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Impact of Local Soil Conditions on the Seismic Performance of Reinforced Concrete Structures: In the Context of the 2023 Kahramanmaraş Earthquakes

Ercan Işık [1,*], Fatih Avcil [1,*], Aydın Büyüksaraç [2], Enes Arkan [3] and Ehsan Harirchian [4]

[1] Department of Civil Engineering, Bitlis Eren University, Bitlis 13100, Türkiye
[2] Çan Vocational School, Çanakkale 18 Mart University, Çanakkale 17400, Türkiye; absarac@comu.edu.tr
[3] Department of Architecture, Bitlis Eren University, Bitlis 13100, Türkiye; earkan@beu.edu.tr
[4] Institute of Structural Mechanics (ISM), Bauhaus-Universität Weimar, 99423 Weimar, Germany; ehsan.harirchian@uni-weimar.de
* Correspondence: eisik@beu.edu.tr (E.I.); favcil@beu.edu.tr (F.A.)

Abstract: Devastating earthquakes around the world highlight the crucial need to understand the seismic performance of structures. Local soil conditions are among the most significant factors influencing a structure's seismic behavior. Earthquake–soil–structure interactions directly affect seismic damage levels. In performance-based earthquake engineering, accurate target displacements enable a more realistic estimation of the expected performance levels for structures. This depends on obtaining realistic local soil conditions. This study conducted structural analyses on seven different variables, considering four different local soil conditions specified in Eurocode 8. The variables selected were importance class, peak ground acceleration (PGA), damping ratio, ground storey height, frame openings, number of storeys, and storey height, applied to a symmetrical and regular reinforced concrete structure. Period, base shear, stiffness, and target displacements were obtained for each variable through pushover analyses for the four various local soil conditions. All structural results were compared with one another and with other variables. This paper also aimed to reveal the effect of local soil conditions in the context of the 6 February 2023 Kahramanmaraş (Türkiye) earthquakes. The study confirms that variations in soil types, as classified in Eurocode 8, have a major impact on the seismic behavior of reinforced-concrete structures. Weaker soils amplify seismic effects, increasing target displacements and structural vulnerability.

Keywords: local soil condition; importance class; damping ratio; PGA; storey; RC

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1. Introduction

Earthquakes are one of the most important natural disasters, and even with today's technology, it is not possible to predict their location, time, or magnitude in advance. The extensive loss of life and property caused by earthquakes that severely damage the built environment highlights the critical need for earthquake-resistant structural design. In this context, the goal is to minimize possible structural damage by considering the earthquake–soil–structure interaction. The different characteristics of these three parameters directly affect the seismic behavior of structures. Studies conducted before or after earthquakes are generally focused separately on these three main factors or their mutual interactions [1–6]. This study aims to reveal the effect of local soil conditions on the seismic behavior of buildings, particularly through the use of different variables in numerical models.

Local soil conditions influence the impacts of seismic waves on the ground surface in earthquake-prone regions. Surface topography and ground stratigraphy significantly affect the amplitude and frequency of seismic motion. The effect of an earthquake on a structure is often amplified differently than it would be in a rock environment. This phenomenon is known as ground amplification, leads to an increase in the expected damage to structures. Topographical irregularities are closely related to ground amplification. Topography that exhibits seismic motion features such as wave type, wavelength, angle of entry, and azimuth can provide evidence of ground amplification. In any case, topography significantly alters ground motion depending on the sensitivity of the ground surface motion to the angle of entry and the slope angle. As the surface slope increases, the focus of seismic waves changes. Ground amplification is generally more significant in the horizontal components than in the vertical components [7]. Local soil conditions determine the seismic performance of a region and directly affect the seismic behavior of structures. The transmission or absorption of seismic waves varies depending on changes in soil properties. One of the factors directly considered in the design and assessment of structures under vertical and horizontal stresses is the local soil conditions [8–11]. Additionally, the groundwater level (GWL) in the foundation soil where a structure is to be built directly impacts the soil's behavior under earthquake effects. The groundwater level is a key factor affecting soil-bearing capacity and seismic performance. Depending on the soil class and GWL, liquefaction can cause structural damage at varying levels. Furthermore, the seismic activity in any given region is another factor influencing the seismic performance of soils. A realistic evaluation of the effects of these and similar factors on structures depends on the detailed, accurate, and comprehensive determination of local soil conditions. Numerous studies have examined the behavior of structures under earthquake risk due to local soil conditions. These studies compare structural analysis results using different variables and soil classes across various structural systems.

Geophysical methods are highly effective in determining local ground effects. While most studies use earthquake records, some studies are conducted with micro-tremors. In areas where geotechnical parameters are well known, analytical calculations based on the surface wave inversion technique and experimental methods that calculate the frequency spectrum directly from recorded ground motion are the two primary techniques used in these studies. In inversion-based techniques, the natural vibration of the medium is recorded, and dispersion-based signal separation from noise can be obtained passively through refraction micro-tremor and spatial autocorrelation methods or actively via multi-analysis of surface wave techniques. In experimental methods, the standard spectral ratio method is used, which is obtained by comparing the frequency spectrum of loose units on the bedrock with the frequency spectrum of the bedrock itself [12–15]. Another method involves obtaining the spectral ratios (H/V) of horizontal and vertical components using single-station micro-tremor records [16–22]. Several studies have examined the seismic performance of structures considering local soil conditions. Avcil et al. [23] investigated the effects of local soil conditions on target displacements in different earthquake zones for a sample reinforced concrete (RC) structure. In another study, Dogan [24] developed a model to estimate the shear strength of the column–beam joint zone, which is critical in RC buildings. Fiamingo et al. [25] revealed the effects of soil on the seismic behavior of a structure damaged in the 2018 Italy earthquake. Mase et al. [26] examined liquefied soils in detail through a field study conducted after the 2014 Thailand earthquake. Civelekler et al. [27] attempted to reveal the local field effects on soil responses in Eskişehir province. Galal and Naimi [28] investigated the near-field fault effect of soil conditions on 20- and 8-storey RC building examples. İnce [29] evaluated the relationship between soil and structural damage in the Istanbul region before a possible earthquake. Çelebi et al. [30]

assessed the impact of soil–structure interaction on the seismic behavior of structures using nonlinear finite element analysis. Yön et al. [31] studied the effects of local soil conditions, as defined in the Turkey Earthquake Code, on storey displacements, section effects, and energy distributions in RC structures. Gallipoli et al. [32] evaluated the resonance effect by considering soil–structure interaction in the Italian city of Matera. İnce et al. [33] numerically investigated the effects of local soil conditions on both design and cost for a two-storey RC building example. Bybordiani and Arici [34] examined the effects of local soil conditions on structures with three different stories constructed in adjacent arrangements using the finite element method. Ülker and Işık [35] (2021) evaluated the effects of local soil classes given in the Turkish Building Earthquake Code (TBEC-2018) on the seismic behavior of steel structures. Akyıldız et al. [36] studied the changes in sectional effects on an RC structure for different soil classes specified in the seismic design code currently used in Türkiye.

Studies including both structural and geotechnical evaluations have also found a place in the literature following the 2023 Kahramanmaraş earthquake, which caused great destruction for Türkiye. In studies evaluating geotechnical damages, ground-related damages were evaluated in detail. In these studies, soil–structure interaction was evaluated based on observation and they did not include any structural analysis [37–42]. In some of the studies evaluating the damages in different structural systems, after the devastating Kahramanmaraş earthquakes, within the scope of civil and earthquake engineering, there are numerical analyses for the structures selected as examples [43–52].

Within the scope of this paper, the effects of local soil conditions were first evaluated in light of the 6 February Kahramanmaraş (Türkiye) earthquake through numerical analysis. Structural analyses were conducted by considering seven different variables for four different local ground classes specified in Eurocode 8, which is widely used worldwide, for the selected RC numerical model. The variables selected included importance class, peak ground acceleration (PGA), damping ratio, the ground storey height of the structure (which is higher than the other storeys), the frame span of the RC structure, total number of storeys, and storey height. The base shear, period, effective stiffness, elastic stiffness, and target displacements used in the seismic performance analysis of structures were obtained separately for each variable and different soil classes. The main objective of this study is to reveal the effects of different soil conditions on various structural parameters. A key aspect that distinguishes this study from others is that it provides a detailed analysis of the effect of local soil conditions on the seismic behavior of the building across many different variables. Unlike previous studies that examined individual parameters in isolation, this study offers a holistic analysis of multiple interacting factors influencing seismic performance. Furthermore, we incorporate insights from the 2023 Kahramanmaraş earthquakes, adding a real-world perspective that is often absent in purely numerical analyses. While soil–structure interaction has been extensively studied, much of the existing research focuses on individual parameters rather than their combined effects. Additionally, most studies rely exclusively on numerical models without validating findings against real earthquake damage. This study bridges these gaps by analyzing multiple structural variables simultaneously and comparing the results with observed damage from the 2023 Kahramanmaraş earthquakes.

2. Method

2.1. Damages by Local Soil Conditions in the Light of 2023 Kahramanmaraş Earthquakes

Türkiye is located in a region with a very high seismic risk. The northeastward rotation of the African plate, the pushing of the Arabian Peninsula toward the north–northwest of Anatolia, the southward rotation of Eurasia, and the neotectonic conditions resulting from the pushing of Anatolia toward the south have caused the formation of the Eastern

Anatolian Fault Zone (EAFZ) and the Northern Anatolian Fault Zone (NAFZ). As a result of these movements, the Anatolian Plate is moving westward (Figure 1).

