Challenge Journal of Structural Mechanics

Research Article

Effect of soil types on nonlinear earthquake behavior of buildings

Memduh Karalar [a,*], Murat Demirköse [a], Necati Mert [b]

[a] Department of Civil Engineering, Zonguldak Bülent Ecevit University, 67100 Zonguldak, Türkiye
[b] Department of Civil Engineering, Sakarya University, 54050 Sakarya, Türkiye

ABSTRACT

The Winkler method, which is widely used today, assumes that the soil behaves elastically and does not take into account the soil shear stress values, it is insufficient to reflect the actual soil behavior. Especially in the earthquake calculations of rigid and massive structures such as high-rise buildings, dams, suspension bridges, viaducts, it is necessary to consider soil as a dynamic system that changes shape and affects the behavior of the structure in terms of inertia. In response to the effect of soil on the structure, the structure also affects soil both kinematically and dynamically. Thus, in the absence of the structure, the earthquake data, which is only a result of the dynamic behavior of the soil in its internal structure, now acquires a more complex soil motion characteristic that is also affected by the presence of the structure. The observations made in some earthquakes show that the changes between the records taken simultaneously on the building foundation and at soil surface not a point far from foundation, show that the structure also affects soil therefore soil motion in response to the effect of the earthquake on the structure. In this study, the effect of soil types on the nonlinear seismic behavior of reinforced concrete structures was investigated. For this purpose, 7-storey building models with different plans and rigidities were created. The behavior of these models under 11 different earthquake loads for the ZA, ZB, ZC, ZD, ZE soil types specified in the Turkish Building Earthquake Code has been investigated. Analyzes were made using the time history method with the help of the SAP2000 program. As a result of the analysis, the displacements, plastic hinge formation, Effective inter-storey drift and period values obtained for different models were compared.

ARTICLE INFO

Article history:
Received 20 June 2023
Revised 21 July 2023
Accepted 4 August 2023

Keywords:
Soil-structure interaction
Time history method
3D dynamic analysis
Soil dominant period

1. Introduction

Since the earthquake effect is a vibrational movement in the earth's crust, it creates a dynamic influence by creating a time-dependent displacement movement on the supports of the buildings. In most of the structural analysis, the foundations are considered as built-in and it is assumed that there is no displacement or rotation in the foundations. However, in reality, collapses and rotations occur in the foundations. In the case of a dynamic loading such as an earthquake acting on the structures, the structure and soil move together and affect each other's behavior (Aydınoglu 1977; Aydınoğlu 1981). According to the stiffness of soil, the behavior of the structures on different soil layers under the influence of earthquakes constitutes a large part of the structure-soil interaction problem. In this case, the structure-soil interaction must be taken into account. In earthquake calculations of such structures, soil environment should be considered as a dynamic system that changes shape and affects the behavior of the structure in terms of inertia (Aydınoglu 1994; Lysmer et al. 1969). In response to the influence of soil on the structure, the structure also affects soil both kinematically and dynamically. In cases where the structure does not exist, the earthquake data, which is only a result of the dynamic behavior of the soil itself, turns into a more complex ground motion as a result of the presence of the structure. Records taken during earthquakes

* *Corresponding author*. Tel.: +90-372-291-2118 ; E-mail address: memduhkaralar@beun.edu.tr (M. Karalar)
ISSN: 2149-8024 / DOI: https://doi.org/10.20528/cjsmec.2024.01.002

