The Effect of a Basement Storey on the Earthquake Response of RC Buildings Constructed on Soft Surface Soil

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Abstract

In this study, the effect of the basement on the earthquake behaviour of reinforced concrete structures built over alluvial origin soft soils found close to the surface were investigated. In this scope, structure-soil models were created of 2 and 6 storey-building building archetypes, on with and the other without basement. Time domain dynamic analyses of the structure-soil models and also a 2D version of PLAXIS, a specially developed software package for solving geotechnical problems, have been performed. According to the result of the dynamic analysis, the vertical settlement and also the relative horizontal displacement graphs for the top (Point A) and soil levels (Point B) were prepared and the structural performance was evaluated by presenting the storey drift as a graphic form.

Keywords: soft soil, basement, earthquake behaviour, reinforced concrete, structure-soil interaction, finite element method.

1. Introduction

The earthquake resistance of reinforced concrete (RC) structures locate in seismically active regions such as Turkey is very important and has to be determined accurately. Determination of the soil properties correctly and taking them into account provides an important contribution to our understanding of the behaviour of structures under earthquake conditions. During earthquakes, because the response of the soil and the structure are different, the soil affects the behaviour of structure and the structure affects the behaviour of the soil. Structures subjected to earthquake effect move with the soil and the soil changes the dynamic behaviour of the structure such as period and mode shape. Therefore, it is very important to examine the soil-structure interaction all significant multi-storey structures [1]. The is especially true since the earthquake regulations of 2007 [2] became a part on the agenda for soil-structure interaction analysis in Turkey.

Investigating the soil structure interactions of RC buildings that are built on ground containing alluvial origin soft soils is potentially of great importance. Such RC buildings are known to suffer problems in resisting earthquake loads. The construction of a basement for such structures offers an effective solution. A properly designed and constructed basement floor, in the event of severe earthquakes, reduces significantly the lateral drift of the above-ground floors, which is often the cause of serious damage and therefore positively affect the seismic behaviour of the structure [3-5].

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2. Soil-Structure Interaction

There are two major components in the soil-structure interaction problem. An infinite stretch of soil and a finite dimensional structure create these two major components. The finite element method is widely used in the analysis of such problems. Soil-structure interaction systems, in order to simplify the calculation, are divided into several groups such as unlimited area, limited area and interfacial interaction [6]. These systems are generally idealized as shown in Figure 1.

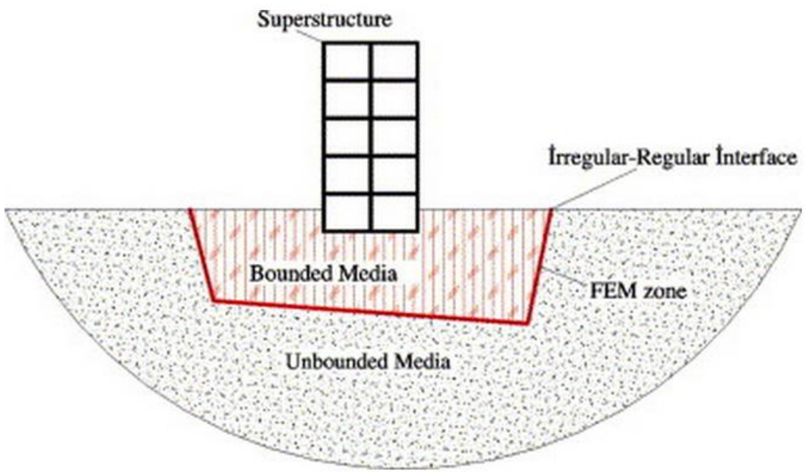
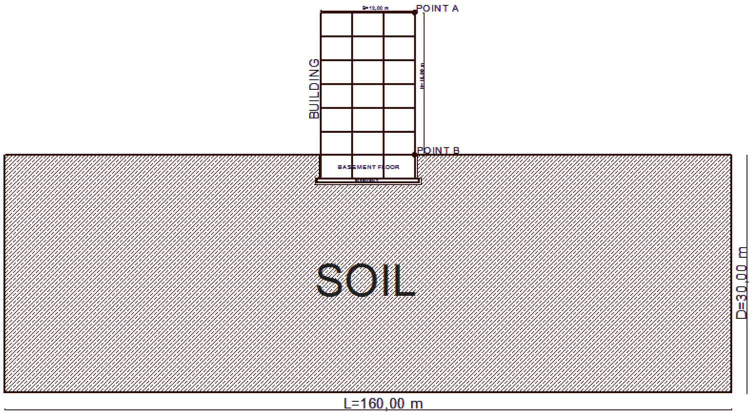


