Comparison of a 10-Story Tunnel Formwork Structure with Different Soil Classes According to the 2018 Earthquake Regulations

Furkan Şahin*, Cüneyt Çelik**, Abdullah Çelik***

* Dr., Corresponding Author, Department of Civil Engineering, Nisantası University, Maslak Mahallesi, Taşyoncası Sokak, No: 1V ve No:1Y Bina Kodu: 34481742, 34398 Sarıyer / Istanbul, Türkiye. E-mail: furkan.sahin@nisantasi.edu.tr ORCID: 0000-0002-1661-5531

** MSc., Department of Civil Engineering, Nisantası University, Maslak Mahallesi, Taşyoncası Sokak, No: 1V ve No:1Y Bina Kodu: 34481742, 34398 Sarıyer / Istanbul, Türkiye. E-mail: cuneyt@biadagroup.com ORCID: 0009-0004-4747-5561

*** Dr., Department of Civil Engineering, Esenyurt University, Zafer, Adile Naşit Blv. No:1, 34510 Esenyurt / Istanbul, Türkiye. E-mail: abdullahcelik111@gmail.com ORCID : 0009-0006-7194-9864

Received: 13.07.2024 Accepted: 16.09.2024

Abstract - In this study, elastic design spectra were defined and compared for a 10-story tunnel formwork structure based on different soil types according to the new earthquake regulations implemented in March 2018. The tunnel formwork project used in the comparison was obtained from a static project author in Istanbul Esenyurt. Earthquake data affecting the design were selected for soil classes ZA, ZB, ZC, ZD, and ZE using coordinates 41.0114327 latitude and 28.676468 longitude from AFAD. Earthquake loads were applied in both X and Y directions to the building under consideration. The maximum relative floor displacements, overturning moments, and base shear forces in the structure were obtained using earthquake data for the ZC soil class.

Keywords: Tunnel form, Elastic design spectrum, TBDY 2018, Earthquake.

1. Introduction

During design, the seismic characteristics of the region's soil conditions where the building is located are crucially determined. Earthquake properties determined according to soil class are obtained from the Turkish earthquake hazard map prepared by the Disaster and Emergency Management Authority (AFAD). Based on AFAD's data for soil class, earthquake loads affecting the structure are calculated and applied. Turkish Building Earthquake Regulation (TBDY) classifies soil types into ZA, ZB, ZC, ZD, and ZE.

TBDY 2018 was officially published in the Official Gazette by the Ministry of Environment, Urbanization, and Climate on March 18, 2018, and came into force. This regulation outlines the minimum design and calculation rules that must be followed in the design of structures planned in earthquake-prone areas.

In TBDY, alongside fixed and moving loads, such as wind, snow, and ice loads, earthquake loads are calculated referring to TS498 and commonly accepted national and international regulations. The application of dynamic loads is more precisely defined within this framework.

TBYD 2018 considers two different approaches for evaluating and designing structures under earthquake loads. The first approach evaluates and designs buildings based on "capacity," while the second approach focuses on "deformation" under earthquake effects. Evaluation and design based on capacity include methods such as equivalent earthquake load, mode combination, and time domain solution methods specified in the regulations. For evaluations and designs involving deformation, non-linear pushover methods and non-linear calculation methods in the time domain are deemed appropriate.

The structural model created during building design must be considered in three dimensions. In this three-dimensional model, earthquake loads must be applied in three different directions: two perpendicular directions and one vertical direction parallel to the building plane. Guidelines in the regulations detail these assignments using graphs and tables. Previous regulations before TBDY 2018 emphasized earthquake loads assigned parallel to the structure more prominently, whereas the effects of vertical earthquake loads were less considered. However, TBDY 2018 has incorporated the effects of vertical earthquake loads on the structural system into regulations and specifications. According to TBDY 2018, in the static-reinforced concrete calculation of structures, the vertical earthquake effect is added to combinations.

Various design types have been developed to dissipate the energy generated by horizontal and vertical earthquake effects on buildings. With the implementation of TBDY 2018, additional earthquake walls are required for toothed floor types. One of the design types affecting buildings is the tunnel formwork system.

The tunnel formwork system was first used in France after World War II due to its low cost and labor usage. In Turkey, it was initially applied in the early 1980s. Initially, the goal in buildings constructed with tunnel formwork was rapid production and low cost. However, the use of tunnel formwork system buildings has evolved due to the casting of floor and wall concretes in place, the use of wall-like shear walls instead of walls, and the use of all vertical elements as load-bearing elements, exhibiting flawless behavior below the elastic limit during earthquakes. Due to the earthquake performance demonstrated by tunnel formwork structures, their use has increased, especially in the construction of multi-story buildings, both globally and in Turkey.

In structures formed with tunnel formwork, all vertical elements consist of shear walls, particularly to counteract shear forces arising from earthquake effects. In earthquake-based designs, structures built using the tunnel formwork system stand out depending on earthquake loads generated for different soil types. Considering the earthquake performance of tunnel formwork structures, their design according to ZA, ZB, ZC, ZD, and ZE soil classes becomes significantly important.

Literature Review

The construction systems of buildings made with tunnel formwork are relatively new compared to those made with traditional formwork systems. Despite the relatively good seismic performance of buildings constructed with tunnel formwork, academic studies on the production of this system in different soil classes have been limited. Recent research has focused particularly on various story heights.

In a study conducted by Yusuf Sümer (2003), two structures were designed with similar vertical load-bearing section systems: one using tunnel formwork and the other with shear-walled and framed structures at heights of 3, 5, 7, and 10 stories. The dynamic analyses of these structures were modeled using the Idestatik 4.0 Finite Element Program, and their results were compared. It was noted that due to the stiffness enhancement effect on reinforced concrete shear walls, buildings constructed with tunnel formwork are safer than those made with traditional formwork systems. He also highlighted that one of the advantages of tunnel formwork systems is their production in standard dimensions, minimizing errors that workers may cause. The ease and speed of production, as well as their ease of use in tall and wide spans, are also significant reasons for preferring this system [1].

Tunnel formwork systems are among the most preferred systems globally and in our country, and various studies related to tunnel formwork systems are documented in the literature [2].

In their study, Türkel and Ergen investigated the relationship between the height, floor area, and cost of high-rise reinforced concrete structures specifically produced with tunnel formwork. They examined structures built in Istanbul between 2006 and 2013, with heights ranging from 25 m to 142 m [3].

Akbaş and Çalışkan conducted an in-depth study on tunnel formwork systems, focusing on their applications, advantages, and disadvantages [4].

Another study conducted cost calculations for structures modeled with different numbers of stories and using the tunnel formwork system, along with reinforced concrete and static solutions. Cost calculations were made for both individual plot applications and regional applications. Additionally, the effects of unit cost, number of stories, and concrete grades were examined [5].

Sinan Api's master's thesis focused on the design, calculation of earthquake loads, and modeling using a finite element program for a 14-story reinforced concrete building to be constructed with a tunnel formwork system.

In a study conducted considering the 2007 earthquake regulation, the influence of different soil types and earthquake zones on internal forces and displacements of square-shaped buildings with similar horizontal stiffness in two directions, constructed with the tunnel formwork system, was compared [7].

