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# DYNAMIC BEHAVIOR and SEISMIC PERFORMANCE of ELEVATED TANKS DUE to GROUND TYPES DEFINED in EC-8 and TEC-06

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## SUMMARY

The aim of this paper is firstly to submit a synthesis work related to how the ground types defined in Eurocode-8 (EC-8 Part:1 2006) and Turkish Earthquake Code (TEC-06) affect response of the elevated tanks and secondly to evaluate the performance of supporting system according to the ground types. For this purpose, an elevated tank with a frame supporting system which has been commonly used in recent years by the Ministry of Public Works and Settlements ise selected in the analyses. For taking into account fluid inside vessel a procedure which is proposed by EC-8 is adapted to the study. By using this procedure the elevated tank-fluid system is modelled with finite element technique. The model is analyzed via the Response spectrum analysis for evaluating the ground type effects on the behaviour of tanks. Finally, consequences of analyses carried out in this paper show that the ground types defined in EC-8 generally give fewer results than the corresponding one in TEC-06. Furthermore it is seen from the results that the supporting system of the elevated tanks doesn't have an adequate performance for a lot of ground types investigated in this study.

## 1. INTRODUCTION

It is known that very few investigations have been carried out about the seismic behaviour of the elevated tanks. However behaviour of such a special type of structure must be well-known and the seismic behaviour of this type of tanks needs to be understood well. Otherwise earthquake damages to the tanks can take several forms and cause several unwanted events such as shortage of drinking and utilizing water, uncontrolled fires and spillage of dangerous liquids etc. Even uncontrolled fires and spillage of dangerous liquids subsequent to a major earthquake may cause substantially more damage than the earthquake itself. Due to these reasons, this type of structure which is special in construction and in function from engineering point of view must be constructed to be resistant against earthquakes.

Although numerous studies have been done about dynamic behaviour of liquid storage tanks, most of them are concerned with ground level cylindrical tanks. However, few exist among these studies related to underground and elevated tanks,. It is generally assumed that the elevated tanks are fixed the ground. So attention is given to the dynamic behaviour of the fluid and structure. Early investigation suggesting simplified two-mass-model about this type of tank is realized by Housner (1963) Also some studies suggesting simple procedures to include fluid-interaction effect for ground level cylindrical and rectangular tank exit [Bauer 1964, Malhotra et al., 2000]. Also these approximations and some new others about fluid-elevated tank-soil/foundation system are summarized by Livaoğlu and Doğangün (2006). Haroun and Ellaithy (1985) developed a model including an analysis of a variety of elevated rigid tanks undergoing translation and rotation. The model considers fluid sloshing modes and it assesses the effect of tank wall flexibility on the earthquake response of the elevated tanks. Resheidat and Sunna (1986) investigated the behavior of a rectangular elevated tank considering the soil-foundation-structure interaction during earthquakes. They neglected the sloshing effects on the seismic behavior

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of the elevated tanks and the radiation damping effect of soil medium. Haroun and Temraz (1992) analyzed models of two-dimensional X-braced elevated tanks supported on the isolated footings to investigate the effects of the dynamic interaction between the tower and the supporting soil-foundation system, but they neglected the sloshing effects. Dutta et al (2000a, 2000b) studied on the comparisons of the supporting system of elevated tank with reduced torsional vulnerability and they suggested approximate empirical equations to determine the values of lateral, horizontal and torsional stiffnesses for different frame supporting systems. They also investigated how the inelastic torsional behaviour of the tank system with accidental eccentricity varied in accordance with the increasing number of panels and columns [Dutta et al. 2001]. Some studies were also conducted to investigate fluid effect on seismic behaviour of elevated tanks using FEM with added mass approximation [Doğangün et.al. 1997, Livaoğlu and Doğangün, 2003]. Furthermore studies taken effects of soil-structure interaction into account exist [Resheidat et al. 1990, El-Damatty et al. 1997]. Finally,  Livaoğlu and Doğangün (2004, 2005) proposed a frequency-dependent simple procedure to take into account effects of both the soil-structure and fluid structure interaction on seismic behaviour of elevated tanks. So, it can be clearly seen that effects of ground types and their effects on the performance of elevated tanks are not generally discussed in the above-mentioned studies. Therefore it is aimed, in this study, to investigate the effects of ground types defined codes like EC-8 and TEC-06 which have been recently come into the practice.

