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Effects of local soil class on dynamic behavior of masonry structures

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Abstract – Masonry structures are a pervasive construction type in our country, particularly in rural and historical settlement areas, due to their economic and straightforward construction. Nevertheless, the seismic resistance of such structures is generally low and is significantly affected by soil properties. This study investigates the effects of different soil classes on the dynamic behaviour of a multi-storey masonry structure. To this end, a prototype three-storey masonry structure was modelled in the SAP2000 program, and modal analysis and time history analyses were conducted for five distinct soil classes as defined in TBDY 2018. The modal analysis yielded the first natural period of the structure as 0.084 s. The time history analysis results demonstrated that the soil class had a significant effect on the structural responses. While the ZC soil class produced the highest base shear force, displacement and stress values, the ZE soil class produced the lowest values. The findings indicate the effect of soil conditions on the structural behaviour and emphasise the necessity of considering the soil-structure interaction in the earthquake design of masonry structures.

Keywords –Masonry Structures, Seismic Behavior, Time History Analysis, Finite Element Modeling, SAP2000, Soil Class.

I. INTRODUCTION

Earthquakes are natural disasters that pose serious risks, especially in areas where masonry-type structures are densely located. These structures are generally vulnerable to moderate and high-intensity tremors [1], [2].

Masonry structures are utilised extensively across the globe due to their economic nature, ease of construction and effective thermal insulation. Masonry buildings represent a substantial proportion of the global building stock, particularly in developing countries and historical settlements. However, these structures exhibit low seismic resistance, rendering them highly vulnerable to earthquake effects due to their brittle behaviour, limited tensile strength, and constrained energy absorption capacity. Consequently, the examination of the seismic behaviour of masonry structures represents a pivotal research area in earthquake engineering.

The dynamic behaviour of masonry structures is characterised by a complex structure that is contingent on numerous factors, including material properties, geometric configuration, floor plan symmetry, and boundary conditions. In contrast to reinforced concrete and steel structures, masonry structures exhibit a lack of ductility and are prone to sudden collapse. The response of masonry structures to seismic events is further influenced by the characteristics of ground motion and the geotechnical conditions of the site. The interaction between soil and structure is a pivotal factor in altering the seismic demand on a structure, underscoring the necessity for ground effects to be incorporated into structural analyses.

There are many studies in the literature examining the dynamic behavior of masonry structures. Zucca et al. [3] evaluated the seismic performance of a historic masonry building damaged during the 2016 Centro Italia earthquake and presented reinforcement recommendations. They studied the seismic behavior of the structure using comprehensive analysis and modeling techniques. As a result of this study, they found that the use of structural injection, mortar renewal and steel connection elements as reinforcement strategies significantly increased the seismic capacity of the structure. In their study, Angelis et al [4]. comprehensively addressed the seismic fragility assessment of a monumental masonry structure. A detailed examination was conducted of the geometrical features, material composition, current damage status and structural irregularities of the structure. Within the scope of the seismic fragility analysis, they evaluated the seismic performance of the structure using both linear and nonlinear analysis methods. The study's findings revealed significant vulnerabilities in specific areas of the structure, which were susceptible to collapse under high seismic pressures.

Usta et al. [5] conducted a numerical investigation into the seismic vulnerability of unreinforced masonry structures, focusing on how different framing materials affect seismic performance. Utilizing SAP2000 V23 [6], the study modeled a two-story unreinforced masonry building subjected to seismic loads to evaluate the effects of various framing materials on displacement, stress patterns, and base shear forces. The findings demonstrated that material selection plays a critical role in determining the structural resilience and overall seismic response of unreinforced masonry buildings. Kapoor et al. [7] conducted a study focused on calibrating finite element models for historical masonry structures, applying their approach to a culturally significant heritage building. The research incorporated both destructive and non-destructive testing methods to validate numerical simulations and evaluate structural behavior. Through comparative analysis of various modeling techniques, the study assessed the precision of finite element models in predicting the seismic performance of historical masonry buildings. The results emphasize the critical role of accurate material characterization and model calibration in improving the dependability of structural evaluations and ensuring realistic seismic response predictions.

