Bilecik Şeyh Edebali Üniversitesi Fen Bilimleri Dergisi

Bilecik Seyh Edebali University Journal of Science

12(1), 93-107, 2025

DOİ: 10.35193/bseufbd.1461163

e-ISSN: 2458-7575 (https://dergipark.org.tr/tr/pub/bseufbd)

Araştırma Makalesi - Research Article

Effects of Building Slenderness on the Behaviour of Shear Wall-Frame System Buildings for Various Soil Classes

Farklı Zemin Sınıfları İçin Perde Çerçeve Sistemli Binalarda Yapı Narinliğinin Davranışa Etkisi

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Geliş / Received: 29/03/2024 ***Revize / Revised: 06/08/2024*** ***Kabul / Accepted: 07/08/2024***

ABSTRACT

In this study, the effect of structural slenderness on both linear and non-linear structural behaviour in buildings with reinforced concrete shear-frame systems was examined. For this purpose, 3 building models with square storey plans were created, with equal total building heights and ratios of height to plan size of 0.67, 1.0, and 2.0, respectively. Additionally, the ratio of shear wall areas to storey areas was kept equal in both directions for each model. The 3 building models created were examined under 15 different scenarios, considering 5 different soil classes recommended in the Turkish Building Earthquake Code. Through linear and non-linear structural analyses, the effects of building slenderness on various parameters were compared. It was observed that although the effect of structural slenderness is relatively small on hard soils, it becomes significantly more pronounced with increasing earthquake load as soil conditions worsen. The effect of building slenderness on structural behaviour is particularly crucial, especially concerning relative storey drifts and second order effects. Additionally, from the non-linear analysis results, it was observed that the damage levels in the structural elements decreased as the structure slenderness decreased.

Keywords- Non-Linear Analysis, Reinforced Concrete Structures, Slenderness Effect, Soil Class, Wall Frame Systems

ÖZ

Bu çalışmada betonarme perde-çerçeve sisteme sahip binalarda yapı narinliğinin doğrusal ve doğrusal olmayan yapısal davranışa etkisi incelenmiştir. Bu amaçla toplam bina yükseklikleri eşit ve yüksekliğinin plan boyutuna oranları sırasıyla 0.67, 1.0, 2.0 olan kare kat planına sahip 3 adet bina modeli oluşturulmuştur. Ayrıca perde duvar alanlarının kat alanlarına oranları her model için her iki doğrultuda eşit alınmıştır. Oluşturulan 3 bina modeli, Türkiye Bina Deprem Yönetmeliği'nde önerilen 5 farklı zemin sınıfı dikkate alınarak 15 duruma göre irdelenmiştir. Doğrusal ve doğrusal olmayan yapısal analizler sonucunda yapı narinliğinin yapısal davranış üzerindeki etkileri karşılaştırılmıştır. Elde edilen bulgulardan yapısal narinliğin etkisi sağlam zeminlerde nispeten az olsa da zemin koşulları kötüleştikçe artan deprem yükü ile önemli derecede arttığı görülmüştür. Özellikle göreli kat ötelenmeleri ve ikincil mertebe etkileri açısından yapı narinliğinin yapısal davranışta etkisi oldukça önemli

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olmaktadır. Ayrıca doğrusal olmayan analiz sonuçlarından yapı narinliğinin azalmasıyla yapısal elemanlardaki hasar seviyelerinin azaldığı görülmüştür.

Anahtar Kelimeler- Doğrusal Olmayan Analiz, Betonarme Yapılar, Narinlik Etkisi, Zemin Sınıfı, Perde Çerçeve Sistemler

I. INTRODUCTION

In the analysis of reinforced concrete buildings, rotations resulting from differential settlements in the foundation are typically disregarded, as structures are assumed to be fixed to the foundation soil. However, in cases where foundation and soil effects are overlooked, particularly in the structural analysis of slender buildings (height / width ratio), neglecting foundation rotations may lead to the potential toppling of buildings without experiencing structural damage. While reducing building height or increasing width presents a solution to mitigate the risk of toppling, circumstances may arise where this solution cannot be implemented due to zoning regulations.

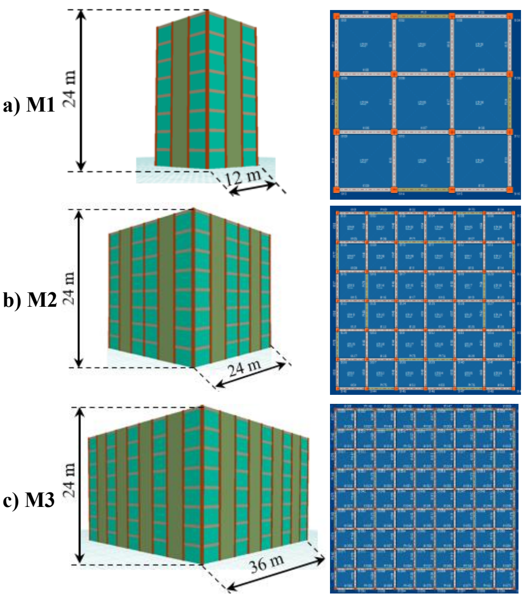
Several studies examining wall frame systems and structural slenderness are summarized in this section. Kasap and Kolay investigate shear forces on shear walls and columns across 8-storey structures, examining the impact of shear thickness on residential and commercial buildings under earthquakes [1]. Beyer et al. utilize experimental data from quasi-static cyclic tests on thin structural RC walls to analyse shear deformations for displacement demands in the inelastic range, discussing shear deformation distribution and variation with upper displacements [2]. Tang and Zhang present a probabilistic seismic demand analysis of a mid-rise slender shear wall in western US, considering soil-structure interaction (SSI) effects and suggesting the inclusion of damages in foundation and surrounding soil for a comprehensive evaluation of SSI effects on damage probability [3]. Sağlıyan et al. analysed the effect of the change in shear ratios depending on the soil class on the relative storey drifts of multi-storey reinforced concrete structures with continuous table girderless slabs. At the end of the studies, it was observed that the relative drift values were below the limit values by 1 % for 7-storey models and 1.5 % for 9-storey models [4]. Uçar and Merter investigated the slenderness of soil storey columns due to uplift and investigated the collapse behaviour of buildings under earthquake loads by incremental pushover analysis and energy-based methods. The results of the incremental pushover analyses performed for the frames considered are evaluated and the hysteretic energy values consumed in these sections are calculated by using the rotation values in the plastic joints formed in the collapse mechanisms obtained. The total energy consumed by the structure was determined as the sum of the hysteretic energy values consumed at the plastic joints of the system in case of collapse [5]. Sahin et al. and Garip and Eren developed a shear ratio calculation for static project authors to use in their calculations. The required shear ratio for shear-framed structures is determined according to the Virtual Work Theorem method by considering Z1, Z2, Z3 soil classes. For this purpose, 7 and 9 storey shear-framed buildings with I=1 in the 1st and 2nd earthquake zones were designed and analysed in SAP2000 structural analysis software. The relative storey drifts obtained as a result of the analyses were compared with the limit values in TBEC-2007 and the adequacy of the shear wall lengths was tried to be determined [6, 7]. Hube et al. in their study is to understand the observed damage in slender walls after 2010 Maule earthquake and to reproduce and analyse experimentally the seismic behaviour of such walls. The second objective is to provide recommendations to estimate the lateral displacement and the effective stiffness of slender walls. Test results showed that a 25% reduction in wall thickness reduced the ultimate displacement capacity, ductility, and energy dissipation ability of the wall. Closed stirrups and crossties were effective in increasing displacement capacity and ductility, and closed stirrups were effective in preventing out-of-plane buckling of the wall after compression failure. The average effective stiffness ratio of the tested walls was 0.39, which is slightly larger than the ACI-318 suggestion of 0.35 [8]. Ulutaş et al. determined the shear wall ratio that should be included in the plan for school type buildings to be safe against earthquakes depending on the number of storeys. These shear wall dimensions were divided into the storey areas and the shear wall ratios were determined depending on the number of storeys [9]. Tunç and Al Ageedi carried out structural analyses on a total of 40 buildings with different building and wall dimensions to determine the optimum ratio of shear wall area to storey plan area in reinforced concrete buildings. According to the results of these 40 storey buildings, it was concluded that the further the walls are from the geometric center, the better their structural performance will be as long as the overall wall symmetry is maintained [10]. Erdil and Gündüz to determine the effectiveness of shear walls to be used in reinforced concrete buildings, shear walls designed in different numbers and thicknesses were placed in different areas in the plan. As a result of the analyses, it was determined that placing shear walls with the same area in the building by dividing them into parts reduces the shear force and moment effectiveness of the shear wall, the global stiffness of the building decreases as a result of the shortening of the shear wall length, and finally the displacements and periods increase [11]. Onat and Usta in their study, investigated the effects of shear walls used in high-rise reinforced concrete buildings and the placement of shear walls on the earthquake performance of the building. When the models with different placement of shear walls were analysed, it was concluded that when the shear walls were placed in L-shape, they obtained the lowest period and relative storey drift values and that the placement of shear walls in this way may be safer than other placement types when designing reinforced concrete high-rise buildings [12]. Atmani et al. investigate considers the influence of plastic length L_p, concrete compressive strength f_{c28}, longitudinal reinforcement ratio ρ_l, transverse reinforcement ratio ρ_{sh}, reduced axial load ν, confinement zone depth CS and focusing on the geometric slenderness λ. A new limit of slenderness and appropriate deformations of rotations are recommended to provide an immediate help to designers and assistance to those involved with drafting codes [13].

