7th International Congress on Advances in Civil Engineering, 6-8 October 2006
Yıldız Technical University, Istanbul, Turkey

The Effects of Local Site Classes on the Dynamic Behavior of Elevated Tanks with Frame and Shaft Supporting Structures

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Abstract

In this study, firstly a synthesis work related to the dynamic behavior of elevated tanks is presented and then seismic analyses of sample elevated tanks with circular frame and cylindrical shell supporting systems are carried out. To analyze and evaluate of seismic behavior of the tanks, modal analysis method is used considering requirements of Turkish Earthquake Code (TEC) and Eurocode 8 version which are became valid in the same period of time (1998). Four local site classes defined in TEC-98 and three local site classes in EC-8 are considered in the seismic analysis. The results for both supporting systems restrained on the local site classes are compared each other. Some conclusions and discussions related to the local site classes effects on the dynamic behavior of elevated tanks are given at the end of the study. .

Keywords: Elevated tanks, Local Site Classes, Eurocede-8, Turkish Earthquake Code

Introduction

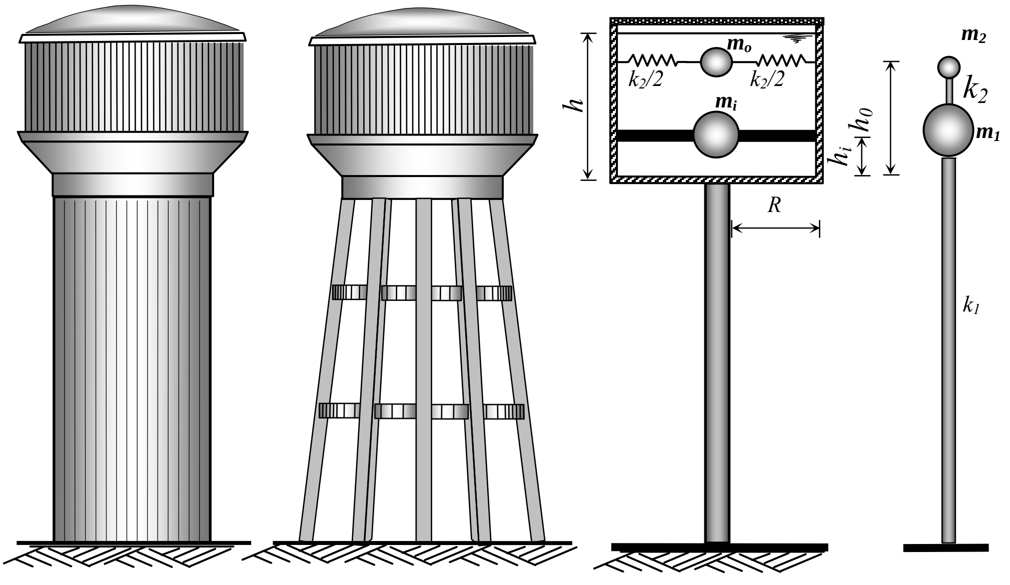
It is known that, some of the liquid storage tanks are damaged in many earthquakes. Damage or collapse of these tanks causes some unwanted events such as shortage of drinking and utilizing water, uncontrolled fires and spillage of dangerous liquids. Even uncontrolled fires and spillage of dangerous liquids subsequent to a major earthquake may cause substantially more damage than the earthquake itself (Livaoğlu 2005). Due to these reasons this type of structures which are special in construction and in function from engineering point of view must be constructed well to be resistant against earthquakes.

There have been performed numerous studies about dynamic behavior of liquid storage tanks. Most of them are concerned with ground level cylindrical tanks. Contrary to this circumstance, very few studies related to underground and elevated tanks exist. It is generally assumed that the elevated tanks are fixed to the ground and attention is given to the dynamic behavior of the fluid and structure. ie. Livaoğlu and Doğangün (2003) investigated effect of the local site classes considering the requirements not EC-8 but TEC-98 on the seismic behavior of elevated tanks. Since studies in earthquake behavior of elevated tanks are rarity, these studies may be summarized as follow, it is aimed to investigate comparatively the effects of subsoil defined TEC-98 and EC-8 on the dynamic behavior of elevated tanks in this study..