2. Materials and Methods

2.1. Soil Classes and Other Variables According to TBDY 2018

Horizontal elastic design spectra were calculated for different soil classes using the methods specified in TBDY 2018. The location information of the structure under consideration was utilized to determine the design spectral acceleration coefficients in the earthquake regulation. Based on this location information, soil classification is shown in Table I. Parameters identified according to Table I, which indicate soil properties, were used to obtain coefficients for local soil effects in the design acceleration spectrum for the short period zone (Fs) and for the 1.0 second period (F1), as shown in Table 2 and Table 3 respectively.

Table 1. Local Soil Classification (TBDY 2018 Table16.1)

Local Ground Class	Ground Type	Average in the upper 30 m		
		(Vs)30 [m/s]	(N60)30 [pulse/30 cm]	(Cu)30 [kPa]
ZA	Solid hard rocks	>1500	-	-
ZB	Slightly segregated medium solid rocks	760-1500	-	-
ZC	Very tight layers of sand, gravel, and hard clay, or segregated, very fractured weak rocks	360-760	>50	>250
ZD	Medium-density sand, gravel or multi-layered clay layers	180-360	15-50	70-250
ZE	Profiles containing loose sand, gravel or soft-solid clay layers or a total of more than 3 meters of soft clay layer (Cu<25 kPa) satisfying PI>20 and W>40% conditions	<180	<15	<70
ZF	Soils requiring site-specific investigation and evaluation; **1)Soils requiring earthquake effect investigation and evaluation (liquefiable soils, highly sensitive clays, collapsible weak cement soils, etc.)** **2)Clays with a total thickness of more than 3 meters of peat and/or high organic content,** **3)Clays of high plasticity (PI>50) with a total thickness of more than 3 m,** **4)Very thick (<35m) soft or medium solid clays ZD ZE ZF**			

Table 2. Local Soil Effect Coefficient for short period (TBDY 2018 Table 2.1)

Local Ground Class	Local ground effect coefficiency for short period region F_S					
	$S_S \leq 0.25$	$S_S = 0.25$	$S_S = 0.50$	$S_S = 0.75$	$S_S = 1.00$	$S_S = 1.50$
ZA	0.8	0.8	0.8	0.8	0.8	0.8
ZB	0.9	0.9	0.9	0.9	0.9	0.9
ZC	1.3	1.3	1.2	1.2	1.2	1.2
ZD	1.6	1.4	1.2	1.1	1.0	1.0
ZE	2.4	1.7	1.3	1.1	0.9	0.8
ZF	Site-specific ground behavior analysis will be performed.					

Table 3. Local Soil Effect Coefficient for 1second period (TBDY 2018 Table 2.2)

Local Ground Class	**Local ground effect coefficiency for 1 second period F_1**					
	$S_1 \leq 0.10$	**$S_1 = 0.20$**	**$S_1 = 0.30$**	**$S_1 = 0.40$**	**$S_1 = 0.50$**	**$S_1 = 0.60$**
ZA	0.8	0.8	0.8	0.8	0.8	0.8
ZB	0.8	0.8	0.8	0.8	0.8	0.8
ZC	1.5	1.5	1.5	1.5	1.5	1.4
ZD	2.4	2.2	2.0	1.9	1.8	1.7
ZE	4.2	3.3	2.8	2.4	2.2	2.0
ZF	Site-specific ground behavior analysis will be performed.					

The obtained local soil effect coefficients for the short period and 1.0 second period design spectral acceleration coefficients (SDS and SD1) were derived from the data available at tdth.afad.gov.tr, a website provided by AFAD. The design was conducted according to the formulas:

SDS=SS x FS II.I

SD1=S1 x F1 II.II

where SS and S1 are the spectral acceleration values obtained from the AFAD website.

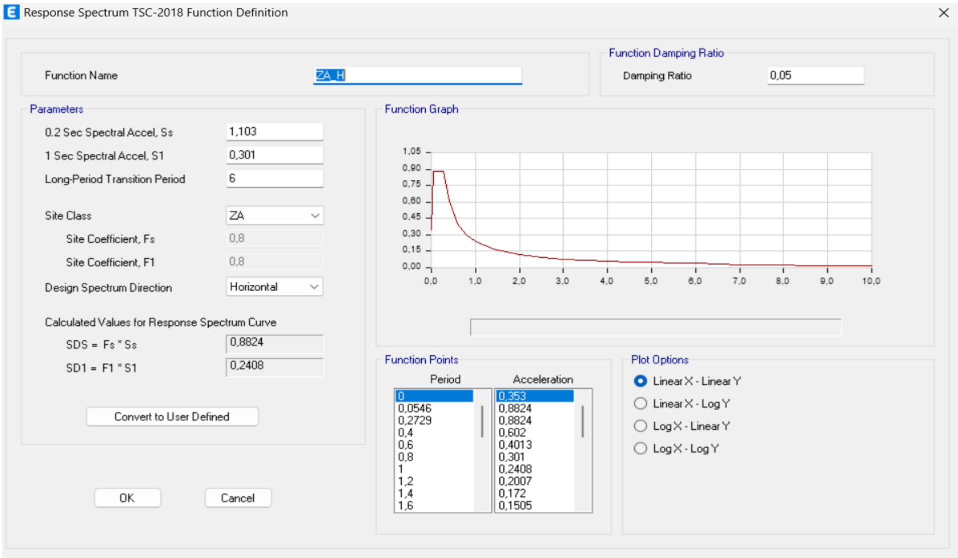
For the 10-story tunnel structure located at coordinates 41.0114327 latitude and 28.676468 longitude, local soil effect coefficients and map spectral acceleration coefficients were calculated for 5 different soil classes and are presented in Table IV.

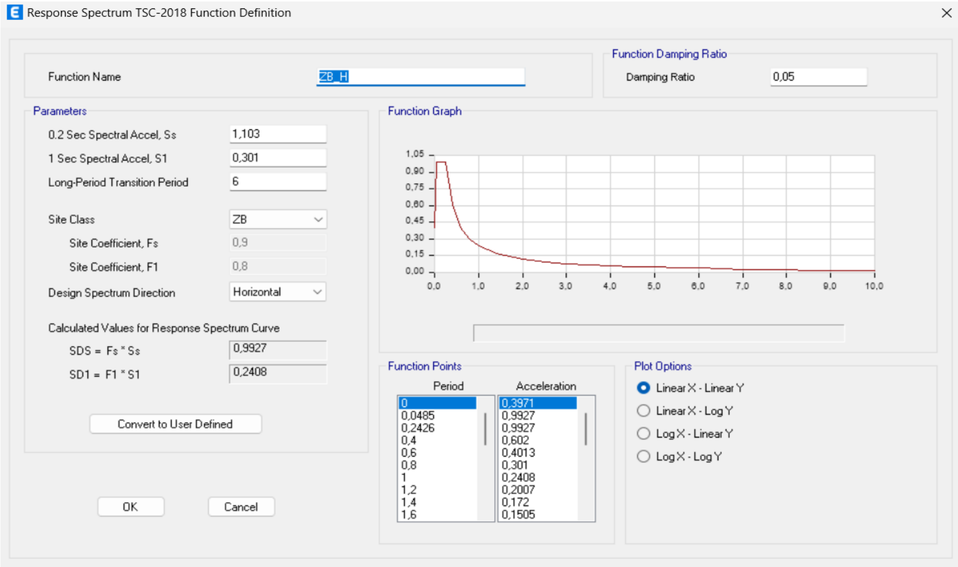
Table 4. Spectrum Acceleration Coefficients Obtained for Different Soil Classes