From the technical literature review, it has been observed that there is limited research on the impact of building slenderness (height-to-width ratio H/L) on structural behaviour. This article aims to comparatively examine the effects of structural slenderness on the behaviour of reinforced concrete shear-frame system buildings. To achieve this, 3 square-plan buildings with equal heights and varying H/L (building slenderness) of 0.67, 1.0, and 2.0 were considered. The structural systems were designed such that the ratio of the total area of shear wall elements to the storey area remained consistent. A total of 15 models were created, incorporating these 3 building configurations and 5 different soil types recommended in the TBEC. Structural analyses were conducted using both linear and non-linear analysis methods. The findings elucidate the effect of structure slenderness on linear and non-linear structural behaviour across different soil types.

II. MATERIAL AND METHOD

In this study, the impact of structural slenderness on the behaviour of different soil classes was investigated for a reinforced concrete building with a wall-frame system. To accomplish this, 3 building models were created, each with a building height of 24 m and plan dimensions of 12 m, 24 m, and 36 m, respectively. This resulted in vertical rectangular prism, cube, and horizontal rectangular prism-shaped buildings with height-to-plan-size ratios of 0.67, 1.0, and 2.0, respectively. Furthermore, the building structural system was symmetrically designed in both horizontal directions, and the shear wall ratios in the models were set equal to the storey areas. Each building model comprised 8 storeys, with a storey height of 3 m. The modelling incorporated the effective section stiffnesses specified in the Turkish Building Earthquake Code (TBEC) [14]. Additionally, a rigid diaphragm was assumed for the slabs, the column-beam connection was considered semi-rigid, and the vertical structural elements were assumed to be fully embedded in the foundation. Details regarding the building models used in the study are provided in Figure 1, and the necessary parameters for structural analysis are outlined in Table 1. Specifically, the column dimensions for each storey were set at 400x400 mm, beam dimensions at 250x500 mm, shear wall dimensions at 250x4000 mm, and slab thickness at 150 mm.

The behaviour of three building models with different slenderness, while maintaining a constant ratio of shear wall areas to storey areas, was evaluated separately for the ZA, ZB, ZC, ZD, and ZE soil classes specified in the TBEC. Design spectra corresponding to the DD2 earthquake level for each soil class are provided in Figure 2, with the necessary parameters outlined in Table 2. Structural analyses were conducted using the Sta4-Cad program [15]. Various aspects were examined, including earthquake load per unit mass, relative storey drifts, levels of secondary storey effects, overturning moments for shear walls, building overturning verifications, and structural performances. The linear and non-linear structural analysis results for each building model were compared to assess their behaviour under seismic loading conditions.



Model	Parameter	Value
a) M1	Storey area (m^2)	144
	Shear wall length in x direction (m)	8
	Shear wall length in y direction (m)	8
	Shear wall ratio in x direction (%)	1.25
	Shear wall ratio in y direction (%)	1.25
	Building slenderness (H/L)	2.0
b) M2	Storey area (m^2)	576
	Shear wall length in x direction (m)	32
	Shear wall length in y direction (m)	32
	Shear wall ratio in x direction (%)	1.25
	Shear wall ratio in y direction (%)	1.25
	Building slenderness (H/L)	1.0
c) M3	Storey area (m^2)	1296
	Shear wall length in x direction (m)	72
	Shear wall length in y direction (m)	72
	Shear wall ratio in x direction (%)	1.25
	Shear wall ratio in y direction (%)	1.25
	Building slenderness (H/L)	0.67

Figure 1. Information on building models

Table 1. Design parameters

Building Importance Coefficient (I)		1
Structural Behaviour Coefficient (R)		5.6
Strength Excess Coefficient (D)		2.5
Live Load Participation Coefficient (N)		0.3
Column Cross-Section Dimensions (mm)		400 x 400
Beam Cross-Section Dimensions (mm)		250 x 500
Thickness of Shear Walls (mm)		250
Slab Thickness (mm)		150
Eccentricity		%5
Damping Ratio		%5
Material Properties	Concrete	C30
	Steel Bar	B420C
Modulus Of Elasticity (MPa)	Concrete	31800
	Steel Bar	200000
Slab Loads	Dl (kN/m^2)	2.12
	LL (kN/m^2)	2
Brick Wall	Thickness (mm)	130
	Load	6.25
Reinforced Concrete Unit Volume Weight (kN/m^3)		25

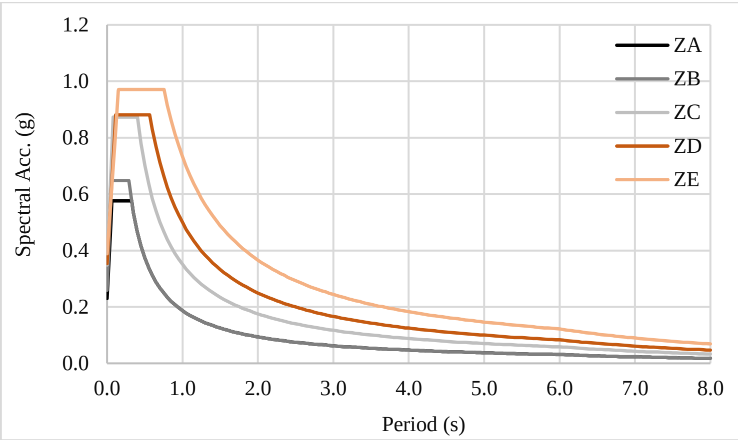


Figure 2. Design spectrums for different soil classes

Table 2. Design spectrums parameters

Soil Classes	T_A (s)	T_B (s)	S_S (g)	S_1 (g)	PGA (g)	S_{DS} (g)	S_{D1} (g)
ZA	0.065	0.325	0.72	0.234	0.303	0.576	0.187
ZB	0.058	0.289	0.72	0.234	0.303	0.648	0.187
ZC	0.08	0.402	0.72	0.234	0.303	0.873	0.351
ZD	0.113	0.566	0.72	0.234	0.303	0.881	0.499
ZE	0.151	0.755	0.72	0.234	0.303	0.971	0.732

Latitude: 41.205507 Longitude: 32.656853

Figure 3 shows the determination of Building Height Classes (BYS) for 5 different soil classes of the 3 building models used in the study. In this way, I represent the Building Importance Coefficient; BKS, Building Usage Class; S_{DS}, Short Period Design Spectral Acceleration Coefficient; DTS, Earthquake Design Class and H_N indicates building height.

