Effects of Soil Stiffness on Seismic Response of Buildings Considering Soil-Pile-Structure Interaction

Effets de la rigidité des sols sur la réponse sismique des bâtiments dans le cadre de l'interaction sol/pieu/structure

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ABSTRACT: In this study, a fifteen-storey moment resisting building sitting on an end-bearing pile foundation in soil socketed in rock is selected in conjunction with four values of shear wave velocity. Effects of corresponding shear strength are studied through numerical modelling using finite difference software FLAC3D. Fully nonlinear dynamic analysis under the influence of Northridge earthquake is performed. The results indicate that soil plasticity should be taken into account while conducting dynamic analysis considering soil-pile-structure interaction. However, the dynamic response of the structure regarding base shear, foundation slab rotation, pile lateral deflection and structure lateral deflection is sensitive to the effect of shear strength with the increase in shear wave velocity and corresponding shear modulus. Also, the results show that the dynamic response of structures sitting on end-bearing pile foundations depends not only on base shear attracted by the superstructure but also on the foundation slab rotation. Therefore, to perform realistic seismic analysis and to conduct reasonable seismic design of mid-rise building resting on end-bearing pile foundations, the consideration of foundation slab rotation is essential.

RÉSUMÉ: Cet article présente l'étude d'un bâtiment de quinze étages fondé sur pieux chargés en pointe dans des argilles molles soumis à quatre valeurs de vitesse de propagation des ondes de cisailement. Pour chaque vitesse de propagation, les effets sur la résistance au cisailement du sol sont étudiés par modélisation numérique en utilisant le logiciel d'analyse par différence finie FLAC3D. Une analyse dynamique non linéaire est réalisée en considérant les enregistrements du séisme Northridge. Les résultats indiquent que la résistance au cisaillement du sol doit être prise en compte lors de l'analyse dynamique en tenant compte de l'interaction sol/pieu/structure. Cependant, la réponse dynamique des structures en ce qui concerne la résistance au cisaillement à l'interface soil/structure, la rotation du casque de pieu, la déformation latérale du pieu et la déformation latérale de la structure est sensible aux effets de la résistance au cisaillement du sol avec l'augmentation de la vitesse de propagation des ondes de cisaillement et du module de cisaillement correspondant. En outre, les résultats montrent que la réponse dynamique des structures reposant sur des pieux chargés en pointe dépend non seulement de la résistance au cisaillement mobilisé à l'interface soil/structure mais aussi de la rotation du casque de pieu. Par conséquent, pour effectuer une analyse sismique réaliste et pour conduire une conception sismique raisonnable d'un bâtiment de moyenne hauteur reposant sur des pieux chargés en pointe, considérer la rotation du casque de pieu est essentielle.

KEYWORDS: soil-pile-structure interaction, FLAC3D, fully nonlinear dynamic analysis, foundation slab rotation

1 INTRODUCTION

Deep foundations such as end-bearing piles are commonly employed to support buildings in earthquake-prone zones, especially in soft soils. Soil plays a vital role in determining the seismic response of structures as the motion of the foundation of the structure differs from the free-field motion due to the inability of the foundation to conform to the deformations of the free-field motion, and the dynamic response of the structure would induce deformation of the supporting soil. This process, in which the response of the soil influences the motion of the structure, and the response of the structure influences the motion of soil, is referred to as soil-structure interaction (Kramer, 1996).

Many researchers (e.g., Carbonari et al., 2011, Hokmabadi et al., 2014b) mentioned that seismic soil-pile-structure interaction (SSPSI) should be considered when carrying out seismic analysis of structures. According to Hokmabadi et al. (2014a), the SSPSI increases the inter-storey drifts of the structure sitting in the soft soil which may increase the potential for the collapse of the structure. Based on available literature, the effect of soil-structure interaction on the dynamic response of structure system, in particular moment resisting buildings is considerable when shear wave velocity of supporting soil is less than 600m/s (e.g., Veletsos and Meek, 1974, Galal and Naimi, 2008).

The shear wave velocity of soil deposit is one of the essential parameters to assess SSPSI. Wair et al. (2012) proposed Equation (1) to correlate shear wave velocity and undrained shear strength of cohesive soils;

$$V_s=23S_u^{0.475} \tag{1}$$

where V_s is shear wave velocity and S_u is undrained shear strength. Also, it is well-known that shear wave velocity (V_s) can be used to estimate the maximum shear modulus (G_{max}) considering the soil density (ρ) according to Equation (2):

$$G_{max}=\rho V_s^2 \tag{2}$$

However, some researchers (e.g., Kang et al., 2012, Banerjee et al., 2014) did not consider the effect of soil plasticity while conducting seismic soil-structure interaction analysis.

