Analysis on Seismic Performance of Energy Dissipation Subsidiary Piers Considering Foundation Effects

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ABSTRACT

This paper attempts to study the effects of dynamic pile-soil-structure interaction (PSSI) on the seismic performance of an energy dissipation subsidiary pier with pile foundation in a deep soil stratum overlying rigid bed rock. Pushover analysis and a series of a nonlinear and inelastic time history analysis on seismic behavior of the pier subjected to various earthquake events were carried out using three models of the structure. In the seismic analysis of pile-soil-pier system, the soil equivalent linear properties of soil were adopted and the seismic input was applied at bed rock, which is an equivalent force. In order to obtain the equivalent linear properties of soil and the bedrock motion, the seismic response analysis for free-field was performed. The results of the comparative analysis reveal that PSSI has slight effect on the seismic capacity of the pier, but significant impact on the seismic responses of the pier, especially under strong earthquake.

Keywords: Cable-stayed bridge, Energy dissipation subsidiary pier, Ground motion inversion, Seismic performance, Pile-soil-structure interaction.

1 Introduction

In recent years, China is planning several sea-crossing projects consisting of long span bridges, which have low natural frequencies. Many of those bridges are located in high seismicity areas, and are likely subjected to severe damage or even collapse under strong earthquakes. In order to decrease the losses caused by strong earthquakes, a new structural system with damage control strategies of sacrificing subsidiary piers has been proposed [1]. Based on the damage control strategies, the authors designed a twin-column pier with buckling restrained braces (BRBs) as a series of energy dissipation elements and studied its seismic performance by cyclic quasi-static experiments. In the experiments, the pier base was fixed, without considering the effects of foundation and soil effects. However, the most of those sea-crossing bridges are constructed on relatively soft ground and use elevated pile foundations because of deep water, which results in a demand on evaluating the effects of pile-soil-pier interaction (PSSI) on the seismic performance of the pier and properly reflect it in seismic design.

Due to the characteristics of pile foundation, such as long piles, massive pile cap, deep mudline, etc., the resonance problem with superstructures may occur. Ingham Tim J [2] demonstrated that the

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stiffness of the piles may determine the effective ground motions input to the structure, and the dynamic behavior of the foundations may alter the ground motions transmitted to the pier. Aijun Ye et al [3] studied the dynamic interaction between the elevated pile foundation and bridge structure using a two-particle model. The study results suggested if the mass of the pile cap was so large that there was a significant dynamic interaction between foundations and superstructures. Soil conditions have a great deal to do with damage to structures during earthquakes. The soil-structure system is certainly more flexible than the commonly assumed fixed-base model, so that the soil-structure system has a longer natural period than the fixed-base structure. A number of studies in recent years have indicated the flexibility of soft deep soil stratum can significantly affect the response behavior of the bridge structure [4-10]. The previous study results have revealed that PSSI can have both beneficial and detrimental effects on structural behavior which is dependent on characteristics of the soil and the earthquake motion [8]. Some responses will be underestimated if PSSI is no neglected [10].

In this paper, to investigate the effect of PSSI on seismic behavior of subsidiary piers, three FE models of the energy dissipation twin-column piers with BRBs are established. In the third model with consideration of PSSI, the soil equivalent linear properties and viscous boundary was used and the inversed bedrock motion inputted at the bottom of the soil. The comparative analyses of three models subjected to the mono directional lateral load and various earthquake actions are carried out.