III. RESULTS AND DISCUSSION

In this study, the influence of structural slenderness on building behaviour across different soil classes was investigated using both linear and non-linear analysis methods. To achieve this, structural analyses were conducted on three reinforced concrete wall-frame system building models, each featuring square storey plans and equal heights of 24 meters. The storey areas of these models were 144, 576, and 1296 square meters, respectively. The ratio of building height to storey plan length (H/L) was varied across the models, resulting in ratios of 0.67, 1.0, and 2.0, respectively. Additionally, when designing the storey plans of the building models, efforts were made to overlap the storey mass and stiffness centres to minimize torsion effects. Furthermore, earthquake calculations considered minimum eccentricity and the structural system was meticulously designed to ensure that the ratio of shear wall area to storey area remained consistent in both horizontal directions across all models. This approach allowed for a comprehensive examination of how structural slenderness influences building behaviour under seismic loading conditions.

A. Linear Analysis

Figure 4 illustrates the ratios of total base shear force to structure weight for different soil classes across each model. It is evident from the figure that the base shear force values, relative to structure weight, are greater in the M2 models for each soil class compared to M1 and M3. Conversely, the building models with the smallest ratios are M1's. These findings suggest that as the H/L value approaches 1.0 for buildings in the examined geometry, the earthquake load acting on the buildings increases proportionally to their weight. Additionally, when considering the effects of soil classes, results for ZA and ZB soil classes appear to be quite close for all 3 models. However, there is an exponential increase in results starting from the ZC soil class. For instance, while the ratio obtained for the ZE soil class in the M1 model is 3.21 times compared to the ZA soil class, this increase is 3.06 and 3.18 times for M2 and M3, respectively. These observations underscore the significant influence of both structural slenderness and soil class on the seismic response of the buildings under consideration.

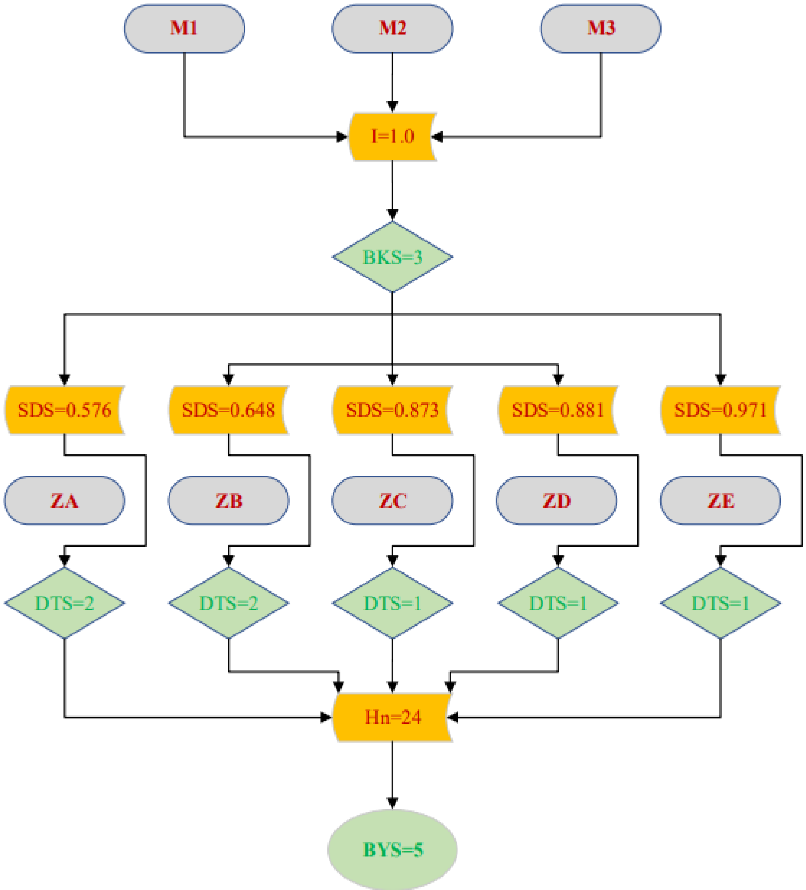


Figure 3. Building height classes of models according to TBEC

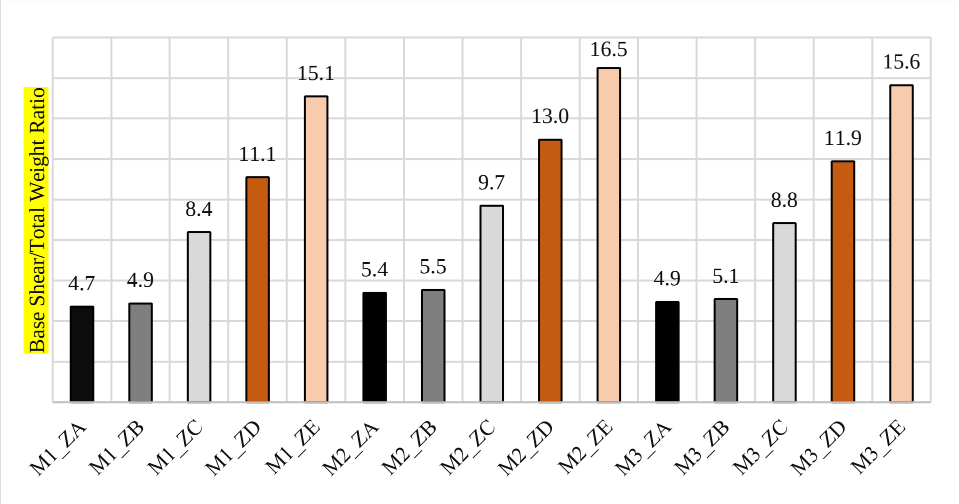


Figure 4. The ratios of total base shear force to structure weight for different soil classes

Figure 5 depicts the maximum second order effects obtained from structural analyses. It is evident from the figure that the models with the highest second order effects are M1, while the models with the lowest are M2 models. In other words, the least second order effects were observed in building models with an H/L ratio of 1.0. When considering the effect of soil type, the largest second order effects for each model are observed in ZC type soil. Specifically, for ZA and ZB soil types, in the M1 model where the structure slenderness is 2.0, there is an approximately 1.42-fold increase compared to the M2 model, which has the smallest second order effects with a slenderness ratio of 1.0. Similarly, this increase was approximately 1.47 for ZC and ZD soil types, and 1.46 for ZE soil type. In M3 models, where the structure slenderness is 0.67, the increase in second order effects is approximately 1.27 times compared to M2 models. These findings underscore the significant impact of both structural slenderness and soil type on the magnitude of second order effects in the analysed building models.