Figure 1. Dynamic Unlimited Area- Structure Interaction [5]

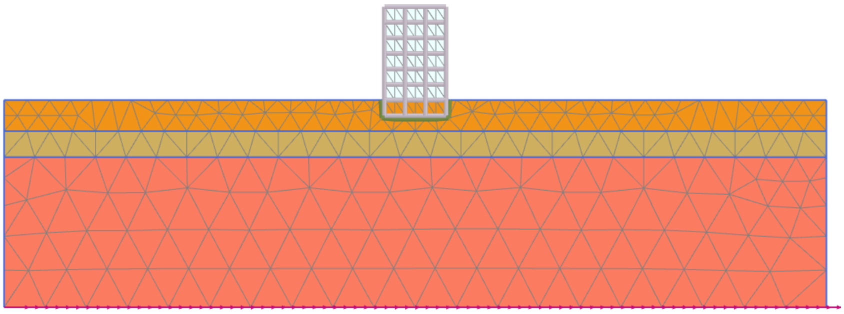
Analysis of soil-structure interaction systems is generally considered following two different approaches: a) Direct Method and b) Separation of the Subsystem Method [6]. In this study, direct method was used and the soil-structure model was simulated using tha finite element method. Superstructure and substructure (soil) were idealized as a single system and earthquake movement was defined in the model database. Time history analysis was carried out and the drift and mode shapes of soil-structure system were found.

3. Numerical Study

The effect of a basement storey on the earthquake behaviour of an RC building on a soft soil section was investigated. For this purpose, the structure-soil model was defined using the PLAXIS 2D finite element code (Figure 2).



a) General form of Structure-Soil Model



b) PLAXIS 2D Finite Element Mesh

Figure 2. Structure-Soil Model

Time history analyses of the structure-soil models in 2 and 6 storeys were carried out. In the time history analyses, a North-South acceleration record from the Marmara Earthquake of 17 August 1999 in Yarimca-Petkim station was used (Figure 3).

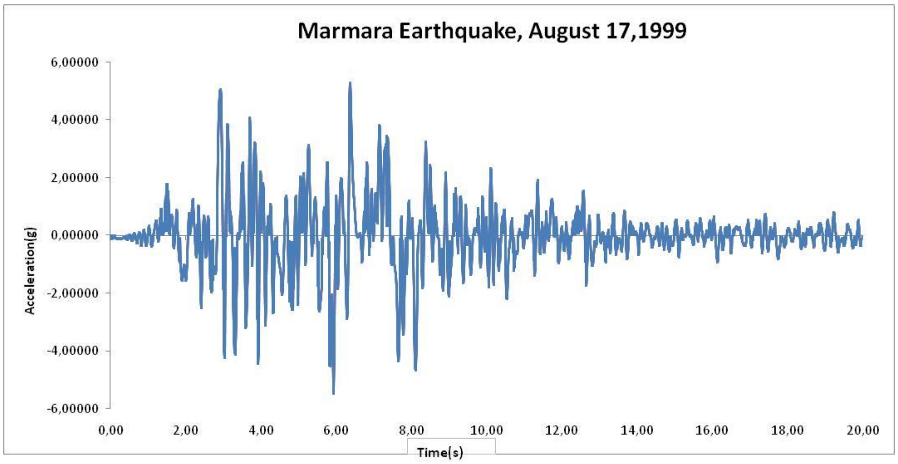


Figure 3. The Records of Marmara Earthquake, August 17, 1999

Floor height was set as 3 m and the general properties of the superstructure are those shown in Table 1. The Finite element model dimensions of the soil component were chosen as 160 m by 30 m. To create the substructure soil models, Adapazari/Sakarya soils were selected as soft soil and other soil properties were taken from the literature [8]. The chosen soil properties are summarised in Table 2.