2 Free-field Seismic Analysis

2.1 Soil profile

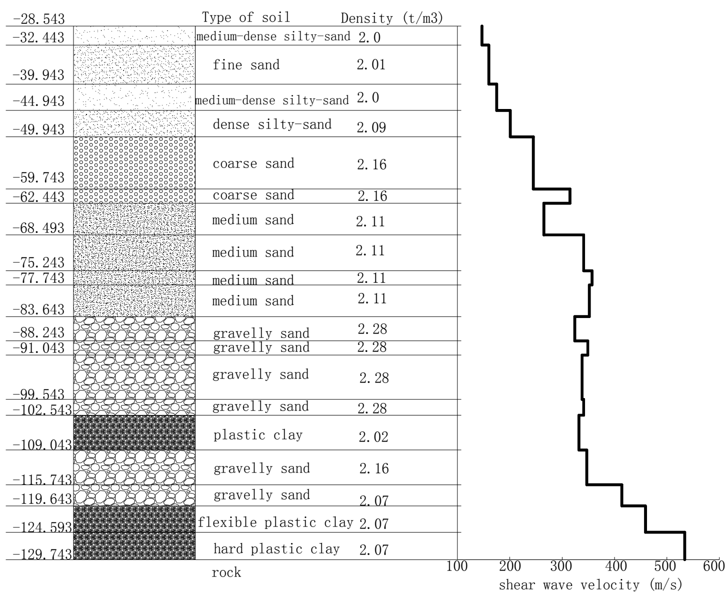


Fig. 1: Soil profile and shear wave velocity

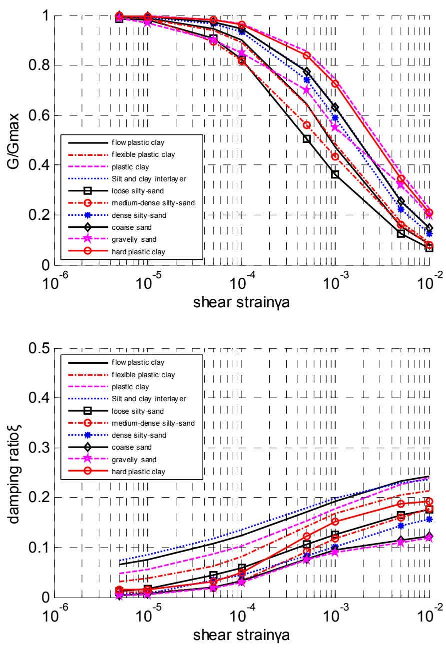


Fig. 2: Shear modulus reduction curves and damping curves

The soil and foundation condition are from a construction site of a long span cable-stayed bridge which is very similar to the bridge here. The soils mainly including soft clay, silty-clay, silty-sand, coarse sand, etc., are vulnerable to be scoured and destroyed. The soil profile considered in this study consists of 19 layers with bedrock underneath [16]. The bedrock is assumed at 101.2m depth below the mudline. The soil properties and the shear wave velocity are shown in Fig 1.

2.2 Seismic analysis of free-field

The soil nonlinearity and inputting mode of the earthquake motion are the key problems in the analysis of pile-soil-structure interaction system. In the present studies, the finite element method considering the soil nonlinearity was widely used. However, the previous studied have demonstrated the analysis with soil nonlinear constitutive model is expensive and time-consuming computation work usually accompanying with slow convergence or no convergence. Due to the influence of the geological conditions, some research results have demonstrated the difference between the bedrock motion and the surface motion is very specific. It is simply untrue that seismic response analysis of free-field and the pile-soil-structure system are executed by using the surface motion as inputted motion at the base of soil column [15]. In this study, the soil nonlinearity will be considered indirectly using equivalent-linear soil properties and the bedrock motion inputting inverted by the surface motion will be adopted in the subsequent analysis of pile-soil-structure system. Therefore, the equivalent linear seismic response of the horizontal layered soil is firstly analyzed to obtain the equivalent-linear soil properties (shear modulus G and damping ratio ξ) and inversed bedrock motion before finite element modeling.

The free-filed seismic response analysis is performed using the commercial software SHAKE2000. SHAKE2000 uses 1D wave propagation theory to iteratively calculate the level of maximum strain in soil and determines the equivalent-linear properties of soil at any desired depth. Since the properties G and ξ depend upon the shear strain level in soil, their variation with shear strain are needed during the free-field analysis in SHAKE2000. These variations are generally evaluated from laboratory test. In this paper, these variations are obtained according to the geological exploration reports of the bridge. Figure. 2 shows all kinds of soil variations of shear modulus (normalized with the maximum shear modulus G_{max}) and damping ratio ξ with shear strain γ_a. The initial shear modulus G0 (G_{max}) (in kN/m^2), which is required to estimate G from the G/G_{max} curve, can be obtained from Eq.(1) [6]:

$$G_0=\rho\upsilon_S^2 \tag{1}$$

Where, ρ and υ_S is the mass density and the shear wave velocity of each layer soil, respectively.

