Arabian Journal for Science and Engineering
https://doi.org/10.1007/s13369-021-05714-4

RESEARCH ARTICLE-CIVIL ENGINEERING

Basement-Storey Effect on the Seismic Response of RC Buildings on Soft Surface Soil

Naci Çağlar[1,2] · Sedat Sert[1] · Ahmet Hamdi Serdar[2]

Received: 21 January 2021 / Accepted: 6 May 2021

Abstract

The effects of the basement storey on the seismic behavior of RC buildings built on near-surface alluvial soft soil are studied in this study. Numerical building models with and without a basement and with different numbers of stories are developed. Time-history dynamic analysis of the structure–soil models was performed using the specialized geotechnical software package PLAXIS-2D. In the first phase of the finite element analysis, the settlement on the soil under the static loads of the building was determined. In the second phase, the earthquake responses of RC buildings with and without a basement storey in terms of lateral displacement were examined by considering the determined stresses after the static loading. The results of the numerical models demonstrate that when the height of the RC buildings is increased, the seismic response of RC buildings without basement storey is detrimentally affected.

Keywords Soft soil · Basement · Earthquake behavior · Reinforced concrete · Structure–soil interaction · Finite element method

1 Introduction

Turkey is located in one of the most active seismic zones in the world, which has earthquake periods quite often with short return periods. During the last century, more than twelve major earthquakes with minimum magnitudes (M_w) of 7 caused significant casualties and severe damages to a lot of structures and lifelines in Turkey [1]. The 1999 Marmara earthquake caused the majority of the building collapse and deaths in small towns located on the narrow flat shorelines of the Marmara Sea. The absence of shear walls, many deficiencies in design, poor detailing, and faulty construction execution may have contributed to the extent of the damage and collapses in buildings by reducing the ductility of the structural elements. Moreover, heavy damage and loss of life were reported and observed in the city of Adapazarı, and many buildings sank due to soil failure [2, 3]. The extensive damage in the center of Adapazarı can be directly related to top soil conditions. Local variations in the characteristics of alluvial sediments in Adapazarı appear to have played an integral role in the occurrence and non-occurrence of soil failure and associated building damage [2–4]. These observations revealed that determining the soil properties and taking them into account provides an important contribution to understand the real response of buildings subjected to heavy ground motions. In the event of an earthquake, the building and the soil will affect each other since the seismic responses of the ground and the structure are different from each other. Structures under earthquake move with the ground, and changes in the ground affect the dynamic behavior of the building, such as the period and mode shapes. Therefore, the soil structure interaction (SSI) effects should be included in the dynamic analysis of all structures located in active seismic zones [5–7].

In recent years, numerous researchers have been performing a lot of studies regarding the effects of SSI on the dynamic seismic response of buildings. Although the dynamic SSI effects could be neglected for regular flexible buildings on rock or very stiff soil, they should be significantly taken into account for structures founded on relatively flexible soil types [8–14]. Investigating the soil structure interactions of RC buildings that built on a ground

✉ Naci Çağlar
caglar@sakarya.edu.tr

[1] Department of Civil Engineering, Sakarya University, Engineering Faculty, 54050 Sakarya, Turkey

[2] Department of Civil Engineering, Faculty of Technology, Sakarya University of Applied Sciences, 54050 Sakarya, Turkey

Published online: 10 June 2021

containing alluvial origin soft soils is potentially of great importance. Such RC buildings are well known to suffer problems in resisting seismic loads. The construction of a basement storey for such RC buildings can offer an effective solution. A properly designed and constructed basement storey, in the event of severe earthquakes, reduces the lateral drift of the above-ground storeys significantly, which is often the cause of serious damage of RC buildings [15–17].

The main purpose of this study is to investigate the contribution of the basement storey to the response of RC buildings subjected to earthquake. In addition, the study aims to show the effect of the basement storey in solving the soil failure and deformation problems in RC buildings on soft surface soil. Moreover, this study focused on the relative displacement changes at the top of the building rather than determining the damages in the structural elements, and consequently, the structural components of the RC building are assumed to undergo linear elastic behavior. In the study, the two-dimensional finite element models of RC buildings and surrounding soil were generated by using of PLAXIS 2D, a commercially available finite element program. In all of the FE analyses, the RC buildings were assumed to behave as a linear elastic material and the soil was assumed to behave as a homogeneous, elasto-plastic medium with a Mohr–Coulomb failure criterion. The results of the numerical models demonstrate that when the height of the RC buildings is increased, the seismic response of RC buildings without basement storey is detrimentally affected.

2 Methodology of SSI Analysis

There are two main methods dealing with soil–structure interaction, namely the direct method and the substructure method. In the direct method, the response of the soil and structure is determined simultaneously by analyzing the idealized soil–structure system in a single step [18]. The soil with the superstructure is modelled up to the artificial boundary (Fig. 1). In some conditions where it is impossible to cover the unbounded soil domain with finite elements with bounded dimensions, the Substructure Method is used as an alternative. A special frequency-independent viscous dashpot boundary on the interface nodes in all directions was proposed [19]. Because this method uses finite element modelling of the core region, it provides a suitable way to solve complex structures such as dams or nuclear reactors. From the other point of view, a large number of degree of freedoms appear due to the discretization of the soil region as it accounts for the nonlinearity of near-structure domain.

In SSI problems, the ability to predict the coupled response of the soil and structure is of great significance. Therefore, combined soil and structure models are required to simulate these problems. However, while structure models are with a good basis in the literature, soil models include complicated analysis due to their unbounded nature. Then the major difficulty in modeling the soil region comes into being from the propagating wave characteristics in the soil medium. The main objective of many related engineering studies is to build up SSI models, which are reliable and easy to implement [6].

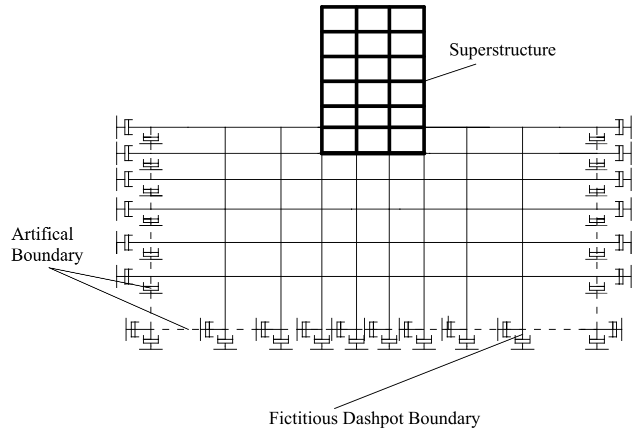


Fig. 1 Direct method configuration [18]

In the SSI analyses, the appropriate boundary conditions need to be applied to avoid the reflection of emanating waves from the artificial boundaries back into the interior domain. In many cases, the soil region proves a complex and nonlinear behavior, which can be discretized using the finite element Method (FEM), the boundary element method (BEM) or hybrid models. These models have a lot of advantages and disadvantages. In the finite element models, the large-scale mesh is required to take account of the surrounding soil medium which is bounded by the far-field that is represented by artificial boundaries. In numerical modelling of wave propagation, the special boundary conditions, which might be referred to as radiation damping, are used to compensate the problems arising as artificial boundaries to introduce artificial reflections that contaminate the solution. These special boundary conditions such as transmitting, non-reflecting and silent boundaries absorb the wave energy. The non-reflecting viscous boundaries have been widely used for various dynamic SSI problems [6, 19, 20]. These boundaries must be identified far away from the structure or source of dynamic load as they are only capable to transmit plane and cylindrical waves.