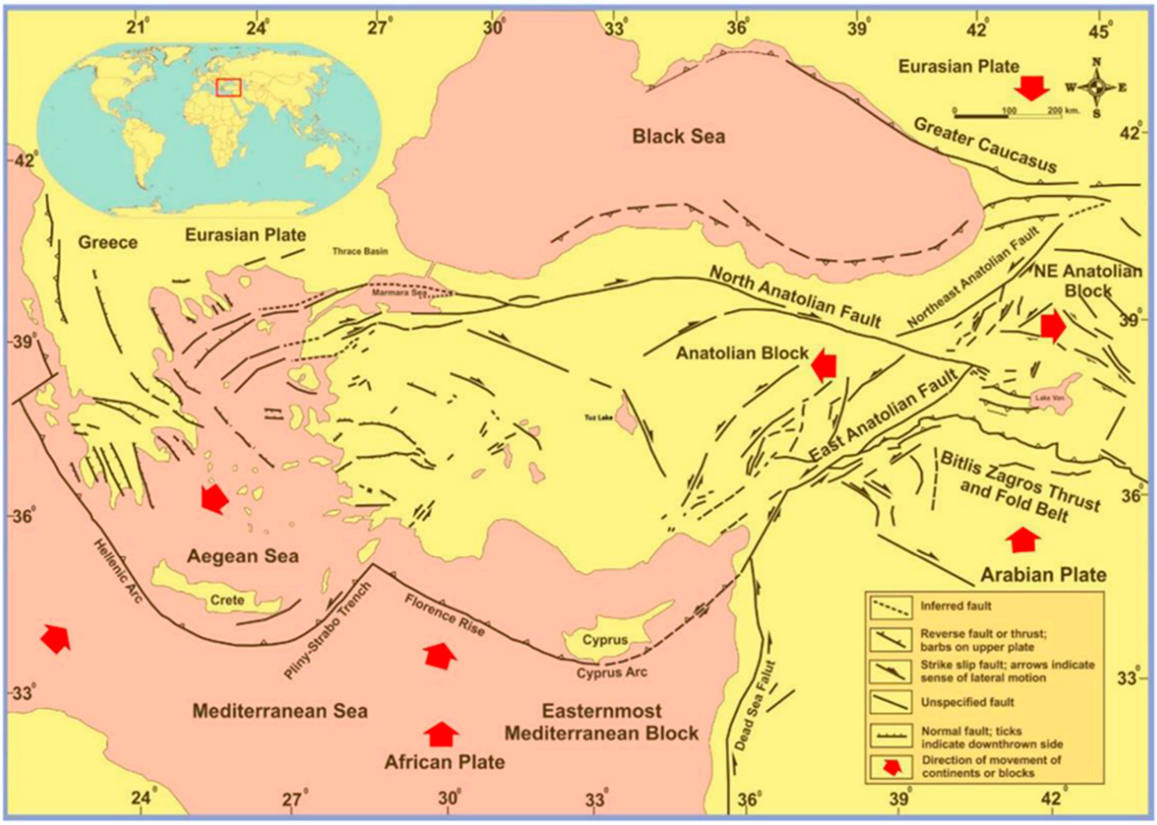

Figure 1. Locations of active tectonic elements in Anatolia and its surroundings [53].

These movements cause large and destructive earthquakes. In the last century, 16 earthquakes with magnitudes of 7.0 and greater have occurred in the two fault zones in Türkiye. Among these earthquakes, the highest loss of life occurred in the 1939 Erzincan earthquake (M_w = 7.9, 32,000 deaths; M_w is moment magnitude), the 1999 Gölcük (Kocaeli) earthquake (M_w = 7.4, 25,000 deaths), and most recently, the 6 February 2023 Kahramanmaraş earthquakes (M_w = 7.7 and 7.5, 50,000 deaths).

The first earthquake in the 6 February 2023 Kahramanmaraş sequence, with a magnitude of M_w = 7.7, struck south-eastern Türkiye at 04:17 (UTC+3), making it the second-largest earthquake in Türkiye's instrumental period in terms of magnitude. This earthquake was the beginning of a series of major earthquakes that followed one after another. Within minutes, an aftershock of M_w = 6.6 occurred. About nine hours later, another main shock with a magnitude of M_w = 7.6 was followed by aftershocks of magnitudes M_L = 5.7 (M_L is local magnitude) and M_w = 6.0, along with numerous smaller aftershocks. Another main shock of M_w = 6.4 struck on 20 February 2023. As a result of these disasters, more than 50,000 people lost their lives across 11 cities, over 100,000 people were injured, and more than 550,000 homes were rendered uninhabitable [54–56]. When considering the fault systems where these earthquakes occurred, the fact that nearly all of them struck various fault segments raises the possibility of further main shocks. Since this zone is part of the East Anatolian Fault Zone, it could be seen as a series of earthquakes triggered by a small movement (Figure 2).

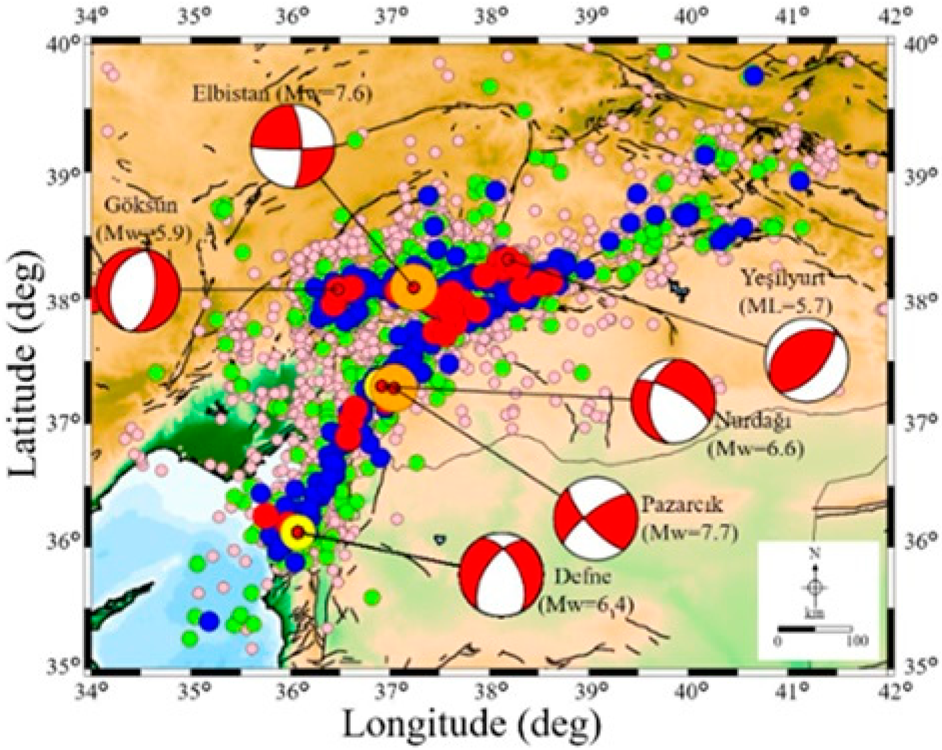

Figure 2. Distribution of earthquakes and subsequent aftershocks on 6 February 2023.

The first earthquake (M_w = 7.7) struck within the Eastern Anatolian Fault Zone (EAFZ) and is located at the northern border of the Dead Sea Fault Zone (DSFZ). Due to the complex tectonic structure of the area, the earthquakes are interrelated. The EAFZ, with its left-lateral strike-slip and approximate 580 km length, transfers stress to adjacent segments after each earthquake. Duman and Emre [57] indicated that there is a probability of major earthquakes occurring in the short term along the Amanos, Pazarcık, and Pötürge fault segments in the EAFZ. In this paper, the expected sites of seismic hazards in the North Anatolian Fault Zone (NAFZ) were identified by applying the Coulomb stress analysis method. The Coulomb analysis, guided by Alkan et al. [58] on stress transfer and the triggering of segments in the EAFZ following the 24 January 2020 Sivrice (Elazığ) earthquake (M_w = 6.8), suggested that the next earthquakes are likely to occur between Diyarbakır, Adıyaman, and Bingöl, as well as the Elazığ region northeast of Kahramanmaraş. A study examining the focal depths of disasters in the EAFZ observed that small- and medium-sized earthquakes systematically migrated from the primary fault to neighboring fault segments [59].

These earthquakes caused extensive structural damage in many provinces. The occurrence of earthquakes in the same province on the same day, along with subsequent aftershocks, exacerbated the extent of the destruction. The earthquakes also caused significant damage to both the ground and structures. When examining the ground-related damages after the Kahramanmaraş earthquakes, it was observed that the damage was primarily concentrated in three areas: proximity to the fault, liquefaction, and the effects of thick sediment basins and bearing capacity problems (Figure 3). In the visuals between Figure 3a–f, undulations and collapses in the ground occurred due to the close fault effect and fracture propagation. The effects of ground liquefaction are illustrated in Figure 3g–h. An example of overturning damage caused by inadequate soil–foundation connection is shown in Figure 3i.