Özbay and Karapınar [8] assessed 213 masonry structures within the region employing a rapid scanning methodology to generate a regional seismic risk distribution map. By calculating performance scores for each structure, the study identified buildings most vulnerable to seismic activity. The evaluated structures were categorized based on their performance scores into four distinct risk levels: high, medium, low, and very low. This classification enabled the researchers to prioritize buildings requiring urgent intervention, providing valuable insights for regional earthquake risk management and mitigation strategies. Amani et al. [9] conducted a comparative study of the 1998, 2007 and 2018 Turkish Earthquake Codes [10], [11], [12] on a sample masonry building. In this study, they evaluated the effects of changes in the codes on the seismic performance of the structure. For this purpose, they performed analyzes according to different codes on the same structural model and compared the results. They evaluated the behavior of the structure under earthquake loads by examining the stress and displacement values of the load-bearing system elements. As a result of the study, they stated that the changes made in the 2018 code in particular increased the safety level of the structure and provided a more accurate performance assessment.

Akgül and Doğan [13] conducted a study in which they evaluated the earthquake risks of typical masonry buildings in the Altındağ/Ankara region according to the 2018 Turkish Building Earthquake Code . For this purpose, they created 5 masonry building models with different floors. They performed earthquake risk analyses on these models and evaluated the results within the scope of TBDY 2018. As a result of this study, they determined that the most important parameters in determining the weakest floor critically against earthquakes are the change in material properties on the floors, the percentage of voids in the walls and the amount of walls surrounded by soil in the basement. Çoban and Başaran [14] evaluated the performance of 10 existing masonry buildings, which were designed and constructed according to 2007 Turkish Earthquake Code within the borders of Afyonkarahisar province, according to the TBDY18 regulation criteria. As a result of the performance analysis they conducted in the STA4CAD program, they stated that although the wall and mortar strengths were increased, the performance levels of most models were in the collapse zone because the design criteria specified in TBDY18 were not fully complied with.

A substantial body of research has demonstrated that local soil conditions have the capacity to amplify earthquake waves, thereby exerting a significant influence on the dynamic behaviour of structures. In light of this, contemporary earthquake codes – such as the Turkish Building Earthquake Code (TBDY, 2018) – have been developed to account for these effects by introducing spectral acceleration design curves, which are dependent on the ground classification. However, it is considered that numerical analyses, especially those using real ground motions, are important in terms of revealing the effects of different ground types on the behaviour of masonry structures in more detail.

The present study investigates the seismic response of a typical three-storey masonry structure for five different soil classes defined in TBDY 2018. The structure model was created using the SAP2000 programme, and modal analysis and nonlinear time history analyses were performed on the structure. The objective of the study is to evaluate the effect of the ground class on structural response parameters such as displacement, base shear force and stress distribution. It is hypothesised that the results will demonstrate the significance of ground conditions in seismic design of masonry structures.

II. MODELING OF MASONRY BUILDING

A. Material modeling of masonry wall

Time history analyses were performed to examine the effect of local soil class. The material properties required for time history analyses were taken from similar studies in the literature (Table 1).

Table 1. Material Properties [15]

Material	**Modulus of Elasticity (MPa)**	**Density (kN/m^3)**	**Poisson's ratio**
Stone	3000	20	0.2

B. Geometric modeling of the masonry structure masonry

In the study, the structure is three-storey in height and its dimensions are 12m x 12m. The floor height of the structure is 3.00 m, and horizontal joists are placed at the floor level in accordance with the real model of the masonry structure. The structure is connected to the ground with a fixed support. The design of the structure is undertaken under its own weight. The geometric model of the structure is given in the figure.

C. Modeling in SAP2000 software

The modeling of walls in the SAP2000 software utilizes a shell area element, and the model was created with 3603 points and 3330 shell elements. Within the SAP2000 framework, the shell element is formulated with three or four nodes, thereby integrating both membrane and plate-bending behavior as distinct components. Finite element models of the building are given in Figure 1.