In modelling the SSI system, the substructure method is more complex than the direct method. In the Substructure Method, the semi-infinite half-space is represented by approximate boundary conditions. In substructure method [21], the soil–structure system is divided into two substructures of simpler problems, which are solved independently, and the results are then superposed to obtain the response of the structure (Fig. 2) which leads this method to be simple and computationally more efficient.

While the direct method is usually used to study two-dimensional models, the substructure method is used for three-dimensional case. The substructure approach is most often simulated in the frequency domain to account for the frequency dependence of the foundation impedance functions. The substructure method has an important advantage where changes owing to the properties of the structure and the seismic environment have not to be repeated once the scattering and impedance problems have been resolved. The fundamental step in the substructure approach is to determine the force–displacement characteristics of the soil. This relationship may be in the form of an impedance (stiffness) function, or, inversely, a compliance (flexibility) function [18].

3 Soil Profiles

Sakarya University has evaluated around 600 drillings and conducted 250 cone penetration tests (CPT) in Adapazari within 10 years after the 1999 earthquakes. The results of soil investigations show that the floads of the meandering streams Sakarya and the Cark cause extreme lateral and vertical changes in the soil profiles [2, 22]. Typical cone point resistance profiles from CPT tests in Adapazari are shown in Fig. 3.

In these profiles, it can be seen that soft surface layers have CPT point resistances of almost lower than 1 MPa. The thickness of these soft surface layers, which contain alternating nonplastic silts and clays, may vary from 3 to 10 m. After these depths, dense/very dense sand and medium overconsolidated clay layers are encountered. The thicknesses and CPT point resistances may reach to 6–8 m and 30 MPa in sands, respectively. At greater depths, the soils consist of interbedded clays, silts and sands which have much better conditions regarding soft surface soils.

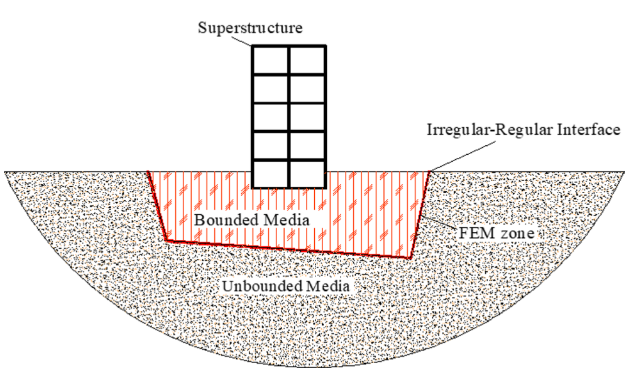


Fig. 2 Substructure method configuration [16]

It can be easily seen from Fig. 4 that lots of very dense soils (standard penetration test number, $N_{30} > 50$) have appeared starting from the depth of 4–6 m and thicknesses may reach to 10 m in Adapazari [22]. Also Bol [23] and Seed et al. [24] confirmed that dense/very dense sand layers are available in different depths in Adapazari in the regions where abandoned channels of Sakarya River are encountered. Moreover, Sancio et al. [4] showed that three of four typical sections in Adapazari have these dense/very dense sand layers (Fig. 5).

Since Adapazari soils show general characteristic of soft/loose surface soils, example sections from Adapazari were selected to simulate soft soil conditions in this study. In finite element models, surface soil thickness was used as 6 m by considering of the profiles in Fig. 5.

4 Numerical Study

The two-dimensional soil–structure numerical models with RC frame structures and surrounding soils were generated using PLAXIS 2D, a commercially available finite element program (Fig. 6) [25]. In total, 14 soil–structure models were prepared. Two cases including the RC frame buildings with basement storey and without basement storey were separately modelled considering impact of the structural slenderness (H/B: Height/Width), soil conditions and ground water table (Table 1).

In all of the FE analyses, the RC frames were assumed to behave as a linear elastic material and the soils were modeled with hardening soil model and assumed to behave as a homogeneous, elasto-plastic medium with a Mohr–Coulomb failure criterion. Both material models are considered separately for describing the seismic response of soil behavior for the proposed soil–structure systems.

The numerical study has been carried out to investigate the effect of the basement storey on the response of RC buildings under static and dynamic loads with regard to slenderness ratio of the building. Buildings with higher slenderness ratio are much more sensitive to earthquake loads [26]. The slenderness ratio, which is one of the most important factors affecting the structural response of RC buildings, is defined as the ratio of the height (H) to base width (B) of the superstructure. A total of seven different slenderness ratios (H/B) were employed to proposed soil–structure systems with constant width of the RC frame B = 6 m. RC buildings constructed with mat foundations on soft surface soil are mostly 5–6 storeys which corresponds to slenderness ratio 2.50–3.00. However, in this study, the maximum slenderness ratio was also chosen as 4.00 in order to show the negative impact on the response of RC buildings subjected to earthquakes. During the dynamic time-history analysis, the Marmara Earthquake acceleration record (Fig. 7) was