- Studies including lumped mass approximation (Housner 1963, Livaoğlu and Doğangün 2006).
- Studies considering added mass approximation (Doğangün et al. 1997, Asthana 1997, Livaoğlu and Doğangün, 2004 and 2005).
- Studies taking effects of soil-structure interaction into account (Resheidat et al. 1990, El-Damatty et al. 1997, Livaoğlu and Doğangün, 2005 and 2006).
- Experimental study (Marashi 1997).

Seismic Analyses of Elevated Tanks with Housner Method

If the water is completely contained to prevent vertical motion of the water sloshing, the water tower may be treated as a normal inverted pendulum. However dynamic behavior of the elevated tanks change, when the fluid in the vessel oscillates. Also observations of real elevated tanks demonstrated this, so if these sloshing effects are not taken into account or in other words considering a single-degree-of- freedom model causes large error (Doğangün et al, 1997, Livaoğlu and Doğangün 2006). Therefore, a method of analyzing elevated tanks considering sloshing effect must be used with the two-mass model as suggested by Housner (1963) or the others submitted by Livaoğlu and Doğangün (2006). In the method suggested by Housner, the elevated tanks mechanical equivalent and the mathematical model are given in Fig 1.



Elevated tank with shell supporting system
Elevated tank with frame supporting system
Mechanical equivalent
Mathematical model

Figure 1. Mechanical equivalent and mathematical model of the elevated tanks.

Mass-spring model has been used since 1950s with a view that determination of the hydrodynamic pressure on tank wall by means of equivalent mass. In this approach, once these equivalent masses are determined than each of these masses distances from the tank bottom level is calculated. Finally, according to assumptions of the earthquake behavior of the tank wall (rigid or flexible), decided appropriate response spectrum acceleration or ground acceleration value is multiplied with calculated equivalent masses and by this way hydrodynamic pressures on elevation of the walls are obtained. Bending moments and overturning moments in the critical cross section is become definite by knowing this hydrodynamic pressure (Doğangün and Livaoğlu 2004).

The procedure of the Housner's model of elevated tanks subjected to horizontal dynamic load can be realized as fallows; the impulsive mass and convective mass illustrated in Fig. 1. can be determined as

$$m_i = m_t \frac{\text{th}\ \left(1{,}74 R/h\right)}{\left(1{,}74 R/h\right)} \qquad m_o = m_t 0{,}318 \frac{R}{h} \text{th}\ \left(1{,}84 R/h\right) \tag{1}$$

Where, m_t, R and h are the total mass of fluid, radius of the vessel and height of the fluid in vessel, respectively. h_i and h_o, symbolizing the heights of the impulsive mass and convective mass from the vessel base are determined by following equations.

$$h_i = \frac{3}{8} h \qquad h_o = \left[1 - \frac{\text{ch}\ \left(1{,}54 h/R\right)}{1{,}84 h/R\, \text{sh}\left(1{,}54 h/R\right)}\right] h \tag{2}$$

In Fig 1, k_1 is stiffness of the supporting system and k_2 is the stiffness that it is connected convective mass to vessel wall and is determined by following equations.

$$k_2 = m_0 \frac{g}{R} 1{,}84 \quad \text{th}\ \left(1{,}84 h/R\right) \tag{3}$$

Design Spectrum for Local Site Classes

Local site classes are given in TEC-98 and Spectrum characteristic periods, T_A and T_B are specified in Table 1 depending on local site classes defined in the code.

