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INVESTIGATION OF THE BEHAVIOR OF RC ELEVATED WATER TANKS ACCORDING TO TURKISH EARTHQUAKE CODES

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ABSTRACT

Water tanks are critical structures that must be used without damage after an earthquake. Due to their vital importance, these structures are required to perform well under the influence of major earthquakes. In this study, the behavior of the RC elevated water tanks under earthquake effects was investigated. The water tank with a volume of 75 m^3, which is widely applied as a type project, was examined according to the calculation principles of the 1968, 1975, 1998, 2007, and 2018 earthquake codes. The analysis of the structure designed in the SAP2000 program was carried out according to the equivalent linear method. When the analysis results were compared according to the earthquake codes considered, it was concluded that the structure showed better behavior as the design criteria and calculation principles were improved from the 1968 earthquake code to the 2018 earthquake code. The comparative analysis results obtained from the study were evaluated specifically for an RC elevated water tank that was heavily damaged in the 6 February 2023 Kahramanmaraş earthquakes.

Keywords: Elevated water tanks, Earthquake code, Equivalent seismic load, Kahramanmaraş earthquakes.

1 INTRODUCTION

Earthquakes that occur as a result of sudden fractures in the earth's crust can have devastating effects on structures. Due to the significant losses and damages caused by major earthquakes, determining the behavior of structures against earthquakes is of great importance both in terms of ensuring the safety of life and property and in taking precautions against future earthquakes. Today, structures built using modern design and construction techniques generally show good behavior against seismic effects, while old structures that do not receive the necessary engineering services are at risk [1-4].

On February 6, 2023, two major earthquakes occurred in the Pazarcık and Elbistan districts of Kahramanmaraş (MW= 7.7 and MW= 7.6). These earthquakes were devastating disasters that deeply affected 11 provinces and caused significant economic losses and deaths. As a result of these earthquakes, more than half a million buildings were damaged and collapsed. In addition to buildings, transportation networks, water storage and distribution systems, and energy transmission lines, which were of great importance after the earthquake, were also severely damaged. Due to the damage, there were problems in using these structures, also called lifelines, and therefore access to basic services was interrupted. As a result of these negativities, studies to determine the seismic safety of these structures, whose use should not be disrupted after the earthquake, have gained great importance [5-9].

Elevated water tanks are structures used primarily for drinking water storage and fire protection in a certain residential area. These structures are widely used in cities and industrial areas, and in recent years they have begun to be used in small settlements. After major earthquakes, it is desired that water tanks are not damaged, especially in large cities, both to fight fires and to prevent epidemics by providing clean water to the public. In this regard, it is vital to design water tanks to be earthquake resistant [10-12].

After major earthquakes affected many regions of the world, significant structural damage or collapses occurred in RC elevated water tanks (Figure 1). Water tanks are expected to remain functional after major earthquakes. It is very important to determine the seismic performance of these structures that need to be used immediately after the earthquake [13-16].

a) **b)** **c)**

Figure 1. a-c) Examples of RC elevated water tanks damaged and collapsed in the earthquake [14, 15].

In the earthquake centered in Kahramanmaraş on February 6, 2023, it was observed that the structures in Türkiye were vulnerable to destructive earthquakes [17]. In recent times, our country has experienced major earthquakes, centered in Erzincan in 1992 (M_S=6.8), Dinar in 1995 (M_W=6.2), Adana-Ceyhan in 1998 (M_W=6.2), Kocaeli and Düzce in 1999 (M_W= 7.5 and M_W= 7.2), Van in 2011 (M_W=7.2), Elazığ in 2020 (M_W=6.8), and Kahramanmaraş in 2023 (M_W= 7.7 and M_W= 7.6). These earthquakes resulted in the loss of tens of thousands of lives and severe damage to thousands of structures. As a result of these earthquakes, earthquake-resistant structural design has become a current and important issue [17-19].

The Erzincan earthquake in 1939 caused heavy losses, and subsequently, the need to use earthquake codes to design earthquake resistant structures emerged. The earthquake codes have been continuously updated because of advancements in science and construction technologies. The current earthquake code (Turkish Building Earthquake Code-2018) was prepared much more comprehensively compared to previous codes. With this code, an AFAD-based earthquake calculation system was introduced in Türkiye. With this system, instead of regional calculations, precise earthquake data is obtained for each settlement. The Turkish Building Earthquake Code-2018 includes more precise seismic parameters compared to the previous earthquake code in terms of calculation principles and establishes a realistic and safe calculation method [18, 20, 21].

"Reinforced Concrete Elevated Water Tanks Type Projects" was published by the Ministry of Rural Affairs in 1971 as a reference for elevated water tanks. These types of projects have been continuously and widely implemented from the date of their publication up to the present day. The analysis and design of the existing water tank types were carried out according to the 1968 earthquake codes valid at the time of publication [11, 21-24].

There are few studies in the literature on the investigation of the dynamic behavior of elevated water tanks. Köksal et. al [25] examined the fluid-structure interactive behavior of a 1000 m^3 volume RC elevated water tank under different seismic activities (Kocaeli, Van, Kahramanmaraş and Kobe earthquakes) using the Smoothed Particle Hydrodynamics (SPH) method with the Westergaard approach. The authors proved that considering the nonlinear behavior of the fluid during an earthquake with the SPH method provides consistency with the actual behavior of RC elevated water tanks and gives more realistic results than the traditional Westergaard approach. Gaikwad and Mangulkar [10] examined the dynamic response of RC elevated water tanks under static and dynamic loading, accounted for the hydrodynamic pressure effect of water. According to the detailed study and analysis results, it was found that the response was significantly different with the equivalent static method and the dynamic method in the same region with the same capacity, the same geometry, the same height, the same importance factor and the response reduction factor. Demirören [11] explained the design rules of reinforced concrete elevated water tanks in detail and investigated their behavior under earthquake effects. In the study, the structural system of the water tank was considered as a type project, and the calculations were repeated for four different earthquake zones according to the 1998 earthquake code, and the relative storey drifts, rigidity irregularities and section effects of the columns were checked. Livaoğlu and Doğangün [16] investigated the effect of soil classes on the dynamic behavior of elevated water tanks with different structural systems. In the study, it was observed that the section effects occurring in the structural members of the elevated water tanks with two different load-bearing systems having the same tank volume were quite large by designing them according to the 1998 earthquake code and the 1st degree earthquake zone. Çelebioğlu [26] investigated the design of water tanks by taking into account the earthquake effect.

