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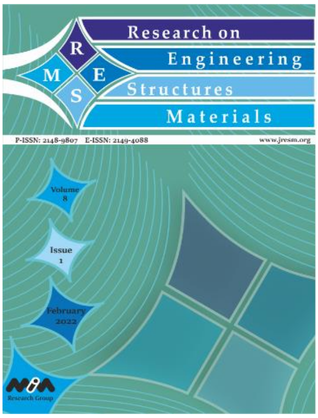

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Research Article

Effect of soil and foundation stiffness on the seismic behavior of mid-rise RC buildings

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Abstract

For a more realistic approach, the effect of soil-structure interaction on the behavior of reinforced concrete buildings should not be neglected. In this study, nonlinear static pushover analysis is applied to the twenty-five 4-storey reinforced concrete frame buildings with different foundation types (raft and continuous foundation) and soils having different bearing coefficients. The foundation type and foundation sections were changed by keeping the reinforced concrete frame system constant. The stiffnesses of the models are observed to be significantly affected by the foundation dimensions and the soil bearing coefficient. Period increase up to 44% is observed per fixed base case. The lateral strength and damage distribution of buildings, seems to be less affected by foundation and soil conditions. The shear force in smaller columns becomes 8% to 24% more than anticipated by a fixed base model. The building displacement demand values with significant changes according to the fixed base case are observed. Amplifications around 40% seems to be possible per fixed base case. Additionally, an equation is established trying to answer the question of "How stiff the foundation should be for a given soil condition?". If the allowable displacement increase per fixed base case and soil stiffness is known, dimensions of structural members of the foundation may be decided by given equation.

1. Introduction

Determining the behavior of structures under earthquake forces is important in reducing the seismic damages [1]. From past to present, civil engineering discipline has considered the effect of soil, foundation and lateral earthquake forces in building design; but for practical reasons, the structure-foundation-soil interaction is generally neglected. In practice, rotations and ground deformations in foundation are ignored with the fixed base assumption. The acceptance of fixed base support is not a realistic approach in understanding the behavior of the buildings. Although the concept of structure-soil interaction, which has been studied since the 1970s, came to the fore with the 2007 Earthquake regulation, it has not had a general use in applications and designs with common and clear rules [2].

In order to obtain more realistic results, it is important to take into account the effects of the deformations in the ground due to the loads transferred by the superstructure on the internal forces and load distributions by considering the structure-foundation-soil interaction [3]. In the study conducted by Girgin et al., an 8-storey reinforced concrete frame and shear-wall building model was analyzed for fixed base, constant and variable soil bearing coefficient cases [4]. While the natural vibration period of the structure is 0.684 s in the x and y directions in the fixed base model, it is 1.0 s in the x direction and

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0.897 s in the y direction in the Winkler model accounting the soil deformations. In the variable bearing coefficient model, it was found to be 0.893 in the x direction and 0.818 in the y direction. The load sharing ratios of the columns are higher in the models with constant and variable bearing coefficients in both directions compared to the fixed base model. Consequently, the load sharing ratios of the shear walls are lower in the models without fixed base assumption. Taking the X direction as an example, the load sharing ratio of the walls is 0.69 in the fixed base model, 0.59 in the model with constant bearing coefficient, and 0.44 in the model with variable bearing coefficient.

In his study conducted in 2009, Karabörk [5] investigated the behavior of structures with the same member dimensions and different floor heights, having hard and soft soil types and different earthquake loads. As a result of the study, it was concluded that in soft soil models the base bending moments decreased by 40% in the X direction, 32% in the Y direction, and the base shear forces by 77% in the X direction and 61% in the Y direction when compared to the models using the hard soil type. In the study, the horizontal displacements at the foundation level of the soft soil models increased by 71% in the X direction and by 78% in the Y direction compared to the models with the hard soil type. It was observed that the period values of soft soil models decreased by 68% in 3-storey buildings, 50% in 6-storey buildings, and 33% in 10-storey buildings, compared to structures based on hard soil type.

When the structure period and the lateral loads on the structure are taken into account, the level of soil-structure interaction changes depending on the soil properties. In their study, Korkmaz and Demir [6] compared the effects of soil type and soil properties on the building behavior by using nonlinear spring models with different stiffnesses. The rotational stiffnesses were taken between 8000-2000 kN/m and named as K1, K2, K3 and K4 in the structure they designed using raft foundation type. They named the fixed base structure as Model 1, and the soil modeled with springs as Model 2. They found the period values as 0.31 for Model 1, 0.47, 0.49, 0.53 and 0.64 for K1, K2, K3 and K4 in Model 2, respectively. As a result of the study, it has been seen that the rigid ground assumption is insufficient in cases where ground conditions are unfavorable.

In structures where ground displacement, foundation rotations and kinematic effects are neglected, buildings are assumed to be connected to an infinitely rigid environment. In their study, Çaycı and İnel [7] compared the seismic behavior of two 7-storey reinforced concrete buildings, which they named 7-75 and 7-98 according to the 1975 and 1998 regulations, under 4 different acceleration records using fixed support assumption and soil-structure interaction model. They used two different soil types, S1 and S2. S2 soil type has low rigidity. In the 7-98 model, they observed the maximum inter-story drift ratio as 2.09% in the fixed base model and 2.82% in the S2 soil type under Kobe acceleration record. They found the same values as 2.83% and 2.68% for the same floor type in the 7-75 model. In the study, plastic hinge damage distributions and levels were examined using S2 soil type under Kobe acceleration recording. In the 7-75 model, they observed that the column elements in the fixed base model are subject to more strain demand, and in the 7-98 model, the ground floor beams have a higher damage level than the fixed base model.

Caycı modeled different buildings with 2, 4 and 7 stories and with 4 soil types with various stiffnesses and a fixed base version [8]. In the study, linear elastic and linear inelastic analyzes were performed. As a result of the analysis, it has been observed that the soil deformations and foundation rotations reduce the demand for the structure in linear elastic models, but these effects are more complex in models with non-linear behavior. As a result of the analysis, it was concluded that the demands on the structure decreased with the increase in soil stiffness in all models. He claims that when the averages of the acceleration records are taken into account, the assumption of linear inelastic fixed support gives close results with the soil-structure interactive models. However, if the acceleration records are examined one by one, the differences between the two evaluations for dynamic analysis are remarkable. According to Caycı, nonlinear inelastic models that take soil-structure interaction into account are the most realistic models.

Kılıçer investigated the effect of soil-structure interaction on reinforced concrete structure design by using the Modified Vlasov Model [9]. He developed a solution technique in which SAP2000 and MATLAB programs are used simultaneously. In the study, three different soil types were selected for reinforced concrete structures with different number of stories and floor plans: fixed base, Winkler Model and Improved Vlasov model. In the fixed base model, the period for the structure was 0.691 in the X direction, 0.670 in the Y direction, in the Winkler model values are 0.892 in the X direction, 0.830 in the Y direction, and in the Modified Vlasov Model values are 1.053 for the X direction and 0.933 for the Y direction. In Kılıçer's study, bending moments are greater in elastic soil models compared to fixed base models.