Table 1. Local site classes and spectrum characteristic periods (T_A ,T_B) defined in TEC

Local Site	Subsoil groups according to Table 3 and topmost layer thickness (h_1)	T_A (s)	T_B (s)
Z1	Group (A) soils.Group (B) soils with $h_1 \leq 15$ m	0.10	0.30
Z2	Group (B) soils with $h_1 > 15$ m. Group (C) soils with $h_1 \leq 15$ m	0.15	0.40
Z3	Group (C) soils with 15 m $< h_1 \leq 50$ m. Group (D) soils with $h_1 \leq 10$ m	0.15	0.60
Z4	Group (C) soils with $h_1 > 50$ m. Group (D) soils with $h_1 > 10$ m	0.20	0.90

The spectrum coefficient, S (T) can be taken from Table 2, depending on the subsoil classconditions and the natural period of structures (T). Design acceleration spectrum ordinate ($S_{pa}(T)$) to be taken into in any vibration mode account can be determined by Table 2: Where, the A_o is effective ground acceleration coefficient and I is the building importance factor specified in TEC-98. $R_a(T)$ is the seismic load reduction factor determined by Table 2 in terms of structural behavior factor (R).

Table 2. Determination of response spectrum characteristics for TEC-98.

Period	Spectrum coefficient $S(T)$	Seismic load reduction factor (R_a)	Design spectrum ordinate, $S_{pa}(T)$
$0 \le T \le T_A$	$1+1,5T / T_A$	$R_a(T)=1.5+(R-1.5)T/T_A$	$S_{pa}(T)=\frac{A_0 \cdot I \cdot S(T)}{R_a(T)}$
$T_A \le T \le T_B$	$2,5$	$R_a(T)=R$	
$T>T_B$	$2,5(T_B / T)^{0,8}$		

The influence of local ground conditions on the seismic action accounted for the three subsoil classes described in Table 3 as given in the EC-8 (Eurocode-8, 1998).

Table 3. Classification of subsoil conditions according to EC-8 (1998) and (2006).

Eurocode-8 (1998)		Eurocode-8 (2006)	
Subsoil Class	Description of Subsoil (Local Site)Classes	Subsoil Class	Description
A	Rock or other geological formation characterized by a shear wave velocity v_s of at least 800 m/s, including at most 5 m of weaker material at the surface.	A	Rock or rock-like geological formation including most 5 m weaker material at the surface $V_{s,30}$ >800 m/s
	Stiff deposits of sand, gravel or overconsolidated clay, at least several tens of m thick, characterized by a gradual increase of the mechanical properties with depth and by v_s values of at least 400 m/s at a depth of 10 m.	B	Deposit of very dense sand, gravel or very stiff clay, at least several tens of m in thicknesses, characterized by a gradual increase of mechanical properties with depth $V_{s,30}$ ≈360~ 800
B	Deep deposits of medium dense sand, gravel or medium stiff clays with thickness from several tens to many hundreds of m, characterized by v_s values of at least 200 m/s at a depth of 10 m, increasing to at least 350 m/s at a depth of 50 m.	C	Deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of m $V_{s,30}$ ≈180~360
C	Loose cohesionless soil deposits with or without some soft cohesive layers, characterized by v_s values below 200 m/s in the uppermost 20 m. Deposits with predominant soft-to-medium stiff cohesive soils characterized by v_s values below 200 m/s in the uppermost 20 m.	D	Deposits of loose-to-medium cohesionless soil (with o r without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil. $V_{s,30}$ <180
		E	A soil profile consisting of a surface alluvium layer with $V_{s,30}$ values of class **C** or **D** and thick-ness varying between about 5m and 20m, underlain by stiffer material with $V_{s,30}$>800 m/s
		S_1	Deposits consisting or containing a layer at least 10 m thick of soft clays/ silts with (PI>40) and height water content, $V_{s,30}$<100 m/s
		S_2	Deposits of liquefiable soils, of sensitive clays, or any other soil profile not included in types **A**-**E** or **S_1**

Values of the parameters describing the elastic response and design spectrums in EC-8 are given in Table 4: In this table, S is soil parameter, β_0 is spectral acceleration amplification factor for 5% viscous damping, T_B , T_C are limits of the constant spectral acceleration branch, T_D value defining the beginning of the constant displacement range of the spectrum, k_1 , k_2 are exponents which influence the shape of the spectrum for a vibration period greater than T_C, T_D respectively, k_{d1} , k_{d2} are exponents which influence the shape of the design spectrum for a vibration period greater than T_C, T_D, respectively.