have shown that the results obtained from soil with a structure and the soil without any structure in the same region is different (Bettes and Zienkiewicz 1969; Parmelee 1967). These differences prove that ın response to the influence of soil on the structure, the structure also affects soil and therefore the earthquake record. Lysmer and Kuhmeyer (1969) developed an artificial boundary model, which it was called viscous boundary conditions, and in the dynamic analysis of the structure-soil system, they prevented the reflection of some of the waves scattered from the source by hitting the artificial boundaries. In another study, Bettess and Zienkiewicz (1969) established the Infinite Element Model for static and harmonic loads. This method was used by Medina (1980) for modeling the soil structure dynamic interaction. In later studies, Iida (1998) conducted a 3-D non-linear, structure-ground dynamic interaction analysis using the finite element technique, by considering the buildings of different storey heights, to investigate the cause of heavy damage especially to medium-height buildings in the Lakebed region with the 1985 Mexico City earthquake. In these analyzes, structures were examined in different categories for linear and non-linear situations, taking into account both fixed-support and structure-soil interaction. As a result, it was observed that the situations where the interaction was not taken into account were insufficient to explain the causes of damage in the buildings. Another investigation was performed by Avilés and Pérez-Rocha (1998). In this investigation, Avilés and Pérez-Rocha (1998) examined the influences of foundation embedment depth on the behavior of the building soil system, the dominant period and damping of the building under dynamic loads. At the end of this investigation, the numerical solution was evaluated on a system consisting of a single-storey structure embedded in a homogeneous, elastic semi-infinite ground. Gouasmia and Djeghaba (2007) also investigated the influences of a multi-storey building on the earthquake influence due to different soil properties and local soil thicknesses, taking into account the structure-soil dynamic interaction. As a result of this study, analyzes were made using soil properties and local soil thickness as variables, and from the findings, it was noted that in case of loose soil with low shear wave velocity and with the increase in soil layer depth, the response of the structure increased and the natural periods were prolonged. The other investigation was performed by Ichihara et al. (2021). In this study, Ichihara et al. (2021) estimated correctly the influence of the nonlinear behavior of the soil-structure interface on the response of the reactor structure with a 3-D finite element model. At the end of this investigation, it was measured that soil separation and sliding have an excessive influence on the spreading features of the soil pressure along sidewalls and max. acceleration response. Bolisetti et al. (2018) offered a valuation of the industry-standard soil-structure interaction analysis codes, SASSI and LS-DYNA for linear and nonlinear SSI analyses of safety-related nuclear constructions and commercial constructions. At the end of this investigation, it was observed that nonlinear soil-structure interaction calculations might be considerably different from those made using linear frequency-domain codes. The other study was performed by Chian et al. (2019). In this study, the performance of structures and geotechnical constructions within the affected areas were examined to improvement visions on their design and construction deficiencies. Chian et al. (2019) contained building damages recognized to a combination of structural resonance, deficiencies in reinforcement detailing, vulnerability to soft story failure, ground settlement, soil liquefaction, and landslides. It was established that constructions which were strictly damaged had natural construction frequencies corresponding with the dominant frequencies of the ground shaking. In another investigation, Vicencio and Alexander (2018) estimated the influence of Soil-Structure Interaction among two structures assumed altered constraints of the structures, inter-building spacing, and soil type. At the end of this investigation, the consequences presented that there were both unfavorable and useful arrangements of the two structures that create significant changes among nonlinear structure-soil-structure interaction and non-linear soil-structure interaction. Essentially it was proved that the opposing influences of structure-soil-structure interaction might be more marked while the nonlinear soil behaviour was supposed. Oz et al. (2020) examined and compared the influence of soil-structure interaction on the seismic ability and response calculations of existing structures built on the several soil conditions altering from stiff to soft. Furthermore, nonlinear static pushover analyses were performed to detect the influence of soil-structure interaction on the capability curvatures of designated structures and the consequences were compared. Other investigations were also performed in the literature (Castelli et al. 2021). At the end of this study; it was detected that the interaction among soil and the construction changes the total displacement ability of constructions in preference to increasing it. As detected from these studies in the literature; there are few investigations about the nonlinear seismic behavior of buildings. Moreover, according to seismic design codes, the effect of soil properties on the nonlinear seismic behavior of buildings has not been observed in the past in detail. For that reason, one of the most significant aims of this study is to determine the influence of soil properties on the nonlinear seismic behavior of buildings. For this purpose, 7-storey building models with different plans and rigidities were created. Then, the behavior of these models under 11 earthquake loads for the different soil types specified in the Turkish Building Earthquake Code 2018 was examined. Analyzes were made using the Non-Linear Analysis Method in the Time History with the help of the SAP2000 program. As a result of the analysis, displacements, plastic hinge formation, max. inter story drift ratio and period values obtained for different models were compared. As a result, this research study is very important to fill these absences in the literature.