In his study in 2020, Ada [10] designed 3, 6 and 12-storey buildings, taking into account the building stock of Turkey, and examined the structure-ground-structure interaction. He compared the situations where the structures have fixed base and the building-ground interaction cases. He observed that the natural vibration period of the structures increases when the effect of the soil on the building behavior is taken into account. In cases where the structures are fixed to the ground, the periods vary between 0.286 and 1.212, while it is between 0.293 and 1.238 in the structure-ground interaction models. He stated that in cases where soil stiffness is low, the period increments are higher than in soils with higher stiffness. It was concluded that the structure-ground-structure interactions are more in cases where the structures are built on soft ground.

Ahmadı investigated the effects of soil geotechnical conditions on the seismic performance of structures by applying a single-mode pushover analysis to reinforced concrete building models with 2, 4 and 8 stories [11]. In his work, he used a rigid foundation and a foundation in which the structure-soil interaction is not neglected. He modeled the connection between the rigid foundation and the ground with elastic springs. It has been observed that the vibration periods of the buildings modeled using the rigid foundation assumption are lower when compared to the structure-ground interaction models in all building models. In the study, the period change ratio of the considered buildings varies between 5% and 43% for ZD and ZE soil classes for buildings with different story heights. The highest displacement demand change rate of 49.11% was observed for the 2-storey ZE soil class in the x direction. Ahmadi claimed that the structure-soil interaction affects the structure behavior more in soils belonging to the ZD and ZE soil classes.

In his study, Öz applied nonlinear analysis to 40 reinforced concrete buildings in order to determine the effect of the soil-structure interaction on the performance of the buildings [12]. Fixed base, firm, medium and soft soil foundation conditions are considered for building models. The importance of soil-structure interaction was compared according to 1998 Turkish Earthquake Code and 2007 Turkish Earthquake Code. The effect of the soil-structure interaction on the lateral strength ratio has been examined. While the firm ground caused an increase of 1.63% in the vibration period of new buildings, this increase was calculated as 2.45% for old buildings. These ratios were calculated as 10.75% and 9.44% for medium soils, and 33.39% and 27.55% for soft soils, respectively. It has been concluded that the interaction between the structure and the ground adversely affects the earthquake performance of the buildings constructed before 1998, and the earthquake performance of the old buildings deteriorates as the ground weakens.

In order to examine the effect of soil stiffness on the seismic behavior, Yaşar et al. conducted a study based on reinforced concrete buildings [13]. 26 different types of buildings, which have different foundation types and dimensions on soils with different stiffness are taken into account. All models were evaluated using nonlinear static analysis. They stated that an increase of approximately 15% is observed in the building period and displacement demands, even in the most ideal situation. It is possible for this increase to reach 82% in unfavorable conditions in terms of soil stiffness and foundation dimensions. The effect of different foundation conditions on the damage distribution in the structure is generally below 10%. The effect on the horizontal strength is less than 2% for the foundation dimensions in accordance with the seismic code.

Studies in the literature show the importance of the effect of soil-structure interaction on building behavior. In the scope of the graduate thesis by the second author, the validity of fixed support assumption for different foundation and soil types are investigated [14]. A 4-storey reinforced concrete building with infill walls was designed and evaluated for cases with raft and continuous foundations of different dimensions and soils with different bearing coefficients. Changes in natural vibration periods, capacity curves, the ratio of strength to seismic weight, damage to plastic hinges when the strength drops to 80%, building roof displacement demands and change of shear forces in columns are compared for different cases. An equation for the increase of seismic displacement demand of RC buildings per fixed support assumption based on foundation and soil stiffness are suggested. Recommendations for the foundation dimensions are given to limit the displacement demand increase per fixed base case. The study aims to contribute the literature on the subject especially with the suggested equations and recommended foundation dimensions which are limited in current literature.

2. Building Models

Building features modeled within the scope of the study is determined based on the information gathered by an inventory study on 475 existing reinforced concrete buildings [15]. TBSC-2018 [16] and TS-500 [17] are considered in the design of the reference model. The floor plan of the 4-storey reinforced concrete reference building model used in the study and the three-dimensional view of the structure are shown in Figure 1. The infill walls, which are modeled as load-bearing elements, are shaded in the figure.

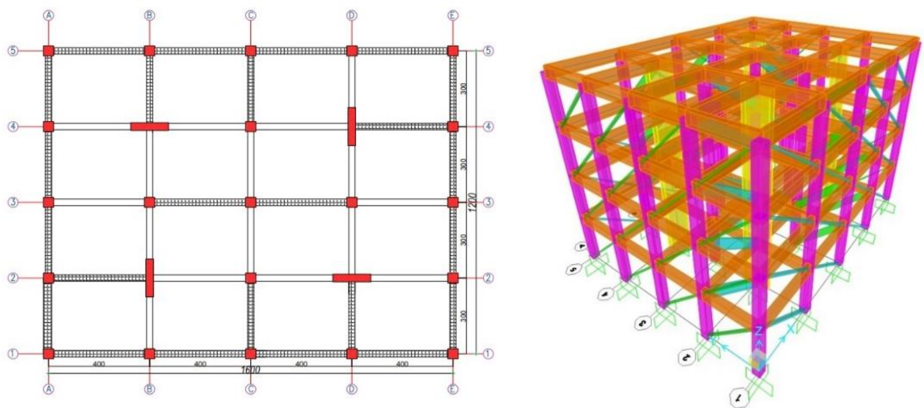

Fig. 1 Plan view of the reference building and 3D view

Columns of the reference reinforced concrete building models are 400x400 mm and 300x1500 mm, 1500x300 mm in size. Through using columns with larger and smaller dimensions, it is aimed to model more critical situations by change in foundation stiffness.

As known, the stiffer columns are expected to be more affected by the change of the foundation stiffness from infinity (as fixed base assumption) to lower levels.

All beams are 250x600 mm. The reinforced concrete frame model has 4 floors and each floor height is 2.80 m. The building is symmetrical in the x and y directions. It consists of 4 bays of 4.0 m on the horizontal axis and 3.0 m on the vertical axis. The longitudinal reinforcement ratio of the columns varies between 1-1.2%. The loads on the slabs are transferred to the beams as triangular and trapezoidal distributed loads and slabs are not included in the modeling. A rigid diaphragm is defined to represent the rigid in-plane behavior of the slabs.