Figure 6 illustrates the base load values per square meter for the considered models. A notable observation from the figure is that despite the increase in building footprint, the unit load on the foundation decreases as the storey area increases. Specifically, although the total building weight increases by 3.75 times for the M2 model compared to the M1 model, the load value per unit area for the foundation decreases by 1.07 times due to the increase in storey area. Similarly, when comparing the M3 and M1 models, where the building weight increases by 8.25 times, the load value per unit area decreases by 1.09 times. These findings indicate that the soil type does not significantly affect the results. It is evident that if the building height remains constant, the load on the foundation decreases even as the total structure weight increases due to the increase in the structure slenderness ratio. This phenomenon occurs in buildings where the same size cross-sections are used.

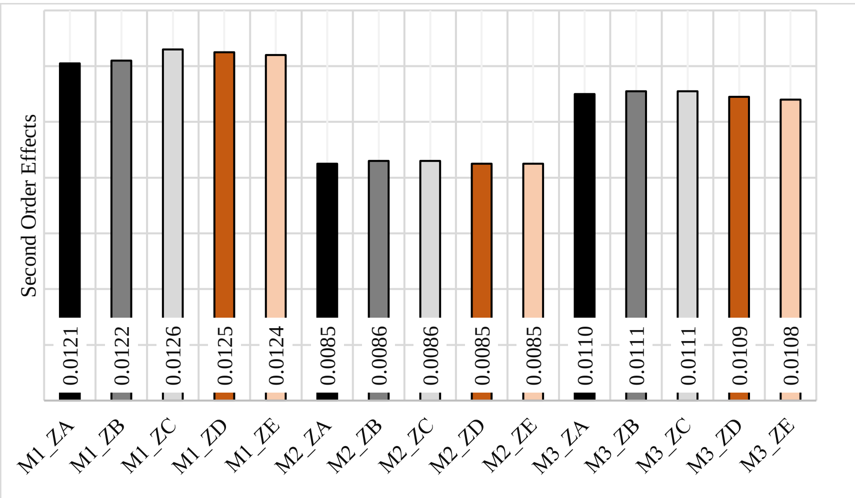


Figure 5. Maximum second order effects for different soil classes

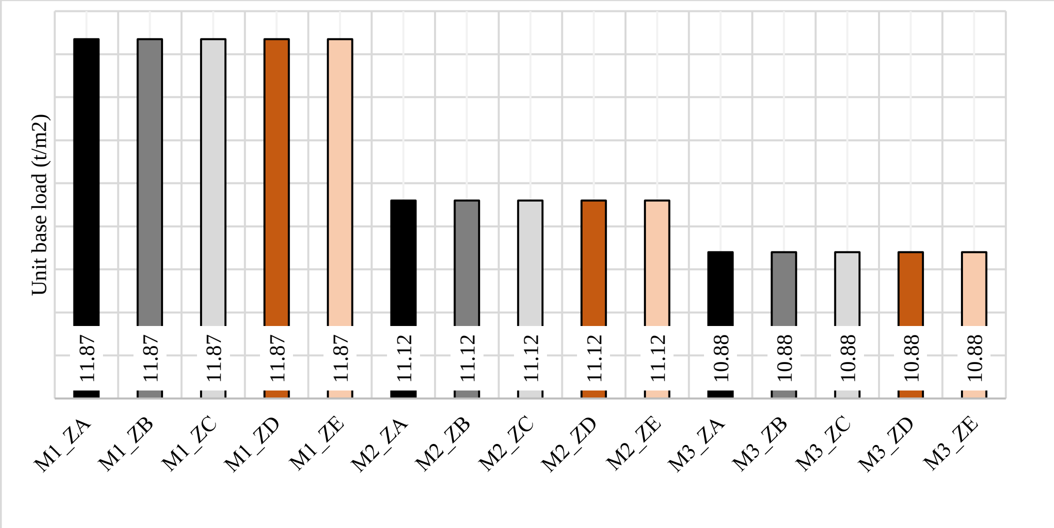


Figure 6. The base load values per square meter

Figure 7 presents the ratios of building base overturning moments to building weights. Observing the figure, it becomes apparent that while the results for ZA and ZB soil types, characterized as hard soil (rock), are relatively similar, the discrepancies between the ratios escalate notably as soil conditions deteriorate, transitioning to more flexible conditions. Specifically, in buildings situated on ZC type soil, described as sandy soil, an increase of 1.79 times for M1, 1.82 times for M2, and 1.81 times for M3 was observed compared to buildings on ZA type soil. This trend continues with more significant disparities as soil conditions worsen. For instance, in buildings on ZD type soil, the increase was calculated as 2.43, 2.46, and 2.48 times for M1, M2, and M3, respectively. Similarly, in buildings on ZE type soil, characterized as soft soil, the ratios increased by 3.32, 3.16, and 3.30 times for M1, M2, and M3, respectively, compared to buildings on ZA type soil. These findings suggest that while the slenderness effect has minimal impact on results for hard soils (ZA and ZB) and relatively hard soil (ZC), the increase in the slender M1 model is most pronounced as soil conditions worsen, indicating the effectiveness of slenderness in adverse soil conditions. Notably, when comparing soft soil (ZE) to hard soil (ZA), the least increase is observed in the M2 model with an H/L ratio of 1.0.

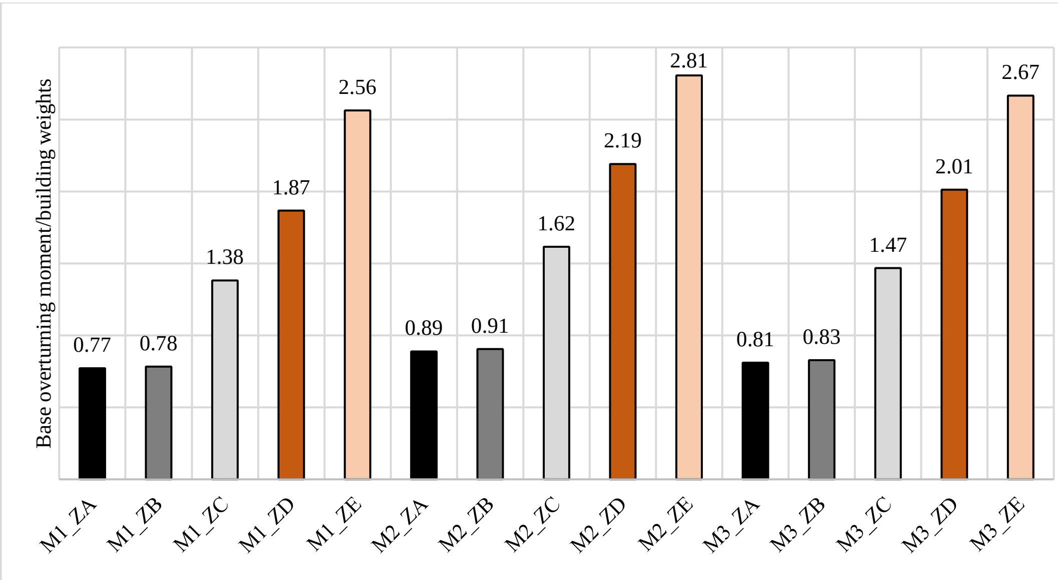


Figure 7. The ratios of building base overturning moments to building weights

Figure 8 displays the average reinforcement ratios required for the structural elements across the 15 models created for different soil classes. In Figure 8, ρ shows the required reinforcement ratio as a result of the calculation, while ρ_{min} represents the minimum reinforcement ratio calculated according to TBEC conditions. It should be emphasized that since Figure 8 shows the required reinforcement amount as a result of the structural analysis, in some cases, ρ/ρ_{min} values were less than 1.0 for some elements. Although, in practice, it is necessary to design according to the minimum reinforcement ratio in such cases, the required reinforcement ratios at the end of the calculation were directly examined in order to make a comparison. Notably, since the minimum reinforcement ratio for shear walls is sufficient in all models, there is no discernible difference in average reinforcement ratios for shear walls. For columns, there is little disparity in the average reinforcement ratios required for ZA and ZB soil types across all models. However, as soil conditions deteriorate, the rates in the M1 model, characterized by higher slenderness, generally surpass those of other models. Conversely, for beams, the required reinforcement increases as soil conditions worsen, progressing from the M1 model, with a significant slenderness effect, to the M3 model, with less slenderness effect. From these evaluations, it is apparent that structures with the same shear wall ratio exhibit increased stress on columns in slender structures, while beams endure heightened stress in structures with less slenderness.