In this study, the seismic performance of critically important RC elevated water tanks that must be used immediately after an earthquake was investigated. Dynamic calculations of the structure were made separately according to the calculation principles of the 1968, 1975, 1997, 2007, and 2018 earthquake codes. The equivalent linear method based on period calculation, which started to be used with the 1968 earthquake code, was preferred as the calculation method. The reason why this method is preferred is that it is a common calculation method for all earthquake codes considered in this study. In this study, the RC elevated water tank type project with a volume of 75 m^3, which is widely used in our country, was discussed. The tank was modeled and analyzed in the SAP2000 program in accordance with the type project. The analysis results were compared, and it was concluded that the design was safe for the structure according to the 2018 earthquake code. In order to show the effect of analysis results on the structure according to earthquake codes, an RC elevated water tank located in Malatya province and heavily damaged as a result of the 6 February Kahramanmaraş earthquakes was considered. The impact of earthquake codes on the damage status of this structure was examined.

The novelty of this study is to compare the design principles of the last five earthquake codes (1968, 1975, 1998, 2007, 2018) in the case of RC elevated water tank and to evaluate the seismic behavior of the water tanks under the influence of destructive earthquakes. After the Kahramanmaraş earthquakes, there were studies in the literature that evaluated seismic behavior based on structural analysis, taking into account the damages occurring in different engineering structures. However, there are very few studies that include detailed structural analyses of water tanks and evaluate their seismic behavior after these earthquakes [25]. In this respect, the study will fill an important gap in the literature and make a significant contribution to earthquake engineering.

2 MATERIAL AND METHOD

2.1 Examination of Seismic Design Codes

In this section, the calculation principles in the last five earthquake codes starting from the 1968 earthquake code are explained in detail in order to determine the effect of the developments in the calculation methods in the earthquake codes on the dynamic behavior of the RC elevated water tank. When the calculation methods for these five codes are examined, it is noteworthy that the seismic calculation is made depending on the structure period based on empirical calculation, which is a common parameter in the codes.

As earthquake codes in Türkiye are updated, calculation methods have also been developed from simple to complex. Developments in the calculation method based on common parameters in earthquake codes are important in terms of seeing the change in the behavior of the structure and making correct comparisons. As a matter of fact, this comparison is decisive to see the effect of earthquake codes on the design of the structure.

In the literature, there are different studies examining the effects of changes in earthquake codes on structure design. Aksoylu and Arslan [27] compared the 2018 and 2007 earthquake codes in terms of calculation methods. For this purpose, they analyzed RC buildings with different storey heights and revealed the fundamental differences of the two codes in terms of seismic force calculation and control. Aksoylu et al [28] compared the 2007 and 2018 earthquake codes with the ASCE 7-16 earthquake code, taking into account parameters such as base shear force, top displacement, building period and relative-story displacement. Alyamaç and Erdoğan [29] examined the earthquake codes published from past to present in detail in terms of design and rules, and tried to determine how much the codes were complied with during the project and implementation stages. Işık [30] investigated the changes and innovations in the design principles according to the last five earthquake codes (1968, 1975, 1998, 2007 and 2018). In the study, the structural analysis of a 4-storey RC building was carried out and the analysis results were compared according to the calculation and design principles of each code. The author revealed that the changes and renewals in the earthquake codes were a necessity and a gain. Karaca et al. [31] investigated the effect of the innovative approach in the 2018 earthquake code on building design. In the study, the authors analyzed the buildings designed according to the 2018 earthquake code according to the 2007 earthquake code and compared the design differences in the earthquake codes. Nemutlu et al. [32] designed and analyzed 4- and 9-storey RC structures separately to show the design differences in the 2007 and 2018 earthquake codes and examined the changes in base shear forces. Nemutlu et al. [33] investigated the changes in the calculation principles by considering the 2007 and 2018 earthquake codes. The differences between the acceleration spectra of Bingöl and Elazığ provinces were examined in the study. The authors proved that the acceleration values in the 2018 earthquake code were more economical and safer than the acceleration values in the 2007 earthquake code. Balun et al. [34] studied the effect of base shear force by considering simplified design rules for cast-in-place RC buildings according to the 2018 earthquake code. As a result of the analyses performed in the study, a comparison was made between the simplified seismic calculation and the standard seismic calculation. The authors determined the favorable or unfavorable situations of the simplified calculation in terms of the seismic design class, local soil class and the number of floors of the structure.

2.1.1 Regulation about the Buildings Constructed in the Disaster Regions-1968

The seismic force (shear force occurring at the base level of the structure) acting on the structures is calculated according to Equation 1 to withstand the seismic forces applied along the main axes perpendicular to each other.

$$F = C \times W \tag{1}$$

where W is the total structure weight ($\sum Wi$) and C is the seismic coefficient. C coefficient is obtained according to Equation 2.

$$C = C_O \times \alpha \times \beta \times \gamma \tag{2}$$

In this equation, C_O is the seismic zone coefficient, α is the seismic site coefficient, β is the structure importance coefficient, and γ represents the structure dynamic coefficient. The period of the structure is determined according to Equation 3, unless it is calculated based on experimental or reliable technical data.

$$T = 0.09H/\sqrt{D} \tag{3}$$

In this equation, H is the height of the structure from its base, and D is the width of the structure in the direction parallel to the horizontal forces affecting the structure. The floor weight to be considered in the calculation of the total seismic force is calculated according to Equation 4.

$$W_i = G_i + n_i \times P_i \tag{4}$$

In this equation, G_i is the total of the dead loads on the i-th floor, P_i is the total of the live loads on the i-th floor, and n_i is the live load coefficient on the i-th floor. n_i is taken as 1 in structures such as cinemas, theaters, schools, stadiums, and, warehouses. The seismic force acting on the structure is distributed throughout the height of the structure, according to Equation 5.

$$F = Fi * \frac{(W_i\, h_i)}{\sum W_i\, h_i} \tag{5}$$

In this equation, Fi is the horizontal force acting on the i-th floor, W_i is the weight of the i-th floor, and h_i is the height of the i-th floor from the base level.