The reinforced concrete building is designed for residential use and the load carrying system is composed of moment transferring reinforced concrete frames with high ductility. The concrete used in the design is C30/37, the reinforcing steel type is S420. The modulus of elasticity of concrete (E_c) and modulus of elasticity of reinforcing steel (E_s) are 32,000 MPa and 200,000 MPa, respectively. Concrete characteristic compressive strength (f_{ck}) is 30 MPa and concrete material safety factor (γ_{mc}) is 1.5. The characteristic yield stress (f_{yk}) of the reinforcing steel is 420 MPa and the material safety factor of the reinforcing steel (γ_{ms}): 1.15.

It is assumed that the building used within the scope of the study is located in the Bahçelievler district of Istanbul (Turkey), which has a dense population with 41.000511° latitude and 28.865811° longitude. Infrequent earthquake ground motion with a recurrence period of 475 years, Earthquake Ground Motion Level -2 (DD -2) and ZC local soil class are taken into account. In the design of the structural system, live loads and wall loads are determined from the Regulation on the Loads to be Taken in the Design of Structural Elements (TS-498) [18].

2.1. Modeling of Infill Walls

Infill walls are expressed as non-structural elements and their effects on the building behavior are generally neglected in building designs. However, infill walls affect building features such as stiffness and load carrying capacity. The ratio and distribution of infill walls in the story may cause short column, weak story, torsion and soft story irregularities. Therefore, it should be taken into account in building design and analysis in order to correctly evaluate the behavior of the building [19, 20].

2.1.1. Modeling of Infill Walls Without Openings

In the literature, various values are suggested for the modulus of elasticity and compressive strength of the material for the modeling of infill walls. In this study, FEMA-356 [21] and TBSC-2018 [16] were taken into account in infill wall modeling. The infill walls are modeled using the equivalent diagonal pressure strut method. The infill wall thickness was chosen as 0.2 m. FEMA-356 recommended compressive strength of 600 psi (4,137 MPa) and shear strength of 10 psi (0.07 MPa) are used for medium strength case. The elasticity modulus of the infill walls are calculated as 2275 MPa according to FEMA-356.

The infill wall shown in Fig. 2 will change shape with the effect of horizontal load and will detach from connection points 2 and 3 and the loads on it will be transferred to points 1 and 4. Since the tensile strength of the material is very small, only the axial compressive force is considered important and defined by the equivalent pressure strut.

While calculating the width of the equivalent pressure bars Equation 1-3 suggested by TBSC-2018 is used. The thickness of the equivalent pressure bars is the same as the selected wall thickness.

$$a_d = 0.175(\lambda_d h_k)^{-0.4} r_d \tag{1}$$

$$\lambda_d = [\frac{E_d t_d \sin 2\theta}{4E_c I_k h_d}]^{1/4} \tag{2}$$

$$\theta = tan^{-1}(\frac{h_d}{L_d}) \tag{3}$$

a_d used in the equations represents the width of the strut, h_k represents the column length, r_d represents the diagonal length of the infill wall, E_d is the modulus of elasticity of the infill wall, t_d is the infill wall thickness, θ is the infill wall diagonal angle, E_c is the modulus of elasticity of the concrete around infill, I_k is the moment of inertia of the column, and h_d is the height of the infill wall.

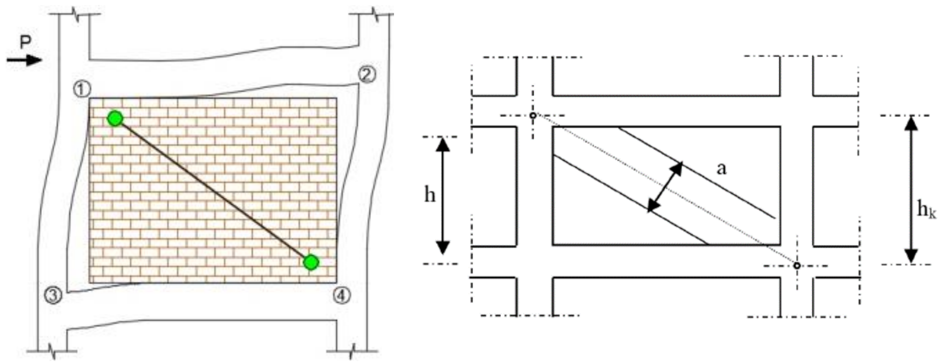

Fig. 2 The equivalent diagonal strut representation for infill wall [22]

The infill walls are located symmetrically in the x and y directions in order to prevent torsional irregularity in the building. The weights of the infill walls are applied to the beams. A single axial load plastic hinge is placed at the midpoint of the infill walls along the diagonal to model the nonlinear behavior.

2.1.1. Modeling of Infill Walls With Openings

Door and window openings in infill walls reduce the stiffness of the wall. The decrease in wall stiffness varies according to the position of the door and window openings on the wall and the gap ratio [23]. The opening percentage is calculated by the ratio of the opening area to the infill wall area. In the study, it is assumed that there are window openings on all exterior walls. The void percentage was chosen as 40% and the stiffness reduction factor λ was taken into account as 0.18 from the type B curve described by Asteris [23] given as Fig. 3. It is assumed that there are no openings in the shaded interior walls in Fig. 1.

While establishing the building models, the bearing coefficient and soil bearing capacity of the reference models for raft and continuous foundations are determined by reference to the table prepared by Bowles in 1996 [24] and shown in Table 1. In order to choose an average value, the bearing coefficient is 45,000 kN/m^3 and the bearing capacity is 450 kN/m^2 according to TBDY2018.

The models used in the study and their nomenclature are summarized in Table 2. The raft foundation given in Table 2 is assumed as a flat slab with given depth without beams in it. The Continuous spread footing consists of the beams with given dimensions connecting the columns in both directions. More details regarding the study that are not mentioned in this paper is given in the master thesis titled as " Zemin ve Temel Rijitliğinin Betonarme Yapı Davranışına Etkisi" [14].

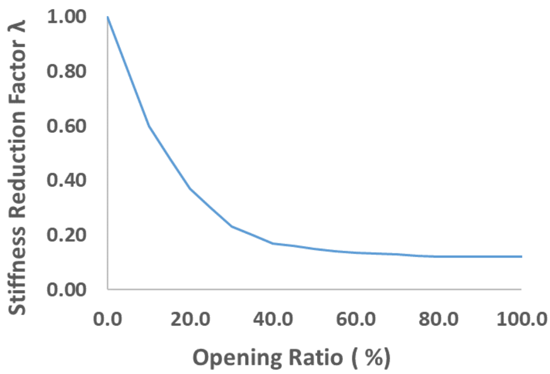

Fig. 3 Stiffness reduction factor of infilled frame in relation to opening percentage, case B: opening upon the compression diagonal [23]

Table 1. Subgrade reaction coefficient (K_s) per Bowles (1997) [24]

Soil Type	K_s (kN/m^3)
Loose Sand	4,800-16,000
Medium Sand	9,600-80,000
Dense Sand	64,000-128,000
Silty Medium Sand	24,000-48,000
Clayey Soil: $q_u \leq 0.2$ MPa	12,000-24,000
Clayey Soil: q_u= 0.2-0.4 MPa	24,000-48,000
Clayey Soil: q_u >0.8 MPa	>48,000

3. Nonlinear Static Pushover Analysis

In scope of TBSC-2018, nonlinear static (pushover) method and nonlinear time history method are used for the evaluation and design of buildings according to displacement based analyses. While the single-mode pushover method can be used for buildings with building height class 5 or higher and meeting certain conditions, the multi-mode pushing method can be used for all buildings with building height class 2 and above. The nonlinear time history method can be used in seismic evaluation of all buildings. In the scope of the study, nonlinear static analysis method is used because of the reduced processing power earthquake independent analysis results.

