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Investigating the effect of soil structure interaction on the seismic response of concrete buildings

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ABSTRACT

For structural engineers, it is common in the analysis to consider a fixed base structure, which means that the foundations and the underlying soil are assumed to be rigid. This assumption is not correct because the underlying soil in the near field often consists of soft layers that have different properties and may behave nonlinearly, which results in a significant change of the seismic motion before reaching the structure foundation. In addition, interaction between the structure, its foundation and the underlying soil during vibrations can significantly alter the structure response. This change depends on the characteristics of the structure, the soil properties and the nature of the seismic excitation. As a result, accurate evaluation of inertial forces and displacement in structures requires a careful examination of soil structure interaction (SSI) effects. In this paper, a numerical study was conducted to investigate the seismic response of concrete buildings exposed to various seismic excitations with nonlinear SSI assumption using PLAXIS V8.6 software. Two types of two-dimensional moment resisting frames including a five-story frame and a ten- story frame have been analyzed. Three types of soil hard (type I), medium (type III) and weak (type IV) are considered with shear wave velocity of 1000, 270 and 90 m /s, respectively. The results of the analysis show that considering the effects of SSI on seismic design is essential. Generally, by decreasing the dynamic stiffness of the underlying soil (with decreasing shear wave velocity VS and shear modulus G), the base shear ratios decrease. In addition, a fixed base assumption can lead to high overestimation of the structural design forces and seismic response.

1. Introduction

The soil structure interaction (SSI) refers to a function in which the soil response affects the structure response and the structure response influence the soil movement. In recent decades, the importance of SSI for static and dynamic issues is well known. Considering the dynamic effects of SSI, enables the designer to estimate the inertial forces and actual displacements of the soil-foundation structure system under the influence of free field movement. For flexible or small buildings that are on hard soil, the interaction effects are usually irrelevant, while the interaction of hard and heavy structures on soft soils is vital. Since the 1990s, many attempts have been made to replace classical design with new methods based on the concept of seismic design based on performance. In addition, structural damage during the earthquake in Mexico City in 1985 and many other recent earthquakes, such as those in Christchurch in 2011 (New Zealand), Japan in 2011 (Fukushima) and the Nepal earthquake in 2015, clearly demonstrate the vital effects of local soil properties on the earthquake response of structures. Therefore, there is a strong engineering motivation for analyzing the site-dependent dynamic response to determine the free-field movement. The determination of a realistic site-dependent free-field surface motion at the base of the structure can be the most important step in the earthquake resistant design of structures.

When SSI is considered, the ground motions imposed at the foundation of the structure are affected by the soil properties, the pathway, and the geometry of the soil environment. Wolf and

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Deeks summarized the four basic SSI effects on the structure response as (Wolf and Deeks: 2004):

- Increase in the natural period of the system,
- Increase in system damping,
- Increase in lateral displacements of the structure,
- Change in the base shear depending on the frequency content of the input motion,
- Dynamic characteristics of the soil and the structure.

Veletsos and Meek concluded that SSI has two basic effects on the structure response compared with the fixed base counterpart (Veletsos and Meek, 1974):

- The soil-structure system has more degrees of freedom, and therefore the dynamic properties are modified,
- A significant portion of the vibrational energy of the soil-structure system may be exhausted through radiation, or through the hysteresis of materials in the soil.

In recent years, several attempts have been made to develop analytical methods to evaluate the responses of structures under seismic excitations. The successful application of these methods is largely dependent on the participation of soil properties in analysis. Therefore, significant efforts have been made to determine soil properties for use in these methods (Tabatabaiefar et al., 2013). Two main analytical methods for dynamic analysis of soil-structure systems under seismic loads are equivalent-linear methods and nonlinear methods. Byrne et al. (1994) provided an overview of the mentioned methods, and discussed the advantage of nonlinear method to equivalent-linear method in various practical applications. Their research results proved that the equivalent linear method is not suitable for use in dynamic SSI analysis; this method does not directly capture all nonlinearity effect, since this method considers linear behavior during the response process.