2.1.2 Regulation about the Buildings Constructed in the Disaster Regions-1975

The sum of the static equivalent horizontal loads to be used in earthquake resistant sizing of structures is determined by Equation 6.

$$F = C \times W \tag{6}$$

In this equation, $\boldsymbol{C}$ is the seismic coefficient and is calculated according to Equation 7.

$$C = C_0 \times K \times S \times I \tag{7}$$

Where $\boldsymbol{C_0}$ is the seismic zone coefficient, $\boldsymbol{K}$ is the structural type coefficient, $\boldsymbol{S}$ is the structural dynamic coefficient, and $\boldsymbol{I}$ is the structure importance coefficient, respectively. The structure dynamic coefficient is calculated according to Equation 8.

$$S = 1/|0.8 + T - T_0| \tag{8}$$

In this equation, $\boldsymbol{T}$ is the natural vibration period of the structure, and $\boldsymbol{T_0}$ is the soil fundamental period. The natural vibration period of the structure is calculated according to

Equation 3. The total structure weight to be used in calculating the seismic force is calculated according to Equation 9.

$$W = \sum_{i=1}^{N} w_i \tag{9}$$

In this equation, $\boldsymbol{w_i}$ is the floor weight and is determined according to Equation 10.

$$w_i = g_i + nP_i \tag{10}$$

Where $\boldsymbol{g_i}$ is the total of the dead loads on the i-th floor, $\boldsymbol{P_i}$ is the total of the live loads on the i-th floor, and $\boldsymbol{n}$ is the live load coefficient, respectively. In structures such as warehouses, $\boldsymbol{n = 0.8}$ is taken. The seismic load acting on the floors is determined according to Equation 11.

$$V_{t=}\Delta F_N + \sum_{i=1}^{N} F_i \tag{11}$$

For $\boldsymbol{H > 25}$ m, the value of the additional equivalent seismic load $\boldsymbol{\Delta F_N}$ acting on the N-th floor of the structure is determined depending on the fundamental vibration period ($\boldsymbol{T_1}$). For $\boldsymbol{H < 25}$ m, $\boldsymbol{\Delta F_N = 0}$ is taken. The remaining part of the total equivalent seismic load, except $\boldsymbol{\Delta F_N}$, is distributed to all floors of the structure, including the N-th floor, with Equation 12.

$$\mathrm{F_i} = (\mathrm{V_t} - \Delta \mathrm{F_N}) \left[\frac{\mathrm{w_i H_i}}{\sum_{j=1}^{N} \mathrm{w_j H_j}} \right] \tag{12}$$

2.1.3 Regulation about the Buildings Constructed in the Disaster Regions-1998

The total equivalent seismic load acting on the structure in the earthquake direction considered is determined by Equation 13.

$$V_t = \frac{WA(T_1)}{R_a(T_1)} \geq 0.10 A_0 I W \tag{13}$$

Where $\boldsymbol{V_t}$ is the equivalent seismic load (base shear), $\boldsymbol{W}$ is the weight of the structure, $\boldsymbol{A(T_1)}$ is the spectral acceleration coefficient, $\boldsymbol{A_0}$ is the local seismic acceleration, $\boldsymbol{R_a(T_1)}$ is the seismic load reduction coefficient, $\boldsymbol{T_1}$ is the first natural period of the structure, and $\boldsymbol{I}$ is the structure importance coefficient, respectively. The first natural period of the structure is calculated according to Equation 14, unless a more precise calculation is made.

$$T_1 = 2\pi \left[\sum_{i=1}^{N} \left(m_i {d_{fi}}^2 \right) \Big/ \sum_{i=1}^{N} \left(F_{fi} d_{fi} \right) \right]^{1/2} \tag{14}$$

The spectral acceleration coefficient is determined according to Equation 15, and the seismic load reduction coefficient is determined according to Equations 16-17.

$$A(T) = A_0 I S(T) \tag{15}$$

$$R_a(T) = 1.5 + (R - 1.5)\, T/T_A \rightarrow (0 \leq T \leq T_A) \tag{16}$$

$$R_a(T) = R \rightarrow (T > T_A) \tag{17}$$

The computation of the floor weight to be taken into account in the calculation of the seismic force in the structure is made according to the formulas defined in the 1975 earthquake code.

2.1.4 Regulation about the Buildings Constructed in the Earthquake Regions-2007

According to this code, the seismic calculation method is the same as the calculation method in the 1998 earthquake code. Based on scientific data, the 1998 earthquake code prepared seismic calculation methods more comprehensively than previous codes. In this respect, the code includes a more realistic and detailed calculation procedure.

2.1.5 Turkish Building Earthquake Code-2018

In the direction of the earthquake considered $(\boldsymbol{X})$, the total equivalent seismic load acting on the entire structure, $\boldsymbol{V_{tE}}(\boldsymbol{X})$, is determined by Equation 18.

$$V_{tE}^{(X)} = m_t S_{aR}\left(T_p^{(X)}\right) \geq 0.04 m_t I S_{DS} g \tag{18}$$

In this equation, $\boldsymbol{m_t}$ is the mass of the structure, and $\boldsymbol{S_{aR}}\left(\boldsymbol{T_p}^{(\boldsymbol{X})}\right)$ is the reduced design spectral acceleration calculated by taking into account the predominant period of the structure $(\boldsymbol{T_p}^{(\boldsymbol{X})})$ in the earthquake direction under consideration. $\boldsymbol{I}$ is the structure importance coefficient, $\boldsymbol{S_{DS}}$ is the design spectral acceleration coefficient defined for the short period, and $\boldsymbol{g}$ is the gravitational acceleration. The reduced design spectral acceleration of the structure is calculated according to Equation 19. The predominant period of the structure is determined according to Equation 14 by taking into account the earthquake direction $(\boldsymbol{X})$.

$$S_{aR}(T) = S_{ae}(T)/R_a(T) \tag{19}$$

Where $\boldsymbol{S_{ae}(T)}$ is the corner period of the horizontal elastic design acceleration spectrum, and $\boldsymbol{R_a(T)}$ is the seismic load reduction coefficient. The calculation of the horizontal elastic design acceleration spectrum and the seismic load reduction coefficient is summarized by Equations 20–25.

$$S_{ae}(T) = \left(0.4 + 0.6\frac{T}{T_A}\right)S_{DS} \rightarrow (0 \leq T \leq T_A) \tag{20}$$

$$S_{ae}(T) = S_{DS} \rightarrow (T_A \leq T \leq T_B) \tag{21}$$

$$S_{ae}(T) = \frac{S_{D1}}{T} \rightarrow (T_B \leq T \leq T_L) \tag{22}$$

$$S_{ae}(T) = \frac{S_{D1}T_L}{T^2} \rightarrow (T_L \leq T) \tag{23}$$

$$R_a(T) = \frac{R}{I} \rightarrow (T > T_B) \tag{24}$$

$$R_a(T) = D + \left(\frac{R}{I} - D\right)\frac{T}{T_B} \rightarrow (T \leq T_B) \tag{25}$$

In these equations, $\boldsymbol{T_A}$ and $\boldsymbol{T_B}$ are the horizontal elastic design acceleration spectrum corner periods, $\boldsymbol{T_L}$ is the transition period to the constant displacement region, $\boldsymbol{R}$ is the structural system behavior coefficient, and $\boldsymbol{D}$ is the overstrength coefficient, respectively. $\boldsymbol{S_{DS}}$ and $\boldsymbol{S_{D1}}$ are calculated according to Equations 26-27.

