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Authors: Fatih Göktepe, Erkan Çelebi, Nadir Karahan

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Effect of Soil Saturation on Seismic Performance of a Structure: A Numerical Approach

Fatih Göktepe*¹, Erkan Çelebi², Nadir Karahan³

Abstract

The aim of this study is to investigate the impact of soil saturation on the seismic performance of a structure when subjected to earthquake-induced vibration. More specifically, this paper examines the effect of the soil saturation level taking into account of soil-structure interaction (SSI) on the structural response. For this purpose, a two dimensional (2D) finite element model was developed with Mohr-Coulomb failure criterion under plane-strain conditions using geotechnical finite element code PLAXIS. To emphasize SSI problems in civil engineering applications, mechanical behavior and various saturation levels of the local soil condition is examined using a numerical model. As can be seen from the analysis results, the saturation level of soils causes an increase on the lateral roof displacement of the saturated elasto-plastic soil. This situation was interpreted as the increase in the saturation levels of the soils caused a decrease in the rigidity. Furthermore, neglecting the effect of SSI leads to underestimated results of the structural behavior.

Keywords: Soil-structure interaction, saturated soils, finite element analysis, elasto-plastic constitutive model

1. INTRODUCTION

The significance of soil-structure interaction in terms of seismic response of buildings depends on the interaction of dynamic characteristics of the structure and the foundation medium. In analyzing the response of structures to the dynamic excitations, it is not common practice to apply the earthquake record to the base of the structure. This condition is only justified for structures that are supported on rigid ground. For structures supported on soft soil, the foundation motion is different from the free field motion and may include

an important rocking component in addition to a lateral or translational component.

The seismic behavior of the structures on weak ground conditions are affected by the dynamic interaction between the massive superstructure, rigid foundation basement, the flexible soil medium and the soil saturation level as well as the frequency of the earthquake input motion [1-9]. Numerical solutions for analyzing the effects of SSI on the structural response can be divided into two categories: i) direct method used by Wang and Schmid [10], Wolf and Song [11], Yazdchi et. al. [12]; and, ii) substructure methods used

* Corresponding Author

¹ Bartın University, Engineering Faculty, Department of Civil Engineering, Bartın, fgoktepe@bartin.edu.tr

² Sakarya University, Engineering Faculty, Department of Civil Engineering, Sakarya, ecelebi@sakarya.edu.tr

³ Sakarya University, Institute of Science and Technology, Sakarya, nadirkarahan@hotmail.com

by Gazetas [13], Stewart et. al. [14]. It is well known that SSI generally reduces the resonant frequencies of soil-structure systems in comparison to those of the fixed-base structures. Moreover, modification of the actual foundation motion from the free-field motion also plays an important role in the dynamic behavior of soil-structure interaction system.

Structure and its underlying soil medium vibrate together as they interact with each other under dynamic excitation. In this application, as in most finite element applications, supporting soil medium is considered to be semi-infinite elastic, isotropic, homogeneous half space. The numerical discretization techniques for two and three dimensional domains, such as the finite element applications, only a finite part of the subsurface area is discretized. The number of finite elements used in the numerical model depends on the capability of the computer used. It is also well known that finite element applications are more effective for bounded domains. In most cases, this is not an important drawback and finite element method is used extensively in the solution of static problems in an infinite domain.

The use of the classical finite element method does not yield accurate results due to the incapability of discretizing the complete infinite domain [15]. To overcome this condition, the transmitting boundary conditions have been used to transmit the outwardly propagating wave at the artificially chosen boundary of the infinite domain. The first attempt to simulate the special types of energy absorbing boundaries was presented in [16-18]. In the last decade, these types of local boundary conditions has been widely used to obtain accurate results for SSI problems.

In this study, the numerical results for SSI effects on the seismic response of a building in reference to slenderness ratio ($H/D=2$) with different soil saturation level conditions at a Giresun local site is presented. For this purpose, a 2D (two dimensional) mathematical model was developed with Mohr-Coulomb failure criterion by using geotechnical finite element code PLAXIS [19]. To evaluate the effect of the soil saturation level taking into account the SSI on the structural response, parametric calculations were accomplished for a structure located in two different

regions in Giresun under two different input motions. The local soil condition with saturation level and the frequency of earthquakes are considered to represent dynamic behavior quite well for soil-structure coupled system.

2. FINITE ELEMENT MODEL OF SSI SYSTEM

In order to investigate the effect of nonlinear soil behavior on seismic performance of a structure, the numerical model was developed by using the computer program Plaxis 2D based on 2D finite element method [20]. The meshing geometry and the discretization dimension for the SSI model are important for this research. For the numerical analyses, linear elastic perfectly plastic model (Mohr-Coulomb model) was chosen to model soil behavior with 6-node triangular elements under cycling loading.