2. Scope of the Study

The aim of this study is to examine the building-soil interaction from different perspectives by giving information about the previous literature studies on building-ground interaction. Furthermore, to investigate the influence of non-linear seismic behavior of buildings on soil types in the context of structure-soil interaction. Since the Winkler method, which is widely used today, accepts the soil as elastic and does not take into account the shear stress values for the real soil, it is insufficient to reflect the actual soil behavior. Therefore, to model the ground more realistically, the ground was first divided into small pieces using the finite element method, which was modeled as solid in the SAP2000 package program. Each part has 8 corners and 6 types of springs were assigned to this corner as horizontal translation and angular rotation in the x, y, z direction, and the numerical values of these springs were found with the formulas developed by Gazetas (1991). Viscous boundaries are defined on the edges of the modeled soils. For this, frame system 7-storey building is defined in SAP2000. Details are given in the following subsections.

2.1. Features of structure soil model

The Direct Method was used to examine the influence of soil types on the non-linear seismic behavior of buildings. In the direct analysis method, the cutting surfaces must be chosen at a very far distance from the structure in order to obtain realistic results. However, the finite element region does not need to be very large for the model to be solvable. When the ground region bounded by the cut-off boundaries is modeled with SEM, the waves propagating in the closed environment collide with the boundaries and return to the analysis environment and adversely affect the solution.

In order to prevent this situation, the cut-off boundaries should be arranged in such a way as to provide wave permeability with special boundary conditions as shown in Fig. 1 (Guiterrez and Chopra 1978). Viscous boundaries are defined for the cutting surfaces depending on the effective damping and stiffness of soil.

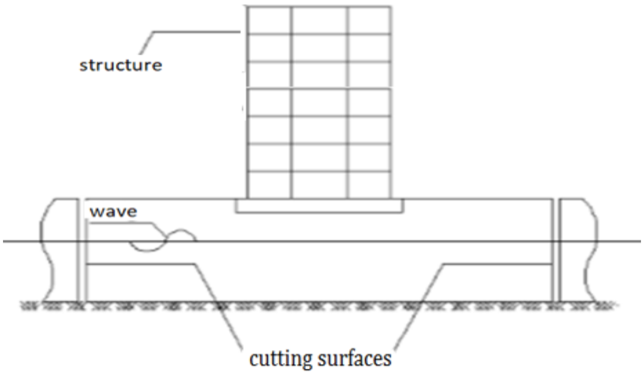

Fig. 1. Cutting soil surfaces (Guiterrez and Chopra 1978).

2.1.1. Features of the building models

As a numerical application, the influence of soil types on the nonlinear seismic behavior of a 7-storey frame system was investigated as shown in Figs. 2–3 and Table 1. The soil safety stress related to the material classes and behavior in the models used in the numerical application, for each of soil groups ZA, ZB, ZC, ZD and ZE specified in TBDY-2018 (2018), soil for each layer is divided into 30 layers depending on soil V_s velocity, soil group obtained with using the average of the mechanical properties calculated separately for each layer was used in modelling. In this section, the assumptions made about the building models and the features considered in the calculation of the models are as follows.