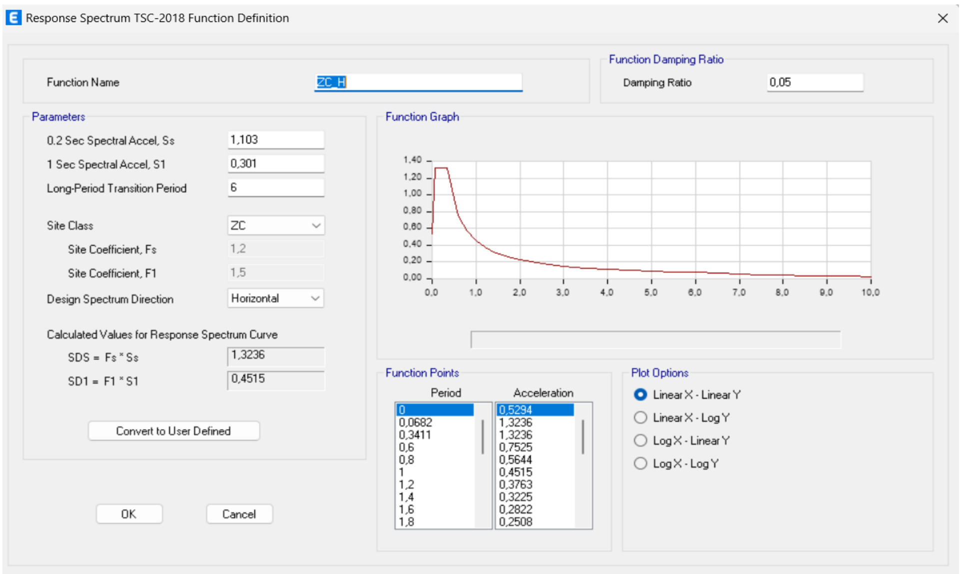
Local Ground Class	S_S	S_1	F_S	F_1	SDS	SD1
ZA	1,103	0,301	0,80	0,80	0,8824	0,2408
ZB	1,103	0,301	0,90	0,80	0,9927	0,2408
ZC	1,103	0,301	1,20	1,50	1,3236	0,4515
ZD	1,103	0,301	1,06	2,00	1,1679	0,6017
ZE	1,103	0,301	1,02	2,80	1,1224	0,8416

2.2. Parameters Defined as Spectra in ETABS Program

The spectral acceleration coefficients obtained for each soil class were defined in the response spectrum interface of the ETABS Finite Element Program. The elastic design spectra defined for different soil classes in ETABS Finite Element Program are illustrated in Figure 1.


Response Spectrum TSC-2018 Function Definition
Function Name
ZA_H
Function Damping Ratio
Damping Ratio
0,05
Parameters
0.2 Sec Spectral Accel, Ss
1,103
1 Sec Spectral Accel, S1
0,301
Long-Period Transition Period
6
Site Class
ZA
Site Coefficient, Fs
0,8
Site Coefficient, F1
0,8
Design Spectrum Direction
Horizontal
Calculated Values for Response Spectrum Curve
SDS = Fs * Ss
0,8824
SD1 = F1 * S1
0,2408
Convert to User Defined
OK
Cancel
Function Graph
Function Points
Period
Acceleration
Plot Options
Linear X - Linear Y
Linear X - Log Y
Log X - Linear Y
Log X - Log Y


Response Spectrum TSC-2018 Function Definition
Function Name
ZB_H
Function Damping Ratio
Damping Ratio
0,05
Parameters
0.2 Sec Spectral Accel, Ss
1,103
1 Sec Spectral Accel, S1
0,301
Long-Period Transition Period
6
Site Class
ZB
Site Coefficient, Fs
0,9
Site Coefficient, F1
0,8
Design Spectrum Direction
Horizontal
Calculated Values for Response Spectrum Curve
SDS = Fs * Ss
0,9927
SD1 = F1 * S1
0,2408
Convert to User Defined
OK
Cancel
Function Graph
Function Points
Period
Acceleration
Plot Options
Linear X - Linear Y
Linear X - Log Y
Log X - Linear Y
Log X - Log Y


Response Spectrum TSC-2018 Function Definition
Function Name
ZC_H
Function Damping Ratio
Damping Ratio
0,05
Parameters
0.2 Sec Spectral Accel, Ss
1,103
1 Sec Spectral Accel, S1
0,301
Long-Period Transition Period
6
Site Class
ZC
Site Coefficient, Fs
1,2
Site Coefficient, F1
1,5
Design Spectrum Direction
Horizontal
Calculated Values for Response Spectrum Curve
SDS = Fs * Ss
1,3236
SD1 = F1 * S1
0,4515
Convert to User Defined
OK
Cancel
Function Graph
Function Points
Period
Acceleration
Plot Options
Linear X - Linear Y
Linear X - Log Y
Log X - Linear Y
Log X - Log Y