Figure 9 presents a comparison of relative storey drifts. Upon examination of this figure, it becomes evident that the results for ZA and ZB soil classes are closely aligned. However, a notable divergence is observed as we transition from ZC to ZE soil classes, highlighting the effect of structural slenderness on the results. Across all soil classes, the relative storey drift levels in the M1 model, characterized by the highest slenderness, exceed those of other models. Conversely, the models with the lowest relative storey drifts are the M2 models with an H/L ratio of 1.0. Specifically, the ratio of the maximum relative storey drift values of the M1 model to the maximum relative storey drift values of the M2 model is approximately 1.35, whereas this ratio is 1.17 for M3-M1. Furthermore, the effect of soil class on relative storey drifts is illustrated in Figure 10. From this figure, it can be observed that the ratio of the maximum relative storey drifts obtained for ZE, ZD, ZC, and ZB soil classes in the M1 model to the maximum relative storey drifts obtained for ZA soil class is 3.47, 2.48, 1.82, and 1.03, respectively. Similarly, these ratios for M2 are 3.22, 2.513, 1.83, and 1.02, and for M3, they are 3.36, 2.53, 1.82, and 1.03. These findings indicate that relative storey drifts increase as soil conditions worsen, with the largest increase observed in the M1 model, characterized by the highest structural slenderness.

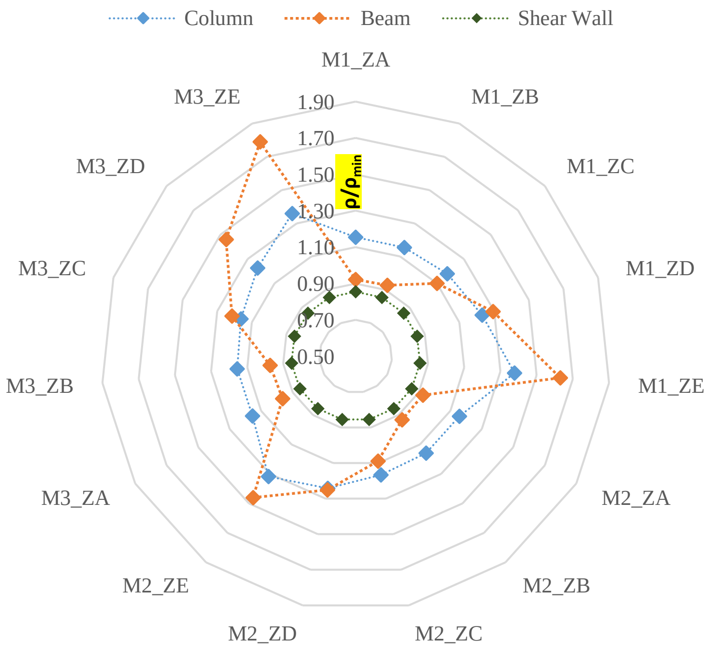


Figure 8. The average reinforcement ratios required for the structural elements ρ/ρ_{min}

Figure 11 illustrates the ratios of the base moment of the edge axis shear walls to the total base moments of the structure. Upon examination of this figure, it is apparent that the edge axis shear walls are subjected to greater stress in M1 models, where the slenderness effect is high. Furthermore, the difference in soil class did not exert a significant influence on this situation. The ratio of total shear wall base moments in structural systems to building base moments was calculated as 0.33 in M1 models, 0.59 in M2 models, and 0.32 in M3 models. Notably, according to the TBEC conditions, the ratio greater than 1/6 stipulated for edge axis walls is not valid for any model. However, the condition that the ratio of the total wall base moment to the total structure base moment exceeds 0.4 is only met in M2 models.

