

A parametric study of nonlinear soil-structure interaction effects on structural response in far-field earthquakes

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ABSTRACT:In recent earthquakes, bridges with shallow foundations suffered different degrees of damage due to soil plastic deformation and foundation movement. Previous studies have shown that the interaction between foundation and surrounding soil can have significant influence on the seismic response of structures. Thus, the understanding of the effects of soil and structural parameters on soil-structure interaction (SSI) is important for mitigating earthquake damage and for improving future seismic design. This paper presents the simultaneous effects of plastic hinge development in structures and the soil cohesion on the seismic performance of nonlinear soil-structure system. Bridge structures with different nonlinear behaviour are considered and simplified as single-degree-of-freedom systems. To take into account SSI effect, a macro-element is applied. Seven farfield ground motions scaled according to NZS 1170.5 design spectrum is used. The maximum displacements of structures incorporating different nonlinear SSI effect corresponding to various bridge and soil parameters are discussed.

Keywords: soil-structure interaction, plastic hinge development, soil cohesion, seismic performance, macro element.

1 INTRODUCTION

The effect of soil-structure interaction(SSI) on structural response during earthquake has attracted the interest of a large number of researchers over several decades. In the first half of the 20th century, the research activities grew rapidly mainly due to the needs to ensure the safety of nuclear power plants and offshore industries in seismic regions, supported by advancing powerful computers and development in simulation tools such as finite and boundary element approaches. Lamb(1904) analyzed the vibration of elastic foundation and the fundamental solution for a homogeneous half-space subjected to a dynamic load on its surface. An integral transform method for obtaining the response resulting from impulsive (2D) or suddenly applied (3D) vertical loads on the surface of an elastic half-space was proposed. Reissner(1936) studied the vibration problem of rigid circular foundation subjected to vertical load. At the same time, Mindlin(1936) proposed closed-form solutions for the displacement field elicited by static, vertical and horizontal loads buried at an arbitrary depth below the surface of an elastic half-space. In the 1950's, Bycroft(1956) did a comprehensive study on the vertical and horizontal displacement, rocking and rotation of the circular foundation. Soil-structure interaction attracts more and more attention of researchers. Amold(1955), Luco(1971), Lysmer(1977) and others, did a detailed research on various types of rigid foundations subjected to various loadings.

The principal objective of soil-structure interaction analysis under seismic loads is to estimate the dynamic response of a combined system composed of three interacting elements: (i) the soil layers beneath and surrounding the foundation; (ii) the foundation; and (iii) the structure (Wolf, 1985 and 1988). Previous research by Chouw(2004) considered the influence of soil-structure interaction on the pounding response of adjacent bridge structures. The results show that SSI can lead to a much larger response. Rivera et al.(2008) found that high-frequency seismic waves were filtered by the kinematic interaction between rigid and massive foundations and the supporting soil. This interaction resulted in smaller motions than those in the corresponding free field. Ghannad et al.(2008) studied the effect of SSI on structural response under near-fault earthquake records. Spyrakoset al.(2009) investigated the

seismic response of base-isolated structures including soil-structure interaction. Pecker and Chatzigogos(2010) studied the effects of SSI on structural response incorporating linear and nonlinear soil-foundation interface. By adopting robust Monte Carlo methodology, Moghaddasi et al.(2011, 2012)carried out study on stochastic quantification of the interaction between soil, shallow foundation and structure. It was concluded that the SSI effect could reduce the structural response but also cause unacceptable displacement and rotation at the foundation. Raychowdhury and Singh(2012) studied the effect of SSI on the seismic response of frame structures. A Winkler-based approach was used to model the soil underneath the foundation. An increase of displacement demand and reduction of base moment, base shear and drift demands were observed if nonlinear SSI was incorporated. Previous studies show that a better understand about SSI effect on structural response is necessary to achieve a more economical and safe structure design.

The aim of this paper is to carry out a parametric study of SSI effect on structural response. Structures with nonlinear behaviour supporting by linear and nonlinear soil-foundation are modelled and analyzed. The effect of plastic hinge development and soil cohesions are considered.

2 MODELING OF STRUCTURE-FOUNDATION SYSTEM

To investigate the effect of plastic hinge development and soil cohesion on structural responses, a bridge pier supported by rigid circular shallow foundation was considered (Figure 1(a)). Different reinforcement ratios were adopted into the pier to represent different cases of plastic hinge development. As for the soil properties, three soil cohesions were considered to represent soft, medium and stiff soil conditions.



Figure 1. Soil-foundation-structure system

This study focuses on a simplified representation of a bridge pier. The pier was simplified as a singledegree-of-freedom system. It was described by mass m_s including the mass of girder and pier, lateral stiffness k_s , height h and structural equivalent viscous damping c_s . In addition, a damping ratio of 5% was assumed. The bridge prototype and the analytical model are shown in Figure 1. To incorporate plastic hinge development, the bilinear Takeda hysteresis rule with stiffness degrading was assumed.