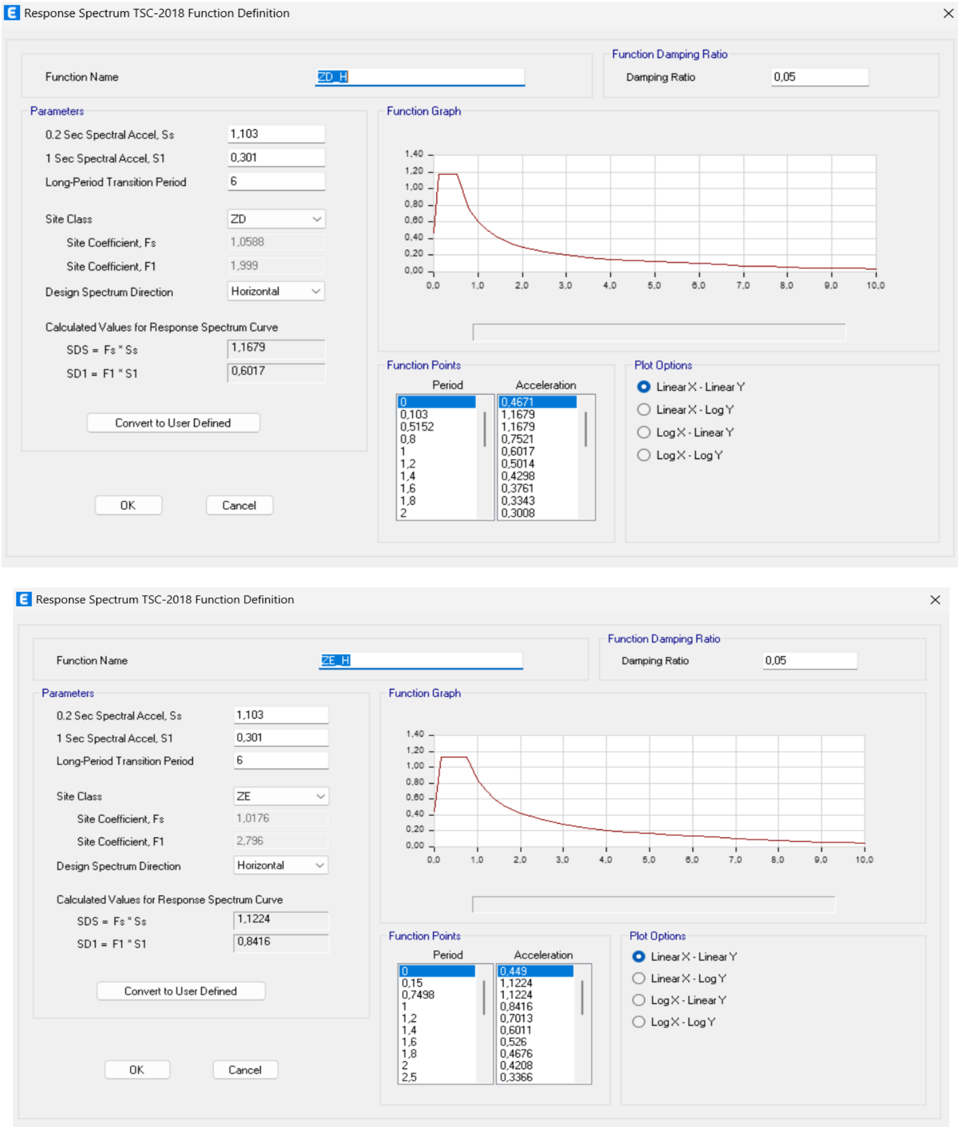


Figure 1. Horizontal elastic design response spectra defined for different soil classes

2.3. Model Creation and Load Definitions

In the analyzed model, a standard thickness of 30 cm was chosen for wall sections (shear walls), and the floor thickness was uniformly selected as 12 cm across all floors. The structure was modeled to be 11 stories tall, including the stair tower. The story heights are uniformly 3 meters for all levels. Span lengths and loads assigned to the structure were obtained from TS 498 (Load values to be used in the dimensioning of building elements). The assigned loads and their magnitudes are shown in Table 5. The structure base was defined as fixed, with no foundation assignment. The structural layout and axis dimensions of the building are illustrated in Figure 2. The ETABS Finite Element Program's plan and three-dimensional view of the structure are shown in Figure 3.