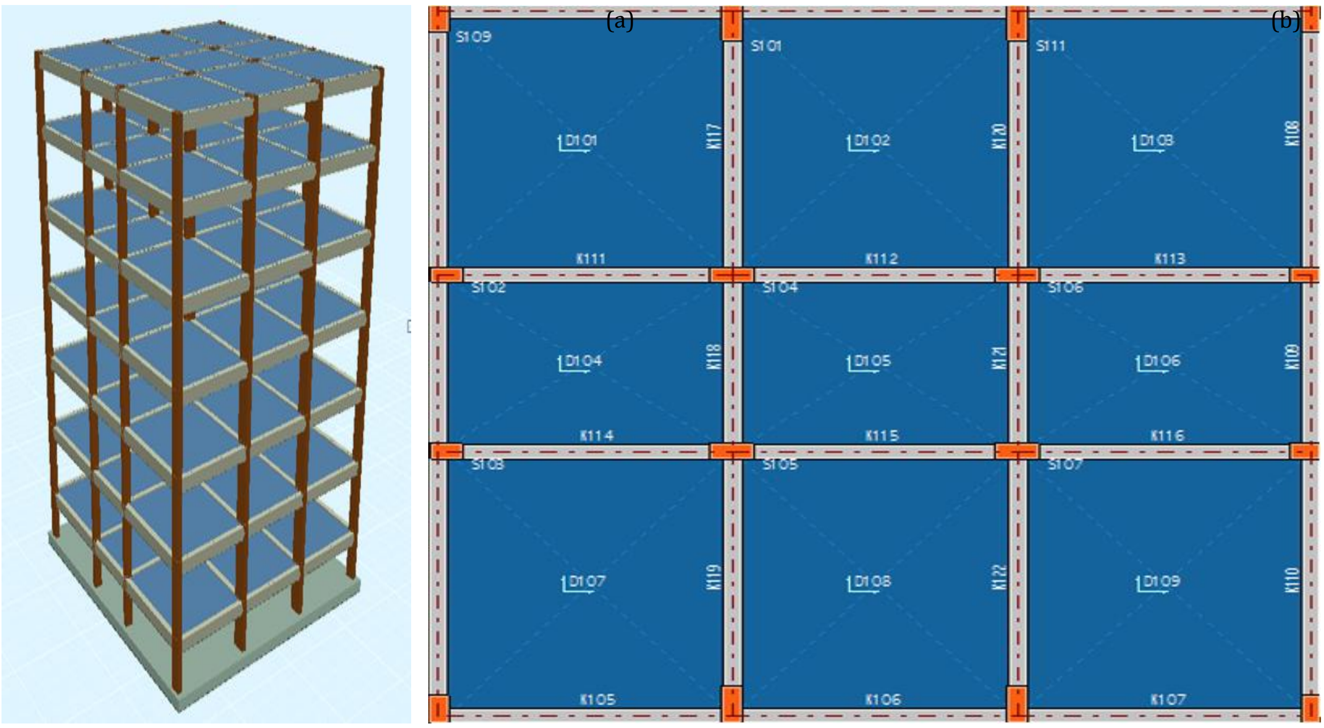

Fig. 2. (a) 3-D plan (b) of the 7-storey frame model.