$$S_{DS} = S_S F_S \tag{26}$$

$$S_{D1} = S_1 F_1 \tag{27}$$

In these equations, $\boldsymbol{S_S}$ is the map spectral acceleration coefficient for the period of 0.2 s, $\boldsymbol{S_1}$ is the map spectral acceleration coefficient for the period of 1.0 s, $\boldsymbol{F_S}$ is the local soil effect coefficient for the period of 0.2 s, and $\boldsymbol{F_1}$ is the local soil effect coefficient for the period of 1.0 s. The total equivalent seismic load is expressed as the sum of the equivalent seismic loads acting on the floors of the structure in Equation 28.

$$V_{tE}{}^{(X)} = \Delta F_{NE}{}^{(X)} + \sum_{i=1}^{N} F_{iE}{}^{(X)} \tag{28}$$

The additional equivalent seismic load acting on the N-th floor (top) of the structure is determined according to Equation 29.

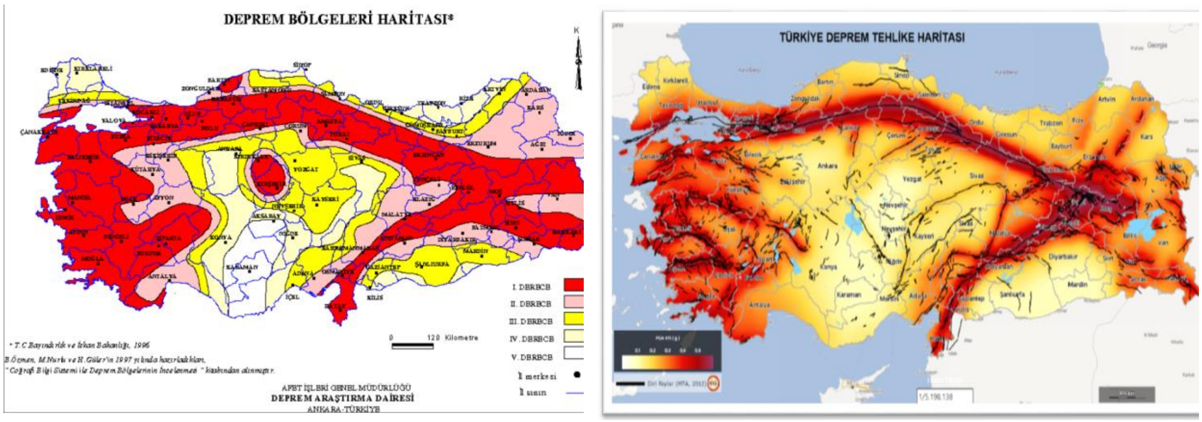
$$\Delta F_{NE}{}^{(X)} = 0.0075 N V_{tE}{}^{(X)} \tag{29}$$

The remaining part of the total equivalent seismic load, except $\Delta \boldsymbol{F_{NE}}^{(\boldsymbol{X})}$, is distributed to the structure floors, including the N-th floor, in accordance with Equation 30.

$$F_{iE}{}^{(X)} = \left(V_{tE}{}^{(X)} - \Delta F_{NE}{}^{(X)}\right) \left[\frac{\mathrm{m_i H_i}}{\sum_{\mathrm{j=1}}^{\mathrm{N}} \mathrm{m_j H_j}}\right] \tag{30}$$

2.1.6 Comparison of Earthquake Codes

Before the 1998 earthquake code, the 1968 and 1975 earthquake codes used a rough calculation approach in seismic calculation methods. Since the 1998 earthquake code, the calculation method has been prepared in more detail based on scientific data. The calculation methods in this code form the basis of the 2007 and 2018 earthquake codes. The concept of an earthquake zone has started to be used with this code, and an earthquake hazard map has been prepared. Calculation methods have been improved with the current 2018 earthquake code. In this code, the concept of an earthquake zone has been eliminated, earthquake hazard maps have been developed, and site-specific design spectrums have begun to be used. Figure 2 shows the earthquake zone map and earthquake hazard map [21, 24, 35-39].



(a) (b)

Figure 2. (a) 1996 Earthquake zone map, (b) 2018 Earthquake hazard map [38, 39].

2.2 Numerical Application

In this study, the RC elevated water tank type project with a volume of 75 m^3 was discussed in the reference "Reinforced Concrete Elevated Water Tanks Type Projects" prepared by the Ministry of Rural Affairs. The structure, which consists of six columns of 40x40 cm in size, is 25 m high, and there is a cylindrical water reservoir on the top floor. The design and analysis of the structure were performed using the SAP2000 program. The model of the structure created in the SAP2000 program is shown in Figure 3. While designing the structure, the columns and beams were modeled as frame elements and the tank as shell elements [40, 41].

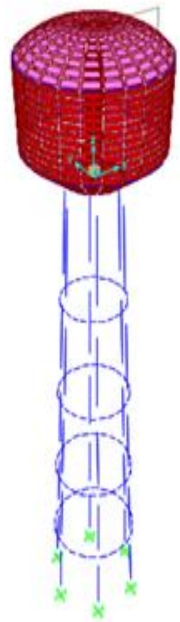


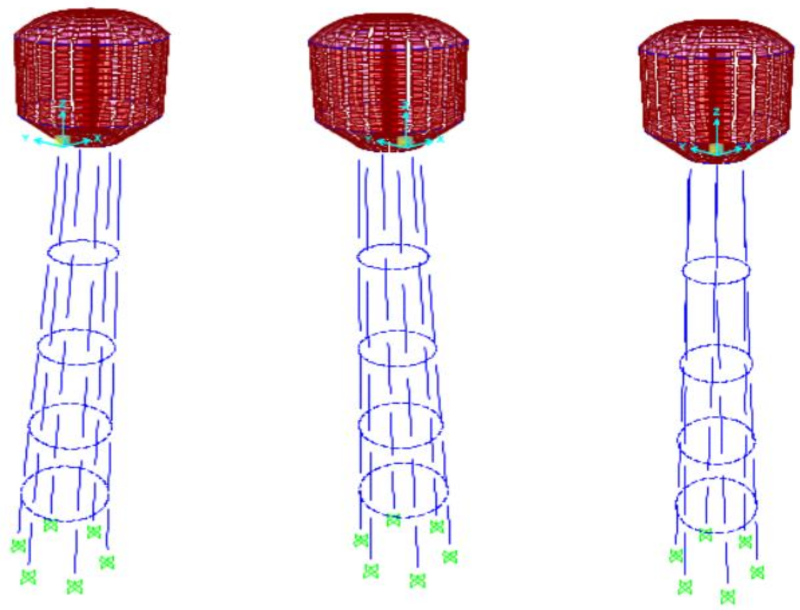
Figure 3. The SAP2000 model of the elevated water tank.