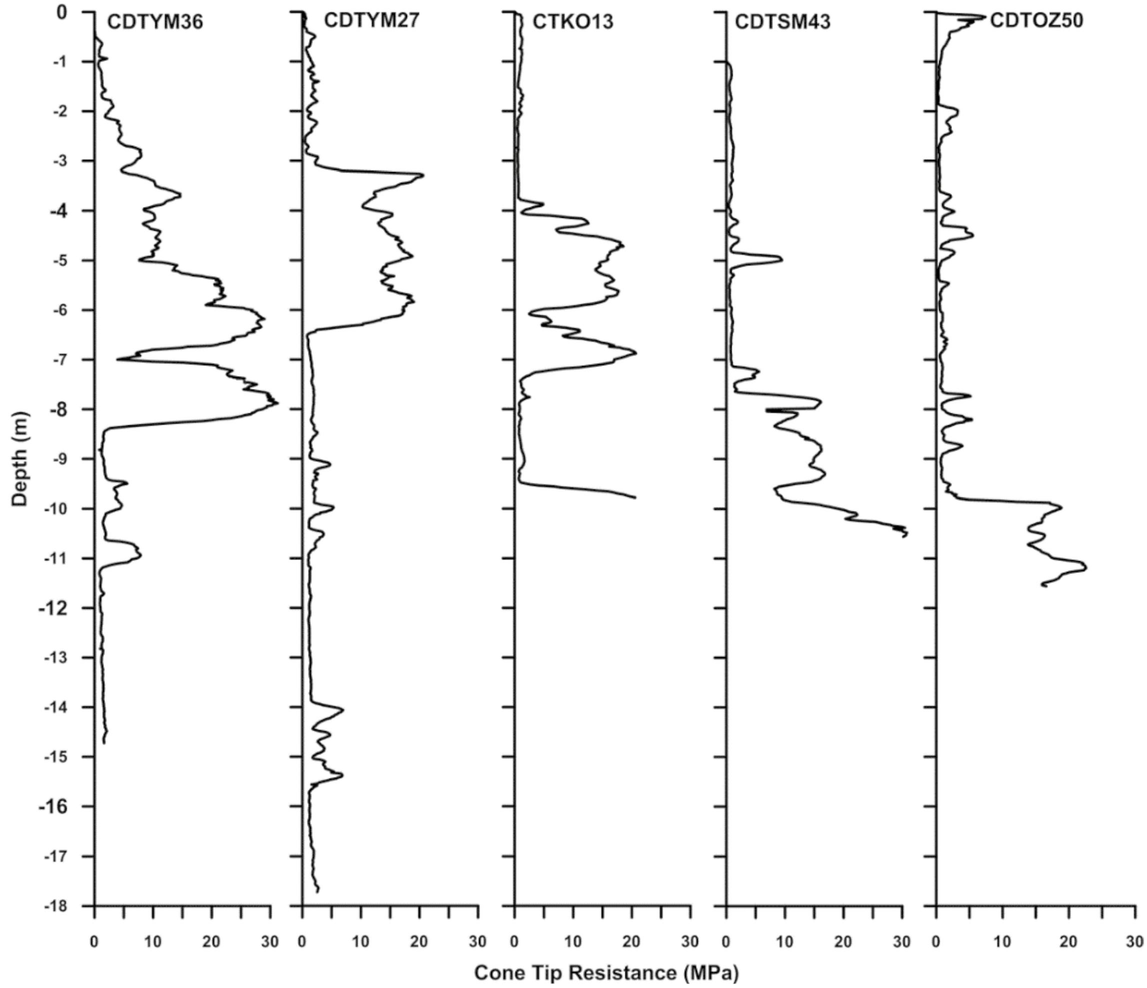
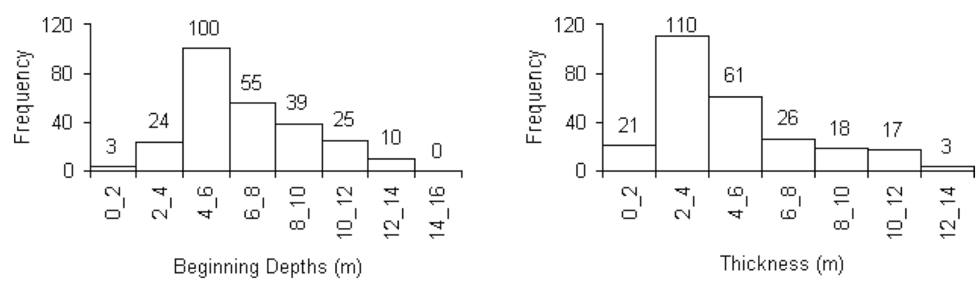


Fig. 3 Different cone point resistance (q_c) profiles in Adapazari

Fig. 4 Beginning depths and thicknesses of very dense sand layers from boring logs [22]



applied horizontally at the entire base, while energy absorbing boundaries of Lysmer type were assigned to the vertical side of soil deposit boundaries.

In the PLAXIS program, soil deposits can be modeled with 6 or 15 noded elements [25]. The corresponding structural elements of superstructure can be modeled with 3 or 5-noded elements. In this study, 15-noded soil elements were selected for a more precise analysis. The superstructure plate elements corresponding to the selected soil elements must have 5 nodes for the continuity and compatibility of the finite element mesh. Therefore, in this study, the soil deposits were modelled by two-dimensional 15-noded triangular elements and the RC buildings were modelled by two-dimensional 5-noded plate elements. As suggested in the literature, the model boundaries should be extended to 10 times of the model height to assure that all shear waves move without any reflection [27–29]. In this study, depth and width of the soil deposits were chosen 30 m and 400 m, respectively. The underlying soils consist of three distinct layers of both soft and dense soils types, with properties similiter to soils

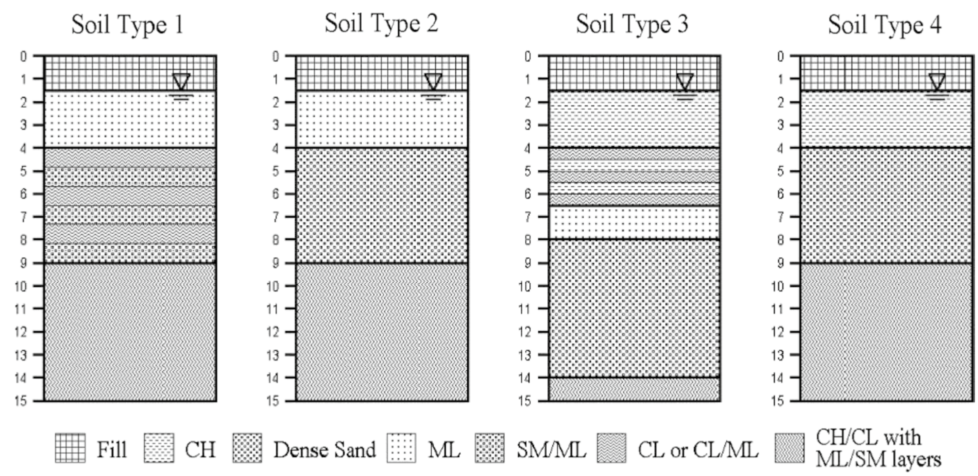


Fig. 5 Typical soil profiles from Adapazari city center [4]