Additionally, the strain-dependent modulus and damping functions are only counted on average, which means approximation of some nonlinearity effects. Therefore, they concluded that the most suitable method for dynamic analysis of a soil-structure system is a nonlinear method. This method accurately shows physical properties and follows any stress-strain relationships in a realistic way (Lu et al., 2011). Based on the capabilities of the nonlinear method, in this study, to achieve accurate and reliable results for dynamic analysis of soil-structure systems, this Method is used.

In this paper, a numerical study was conducted to investigate the seismicity of concrete buildings under the influence of various seismic excitations with regard to nonlinear SSI using PLAXIS V8.6 software. Two types of two-dimensional concrete bending frame with different heights for this analysis are considered. The first frame consists of five floors and the second frame consists of ten floors. In this analysis, three different soil types were used to indicate the hard, moderate and poor soil conditions according to the 2800 standard and two seismic records with different frequency content for input excitations.

2. Dynamic SSI approaches

2.1 Direct approach

The most rigorous way of solving a dynamic SSI problem may be using a direct approach, which involves modeling the entire soil-structure system in the time domain, accounting for spatial variation of soil properties, material and geometric nonlinearities, wave propagation complexities and careful treatment of interface and boundary conditions. The direct approaches are usually performed by using the Finite-Element Method (FEM) where the whole SSI system is modeled and analyzed in a single step. The Equations of Motion (EOM) for an SSI Finite-Element model can be written as (Eq. 1):

$$[M]\{\ddot{u}\} + [k]\{u\} = -[M]\{\ddot{u}_g\} \tag{1}$$

Where, [M] and [k] are respectively mass and stiffness matrices, {u} is a displacement vector corresponding to the degrees of freedom of the internal nodes within the SSI model, and $\{u_g\}$ is the input displacement vector for the nodes which usually lie at the bottom of the model (Lu, 2016).

2.2 Substructure approach

The substructure method is also called a multi-step approach where an SSI problem is solved by combining solutions from kinematic and inertial interaction phenomena, as illustrated in Figure 1.

In the kinematic interaction analysis (Fig. 1b), seismic excitations are applied to the bottom of the SSI model where the structure and foundation are assumed to have stiffness but no mass. The EOM for kinematic interaction can be written1 as (Eq. 2):

$$[M_{soil}]\{\ddot{u}_{KI}\} + [k]\{u_{KI}\} = -[M_{soil}]\{\ddot{u}_{KI}\} \tag{2}$$

Where, $[M_{soil}]$ is the mass matrix in which the entries corresponding to the structure and the foundation are zero and the subscript KI denotes kinematic interaction.

Mathematically, the EOM for inertial interaction can be extracted from the total EOM (Eq. 2) by subtracting those for the kinematic interaction (Eq. 3):

$$[M]\{\ddot{u}_{II}\} + [k]\{u_{II}\} = -[M_{structure}]\{\ddot{u}_g + \ddot{u}_{KI}\} \tag{3}$$

Where, $\{u_{II}\} = \{u\} - \{u_{KI}\}$ is the inertial interaction component of the displacement vector {u}, and is the mass matrix where the soil entries are equal to ZERO (Lu et al., 2016).

3. Material and Methods

3.1Model description

The soil structure system considered in this analysis, along with the finite element mesh, is shown in Fig2. PLAXIS 2D V8.6 software is utilized for Modeling and analysis of soil-structure systems using direct method. plate elements were used For modeling of beams, columns, and raft foundation. Triangular elements of 15 nodes have been used to model the soil environment and the rigid boundaries for modeling the bedrock. To simulate frictional contact and possible slip as a result of the seismic excitation, the interface element is used. It is assumed that the properties of the interface elements are similar to the soil properties. The Mohr-Coulomb model in this study was used as a constitutive model for simulating nonlinear behavior of soil environment.