In order to determine the dynamic properties of the structure, modal analysis was first performed. The mode shapes, structural periods and mass participation ratios obtained as a result of the analysis were calculated. Modal analysis results are given in Table 1 and mode shapes are given in Figure 4.

According to the analysis results, high period values were obtained in the first two modes. The reason for this is that the stiffness and mass affecting the period of the structure are greatly affected by the height of the structure. The reason why the period and frequency values of the first two modes are the same is that the structure has symmetry in the x and y directions in terms of design features and the structural features are the same in both directions. When the mass participation ratios are examined, it is seen that the contribution of the first and second modes to the total response is about 89 percent. It is seen from the analysis results that torsion has no effect on the total response of the structure. In fact, it is understood from the plan of the structure that the floor masses are distributed uniformly in the building and coincide with the center of rigidity. In this case, only transverse displacement occurred in the structure; no rotational displacement occurred since there was no torsional moment acting on the structure around the vertical axis.

Table 1. Modal analysis results.

Mode number	Direction	Period (s)	Frekans (Hz)	Participation factor (%)
1st	x	1.16	0.86	89.03
2nd	y	1.16	0.86	89.03
3rd	Torsion	0.87	1.15	0
4th	x	0.33	3.06	65.86
5th	y	0.33	3.06	65.86



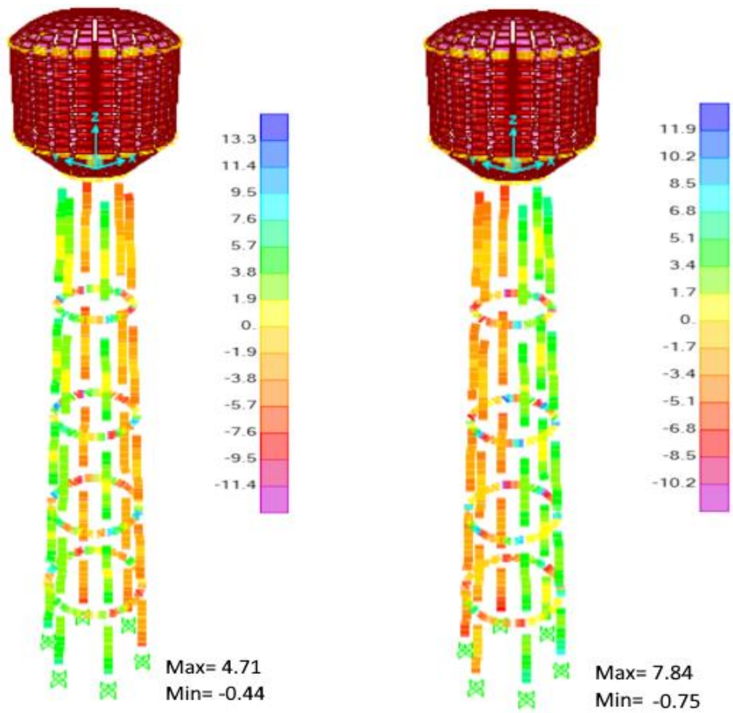
Mode 1 (x)
T_1= 1.16 sec.

Mode 2 (y)
T_2= 1.16 sec.

Mode 3 (torsion)
T_1= 0.87 sec.

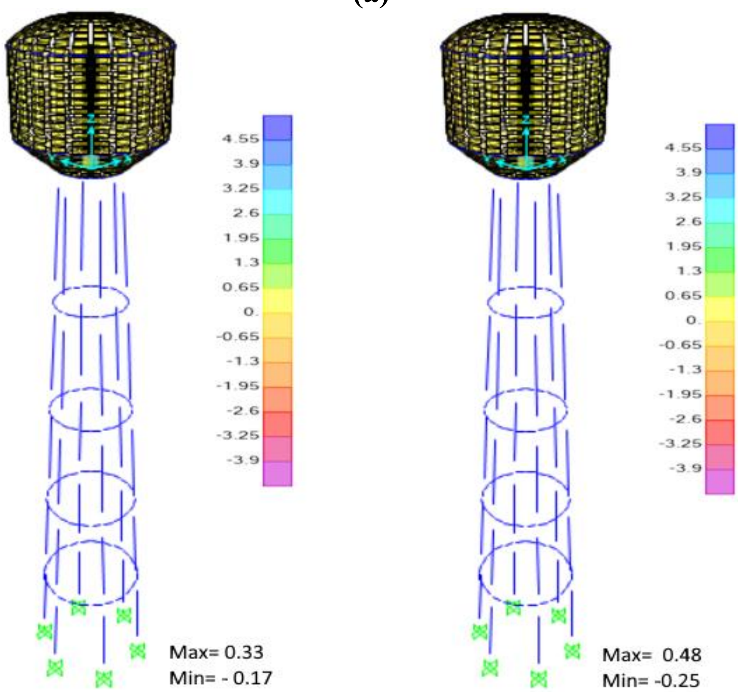
Figure 4. Mode shapes and period values of the structure.

During the dynamic analysis of the structure, the most critical stress concentrations were obtained for both directions of the earthquake by taking into account the loading conditions in the water tank. Stress values were calculated separately for the frame system carrying the reservoir and the reservoir. According to the analysis results, while there are no significant stress concentrations in the reservoir, it is seen that high compressive and tensile stresses occur in the column and beam supporting the reservoir in both directions of the earthquake (Figure 5). The stress values in the water tank are given in Table 2.



X direction Y direction

(a)



X direction Y direction

(b)

Figure 5. Stress concentration for water tank (MPa), (a) in the frame system (b) in the reservoir.

Table 2. Maximum stresses in the water tank.

Structural system	Compressive stresses (MPa)		Tensile stresses (MPa)	
Earthquake direction	x	y	x	y
Frame system	0.44	0.75	4.71	7.84
Reservoir	0.17	0.25	0.33	0.48

The dynamic calculation of the structure was carried out separately according to the principles of each earthquake code taken into account. The equivalent linear method was used as the dynamic calculation method. The seismic load calculated according to each earthquake code was defined separately in the SAP2000 program, and the dynamic analysis of the structure was carried out. According to this method, torsional moments of at least ±5% eccentricity at the geometric center of the structure, depending on the seismic forces acting on the floors, were included in the calculations. While performing dynamic calculations according to the 2018 earthquake code, dynamic parameters were obtained by assuming that the structure is located at a latitude of 38.38769° and a longitude of 38.16945° in Malatya Province. The self-weight of the structure, water load, hydrodynamic pressure effect of water, snow load, and wind load were used in the calculations as load effects. In the SAP2000 program, the weight of the structure under all these load effects was calculated as W = 1711.96 kN.