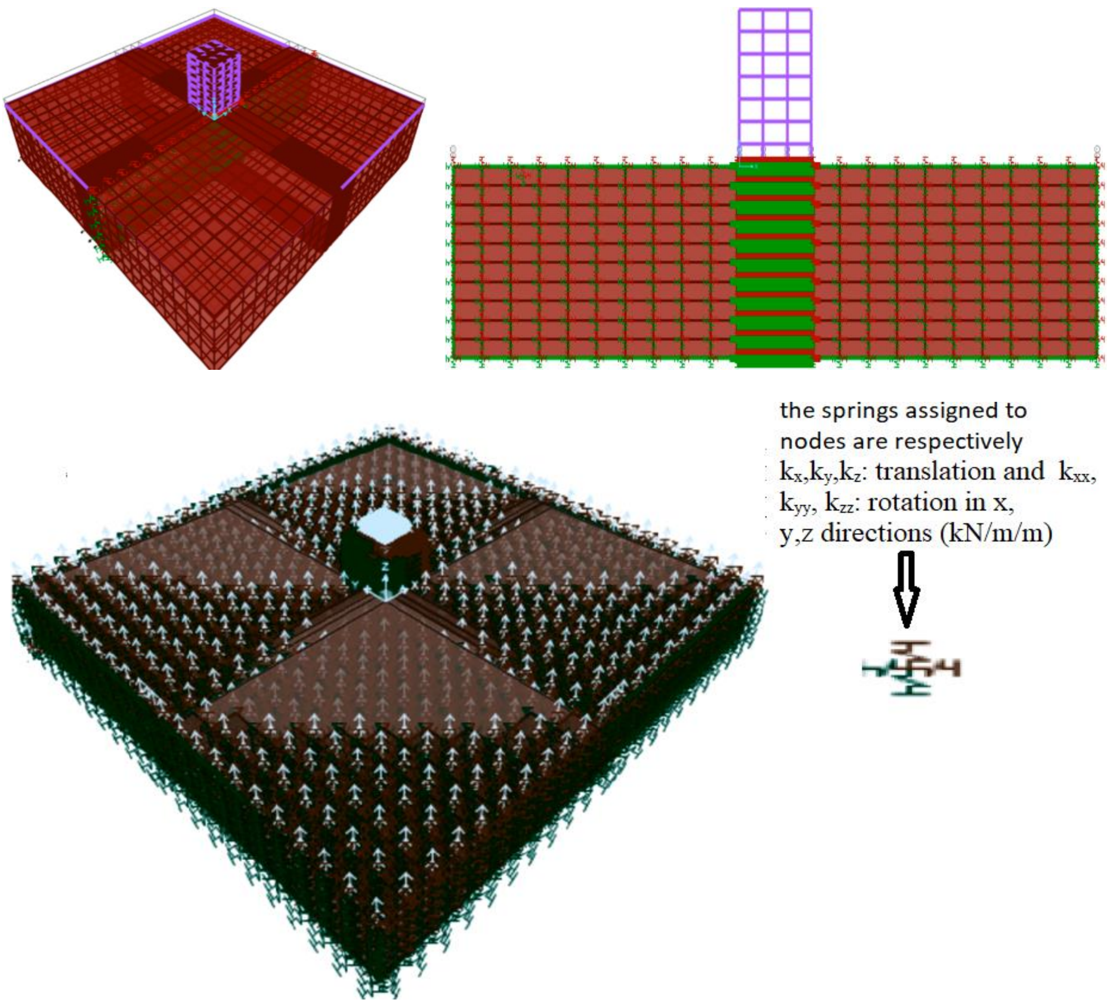

Fig. 3. 2D and 3D views of the 7-storey building.

Table 1. General characteristics of the building.

Number of floors	7
Purpose of usage	housing
Carrier system behavior coefficient	7
Building importance coefficient	1
Soil class	ZA, ZB, ZC, ZD, ZE
Base area	16.60·15.30=253.98 m^2
Floor height	3
Total building height	45
Concrete class	C35
Steel class	S420
Live load factor (n)	0.3
Slab live load (t/m^2)	0.2
Slab fixed load (t/m^2)	0.3
External beam load (t/m^2)	1.2
Internal beam load (t/m^2)	0.8
Column dimensions	30×60, 30×80, 50×30, 70×30
Slab thickness	15 cm
Foundation thickness	60 cm

The depth of each soil is taken as 30 meters according to the TBDY-2018 (2018) Earthquake Code, and are divided into 30 layers, and the mechanical properties of the soil belonging to each layer are calculated with empirical formulas, assuming that V_s and V_p increase approximately linearly and equally in each interval.V_p, γ, E, G, parameters and q_n parameter showing the mechanical properties of the soils were calculated (Tezcan et al. 2006). Here, V_p and V_s are defined as longitudinal and transverse wave velocities (m/s), γ is defined as unit weight (kN/m^3), E is defined as modulus of elasticity (kN/m^2) and G is defined as slip modulus (kN/m^2). μ is defined as Poisson's ratio and q_n is defined as soil safety stress (kg/cm^2). The q_n parameter is taken as 30 meters for the depth of each soil according to the 2018 Earthquake Code, and the V_s and V_p wave velocities ranges are divided into 30 layers, and it is assumed that V_s and V_p increase linearly and equally in each interval, and the soil properties of each layer are calculated with empirical formulas calculated.

For calculations, the 7-floor lodging building, 135×135 dimensions and 30 meters deep, soil mass is taken into account, the lower part of soil is used as bedrock. Viscous boundaries (depending on effective stiffness and damping) are placed on the defined sides. Then, each soil group modeling was performed to represent the ZA, ZB, ZC, ZD and ZE soil groups specified in the

2018 Earthquake Code. Transverse wave velocity (V_s) ranges are specified in the ZA, ZB, ZC, ZD and ZE soil groups specified in the 2018 Earthquake regulations. In order to take into account the structure-soil interaction, the base dimensions of the 7-storey frame system building in the *x*, *y*, and *z* directions of the soil mass of 135×135×30 m, respectively, and the structure on this soil mass should be analyzed. According to the TBDY-2018 (2018) regulation, the earthquake was applied to the building in horizontal and vertical directions. After modeling both the building and soil, soil is divided into finite elements for ground interaction. Each finite element has 8 nodes and each node has 6 degrees of freedom in the x, y, z directions as translation and rotation (Gazetas 1991). Furthermore, In the Plastic Hinge Hypothesis, it is thought that the plastic deformations that are continuously spread in a region of length l_p on the rod element are collected at a point defined as the plastic hinge.