Figure 3. Examples of ground-based damage (**a**–**f**): undulations and collapses in the ground; (**g**,**h**): liquefaction; (**i**): inadequate soil–foundation connection.

In regions such as Hatay and Gölbaşı (Adıyaman), settlements were made on very thick sedimentary units, and most structures were built with shallow foundations. The basin-type sedimentary formations in these areas caused significant shaking during earthquakes, leading to severe damage, primarily due to ground-related issues such as bearing capacity problems and liquefaction. In Hatay city center and its districts, multi-storey buildings sustained extensive damage, and more than 22,000 people lost their lives. In Gölbaşı (Adıyaman), predominantly single- or two-storey buildings remained largely unaffected, while buildings of three or more storeys suffered heavy damage. In the Kahramanmaraş earthquakes, much of the damage was linked to factors like soil liquefaction, the amplification of seismic waves, and construction quality. Especially regarding the role of soil in earthquake impacts, the specific soil characteristics of the region in question (liquefaction potential, amplification effects, etc.) should be carefully considered when applying these findings to other earthquake-prone areas. Specific mitigation strategies and construction techniques are necessary to address the local geotechnical conditions and seismic hazards. As a result, considering the details of the earthquake–soil–structure triple interaction will minimize possible damage.

2.2. Seismic Performance Evaluation of the Sample RC Structural Model

In this part of the paper, analyses of structures were performed for the effects of different soil classes on different variables for the sample 7-storey RC building. Structural analyses were carried out separately for each parameter with Seismostruct 2024 software [60]. Pushover analysis was used in all numerical analyses. Damping ratio, importance class of the structure, different earthquake zone, and four different structural models for each of four different local soil classes, were considered as variables.

Materials and Assumptions

A mutual interaction occurs between the ground and the structure, and this interaction significantly affects the seismic behavior of the structures during earthquakes. The interaction of different parameters in the earthquake–structure–soil interaction directly affects the predicted performance level of the structures. Consideration of the parameters that are effective in this interaction is of great importance in earthquake design and can be a critical factor for the durability of structures. Local soil conditions naturally vary in the earthquake region. In this context, to reveal the effects of different local soil classes, while selecting the local soil class, which is the main variable, four different local soil classes in Eurocode 8, which is more widely used around the world, were taken into account. The characteristic properties of these soil classes are shown in Table 1.

Table 1. Classification of the local soil classes [61].

Soil Class	Description of Stratigraphic Profile	V_{s30} (m/s)	N_{SPT} (Blows/30 cm)	C_u (kPa)
A	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface	>800	-	-
B	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of meters in thickness, characterized by a gradual increase of mechanical properties with depth	360–800	>50	>250
C	Deep deposits of dense or medium-dense sand, gravel, or stiff clay with thickness from several tens to many hundreds of meters.	180–360	15–50	70–250
D	Deposits of loose-to-medium cohesion less soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil.	<180	<15	<70

The sample RC structural model was selected as the reference building and the blueprint of the storey of this model is shown in Figure 4.

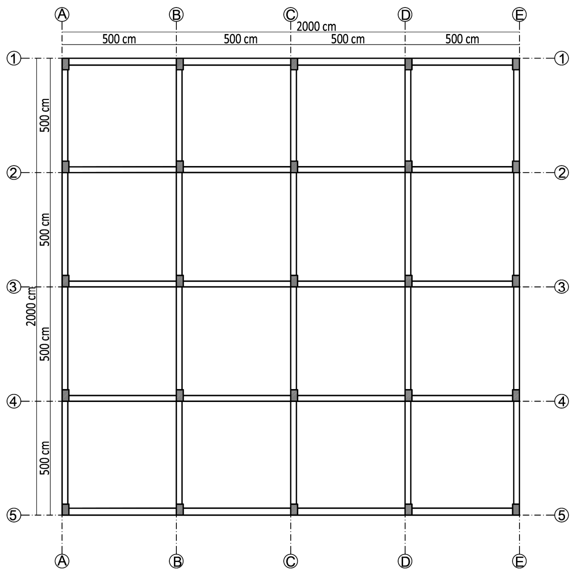

Figure 4. The blueprint of the sample RC numerical model.

Since regular reinforced concrete buildings were examined within the scope of this study, a reinforced concrete building model that does not contain any irregularities and is symmetrical in both X and Y directions was selected. Each opening was considered as 5 m in both directions, taking into account the average distance between two columns in the reinforced concrete structures examined in the earthquake region. In earthquake regions, the commonly preferred storey heights in reinforced concrete buildings vary between 2.80–3.20 m. In the sample structural model, these values are taken into account and the average storey height is taken into account and is selected as 3 m. No changes were made to the storey heights in the building model, and all storey heights were taken as equal. Therefore, the sample structural model does not contain any irregularities both vertically and in plan. The concrete grade was selected as C25/30 and the reinforcement material grade was selected as S420. Material grades for concrete and reinforcement are taken from the seismic design code (TBEC-2018) [62] currently used in Türkiye. The same size and reinforcements were used in all columns and beams. In the region affected by the 2023 Kahramanmaraş earthquakes, medium-rise reinforced concrete buildings were widely preferred. The reference building was taken as 7-storey in order to represent such structures. The sample reinforced-concrete structural model was considered as a pure reinforced-concrete frame, especially considering the RC structures before 2000 in the earthquake region. Therefore, the reference model does not contain any reinforced concrete shear walls. After numerical modeling, structural analyses were performed by applying both vertical and horizontal loads. The 2D and 3D models of the building and the applied loads are illustrated in Figure 5.

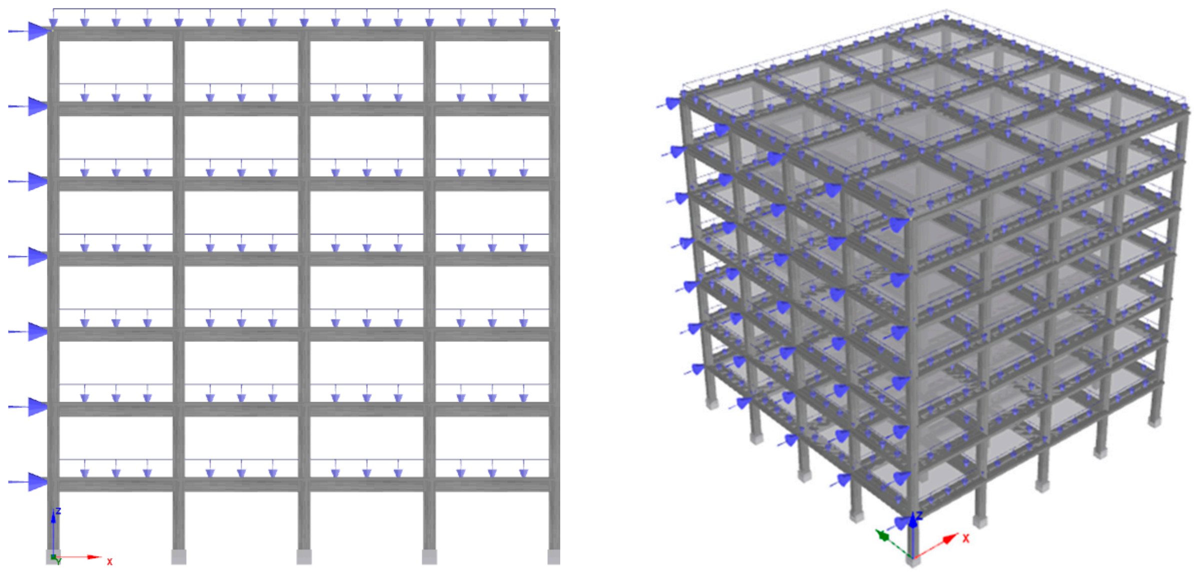

Figure 5. The 2D and 3D structural models and applied load.

In all structural models, force-based plastic hinge frame elements (infrmFBPH) were selected for the columns and beams. These elements restrict plasticity to a specific length and simulate force-based flexibility in extension. To accurately represent the stress–strain distribution across the section, an appropriate number of fiber elements were utilized. For the chosen sections, a total of one hundred fiber elements were assigned. The plastic–hinge length (L_p/L) was determined to be 16.67%. The column boundary conditions were set to resemble those of a cantilever, resulting in a fully fixed base and a free top end. The structural characteristics of the RC structural model are shown in Table 2.

Table 2. Structural characteristics of the RC structural model.

Parameters		Value
Concrete grade		C25/30 (25 MPa)
Reinforcement grade		S420 (420 MPa)
Beams (mm)		250 × 500
Height of floor (mm)		120
Storey heights (mm)		3000
Concrete cover (mm)		25
Columns (mm)		400 × 500
Columns longitudinal reinforcement	Corners	4Φ20
	Top bottom	4Φ16
	Left right	4Φ16
Columns transverse reinforcement		Φ8/150
Beam transverse reinforcement		Φ8/150
Type of the constraint		Rigid diaphragm
Incremental loads		5 kN
Permanent loads		5 kN/m

Pushover analysis was applied to all structural models. Pushover analysis is a structural engineering method used to estimate the seismic performance of a building or structure under earthquake loading. It is a static, nonlinear procedure that involves applying increasing lateral forces (representing the effects of an earthquake) to a model of the structure until it reaches a target displacement or failure point. The analysis helps to assess how a structure will behave under seismic forces, identifying potential weak points and providing valuable insights into its vulnerability. Pushover analysis is particularly useful for evaluating buildings that are expected to perform nonlinearly during an earthquake, offering a more realistic picture of their behavior compared to linear analysis methods [63–67]. The study does not explicitly mention using a recorded accelerogram from the 2023 Kahramanmaraş earthquakes. Instead, seismic forces were applied based on pushover analysis, which is a static, nonlinear procedure rather than a dynamic time-history analysis.