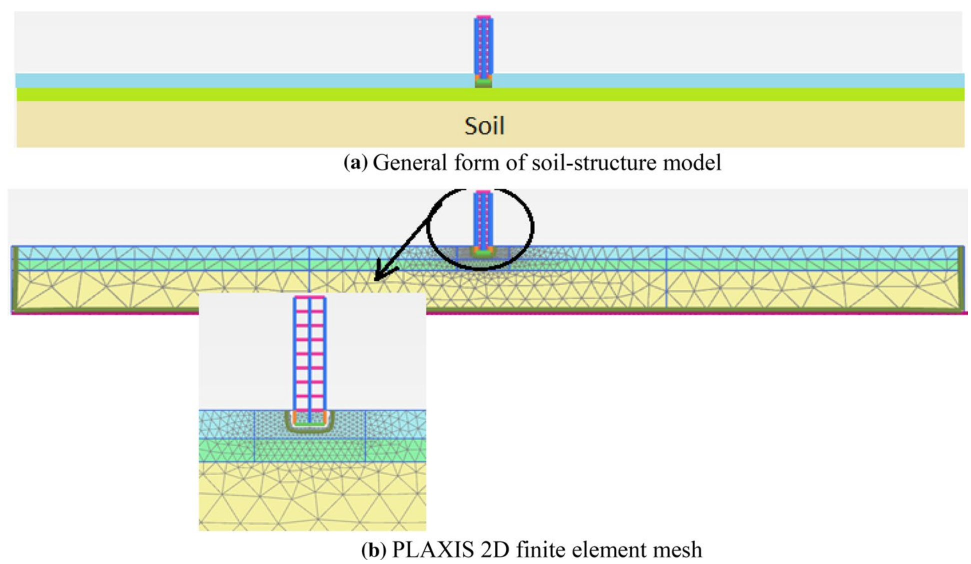


Fig. 6 Numerical model of soil–structure system

Table 1 Finite element models

	Slender-ness ratio H/B	Base-ment storey
Model 1	1.00	Yes
Model 2		No
Model 3	1.50	Yes
Model 4		No
Model 5	2.00	Yes
Model 6		No
Model 7	2.50	Yes
Model 8		No
Model 9	3.00	Yes
Model 10		No
Model 11	3.50	Yes
Model 12		No
Model 13	4.00	Yes
Model 14		No

found in Adapazari/Sakarya. From the ground surface to a depth of 6 m, there is a soft silty clay soil. Underneath this layer, down to a depth of 11 m, there is a very dense sand layer. The underlying layer consists of clayey soil. The mechanical properties of soils were gathered from the literature [15]. Variation of the underlying soft and dense soils mechanical properties along the depth is summarized in Table 2. The mechanical properties of all structural elements of superstructure in terms of the axial and bending stiffnesses were converted to have input values of the plate elements (Table 3).

5 Validation of the FEA Model

The results of the dynamic analysis of soil–structure model are compared with observed the response of the real RC building (Fig. 8). A careful study of the results from Fig. 8

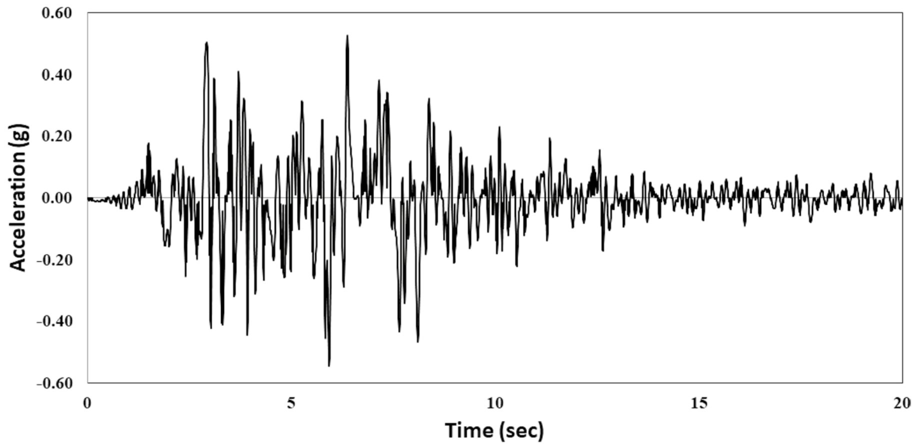


Fig. 7 Marmara earthquake N-S record, 17 August 1999

Table 2 Mechanical properties of underlying soils [15]

Depth	(m)	0–6	6–11	11-…
Layer name		Silty-clay	Dense sand	Clay
Material model		Hardening soil Model	Hardening soil model	Hardening soil model
Material type		Undrained	Undrained	Undrained
γ_{unsat}	(kN/m^3)	17.5	17	17
γ_{sat}	(kN/m^3)	18	18	20
e_0		0.9	0.6	0.9
E'^{ref}_{50}	(kPa)	5000	60,000	15,000
E'^{ref}_{oed}	(kPa)	5000	60,000	15,000
Power	m	0.8	0.5	0.9
c'	(kPa)	10	1	20
φ'	(o)	20	38	25
ψ	(o)	0	8	0
E'^{ref}_{ur}	(kPa)	15,000	180,000	45,000
υ'_{ur}		0.2	0.2	0.2
p^{ref}	(kPa)	100	100	100
K_0^{nc}		0.658	0.384	0.577
$c'_{increment}$	(kPa)	1	0	1
y_{ref}	(m)	0	0	−11
R_f		0.9	0.9	0.9
OCR		3	2	1.5

Table 3 Adapted values of mechanical properties of RC frame structures

			Column/Beam	Basement
Axial Stiffness	EA	(kN/m)	4.48×10^6	4.48×10^6
Flexural Stiffness	EI	(kNm^2/m)	5.97×10^4	5.97×10^4

leads to an observation of fairly good agreement between the real problem and FEA model outcomes. During 1999 earthquakes, some foundation bearing capacity failure and excessive displacement of RC buildings constructed with mat foundations on soft surface soil have been observed in the study area [2]. In this case, building moves as rigid block and therefore, there is no damage at the structural elements of RC buildings since the integrity of the building is not demolished. As can be seen from Fig. 8, there is no damage in the structural elements of the real RC building. The most significant effect was observed as excessive displacement in the soft soil on which the building constructed. The reason of this failure is the fact that the building has no basement storey. Therefore, the failure of the soil body and excessive displacements obtained in the finite element analysis coincide with the real behavior presented in Fig. 8. Earthquake

Fig. 8 The response of the actual building in Marmara Earthquake and the FEA Model

damage has occurred on many RC buildings that were constructed on alluvial soil in downtown Adapazari. This was especially pronounced in the case of buildings that were constructed without a basement storey, which experience excessive displacement and tilting.