In this study, linear and nonlinear soil-foundation interface are considered. To simulate the dynamic response of the soil-foundation interface with a linear condition, springs with elastic force-deformation behaviour represent initial static stiffness of the soil-foundation system were attached at the base of the structural system. In addition, dashpots were used together with the springs to describe the radiation damping. The initial stiffness of the soil springs and the radiation damping of the dashpots were calculated according to Gazetas(1991).

Vertical, horizontal and rotational stiffness,

$$k_{N} = \frac{4Gr}{1-\upsilon}, \qquad k_{V} = \frac{8Gr}{2-\upsilon}, \qquad k_{M} = \frac{8Gr^{3}}{3(1-\upsilon)}$$

Vertical, horizontal and rotational damping,

$$c_{N} = \rho \left[\frac{3.4}{\pi (1-\upsilon)} V_{s} \right] A, \qquad c_{V} = \rho V_{s} A, \qquad c_{M} = \rho \left[\frac{3.4}{\pi (1-\upsilon)} V_{s} \right] I_{r}$$

where G is the shear modulus of soil, r is the foundation radius, v is the Poisson's ratio, ρ is the soil density, V_s is the shear wave velocity in the soil, A is the area of foundation, I_r is the moment of inertia.

For considering the nonlinear case of soil-foundation interface, a single macro-element proposed by Chatzigogos et al.(2009) was used. This macro-element is developed for dynamic analysis of structures taking into account the nonlinearities expected at the foundation level. The whole soil-foundation system is described at the centre of the foundation and linked to the base of single degree-of-freedom structural system. A nonlinear force-displacement constitutive law is applied to this centre of the foundation. The linear part of the constitutive law is assumed the same initial static stiffness as that considered in the linear case of soil-foundation and a separation of the foundation from the supporting soil are considered. In addition, the same dashpots, used for the linear soil-foundation model, are coupled with the macro-element.

3 SELECTION AND SCALING OF FAR-FIELD GROUND MOTIONS

To investigate the nonlinearities of structure-foundation-soil system, seven far-field ground motions with magnitude of 6.5-8.5 and hypocentral distance of 25-100 km were selected. Information about the selected ground motions are shown in the Table 1. Ground motions were scaled according to the method introduced in NZS 1170.5 design code (Oyarzo Vera, 2012). The target spectrum with a 5% damping ratio was chosen to match a subsoil class D site with a hazard factor of 0.25 (for Whanganui City) and a return period factor of 1.0. Figure 2 shows the target spectrum and scaled acceleration response spectra of the ground motions.

Number	Record Name	Magnitude	Hypocentral Distance (km)	PGA (m/s ²)
EQ1	Compton Castelgate, Northridge 1, USA, 1994	6.7	43	1.24
EQ2	Freemont M.S. Jose, Loma Prieta, USA, 1971	6.9	39	1.27
EQ3	HKD085, Hokkaido, Japan, 2003	8.3	43	2.77
EQ4	KOC017, Japan, 2001	6.8	95	0.41
EQ5	LA-R. Los Cerritos, Northridge1, USA, 1994	6.7	48	0.69
EQ6	Llolleo, Chile, 1985	7.8	25	6.98
EQ7	Taft Lincoln Sch., Kern Country, USA, 1952	7.4	43	1.80

Table 1. Selected ground motions



Figure 2. Scaled acceleration response spectra of the selected ground motions

4 NUMERICAL RESULTS AND DISCUSSION

In this study, numerical analysis was carried out using seven far field ground motions. To study the plastic hinge development and soil cohesions on structural response incorporating SSI effect, the maximum total displacement u_{tot} at the top of the structure were analysed. In addition, the maximum structural relative displacement u_s at the top of the structure were considered to evaluate the contribution of structural deformation to the total displacement of structure. To have a better perception of the SSI effect on structural responses, the average value of maximum displacements of structure under seven ground motions were used for the discussion.

4.1 The effect of linear and nonlinear soil-structure interaction on structural displacements

In this section, numerical analysis was conducted on the SDOF system with three different base conditions: fixed base, linear base and nonlinear base. The yield forces of piers with different reinforcement ratios were calculated from the analysis of moment-curvature relationship (Priestley et al., 2007). Different yield forces were adopted into the hysteresis rule of a SDOF numerical model to represent different development of plastic hinges. Considering a medium soil case, the following soil properties were used in the modelling of soil-foundation system: the soil density of: 1850kg/m³, the soil cohesion of 60kPa, the shear wave velocity of 200m/s, the soil shear modulus of 74MPa, and the Poisson's ratio of 0.4. (Bi et al., 2011, and NZS 1170.5)

Figure 3 shows the ratio of the maximum total displacement in linear and nonlinear cases to that of a structure with an assumed fixed base. It can be observed that the maximum total displacement experiences a noticeable reduction when SSI is considered. The reduction is more obvious in nonlinear case compared to that of linear case. This might be a result of energy dissipation of the soil-foundation system. In addition, when structures with different yield forces are considered, the structure with a higher yield force experiences a significant decrease on displacement demand. The structure with lower yield force shows an earlier plastic behaviour, which reduces the stiffness of the structure and finally leads to a large structural displacement.