## 2. EARTHQUAKE ANALYSES OF ELEVATED TANKS

In the literature, many simplified analysis procedures exist as suggested by Housner (1963), Bauer (1964) and Veletsos with co-workers for the ground level tanks. In the Housner's approach two masses ($m_1$ and $m_2$) are assumed to be uncoupled and the earthquake forces on the support are estimated by considering two separate single-degree-of-freedom systems. The mass of $m_2$ represents only the sloshing of the convective mass, the mass of $m_1$ consists of the impulsive mass of the fluid. The mass derived by the weight of container and by some parts of self-weight of the supporting structure (two-thirds of the supporting structure weight is recommended in ACI 371R and total weight of the supporting structure is recommended in reference by Priestley et al, (1986)). This two-mass model suggested by Housner was updated by Epstein (1976) and has been commonly used for seismic design of the elevated tanks. If one needs to consider additional higher-modes of convective masses ($m_{cn}$), Bauer's or Eurocode 8 models can be used that the equivalent masses and heights for this model based on the work of Veletsos and co-workers [Malhotra et al., 2000] with certain modifications that make the procedure simple. The recommended design values for the cylindrical ground supported tanks in the EC 8 are given in Table 1. In this table $C_i$ is the dimensionless coefficient, $C_c$ is the coefficient dimension of (s/m$^{1/2}$), $h_i'$ and $h_c'$ are the heights of the impulsive and convective masses for overturning moment, respectively.

After determination of two masses of $m_1$ and $m_2$ with their heights from ground level and stiffnesses of $k_1$ and $k_2$, for the elevated tank-fluid system, the model can be idealized as seen from Fig 1.

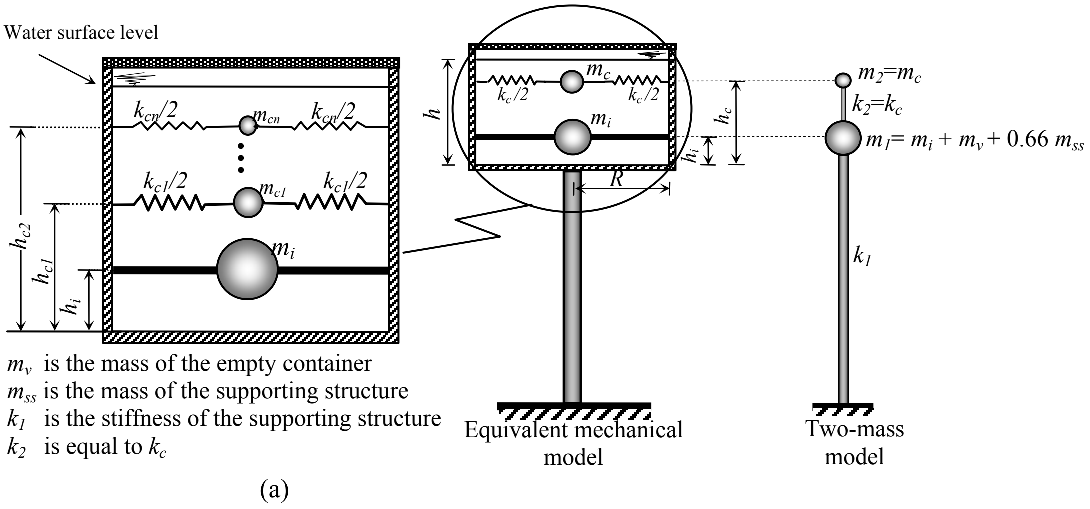


**Figure 1: (a) The multi mass model for the cylindrical tank, (b) their equivalent mechanical and idealized models for elevated tank**

By using standard structural dynamic procedures, periods, base shears and overturning moments for the design of tanks can be estimated. Modal properties like effective modal mass, heights and stiffness can be calculated from this two degree-of-freedom system

**Table 1: Recommended design values for the first impulsive and convective modes of vibration as a function of the tank height-to-radius ratio (*h/R*) [Eurocode-8:Part 4, 2006]**