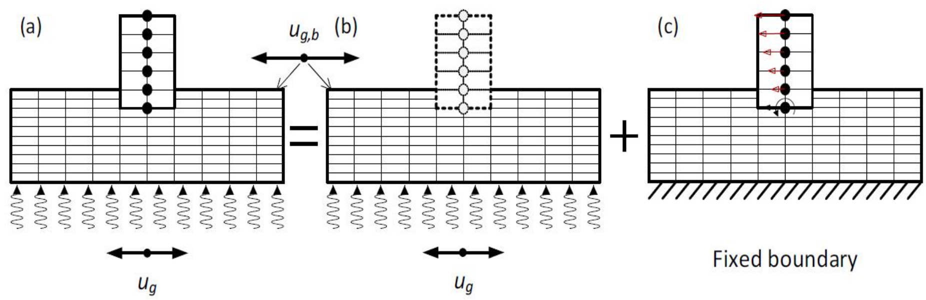

Figure 1. (a) SSI problem (b) kinematic interaction analysis (c) inertial interaction analysis

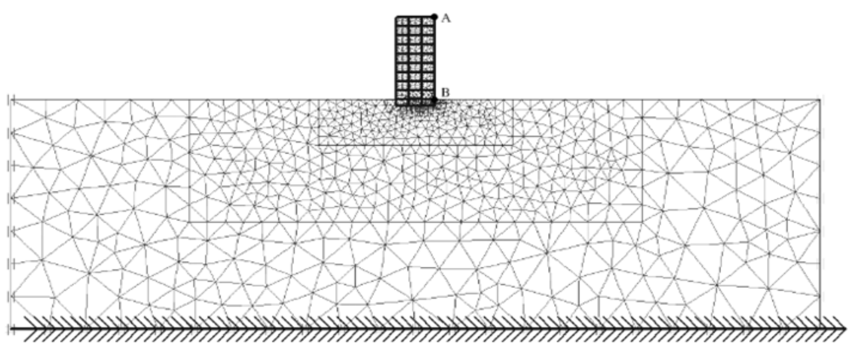

Figure 2. Soil and Structural System and Finite Element Modeling

The Mohr-Coulomb model is an elastic-perfectly plastic model that has been used by many researchers in modeling the dynamic SSI to simulate soil behavior under seismic excitations (Conniff and Kiousis, 2007; Rayhani and El Naggar, 2008). In numerical analysis, it is necessary to apply special boundary conditions through efficient techniques to prevent reflection abnormal waves in the meshes are taken into account (Semblat, 2011). Therefore, for the lateral boundaries of the soil, the viscous adsorbent boundaries developed by Lysmer and Kuhlemeyer (1969) have been used. The proposed method is based on the use of independent dampers in normal and shear directions along the model boundaries.

The horizontal distance between the soil boundaries is assumed to be 250 m and the depth of the soil is assumed to be 75 m. The domain of soil is divided into three regions: the first area with a horizontal length of 60 meters and a depth of 15 meters with soft mesh; the second area with a length of 140 meters and a depth of 40 meters with a relatively coarser mesh, and the third area with a length of 250 meters and a depth of 75 meters with Coarse mesh as shown in Figure 1. As mentioned in the previous section, three types of soil are considered. The first type of soil is hard soil with a shear wave velocity of 1000 m/s to indicate the soil conditions of type I, as described in standard 2800. The second type of soil is a medium soil with a shear wave velocity of 270 m/s to indicate the soil conditions of type III and the third type of soil, poor soil with a shear wave velocity of 90 m/s to indicate the condition of soil type IV. In each analysis, three subsoil areas are considered uniform. Soil categories, properties and parameters used for input data are given in Table 1.

Table 1 Soil classes, properties and assumed parameters

Soil Type	γ	G (GPa)	υ	Vs	C (KPa)	ϕ (^{o})	R_{inter}
I	21	2.10 E+06	0.35	1000	30	38	0.67
III	19	1.38 E+05	0.30	270	0	35	0.67
IV	17	1.38 E+04	0.25	90	0	33	0.67

3.2 Specification of concrete moment resistant frames

Two concrete intermediate moment resistant frames with different heights for this analysis are considered. The first building consists of 5 floors, and the second building consists of 10 floors. The typical story height is considered to be 3 meters and each building has a basement of 2 meters height. The total width of each frame is 12 meters, which includes 3 bays of 4 meters width. Dead and live loads are determined as uniform distributed loads over the beams. In this study, the total loads on each beam were considered to be 50 kN / m. The dimensions of the frames are shown in Table 2. A raft foundation with thickness of 0.6 m for 5-story frame and 1 meter for 10-story frame is considered.