The schematic diagram of the problem with numerical details and the FE discretization size of the soil-structure system including the lateral extent of the finite soil domain L , and the depth of the soil region H , are given in Figure 1. In the first phase of the study, the effect of the discretization dimension was examined. The validation of the SSI model was obtained by analyzing seismic response at the free soil surface by authors [21]. In reference to this study, the optimal size of the calculation area was estimated as $L=200m$ and $H=75 m$. Moreover, the impact of different mesh densities on dynamic behavior was tested in the FE model in earlier studies of authors.

For this study, finer FE mesh sizes ($\Delta h \leq 1 m$) was used in the area ($H_1=15 m$ and $L_1=60 m$). The mesh of remaining area (hereby, $H_2 = 40 m$, $L_2 = 130 m$) was designed to be relatively coarse from the localized area mentioned above ($\Delta h = 2 m$). For distant elements near the lower edge, the element size was chosen as 4 m. The time step integration was selected as $\Delta t < 0.075 s$ in accordance with the Courant condition for the numerical analysis [21]. The structure considered for SSI system is ten-storey reinforced concrete frame with three frame span. The height of building is 30 m measured from the soil surface and it has a width of 12 m (Figure 1). The evaluation points were chosen for numerical investigations is the roof floor level (Point

A) and free ground surface at a distance of 60 m from the structure (Point B).

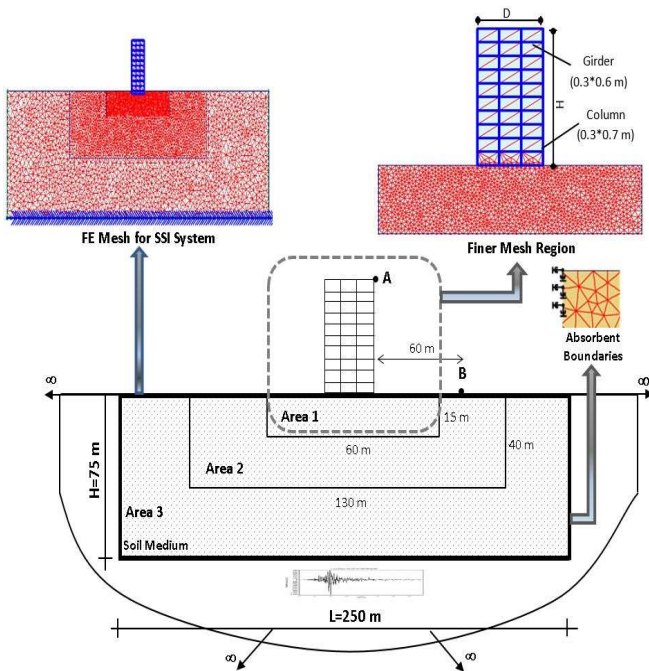


Figure 1. Schematic illustration and FE mesh of SSI system

The case study site located to the north of the North Anadolu Fault Zone demonstrates a very rough morphology in eastern sea mountain chain [22]. In order to evaluate the effects of the soil saturation levels on the seismic structural behavior under different seismic loading, the structure located in two different regions in Giresun was investigated (Figure 2).



Figure 2. Location map of Giresun region and its surroundings

The material parameters of the for the superstructure and the saturated soils reported as a result of site investigation for Giresun regions are given in Tables 1 to 3, respectively. The main difference between these two regions of Giresun is that the local soil condition of the first region is fully saturated relative to the second region.

Table 1. Mechanical Properties of the superstructure in the study area

| Parameter | Symbol | Magnitude | Unit |
|-------------------|--------|---------------------|----------------------|
| Columns | | | |
| Normal stiffness | EA | 1.191×10^7 | (kN) |
| Flexural rigidity | EI | 156420 | (kNm ²) |
| Weight | w | 50 | (kN/m ²) |
| Girders | | | |
| Normal stiffness | EA | 1.191×10^7 | (kN) |
| Flexural rigidity | EI | 156420 | (kNm ²) |
| Weight | w | 50 | (kN/m ²) |