One of the results obtained from numerical analysis for each structural model considered within the scope of the study is the target displacements. It is crucial to define target displacements for failure assessment when specific performance limits of structural components are reached in performance-based structural engineering [68,69]. In the widely adopted Eurocode 8 (Part 3), target displacements are determined by considering limit states [61,70,71]. A detailed explanation of the limit states considered in the paper is provided in Table 3, where all results from the numerical analyses are also presented.

Table 3. Classification of the limit states in Eurocode 8 (Part 3) [60,70,71].

Limit State	Description	Return Period (Year)	Probability of Exceedance (in 50 Years)
Limit state of damage limitation (DL)	Only lightly damaged, damage to non-structural components economically repairable.	225	0.20

Table 3. *Cont.*

Limit State	Description	Return Period (Year)	Probability of Exceedance (in 50 Years)
Limit state of significant damage (SD)	Significantly damaged, some residual strength and stiffness, non-structural components damaged, uneconomic to repair.	475	0.10
Limit state of near collapse (NC)	Heavily damaged, very low residual strength and stiffness, large permanent drift but still standing.	2475	0.02

The limit states taken into consideration are shown on the typical pushover curve in Figure 6.

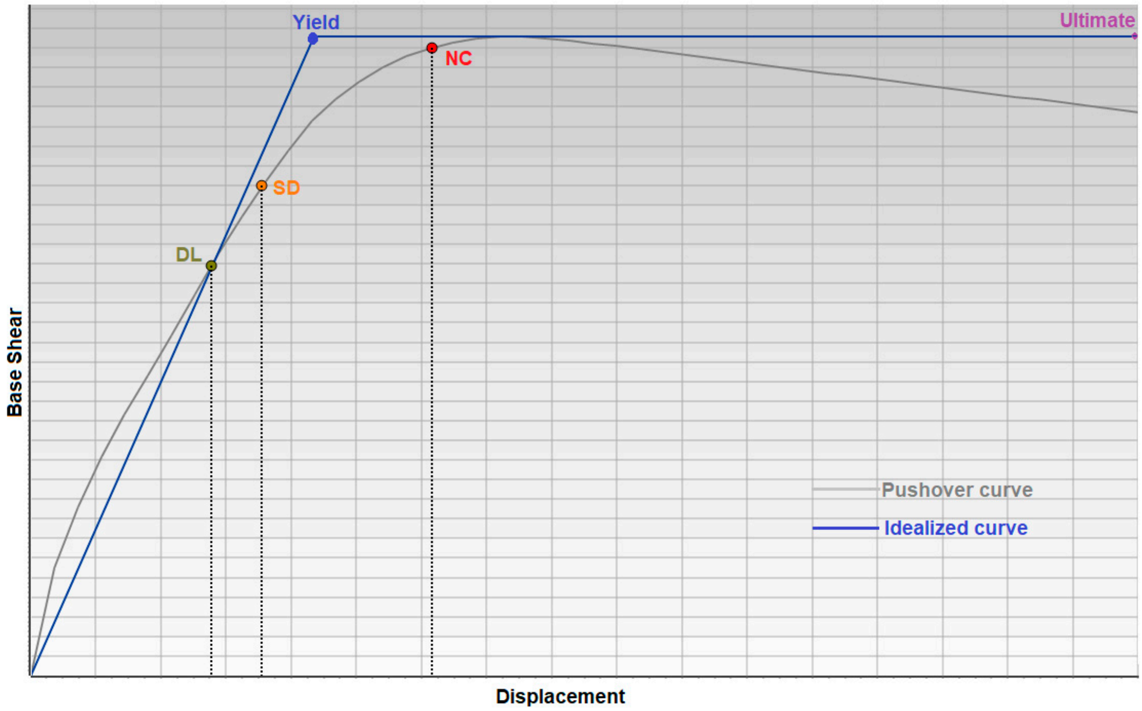

Figure 6. Limit states on the typical pushover curve.

3. Results and Discussion

3.1. Seismic Performance Analysis for Different Damping Ratios

The damping ratio is one of the important characteristics of the earthquake ground motion, which is one of the parameters used in structural analyses. This ratio can be expressed as the decrease in the magnitude of the vibration motion over time. Structural dynamic parameters (natural frequency, period, and damping ratio) can be obtained using theoretical and experimental methods [72,73]. Although the damping ratio is difficult and complex to define, it is very important in terms of realistically determining the nonlinear behavior of the structure [74–76]. In this paper, structural analyses were applied by considering four different damping ratios such as 2%, 5%, 7%, and 10%. The comparison of the target displacements attained for various damping ratios as variables is shown in Table 4.

Table 4. Target displacements for different soil classes and damping ratios.

Soil Class	Target Displacements (m)	Damping Ratio (%)			
		2	5	7	10
ZA	DL	0.0507	0.0424	0.0387	0.0346
	SD	0.0650	0.0544	0.0496	0.0444
	NC	0.1127	0.0943	0.0861	0.0770
ZB	DL	0.0760	0.0636	0.0580	0.0519
	SD	0.0975	0.0816	0.0745	0.0666
	NC	0.1690	0.1414	0.1291	0.1155
ZC	DL	0.0874	0.0731	0.0668	0.0597
	SD	0.1121	0.0938	0.0856	0.0766
	NC	0.1944	0.1626	0.1485	0.1328
ZD	DL	0.1368	0.1145	0.1045	0.0934
	SD	0.1755	0.1468	0.1340	0.1199
	NC	0.3042	0.2545	0.2324	0.2078

As the soil properties weakened, the target displacements increased to larger values from a structural safety perspective. Additionally, as the damping ratio increased, the target displacements decreased due to the reduction in earthquake effects. To better understand all the results, the comparisons are shown in Figure 7.

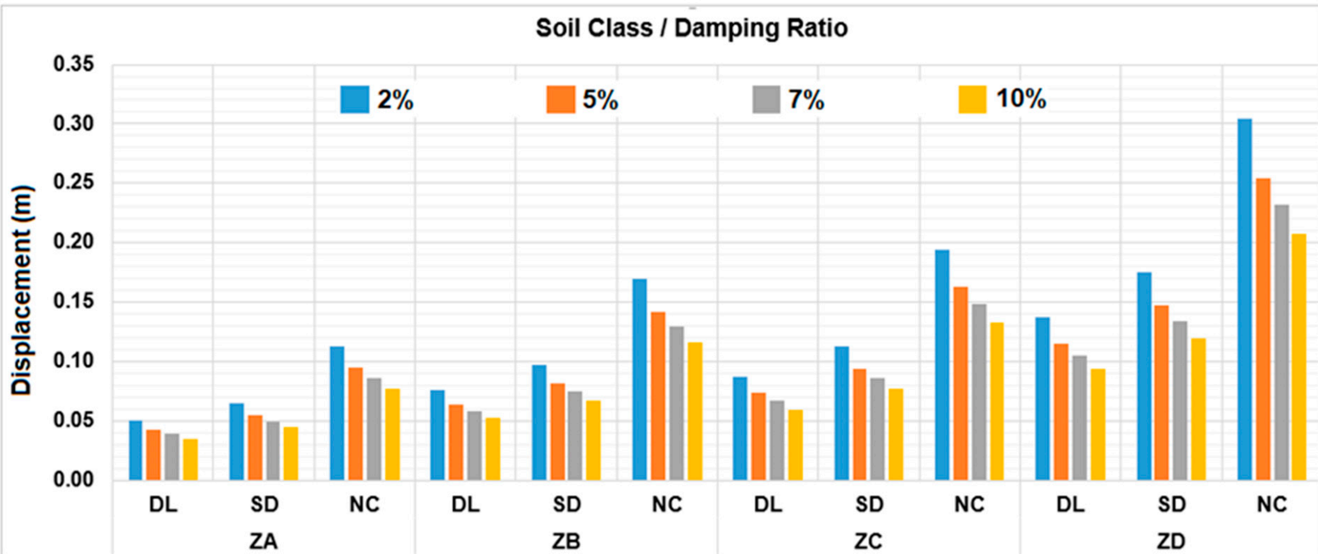

Figure 7. Comparison of target displacements for different soil and damping ratios.

3.2. Seismic Performance Analysis for Different Importance Class of the Structure

One of the other parameters used in the design and evaluation of structures under the effect of earthquakes is the importance class of the structure, which changes depending on the purpose of usage of the structure. This parameter varies especially according to its use after the earthquake and the number of people who will use it. For this purpose, the concept used in seismic design codes is the importance class of the structure, which can take different coefficients for different types of structures. Considering the usability priority of any structure adds meaning to structural analyses. It is an expected result that the sensitivity to be shown in buildings that must be used after earthquakes will be different.