3.3 Input motion characteristics

To find out the effect of seismic excitation properties on the response of the soil-structure system, two different input motions, one with low frequency content, and the other with high frequency content, have been selected as accelerogram of the

Loma Prieta and Northridge earthquakes (Peer Ground Motion Database).

Table 2 Dimensions of the moment resisting building frames

Number of stories	Number of bays	Bay Width (m)	Total Height (m)	Total Width (m)
5	3	4	14	12
10	3	4	29	12

4. Results and discussions

4.1. Seismic response at the ground surface

Since the acceleration is the most concerned response for the structure excitations, maximum acceleration at location B has been investigated to find out the effect of building on the ground surface response, in the presence of a building and without it for poor soil conditions. The maximum accelerations obtained at location B are given in Table 3 for different input motions for 5 and 10 story buildings. These results indicate that the surface response strongly depends on the characteristics of the input motion and the soil conditions. When the building exists, it is clear that the maximum acceleration achieved reduces the value compared to the case of without buildings. These results reflect the mutual between the building, the underlying soil, and input motions that indicate that even the ground surface response can be affected by the presence of the building and the characteristics of the input motion.

4.2. Variation of structures fundamental frequency

The most important step for the seismic design of the structure is determining its fundamental frequency. Most structural engineers consider the buildings to be rigid at its base. Since the bottom soil near the surface often contains soft layers that have different characteristics, this assumption is not correct and may strongly affect fundamental frequency of the soil-structure system. For comparison, the fundamental frequency of each building is calculated using the simple equation of 2800 code. Additionally, the selected input motions are applied at the bedrock with full SSI and with different soil conditions, then the Fourier power spectrum of the acceleration above the building in place A is obtained for each case. Since the seismic response power spectrum is always populated over a wide range of frequency as it is influenced by the content of the input motion frequency, the critical frequency accompanied with the highest amplification of the power amplitude compared to the input motion is picked out and considered to be the fundamental frequency of the soil structure system with full SSI.

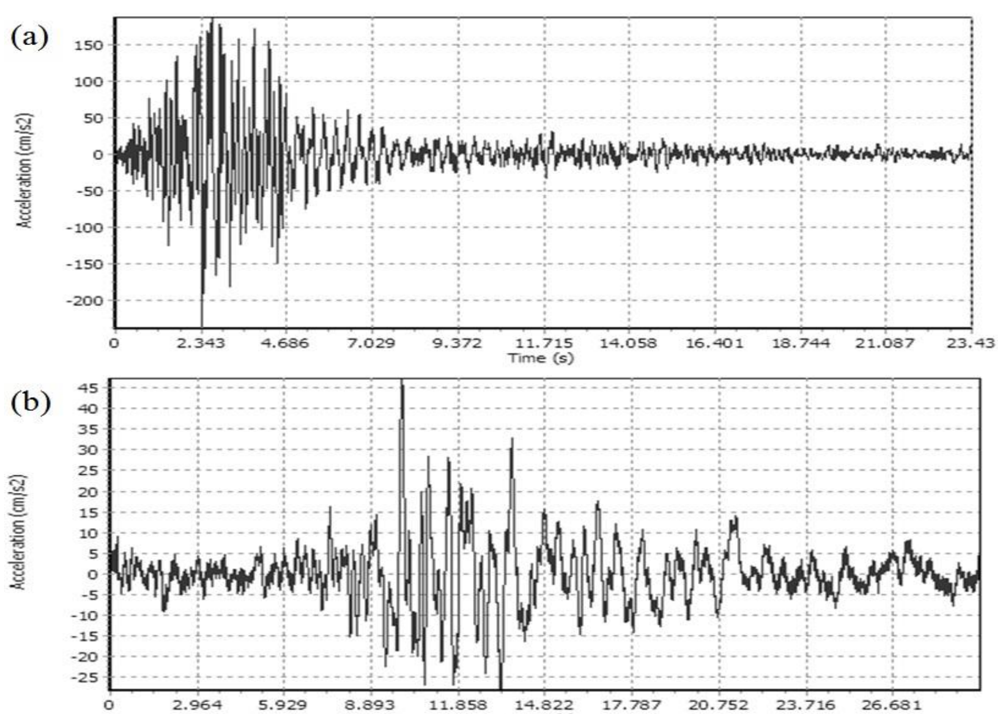

Figure 3. Acceleration time histories of the input motions, (a) Northridge, (b) Loma Prieta