Table 4. Values of the parameters describing the spectrums (EC-8 1998).

Subsoil class	S	β_0	K_1	k_2	T_B (s)	T_C	T_D	k_{d1}	k_{d2}	For considered tanks		
										η	q	a_g
A	1,0	2,5	1,0	2,0	0,10 s	0,40 s	3,0s	2/3	5/3	1,08	1,0	4m/s^2
B	1,0	2,5	1,0	2,0	0,15 s	0,60 s	3,0 s	2/3	5/3	1,08	1,0	4m/s^2
C	0,9	2,5	1,0	2,0	0,20 s	0,80 s	3,0 s	2/3	5/3	1,08	1,0	4m/s^2

The elastic response spectrum $S_e(T)$ and design spectrum $S_{pe}(T)$ for the reference return period is defined by the expressions given in EC-8 as Table 5. Where, a_g is design ground acceleration for the reference return period, T is vibration period of a linear single degree of freedom system, η is damping correction factor with reference value η=1 for 5% viscous damping, α is ratio of the design ground acceleration a_g to the acceleration of gravity g and q is behavior factor.

Table 5. Determination of elastic and design spectrums due to EC-8 (1998) and (2006)

Period	Elastic spectrum ordinate, $S_e(T)$		Design spectrum ordinate, $S_{pa}(T)$	
	EC-8 1998	EC-8 2006	EC-8 1998	EC-8 2006
$0 \leq T \leq T_B$	$a_g S\left[1+\frac{T}{T_B}(\eta\beta_0-1)\right]$	$a_g \cdot S\left[1+\frac{T}{T_B}(\eta 2.5-1)\right]$	$\alpha S\left[1+\frac{T}{T_B}\left(\frac{\beta_0}{q}-1\right)\right]$	$a_g S\left[\frac{2}{3}+\frac{T}{T_B}\left(\frac{2.5}{q}2.5-\frac{2}{3}\right)\right]$
$T_B \leq T \leq T_C$	$a_g S\eta\beta_o$	$2.5 \cdot a_g \cdot S \cdot \eta$	$\alpha S\frac{\beta_0}{q}$	$\frac{2.5}{q} \cdot a_g \cdot S$
$T_C \leq T \leq T_D$	$a_g S\eta\beta_0\left[\frac{T_C}{T}\right]^{k_1}$	$2.5 a_g \cdot S \cdot \eta \cdot \left[\frac{T_C}{T}\right]$	$\alpha S\frac{\beta_0}{q}\left[\frac{T_C}{T}\right]^{k_{d1}} \geq 0,20\alpha$	$\begin{cases} = \frac{2.5}{q} a_g \cdot S \cdot \left[\frac{T_C}{T}\right] \\ \geq \beta \cdot a_g \end{cases}$
$T \geq T_D$	$a_g S\eta\beta_0\left[\frac{T_C}{T_D}\right]^{k_1}\left[\frac{T_D}{T}\right]^{k_2}$		$\alpha S\frac{\beta_0}{q}\left[\frac{T_C}{T_D}\right]^{k_{d1}}\left[\frac{T_D}{T}\right]^{k_{d2}} \geq 0,20\alpha$	

It is assumed that the elevated tanks considered in this study will be sited in Seismic zone one. S_o, the ratio of the design ground acceleration a_g to the acceleration of gravity g is taken to be 0.4. Therefore design ground acceleration will be 4 m/s^2. Building importance (I) factor is taken to be 1.5 and finally structural behavior factor (R) is 2. Design spectrums are determined for different subsoil classes defined in EC-8 and TEC-98 as shown in Fig 2.