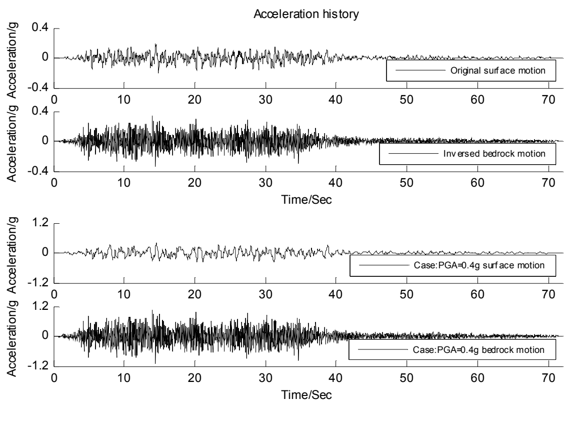


Fig. 3: Surface motion and bedrock motion

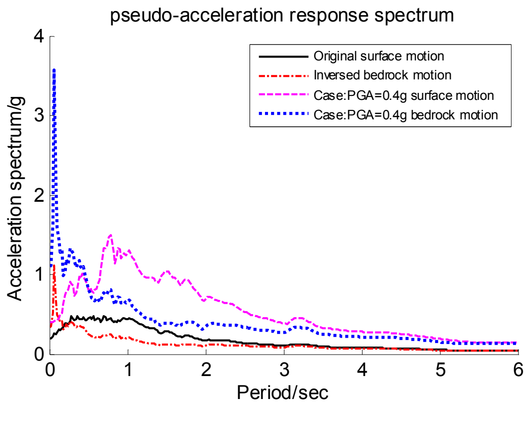


Fig. 4: Pseudo-acceleration response spectrum

An artificial surface wave with PGA=0.2g is inversed to obtain the bedrock motion of the site.

Meanwhile, the equivalent-linear soil properties under this case are also calculated. By magnifying the PGA of the bedrock motion as the input wave at the soil base, the equivalent linear seismic response of the horizontal layered soil is analyzed to obtain the surface motion with PGA=0.4g and equivalent-linear properties. The acceleration histories and spectrums of the original ground motion, inversed bedrock motion, magnified bedrock motion and the ground motion with the case of PGA=0.4g are showed in Fig.3 and Fig.4, respectively. These figures illustrate that the soil layers can filter some high frequencies and reduce the amplitude of the bedrock motion. The ground motion with the case of PGA=0.4g is not simply magnifying amplitude of the original ground motion, their spectral characteristics also different.

3 Finite element models of energy dissipation subsidiary pier

This paper focuses on an energy dissipation twin-column pier with BRBs as a series of energy dissipation members. The height of the pier is 60m. The branch column with reinforced concrete rectangular section has the section of 8.5m×5.2m and the wall thickness 1.5m. The detail prototype of the pier is shown in the literature1. The foundation system consists of a 4×7 pile groups connected with a massive pile cap of 43.0m×27.0m. The piles with the depth of 108m and the radius of 2.8m /2.5m are made of reinforced concrete and the upper parts reside in a steel shell.

To accurately predict the seismic analysis of the pile-soil-pier system, the three-dimensional model may be one of the best choices. However, for a pile-soil-pier system with large-scale soil, seismic analysis of a 3D FE model is very cumbersome and requires huge memory. Some studies have testified that 2D FE model can qualitatively represent the main features of the effect of PSSI on the seismic response of the pier [13]. In this paper, three 2D FE models of the energy dissipation twin-column piers with BRBs are established using open source code OpenSees, the Open System for Earthquake Engineering Simulation, developed specially to simulate the performance of structural and geotechnical systems subjected to earthquake motions [11].

The first model is rigid foundation model, only the pier model, the bases of which are fixed adopting the hypothesis of rigid foundation. The model is composed of inelastic fiber beams to represent the pier and inelastic truss elements to represent the energy dissipation members BRBs, where much of the inelastic behavior is expected to occur. The equivalent mass of the superstructure is concentrated and an equivalent vertical load of 2500 kN of the superstructure weight and live loads is applied at the top of the pier.