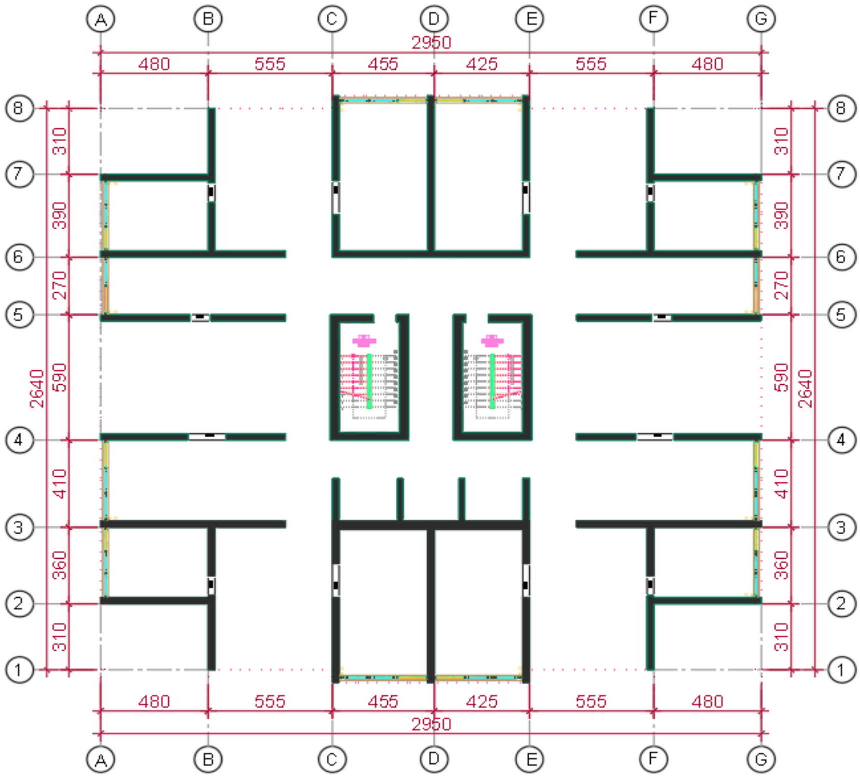


Figure 2. Mold Plan and Axle Dimensions of the Analysis Model

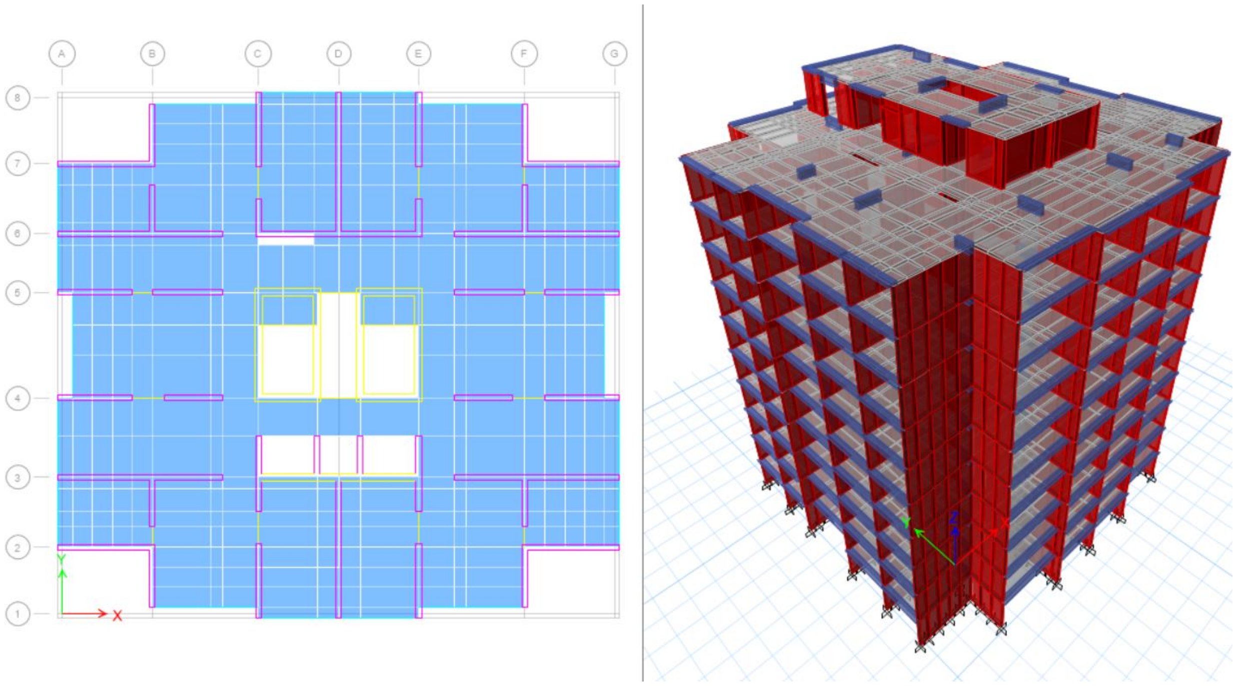


Figure 3. ETABS Plan and Three-Dimensional Visualization of the Analysis Model

Table 5. Loads Acting on the Structure

Load Type	Symbol	Unit	Load
Self-Weight	G	kN	Software-defined
Live Load (floor)	Q	kN	2
Live Load (roof)	Q	kN	1,5
Dead Load	Wall	kN/m	2
Dead Load	Cover	kN/m2	2,5

3. Results and Discussion

3.1. Conclusion

In this study, the relative story drifts, base shear forces, and overturning moments of a 10-story tunnel formwork structure were compared based on different soil classes. Since the earthquake loads are higher in the X direction, comparisons were made only for the earthquake force assigned in the X direction. The seismic conditions for the structure according to local soil classes ZA, ZB, ZC, ZD, and ZE are named as E(ZA)X, E(ZB)X, E(ZC)X, E(ZD)X, and E(ZE)X, respectively.

The maximum story displacements and drifts of the structure under different soil conditions are shared in Table 6. The maximum story displacements occur on the tenth floor, with the highest displacement being 54.73 mm for soil class ZC. The maximum drift, with a dimensionless value of 0.00225, occurs on the seventh floor, also for soil class ZC. The lowest story displacement and drift were obtained in the analysis for soil class ZA.

Table 6. Maximum Story Displacements and Drifts for Different Soil Conditions

E(ZA)X					E(ZB)X				
TABLE: Max Story Displacements and Drifts					TABLE: Max Story Displacements and Drifts				
Story	Elevation	Location	Displacement	Drifts	Story	Elevation	Location	Displacement	Drifts
	m		mm			m		mm	
STORY11	33,00	Top	32,26	0,00109	STORY11	33,00	Top	33,21	0,00112
STORY10	30,00	Top	**32,39**	0,00125	STORY10	30,00	Top	**33,33**	0,00128
STORY9	27,00	Top	28,65	0,00130	STORY9	27,00	Top	29,48	0,00134
STORY8	24,00	Top	24,75	0,00132	STORY8	24,00	Top	25,47	0,00136
STORY7	21,00	Top	20,79	**0,00133**	STORY7	21,00	Top	21,39	**0,00137**
STORY6	18,00	Top	16,80	0,00131	STORY6	18,00	Top	17,28	0,00134
STORY5	15,00	Top	12,89	0,00124	STORY5	15,00	Top	13,26	0,00127
STORY4	12,00	Top	9,18	0,00112	STORY4	12,00	Top	9,44	0,00115
STORY3	9,00	Top	5,84	0,00093	STORY3	9,00	Top	6,01	0,00096
STORY2	6,00	Top	3,10	0,00068	STORY2	6,00	Top	3,19	0,00070
STORY1	3,00	Top	1,07	0,00036	STORY1	3,00	Top	1,11	0,00037
BASE	0,00	Top	0,00	0,00000	BASE	0,00	Top	0,00	0,00000

E(ZC)X				
TABLE: Max Story Displacements and Drifts				
Story	Elevation	Location	Displacement	Drifts
	m		mm	
STORY11	33,00	Top	54,34	0,00185
STORY10	30,00	Top	**54,73**	0,00211
STORY9	27,00	Top	48,41	0,00220
STORY8	24,00	Top	41,82	0,00223
STORY7	21,00	Top	35,13	**0,00225**
STORY6	18,00	Top	28,39	0,00220
STORY5	15,00	Top	21,78	0,00209
STORY4	12,00	Top	15,51	0,00188
STORY3	9,00	Top	9,86	0,00157
STORY2	6,00	Top	5,23	0,00115
STORY1	3,00	Top	1,81	0,00061
BASE	0,00	Top	0,00	0,00000

E(ZD)X				
TABLE: Max Story Displacements and Drifts				
Story	Elevation	Location	Displacement	Drifts
	m		mm	
STORY11	33,00	Top	47,94	0,00166
STORY10	30,00	Top	**48,47**	0,00187
STORY9	27,00	Top	42,88	0,00195
STORY8	24,00	Top	37,05	0,00198
STORY7	21,00	Top	31,12	**0,00199**
STORY6	18,00	Top	25,15	0,00195
STORY5	15,00	Top	19,29	0,00185
STORY4	12,00	Top	13,74	0,00167
STORY3	9,00	Top	8,74	0,00139
STORY2	6,00	Top	4,63	0,00102
STORY1	3,00	Top	1,61	0,00054
BASE	0,00	Top	0,00	0,00000

E(ZE)X				
TABLE: Max Story Displacements and Drifts				
Story	Elevation	Location	Displacement	Drifts
	m		mm	
STORY11	33,00	Top	46,08	0,00159
STORY10	30,00	Top	**46,59**	0,00179
STORY9	27,00	Top	41,21	0,00187
STORY8	24,00	Top	35,61	0,00190
STORY7	21,00	Top	29,91	**0,00191**
STORY6	18,00	Top	24,17	0,00188
STORY5	15,00	Top	18,54	0,00178
STORY4	12,00	Top	13,20	0,00160
STORY3	9,00	Top	8,40	0,00134
STORY2	6,00	Top	4,45	0,00098
STORY1	3,00	Top	1,54	0,00051
BASE	0,00	Top	0,00	0,00000

The base shear forces obtained under different soil conditions for the 10-story tunnel formwork structure are shown in Figures 4, 5, 6, 7, and 8. When examining the figures for story shear forces, the maximum base shear forces are found to be 9380.36 tonf for soil class ZC (Figure 4), 8280.36 tonf for soil class ZD (Figure 5), 7958.06 tonf for soil class ZE (Figure 6), 5727.51 tonf for soil class ZB (Figure 7), and 5565.38 tonf for soil class ZA (Figure 8). The ratio of the base shear force due to the earthquake effect for soil class ZC to the base shear force for soil class ZA (5565x100/9380=1.68) reaches up to 70%.