| $h/R$ | $C_i$ | $C_c$ | $m_i/m_w$ | $m_c/m_w$ | $h_i/h$ | $h_c/h$ | $h_i'/h$ | $h_c'/h$ |
|---|---|---|---|---|---|---|---|---|
| 0.3 | 9.28 | 2.09 | 0.176 | 0.824 | 0.400 | 0.521 | 2.640 | 3.414 |
| 0.5 | 7.74 | 1.74 | 0.300 | 0.700 | 0.400 | 0.543 | 1.460 | 1.517 |
| 0.7 | 6.97 | 1.60 | 0.414 | 0.586 | 0.401 | 0.571 | 1.009 | 1.011 |
| 1.0 | 6.36 | 1.52 | 0.548 | 0.452 | 0.419 | 0.616 | 0.721 | 0.785 |
| 1.5 | 6.06 | 1.48 | 0.686 | 0.314 | 0.439 | 0.690 | 0.555 | 0.734 |
| 2.0 | 6.21 | 1.48 | 0.763 | 0.237 | 0.448 | 0.751 | 0.500 | 0.764 |
| 2.5 | 6.56 | 1.48 | 0.810 | 0.190 | 0.452 | 0.794 | 0.480 | 0.796 |
| 3.0 | 7.03 | 1.48 | 0.842 | 0.158 | 0.453 | 0.825 | 0.472 | 0.825 |

## 3. DESIGN SPECTRUM FOR GROUND TYPES

In this study, the term of ground types is selected in accordance with EC-8. Table 2 presents ground types and shear wave velocities given in the codes like TEC-06 and EC-8. However, the site conditions have been classified into different categories in earthquake codes, these categories are named ground types, soil profile types, or subsoil classes. As seen from this table TEC-06 gives more information about ground types depending on the topmost layer thickness of soil ($h_1$). Four and six ground types are defined in TEC-06 and EC-8, respectively. It should be noted that in the 1998 version of EC-8 only three ground types of A, B and C were defined. However, five main ground types as to be A, B, C, D, E and two special ground types S1 and S2 have been described in the current version.

**Table 2: Ground types defined in the TEC-06 and EC8 [Doğangün and Livaoğlu 2006].**

| TEC | | | EC8 | |
|---|---|---|---|---|
| Ground types | | Description | Ground types | Description |
| Z1 | - | Massive volcanic rocks, unweathered sound metamorphic rocks, stiff cemented sedimentary rocks $V_s$> 1000 m/s; Very dense sand, gravel $V_s$ >700 m/s; Hard clay, silty clay $V_s$ > 700 m/s | A | Rock or rock-like geological formation including most 5 m weaker material at the surface $V_{s,30}$ >800 m/s |
| | $h_1$≤15 m | Soft volcanic rocks such as tuff and agglomerate, weathered cemented sedimentary rocks with planes of discontinuity $V_s$ ≈700~1000; Dense sand, gravel $V_s$ ≈400~700; Very stiff clay, silty clay $V_s$ ≈300–700 | 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 |
| Z2 | $h_1$>15 m | Soft volcanic rocks such as tuff and agglomerate, weathered cemented sedimentary rocks with planes of discontinuity $V_s$ ≈700~1000; Dense sand, gravel $V_s$ ≈ 400~700; Very stiff clay, silty clay $V_s$ ≈300~700 | | |
| | $h_1$≤15 m | Highly weathered soft metamorphic rocks and cemented sedimentary rocks with planes of discontinuity $V_s$ ≈400~700; Medium dense sand and gravel $V_s$ ≈200~400;Stiff clay,silty clay $V_s$ ≈200~300 | 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 |
| Z3 | 15m<$h_1$≤50 | Highly weathered soft metamorphic rocks and cemented sedimentary rocks with planes of discontinuity $V_s$ ≈400~700; Medium dense sand and gravel $V_s$ ≈200~400; Stiff clay, silty clay $V_s$≈ 200~300 | | |
| | $h_1$≤ 10 m | Soft, deep alluvial layers with high water table $V_s$ < 200; Loose sand $V_s$ ≈ 200; Soft clay, silty clay $V_s$ < 200 | | |
| Z4 | $h_1$>50 m | Highly weathered soft metamorphic rocks and cemented sedimentary rocks with planes of discontinuity $V_s$ ≈400~700; Medium dense sand and gravel $V_s$ ≈200~400; Stiff clay, silty clay $V_s$ ≈200~300 | 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 |
| | $h_1$> 10 m | Soft, deep alluvial layers with high water table $V_s$ < 200; Loose sand $V_s$ <200; Soft clay, silty clay $V_s$ < 200 | | |
| - | | In all seismic zones, soft, deep alluvial layers with high water table $V_s$ < 200, loose sand $V_s$ <200 and soft clay, silty clay $V_s$ < 200 with water table less than 10 m from the soil surface shall be investigated and the results shall be documented to identify whether the *Liquefaction Potential* exists, by using appropriate analytical methods based on in-situ and laboratory tests. | 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 **$S_1$** |