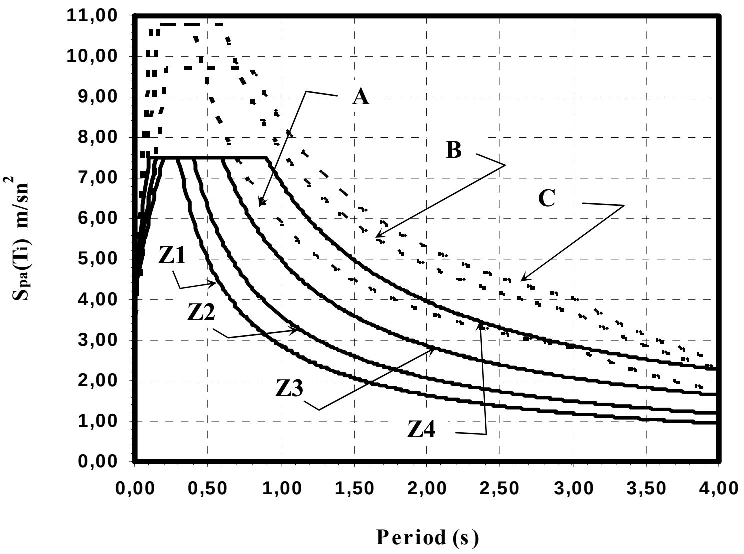


Figure 2. Design spectrums for subsoil classes defined in EC-8(1998) and TEC-98.

Structural Data and Finite Element Model

Elevated tanks with 900 m^3 of vessel volume and two different supporting systems (frame supporting system and shell supporting system) are considered (Fig 3). The project of elevated tank given in Fig 3. is put into practice by Ministry of Public Works and Settlement of Turkey up tto recent years. For all elevated tanks, thicknesses and the radius of the vessel shell are 0,3 m and 4,3 m respectively. Other dimensions of the elevated tanks are illustrated in Fig 3. Degrees of freedom at the base nodes are fixed, at the other nodes are left free.