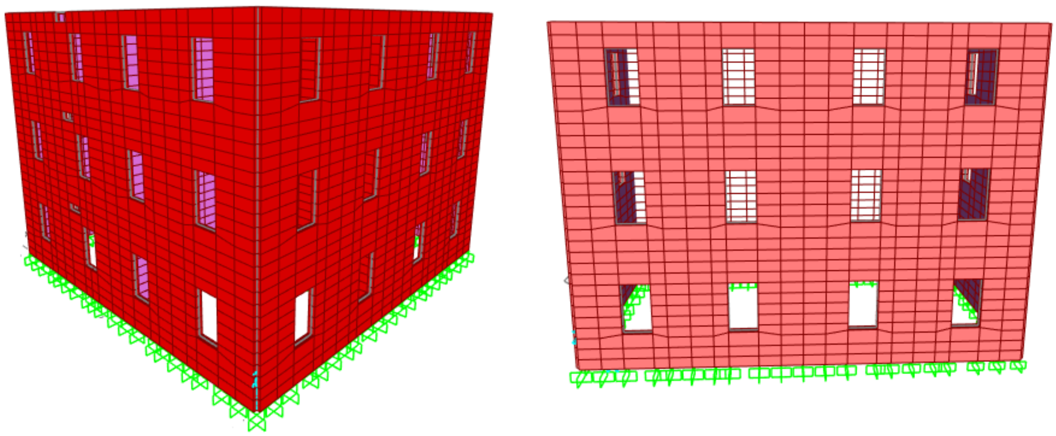


Fig. 1 Finite element model of the building

III. NUMERICAL ANALYSIS

A. Determination of seismic parameters

In order to analyze the dynamic behavior of the masonry structure, the acceleration record of the 1999 Kocaeli earthquake was used.The earthquake data corresponding to the DD-2 ground motion level (earthquake ground motion level with %10 probability of exceedance in 50 years (recurrance period 475 years), as defined in the Turkish Building Earthquake Code 2018, were retrieved from the Turkey Earthquake Hazard Map interactive web platform [16]. Table 2 provides information about the 5 different local soil classes defined in TDBY 2018. Earthquake data obtained for 5 different local soil classes are shown in Table 3.

Table 2. Local soil classes [12]

Local Soil Class	**Definition**
ZA	Solid, hard rocks
ZB	Slightly weathered, medium-solid rocks
ZC	Very dense layers of sand, gravel and hard clay or weak, weathered, highly fractured rocks
ZD	Medium dense – dense sand, gravel or very solid clay layers
ZE	Profiles containing loose sand, gravel or soft-solid clay layers or soft clay layers (cu < 25 kPa) with a total thickness of more than 3 meters satisfying the conditions PI > 20 and w > 40%

Table 3. Earthquake data [16].

Local Soil Class	Parameter	Value
ZA	S_{DS}	1.411
	S_{D1}	0.381
ZB	S_{DS}	1.588
	S_{D1}	0.381
ZC	S_{DS}	2.117
	S_{D1}	0.714
ZD	S_{DS}	1.764
	S_{D1}	0.868
ZE	S_{DS}	1.411
	S_{D1}	1.070

S_{DS} : Short period design spectral acceleration coefficient
S_{D1}: Design spectral acceleration coefficient for 1.0 second period

The information concerning the acceleration records utilised in time history analyses for differing soil classes is exhibited in Table 4. To ensure compatibility with the region near the building, the SeismoMatch software was used for spectral matching.

Table 4. The earthquake used in the time history analysis [17].

Soil class	Earthquake	Date	Station Code	Mw	Original		Matched	
					PGA (g)	PGV (cm/s)	PGA (g)	PGV (cm/s)
ZA	Kocaeli_E	17.08.1999	8101	7.6	0.373	56.377	0.557	97.082
	Kocaeli_N				0.320	53.669	0.594	151.845
ZB	Kocaeli_E				0.373	56.377	0.597	97.082
	Kocaeli_N				0.320	53.669	0.670	151.844
ZC	Kocaeli_E				0.373	56.377	1.048	156.808
	Kocaeli_N				0.320	53.669	1.125	228.365
ZD	Kocaeli_E				0.373	56.377	0.744	93.361
	Kocaeli_N				0.320	53.669	0.807	167.288
ZE	Kocaeli_E				0.373	56.377	0.637	107.459
	Kocaeli_N				0.320	53.669	0.606	197..925

Design spectra obtained for different soil classes are shown in Figure 2.