6 Result and Discussions

A numerical study has been carried out to investigate the effect of the basement storey on the horizontal and vertical displacement behavior of reinforced concrete buildings under the static and dynamic loads. Static loads are the weight of the RC buildings. In the first phase of the finite element analysis, the vertical displacement (settlement) on the soil under the static loads was determined. In the second phase, the response of RC buildings under the earthquake loads was examined by taking into account the determined stresses after the static loading. In buildings with basement storey, there is no excessive settlement under the static loads for all values of H/B. However, in buildings without basement storey, soil failure was determined due to excessive displacements under static loads for values of H/B = 2.50 and higher (Table 4, Fig. 9). The numerical analysis results show that basement storey is very effective in solving the soil failure problem in RC buildings on soft surface soil. With the construction of basement storey in RC buildings on soft surface soil, the net stress and the thickness of compressible soft layer decrease, besides, the foundation bearing capacity increases, and the risk of overturning decreases with the increase of the embedment depth. This fact is clearly evident in Table 4 and drastic decreases in vertical displacements are remarkable. For example, when H/B = 2.00 for an RC building without and with basement storey, vertical displacements under the static loads are 68.73 cm and 1.05 cm, respectively. Moreover, the analysis

Table 4 Settlement (under the static loads, cm)

H/B	With no basement storey	With basement storey
1.00	5.55	0.38
1.50	18.18	0.67
2.00	68.73	1.05
2.50	Soil body collapsed	1.47
3.00	Soil body collapsed	1.95
3.50	Soil body collapsed	2.53
4.00	Soil body collapsed	3.23