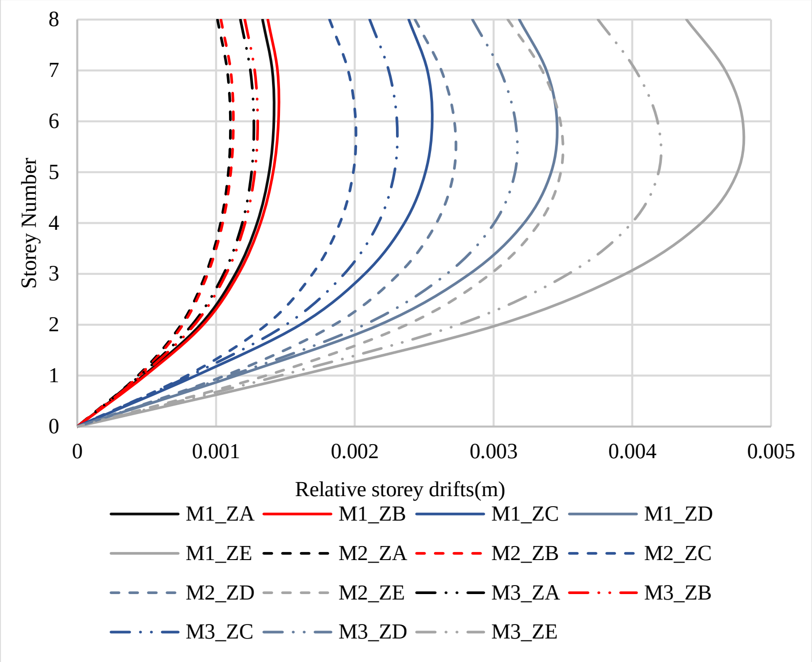


Figure 9. The comparison of relative storey drifts

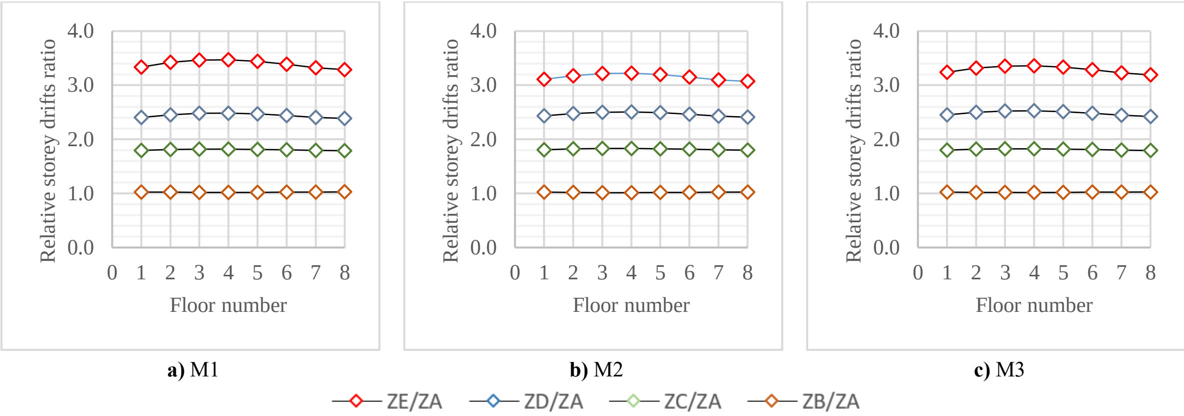


Figure 10. The effect of soil class on relative storey drifts

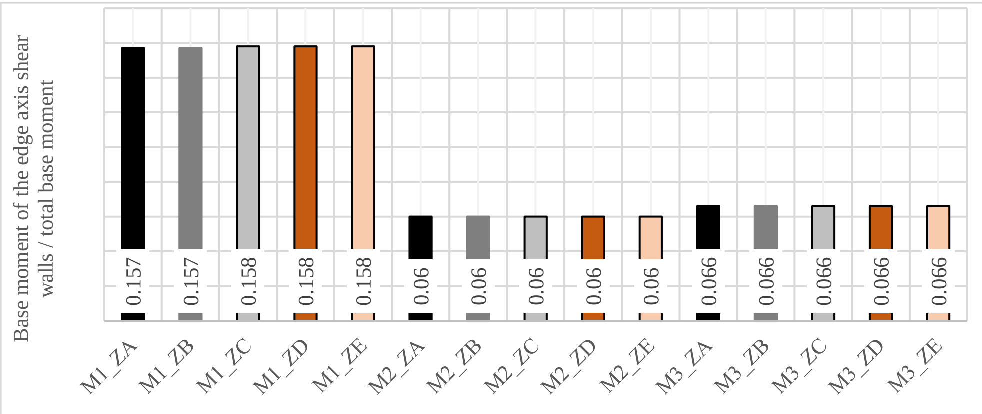


Figure 11. The ratios of the base moment of the edge axis shear walls to the total base moments

B. Nonlinear Analysis

The material models used for the nonlinear multi-mode pushover analysis are given in Figure 12. For each soil class, unit deformations in structural elements were evaluated according to TBEC, and damage levels were determined (see Figure 13). In the nonlinear calculation model, columns and beams are modelled as frame elements, while shear wall elements are modelled as area elements. Effective section stiffnesses were considered in the calculations in accordance with TBEC. The analysis model assumed fully rigid joints, and the nonlinear behaviour was represented using the distributed plastic hinge model. Both dead loads and live loads, multiplied by the live load participation coefficient, were accounted for as mass sources. Concrete and reinforcement damage limit values are determined by the equations (1), (2), (3) and (4) for the *Collapse Prevention* (CP) performance level. Definition of the parameters in these equations are;

- ε_c: concrete unit strain
- ω_{we}: effective confining reinforcement ratio,
- $\propto_{se}$: confinement reinforcement efficiency coefficient,
- $\rho_{sh,min}$: the smaller of the volumetric transverse reinforcement ratio in two horizontal directions,
- f_{ywe}: expected yield strength of the stirrup reinforcement,
- f_{ce}: expected compressive strength of concrete,
- ρ_{sh}: volumetric stirrup reinforcement ratio,
- A_{sh}: area of stirrup reinforcement,
- s: spacing of stirrup reinforcement,
- a_i: the distance between the axes of longitudinal reinforcements supported by a stirrup arm or tie spacer horizontally,
- b_o and h_o: the cross-sectional size between the axes of the stirrup reinforcement surrounding the core concrete

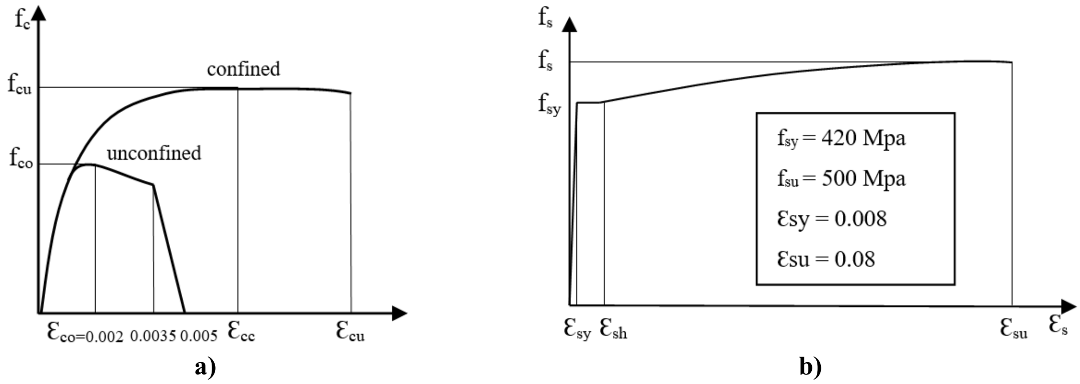


Figure 12. Nonlinear material models a) Concrete b) Steel bar [14,16]

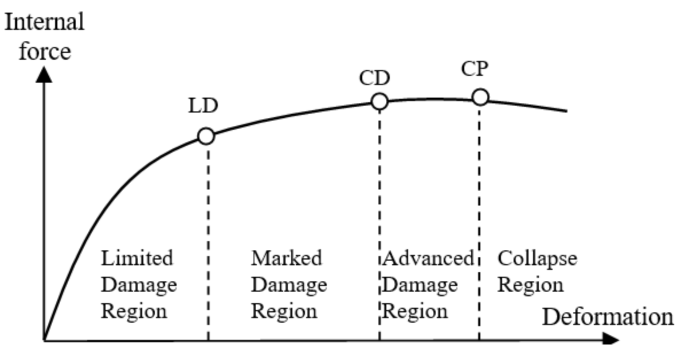


Figure 13. Sectional damage regions according to TBEC [14]

Limit values for *Controlled Damage* (CD) performance level are considered as 75% of CP values, and limit values for *Limited Damage* (LD) performance level are 0.0025 for concrete crushing and 0.0075 for reinforcement. Accordingly, the damage levels of structural elements, beams and vertical structural elements, and their distribution on storeys are given in Table 3. In addition, modal capacity diagrams for the x-x direction are given in figure 14. It can be seen from the modal capacity diagrams that the models with the highest stiffness for each soil class are the M2 models. This situation can be explained by the fact that the horizontal stiffness in the

M1 models is lower than in other models, and in the M3 models, the structural period is extended by increasing the mass, although the slenderness effect is minimal.

$$\varepsilon_c{}^{(CP)} = 0{,}0035 + 0{,}04\sqrt{\omega_{we}} \le 0{,}018 \quad (1)$$

$$\omega_{we} = \propto_{se} * \rho_{sh,min} \frac{f_{ywe}}{f_{ce}} \quad (2)$$

$$\rho_{sh} = \frac{A_{sh}}{b_k * s} \quad (3)$$

$$\propto_{se} = \left(1 - \frac{\sum a_i^2}{6 * b_0 * h_0}\right) * \left(1 - \frac{s}{2 * b_0}\right) * \left(1 - \frac{s}{2 * h_0}\right) \quad (4)$$