In the dynamic calculation of the structure according to 1968 earthquake codes, the C_O seismic zone coefficient was taken as 0.06, the seismic site coefficient as $\alpha = 1$, the structure importance coefficient as $\beta = 1$, the structure height as 29.7 m, and the structure width as 4.85 m, and the period of the structure was calculated as $T = 1.21$ s. Depending on the period of the structure, $\gamma = 0.41$ and the seismic coefficient $C = 0.025$ were determined. Thus, the seismic force was calculated as $F = 42.11$ kN. The floor weights calculated based on the seismic force are summarized in Table 3. The obtained forces were applied to the structure as equivalent seismic force in the SAP2000 program.

Table 3. Distribution of seismic force among floors according to the 1968 earthquake code.

Floor	Wi	Hi	$W_i \times H_i$	$F \times (W_i H_i)/\sum W_i H_i)$
5	1143.41	25	28585.25	33.81
4	137.00	20	2740	3.24
3	140.41	15	2106.15	2.49
2	143.86	10	1438.6	1.70
1	147.28	5	736.4	0.87
Total	1711.96	-	35606.4	42.11

In the dynamic calculation of the structure according to 1975 earthquake codes, the seismic coefficient was taken as C_0 =0.10, the structural dynamic coefficient was taken as S =1, the structural type coefficient was taken as K=3, the structure importance coefficient was taken as I =1, and the seismic coefficient C was calculated as 0.30. The seismic force was obtained as F =513.59 kN. The floor weights calculated based on the seismic force are summarized in Table 4. The obtained forces were applied to the structure as equivalent seismic force in the SAP2000 program.

In the dynamic calculation of the structure according to 1998 earthquake codes, the first natural period was calculated as $T_1 = 0.64$ s. The local soil class was determined to be of type (B) according to the Z2 soil classification. The spectrum coefficient $S(T_1)$ was calculated to be 1.725. The seismic load reduction coefficient was taken as R=4 and the spectral acceleration coefficient was calculated as $A(T) = 0.69$. Thus, the total equivalent seismic load was calculated as $V_t = 295.30$ kN, and the additional equivalent seismic load acting on the N-th floor of the structure was calculated as $\Delta F_N = 13.15$ kN. The floor weights calculated based on the seismic force are summarized in Table 5. The obtained forces were applied to the structure as equivalent seismic force in the SAP2000 program.

Table 4. Distribution of seismic force among floors according to the 1975 earthquake code.

Floor	Wi	Hi	$W_i \times H_i$	$F \times (W_i H_i)/\sum W_j H_j)$
5	1143.41	25	28585.25	412.32
4	137.00	20	2740	39.52
3	140.41	15	2106.15	30.38
2	143.86	10	1438.6	20.75
1	147.28	5	736.4	10.62
Total	1711.96	-	35606.4	513.59

Table 5. Distribution of seismic force among floors according to the 1998 earthquake code.

Floor	Wi	Hi	$W_i \times H_i$	$F_i = (V_t - \Delta F_N)\left[\frac{w_i H_i}{\sum_{j=1}^{N} w_j H_j}\right]$	$F_i + \Delta F_N$
5	1143.41	25	28585.25	226.51	239.66
4	137.00	20	2740	21.71	21.71
3	140.41	15	2106.15	16.69	16.69
2	143.86	10	1438.6	11.40	11.40
1	147.28	5	736.4	5.84	5.84
Total	1711.96	-	35606.4	282.15	295.30

In the dynamic calculation of the structure according to 2007 earthquake codes, the first natural period of the structure as calculated as $T_1 = 0.51$ s. The local soil class was determined to be of type (B) according to the Z2 soil classification. The spectrum coefficient $S(T_1)$ was calculated to be 2.06. The seismic load reduction coefficient was taken as R=4 and the spectral acceleration coefficient was calculated as $A(T_1) = 0.824$. The total equivalent seismic load was calculated as $V_t = 352.66$ kN, and the additional equivalent seismic load acting on the N-th floor of the structure was calculated as $\Delta F_N = 13.22$ kN. The floor weights calculated based on the seismic force are summarized in Table 6. The obtained forces were applied to the structure as equivalent seismic force in the SAP2000 program.

Table 6. Distribution of seismic force among floors according to the 2007 earthquake code.

Floor	Wi	Hi	$\mathbf{W_i \times H_i}$	$\mathbf{F_i = (V_t - \Delta F_N)\left[\frac{w_i H_i}{\sum_{j=1}^{N} w_j H_j}\right]}$	$\mathbf{F_i + \Delta F_N}$
5	1143.41	25	28585.25	272.51	285.73
4	137.00	20	2740	26.12	26.12
3	140.41	15	2106.15	20.08	20.08
2	143.86	10	1438.6	13.71	13.71
1	147.28	5	736.4	7.02	7.02
Total	1711.96	-	35606.4	282.15	352.66

In the dynamic calculation of the structure according to 2018 earthquake codes, the design spectrums were obtained from the Türkiye Earthquake Hazard Map Interactive Web Application [22]. In accordance with the ZC local soil class, the short period design spectral acceleration coefficient for 0.2 s (S_{DS}) was determined as 0.895 and the design spectral acceleration coefficient for the 1.0 s (S_{D1}) was determined as 0.317. Horizontal elastic design acceleration spectrum corner periods were calculated as $T_A = 0.071$ s and $T_B = 0.396$ s. In the horizontal elastic design spectrum, the transition period to the constant displacement region is $T_L = 6$ s. In the direction of the earthquake considered (X), the predominant period of the structure was calculated as $\left(T_p{}^{(X)}\right) = 0.51$ s.

The horizontal elastic design spectral acceleration value was obtained as $S_{ae}(T) = 0.622g$. Taking the structure importance coefficient $I = 1$, the seismic load reduction coefficient was determined as $R_a(T) = 8$. Depending on these parameters, the reduced design spectral acceleration value of the structure was $S_{aR}(T) = 0.078$. The total equivalent seismic load acting on the entire structure was calculated as $V_t = 133.53$, and the additional equivalent seismic load acting on the N-th floor of the structure was calculated as $\Delta F_N = 5$ kN. The floor weights calculated based on the seismic force are summarized in Table 7. The obtained forces were applied to the structure as equivalent seismic force in the SAP2000 program.

Table 7. Distribution of seismic force among floors according to the 2018 earthquake code.