Since the effects of structural properties and soil conditions affect elastic and inelastic responses in a different proportion, a factor usually used to reduce the elastic spectral ordinates to account for inelastic behaviour depending on the structural properties and soil conditions. The ordinates of elastic design spectra $S_e$ and inelastic design spectra $S_d$ for the reference return period defined by the earthquake codes. In this table, $\beta$ shows lower bound factor for the horizontal design spectrum, recommended value for $\beta$ is 0.2 and $\gamma_I$ shows importance factor. $S$ is the soil factor defined in EC-8 depending on ground types and $\eta$ is the damping correction factor with a reference value of $\eta$=1 for 5% viscous damping

**Table 3: Ordinates of elastic and inelastic design spectra ($S_e$ and $S_d$ ) for TEC-06, and EC8-03 [Doğangün and Livaoğlu 2006]**

| | $T \le T_B$ | $T_B \le T \le T_C$ | $T \ge T_C$ |
|---|---|---|---|
| TEC-06 | $S_e = a_{gR}\left[1+1.5\frac{T}{T_B}\right]$<br>$S_d = \frac{a_g}{R_a}\left[1+1.5\frac{T}{T_B}\right]$ | $S_e = 2.5\cdot a_{gR}$<br>$S_d = \frac{2.5\cdot a_g}{R_a}$ | $S_e = 2.5\cdot a_{gR}\left[\frac{T_C}{T}\right]^{0.8}$<br>$S_d = \frac{2.5a_g}{R_a}\left[\frac{T_C}{T}\right]^{0.8}$ |
| EC-8 | $S_e = a_g\cdot S\left[1+\frac{T}{T_B}(\eta 2.5-1)\right]$<br>$S_d = a_g S\left[\frac{2}{3}+\frac{T}{T_B}\left(\frac{2.5}{q}2.5-\frac{2}{3}\right)\right]$ | $S_e = 2.5\cdot a_g\cdot S\cdot\eta$<br>$S_d = \frac{2.5}{q}\cdot a_g\cdot S$ | $T_C \le T \le T_D \rightarrow S_e = 2.5a_g\cdot S\cdot\eta\cdot\left[\frac{T_C}{T}\right]$<br>$T_C \le T \le T_D \rightarrow S_d \begin{cases} = \frac{2.5}{q}a_g\cdot S\cdot\left[\frac{T_C}{T}\right] \\ \ge \beta\cdot a_g \end{cases}$ |
| | | | $T_D \le T \le 4\text{s} \rightarrow S_e = 2.5a_g\cdot S\cdot\eta\cdot\left[\frac{T_C T_D}{T^2}\right]$<br>$T \ge T_D \rightarrow S_d = \frac{2.5}{q}a_g\cdot S\cdot\left[\frac{T_C T_D}{T^2}\right] \ge \beta\cdot a_g$ |

In this study the tanks are considered as being situated in the first earthquake zone. These tanks have high importance factor of 1.5 and ductility reduction factor of 2. Inelastic design spectra were drawn and given in Fig. 2 by using the expressions shown in Table 2-3 for all ground types defined in the codes. As seen from Fig. 2, only TEC considers the same peak values for all ground types. EC-8 gives the maximum peak values for ground types excluding ground type of A.