The method of performing the pushover analysis by increasing the loads in accordance with the assumed distribution step by step up to the lateral load strength limit is called the incremental pushover analysis method. The load shape may be proportional to the first vibration mode shape of the building in incremental pushover analysis for seismic loading [25] . At each step, the displacement, plastic deformation, internal force increments and cumulative values in the system are determined.

Within the scope of the study, different cases of 4-storey reinforced concrete frame building given in Table 2, with raft and continuous foundation conditions and different ground stiffness, are analyzed in two principal directions with the SAP2000 version 23.0.0 software [26]. Nonlinear static pushover analysis method is used in the analyses. Total of 50 cases are analyzed.

Table 2. Properties of building models considered in the study

Model identifier	Description	Foundation Dimensions	Subgrade Mod. (kN/m^3)
Reference Model	Fixed base reference building model		
R30/YK11200 R30/YK25000 R30/YK45000 R30/YK80000	Raft foundation model designed beneath the TBSC-2018 limits.	Raft foundation thickness = 300 mm	11200 25000 45000 80000
R40/YK11200 R40/YK25000 R40/YK45000 R40/YK80000	Raft foundation model designed per TBSC-2018 limits.	Raft foundation thickness = 400 mm	11200 25000 45000 80000
R60/YK11200 R60/YK25000 R60/YK45000 R60/YK80000	Raft foundation model designed over TBSC-2018 limits.	Raft foundation thickness = 600 mm	11200 25000 45000 80000
STK/YK11200 STK/YK25000 STK/YK45000 STK/YK80000	Continuous spread footing model designed beneath the TBSC-2018 limits.	Width = 400 mm No Abutment	11200 25000 45000 80000
STR/YK11200 STR/YK25000 STR/YK45000 STR/YK80000	Continuous spread footing model designed per TBSC-2018 limits.	Width = 600 mm Abutment = 200 mm	11200 25000 45000 80000
STC/YK11200 STC/YK25000 STC/YK45000 STC/YK80000	Continuous spread footing model designed over TBSC 2018 limits.	Width = 700 mm Abutment = 400 mm	11200 25000 45000 80000

Nonlinear models are prepared considering common related documents such as FEMA-356 and TBSC-2018. While the P-M2-M3 plastic hinges are assigned to both ends due to bending and normal force acting on the columns, only M3 plastic hinges are assigned to both ends of the beams due to negligible axial force. Plastic hinges are defined with SAP2000 software by using ASCE 41-13 criteria in plastic hinge definitions [27]. Infill walls are assigned with user-defined P axial load joints in the middle of the compression struts representing the wall element.

4. Analyses Results

The capacity curves obtained as a result of the analyzes made within the study are given in Fig. 4 and Fig. 5 for the x and y directions, respectively. For a better representation, the base shear capacity is shown by dividing the seismic weight of the building model, and the lateral displacement value by the building height. In calculation, the fixed base building model seismic weight is used for all models to prevent the comparison being affected by the foundation weight and considering the mass participation reflecting the dynamic behavior.

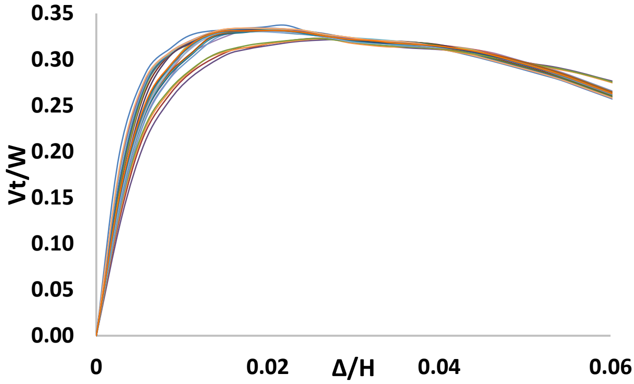

Fig. 4 Capacity curves in the x direction of the building models with different foundation and subgrade modulus

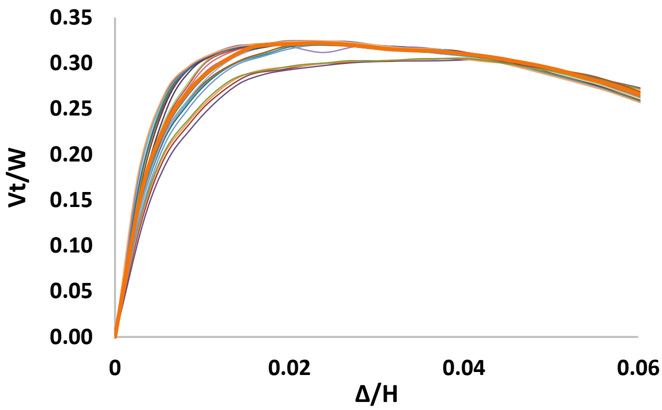

Fig. 5 Capacity curves in the y direction of the building models with different foundation and subgrade modulus

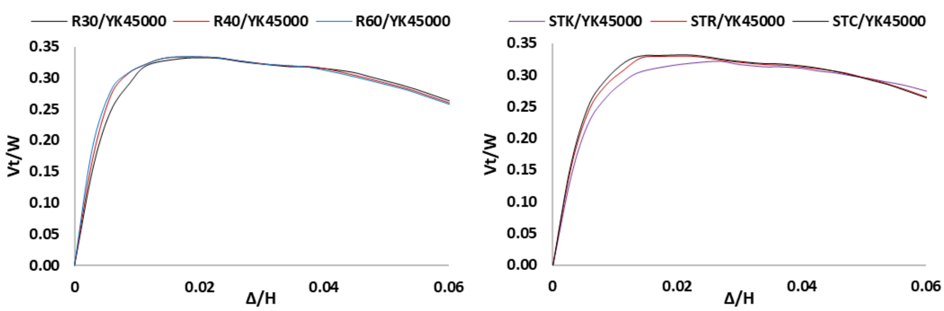

Fig. 6 Capacity curves in the x direction for different foundation dimensions whit same subgrade modulus of 45000 kN/m^3

Since there are many curves in Figures 4 and 5, it becomes difficult to understand the differences between the models. In order to see the effect of foundation dimension more clearly for raft and continuous foundation types, the capacity curves are shown in Fig. 6 for different foundation dimensions and types by keeping the soil stiffness constant. The trend is similar for other soil stiffness cases which is also examined by numerical figures in the below discussions.