Numerical methods including finite element and finite difference methods have become increasingly popular to study complex interactive behaviour as these methods offer researchers the ability to model complex conditions of the site with a high degree of accuracy by considering nonlinear soil behaviour and heterogeneous material conditions using two- or three-dimensional elements. Also, fully coupled analysis of pile groups becomes feasible by employing numerical simulations.

In this study, the influence of soil stiffness on the seismic response of a moment resisting building is investigated by adopting a fully nonlinear direct method in which soil deposit, an end-bearing pile foundation and a superstructure are analysed simultaneously. To achieve this, FLAC3D (Itasca, 2011), a three-dimensional explicit finite-difference program, is utilised for numerical simulation. A 15-storey moment resisting reinforced concrete building is selected to represent ordinary mid-rise buildings. Shear wave velocity of 150, 200, 250 and 300m/s are considered in this study. The effects of soil shear strength are also examined.

2 CHARACTERISTICS OF THE MODEL

In this study, a fifteen-storey three-bay moment resisting building is selected to represent conventional reinforced concrete mid-rise buildings. The overall size of the adopted building is 45 meters in height and 12 meters in width in both directions. SAP2000 V14 (CSI, 2010) has been utilised for structural analysis and design. The specified compressive strength of concrete and concrete unit weight are assumed to be 40MPa and 23.5kN/m3, respectively. Also, the elastic-perfectly plastic behaviour is considered for structural components. The structural sections are designed based on a routine design procedure according to relevant building standards (AS1170.0, 2002; AS1170.4, 2007; AS3600, 2009). Additionally, according to ACI318 (2008), cracked sections for reinforced concrete sections are employed by modifying the stiffness of the structural members ($0.35I_g$ for beams, $0.7I_g$ for columns and piles and $0.25I_g$ for slabs). The fundamental natural period of the building adopted in this study is 1.28 seconds.

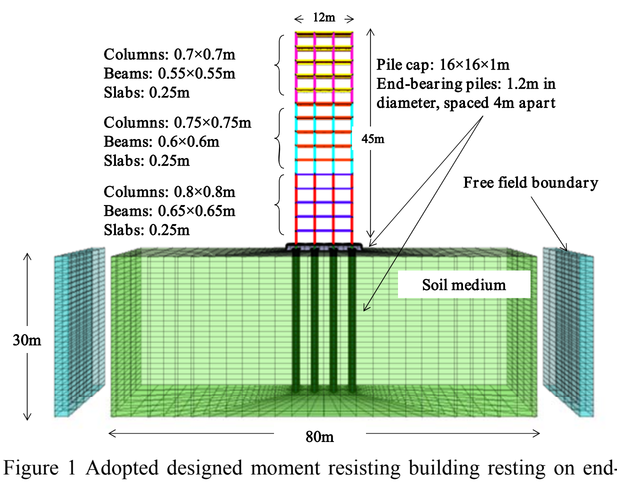

Figure 1 Adopted designed moment resisting building resting on end-bearing pile foundation and soil system

Pile foundations are designed to support the building to fulfil the requirements of bearing capacity and settlement by following routine engineering design procedures (Bowles, 1988; Poulos and Davis, 1980; AS2159, 2009; Hokmabadi and Fatahi, 2015). The foundation is composed of a 16×16×1m reinforced concrete foundation slab, and a group of 4×4 reinforced concrete end-bearing piles, 30m in length (L) and 1.2m in diameter (D). By adopting this setup of pile foundation, each pile can be placed beneath one of the columns of the building so that applied loads can be transferred to the piles easier. Also, the pile spacing (centre to centre) is 4m (3.3D), which is in a good agreement with other researchers' design (e.g., Small and Zhang, 2002; Shelke and Patra, 2008). Additionally, the toes of piles are socketed in bedrock. Figure 1 shows a detailed overview of the building and foundation system adopted in this study.