In this study, four different importance classes in Eurocode 8 were used, and these are shown in Table 5.

Table 5. Structure importance classes [77].

Importance Class	Description
I	Buildings of minor importance for public safety, e.g., agricultural buildings.
II	Ordinary buildings; not belonging to the other categories.
III	Buildings whose seismic resistance is of importance in view of the consequences associated with a collapse, e.g., schools, assembly halls, cultural institutions.
IV	Buildings whose integrity during earthquakes is of vital importance for civil protection, e.g., hospitals, fire stations, power plants.

The comparison of target displacements obtained from numerical analyses in the case where only local soil classes and structural importance class are selected as variables and other structural properties are constant is illustrated in Table 6.

Table 6. Target displacements according to different local soil conditions and importance classes of structure.

Soil Class	Target Displacements (m)	Importance Class			
		I	II	III	IV
ZA	DL	0.0339	0.0424	0.0509	0.0593
	SD	0.0435	0.0544	0.0653	0.0761
	NC	0.0754	0.0943	0.1131	0.1320
ZB	DL	0.0509	0.0636	0.0763	0.0890
	SD	0.0653	0.0816	0.0979	0.1142
	NC	0.1131	0.1414	0.1697	0.1980
ZC	DL	0.0585	0.0731	0.0877	0.1024
	SD	0.0750	0.0938	0.1126	0.1313
	NC	0.1301	0.1626	0.1951	0.2277
ZD	DL	0.0916	0.1145	0.1373	0.1602
	SD	0.1175	0.1468	0.1762	0.2055
	NC	0.2036	0.2545	0.3054	0.3563

As in the structural analyses conducted for other variables, the target displacement values increased with the weakening of the local soil properties. The situation is not very different in the usability priority of the structure after the earthquake. The target displacement values naturally increased due to the usage priority. Comparisons are shown in Figure 8 for a better understanding of all the results.

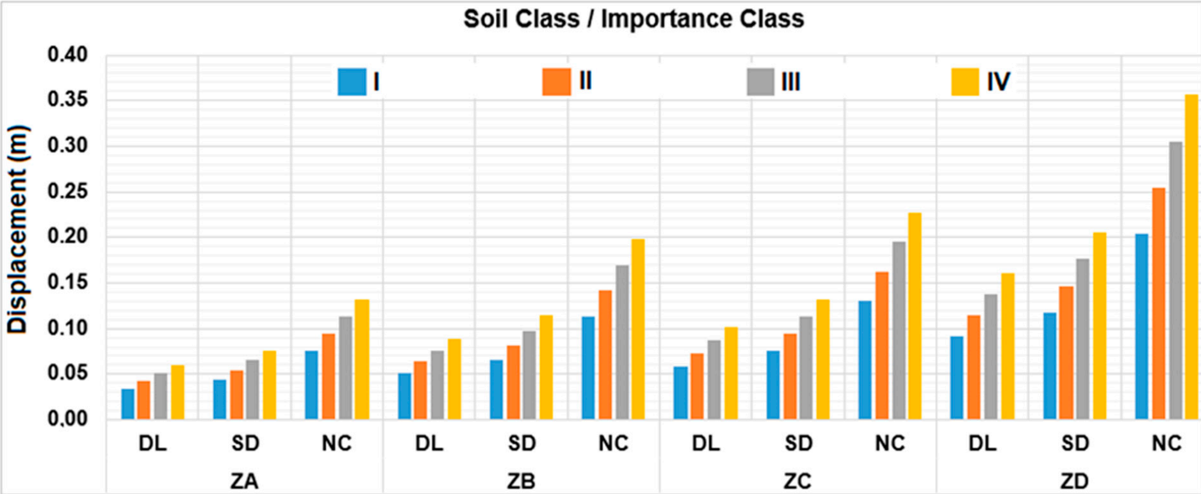

Figure 8. Comparison of target displacements for different soil classes and structure importance classes (I, II, III, IV).

3.3. Seismic Performance Analysis for Different Earthquake Zone Effect/PGA

The seismicity of a region is one of the significant parameters considered in both the design and evaluation of buildings. The magnitude of an earthquake plays an active role in determining the damage caused by the potential earthquake to structures. This is generally represented by PGA (peak ground acceleration). In this study, four different earthquake zones specified in the previous earthquake zone map of Türkiye were considered. Structural analyses were carried out using PGA values of 0.400 g for the I. degree earthquake zone, 0.300 g for the II. degree zone, 0.200 g for the III. degree zone, and 0.100 g for the IV. degree zone. These parameters, along with local soil classes, were chosen as variables in the analyses, while all other structural features were considered constants. The target displacements from different soil classes and changes in earthquake zones are shown in Table 7.

Table 7. Target displacements for different soil classes and PGAs.

Soil Class	Target Displacements (m)	PGA (g)			
		0.100	0.200	0.300	0.400
ZA	DL	0.0212	0.0424	0.0636	0.0848
	SD	0.0272	0.0544	0.0816	0.1088
	NC	0.0471	0.0943	0.1414	0.1885
ZB	DL	0.0318	0.0636	0.0954	0.1272
	SD	0.0408	0.0816	0.1224	0.1631
	NC	0.0707	0.1414	0.2121	0.2828
ZC	DL	0.0366	0.0731	0.1097	0.1462
	SD	0.0469	0.0938	0.1407	0.1876
	NC	0.0813	0.1626	0.2439	0.3252
ZD	DL	0.0572	0.1145	0.1717	0.2289
	SD	0.0734	0.1468	0.2202	0.2936
	NC	0.1273	0.2545	0.3818	0.5091

As the earthquake hazard of the location of the structure increases, the target displacements expected from the structure also increase. In case the soil properties are good, the target displacements decrease. This shows that structures built on solid ground will have less displacement under the effect of earthquake. The graphical comparison of these results is shown in Figure 9.

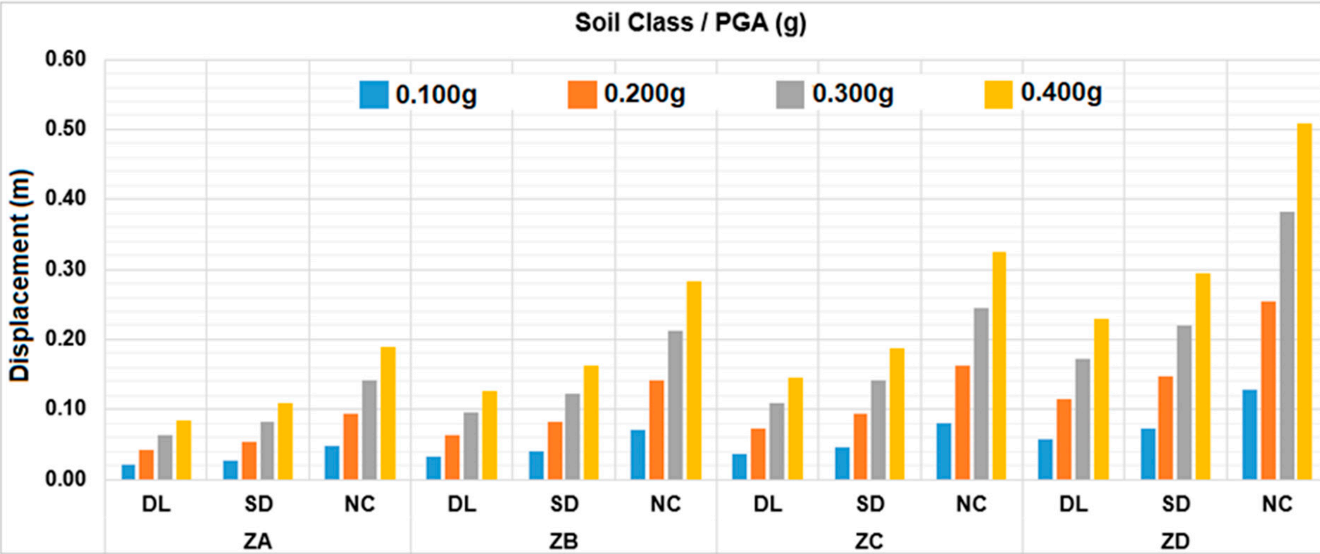

Figure 9. Comparison of target displacements for different soil classes and PGAs.

3.4. Seismic Performance Analysis for Other Structural Variables

In addition to the variables explained above, four other variables were taken into consideration within the scope of this study. Structural analyses were performed by creating separate structural models for each variable. Detailed explanations for each model are given below.

Model I: Another variable considered in this study is the number of stories. A six-storey structural model was preferred to compare the changes in the number of stories. In the RC building selected as a six-storey example, only the number of stories was selected as a variable and all other structural characteristics were selected as the same. The 2D and 3D models obtained for the six-storey sample RC building are shown in Figure 10.