Table 1. General Properties of the Superstructure

			Column/Beam	Basement
Axial Stiffness	EA	(kN/m)	$9{,}00 \times 10^6$	$12{,}00 \times 10^6$
Flexural Stiffness	EI	(kNm^2/m)	$6{,}75 \times 10^4$	$16{,}00 \times 10^4$

Tablo 2. General Properties of the Substructure (soil) [8]

Name	Silty Clay	Dense Sand	Clay
Depth (m)	0-6	6-11	11-30
Material Model	Hardening Soil Model	Hardening Soil Model	Hardening Soil Model
Material Type	Undrained	Undrained	Undrained
ρ_n (kN/m^3)	17.5	17	17
$\rho_{saturated}$ (kN/m^3)	18	18	20
Void Ratio e_0	0.9	0.6	0.9
$E_{50}'^{ref}$ (kPa)	5000	60000	15000
$E_{oed}'^{ref}$ (kPa)	5000	60000	15000
power, m	0.8	0.5	0.9
c' (kPa)	10	1	20
ϕ' (°)	20	38	25
ψ (°)	0	8	0
$E_{ur}'^{ref}$ (kPa)	15000	180000	45000
υ_{ur}'	0.2	0.2	0.2
p^{ref} (kPa)	100	100	100
K_n^{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

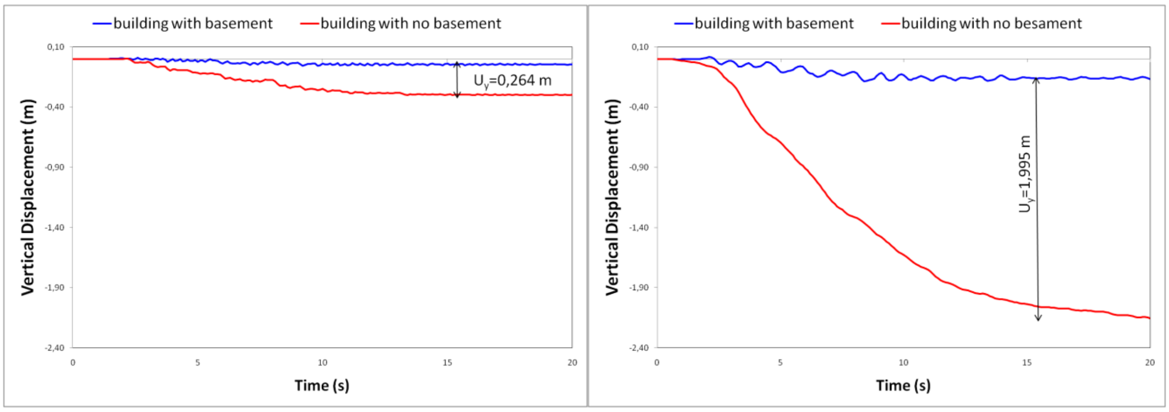
4. Analysis Results

Earthquake 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 experienced excessive settlement and tilting (Figure 4).

Figure 4. Example of What Happens When the Foundation Bearing Capacity of a Structure Without Basement is Exceeded [9] and Finite Element Mesh

In the present study, the accuracy of the finite element model was investigated by comparing the results of dynamic analysis of the structure-soil model against the observed behaviour of the real structure. It is clear to seen that the computed settlement and heave values are comparable to those found in reality (Figure 4).

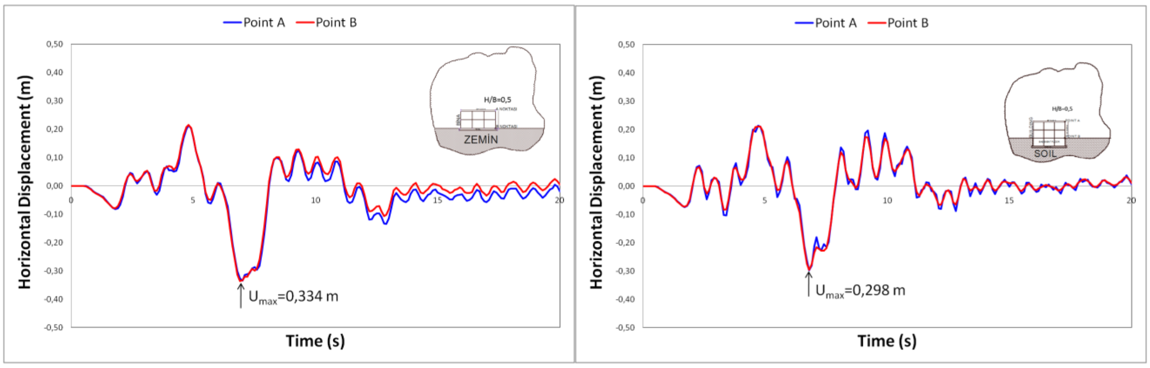
The earthquake responses of RC buildings with and without a basement storey are plotted in Figure 5-7. From Figure 5, whilst the settlement (vertical deflection) of a low-rise (2-storey) RC building is around 0.30 m, it rises to around 2.15 m in high-rise (6-storey) RC building. The effect of a basement storey is to substantially decrease the settlement of the structure, which is a desirable outcome. The settlement values of the low-rise RC building with a basement storey are about 0.05 m and of high-rise RC building about 0.16 m; the excessive settlement values that occur to the high-rise RC building are reduced by almost 2 m.