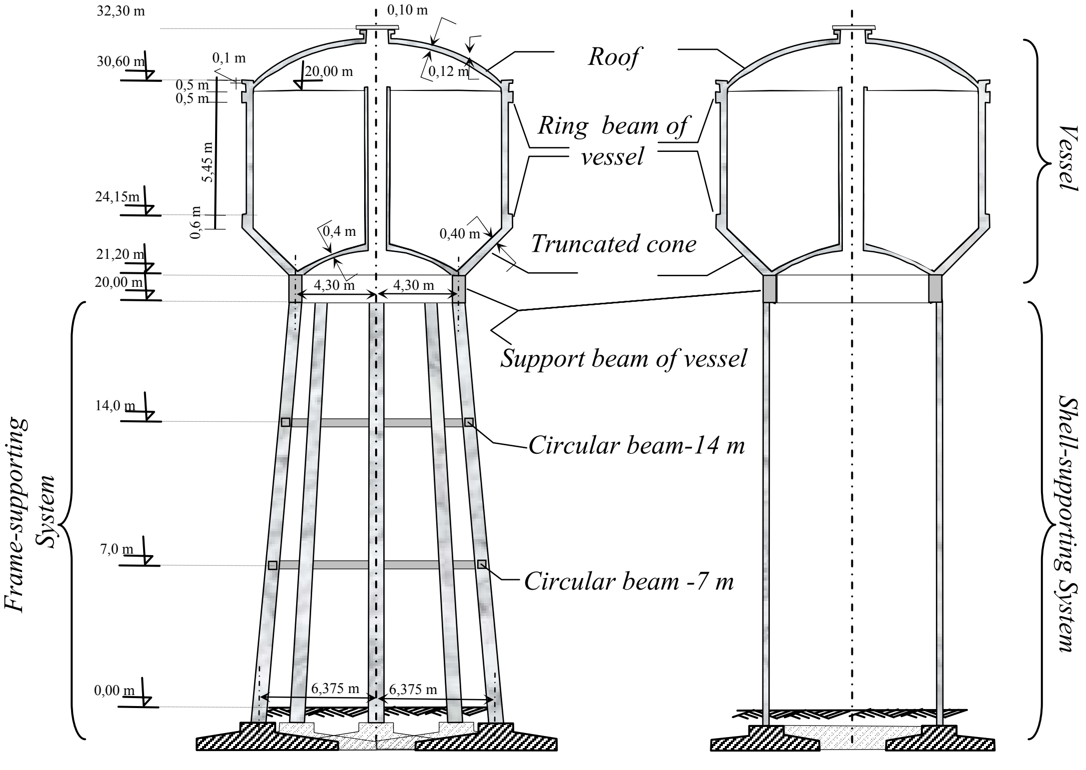


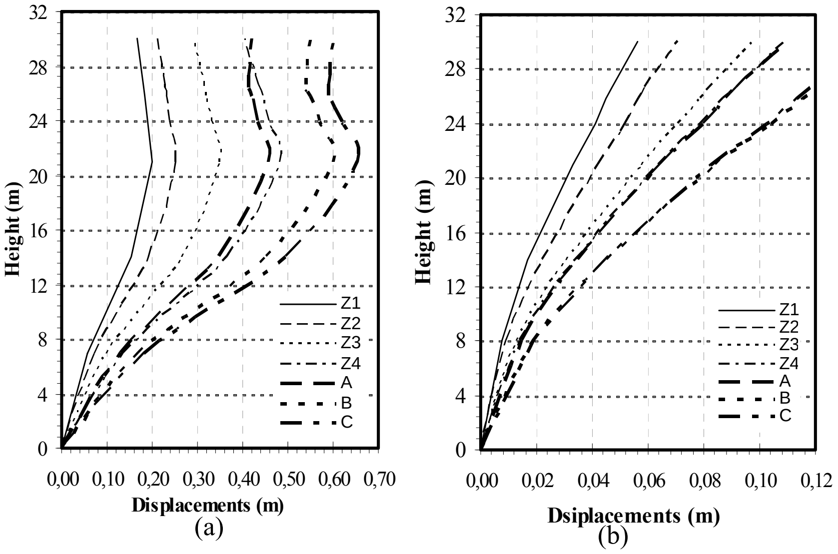
Figure 3. Vertical cross section of the elevated tanks with the frame and shell supporting system.

Columns and beams are modeled with frame element, vessel and truncated cone walls are modeled with shell element. Added mass approach is used to consider the impulsive mass in the model. In this approach, two masses which are calculated via Eq. 2 in different heights from the vessel bottom level are determined by Eq.1. Convective mass and impulsive mass and their heights are calculated as m_o=235000 kg and, its height from vessel bottom level h_i is 3,0 m and m_i=661000 kg and its height h_o is 4,70 m, Impulsive mass is added finite elements of vessel wall and truncated cone meshed suitable with height level of impulsive mass. Convective mass is replaced at the centre of vessel by means of a joint to be connected k_2 (k_2=696,2 kN/m) stiffness to shell element's joints at the h_0 level. These models are analyzed by using SAP2000 (SAP2000, 1995) package program. In the analyze, mode number taken into account in modal analysis for all elevated tanks is ten. Young's Modulus and unit weight of concrete are taken as to be 32000 MPa and 25 kN/m^3, respectively.

Evaluation of Results

Seismic analysis of elevated tanks ere made considering totally seven different subsoil classes defined in EC-8 and TEC-98. Displacements obtained from these subsoil classes for two elevated tanks are illustrated to compare the results (Fig 4). Shear forces for selected column-level obtained from seismic analysis of tanks are given Fig 5.

For elevated tanks with frame supporting system, evaluating Fig. 4 it can be seen that maximum displacement occur in 21 m height from the ground level for C subsoil classes defined in EC-8. The differences of the results are obtained between the subsoil class Z1, and Z2, Z3 Z4 as 26%, %119 and 204% respectively. The differences between the results obtained for subsoil classes A and B defined in EC-8 are 31% and for subsoil classes A and C is 42%.



(a) (b)

Figure 4.Displacement for subsoil classes (a) for frame supporting system and (b) shell supporting system.