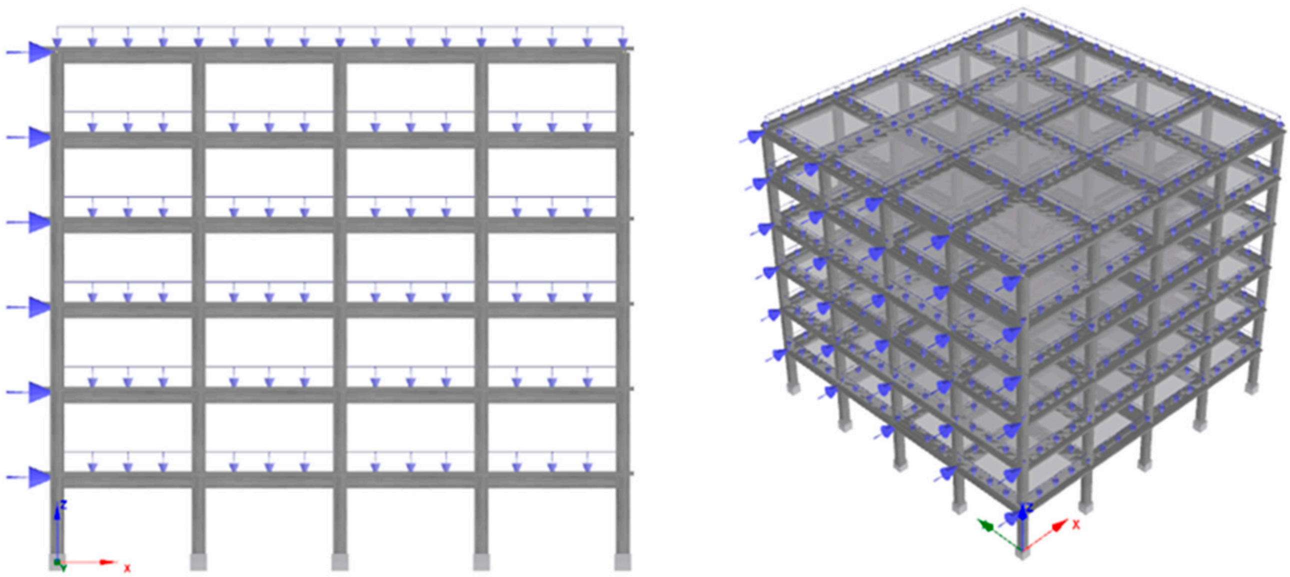

Figure 10. Applied loads for a six-storey sample RC building with 2D and 3D models.

The 2D models of these structural models are shown in Figure 11.

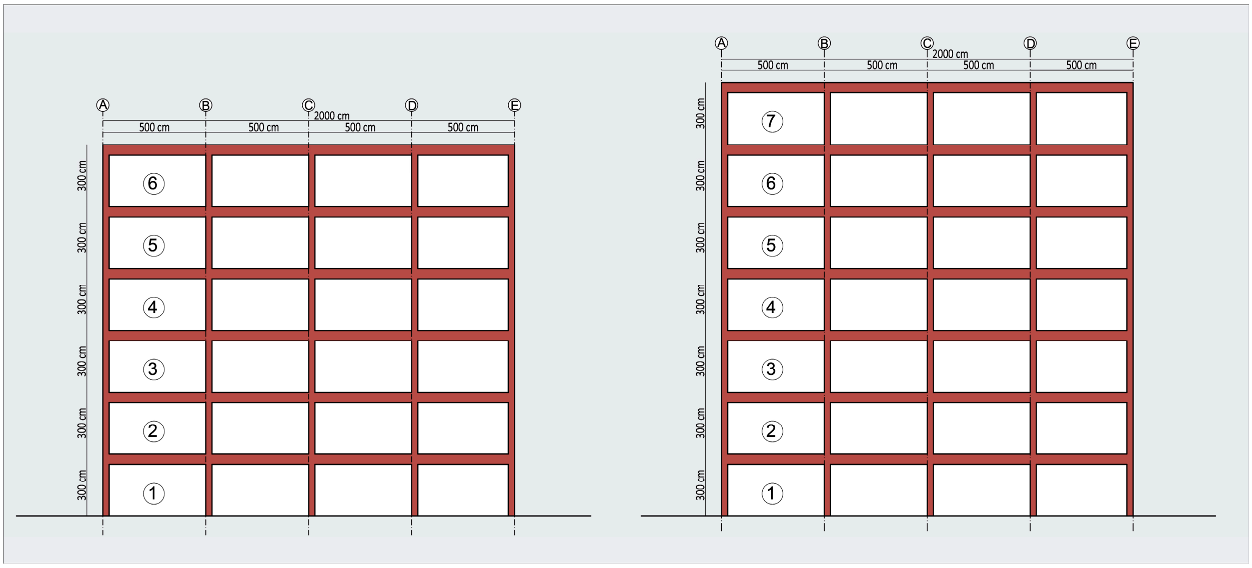

Figure 11. The 2D models of different numbers of stories.

Model II: One of the most common damages observed after an earthquake is structural damage caused by a soft/weak storey. This situation, which may occur due to different reasons, is due to the difference in strength/rigidity between storeys. In this study, the ground storey height was selected to be greater than the other storeys in order to reveal the effect of this situation. While all storey heights in the reference building were selected to be equal and 3 m, in the model created for comparisons, the ground storey height was selected to be 4 m, and the heights of all other storeys were selected to be equal and 3 m. Only the ground storey height was taken into account as a variable. The 2D models obtained are shown in Figure 12.

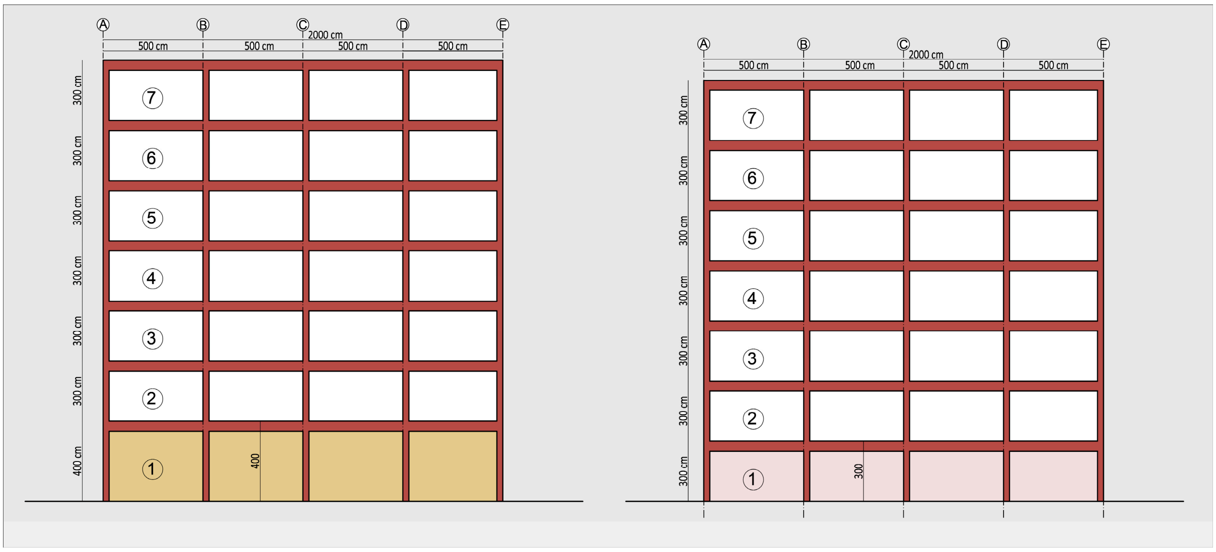

Figure 12. Structural models for the change of ground storey height.

Model III: Another variable was the change in RC frame openings. While each opening in both directions was 5 m in the reference building model, this value was selected as 6 m for comparisons. In this model, only the frame opening and local soil classes were selected as variables. The comparison of the storey plans of this model is made in Figure 13.

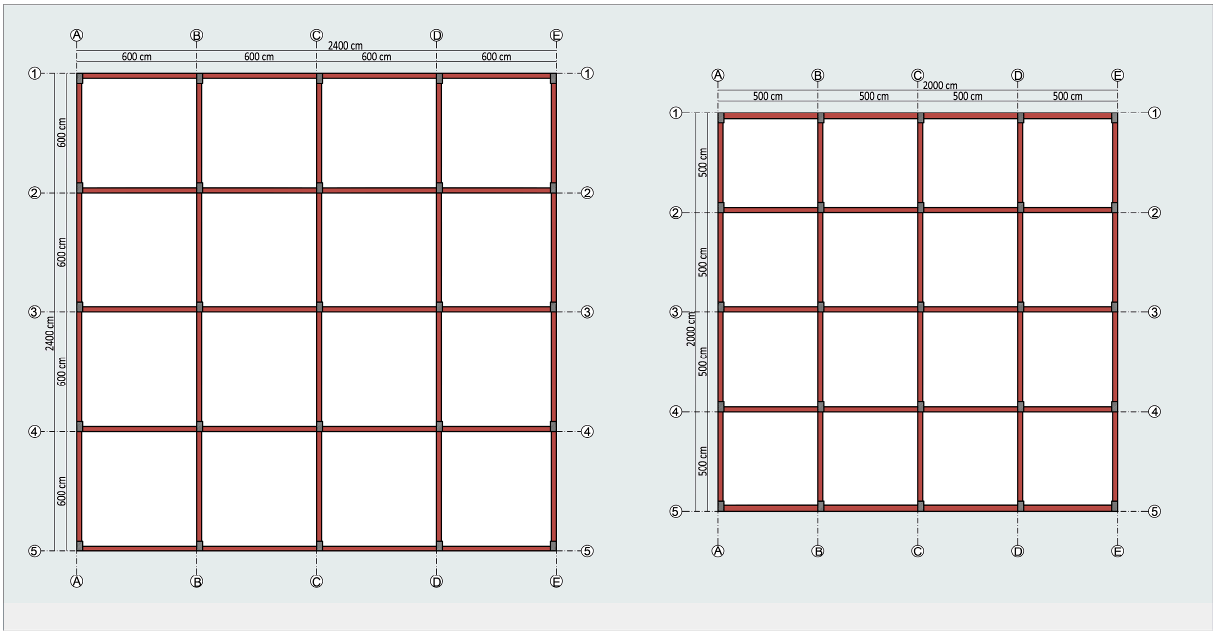

Figure 13. Storey formwork plans used for different frame openings.