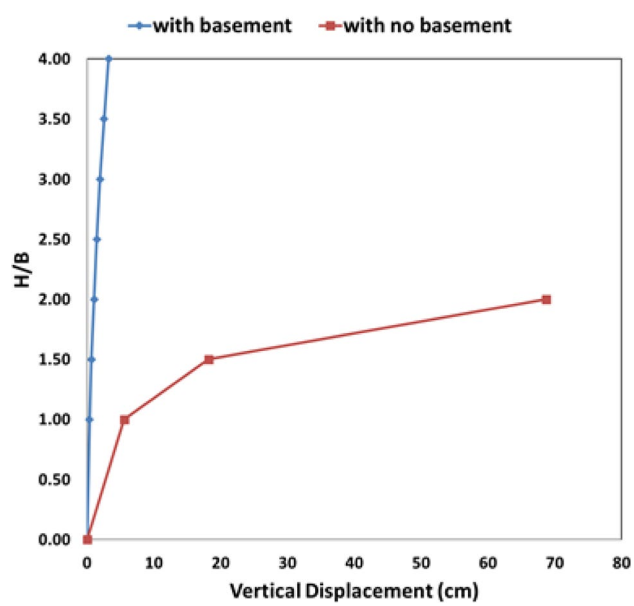


Fig. 9 Vertical settlements for point B

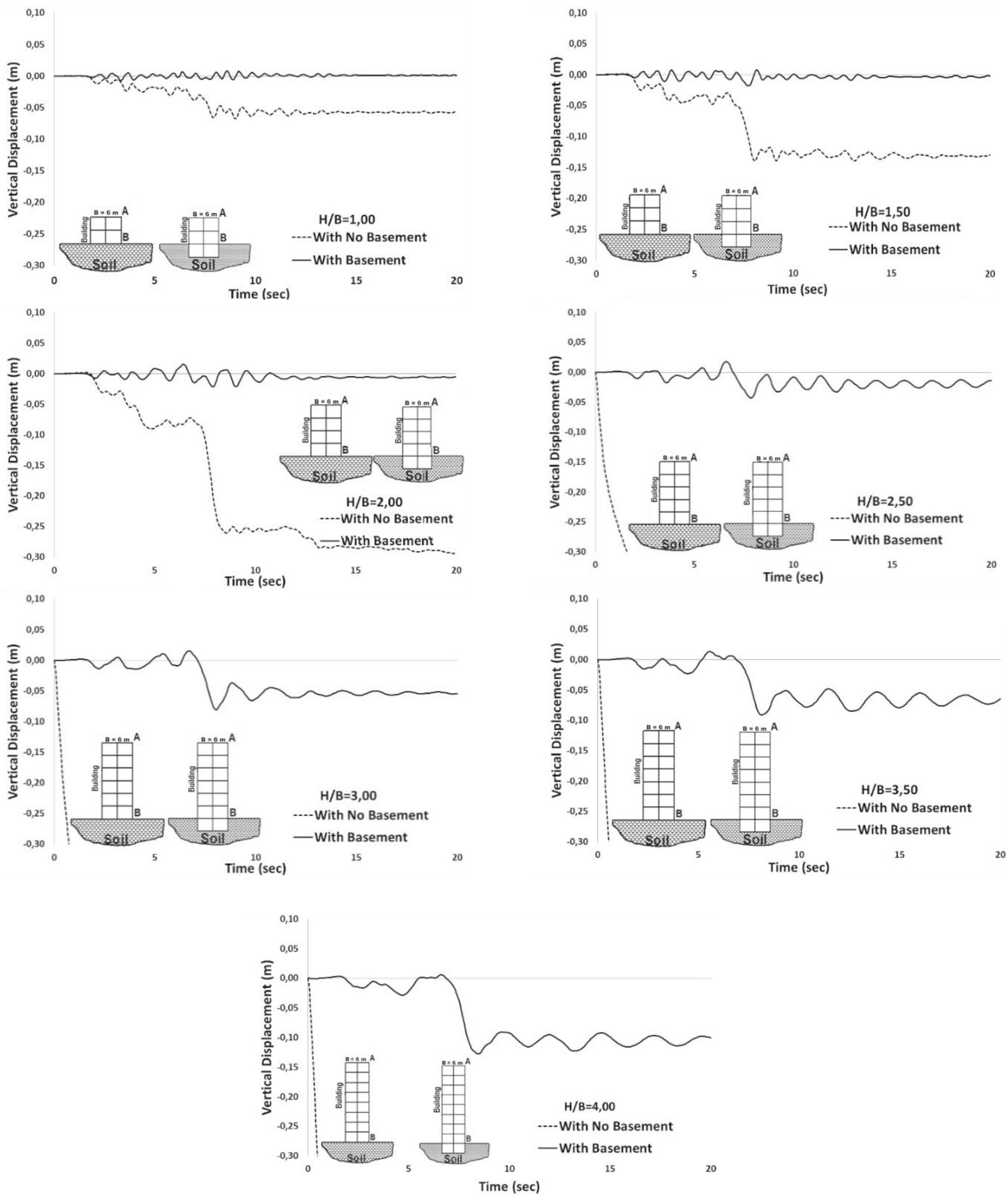


Fig. 10 Vertical displacement of the RC frame structures

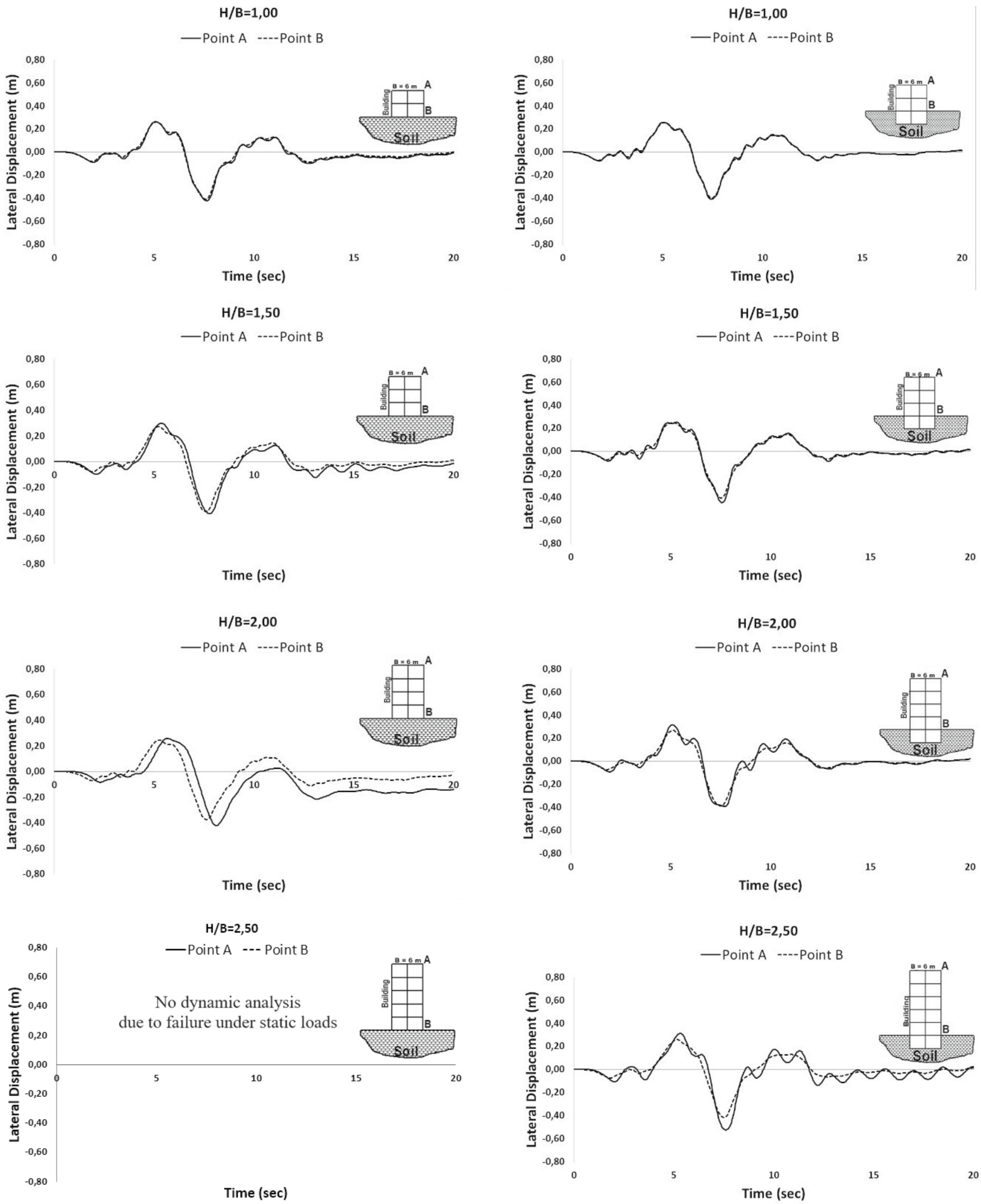


Fig. 11 Lateral displacement of the RC frame structures

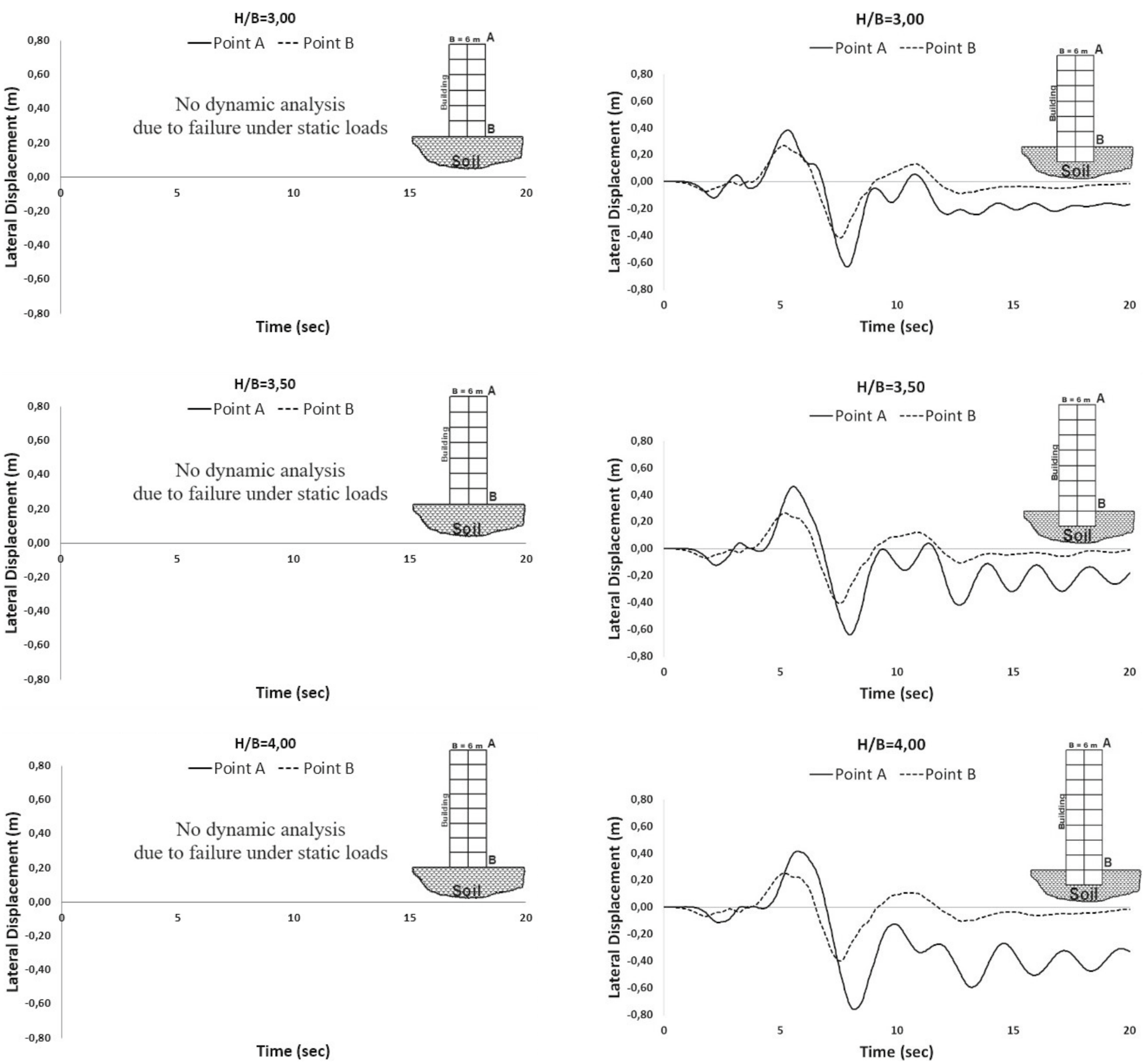


Fig. 11 (continued)