The stiffness of the buildings seems to be affected by the foundation dimensions since the slope of the curves are lower as the foundation dimensions gets smaller. The lateral strength is observed to be less affected with close max values except the STK/YK45000 model. This model is the continuous spread footing model designed beneath the TBSC-2018 limits which emphasizes the importance of the complying code requirements.

The natural vibration periods of the structures obtained for the first mode and their ratios to the reference model are given in Table 3 for the x and y directions. The fixed-support reference model has lower period values in both directions than the models with finite foundation stiffness. The greatest variation is observed in the continuous foundation model designed under the code limits with a bearing coefficient of 11200 kN/m^3 reaching to 44% of increase in the period. As also seen in the results of capacity curves, the stiffness of the models are observed to be significantly affected by the foundation dimensions and the soil bearing coefficient.

The horizontal strength ratios corresponding to the base shear strength determined as a result of the analyzes and their variation according to the reference model in the x and y directions are given in Table 4. For better understanding, lateral strength values are given in proportion to the seismic weight (G+nQ) of the reference model. The table validates the graphical observations of the capacity curves as the lateral strength being less affected. As long as the code requirements are met for foundations, the drop in lateral strength capacity is limited around 4%. If the foundation dimensions are lower than code requirements, this figure may reach to 9% even if the soil conditions are favorable. The closer values for the same foundation dimensions with different soil stiffness, suggest that the lateral strength is more of an issue of foundation stiffness than that of the soil.

As a result of the pushover analysis, the plastic hinge state and distributions in the step where the strength decreases to 80% are examined for the x direction and Fig. 7 and Fig. 8 are obtained. The letters A-E in Fig. 7 show the coordinates of the typical joint behavior [21]. In Fig. 8, IO: Immediate Occupancy, LS: Life Safety, CP: Collapse Prevention damage limit. The vertical axis in models shows the number of plastic hinges.

Table 3. Dominant vibration period values and their ratios to the reference model

Model identifier	Natural vibration periods		Ratio with respect to reference	
	T_x (s)	T_y (s)	X direction	Y direction
Reference Model	0.340	0.333	1.000	1.000
R30/YK11200	0.435	0.420	1.279	1.261
R30/YK25000	0.419	0.407	1.232	1.222
R30/YK45000	0.411	0.401	1.209	1.204
R30/YK80000	0.405	0.396	1.191	1.189
R40/YK11200	0.412	0.399	1.212	1.198
R40/YK25000	0.396	0.386	1.165	1.159
R40/YK45000	0.388	0.380	1.141	1.141
R40/YK80000	0.382	0.376	1.124	1.129
R60/YK11200	0.391	0.379	1.150	1.138
R60/YK25000	0.374	0.366	1.100	1.099

Model identifier	Natural vibration periods		Ratio with respect to reference	
	T_x (s)	T_y (s)	X direction	Y direction
R60/YK45000	0.366	0.360	1.076	1.081
R60/YK80000	0.361	0.356	1.062	1.069
STK/YK11200	0.490	0.462	1.441	1.387
STK/YK25000	0.465	0.434	1.368	1.303
STK/YK45000	0.451	0.422	1.326	1.267
STK/YK80000	0.441	0.415	1.297	1.246
STR/YK11200	0.447	0.420	1.315	1.261
STR/YK25000	0.429	0.405	1.262	1.216
STR/YK45000	0.420	0.399	1.235	1.198
STR/YK80000	0.414	0.395	1.218	1.186
STC/YK11200	0.431	0.407	1.268	1.222
STC/YK25000	0.416	0.396	1.224	1.189
STC/YK45000	0.409	0.391	1.203	1.174
STC/YK80000	0.404	0.388	1.188	1.165

Table 4. Base shear strength/seismic weight of the models and their ratios to the reference model for x and y directions

Model identifier	Base shear force (kN)		Base shear force/ Seismic Weight		Ratio with respect to reference	
	X	Y	X	Y	X	Y
Reference Model	4935	4911	0.337	0.336	1.000	1.000
R30/YK11200	4858	4689	0.332	0.320	0.984	0.955
R30/YK25000	4875	4741	0.333	0.324	0.988	0.965
R30/YK45000	4867	4727	0.333	0.323	0.986	0.963
R30/YK80000	4862	4724	0.332	0.323	0.985	0.962
R40/YK11200	4864	4735	0.332	0.324	0.986	0.964
R40/YK25000	4882	4738	0.334	0.324	0.989	0.965
R40/YK45000	4880	4739	0.333	0.324	0.989	0.965
R40/YK80000	4876	4737	0.333	0.324	0.988	0.965
R60/YK11200	4885	4731	0.334	0.323	0.990	0.963
R60/YK25000	4885	4742	0.334	0.324	0.990	0.966
R60/YK45000	4889	4748	0.334	0.324	0.991	0.967
R60/YK80000	4889	4744	0.334	0.324	0.991	0.966
STK/YK11200	4704	4444	0.321	0.304	0.953	0.905
STK/YK25000	4724	4463	0.323	0.305	0.957	0.909
STK/YK45000	4715	4467	0.322	0.305	0.955	0.910
STK/YK80000	4724	4468	0.323	0.305	0.957	0.910
STR/YK11200	4835	4685	0.330	0.320	0.980	0.954
STR/YK25000	4848	4680	0.331	0.320	0.982	0.953

Model identifier	Base shear force (kN)		Base shear force/ Seismic Weight		Ratio with respect to reference	
	X	Y	X	Y	X	Y
STR/YK45000	4836	4692	0.330	0.321	0.980	0.956
STR/YK80000	4847	4698	0.331	0.321	0.982	0.957
STC/YK11200	4839	4706	0.331	0.322	0.981	0.958
STC/YK25000	4849	4690	0.331	0.320	0.982	0.955
STC/YK45000	4850	4710	0.331	0.322	0.983	0.959
STC/YK80000	4850	4712	0.331	0.322	0.983	0.960