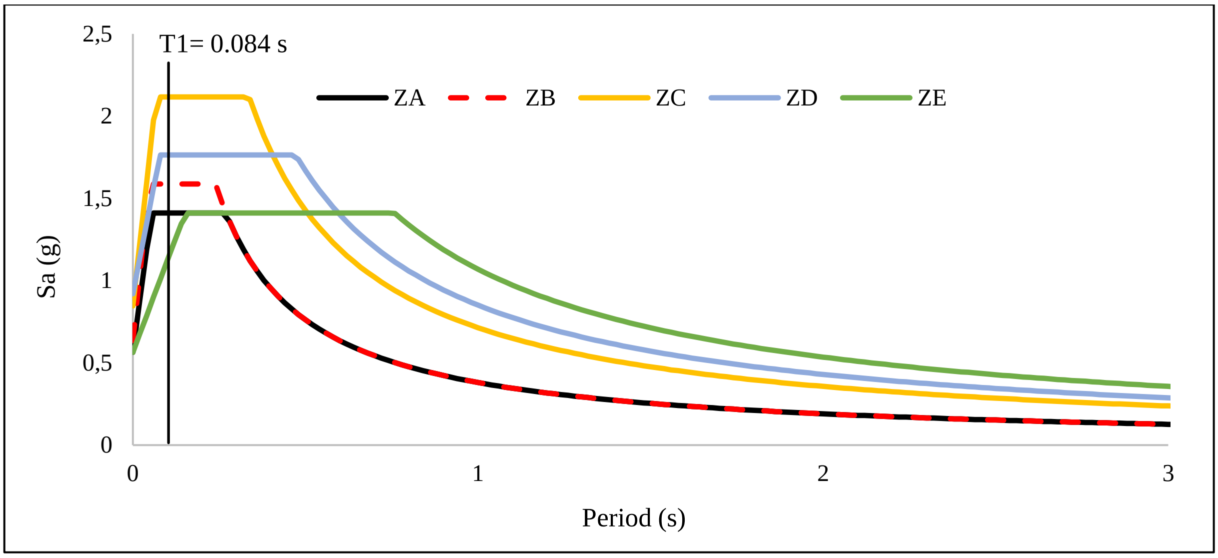
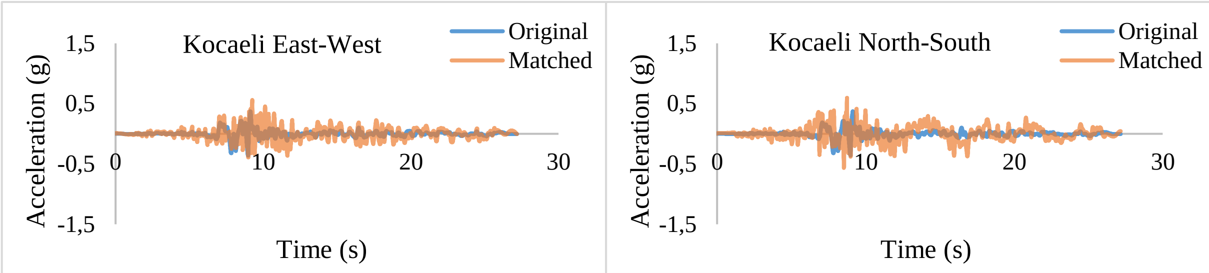


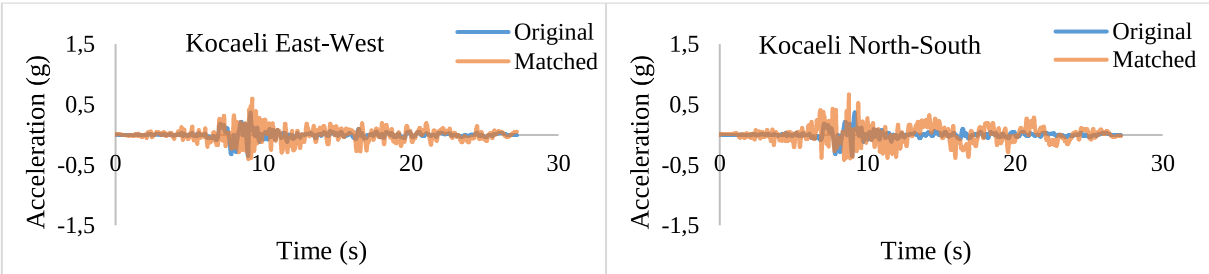
Fig. 2 Spectrums

As demonstrated in Figure 2, the soil classes have a substantial impact on the acceleration values to which the structure will be exposed. The acceleration values to which a structure will be exposed vary depending on its initial period, with the values for different soil classes differing. While the maximum acceleration value remains constant for both ZA and ZE soil classes, the probability of the structure being exposed to maximum acceleration values is considerably higher in the ZE soil class. The analysis indicates that the highest acceleration values will be observed in the ZC soil class, while the lowest values will be observed in the ZE soil class. While the maximum spectral acceleration for ZC soil class is approximately 2.1g, this value is approximately 1.4g for ZA soil class. This discrepancy clearly demonstrates the impact of the underlying soil on the dynamic behaviour of the structure and emphasises the significance of soil class in structural design.

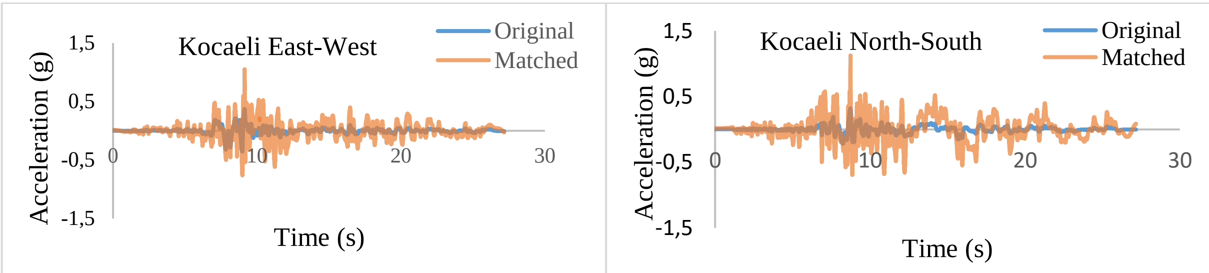
The acceleration records that are utilised in time history analyses are illustrated in Figure 3.