The above mentioned building and foundation are sitting in soil. To investigate the effects of soil stiffness including shear wave velocity (V_s) and shear strength (S_u) on the seismic response of the building and foundation, four values of shear wave velocity (V_s) are selected to perform dynamic analysis (Table 1). In this study, shear strength is assumed to be undrained shear strength. Shear strength (S_u) and shear wave velocity (V_s) are corrected by adopting Equation (1) and maximum shear modulus is found using Equation (2). The density and Poisson's ratio are assumed to be 1470kg/m^3 and 0.4, respectively. The Australian seismic code evaluates local site effects based on the properties of the top 30 meters of the soil profile due to the fact that the main part of the amplification and attenuation occurs within the first 30 meters of the soil. Thus, a 30-meter soil medium is considered in this study. Also, bedrock level is assumed at the bottom of the soil medium.

Table 1 Geotechnical characteristics of the adopted soils

V_s (m/s)	G_{max} (MPa)	S_u* (kPa)
150	33.1	50
200	58.8	95
250	91.9	150
300	132	220

* Estimated from Equation (1)

3 NUMERICAL SIMULATION OF SOIL-PILE-STRUCTURE INTERACTION

Equivalent linear method and fully nonlinear method are the two main analytical procedures for dynamic analysis of soil-pile-structure systems under seismic loading. Beaty and Byme (2001) and Byrne et al. (2006) discussed the advantages of fully nonlinear method outweighing equivalent linear method. Due to the assumption of linearity during solution process, an equivalent linear method is not the most appropriate for the study of SSPSI. Also, strain-dependent modulus and damping functions are only taken into account in an average sense to approximate soil nonlinearity. On the other hand, the fully nonlinear method can correctly present the physics and follow a realistic stress-strain relationship, as the method can follow any prescribed nonlinear constitutive model, capture nonlinear material law, consider the interference of components with different frequencies, and model permanent deformation. Based on the above mentioned merits, fully nonlinear method is adopted in this paper to obtain more reliable results.

FLAC3D (Itasca, 2011), a finite difference software, is employed to model soil-pile-structure interaction under seismic loading and to solve the governing equations of a system including equilibrium and compatibility equations.

Structural components adopt elastic-perfectly plastic behaviour for conducting the inelastic analysis. 5% damping ratio is assigned to the building and the pile foundation. Hysteretic damping has been applied to capture the cyclic non-linear behaviour of the soil following the actual stress-strain path during cyclic loading as suggested by Vucetic and Dobry (1991) and Masing rule assumption for loading/unloading (Itasca, 2011). Also, Mohr-Coulomb model has been considered to simulate plastic flow in soil elements. Thus, hysteretic damping provides energy dissipation in elastic range by reducing the shear modulus from an initial value of G_{max} and increasing the damping ratio correspondingly, while the natural damping induced by the adopted constitutive model applies in the plastic range.

Interface elements are required in numerical simulation to incorporate different mechanical behaviours of contacting elements. In this study, interface elements are implemented on the outer perimeter of the piles to capture possible sliding and separation between the piles and soil. It should be noted that there is no interface or attachment between the foundation slab and the surface of the soil deposit to avoid pile-raft behaviour which may not be realistic for end-bearing pile foundation under seismic loading. Thus there is no direct load transformation between the foundation slab and the soil surface. The interface elements are represented by the system consisting normal springs and shear sliders, where Mohr-Coulomb failure criterion defines the shear strength of interface elements. The normal and shear stiffness values are estimated according to the recommendation provided by Itasca (2011).

Free-field boundaries are utilised in the model thus waves propagating upward undergo no distortion at the artificial boundaries as the free-field grid supplies conditions identical to those in an infinite model. A rigid boundary is adopted at the bedrock level to simulate large dynamic impedance (e.g., low-velocity sediments sitting on high-velocity bedrock).

A near-field seismic acceleration, Northridge earthquake, 1994 (Figure 2), is utilised to perform dynamic analysis in time domain. For all cases conducted in this study, seismic input motion applies at the bedrock level.

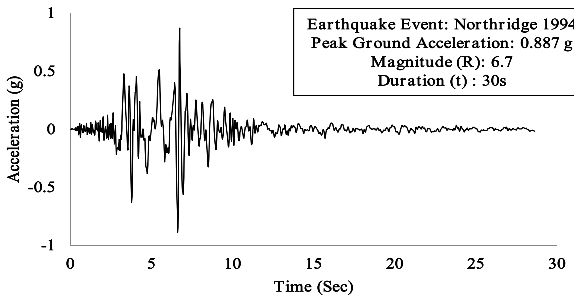

Figure 2 Acceleration record of Northridge Earthquake (1994)

4 RESULTS AND DISCUSSION

The results of the dynamic analysis for a 15-storey model under the influence of Northridge earthquake including or excluding the effects of soil plasticity in conjunction with corresponding shear wave velocities are derived from FLAC3D history records. The results regarding base shear, maximum foundation slab rotation, and maximum lateral deflection of the piles and the building are presented and discussed in this section.