Floor	**Wi**	**Hi**	$W_i \times H_i$	$F_i = (V_t - \Delta F_N)\left[\frac{w_i H_i}{\sum_{j=1}^{N} w_j H_j}\right]$	$F_i + \Delta F_N$
5	1143.41	25	28585.25	103.20	108.20
4	137.00	20	2740	9.89	9.89
3	140.41	15	2106.15	7.60	7.6
2	143.86	10	1438.6	5.20	5.2
1	147.28	5	736.4	2.66	2.66
Total	1711.96	-	35606.4	128.55	133.53

The seismic force values calculated based on the equivalent linear method according to each earthquake code in the examined elevated water tank are summarized in Figure 6.

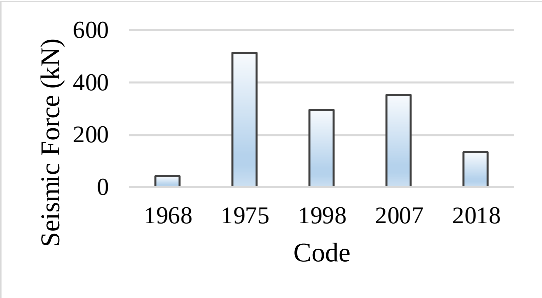


Figure 6. Comparison of seismic forces according to relevant codes.

The structural analysis results of the elevated water tank, which was analyzed in the SAP2000 program according to the relevant earthquake codes, are given in Table 8. The effects of compressive force and bending moment on the column members at the ground floor were taken into account. The maximum displacement in the structure occurred at the top point of the tank. When the analysis results in terms of base shear force, overturning moments, and displacement were examined, it was observed that the structural responses in the structure increase in proportion to the seismic forces.

Table 8. Comparative analysis results.

Codes	**Structural effects**				
	Max. displacement	**Base shear force**	**Overturning moments**	**Compression force**	**Bending moment**
1968	0.02	1360.7	37142.1	63.926	298.34
1975	0.26	16594.3	452959.5	779.615	3638.44
1998	0.15	9642	263231.9	342.36	2113.68
2007	0.18	11496.1	313842	408.86	2520.24
2018	0.06	4353.4	118845.5	521.78	3415.06

The displacement values obtained according to the relevant earthquake code are shown graphically in Figure 7. According to this, it is seen that the maximum value of peak displacement occurred in the 1975 earthquake code, while the minimum value occurred in the 1968 code.

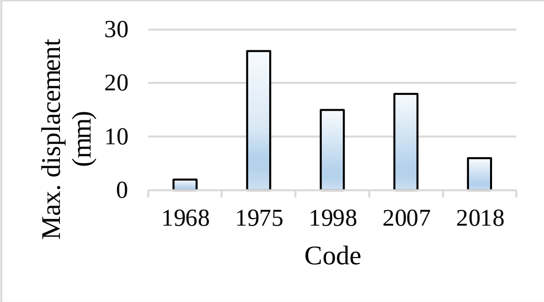


Figure 7. Change of displacement value in the structure according to the relevant codes.

According to the structural analysis results, the base shear force values obtained depending on the relevant earthquake code are shown graphically in Figure 8. It is seen that the maximum value of base shear force occurred in the 1975 earthquake code, while the minimum value occurred in the 1968 code.

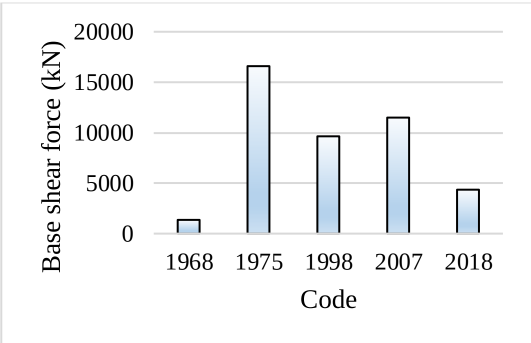


Figure 8. Change of base shear force value in the structure according to the relevant codes.

According to the structural analysis results, the overturning moment values obtained depending on the relevant earthquake code are shown graphically in Figure 9. It is seen that the maximum value of overturning moment occurred in the 1975 earthquake code, while the minimum value occurred in the 1968 code.

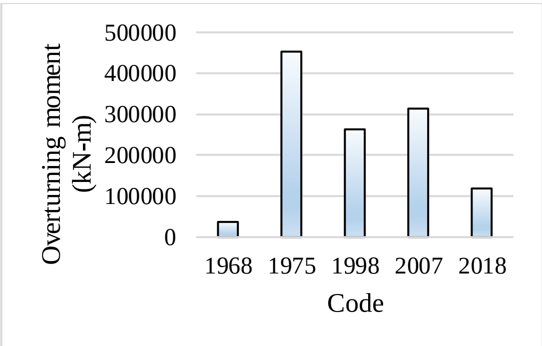


Figure 9. Change of overturning moment value in the structure according to relevant codes.

When the analysis results in Table 8 are examined, it is seen that the elevated water tanks are exposed to high forces and strained under the effect of the earthquake. Accordingly, the most reliable analysis results for the structure were obtained from the design according to the 2018 earthquake code. This is due to the advancement of calculation methods when earthquake code revisions and the improved adherence to the principle of ductility in design.

In the province of Malatya, which was affected by the Kahramanmaraş earthquakes, water tanks, like most engineering structures, were significantly damaged and became unusable. Figure 10 shows an RC elevated water tank located in the Yeşilyurt district that was heavily damaged as a result of the earthquakes in question. This water tank was constructed by selecting from the type project examples whose structural behavior was investigated in the study. As a result of the Kahramanmaraş earthquakes, major damage occurred to the columns and beams that form the load-bearing system of the elevated water tank.

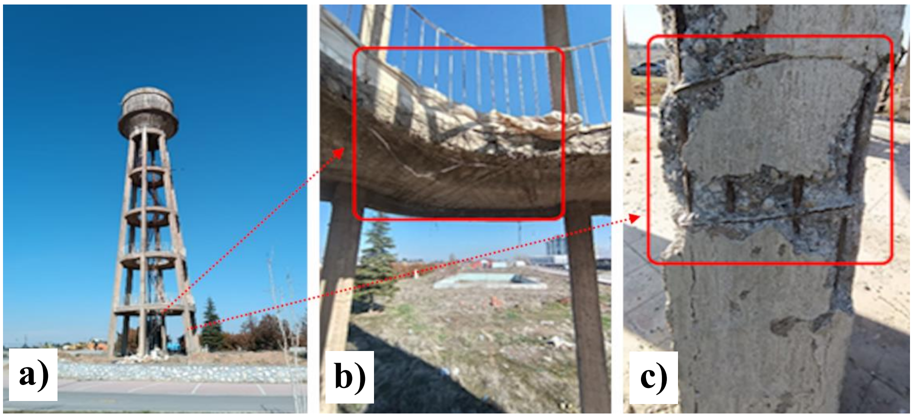


Figure 10. The RC elevated water tank damaged by the 6 February 2023 Kahramanmaraş earthquakes, a) general view, b) damaged ring beam, c) damaged column.