The spring constants were calculated for the 6 degrees of freedom to be assigned to the nodal points of the finite element belonging to the soil groups (Gazetas 1991).The spring constants are respectively k_x, k_y, k_z: translation in *x*, *y*, *z* directions (kN/m), k_{xx}, k_{yy}, k_{zz}: rotation in *x*, *y*, *z* directions (kN/m/m).In the definition of the dampers, the values obtained by using the equations defined in the literature for the horizontal and vertical components of the stiffness of the soil and the horizontal and vertical components of the damping ratio were used (Ala 2007). In the evaluation, it was assumed that the building model was on ZA, ZB, ZC, ZD and ZE class soils.

2.1.2. Earthquake acceleration recording features

Real earthquake records compatible with TBDY-2018 (2018) were selected to be used in dynamic analysis. The acceleration records required for nonlinear inelastic dynamic analyzes in the time history were selected using the PEER database (PEER, 2011). The station information, shear wave velocity ($V_{s,30}$) and scale coefficients of the selected acceleration record sets are given in Table 2.

Table 2. Selected earthquake records and their characteristics.

PEER no.	Earthquake	Year	Station	Earthquake magnitude	Shortest distance	Soil ($V_{s,30}$)
838	Landers	1992	Barstow	7.28	34.86	370
1101	Kobe Japan	1995	Amagazaki	6.90	11.34	256
1614	Düzce	1999	Lamont (1061)	7.10	11.46	481
1616	Düzce	1999	Lamont (362)	7.10	23.41	517
1619	Düzce	1999	Mudurnu	7.10	34.30	535
1636	Manjil	1999	Qazvin	7.37	49.97	303
1762	Hector Mine	1999	Amboy	7.13	41.81	383
3753	Landers	1992	Fun Valley	7.28	25.02	388
3757	Landers	1992	North P. Springs	7.28	26.95	367
5836	El Mayor	2010	Meloland G. Array	7.20	29.00	265
6969	Darfield	2010	Styx Mill Trans. St.	7.00	20.86	247

3. Analysis Results

In this study, the influences of soil types on non-linear seismic performance of reinforced concrete structures were investigated. In this context, the 7-storey frame system was modeled together according to ZA, ZB, ZC, ZD and ZE soil types according to TBDY-2018 (2018) and scaled with the SeismoSelect package program according to the simple scaling rule with real earthquake records. Analyzes were made. In the analyzes made, the building and soil were modeled together, and change of building base shear forces (tons), the number of structural elements with plastic hinge formed in the buildings, the max roof displacement (cm), the max inter-story drift ratio and the building soil periods (sec) and soil dominant periods were determined according to soil types has been investigated. Results are given in Tables 3–6.

4. Conclusions

In this study, it is investigated the influence of soil types on the nonlinear seismic behavior of reinforced concrete structures. For this purpose, 7-storey building models with different plans and rigidities were created. The behavior of these models under 11 different earthquake loads for the ZA, ZB, ZC, ZD, ZE soil types specified in the Turkish Building Earthquake Code has been examined. Analyzes were made using the time history method with the help of the SAP2000 program. According to analysis consequences, influence of soil types on the nonlinear seismic behavior of reinforced concrete structures is evaluated as below.

- The properties of the soil on which the building will sit are very important in terms of the non-linear earthquake behavior of the buildings. Because these properties of the soil are transmitted to the structures by changing the magnitude of the earthquake acceleration and they are generally transmitted to the structures by increasing the magnitude of the earthquake acceleration from the ZA group soil to the ZE group soil. This situation is very important in terms of the magnitude of non-linear earthquake behavior in buildings.