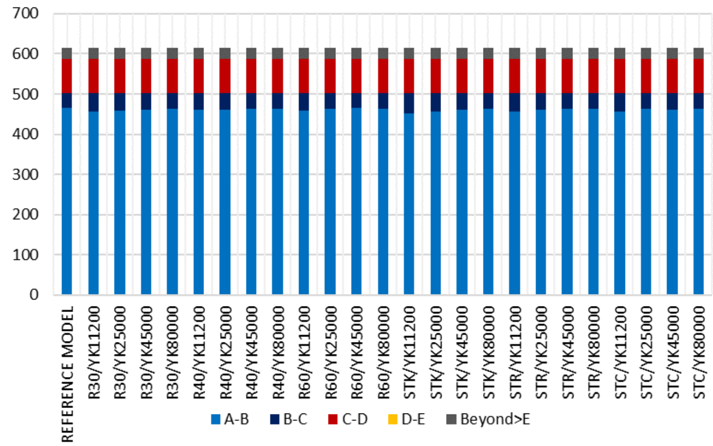

Fig. 7 Distribution of the plastic hinge status of the building models

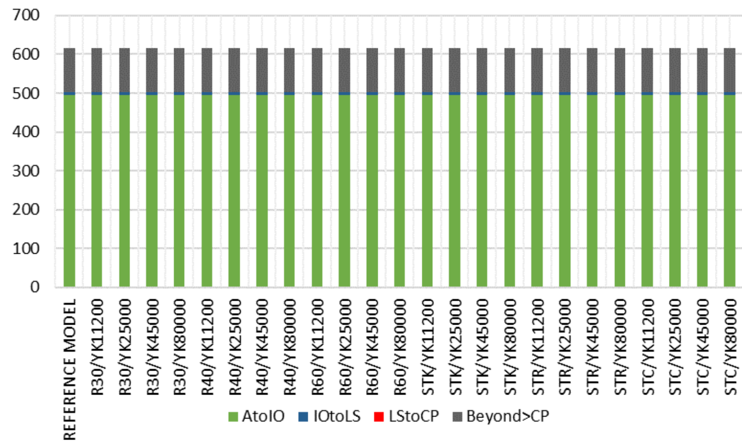

Fig. 8 Distribution of the plastic hinge damage states of the building models

The status of the plastic hinges given in Fig. 7 is not observed to be highly affected by the difference in the foundation and soil stiffness. Even if there are differences it is between C-D and >E levels both of which indicated the collapsed hinges. The difference is much limited when A-C and >C (non-collapsed and collapsed) states are considered. The A-B values in Fig. 7 is related to the yielding of the structural members. This figure is also less affected if the foundation is code complying. However, if the foundation is not fulfilling code requirements, differences up to 10% is possible. This is more detailed in the below discussion regarding the shear force distribution among the columns. For the damage state data shown in Fig. 8, there seems to be some differences. The number of damaged plastic hinges beyond LS level is 1.7% and 2.6% lower for models with foundation than the fixed base reference model. However, this level of difference is hard to be mentioned as significant. The damage distribution seems to be hardly affected by the foundation and soil stiffness in terms of the cases considered in the study.

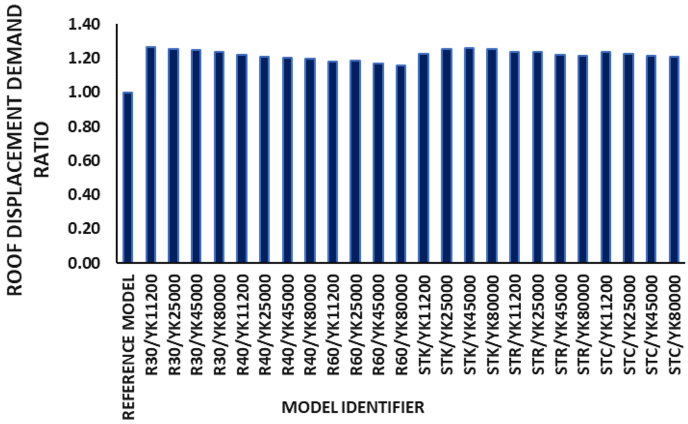

Fig. 9 Ratio of roof displacement demands for x direction of building models

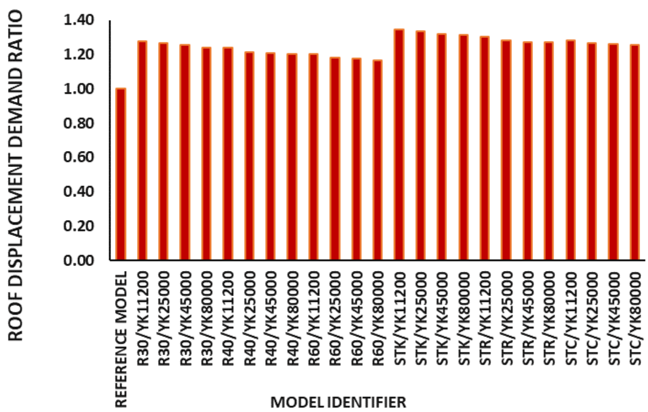

Fig. 10 Ratio of roof displacement demands for y direction of building models

The building displacement demand values with significant changes according to the fixed base case are given in Fig. 9 and 10. Displacement demands are given as roof displacement demand values calculated by considering the TBSC-2018 Earthquake Code. High variations in rates are noticeable. Displacement demand amplifications around 40% seems to be possible per fixed base case. Figures shows that both the foundation and soil stiffness is affective on the displacement demand increase per the fixed base assumption.

Besides affecting the overall stiffness of the building, the foundation stiffness also affects the distribution of the total shear among columns. The columns with large dimensions are more affected by the loss of the fixed base assumption when compared to smaller columns as finite foundation dimensions are weaker to prevent the rotation at the bigger columns/shear walls [4]. This leads to the greater loss of stiffness in larger columns than the smaller columns which result in the shear force increase in smaller columns than the expected by analyses with fixed base assumption.

Table 5. Shear force of a 400x400 mm column for x direction at 0.01 m roof displacement for different foundation cases and its ratio to the fixed base case

Model identifier	Shear force (kN)	Ratio
Reference Model	74.0	1.00
R30/YK45000	85.0	1.15
R40/YK4500	84.3	1.14
R60/YK4500	79.9	1.08
STK/YK4500	86.3	1.17
STR/YK4500	91.2	1.23
STC/YK4500	91.5	1.24

The displacement-shear force values of a 400x400 mm column are investigated for different foundation conditions to investigate the stiffness change of the columns per fixed base case. Shear force values corresponding to 0.01 m roof displacement (as an average value before yielding) of models with a bearing coefficient of 45000 kN/m^3 are listed in Table 5. There is a similar trend for the other bed coefficient values. Table 5 shows an increase between 8% to 24% in the shear force of the column. The numerical figures are hardly deemed as negligible. This is also related to change in the yielding states of the plastic hinge status date given in Fig. 7.