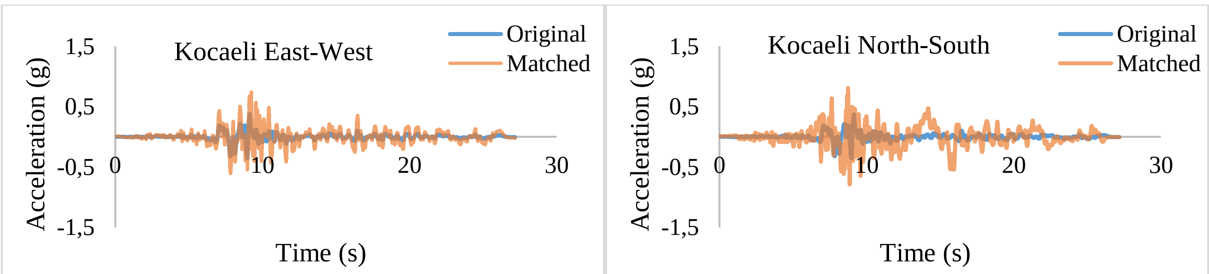
a) ZA soil class



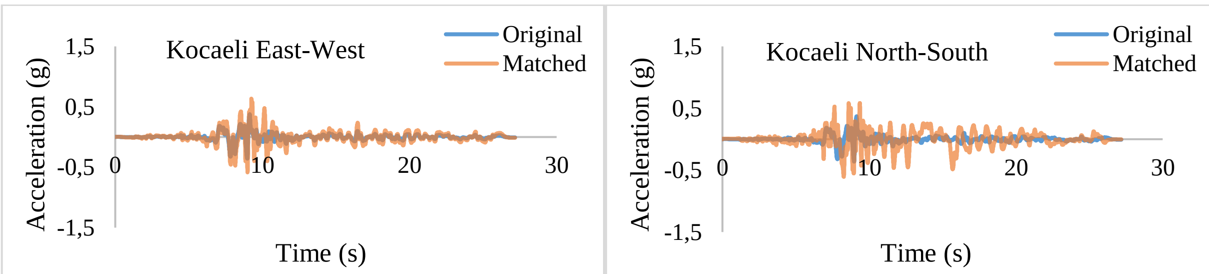
b) ZB soil class



c) ZC soil class



d) ZD soil class



e) ZE soil class

Fig. 3 Original and matched acceleration records

IV. RESULTS AND DISCUSSION

A. Modal analysis

Mode shapes are crucial in determining the dynamic response of structures. In the modal analysis calculations were performed for 200 modes. Table 5 provides the mass participation ratios for selected modes. Figure 5 illustrates the first four mode shapes along with their corresponding period values.

Table 5. Mass participation ratios and period values.

Mode	Period (s)	Mass participation ratios		
		X direction	Y direction	Z direction
1	0.084	0.72	0.00	0.00
2	0.084	0.72	0.72	0.00
3	0.071	0.72	0.72	0.00
4	0.062	0.72	0.72	0.00
5	0.061	0.72	0.72	0.00
200	0.014	0.91	0.91	0.82

When examined in Table 5, it is seen that 90% mass participation is achieved in x and y directions when the 200th mode is reached. As a result of the modal analysis, the first period of the structure was determined as 0.084 s. In the first mode, mass participation occurred only in the x direction.

The first 3 mode shapes resulting from the modal analysis are shown in Figure 4.