of RC buildings without basement storey for H/B higher than 2.00 is terminated with the soil body collapsed message of PLAXIS program before the whole static load is applied. This message means that the shear strength of soils is exceeded. In other words, when the stresses caused by static loading in soft soils exceed the shear strength of the soils, the soil body may collapse and in this situation, the deformations represent excessive displacements.

As can be seen from Fig. 10, the greatest value of vertical displacement under earthquake loading in RC buildings with the basement storey is about 10 cm for H/B = 4.00. However, as the H/B ratio increases, there is a significant increase in vertical displacements in buildings with no basement storey. In RC buildings with over H/B = 1.00, there are significant increases in vertical displacement of the soil and also tend to failure with a sudden increase in the 7-–th second of the earthquake. In RC buildings with no basement storey, the maximum value of vertical displacement of soil is about 6.72 cm and 28 cm for H/B = 1.00 and H/B = 2.00, respectively. Therefore, as it can be seen from these results, even if there are no excessive settlement under static loads, basement-storey effect is evident on the seismic response of RC buildings on soft surface soil under dynamic loads. The basement-storey effect is to substantially decrease the settlement of the RC buildings, which is a desirable outcome.

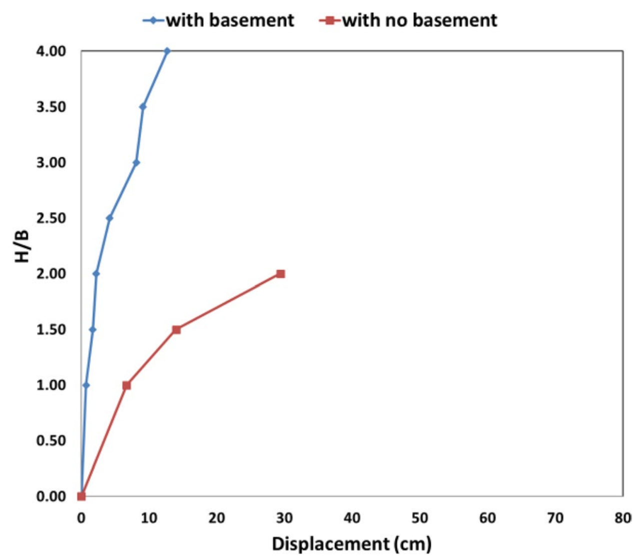


Fig. 12 Maximum relative lateral displacement of RC Buildings between points A and B

In the RC building with a basement storey, the maximum values of vertical displacements of the soil are about 0.72 and 12.7 cm for H/B = 1.00 and H/B = 4.00, respectively. In cases that RC buildings were built with basement storey, the basement storey helped to prevent the soil failure and collapse of building due to excessive displacements under static and dynamic loads.

The earthquake responses of RC buildings with and without a basement storey in terms of lateral displacement are plotted in Fig. 11. In cases where the slenderness ratio is higher than 2.00, soil failure occurs due to excessive settlements under static loads. Dynamic analysis cannot be performed because of the soil failure occurrence. Maximum relative lateral displacement of RC buildings between points A and B is also plotted in Fig. 12.

As can be clearly seen from Fig. 11, the contribution of the basement storey to seismic response in a low-rise (H/B = 1.00 and H/B = 1.50) RC building is negligible. The lateral displacements for point A and point B of RC Buildings with basement storey are stable and oscillates around the equilibrium position, almost the same as the RC building without basement storey.

As clearly seen from Fig. 11, in RC building with basement storey and H/B = 4.00, there are significant increases in vertical displacement of the soil and oscillates around the new equilibrium position due to permanent displacement of the soil in the 7–8th second of the earthquake. Due to the permanent displacement of the soil, lateral displacements of point A seem to oscillate around the new equilibrium position. Consequently, basement storey significantly affects the seismic response of RC buildings over soft surface soil considering the displacements of Point A (Fig. 11) and the relative displacements between Point A and Point B (Fig. 12).

7 Conclusions

The results of the analysis in this paper confirm the damage observed in Adapazarı city after 1999 earthquakes. In that event, a great number of reinforced concrete buildings of 4–5 storeys without basement storey faced with earthquake related foundation bearing capacity and excessive displacement problems. At the end many of them were collapsed during the earthquake or had to be demolished by the owners or the government soon after. Although the number of reinforced concrete buildings built with basement was much less at that time, it can be clearly said that they resisted the earthquake much better.

The numerical analysis results show that the soil failure and deformation problems in RC buildings on soft surface soil can be solved with the use of basement storey. The weight of excavated soil for basement storey decreases the net weight of the building. At the same time, thickness of compressible soft layer decreases. Moreover, the foundation bearing capacity increases, and the risk of overturning decreases with the increase of the embedment depth.

There is a significant increase in vertical displacements of soil in RC buildings with no basement storey. The basement storey helps in preventing the soil failure and collapse of the building due to excessive settlements/displacements under static and dynamic loads. The contribution of the basement storey to seismic response in a low-rise RC building is negligible. However, as the building height increases, especially for H/B = 4.00, the basement storey significantly affects the seismic response of the RC buildings over soft surface soil.

This study confirms that alluvium originated soft Adapazarı soils have bearing capacity and settlement/deformation problems. Regarding these problems, it can be said that taking soil structure interaction into account is necessary and the real structure behavior cannot be predicted without considering the soil properties and structure–soil relationship. The results show that when the height of the building is increased, the negative effects of soft and loose alluvial soils on the structural behavior are also increased. After evaluating the results, it was concluded that the buildings without basement are clearly affected by soft soil properties with increasing building height. It was also concluded that the buildings with basements are less prone to be damaged.