Table 2. Mechanical properties of underlying soil for first region of Giresun

| Symbol | Parameter | Magnitude | Unit |
|------------------|-------------------------------------|--------------------|----------------------|
| E | Young's modulus | 2.84×10^6 | (kN/m ²) |
| ν | Poisson's ratio | 0.43 | - |
| γ_{unsat} | Natural unit weight | 16.77 | (kN/m ³) |
| γ_{sat} | Saturated unit weight | 20 | (kN/m ³) |
| V_p | Compression wave velocity | 2176 | m/s |
| V_s | Shear wave velocity | 762.6 | m/s |
| c | Cohesion | 57 | (kN/m ²) |
| ϕ | Friction angle | 5 | (°) |
| ψ | Dilatancy angle | 0 | (°) |
| GWT | Ground water table | 4 | m |
| R_{inter} | Interface strength reduction factor | 0.67 | - |

Table 3. Mechanical properties of underlying soil for second region of Giresun

| Symbol | Parameter | Magnitude | Unit |
|------------------|-------------------------------------|--------------------|----------------------|
| E | Young's modulus | 3.12×10^6 | (kN/m ²) |
| ν | Poisson's ratio | 0.37 | - |
| γ_{unsat} | Natural unit weight | 18.68 | (kN/m ³) |
| γ_{sat} | Saturated unit weight | 18.68 | (kN/m ³) |
| V_p | Compression wave velocity | 1702 | m/s |
| V_s | Shear wave velocity | 773 | m/s |
| c | Cohesion | 88 | (kN/m ²) |
| ϕ | Friction angle | 5 | (°) |
| ψ | Dilatancy angle | 0 | (°) |
| GWT | Ground water table | - | m |
| R_{inter} | Interface strength reduction factor | 0.67 | - |

3. PARAMETRIC STUDY AND RESULTS

The slender ratio describes quotient between the width of a building and its height is an important parameter for the considered SSI system. One

slenderness ratio ($H/D=2$) is handled in FE analysis. In order to obtain SSI effects on the seismic structural response, the numerical model is tested under two different input motions such as 1999 Kocaeli ($M_w=7.4$) and 1992 Erzincan ($M_s=6.8$) earthquakes. For the computational model, elasto-plastic soil layer is assumed to be supported by horizontally extended rigid base rock, therefore, total reflection of the incident waves from this boundary is assumed.

3.1. Results for Kocaeli Earthquake

In order to assess the impact of the SSI with plasticity effect for the slenderness ratio ($H/D=2$) of structure, the peak lateral floor displacement (u_x) of the Kocaeli earthquakes have been given comparatively according to different local soil conditions of Giresun in Figure 3.

The results of analysis show that the effect of the soil saturation level taking into account the SSI changed the results for the first region of Giresun. The peak horizontal displacement corresponding to roof floor changed by increasing approximately 11% for the elasto-plastic soil condition compared to the calculation results based on the assumption of fixed-base support. Moreover, it was determined that the elastic soil condition increased the displacement values by 47% (Figure 3a).

On the other hand, the peak lateral floor displacement of the building increased around 9% on the elasto-plastic soil condition for the second region of Giresun when compared with fixed base condition. As expected, when SSI is taken into account, the peak lateral displacement increased by about 8% for the elastic local soil condition of the second region (Figure 3b). That means the saturation level of soils with the SSI causes an increase on the lateral roof displacement for the fully saturated elasto-plastic soil condition.

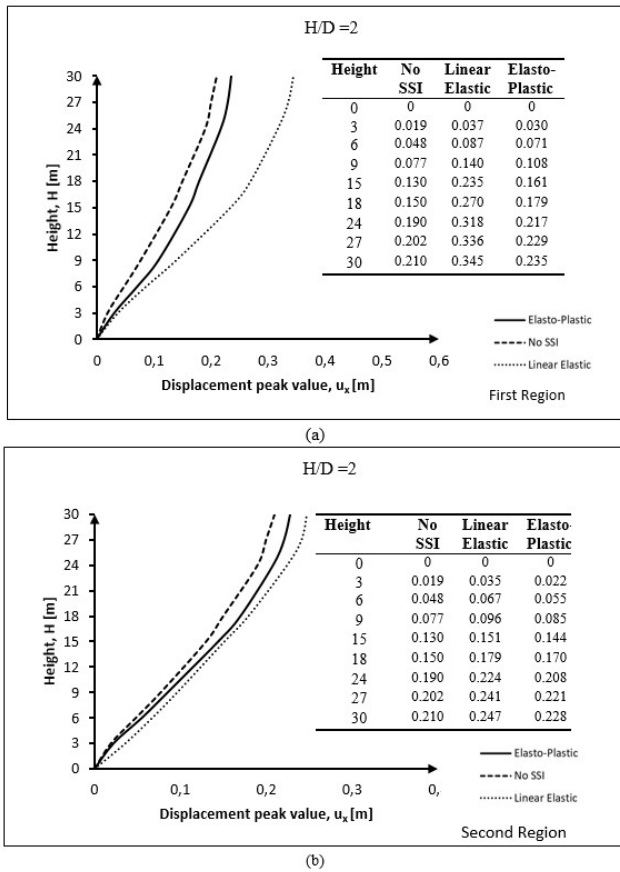


Figure 3. Variation of displacement peak value of the structure affiliated to the various saturation levels for H/D=2 under Kocaeli earthquake