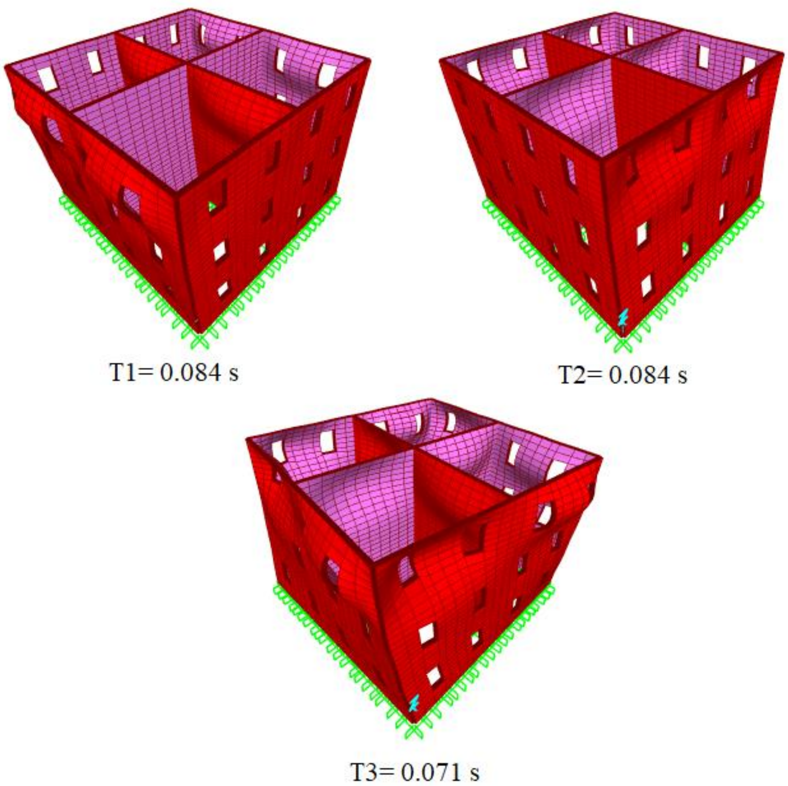


Fig. 4 First three mode shapes and period values.

As seen in Figure 4, bending movement occurred in the x direction in the 1st mode. In the 2nd mode, the bending mode in the y direction is dominant. The first torsion mode occurred in the 3rd mode.

B. Time History Analysis

In the context of the study, linear time history analyses were conducted on the building model utilising the acceleration records of the earthquakes provided in Table 4. These analyses were performed in both the x and y directions.

As a result of time history analysis, the base shear forces occurring for different soil classes are shown in Figure 5.

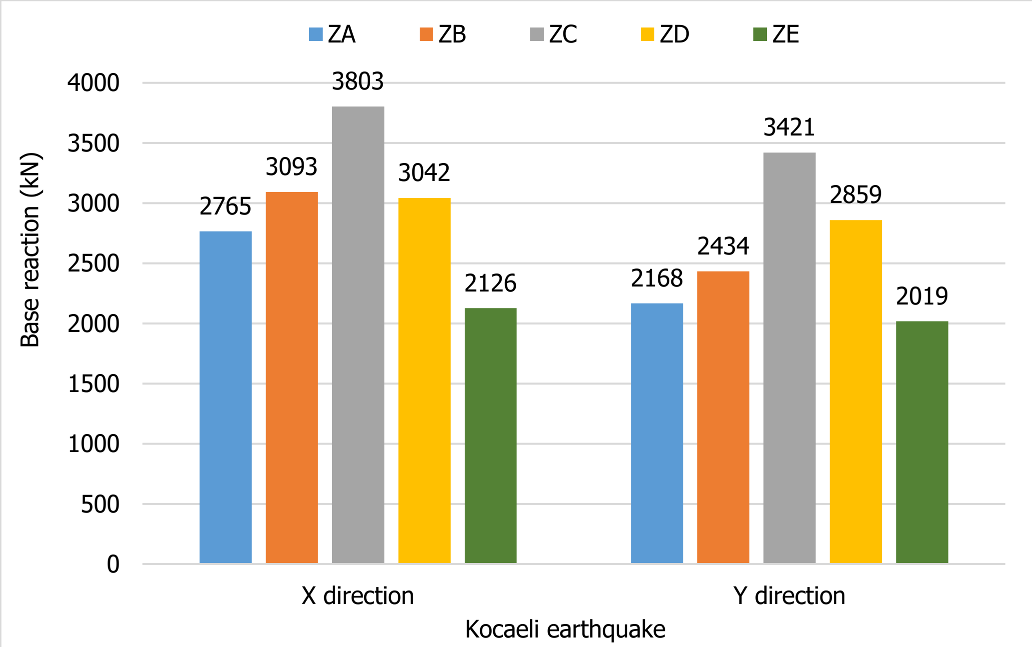
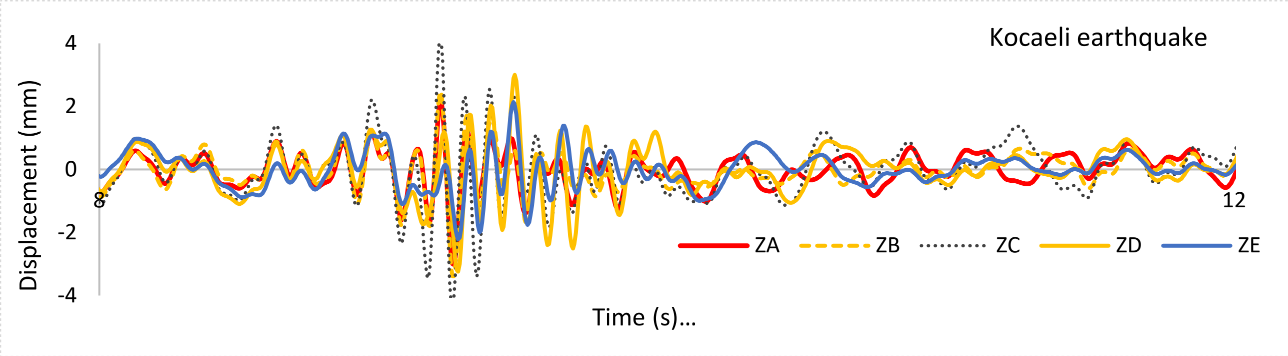