E(ZA)X			
TABLE: Max Story Shears			
Story	Elevation	Location	X-Dir
	m		tonf
STORY11	33,0	Bottom	280,44
STORY10	30,0	Bottom	1259,51
STORY9	27,0	Bottom	2266,76
STORY8	24,0	Bottom	3135,87
STORY7	21,0	Bottom	3864,07
STORY6	18,0	Bottom	4451,06
STORY5	15,0	Bottom	4900,32
STORY4	12,0	Bottom	5219,76
STORY3	9,0	Bottom	5423,77
STORY2	6,0	Bottom	5530,25
STORY1	3,0	Bottom	**5565,38**
BASE	0,0	Bottom	0,00

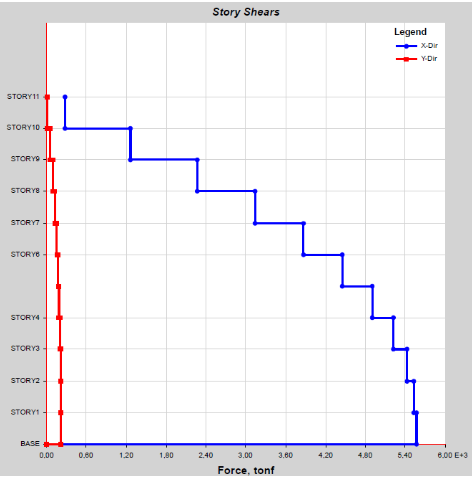


Figure 4. Maximum Story Shear Forces for Soil ZA Class

E(ZB)X			
TABLE: Max Story Shears			
Story	**Elevation**	**Location**	**X-Dir**
	m		tonf
STORY11	33,0	Bottom	288,60
STORY10	30,0	Bottom	1296,19
STORY9	27,0	Bottom	2332,80
STORY8	24,0	Bottom	3227,23
STORY7	21,0	Bottom	3976,66
STORY6	18,0	Bottom	4580,77
STORY5	15,0	Bottom	5043,13
STORY4	12,0	Bottom	5371,89
STORY3	9,0	Bottom	5581,87
STORY2	6,0	Bottom	5691,46
STORY1	3,0	Bottom	**5727,61**
BASE	0,0	Bottom	0,00

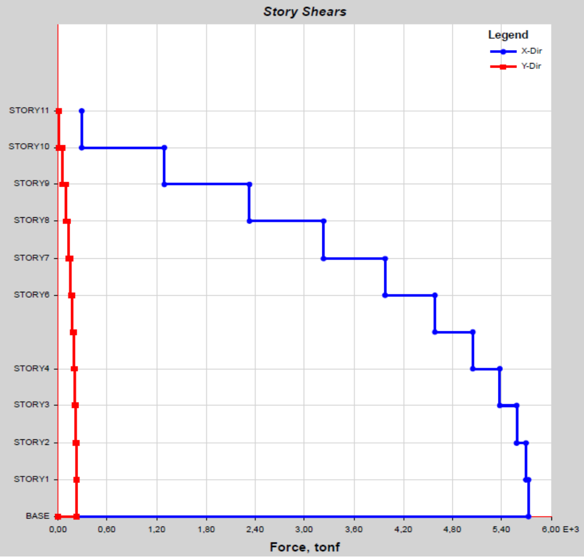


Figure 5. Maximum Story Shear Forces for Soil Class ZB

E(ZC)X			
TABLE: Max Story Shears			
Story	**Elevation**	**Location**	**X-Dir**
	m		tonf
STORY11	33,0	Bottom	472,95
STORY10	30,0	Bottom	2123,17
STORY9	27,0	Bottom	3820,86
STORY8	24,0	Bottom	5285,69
STORY7	21,0	Bottom	6513,03
STORY6	18,0	Bottom	7502,36
STORY5	15,0	Bottom	8259,53
STORY4	12,0	Bottom	8797,90
STORY3	9,0	Bottom	9141,72
STORY2	6,0	Bottom	9321,16
STORY1	3,0	Bottom	**9380,36**
BASE	0,0	Bottom	0,00

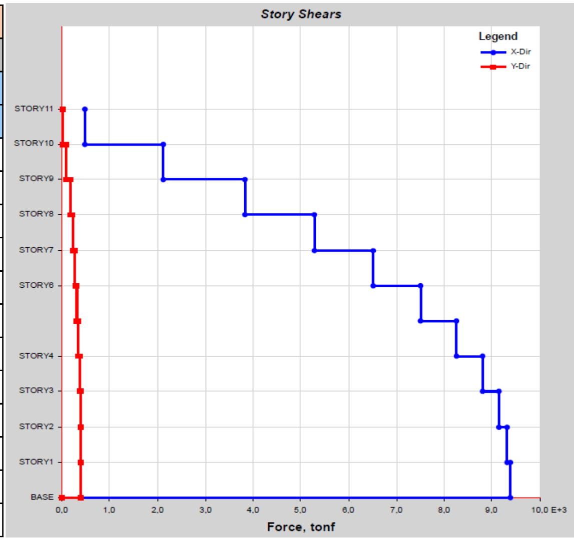


Figure 6. Maximum Story Shear Forces for Soil Class ZC

E(ZD)X			
TABLE: Max Story Shears			
Story	**Elevation**	**Location**	**X-Dir**
	m		tonf
STORY11	33,0	Bottom	417,73
STORY10	30,0	Bottom	1874,43
STORY9	27,0	Bottom	3373,00
STORY8	24,0	Bottom	4666,02
STORY7	21,0	Bottom	5749,40
STORY6	18,0	Bottom	6622,69
STORY5	15,0	Bottom	7291,04
STORY4	12,0	Bottom	7766,24
STORY3	9,0	Bottom	8069,72
STORY2	6,0	Bottom	8228,11
STORY1	3,0	Bottom	**8280,36**
BASE	0,0	Bottom	0,00

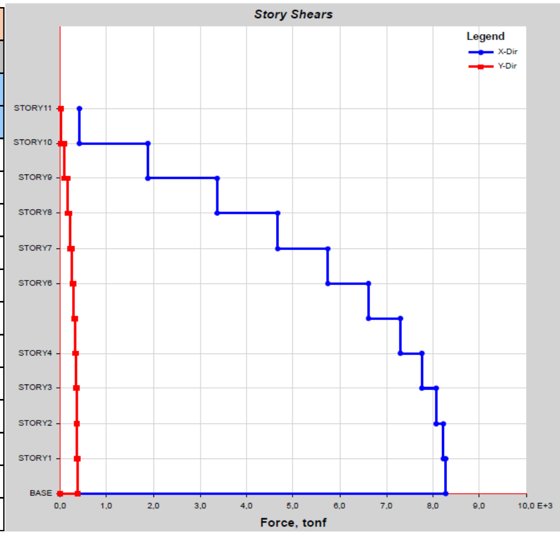


Figure 7. Maximum Story Shear Forces for Soil Class ZD

E(ZE)X			
TABLE: Max Story Shears			
Story	Elevation	Location	X-Dir
	m		tonf
STORY11	33	Bottom	401,46
STORY10	30	Bottom	1801,49
STORY9	27	Bottom	3241,76
STORY8	24	Bottom	4484,47
STORY7	21	Bottom	5525,69
STORY6	18	Bottom	6364,98
STORY5	15	Bottom	7007,30
STORY4	12	Bottom	7463,99
STORY3	9	Bottom	7755,64
STORY2	6	Bottom	7907,85
STORY1	3	Bottom	**7958,06**
BASE	0	Bottom	0,00