Table 2 Base shear considering soil plasticity in conjunction with different shear wave velocities

Vs (m/s)	Base shear including soil plasticity V* (MN)	Base shear excluding soil plasticity V (MN)	Base shear ratio V*/V
150	20.4	24.9	0.818
200	24.4	25.8	0.943
250	25.3	26.9	0.944
300	26.9	27.0	0.996

Table 2 compares the structural demand of the building regarding base shear subjected to the earthquake. It should be noted that including soil plasticity means the corresponding soil shear strength adopting Equation (1) is considered and natural damping is introduced into the model, while by excluding soil plasticity, the shear strength and thus natural damping is not taken into account. In general, the ratio of the base shear (V*/V) for the case including soil plasticity (V^*) to that of the corresponding case excluding soil plasticity (V) are less than one in all cases. Therefore, it may be concluded that the consideration of soil plasticity contributes to the reduction of the base shear and thus the demand of the building compared with the cases excluding the effects of soil plasticity. It is also realised that by increasing the soil stiffness (i.e. shear wave velocity and corresponding shear modulus), the ratio of base shear (V*/V) approaches unity, which may draw the conclusion that the base shear of the building becomes less dependent on the shear strength.

Figure 3 illustrates the maximum foundation slab rotation of cases with and without the consideration of soil plasticity in conjunction with four different values of shear wave velocity. The general trend is that the maximum foundation rotation decreases with the increase in shear wave velocity and corresponding shear modulus. The lower dynamic properties lead to lower soil stiffness, and thus, more deformation of the soil deposit is induced by the dynamic motion of the building and the pile foundation under the seismic loading. By the comparison of the difference of maximum rotation of foundation slab between the cases including soil plasticity and the cases excluding soil plasticity, it can be summarised that the difference becomes less with the increase of shear wave velocity, and therefore maximum foundation slab rotation becomes less dependent on the shear strength with relatively high shear wave velocity. For example, for the cases with shear wave velocity of 200m/s, the difference of foundation slab rotation is 0.033 degree, while the difference is 0.01 degree for the cases with shear wave velocity of 300m/s.

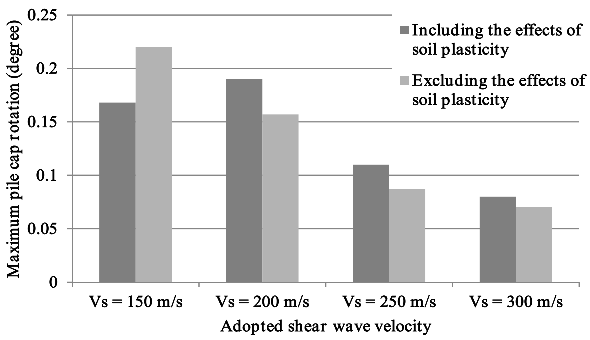

Figure 3 Maximum pile cap rotation including and excluding soil plasticity with different shear wave velocities

The effects of soil plasticity contribute to the response of the soil-structure system in two folds which are wave propagation from bedrock to soil surface and the deformation of the building foundation and bearing capacity. By introducing soil plasticity, earthquake energy can be dissipated by soil plasticity in the process of wave propagation. Consequently, the structure receives less energy and therefore potentially foundation rotation would be less. On the other hand, the building and foundation may experience more deflection and rotation as the soil around foundation reaches its shear strength due to the motion of the building under a strong seismic excitation. Depending on how these two aspects play and contribute in a particular case, in which the characteristics of the building, foundation, soil and earthquake should be considered, the consideration of soil plasticity may contribute to increase or decrease of the foundation rotation. Take the cases of shear wave velocity of 150m/s in Figure 3 as an example, the lower value of foundation rocking for the case including the effects of shear strength compared with the case excluding the effects of shear strength implies that the soil plasticity in wave propagation plays a more critical role in the response of the foundation, specifically enormous natural damping has been triggered to dissipate the earthquake energy, and in turn less energy has been attracted by the building.