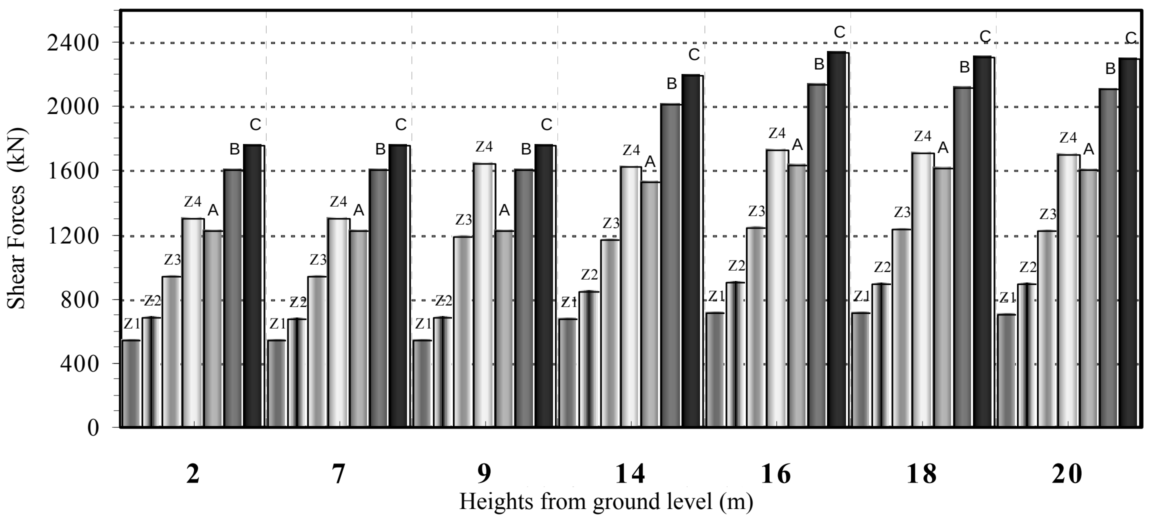


Figure 5. Shear forces for selected column-level obtained from seismic analysis of elevated tank.

Shear forces of circular beam on elevated tanks with frame supporting system may be considerably changed for different subsoil classes. For example, the values are changed 26 % between Z1 and Z2 74% between Z1 and Z3 and 141% between Z1 and Z4 classes. Similarly, variation of the shear forces between A and C is 40%.

The differences between the results obtained for subsoil classes Z1 and Z4 defined in Turkish Earthquake Code are minimum 26% and maximum 204% for elevated tanks with frame supporting system. The differences between the results obtained for subsoil classes A and C defined in EC-8 are minimum of 31% and maximum of 42%.

Conclusions

The results shows that subsoil parameters (classes) largely affect the magnitude of shear forces which are very important for elevated tanks subjected to strong earthquakes. So, subsoil parameters must be carefully determined for earthquake resistant design of elevated tanks more exactly according to classical design of elevated tanks.

In spite of putting into considering elevated tanks with frame supporting system practice by Ministry of Public Works and Settlement of Turkey, The elevated tanks couldn't be used on seismic zone one and for Z2, Z3 and Z4 subsoil classes. Because of this reason, the frame supporting system and its dynamic characteristics like rigidity and ductility should be revaluated.

It is said that according to property of shear wave velocity (v_s), Z1, Z2 defined TEC-98 with A defined EC-8, Z3 with B and Z4 with C. almost show similar characteristic. The ordinates of design spectrum for each subsoil classes given in EC-8 are larger than that of the design spectrum given in the Turkish Earthquake Code. Therefore results from the EC-8 are larger than equivalent subsoil classes defined TEC-98 for every circumstance.

Both codes considered in this study have been updated beginning of the year of 2006. In accordance to conclusions obtained from the study and the other studies carried out by authors, it was shown that the soil condition defined EC 8-98 are not sufficiently qualified. But this deficiencies improved on the update version of EC 8. However updated TEC has not included any change in this issue.

Acknowledgements

The present work is supported by Grant-in-Aid for Scientific Research (Project No.105M252) from the Scientific and Technological Research Council of Turkey (TÜBİTAK).

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