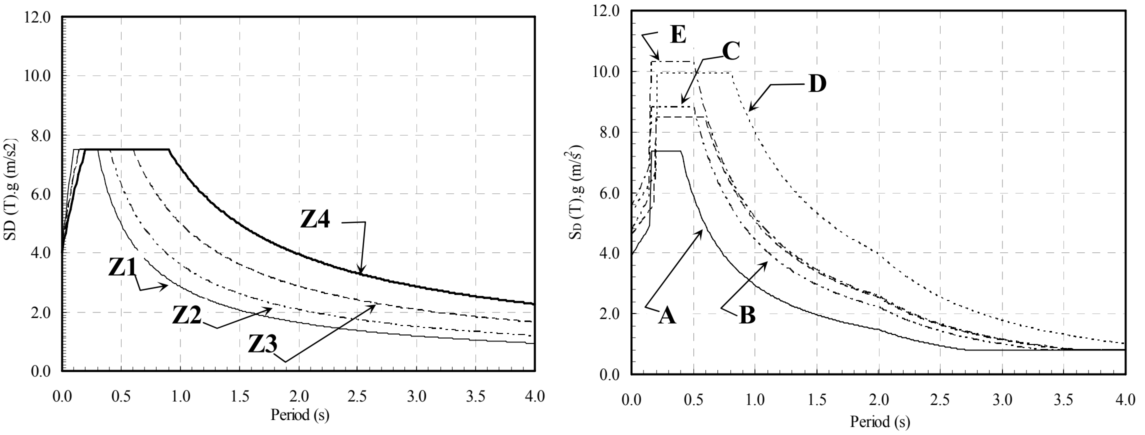


**Figure 2: Design spectrums for different ground types defined in EC-8 and TEC-06**

## 4. STRUCTURAL DATA and MODEL

In this study, a reinforced concrete elevated tank with a container capacity of 900 m$^3$ is considered in seismic analysis (Fig. 4). The elevated tank has a frame supporting structure in which columns are connected by the circumferential beams at regular interval at 7 m and 14 m height level. The tank container is Intze type and this elevated tank system has been used as a typical project in Turkey up to recent years by Ministry of Public Works and Settlement. Young's modulus of concrete and the weight per unit volume are taken to be 32,000 MPa and 25 kN/m$^3$, respectively. The container is filled with the water density of 1,000 kg/m$^3$. Calculated mass properties are $m_t$ = 613,970 kg, $m_c$ = 281,030 kg, $k_2$ = 32,900,000 N/m. Other dimensions of the elevated tanks are illustrated in Fig 3.

### 4.1. Finite Element Model of the Considered Tanks

Finite element model (FEM) considered for the elevated tank-fluid system in this study is given in Fig. 4. Degrees of freedom at the base nodes were fixed and the other left free. Columns and beams were modelled with frame element, vessel and truncated cone walls were modelled with shell element. Added mass approach is used in this study. In this approach, two masses which are obtained in different heights (calculated by Table 1) from the ground level of vessel were determined. Convective mass and impulsive mass and their heights were calculated as $m_c$=281030 kg and its height from vessel ground level $h_c$ is 5.52 m, $m_i$=613970 kg and its height from vessel ground level $h_i$ is 3.51 m. Impulsive mass added finite elements of vessel wall and truncated cone meshed in accordance with height level calculated for the impulsive mass. The convective mass placed in the centre of vessel at the level of calculated height. This mass connected to the finite element of wall with springs having stiffness of $k_2$ ($k_2$=846.7 kN/m) along the axissymmetrical direction. Mode number taken into account in modal analysis is ten for all elevated tanks. SAP2000 [SAP2000 2005] package program is used for carrying response spectrum analysis of fluid elevated tank system.