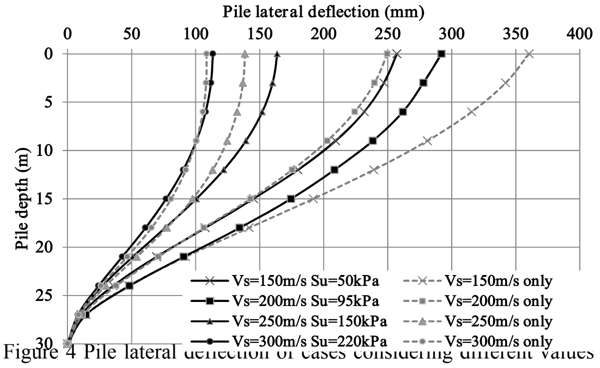

Figure 4 Pile lateral deflection of cases considering different values of shear wave velocity with and without soil plasticity

Figure 4 presents the pile lateral deflections along the pile depth when the maximum lateral deflection occurs at the pile head under earthquake loading for cases adopting four different values of shear wave velocity with and without considering soil plasticity. The results show a good agreement with the results of foundation slab rotation (see Figure 3) as the order of the occurrence of maximum values is the same for both foundation slab rotation and pile lateral deflection. For example, the case of shear wave velocity of 150m/s excluding soil plasticity yields the highest values for both foundation slab rotation and pile lateral deflection, and the case of shear wave velocity of 300m/s excluding soil plasticity has the lowest corresponding values. Evidently, the foundation slab rotation is generated only by the bending of the piles during the earthquake as piles are socketed in the strong rock at the toe level.

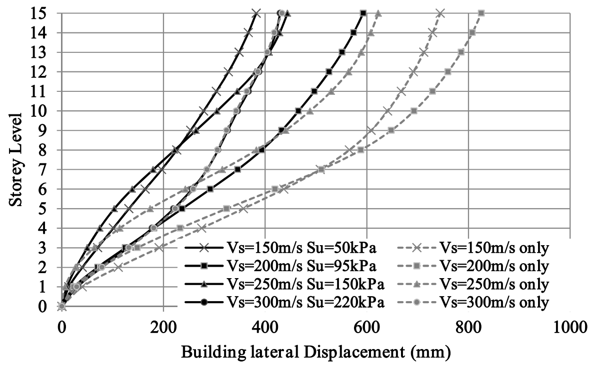

Figure 5 Maximum building lateral deflection with and without considering soil plasticity cosidering different shear wave velocities

Figure 5 depicts the lateral deflection of each storey when the roof level reaches the maximum deflection during the seismic event. It is observed that the maximum lateral deflections of the cases with higher shear wave velocity considering soil plasticity do not differ much from that of the case without shear strength limit. For example, when the shear wave velocity is 300 m/s, the maximum lateral deflection of the cases including and excluding soil plasticity are 430mm and 433mm, respectively. However, the maximum lateral deflections of the building sitting on soil deposit with lower shear wave velocity such as 150m/s considerably increase when soil plasticity is excluded. Specifically, the case including soil plasticity yields 383mm while the case excluding soil plasticity yields 745mm. Thus, the shear strength should be taken into account to conduct realistic dynamic analysis and perform reasonable design for conventional mid-rise buildings supported by end-bearing pile foundations, especially in soft soils. In this particular study, the soil shear wave velocity of 200 m/s results in the largest structural lateral deflections. This is due to the fact that since the building experiences more or less same base shear (see Table 2), the rotation of foundation slab (see Figure 3) induced by pile bending during the earthquake can exaggerate the seismic response of the building influencing lateral deflections. Consequently, this indicates that rotation of foundation slab (which is commonly ignored by practising engineers) should be taken into account in combination with base shear in a coupled manner when analysing the seismic response of buildings supported by deep foundations, to obtain accurate and reliable results.

5 CONCLUSION

In this paper, a three-dimensional finite difference numerical analysis of a soil-pile-structure system is conducted adopting direct and fully nonlinear analysis method and the effects of soil stiffness and soil plasticity on the seismic response of a moment resisting building are numerically investigated.

Numerical results show that by increasing the soil stiffness (shear wave velocity and shear modulus), the base shear of buildings increases. Also, the effect of soil plasticity should be considered while conducting seismic analysis of mid-rise buildings sitting on end-bearing piles. However, the response of structure-foundation system regarding foundation slab rotation, pile lateral deflection and structural lateral deflection becomes less dependent on the soil plasticity for stiffer soils. Additionally, it is significantly important to consider the foundation slab rotation in dynamic analysis of mid-rise moment resisting buildings sitting on end-bearing pile foundations to deliver a realistic and safe design of both structural and foundation elements.

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