Figure 3. Influence of the support condition on the maximum total displacements of the structure

4.2 The effect of different plastic hinge development on structural response incorporating SSI

By adopting different yield forces, the effect of plastic hinge development was investigated. Figure 4 shows the maximum total displacement of structure and structural relative displacement as a function of the yield force. While the total displacement is significant for secondary attached to the main structure(Lim and Chouw, 2015), the relative displacement provide the direct impact of the earthquake loading considered on the main structure. It is clear that the plastic hinge development has a slight effect on the structural total displacement when linear and nonlinear SSI are considered. However, the effect of plastic hinge development on structural displacement cannot be neglected. Note that the maximum structural displacement increases in the fixed base case with an increasing yield force, whereas an obvious reduction is observed when SSI is incorporated(Figure 4(a)). The reduction is more significant in the case of nonlinear soil. It indicates that the development of plastic hinge may lead to an increase in the structural relative displacement when SSI is considered especially in a nonlinear case (Figure 4(b)).



Figure 4. Effect of yield force on structural displacement

Figure 5 shows the ratio of relative to total displacement of the structure when different yield forces are considered. It can be observed that the structural relative displacement contribute to the total displacement when significant plastic hinges were developed in the structure. In the case of nonlinear foundation and soil the contribution of relative displacements decreases if the structure has a higher yield force. These observations indicate that the SSI effect is more significant if the structure experiences a light plastic hinge development, because the energy is mostly dissipated by the soil-foundation system rather than by of the structure.



Figure 5. Contribution of structural relative displacement to structural total displacement

4.3 The effect of soil cohesion on structural response

In addition to the effect of different plastic hinge development on displacement demand of structures, the effect of soil cohesions on structural response incorporating linear and nonlinear SSI effect was investigated. The corresponding soil properties are given in Table 2 (Bi et al., 2011, and NZS 1170.5). Structures with linear and nonlinear behaviour were considered. A relatively low yield force (0.6MPa) was adopted into the nonlinear analyses.

Soil Type	Soil Cohesion (MPa)	Shear Wave Velocity (m/s)	Shear Modulus (MPa)	Density (kg/m ³)	Poisson's ratio
Soft	0.03	150	42	1850	0.4
Medium	0.06	200	74	1850	0.4
Firm	0.12	300	166	1850	0.4

Table 2. Soil properties

Figure 6 shows the maximum total and relative displacements of linear and nonlinear structures with different soil-foundation interface. When linear soil-foundation interface is considered (i.e. no spatial uplift is permitted), the total displacement decreases slightly with the increase of soil cohesion, while the structural relative displacement experiences a minimal increase. However, in the case of nonlinear soil-foundation interface, both the total and relative displacements of structures increase noticeably. The influence of nonlinearities of structure is not obvious in all soil cohesion considered.



(a) Maximum total displacement

(b) Maximum structural relative displacement

Figure 6. Effect of soil cohesions on structural displacement of linear and nonlinear structures

Figure 7 shows the contribution of the relative displacement to total structural displacement when different soil cohesions are considered. It is clear that the structural relative displacement accounts for most of the total displacement in the case of higher soil cohesion in all considered combinations of structure and soil-foundation interface. The trend is obvious in the case of nonlinear soil-foundation interface. In addition, the nonlinearities of structure reduce the contribution of structural relative displacement to the total displacement. These observations indicate that the decrease of soil cohesion may lead to a significant reduction in the structural displacement demand but a larger response of soil-foundation system especially in nonlinear case. This could be a result of change of vertical bearing

capacity and energy dissipation of the soil. It is also can be found that the nonlinearities of structure increase the displacement of structure.



(a) Structure with linear soil-foundation condition (b) Structure with nonlinear soil-foundation condition

Figure 7. Influence of the soil cohesion on the contribution of structural relative displacement to total displacement of structures

5 CONCLUSIONS

This study focuses on the role of the plastic hinge development and soil cohesions on the displacement of structures under earthquake loadings. The dynamic analysis of a single degree-of-freedom system with linear and nonlinear base conditions were carried out using seven far-field ground motions. The linear and nonlinear soil-foundation systems were modeled using the macro-element. The numerical results of the average values of maximum total and relative displacements reveal:

1. Both total and relative displacements reduce significantly when SSI is taken into account especially in the nonlinear case. Additionally, the SSI effect on reducing structural displacement is more significant if the structure has a larger yield force and is lying on soft soil.

2. The effects of plastic hinge development on the total displacement are negligible compared to the effects on relative displacement, when SSI is considered. With the development of plastic hinges, the contribution of relative displacement to the total displacement increases significantly. It indicates that the structural response caused by foundation movement and soil nonlinearities can be reduced when a lower yield force is considered in the structure.

3. In the case of structure with shallow foundation on soil with low soil cohesion, the nonlinearities of soil-foundation system induces significant movement of foundation. Nonlinear SSI makes great contribution to the total displacement of the structure by dissipating more energy and increasing foundation movement.

In summary, the plastic hinge development in the structure and SSI plays a crucial role in the structural response. A deep understanding of SSI is essential to enable a more economical and holistic design of structures.

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