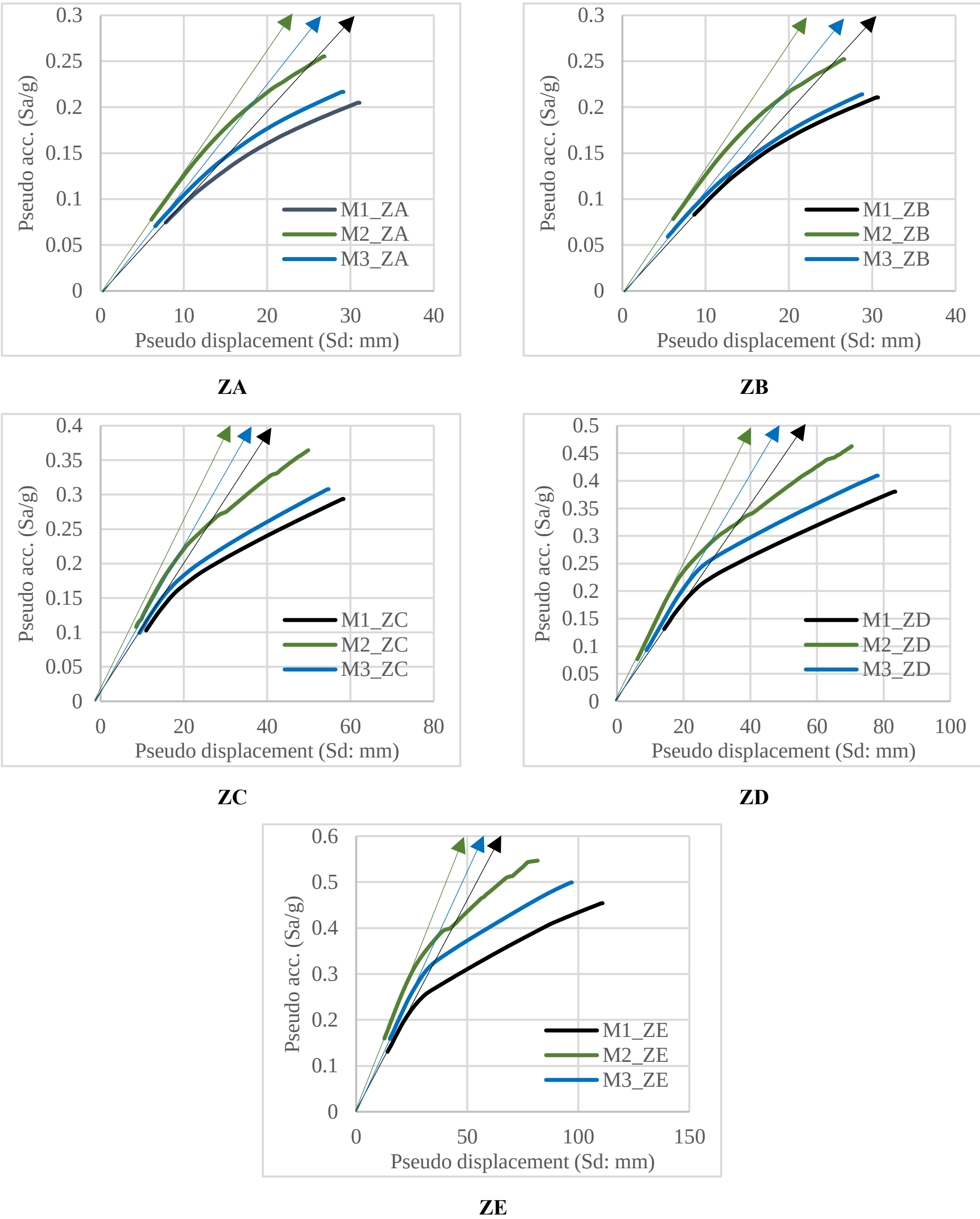


Figure 14. Modal capacity diagrams for the x-x direction

Table 3 shows that there is no damage to the models for ZA and ZB. However, it is seen that the damage levels, especially in the beam elements, increase with increasing horizontal load for ZC, ZD and ZE. In addition, it is seen that the damage levels on structural elements decrease as the structure slenderness decreases. From the results obtained, it was seen that the best structural performance was in the M3 models, and the most negative results were in the M1 models, which have the highest slenderness. Based on the analysis results, it can be said that although structural slenderness did not have a significant effect on hard soils, it could have a significant impact on structural behaviour as soil conditions deteriorated. In addition, structural performance values are given in Table 4. Table 4 shows that all models for ZA and ZB soil types remain in the LD performance level; and all models except the M3 model for ZC, ZD, ZE soil types move to the CD performance level. Although the performance values obtained depending on the structural slenderness for different soil types are similar, Figure 15 reveals the differences in the damage distribution percentages in the structural elements.

Table 3. Damage levels of beams and vertical elements and their distribution on storeys (%)

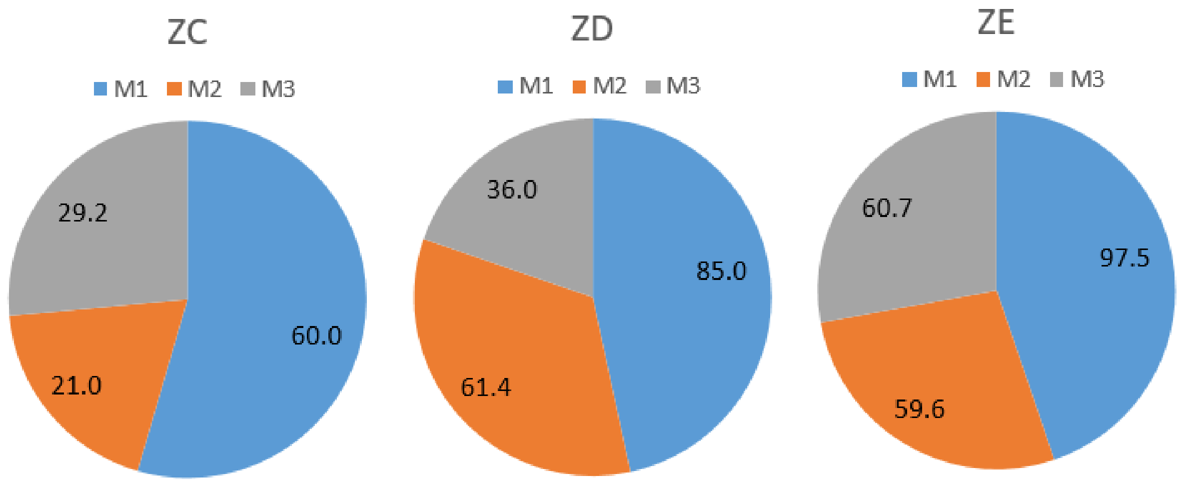
Soil Classes	Storeys	M1						M2						M3					
		Beam			Vert. Elements			Beam			Vert. Elements			Beam			Vert. Elements		
		LDR	MDR	ADR	LDR	MDR	ADR	LDR	MDR	ADR	LDR	MDR	ADR	LDR	MDR	ADR	LDR	MDR	ADR
ZA	8	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0
	7	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0
	6	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0
	5	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0
	4	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0
	3	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0
	2	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0
	1	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0
ZB	8	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0
	7	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0
	6	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0
	5	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0
	4	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0
	3	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0
	2	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0
	1	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0
ZC	8	60	40	0	95.9	4.1	0	100	0	0	100	0	0	75	25	0	100	0	0
	7	40	60	0	99.3	0.7	0	100	0	0	100	0	0	50	50	0	100	0	0
	6	0	100	0	97	3	0	100	0	0	100	0	0	50	50	0	100	0	0
	5	0	100	0	94.7	5.3	0	100	0	0	100	0	0	63.9	36.1	0	94.8	5.2	0
	4	0	100	0	84.3	15.7	0	76.5	23.5	0	95.9	4.1	0	63.9	36.1	0	100	0	0
	3	20	80	0	95.1	4.9	0	0	100	0	76.9	23.1	0	63.9	36.1	0	100	0	0
	2	100	0	0	100	0	0	55.9	44.1	0	96.3	3.7	0	100	0	0	100	0	0
	1	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0	100	0	0
ZD	8	20	80	0	95.1	4.9	0	41.2	58.8	0	99.1	0.9	0	69.4	30.6	0	94	6	0
	7	0	100	0	99.2	0.8	0	5.9	94.1	0	99.1	0.9	0	47.2	52.8	0	98.7	1.3	0
	6	0	100	0	99.3	0.7	0	0	100	0	99.2	0.8	0	48.6	51.4	0	99.7	0.3	0
	5	0	100	0	99.4	0.6	0	0	100	0	98.6	1.4	0	36.1	63.9	0	94.9	5.1	0
	4	0	100	0	99.5	0.5	0	5.9	94.1	0	99.6	0.4	0	50	50	0	99.4	0.6	0
	3	0	100	0	99.5	0.5	0	55.9	44.1	0	100	0	0	61.1	38.9	0	97.3	2.7	0
	2	0	100	0	100	0	0	100	0	0	66.2	33.8	0	100	0	0	100	0	0
	1	100	0	0	100	0	0	100	0	0	76.4	23.6	0	100	0	0	100	0	0
ZE	8	0	100	0	94.3	5.7	0	29.4	70.6	0	98.6	1.4	0	31.8	68.2	0	98.5	1.5	0
	7	0	100	0	98.8	1.2	0	5.9	94.1	0	99.3	0.7	0	19.4	80.6	0	99.4	0.6	0
	6	0	100	0	99	1	0	0	100	0	98.1	1.9	0	0	100	0	99.4	0.6	0
	5	0	100	0	99.4	0.6	0	0	100	0	99	1	0	0	100	0	99.4	0.6	0
	4	0	100	0	99.6	0.4	0	29.4	70.6	0	99.9	0.1	0	36.1	63.9	0	99	1	0
	3	0	100	0	99.4	0.6	0	58.8	41.2	0	82.7	17.3	0	57.6	42.4	0	98.4	1.6	0
	2	0	100	0	99.9	0.1	0	100	0	0	65.1	34.9	0	69.4	30.6	0	97.7	2.3	0
	1	20	80	0	100	0	0	100	0	0	72.3	27.7	0	100	0	0	96.2	3.8	0