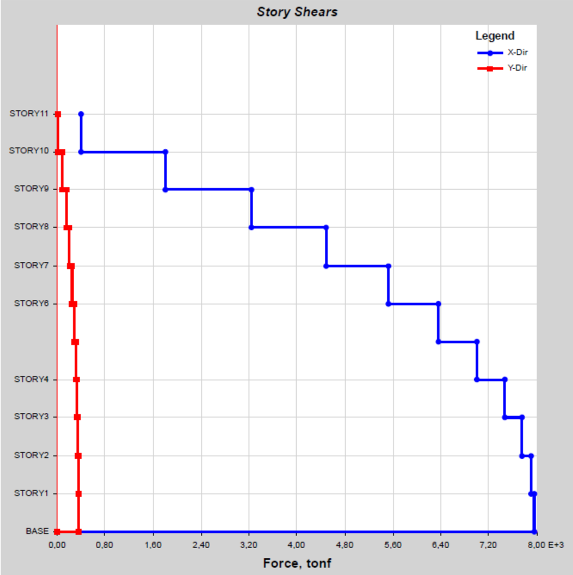


Figure 8. Maximum Story Shear Forces for Soil Class ZE

Another aspect examined in the study is the overturning moment of the 10-story tunnel formwork structure. The overturning moments obtained from the earthquakes assigned according to different soil conditions are shown in Figures 9, 10, 11, 12, and 13. Similar to the story shear forces and relative story drifts, the largest overturning moment was obtained in the design for soil class ZC, with 215780 tonf m. The next highest overturning moment was obtained in the design for soil class ZD, with 190479 tonf m. The maximum overturning moment for the design with soil class ZE was 183067 tonf m. The maximum overturning moment for the design with soil class ZA was 131751 tonf m, and for soil class ZB, it was 128020 tonf m. The ratio of the maximum overturning moment for soil class ZC to the maximum overturning moment for soil class ZA (128020x100/215780=59) is found to be 59%. The analysis for all soil conditions shows that the percentage of the overturning moment increases from the top floor to the bottom floor. The percentage change between floors is shown in Table 7.

E(ZA)X			
TABLE: Max Story Overturning Moments			
Story	Elevation	Location	Y-Dir
	m		tonf-m
STORY11	33,0	Top	41,32
STORY10	30,0	Top	1162,99
STORY9	27,0	Top	5253,39
STORY8	24,0	Top	12354,88
STORY7	21,0	Top	22055,25
STORY6	18,0	Top	33920,59
STORY5	15,0	Top	47523,64
STORY4	12,0	Top	62440,98
STORY3	9,0	Top	78272,68
STORY2	6,0	Top	94667,36
STORY1	3,0	Top	111324,08
BASE	0,0	Top	**128020,87**

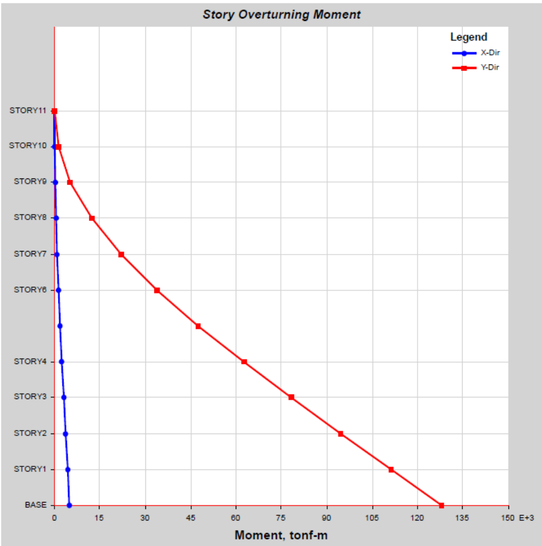


Figure 9. Maximum Story Overturning Moments for Soil Class ZA

E(ZB)X			
TABLE: Max Story Overturning Moments			
Story	**Elevation**	**Location**	**Y-Dir**
	m		tonf-m
STORY11	33,0	Top	42,56
STORY10	30,0	Top	1200,40
STORY9	27,0	Top	5410,43
STORY8	24,0	Top	12718,21
STORY7	21,0	Top	22701,17
STORY6	18,0	Top	34911,63
STORY5	15,0	Top	48910,74
STORY4	12,0	Top	64262,28
STORY3	9,0	Top	80554,95
STORY2	6,0	Top	97427,01
STORY1	3,0	Top	114568,81
BASE	0,0	Top	**131751,94**

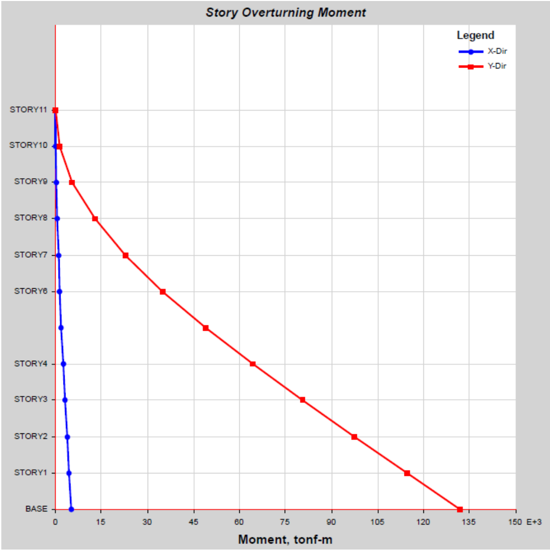


Figure 10. Maximum Story Overturning Moments for Soil Class ZB

E(ZC)X			
TABLE: Max Story Overturning Moments			
Story	**Elevation**	**Location**	**Y-Dir**
	m		tonf-m
STORY11	33,0	Top	69,52
STORY10	30,0	Top	1954,51
STORY9	27,0	Top	8848,68
STORY8	24,0	Top	20819,84
STORY7	21,0	Top	37170,35
STORY6	18,0	Top	57170,75
STORY5	15,0	Top	80099,44
STORY4	12,0	Top	105243,60
STORY3	9,0	Top	131928,66
STORY2	6,0	Top	159562,54
STORY1	3,0	Top	187637,96
BASE	0,0	Top	**215780,82**

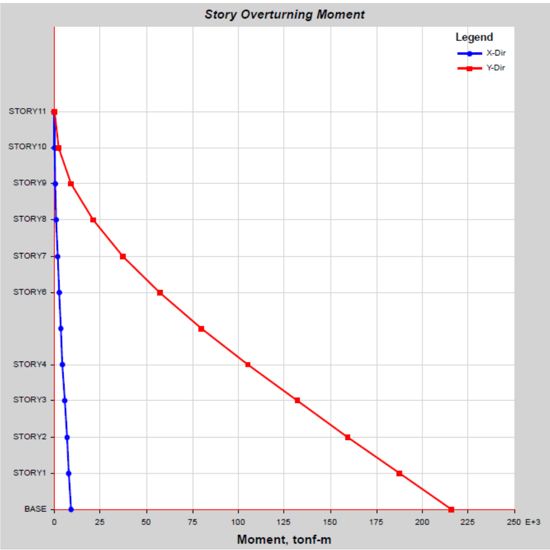


Figure 11. Maximum Story Overturning Moments for Soil Class ZC

E(ZD)X			
TABLE: Max Story Overturning Moments			
Story	**Elevation**	**Location**	**Y-Dir**
	m		tonf-m
STORY11	33,0	Top	61,30
STORY10	30,0	Top	1723,03
STORY9	27,0	Top	7808,67
STORY8	24,0	Top	18377,07
STORY7	21,0	Top	32810,63
STORY6	18,0	Top	50466,51
STORY5	15,0	Top	70706,91
STORY4	12,0	Top	92903,09
STORY3	9,0	Top	116459,32
STORY2	6,0	Top	140853,08
STORY1	3,0	Top	165636,54
BASE	0,0	Top	**190479,49**