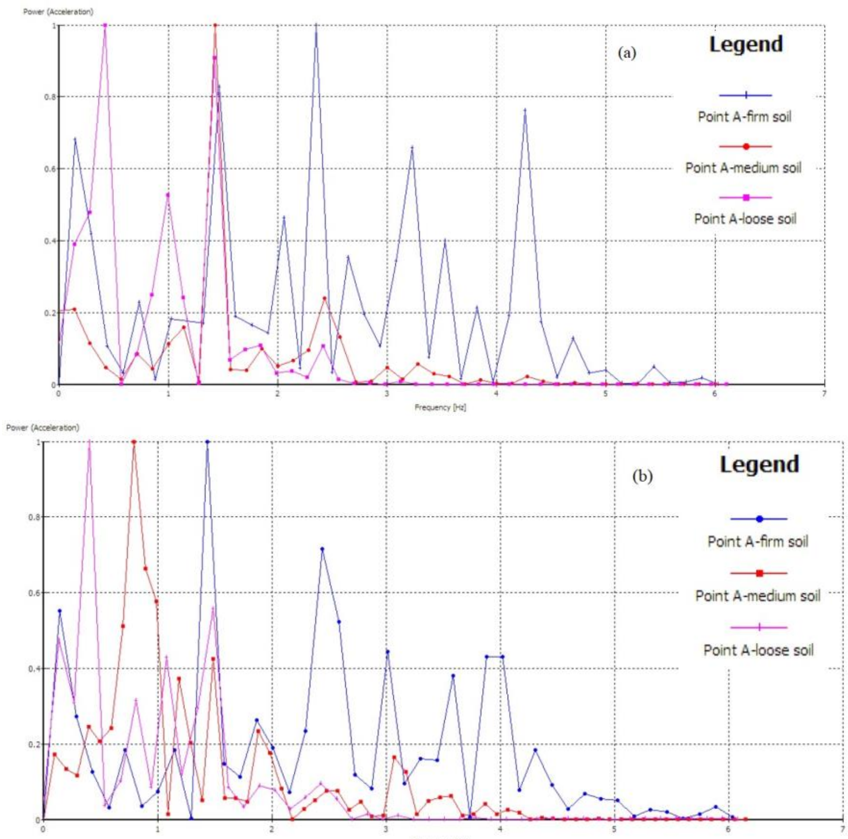

Figure 4. Acceleration time histories of the input motions, (a) Northridge, (b) Loma Prieta, (a) 5 story building (b) 10 story building

Table 4 Fundamental frequencies for different boundary conditions

building type	Boundary Conditions	Fundamental Frequency fo (Hz)		
		Soil type I	Soil type III	Soil type IV
5story frame	Code 2800	1.860		
	SSI (Plaxis 2D)	2.353	1.429	0.426
10story frame	Code 2800	0.965		
	SSI (Plaxis 2D)	1.437	0.875	0.405

Table 3 Maximum acceleration (m/s^2) at location B, soil type IV

Input motion	Story of building		
	5	10	Without
Northridge	4.093	2.893	4.725
Loma Prieta	0.738	0.895	0.929

5. Conclusion

In this study, the numerical investigation of the seismic response of buildings with five and ten story with regard to the effect of soil-structure interaction is presented. For each building, different soil conditions and input motions have been investigated. The analysis was performed using Plaxis 2D software. The results were compared with the results obtained when the buildings were considered fixedat their base. Based on the analysis, the following results can be expressed:

- The existence of building reduced the ground surface acceleration amplitude to different extents depending on the height of the building, the type of soil and the characteristics of the input motion.
- High frequency content and large amplitude of the input motion could excite the soil nonlinearity leading to high energy dissipation and damping ratio, and consequently, substantial suppression of the surface acceleration.
- SSI assumption leads to a higher fundamental frequency for buildings located on hard soil (type I).

While poor soil conditions (type IV) severely reduce the fundamental frequency.

- The results clearly indicate that it is necessary to consider the effects of SSI on the seismic design of buildings, since this can lead to a great reduction in design forces without altering the safety of the structure.

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