- In the analyses, it is observed that the max peak displacement of building increases as elastic modulus of soil that is, stiffness of soil, decreases from ZA to ZE soil group. These values in the *x* and *y* directions 4.41-4.80 cm, 4.91-5.40 cm, 6.38-7.02 cm, 8.91-10.47 cm, and 12.6-13.81 cm, respectively.
- In the analyses, made with the 7-storey buildings, it was observed that the number of structural elements with plastic hinge increase as the elasticity modulus of the soils decrease from ZA to ZE soil group. While these values in a 7-storey building are from ZA soil group to ZE soil group, 74, 82, 117, 135, and 163 respectively.
- In the analyses, it is seen that the motion of soil and the amplitude of the earthquake vary depending on the soil properties, especially from ZA soil group to ZE soil group, due to the structure-soil interaction. This situation increases the cross-section influences that will occur in building, and accordingly, it has been observed that the level of non-linear behavior has increased.
- The variation of the effects of structural irregularities on the nonlinear seismic behavior of buildings according to soil types can be examined with different building models. In addition, the effect of concrete quality on the nonlinear seismic behavior of buildings according to soil types can be examined with different building models.

Table 3. 7-storey building base shear forces (tons).

Soil type	2018 TBDY	
	Direction	
	x	y
ZA	121.10	135.17
ZB	107.77	121.10
ZC	148.55	163.25
ZD	157.37	174.86
ZE	162.31	180.35

Table 4. Maximum peak displacement (cm).

Soil type	2018 TBDY	
	Direction	
	x	y
ZA	0.0055	0.0051
ZB	0.0066	0.0064
ZC	0.0093	0.0090
ZD	0.0127	0.0123
ZE	0.0155	0.0145

Table 5. Building periods (sec).

Soil type	2018 TBDY	
	Direction	
	x	y
ZA	0.73	0.68
ZB	0.83	0.77
ZC	1.11	1.04
ZD	1.57	1.47
ZE	2.28	2.12

Table 6. Soil dominant periods (sec).

Soil type	Soil dominant periods $t_o = 4H/V_s$ (s) (Keçeli 1990)	Building dominant periods $T=C_t \cdot H_N^{0.75}$, $C_t=0.1$ (TBDY-2018 4.7.3.4(a) Eq. 4.27)
ZA	0.077	
ZB	0.107	
ZC	0.211	1.1
ZD	0.447	
ZE	0.720	

Acknowledgements

None declared.

Funding

The authors received no financial support for the research, authorship, and/or publication of this manuscript.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Author Contributions

All of the authors made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; were involved in drafting the manuscript or revising it critically for important intellectual content; and gave final approval of the version to be published.

Data Availability

The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

References

Ala N (2007). Adapazarı Zemininde Yapılan Betonarme Yapılarda Zemin-Yapı Etkileşimi, *M.Sc. thesis*, Sakarya University, Sakarya, Türkiye. (in Turkish)

ASCE 7-10 (2010). Minimum Design Loads for Buildings and Other Structures. ASCE Standard, ASCE/SEI 7-10. American Society of Civil Engineers, Reston, Virginia, USA.

Aviles J, and Perez-Rocha LE (1998). Effects of foundation embedment during building-soil interaction. *Earthquake Engineering and Structural Dynamics*, 27, 1523-1540.

Aydınoğlu MN (1977). Üstyapı-Zemin Ortak Sisteminin Deprem Hesabı. *Ph.D. thesis*, İstanbul Technical University, İstanbul, Türkiye. (in Turkish)

Aydınoğlu MN (1981). Yapı-Zemin Dinamik Etkileşiminin Genel formülasyonu ve Zemin Gömülü Yapılar için bir Alt Sistem Yöntemi. *Associate Professorship thesis*, İstanbul, Türkiye. (in Turkish)

Aydınoğlu MN (1994). Statik ve Dinamik Yapı-Zemin Etkileşimi., *Zemin Mekaniği ve Temel Mühendisliği 5. Ulusal Kongresi*, 218-229, METU, Ankara, Türkiye. (in Turkish)

Bettes P, Zienkiewicz OC (1969). Diffraction and refraction of surface waves using finite and infinite elements. *International Journal of Numerical Engineering*, 95(EM4), 859-877.