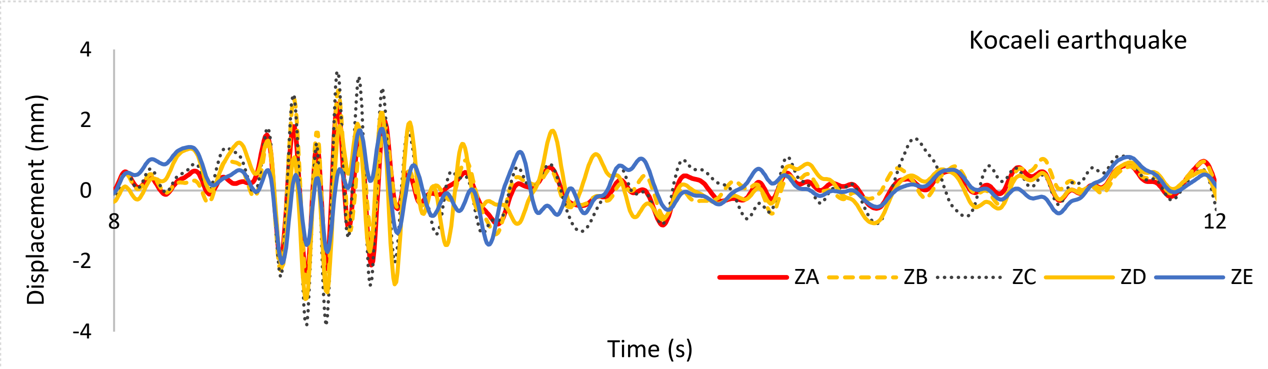
Fig. 5 Base shear forces

As demonstrated in Figure 5, the soil class exerts a substantial influence on the base shear forces that are observed. The highest base shear forces were observed to occur in both directions in the ZC soil class. In contrast, the ZE soil class exhibited the lowest base shear forces. The base shear force in the x and x directions in the ZC soil class is 44% and 41% higher than the base shear force in the ZE soil class, respectively. As demonstrated in Figure 3, given that the first period of the structure is 0.084 s, the highest acceleration values will be experienced in the ZC soil class and the lowest acceleration values will be experienced in the ZE soil class. The observed disparities in base shear force can be attributed to this phenomenon.

As a result of time history analyses, greater base shear forces occurred in the x direction for all soil classes. Given the structure's comparable rigidity in the x and y directions, it is hypothesised that this discrepancy is attributable to the content of the acceleration record in the x and y directions.

The displacement-time graph obtained for the peak point as a result of time history analyses is shown in Figure 6. In this figure, the time interval (8-12 s) when the Kocaeli earthquake was at its most intense is shown.





b) Y direction

Fig. 6 Time-displacement graph

As demonstrated in Figure 6, the soil classes have a substantial impact on the displacements that result from time history analyses. The ZC soil class, which exhibits the highest displacement values in both directions, contrasts with the ZE soil class, which demonstrates the lowest displacement values. The underlying reason for this phenomenon is elucidated in Figure 3, which demonstrates that the acceleration to which the structure will be exposed due to the first period is the highest in the ZC soil class and the lowest in the ZE soil class. The maximum displacements in the x and y directions for the ZC soil class are 2.1 and 1.9 times the displacements for the ZE soil class, respectively.