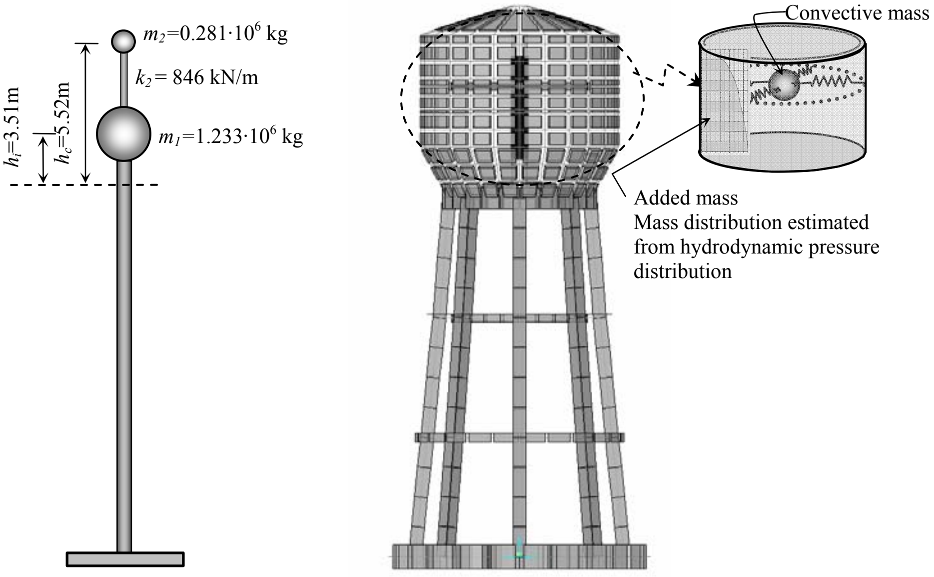


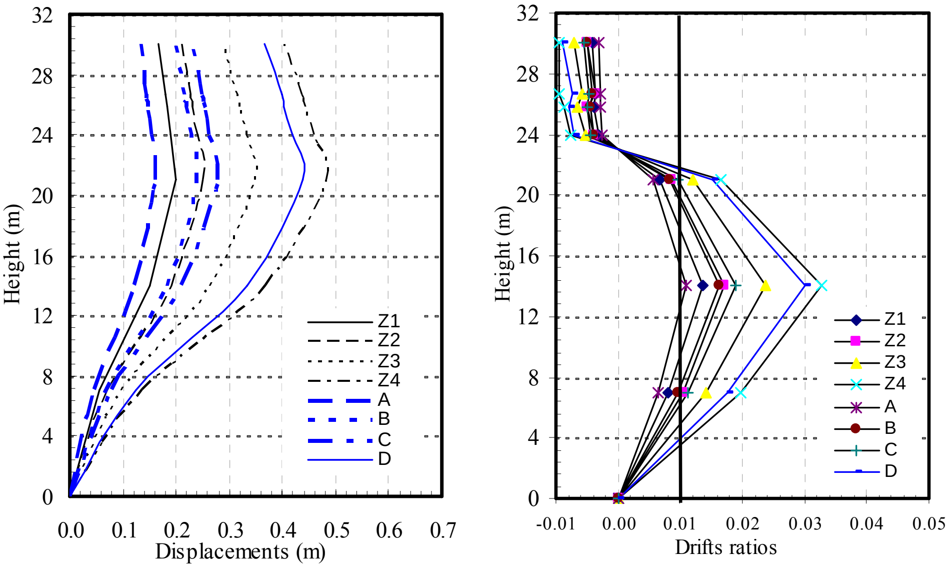
**Figure 3: Equivalent model and finite element model of the considered systems**

## 5. EVALUATION OF RESULTS

Eight analyses due to ground type conditions were carried out by using the described procedure. The analyses were realized via a computer program SAP-2000. The displacement response obtained along the height of the elevated tanks, base shear forces and overturning moments are illustrated and discussed in the following title comparatively and also by using internal force results, performance of the supporting structure are investigated.

### 5.1. Displacement Response

Considering totally eight ground types defined in EC-8 and TEC-06, seismic analyses of elevated tanks are done. Obtained displacements along the height according to different ground types for the elevated tanks are comparatively illustrated (Fig. 4a). Also, for the eight ground types, Fig. 4b shows the drifts of which limit defined via TEC-06. As can be seen from the Fig. 4a., the maximum displacement was obtained for the Z4 class as 0.48 m at 21 m height level and at the same level, the minimum displacement was estimated for the A class as 0.16 m. The difference ratios obtained according to subsoil class Z1 to the Z2, Z3 and Z4 are calculated as 26%, 119% and 204% respectively. Similarly, between the ground types of EC-8, more results are respectively calculated for B, C and D than the A class as 50%, 72% and 83%. On the other hand it was generally seen that the displaced shapes of the tanks change while the ground types are changed from the A to D or Z1 to Z4. So deterioration with stability of the tanks is more clearly seen for the Z3, Z4 and D classes than the others. Also the calculated displacements show that from the similar ground types defined in EC-8 and TEC-06, ground types defined in TEC-06 give bigger results than the corresponding one defined in EC-8.



(a) (b)

**Figure 4: According to the ground types (a) displacement response of the tanks (b) drift ratios.**

Fig. 4.b shows comparatively drift results. This figure also shows that ground types defined in TEC-06 causes more drifts than the EC-8 for the similar ground types. As a consequence, it can be easily said that if the results are evaluated for the TEC-06 permissible limit, the calculated responses require that any ground type do not allows the design of these elevated tanks.

### 5.2. Base Shear Forces and Overturning Moments

The comparative variation of the estimated base reactions like base shears and overturning moments for investigated elevated tanks are illustrated in Fig. 5. As seen from these figures different responses were estimated for the tanks situated in different soil types. i.e. the maximum base shear force reaches 13160 kN for Z4 and 11958 kN for D, while for A and Z1 ground types minimum base shears were obtained as 4360 kN and 5464 kN, respectively. The increases between the similar soil types defined TEC-06 and EC-8 is interesting that i.e. between A and Z1 or D and Z4 etc, the ratios occurred interval of 5%~25%. This shows that the similar definition made on the different codes gives different result and also shows that ground types defined in TEC-06 may give bigger response than the other approximately as 25%. Furthermore, maximum deviations in the base shear or overturning moments due to soil classes were estimated as 174% between the A and D and 141% between the Z1 and Z4 ground types.