a) 2 storey building b) 6 storey building

Figure 5. Vertical Displacement of the Structures

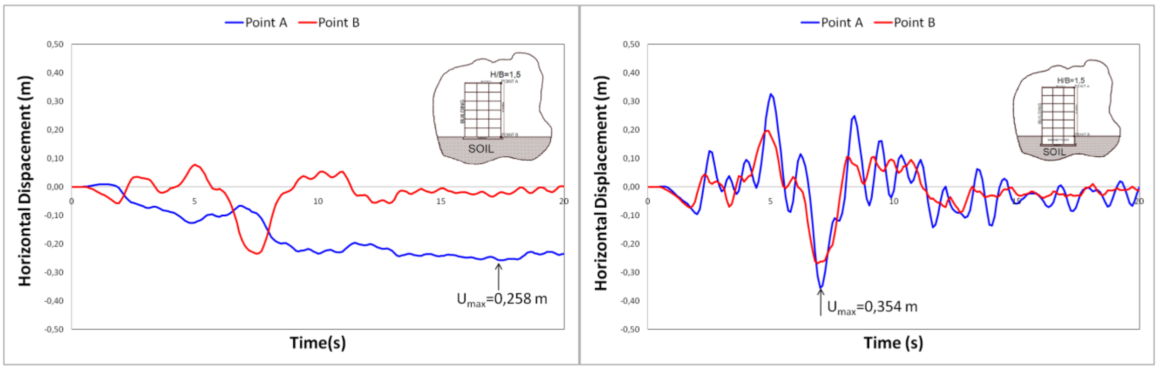
The horizontal displacements of RC buildings subjected to earthquake are plotted in Figures 6 and 7. The earthquake response of a 2-storey low-rise structure, with and without basement is presented in Figure 6. Conversely, the earthquake response of a 6 storey high-rise structure, with or without basement is presented in Figure 7.



a) with no basement b) with basement floor

Figure 6. 2 Storey Structure Behaviour under Earthquake Effect

From Figure 6 we see that the contribution of the basement storey to earthquake response in a low-rise RC building is negligible. The drift value of the top point (A point) of a building with basement storey is stable and oscillates around the equilibrium position, almost the same as the RC building without basement storey.



a) without basement b) with basement

Figure 7. 6 Storey Structure Behaviour under Earthquake Effect

When a 6 storey RC building is constructed with basement, to create a 7^{th} floor, even though the weight of the structure has increased the earthquake response is positively affected. In Figure 7 the drift value of the top point (A) of an RC building with a basement is stable and oscillates around the equilibrium position compared to a building without basement.

5. Conclusions and Closing Remarks

The results of analysis show that alluvial soft soils like those in Adapazari face excessive settlement and bearing capacity problems, and it is clearly evident that soil-structure interaction has to be taken into account. Analyses carried out ignoring the soil do not convey the true response of structures.

When the results are evaluated, the link between the negative impact of soft soil on structural response with increasing height is observed. The results demonstrate that when the height of the structure is increased, the earthquake response of RC buildings without basement is detrimentally affected.. When the same structure is built with basement, although the weight of structure increases (the net stress which is effecting the soil decreases because of the excavation), the earthquake response is less damaging.

These results are borne out in the observed damage that occurred in Adapazari after the earthquake of 17 August 1999. Problems of foundation bearing capacity failure and earthquake related structure collapse occurred to a significant number of 4-5 storey RC buildings without basement storey, causing many of these structures to collapse during the earthquake or to be demolished after the earthquake. Even though the number of RC buildings with a basement storey was much less than those without a basement storey, they have shown better resistance to earthquake loading.

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