The variation of the time history of horizontal displacement at the top of building taking into account the SSI (dashed curves) and fixed-base support (solid curves) with different saturation levels for the 1992 Kocaeli earthquake is shown in Figure 4a-b. From these time-domain responses, the lateral peak displacements increased around 20% and 12% respectively compared to the different local soils of Giresun associated fixed-base conditions. The change in the seismic response of building taking into the soil saturation level is clearly seen from the numerical results in the time period ($t > 35$ sn) with consideration of SSI effect.

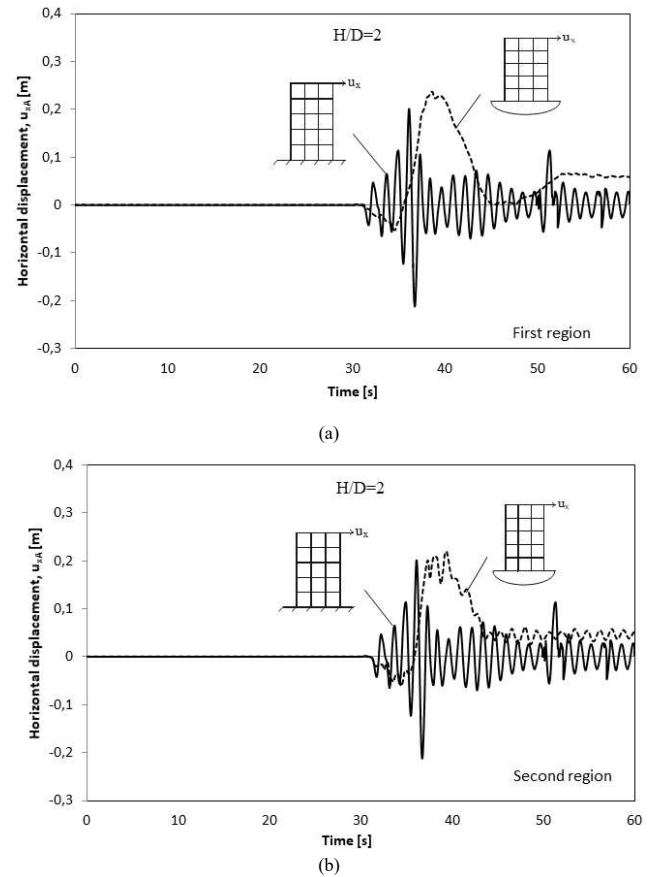
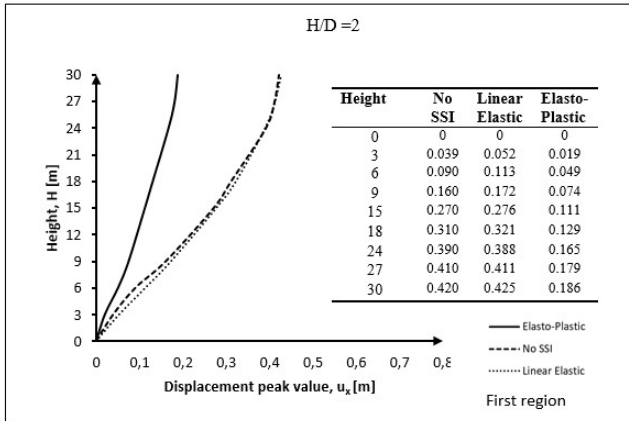


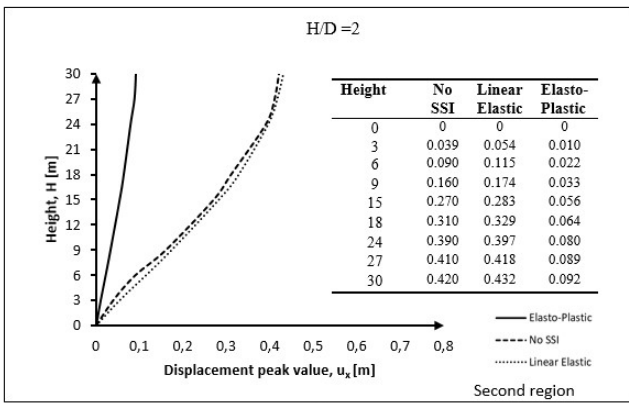
Figure 4. Effect of the various saturation level of soils with the SSI on seismic performance at the roof floor for H/D=2 under 1999 Kocaeli earthquake ground motion