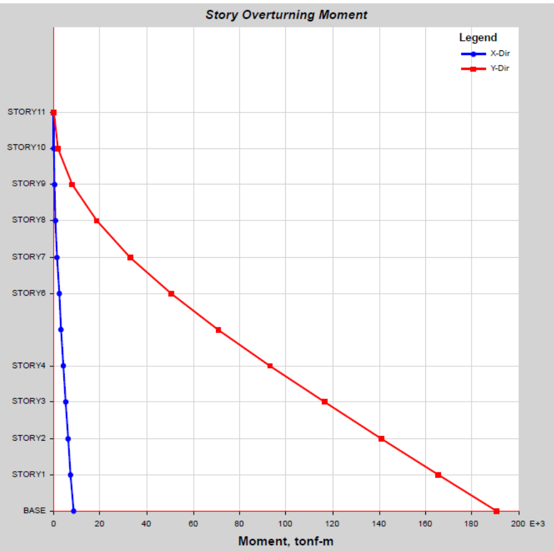


Figure 12. Maximum Story Overturning Moments for Soil Class ZD

E(ZE)X			
TABLE: Max Story Overturning Moments			
Story	**Elevation**	**Location**	**Y-Dir**
	m		tonf-m
STORY11	33,0	Top	58,87
STORY10	30,0	Top	1650,36
STORY9	27,0	Top	7498,65
STORY8	24,0	Top	17656,83
STORY7	21,0	Top	31528,96
STORY6	18,0	Top	48498,83
STORY5	15,0	Top	67952,21
STORY4	12,0	Top	89285,51
STORY3	9,0	Top	111925,75
STORY2	6,0	Top	135370,88
STORY1	3,0	Top	159190,44
BASE	0,0	Top	**183067,02**

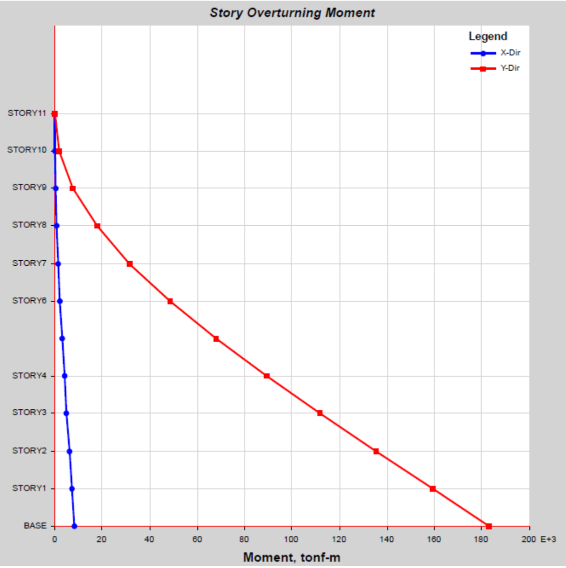


Figure 13. Maximum Story Overturning Moments for Soil Class ZE

Table 7. Percentage Change in Overturning Moment Between Floors

Max Story Overturning Moments		
Story	**Y-Dir**	(%)
	tonf-m	percent
STORY11	41,32	0,00
STORY10	1162,99	3,55
STORY9	5253,39	22,14
STORY8	12354,88	42,52
STORY7	22055,25	56,02
STORY6	33920,59	65,02
STORY5	47523,64	71,38
STORY4	62440,98	76,11
STORY3	78272,68	79,77
STORY2	94667,36	82,68
STORY1	111324,08	85,04
BASE	**128020,87**	86,96

3.2. Discussion

In this study, the relative story drifts, story shear forces, and maximum story overturning moments of a 10-story tunnel formwork structure were compared based on different soil classes. The structure under study is symmetrical with respect to the y-axis and has shear wall thicknesses of 25 cm. The slab thicknesses were chosen to be equal across all floors, at 15 cm. Horizontal elastic design spectra defined for soil classes ZA, ZB, ZC, ZD, and ZE in the TBDY 2018 regulation were applied to the structure, and the story displacements, relative story drifts, story shear forces, and story overturning moments were examined.

The largest story displacements and relative story drifts in the structure were obtained for soil class ZC, while the smallest story displacements and relative story drifts were obtained for soil class ZA. Similarly, the maximum values for story shear forces and story overturning moments were also observed in the soil class ZC.

When the maximum values obtained according to soil classes are examined, they are ranked from the most unfavorable to the most favorable as ZC, ZD, ZE, ZB, and ZA.

The results obtained in this study for a tunnel formwork structure are expected to be similar for other structural system elements. It is recommended that future studies examine structures with different structural systems. Additionally, the values obtained are expected to vary for tunnel formwork structures with different heights and shear wall thicknesses.

References

[1]. Sümer, Y. (2003). Optimum Structural System Selection in Earthquake Resistant Building Design. Sakarya University Journal of Science, 7(3), 43-50.

[2]. Karaca, H., Optimization Research with Analysis of Direct Costs in Ten Storey Residential Buildings Designed with Tunnel Formwork Construction System and Traditional Construction System. Master's Thesis, Y.T.Ü., Institute of Science and Technology, Istanbul, 1994.

[3]. Türkel, E. B., & Ergen, E. (2016). The Relationship Between Height and Floor Area and Cost in Reinforced Concrete High-Rise Structures Using Tunnel Formwork System. Pamukkale University Journal of Engineering Sciences, 22(6), 418-426.

[4]. Akbaş, A., Çalışkan, Ö. (2023). Tunnel Formwork System, 2nd Internationaş Conference on Engineering, April 4-6, 2023, Konya, Turkey.

[5]. Harmankaya, Z., Y. (2011). The Effects of Number of Storeys and Concrete Class on the Cost of Multi-storey Building Production Applied with Tunnel Formwork in Turkey. Gazi University Journal of Engineering and Architecture Faculty, Volume 26, No:2, 427-433.

[6]. Api, S., (2005). Project Design of 14 Storey Reinforced Concrete Building to be Constructed Using Tunnel Formwork. Istanbul Technical University Institute of Science and Technology, Published Master's Thesis, Istanbul.

[7]. Bulgu, N. N., (2007). Investigation of the Behavior of Buildings Constructed with Tunnel Formwork under Earthquake Loads. Istanbul Technical University Institute of Science and Technology, Published Master's Thesis, Istanbul.