When the damage status of the structure was examined, it was observed that concrete failures, crushes, reinforcement buckling, and heavy reinforcement corrosion occurred in almost all of the beams and columns. As a result of these factors, it was determined that the structural members lost their carrying capacity and suffered severe damage. As seen in Figure 10, the main reasons for these damages in the structural members can be listed below.

- Aggregate granulometry is not suitable and therefore concrete quality is poor
- The reinforcement used has low strength
- All members have high stirrup spacing, and no stirrup densification was done
- Column sections are of inadequate size

As a result of all these deficiencies and defects, severe damage occurred to the structure in question. When the type project details of RC elevated water tanks, which are widely constructed in our country, are examined, a major deficiency in providing the necessary seismic performance of the structure is evident. The reason for this is the inadequacies in the structure design codes valid at the time when the type projects were prepared [21, 23, 24]. These inadequacies have manifested as deficiencies, including material classes, reinforcement ratios, and limitations on section ratios.

When the above analysis results are evaluated together with the damage state in the RC elevated water tank in Figure 10, it is concluded that the structure should be designed and constructed in accordance with the design conditions in the 2018 earthquake code to ensure its safety against earthquake effects.

3 RESULTS AND DISCUSSION

The use of lifeline structures after major earthquakes is of vital importance in ensuring social continuity. Water tanks are also one of the lifeline structures. These structures, which must be used uninterruptedly after major earthquakes, are expected to show good seismic behavior. However, after the Kahramanmaraş earthquakes, it was clearly seen that the necessary importance was not given in the design and construction processes of these structures. These structures received significant damage as a result of these earthquakes and their structural safety became critical. When the damage status was evaluated together with the design criteria in the current earthquake code, it was understood that the structure design was inadequate to ensure safety against earthquakes. As a result of this inadequacy, the effect of the design principles in the earthquake codes on the seismic behavior of the water tank was questioned.

In this study, the seismic behavior of the RC elevated water tank structure, which is of vital importance to be used undamaged after the earthquake, was investigated according to the earthquake codes of 1968, 1975, 1998, 2007, and 2018. An elevated water tank with a volume of 75 m^3 was selected from the type project examples published by the Ministry of Rural Affairs, which is widely applied in our country, and its design was made in the SAP2000 program.

Modal analysis was performed to determine the dynamic properties of the structure. According to the analysis results, the same modal response results were obtained in both directions of the earthquake due to the design feature of the water tank. In the first two modes, the contribution of the structural mode to the total response is 89%. High period values were obtained depending on the rigidity, mass properties, and height of the structure. It is also seen that torsion does not contribute to the dynamic response. Modal analysis results provide important information about the dynamic behavior of RC elevated water tanks.

Stress analysis was performed to better understand the behavior of the structure under seismic effects. In the water tank, stress values for the frame system and the reservoir were calculated separately. While no significant stress concentration occurred in the reservoir, very high compressive and tensile stresses occurred in the frame system. The most obvious reason for this is that the material properties and structural dimensions are inadequate against seismic effects in the structural members that statically support the weight of the reservoir. When the stress analysis results are evaluated specifically for the water tank in Figure 10, which was significantly affected by the Kahramanmaraş earthquakes, it is thought that the damages in the structure are due to being exposed to such high axial compressive and tensile stress cycles during the earthquakes.

In order to see the effect of design approaches in earthquake codes on the dynamic behavior of the water tank, the structural behavior of the tank was examined comparatively. For this purpose, seismic forces, displacements, base shear forces, and overturning moments in the structure were determined according to the calculation methods in all earthquake codes from the code valid on the date the type projects were published to the present day. The equivalent linear method was chosen as the dynamic calculation method.

Since the 1968 earthquake code, the equivalent linear method has been used in dynamic calculations of structures based on the structure period. This method continued to be developed and used in the 1975 earthquake code. In the 1998 earthquake code, the method was developed by including the effective ground acceleration coefficient depending on the earthquake zone and the spectrum coefficient depending on the local soil classes in the calculation formulations. In the 2007 earthquake code, the same calculation method continued to be applied, similar to the 1998 code, with some restrictions. The equivalent linear method with the 2018 earthquake code has been comprehensively developed based on the ductile design approach. According to this code, design acceleration spectra are obtained using Türkiye Earthquake Hazard Maps Interactive Web Application. Local ground effect calculations are made in more detail than in previous codes. With all these improved design principles, the most accurate results are obtained by making more realistic calculations according to the 2018 earthquake code.

When the dynamic analysis of the 75 m^3 volume elevated water tank structure examined in this study is carried out separately according to the calculation principles of each earthquake code, it is seen that the most unfavorable results were obtained from the design according to the 1975 earthquake code. The reason for this is that there is a rough calculation method in this earthquake code, and the principle of ductility is not taken into consideration. With the 1998 earthquake code, calculation methods have been significantly improved, and the ductility requirement, which will contribute greatly to the seismic performance of structures, has begun to be taken into account in design. It was observed that the analysis results changed safely depending on the development of calculation methods from the 1975 earthquake code to the 2007 earthquake code. When the dynamic analysis of the structure was performed according to the current and valid 2018 earthquake code, more realistic and reliable analysis results were obtained.

4 CONCLUSION AND SUGGESTIONS

The water tank examined in this study is not an exceptional example. This example represents the general situation of RC elevated water tanks in Türkiye. In order for these structures to provide the necessary performance against future major earthquakes, the type projects used today need to be updated according to the 2018 earthquake code.

It was concluded that the structure showed better performance as the design criteria and calculation principles were improved from the 1968 earthquake code to the 2018 earthquake code. Obviously, structures in this situation are at risk. If structural repair and strengthening are not made by taking the necessary precautions, it is inevitable that a collapse will occur in the structure at any time.

In this study, the seismic behavior of RC elevated water tanks was investigated based on dynamic analysis. Apart from these structures, there are tank types with different materials and different design features. Similar studies can be conducted in the future to evaluate the seismic behavior of different tank types. This and similar studies will be a source for future studies.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

Artificial Intelligence (AI) Contribution Statement

This manuscript was entirely written, edited, analyzed, and prepared without the assistance of any artificial intelligence (AI) tools. All content, including text, data analysis, and figures, was solely generated by the author.

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