Bolisetti C, Whittaker AS, Coleman JL (2018). Linear and nonlinear soil-structure interaction analysis of buildings and safety-related nuclear structures. *Soil Dynamics and Earthquake Engineering*, 107, 218-233.

Castelli F. Grasso S, Lentini V, Sammito MSV (2021). Effects of soil-foundation-interaction on the seismic response of a cooling tower by 3D-FEM analysis. *Geosciences*, 11, 200.

Chian SC, Wilkinson SM, Whittle JK, Mulyani R, Alarcon JE, Pomonis A, Saito K, Fraser S, Goda K, Macabuag J, Offord M, Hunt-Raby AC, Sammonds P, Franco G, Stone H, Ahmed B, Hughes FE, Jirouskova NK, Kaminski S, Lopez J (2019). Lessons learnt from the 2009 Padang Indonesia, 2011 Tōhoku Japan and 2016 Muisne Ecuador Earthquakes. *Frontiers in Built Environment*, 5 (73), 1-20.

Eurocode-8 (2004). Design Provisions for Earthquake Resistance of Structures. European Committee for Standardization, Brussels.

Gazetas G (1991). Foundation Vibrations, Foundation Engineering Handbook. Van Nostrand Reinhold, 2nd edition, 553-593, New York, USA.

Gouasmia A, Djeghaba K (2007). Non-linear dynamic soil-structure interaction analysis of buildings. *Technological and Economic Development of Economy*, 13(4), 266-271.

Guiterrez JA, Chopra AK (1978). A substructure method for structures and geotechnical aspects. Earthquake *Engineering and Structure Dynamics*, 6, 51- 69.

Ichihara Y, Nakamura N, Moritani H, Choi B, Nishida A (2021). 3D FEM soil-structure interaction analysis for Kashiwazaki–Kariwa Nuclear Power Plant considering soil separation and sliding. *Frontiers in Built Environment*, 7, 676408.

Iida M (1998). Three-dimensional non-linear soil–building interaction analysis in the lakebed zone of Mexico city during the hypothetical Guerrero earthquake. Earthquake Engineering and Structural *Dynamics*, 27, 1483-1502.

Kayhan AH, Korkmaz KA, Irfanoglu A (2011). Selecting and scaling real ground motion records using harmony search algorithm. *Soil Dynamics and Earthquake Engineering*, 31, 941–953.

Lysmer J, Kuhlemeyer RL (1969). Finite dynamic model for infinite media, Jo*urnal of the Engineering Mechanics Division*, 95(EM4), 859-877.

Medina F (1980). Modelling of soil-structure interaction by finite and infinite elements. Report No. UCB/EERC-80/43, University of California, Berkeley, CA, USA.

Oz I, Senel SM, Palanci M, Kalkan A (2020). Effect of soil-structure interaction on the seismic response of existing low and mid-rise rc buildings. Applied Sciences, 10, 8357.

Parmelee RA (1967). Building-foundation interaction effects. *Journal of Engineering Mechanics Division*, 93(EM2), 131-152.

PEER Database (2011). University of California, Berkeley. http://nisee.berkeley.edu/spl/ [accessed 01-04-2023]

Pişen S, Pekşen E (2009). Sığ zeminler için farklı yöntemlerden elde edilen zemin emniyet gerilmesi değerlerinin karşılaştırılması. *Journal of Applied Earthsciences*, 8(2), 36-46. (in Turkish)

TBDY-2018 (2018). Türkiye Bina Deprem Yönetmeliği. Afet ve Acil Durum Başkanlığı, Ankara, Türkiye, 30364.

Tezcan SS, Ozdemir Z, Keceli A (2006). Allowable bearing capacity of shallow foundations based on shear wave velocity. *Journal of Geotechnical and Geological Engineering*, 24, 203-218.

Vicencio F, Alexander NA (2018). Dynamic interaction between adjacent buildings through nonlinear soil during earthquakes. *Soil Dynamics and Earthquake Engineering*, 10, 130-141.