3.2. Results for Erzincan Earthquake

In addition to the applied earthquake loading for proposed SSI model, the Erzincan earthquake record is also used to analyze the seismic structural behavior as shown in Figures 5, 6. It is observed that the values of the peak lateral floor displacement decreased by approximately 55% for the rigid base support assumption in the event of $H/D = 0.4$ with the first soil condition. In addition to this, it was determined that the SSI effect increased to 2.5 times the corresponding peak displacement values (Figure 5a). For the second region of Giresun, the peak lateral displacement decreased to 4.5 times by ignoring the SSI effect. Unlike this case, the corresponding peak displacement values increased to 4.5 times with SSI effect (Figure 5b). Similar to Kocaeli earthquake, the lateral roof displacement for the saturated elasto-plastic soil condition increased due to the SSI considered with plasticity effect.



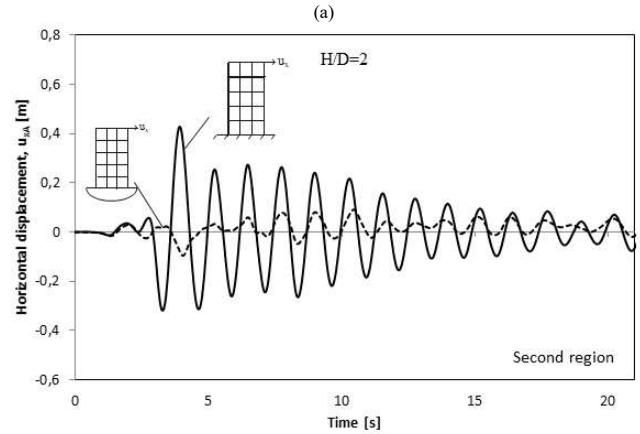
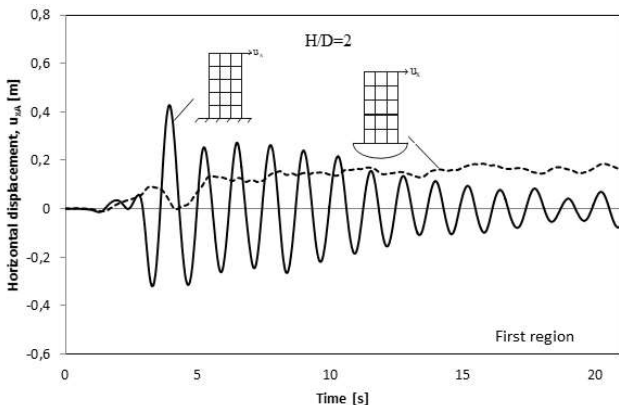
(a)



(b)

Figure 5. Variation of displacement peak value of the structure affiliated to the various saturation levels for H/D=2 under Erzincan earthquake

According to time history of the horizontal displacements at the top of building, the lateral peak displacements decreased around 2 times and 4 times respectively compared to the different soil saturation level of Giresun soils associated fixed-base conditions. Considering the effect SSI, account the mechanical behavior of underlying soil have considerably effect on the SSI system (Figure 6a-b).



(b)

Figure 6. Effect of the various saturation level of soils with the SSI on seismic performance at the roof floor for H/D=2 under 1992 Erzincan earthquake ground motion

4. CONCLUSION

In this study, the seismic behavior of a structure located in different saturation levels was studied via 2-D finite element model utilizing direct numerical approach. The mechanical behavior and various saturation levels of the underlying soil condition were tested under the different frequency content of the seismic motion. The numerical results of this study play an important role for geotechnical and structural engineers working with the soil saturation level problems taking into account the SSI in terms of providing practical information in seismic analysis.

From the results of the analysis, the seismic response of the structures is affected by the degree of soil saturation. Both two earthquake inputs, the lateral roof displacement for the saturated elasto-plastic soil condition increased when compared to those obtained results of second region in Giresun. Furthermore, the SSI effects are different for the considered soil conditions. Neglecting the effect of SSI leads to underestimated results of the structural behavior. The saturation level of soils with the SSI causes an increase on the lateral roof displacement for the saturated elasto-plastic soil condition.

In addition to this, the overall response of the structure is significantly affected by the mechanical behavior of the soil. Moreover, the seismic frequency of input motion play an important role in the dynamic behavior of soil-structure interaction system. If the frequency of

external load is imminence to the SSI system, the sudden increase in the dynamic response is more pronounced for the resonance state.

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