023). Table 12 presents the required concrete and reinforcement amounts based on the analysis results of the rectangular water tank designed to be built underground in ZA and ZE soil classes. Different amounts of reinforcement are needed, with an increase of 23 m3 of concrete and 1804t of reinforcement required for an underground water tank to be built on ZE soil class ground. The lower physicalproperties and soil-bearing capacity of the ZE soil class compared to the ZA soil class led to the determination that the slab floor could not withstand the equivalent loads. A solution was found by widening the foundation base. Therefore, it has been determined that in a rectangular underground water tank to be built in ZE soil class, the recommended amount of reinforcement and concrete will need to be increased in the raft foundation due to the larger foundation dimensions.

The analysis results showed that when designing an underground tank in different soil classes and earthquake loading conditions, there were significant differences in terms of material, reinforcement needs, and design foundation geometries due to soil class differences. This study determined that there is a need to expand the raft foundation base of a water tank to be built on ZE class soils, which have less bearing capacity than the ZA soil class. This indicates an increase in the required concrete and reinforcement, especially for raft foundations, highlighting the impact of soil classes on structural requirements and the need to consider these in the design process. Similar to this study, there are few studies in the literature on the effect of soil class differences on underground water tank designs (Anchor 1992, Sani *et al.* 2014, Huang *et al.* 2016, Anirudha *et al.* 2016, Dubey 2021).

This research includes stress and deformation analyses of the rectangular underground water tank design sith 8x5x5 m dimensions when constructed in different soil classes under earthquake loading conditions. In the analysis, the tanks were filled with water and stress, moment, and deformation calculations were made by ignoring the SSI effect. Hydrostatic pressure and gravitational acceleration were included in the models. While the maximum displacement for rectangular geometry in the ZA soil class was found to be 0.67 mm, it was calculated as 2.286 mm in the ZE soil class. The safety of the design was confirmed by the maximum stress values calculated for both soil classes remaining below the determined maximum strength of the concrete (25 MPa). For both classes, the maximum stress values at the ground base remained below the bearing capacity of the soil, ensuring the ability to build structures on the ground. However, one of the most important results obtained from this study is that it is recommended to build a raft foundation in an underground water tank of this size to be built in the ZE soil class.

4. Conclusions

This study was carried out to determine the design parameters resulting from stress, moment, and deformation analyses for a rectangular underground water tank to be constructed on ZA and ZE class soils classified by the TBDY2018, one of the earthquake building design regulations in Turkey. The stress, moment, and deformation analysis results showed that the rectangular water tanks to be built in the ZA soil class have structural resistance to the stresses induced by soil, water, and earthquakes without any significant problems. The obtained design values from the stress, deformation, and structure overturning moment analyses were found to be within the structural safety limits, confirming the accuracy of these designs. On the other hand, it has been found that underground water tanks to be built in ZE soil class can also withstand lateral overburden and earthquake loads. However, it was determined that the deformations in the tank structure in ZE class soil were higher than in the ZA class soil due to the loose, weathered, and low bearing strength of the ZE class soils. This study also emphasizes the importance of using raft foundations under underground water tanks to be built on ZE class grounds in order to increase safety and prevent increasing deformations over time, such as creep.

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