LDR: Limited Damage Region MDR: Marked Damage Region ADR: Advance Damage Region

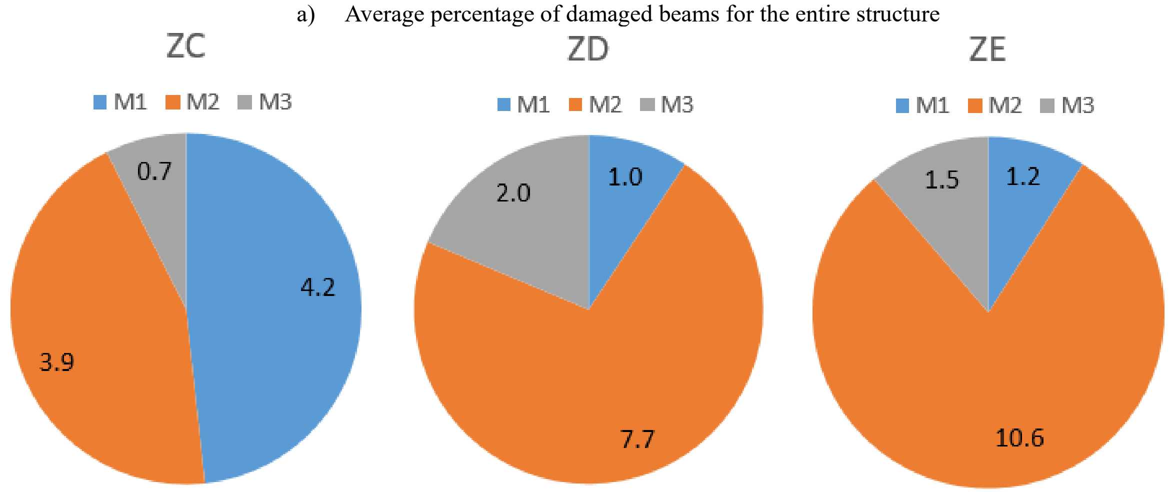
Table 4. Structural performance values

	ZA	ZB	ZC	ZD	ZE
M1	LD	LD	CD	CD	CD
M2	LD	LD	CD	CD	CD
M3	LD	LD	LD	CD	CD

LD: Limited Damage CD: Controlled Damage



a) Average percentage of damaged beams for the entire structure



b) Average percentage of damaged vertical structural elements for the entire structure
H/L values: M1=2.0; M2=1.0; M3=0.67

Figure 15. Average percentage of damaged structural elements for the entire structure

IV.CONCLUSION

In this study, the effect of building slenderness on behaviour by considering different soil classes was investigated using linear and non-linear methods. For this purpose, three models were created with the ratio of height to plan size as 0.67, 1.0 and 2.0. For models with equal building heights and a square storey plan, a wall frame structural system setup was created with equal ratios of total shear wall area to storey area in both horizontal directions. Each model was considered with 5 different soil classes and a total of 15 models were studied. The results obtained are summarized below.

- As the H/L ratio approaches 1.0, the earthquake load acting on the structure increases in proportion to its weight. In addition to, although the earthquake load acting on the structure is quite close for ZA and ZB, it increases rapidly for ZC, ZD and ZE.
- These results show that if the building height is the same, the unit load on the foundation decreases even though the total structure weight increases, due to the increase in the structure slenderness ratio, in structures where the same size structural element sections are used.
- It has been observed that the ratio of building base overturning moments to building weights increases due to increasing earthquake loads as soil conditions worsen. Although the results for ZA and ZB, which are described as hard rock soil, are quite close, it has been observed that the difference between the ratios increases rapidly as the soil conditions worsen.
- There was no significant variance noted in the average reinforcement ratios required for columns across models situated on ZA and ZB class soils. However, as the soil type deteriorated, the rates for the M1 model, characterized by the highest slenderness, generally surpassed those of other models. In contrast, for beam elements, the necessary reinforcement increased as the soil quality degraded. it can be concluded that for

structures with identical shear wall ratios, columns expose greater loads in slender structures, whereas beam elements expose greater loads in structures with less slenderness.

- When the relative storey-drifts were evaluated, it was seen that the ZA and ZB results were quite close to each other. However, the effect of structural slenderness from ZC to ZE on the results is clearly seen. For all soil classes, the relative storey drift levels in the M1 model, which has the highest slenderness, were higher than the other models. The models with the lowest relative storey drifts were the M2 models with the H/L ratio of 1.0.

- When the ratio of the base moment of the edge walls to the total base moment of the structure is examined, it is seen that the edge walls are more stressed in M1 models where the slenderness effect is high. In addition, the difference in soil class did not have a significant effect on this situation.

- According to the linear analysis results, it can be summarized that although it showed that the slenderness effect had little effect on the results for hard soils ZA, ZB and relatively hard soil ZC, it showed that slenderness was effective in adverse soil conditions as the soil conditions worsened.

- When the non-linear calculation results were examined, it was seen that there was no damage to the models for ZA and ZB. However, it was observed that the damage levels, especially in the beam elements, increased with increasing horizontal load for ZC, ZD and ZE. In addition, it has been observed that the damage levels in structural elements decrease as the structure slenderness decreases.

- The results showed that the best structural performance was in the M3 models, and the most negative results were in the M1 models, which have the highest slenderness. When the nonlinear calculation results were examined, it was seen that, similar to the linear calculation results, although structural slenderness did not have a significant effect on hard soils, it could have a significant effect on structural behaviour as soil conditions deteriorated.

- As the natural period decreased due to the increase in stiffness, the M2 models were exposed to more horizontal loads in proportion to their weight for each soil class, as they were subjected to greater earthquake effects.

- In the M1 models, the increasing average relative storey displacement value due to the low horizontal stiffness was effective in increasing the secondary order effects. In the M3 models, although the slenderness effect is minimal, second order effects increased due to the excess vertical load from the increased mass. In this case, when horizontal displacement and vertical load effects are considered together, the least secondary order effects emerged in the M2 models. This situation can be further explained by the fact that M2 models are exposed to relatively more horizontal loads than other models due to their rigidity, considering that the storey heights are equal.

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