In the structural model for different frame openings, other structural features were kept constant. Frame opening and local soil classes were selected as variables. The 2D structural models for frame opening changes are illustrated in Figure 14.

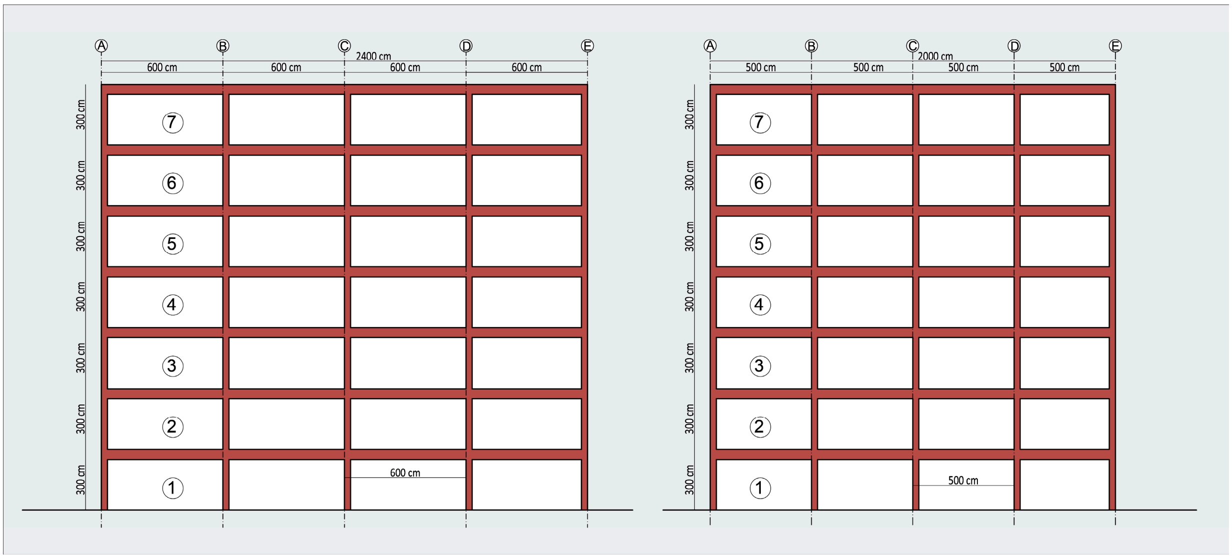

Figure 14. The 2D structural models obtained for different frame openings.

Model IV: Since reinforced-concrete buildings with different storey heights were observed in the earthquake region, storey height was selected as the variable in this model. A variable considered in the study was the height value of each storey in the building. In the analyses where all other structural characteristics were the same, each storey height was selected as 3 m for the reference building, while in the model where the comparisons would be made, each storey height was considered as 2.80 m. Therefore, while the total height of the reference building was 27 m, the total building height for the structural model created for comparison was 19.80 m. The 2D visuals obtained for both models are illustrated in Figure 15.

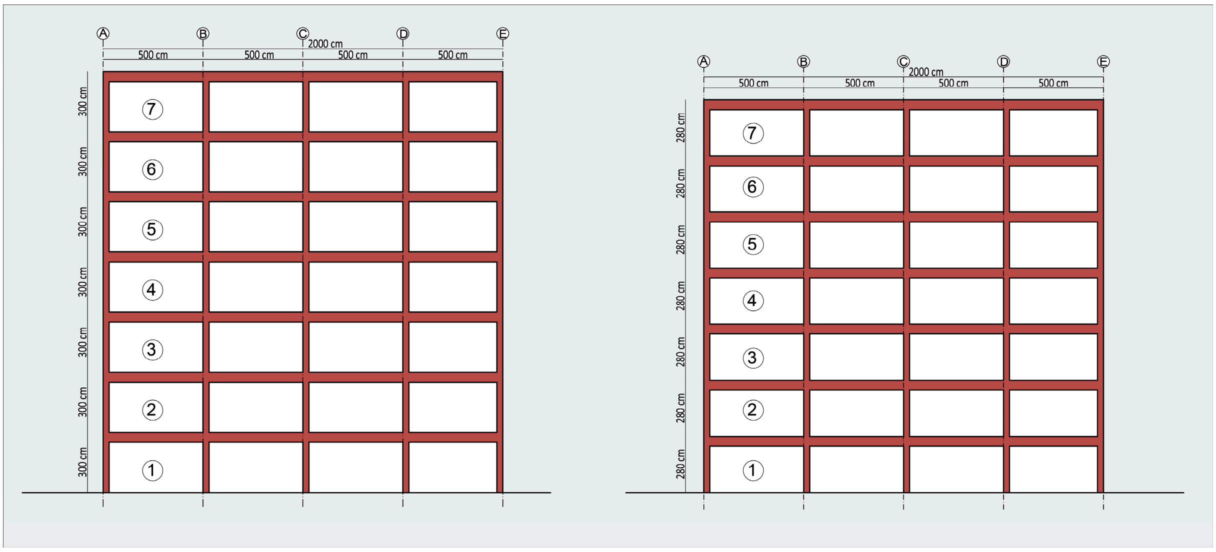

Figure 15. The 2D models obtained for different storey heights.

The comparison of the target displacement values attained for the created structural models for different soil classes is shown in Table 8. In all these structural models, the damping ratio was 5%, the structural importance class was II and the earthquake zone was the II-degree earthquake zone. All other structural parameters are considered the same as the reference building model.

Table 8. Target displacements for different soil classes and different structural models.

Soil Class	Target Displacements (m)	Model I	Model II	Model III	Model IV
ZA	DL	0.0369	0.0464	0.0473	0.0387
	SD	0.0473	0.0595	0.0607	0.0496
	NC	0.0821	0.1032	0.1053	0.0861
ZB	DL	0.0553	0.0696	0.0710	0.0580
	SD	0.0710	0.0893	0.0911	0.0745
	NC	0.1231	0.1548	0.1579	0.1291
ZC	DL	0.0637	0.0801	0.0817	0.0667
	SD	0.0817	0.1027	0.1048	0.0856
	NC	0.1416	0.1780	0.1816	0.1484
ZD	DL	0.0932	0.1253	0.1278	0.1020
	SD	0.1214	0.1607	0.1640	0.1315
	NC	0.2152	0.2787	0.2842	0.2299

The obtained results show that there are significant decreases in target displacements with good local soil conditions. For Model I, where the number of stories in the structure is reduced, target displacements have decreased compared to the seven-storey model, which is the reference building. The target displacements obtained for the structural model created by increasing the ground storey height and created relatively are greater than the target displacements obtained according to the reference building. An increase in target displacements occurred with the increase in frame opening. A decrease in target displacements was also observed for Model IV, where the height of each storey in the structure was reduced. Considering all of these parameters together in any structural design will ensure that the earthquake performance of the structures is at the desired level. The comparison of the target displacement values attained for different structural models is given in Figure 16.

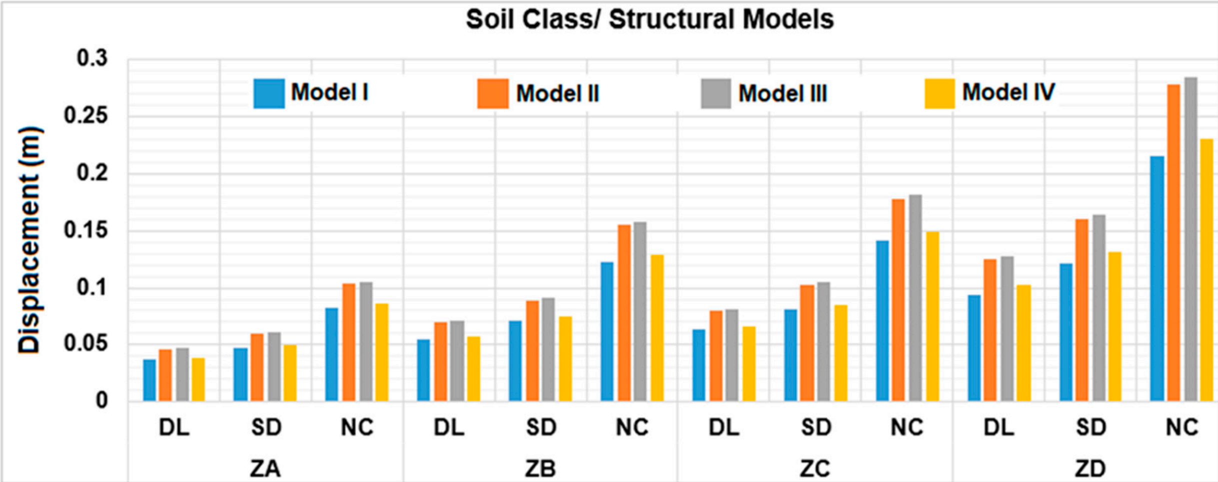

Figure 16. Comparison of target displacements for different soil classes and structural models.