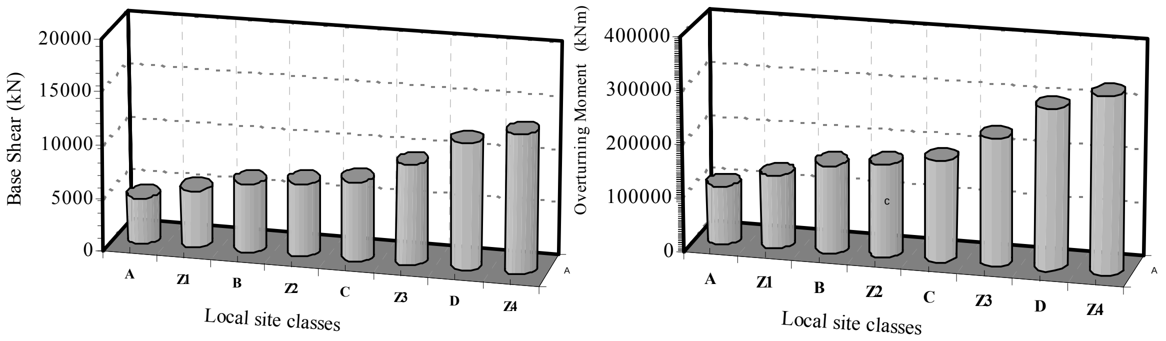


**Figure 5: Base shear forces and overturning moments for elevated tanks situated in different ground types**

## 5.3. Comparisons of the Performance of the columns due to Ground Types

According to the analyses carried out, to better judge the strength of the supporting columns, the results discussed are obtained for the tanks. The maximum internal forces like axial forces and moments obtained from response spectrum analyses are comparatively illustrated in Fig. 6 according to ground types. These comparisons clearly exhibit that the ground types play an effective role in increasing all calculated internal forces. i.e. Z2 ground types cause 26% more bigger response of axial forces than Z1. Similarly this response occurred 141% more for D ground type. Furthermore EC-8 ground types give 174% increases between the A and D ground types.

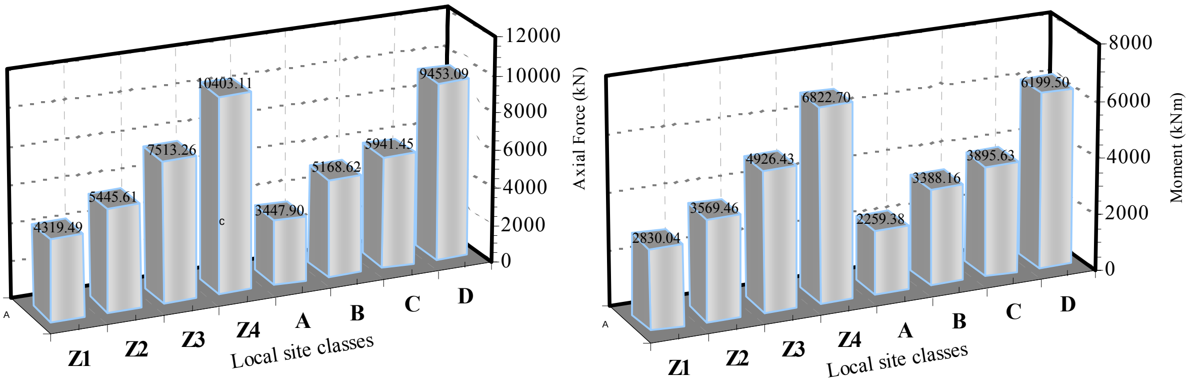


**Figure 6: Maximum axial forces and moments obtained from a column of the elevated tank due to ground types.**

Fig.7 shows the calculated axial load-moment interaction diagram for a typical supporting column. For the interaction curve, an estimated concrete compressive strength of design, $f_{cd}$, of 25 MPa was used. In the determination of interaction diagram as seen in Fig. 7, the characteristic and design yield strengths were accepted as 420 MPa and 365 MPa, respectively that this type of reinforcement has been commonly used in Turkey. When the capacity of columns subjected to combined axial load and bending moment is compared with the estimated loads and moments from the seismic analyses, clearly one can state that most of them have not adequate capacity except the columns of elevated tanks situated in Z1, A and B ground types. These results show that elevated tanks investigated here can only be built in Z1 ground type in accordance to TEC-06 and due to EC-8 A and B. they are only appropriate ground type for these structures. For the other ground types the internal forces obtained exceed the capacity of the columns. If similar comparisons are made in accordance with results obtained by static analysis, it can be easily seen that both estimated axial loads and bending moments are inside the limit values.