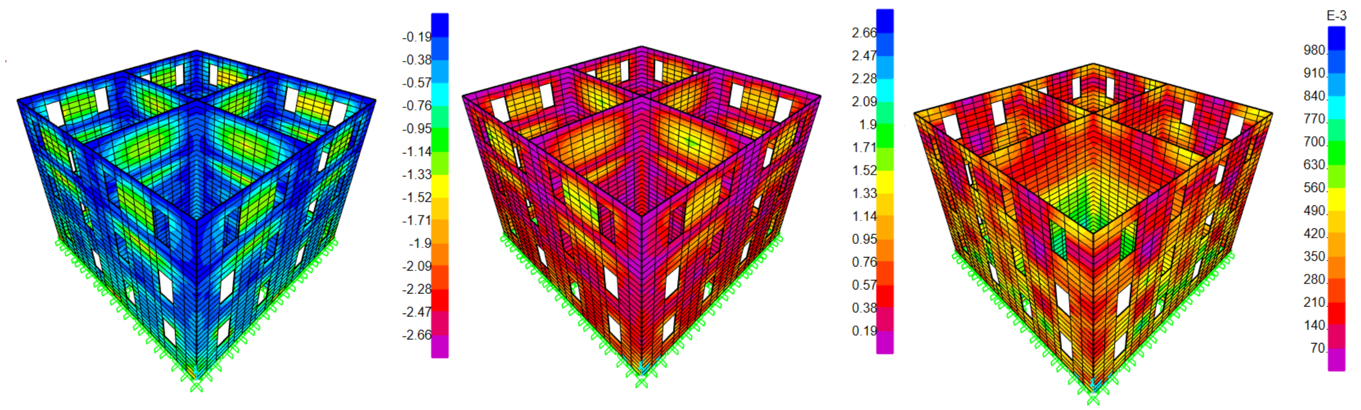
The maximum stresses resulting from time history analyses for different soil classes are shown in Table 6.

Table 6. Maximum stresses occurring

Model	Stress (MPa)	
ZA	Tensile	1.933
	Compressive	1.955
	Shear	0.749
ZB	Tensile	2.164
	Compressive	2.186
	Shear	0.834
ZC	Tensile	2.769
	Compressive	2.798
	Shear	1.052
ZD	Tensile	2.151
	Compressive	2.153
	Shear	0.890
ZE	Tensile	1.482
	Compressive	1.452
	Shear	0.593

As demonstrated in Table 6, the soil classes have a significant impact on the stresses that emerge as a consequence of time history analyses. The ZC soil class exhibits the highest stress values, while the ZE soil class demonstrates the lowest. The maximum tensile, compressive and shear stresses in the ZC soil class are 87%, 93% and 77% higher than those in the ZE soil class, respectively.

In Figure 7 the compression, tensile and shear stresses obtained for the ZC soil class as a result of time history analyses are shown. Since similar contours occur for other loadings, the contours are given only for the ZC soil class.



Compressive stress (MPa) Tensile stress (MPa) Shear stress (MPa)

Fig. 7 Stress Stress contours obtained for soil class ZC

As seen in Figure 7 tensile and compressive stresses reached their highest values at the edges of the window openings and in the middle regions of the walls for all models. The shear stresses reached their highest values in the base regions of the structure.

V. CONCLUSION

The present study investigates the seismic behaviour of a three-storey masonry building for various soil classes. To this end, a model of the masonry structure was developed in the SAP2000 program. Modal analysis and time history analyses were performed on this model for five different soil classes stated in TBDY 2018. The ensuing results, obtained from these analyses, are hereby summarised.

The results of the modal analysis indicate that the first period of the structure is 0.084 s. In mode 1, the bending mode in the x direction is dominant, in mode 2, the bending mode in the y direction is dominant, and in mode 3, the torsional mode is dominant.

It was observed that the soil class had a significant effect on the results of the time history analyses. The time history analyses indicated that the ZC soil class exhibited the highest base shear force, displacement and stress values, while the ZE soil class exhibited the lowest values. For example, The maximum displacements in the x and y directions for the ZC soil class are 2.1 and 1.9 times the displacements for the ZE soil class, respectively. The maximum tensile, compressive and shear stresses in the ZC soil class are 87%, 93% and 77% higher than those in the ZE soil class, respectively. The base shear force in the x and x directions in the ZC soil class is 44% and 41% higher than the base shear force in the ZE soil class, respectively

While the maximum spectral acceleration for ZC soil class is approximately 2.1g, this value is approximately 1.4g for ZA soil class. This discrepancy clearly demonstrates the impact of the underlying soil on the dynamic behaviour of the structure and emphasises the significance of soil class in structural design. Accurate consideration of site-specific soil properties is essential to ensure reliable and safe structural performance under earthquake loading.

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