Period, base shear force, elastic and effective stiffness values were also obtained for all structural models considered within the scope of the study. These results obtained from numerical analysis for all structural models are shown in Table 9.

Table 9. Comparison of the results obtained for structural models.

Soil Class	Parameter	Reference	Model I	Model II	Model III	Model IV
ZA	Period (s)	0.696	0.5971	0.7845	0.7765	0.63257
	Base Shear (kN)	6693.49	6515.39	4898.13	6924.58	7203.13
	K-elass (kN/m)	129,717	153,480.00	110,111.44	121,184.71	152,322.00
	K-eff (kN/m)	66,112.1	74,950.30	58,385.54	62,009.67	78,548.80
ZB	Period (s)	0.696	0.5971	0.7845	0.7765	0.63257
	Base Shear (kN)	6693.49	6515.39	4898.13	6924.58	7203.13
	K-elass (kN/m)	129,717	153,480.00	110,111.44	121,184.71	152,322.00
	K-eff (kN/m)	66,112.1	74,950.30	58,385.54	62,009.67	78,548.80
ZC	Period (s)	0.696	0.5971	0.7845	0.7765	0.63257
	Base Shear (kN)	6693.49	6515.39	4898.13	6924.58	7203.13
	K-elass (kN/m)	129,717	153,480.00	110,111.44	121,184.71	152,322.00
	K-eff (kN/m)	66,112.1	74,950.30	58,385.54	62,009.67	78,548.80
ZD	Period (s)	0.696	0.5971	0.7845	0.7765	0.63257
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	K-elass (kN/m)	129,717	153,480.00	110,111.44	121,184.71	152,322.00
	K-eff (kN/m)	66,112.1	74,950.30	58,358.54	62,009.67	78,548.80

The study uses static pushover analysis, which fails to account for cyclic degradation, frequency-dependent responses, or long-term soil softening effects. The structural analyses performed by considering different damping ratios, building importance classes, and different soil classes for earthquake zones, period, base shear force, and elastic and effective stiffness values remained the same in all structural models. The independence of these variables from structural properties did not change the results. In addition, the change in local soil conditions did not change these results. For Model I, where the number of storeys in the structure was reduced, the period value decreased with the increase in the stiffness value. This decrease was lower than the reference building for this model. Structural Model II, which was created by increasing the ground storey height and was relatively created, caused this negativity in the structure to decrease the stiffness in the structure and therefore to increase the period value. For Model III, which was created by increasing the frame opening, the period value increased compared to the reference building, while the stiffness values decreased. For Model IV, where the height of each storey in the structure was reduced, the period value decreased depending on the increase in the stiffness value. In general, for the ZD soil class: Recommend higher damping ratios, smaller frame spans, and reinforced foundation designs. For ZB/ZC soil classes: Increase use of base isolators or shear walls to counteract soil softening effects.

4. Conclusions and Recommendations

The level of destruction of structures during earthquakes usually depends on the interaction between the earthquake, the ground, and the structure. Correct analysis of these factors can help to predict the seismic performance of structures during and after the earthquake more realistically. Although it is difficult to determine the earthquake risk of any region precisely today, regional earthquake hazards can be statistically evaluated with seismic hazard analyses. In order for these analyses to yield accurate and realistic results, local ground conditions in particular must be evaluated in detail. Because earthquakes usually start on the ground, it is known that local ground conditions play a critical role in determining the characteristics of the earthquake. Local ground properties can directly affect the seismic performance of structures; therefore, it is important to consider these factors in structural analyses. When the results of large and destructive earthquakes that have occurred in the world and in Turkey are examined, it is observed that the damage rates due to ground conditions are increasing. This situation is mostly due to the increase in the plain settlements of the cities and the observation of the basin effect more in the structures related to this, the ignoring of the ground amplification effect in loose soils, the effect of seismic waves originating from topographic irregularities on the structures from different angles, the bearing capacity changes due to the differences in groundwater levels and the effects of nearby faults. Although liquefaction potential is a concept that can be determined in advance, it causes permanent deformation in the structures especially in the soils that have not been improved against liquefaction in old settlements during earthquakes.

This study examined the local soil conditions affecting the earthquake performance of the structures in detail through seven different variables. For example, while the local soil conditions were determined as the first variable in the selected RC structure model, other factors such as damping ratio, structure importance class, earthquake zone, ground floor height, number of floors, frame opening, and floor height were also taken into account. The results of the static pushover analyses performed separately for each structure model were obtained to understand the seismic performance of the structures.

All the quantitative results obtained once again revealed that the local soil conditions significantly affect the performance of the structures in a possible earthquake. For this reason, it is clearly emphasized that local ground conditions should be known realistically in seismic performance assessments and designs to be made on new and existing building stock. Determining local ground conditions with detailed analyses may allow for more realistic damage estimates and distributions of structures. In cases where ground properties are poor, ground improvement and reinforcement works can be carried out with different methods or superstructure construction can be continued by selecting different foundation types. This study reveals that structural analyses conducted by considering the interaction of various parameters with local ground conditions emphasize the importance of design. It has been observed that structural irregularities negatively affect the seismic performance of structures. The study focuses especially on regular reinforced concrete building models and may constitute a source for similar studies for irregular structures and different load-bearing systems. Many parameters have important effects on the design and evaluation of structures. In this context, it is necessary to consider these parameters and their interactions in terms of performance-based earthquake engineering.

Field observations of the Kahramanmaraş earthquakes reveal that structures on soft soil suffered much more damage, which is in line with our numerical results that demonstrate larger target displacements for weak soil classes (ZD). Although further calibration using actual ground motion data might improve validation, this alignment demonstrates the dependability of our model.

The findings of this study could impact seismic design practices in several ways: Structural target displacement limits could be adjusted based on soil class and damping ratio findings. Areas with soft soils might need more stringent building codes, particularly concerning frame span restrictions and damping improvements. Older buildings in soft-soil regions may require stiffness upgrades (such as base isolators or bracing systems) to mitigate the effects of increased displacement.

The study's approach to assessing soil effects using Eurocode 8 classifications can be applied to regions with varying seismic risks. The findings on soft-soil amplification are particularly relevant for coastal cities and sedimentary basins, where seismic waves are more damaging. Cities with diverse urban development, such as Istanbul and Mexico City, could benefit from zoning policies tailored to soil variability.

The pushover analysis used in this paper offers important insights into seismic performance, but it ignores frequency-dependent soil response and the impacts of cyclic deterioration. Nonlinear dynamic analysis should be incorporated into future research to more thoroughly examine these consequences.

This study includes numerical analyses for medium-rise regular reinforced concrete buildings under different local site conditions. The study is based on reinforced concrete frame structures consisting of columns and beams. This and similar studies can be a source for irregular and high-rise reinforced concrete buildings with different structural systems. In this context, the effects of different parameters considered in this study on structures including RC shear walls, steel structures, and masonry structures can support future research. The effects of local soil conditions on torsion in structures containing irregularities can be examined in detail in other studies. In addition, more detailed studies on soil liquefaction and soil amplification will enable a clearer demonstration of the effects of local soil classes on the seismic behavior of structures.

The varying conditions of soil, even within the same broad soil type, can significantly influence the seismic behavior of reinforced concrete structures. Differences between loose and compacted soils, for example, can lead to different responses in terms of how seismic waves affect a building's foundation and superstructure. The seismic behavior of reinforced-concrete structures is greatly influenced by the condition of the underlying soil. Loose soils tend to amplify seismic waves, increase settlement risks, and make foundations more susceptible to liquefaction, while compacted soils offer more stability, reducing seismic wave amplification and settlement risks. Engineers must account for these differences when designing structures, particularly in seismic zones, by considering soil properties in foundation design, structural reinforcement, and seismic mitigation strategies. This ensures that reinforced concrete structures remain safe and resilient during seismic events.

Especially in Gölbaşı and Hatay, soil liquefaction played a significant role in the destruction of buildings and infrastructure. For regions with similar sandy, loose, or water-saturated soils, engineers could adopt more rigorous soil–structure interaction models. These models would simulate the behavior of foundations during an earthquake, helping to predict potential settlement, tilting, or tilting caused by soil liquefaction. Engineers can integrate soil liquefaction risk analysis into building foundation designs, opting for deep foundations (like piles) or reinforced foundations (like mat foundations) in vulnerable zones, reducing the likelihood of failure in liquefied soils.

The earthquake region experienced significant damage due to the collapse of poorly constructed buildings. Many older buildings lacked the necessary reinforcement to withstand ground shaking. In similar seismic regions, retrofitting older structures to resist seismic forces can significantly reduce earthquake damage. Governments could initiate large-scale seismic retrofit programs targeting older buildings, particularly those on soft soils. This could involve reinforcing walls, retrofitting roofs, or adding bracing systems to existing buildings to improve their earthquake resistance.

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