The question of a “How stiff foundation is required on a soil with certain stiffness value?” is a matter of concern for both designers and researchers on the subject. In order to examine this phenomenon, a study is conducted to relate the displacement demand increase per the fixed base case due to finite foundation and soil stiffness. An equation, which is given as Eq. 4, is established to determine the displacement amplification of models depending the foundation and soil stiffness. The DAF in Eq. 4 is the “Displacement Amplification Factor” meaning the ratio of the displacement demand of the model (per TSBC-2018) to that of the fixed base version. I_F is the moment of inertia of the foundation member representing the foundation stiffness in m^4 and BC_{Soil} is the bearing coefficient of soil in kN/m^3 representing the soil stiffness. The stiffness of continuous foundation is the moment of inertia of the cross section of the RC element. The equivalent stiffness value for raft foundation is taken as d^4/4, where d is the height of the raft RC member. In the establishment of the Eq. 4, total of 100 values, 50 data from this study and another 50 from the study by Yaşar et al. [13], are used.

$$DAF = \frac{X_1}{(I_F - X_2)^{X_3} * (BC_{Soil} - X_4)^{X_5}} + X_6 \qquad (kN, m) \tag{4}$$

Table 6 shows the constant X_i values found by optimization study for best fitting to the determined model displacement amplification values. The relation between the values obtained by non-linear analyses and estimated by Eq. 4 is illustrated in Fig. 11. The correlation coefficient is found to be 0.8056 for this estimation.

By using Eq. 4, a designer or researcher may find the displacement increase per their fixed base model for their case and may decide the foundation dimensions in a more rational way. If the allowable displacement increase per fixed base case and soil stiffness is known, the required foundation stiffness may be decided by Eq. 4 and structural members of the foundation is dimensioned based on that value.

Table 6. Constants in the displacement amplification factor estimation in Eq. 4

X_1	X_2	X_3	X_4	X_5	X_6
1.64	0.0008	0.017	5500	0.037	0.004

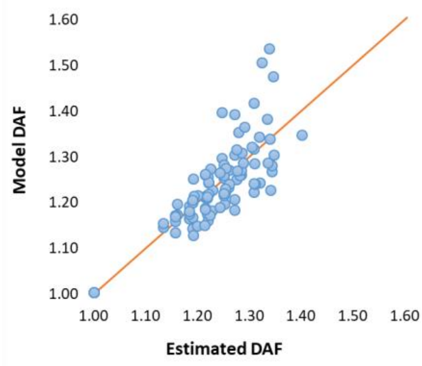

Fig. 11 Displacement amplification factors of the models and estimated values by Eq. 4

If the moment of inertia of the foundation member reaches a value close to X_2, the displacement amplification goes to infinity. This implies a square beam section of 313 mm for continuous spread footing, and a depth of 238 mm raft foundation section with an effective width of 3h. These values appear to be limiting dimensions for a foundation according to Eq. 4. Additionally, a soil with a bearing coefficient of 5500 kN/m^3 is required as a limiting value for a shallow foundation as considered in the study. These values may be seen as low. However, it should be noted that these indicates extremes with a very high displacement amplification. In that sense, values may be considered as reasonable.

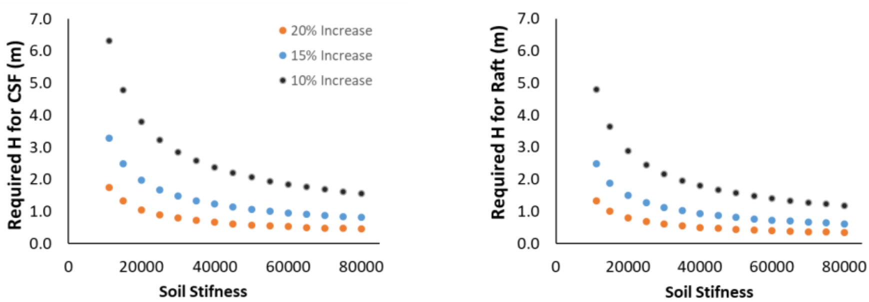

Fig. 12 Minimum raft and continuous foundation heights depending on the stiffness of the ground in cases of 10%, 15% and 20% displacement increase

In order to illustrate the values indicated by Eq. 4 Table 7 and Fig. 12 is given. Table 7 lists minimum raft and continuous foundation heights depending on the stiffness of the ground in cases of 10%, 15% and 20% displacement increase compared to the fixed base foundation. Fig. 12 demonstrate the same values for visualization. As seen, the foundation structural member height is very high for soft soils and asymptotically decreases as the soil gets stiffer which seems in accordance with expected behavior. Although some values obtained by equation seems to be impractical for construction, it may be beneficial to have an overall idea about the displacement amplification of the building and visualizing the soil stiffness on the behavior. The given equation may be used to determine a feasible point between allowable displacement demand increase and construction cost.

Table 7. Minimum raft and continuous foundation heights depending on the stiffness of the ground in cases of 10%, 15% and 20% displacement increase compared to the fixed base foundation

Subgrade Modulus (kN/m^3)	10% Increase		15% Increase		20% Increase	
	Raft h (m)	CSF h (m)	Raft h (m)	CSF h (m)	Raft h (m)	CSF h (m)
11200	4.80	6.31	2.49	3.28	1.33	1.75
15000	3.63	4.78	1.88	2.48	1.01	1.32
20000	2.89	3.80	1.50	1.97	0.80	1.05
25000	2.46	3.23	1.27	1.68	0.68	0.90
30000	2.17	2.86	1.13	1.48	0.60	0.80
35000	1.96	2.58	1.02	1.34	0.55	0.72
40000	1.80	2.37	0.94	1.23	0.50	0.66
45000	1.67	2.20	0.87	1.14	0.47	0.62
50000	1.57	2.06	0.82	1.07	0.44	0.58
55000	1.48	1.95	0.77	1.01	0.42	0.55
60000	1.40	1.85	0.73	0.96	0.40	0.53
65000	1.34	1.76	0.70	0.92	0.39	0.51
70000	1.28	1.69	0.67	0.88	0.37	0.49
75000	1.23	1.62	0.64	0.84	0.36	0.47
80000	1.18	1.56	0.62	0.81	0.35	0.46

8. Summary & Conclusions

For a more realistic approach, the effect of soil-structure interaction on the behavior of reinforced concrete buildings should not be neglected. In the study, nonlinear static pushover analysis is applied using the SAP2000 analysis program to the 4-storey reinforced concrete frame system building with different foundation types (raft and continuous foundation). 25 models with soils having different bearing coefficients and foundations of different types and sizes are considered in the scope of the study. The foundation type and foundation sections were changed by keeping the reinforced concrete frame system constant. The bearing coefficients used in the models are 11.200, 25.000, 45.000, 80.000 kN/m^3. The findings obtained as a result of the study are summarized below:

- The stiffnesses of the models are observed to be significantly affected by the foundation dimensions and the soil bearing coefficient. The dominant natural vibration periods of the buildings are higher in the soil-structure interactive models than in the reference fixed base model. Period increase up to 44% is observed depending on the foundation and soil stiffness. Values around 20% increase may easily be observed for code complying foundations and average soil conditions.