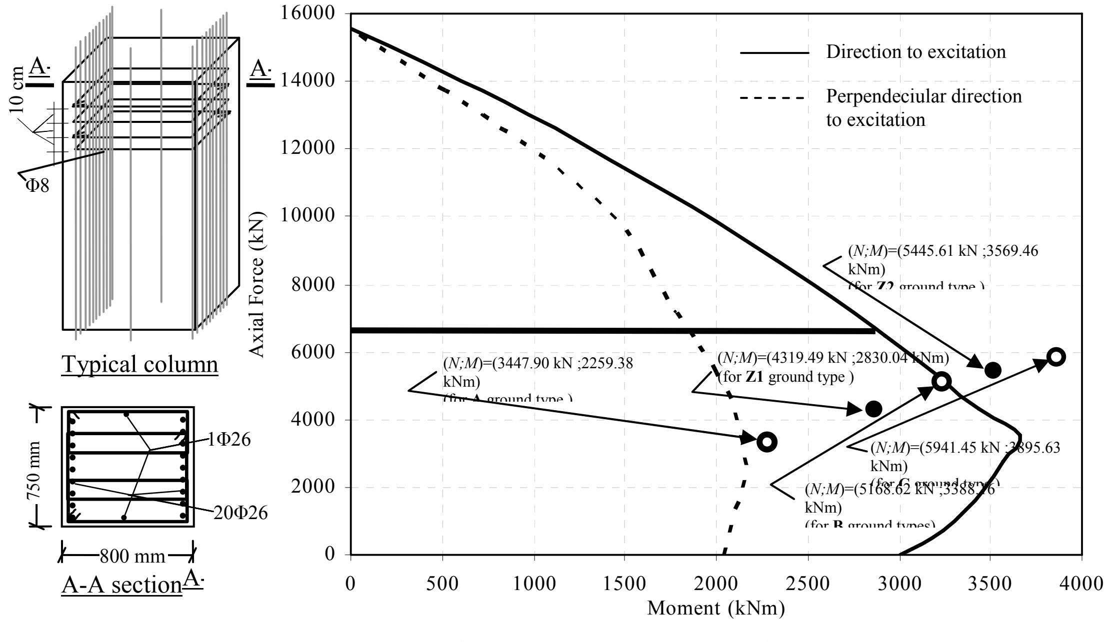


**Figure 7. Axial load-moment interaction diagram and estimated maximum reaction forces for a column.**

According to Turkish Codes [TS 500 2000, TEC-06] shear capacity of columns of the nominal ductility level ($V_{cap}$) may be estimated with the below equation:

$$V_{cap} \cong 0.8\left(0,65 f_{ctd} A_c (1+0,007\frac{N_d}{A_c})\right)+\frac{A_{sw} f_{ywd}\cdot d}{s} \qquad (1)$$

Where $A_c$ is gross section area of column, $f_{ctd}$ is design tensile strength of concrete, $N_d$ is factored axial force calculated under simultaneous action of vertical loads and seismic loads, $A_{sw}$ is section area of transverse reinforcement, $f_{ywd}$ is design yield strength of transverse reinforcement, $d$ is effective interval in the section area of column and $s$ is spacing of transverse reinforcement. The shear capacity of the columns was estimated equal to 1205 kN using the values of $A_c$ = 600,000 mm$^2$, $f_{ctd}$ =1.15 N/mm$^2$, $N_d \approx 5$ x106 N, $A_{sw}$ =301.5 mm$^2$, $f_{ywd}$ = 365 N/mm$^2$, $d$ =750 mm and $s$ =100 mm. The shear force was determined interval of 795~1915 kN for Z1 to Z4 and of 634~1740 kN for A to B from the response spectrum analysis. If this shear force and the above capacity of columns are compared, it would be seen that shear capacity was exceeded for Z3, Z4 and D ground types. Shear reinforcement however is adequate for the other ground types.

## 6. CONCLUSIONS

Although the corresponding ground types defined different codes have almost similar properties, only one defined in TEC-06 has given almost more results than the corresponding types defined in EC-8. However complex definitions are given by the TEC-06, the EC 8 essentially tries to represent ground types.

According to the results of analyses, ground types except for A, B, Z1 are not appropriate to build the elevated tanks in view of performance of supporting system. Furthermore, due to the limit drift defined in TEC-06 any ground types are not appropriate for the 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 1.seismic zone and for almost all ground types. This type of structure in Turkey should be redesigned considering new provisions and techniques.

## ACKNOWLEDGEMENTS

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