References

1. Arslan, M.H.; Korkmaz, H.H.: What is to be learned from damage and failure of reinforced concrete structures during recent earthquakes in Turkey? Eng. Fail. Anal. (2007). https://doi.org/10.1016/j.engfailanal.2006.01.003
2. Önalp, A.; Arel, E.; Bol, E.: A general assessment of the effects of 1999 earthquake on the soil-structure interaction in Adapazari. ITU Press, Adapazari, pp. 76–89. ITU Press (2001). ISBN: 975-561-192-4
3. Bol, E.; Önalp, A.: Geotechnical and geomorphological properties of Adapazarı soils. Ninth Turkish Cong. Soil Mech. Found. Eng. **1**, 1–8 (2002) (**in Turkish**)
4. Sancio, R.B.; Bray, J.D.; Stewart, J.P.; Youd, T.L.; Durgunoğlu, H.T.; Önalp, A.; Seed, R.B.; Christensen, C.; Baturay, M.B.; Karadayılar, T.: Correlation between ground failure and soil conditions in Adapazari, Turkey. Soil Dyn. Earthq. Eng. (2002). https://doi.org/10.1016/S0267-7261(02)00135-5
5. Trifunac, M.D.; Todorovska, M.I.; Hao, T.-Y.: Full-scale experimental studies of soil-structure interaction. In: Proceedings of the 2nd U.S.-Japan Workshop on Soil-Structure Interaction, Tsukuba City, Japan, 6–8 March (2001)
6. Wolf, J.P.; Song, C.: Some cornerstones of dynamic soil–structure interaction. Eng. Struct. (2002). https://doi.org/10.1016/S0141-0296(01)00082-7
7. Caglar, N.; Sert, S.; Imbabi, M.S.; Serdar, A.H.: The effect of a basement storey on the earthquake response of RC buildings constructed on soft surface soil. In: The 3rd International Symposium on Innovative Technologies in Engineering and Science, ISITES2015, pp. 1–7 (2015)
8. Boutin, C.; Soubestre, J.; Schwan, L.; Dietz, M.: Multi-scale modeling for dynamics of structure-soil-structure interactions. Acta. Geophy. (2014). https://doi.org/10.2478/s11600-014-0230-9
9. Fnais, M.; Al-Amri, A.; Abdelrahman, K.; Al-Yousef, K.; Loni, O.A.; Moneim, E.A.: Assessment of soil-structure resonance in southern Riyadh City, Saudi Arabia. Arab. J. Geosci. (2014). https://doi.org/10.1007/s12517-013-1247-0
10. Gullu, H.; Pala, M.: On the resonance effect by dynamic soil-structure interaction: a revelation study. Nat. Hazards (2014). https://doi.org/10.1007/s11069-014-1039-1
11. Aydemir, M.E.: Inelastic displacement ratios for evaluation of stiffness degrading structures with soil structure interaction built on soft soil sites. Struct. Eng, Mech. (2013). https://doi.org/10.12989/sem.2013.45.6.741
12. Tabatabaiefar, S.H.; Fatahi, B.; Samali, B.: Lateral seismic response of building frames considering dynamic soil-structure interaction effects. Struct. Eng, Mech. (2013). https://doi.org/10.12989/sem.2013.45.3.311
13. Tehranizadeh, M.; Barkhordari, M.S.: Effect of peripheral wall openings in basement and number of basement floors on the base level of braced framed tube system. Int. J. Civ. Eng. (2018). https://doi.org/10.1007/s40999-017-0270-z
14. Barkhordari, M.S.; Tehranizadeh, M.: The effect of soil around the basement walls on the base level of braced framed tube system. Civ. Eng. J. (2018). https://doi.org/10.28991/cej-03091139
15. Sert, S.; Ural, N.; Arel, E.: Effects of foundation design on earthquake damages. In: International Conference Earthquake Engineering in 21st Century Conference. Republic of Macedonia, Skopje (2005)
16. Guiterrez, J.A.; Chopra, A.K.: A substructure method for earthquake analysis of structures including structure soil interaction. Earthq. Eng. Struct. Dyn. (1978). https://doi.org/10.1002/eqe.4290060107
17. Parmelee, R.A.: Building-foundation interaction effects. J. Eng. Mech. Div. **93**(2), 131–152 (1967)
18. Jaya, K.P.; Meher, P.A.: Embedded foundation in layered soil under dynamic excitations. Soil Dyn. Earthq. Eng. (2002). https://doi.org/10.1016/S0267-7261(02)00032-5
19. Lysmer, J.; Kuhlemeyer, R.L.: Finite element model for infinite media. J. Eng. Mech. Div. (1969). https://doi.org/10.1061/JMCEA3.0001144
20. White, W.; Valliappan, S.; Lee, I.K.: Unified boundary for finite dynamic models. J. Eng. Mech. Div. (1977). https://doi.org/10.1061/JMCEA3.0002285
21. Kausel, E.; Roesset, J.M.: Dynamic stiffness of circular footings. J. Eng. Mech. Div. (1975). https://doi.org/10.1061/JMCEA3.0002072
22. Sert, S.; Bol, E.: Depth of dense soil layers in Adapazarı (in Turkish). Geotechnics Symposium of Adana Branch of the Turkish Chamber of Civil Engineers, 239–251 (2005)
23. Bol, E.: Geotechnical properties of Adapazarı soils. PhD Thesis, Sakarya University, Sakarya, Turkey (2003) (**in Turkish**)
24. Seed, R.B.; Çetin, K.Ö.; Moss, R.E.S.; Kammerer, A.M.; Wu, J.; Pestane, J.M.; Riemer, M.F.; Sancio, R.B.; Bray, J.D.; Kayen, R.E.; Faris, A.: Recent advances in soil liquefaction engineering: a unified and consistent framework. In: 26th Annual ASCE Los Angeles Geotechnical Spring Seminar (2003)
25. Plaxis: Plaxis 2D - Reference Manual 2017. Plaxis B.V, Delft, Netherlands (2017)
26. Awida, T.A.: Slenderness ratio influence on the structural behavior of residential concrete tall buildings. J. Civ. Eng. Architect. (2011). https://doi.org/10.17265/1934-7359/2011.06.006
27. Veletsos, A.S.; Younan, A.H.: Dynamic soil pressures on rigid vertical walls. Earthq. Eng. Struct. Dyn. (1994). https://doi.org/10.1002/eqe.4290230305
28. Psarropoulos, P.N.; Klonaris, G.; Gazetas, G.: Seismic earth pressures on rigid and flexible retaining walls. Soil Dyn. Earthq. Eng. (2005). https://doi.org/10.1016/j.soildyn.2004.11.020
29. Salem, A.N.; Ezzeldine, O.Y.; Amer, M.I.: Seismic loading on cantilever retaining walls: full scale dynamic analysis. Soil Dyn. Earthq. Eng. (2020). https://doi.org/10.1016/j.soildyn.2019.105962