- The lateral strength of buildings seems to be less affected by foundation and soil conditions. As long as the code requirements are met for foundations, the drop in lateral strength capacity is limited around 4%. If the foundation dimensions are lower than code requirements, this figure may reach to 9% even if the soil conditions are favorable.
- The closer values of lateral building strength for the same foundation dimensions with different soil stiffness, suggest that the lateral strength is more of an issue of foundation stiffness than that of the soil.
- The damage distribution of the plastic hinges seems to be hardly affected by the foundation and soil stiffness with figures less than 3% in terms of the cases considered in the study. However, if the foundation is not fulfilling code requirements, differences up to 10% is possible for yielding distribution of the structural members.
- The building displacement demand values with significant changes according to the fixed base case are observed. Amplifications around 40% seems to be possible per fixed base case.
- Besides affecting the overall stiffness of the building, the foundation stiffness also affects the distribution of the total shear among columns. The shear force in smaller columns becomes more than anticipated by a fixed base model. Obtained values shows an increase between 8% to 24% in the shear force of the selected column which are hardly negligible.
- An equation is established trying to answer how stiff the foundation should be for a given soil condition. If the allowable displacement increase per fixed base case and soil stiffness is known, the required foundation stiffness may be decided by given equation and structural members of the foundation is dimensioned.

References

[1] Ozmen HB. A view on how to mitigate earthquake damages in Turkey from a civil engineering perspective. Res Eng Struct Mater. 2021; 7(1):1-11. https://doi.org/10.17515/resm2020.231ea1113ed

[2] Turkish Earthquake Code-TEC (2007): Specifications for structures to be built in seismic areas. Ankara, Turkey; 2007.

[3] Demirtaş B, Bayraktar A, Dumanoğlu A. Model updating effects on the seismic behavior of tall buildings under far and near-fault ground motions. Res Eng Struct Mater. 2016; 3(2):99-112. https://doi.org/10.17515/resm2016.64st0719

[4] Girgin S, Mısır S, Özden G, Kahraman S. The Role of Structure-Soil Interaction in Structural Design. Dokuz Eylül Üniversitesi Mühendislik Fakültesi Fen ve Mühendislik Derg. 2008; 10(1):27-37.

[5] Karabörk T. Nonlinear 3D Dynamic Analysis of Reinforced Concrete Structures Considering the Soil-Structure Interaction. Yapı Teknol Elektron Derg. 2009; 5(1):25-36.

[6] Korkmaz K, Demir F. Effects of Soil-Structure Interaction on Seismic Behavior of Buildings. Mehmet Akif Ersoy Üniversitesi Fen Bilim Enstitüsü Derg. 2012; 3(1):12-7.

[7] Çaycı BT, İnel M. The Effects of Soil Structure Interaction on Seismic Behavior in Existing Reinforced Concrete Buildings. In: 3rd Turkish Earthquake Engineering and Seismology Conference. 2015.

[8] Cayci BT, Inel M, Ozer E. Effect of Soil-Structure Interaction on Seismic Behavior of Mid- and Low-Rise Buildings. Int J Geomech. 2021; 21(3). https://doi.org/10.1061/(ASCE)GM.1943-5622.0001944

[9] Kılıçer S. The Effect of Soil-Structure Interaction on the Design of Reinforced Concrete Structures. Dissertation. Karadeniz Technical University, Trabzon, Turkey; 2016.
[10] Ada M. Investigation of the structure-soil-structure interaction on group of structures. Dissertation. Yıldız Technical University; 2020.
[11] Ahmadı M. Inelastic Static (Pushover) Analysis For Estimating Seismic Demands Of RC Buildings Including Soil-Structure Interaction. Dissertation. Sakarya University, Sakarya, Türkiye; 2020.
[12] Öz İ. Evaluation of vulnerability of existing buildings using soil-structure interaction models represented by springs. Dissertation. Pamukkale University Institute of Science, Denizli, Turkey; 2021.
[13] Yaşar N, Tanrıverdi B, Ozmen HB. 7 katlı betonarme bir binada farklı temel durumları ve zemin rijitliğinin yapı davranışına etkisi. Disiplinlerarası Yenilik Araştırmaları Derg. 2022; 2(1):1-14.
[14] Tarakcı NG. Zemin ve Temel Rijitliğinin Betonarme Yapı Davranışına Etkisi. Dissertation. Graduate Education Institute, Usak University, Usak, Turkey; 2022.
[15] Ozmen HB, Inel M, Senel SM, Kayhan AH. Load carrying system characteristics of existing turkish rc building stock. Int J Civ Eng. 2015; 13(1).
[16] TBSC. Turkish Building Seismic Code. Ministry of Environment and Urban Planning, Ankara, Turkey; 2018.
[17] TS-500: Requirements for design and construction of reinforced concrete structures. Turkish Standards Institute, Ankara, Turkey; 2000.
[18] TS-498: Design Loads for Buildings. Turkish Standards Institute, Ankara, Turkey; 2021.
[19] Köse MM, Karslıoğlu Ö. Effects of Infill Walls on the Natural Modal Period and Mode Shape of the Buildings. In: 6th National Earthquake Engineering Conference. 2007.
[20] Ozmen HB, Inel M, MERAL E. Evaluation of the main parameters affecting seismic performance of the RC buildings. Sadhana - Acad Proc Eng Sci. 2014; 39(2).
[21] FEMA-356. Prestandard and commentary for the seismic rehabilitation of buildings, Federal Emergency Management Agency. American Society of Civil Engineers (ASCE), Washington, DC, USA. Washington, USA; 2000.
[22] Öztürkoğlu O, Uçar T, Yeşilce Y. Yapılarda Dolgu Duvar-Çerçeve Etkileşiminin İncelenmesi. Dokuz Eylül Üniversitesi Mühendislik Fakültesi Fen ve Mühendislik Derg. 2015; 17(3):109-21.
[23] Asteris PG. Lateral Stiffness of Brick Masonry Infilled Plane Frames. J Struct Eng. 2003; 129(8):1071-9. https://doi.org/10.1061/(ASCE)0733-9445(2003)129:8(1071)
[24] Bowles JE. Foundation Analysis and Design International Fifth Edition. Civil Engineering Materials. 1997. 1143 p.
[25] Işık E, Harirchian E, Bilgin H, Jadhav K. The effect of material strength and discontinuity in RC structures according to different site-specific design spectra. Res Eng Struct Mater. 2021; 7(3):413-30. https://doi.org/10.17515/resm2021.273st0303
[26] SAP2000. Integrated Software for Structural Analysis and Design. Berkeley, USA: Computers and Structures Inc.;
[27] ASCE/SEI 41-17: Seismic Evaluation and Retrofit of Existing Buildings. Reston, VA: American Society of Civil Engineers; 2017.