In the second model named pile-pier model, the pile foundation cut and fixed at the mudline is added ignoring the pile-soil interaction. Because the steel protective canister can enhance the strength and plasticity, piles are modeled using linear beam-column elements. The pile cap is modeled by elastic isoparametric element with four-nodes.

The third model is a soil-pile-pier system model, taking account of PSSI. The pier model is the same as the model1. Soil domain is discretized elastic isoparametric element with four-nodes. The soil divided into 53 layers with thickness of about 2m is analyzed under plane-strain condition. The soil nonlinearity is considered indirectly using equivalent-linear soil properties. These soil properties are obtained from the above free-field analysis of soil column using the software SHAKE2000. Lateral boundary are set far from the foundation (the distance is 6 times as long as the width of foundation), so that the wave radiating from foundation to lateral boundary can be absorbed by soil damping and radiation damping. Therefore, the lateral boundary can be considered as free. The nodes at the base of the column are fixed against displacements in the vertical direction in accordance with the assumption that the soil layers are underlain by bedrock, and viscous boundary proposed by Lysmer-Kuhlemeyer(L-K)[12][14] is used as radiation boundary in the horizontal direction. Following the method of Joyner and Chen (1975), the dashpot coefficient is defined as the product of the mass density and shear wave velocity of the underlying bedrock, as following Eq.(2) :

$$C_V = \rho_{\text{rock}} V_s A \tag{2}$$

Where, ρ_{rock} and V_s is the mass density and the shear wave velocity of the bedrock, respectively, and A is the area of the base of the soil column.

The soil-pile interfaces are assumed to be perfectly bonded, ignoring gapping and sliding between soil nodes and pile nodes. The energy dissipation in soil is approximately captured through the equivalent-linear damping ratio ξ_{eff} in soil obtained from the SHAKE2000 analysis. The damping form used in soil analysis is the Rayleigh damping in proportion to mass and stiffness. Damping in pier and pile structure is assumed to be 5% of the critical damping. Fig.5 shows three 2D FE models of the pier.

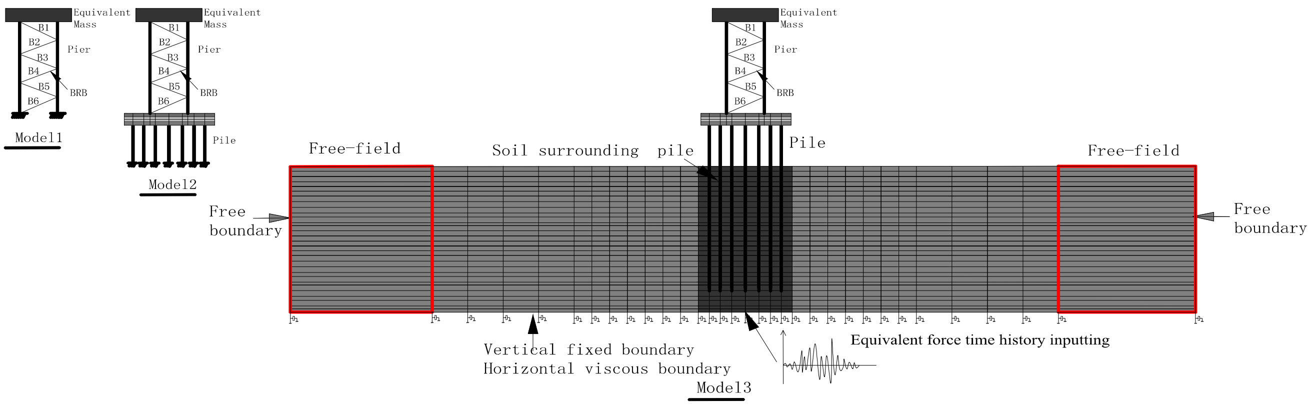


Fig. 5: FE models of energy dissipation subsidiary pier

3.1 Pushover analysis

Recently, pushover analysis procedures are gradually used for estimating the seismic performance for bridges because of its simple concept and easy calculation. To assess effects of PSSI on seismic behavior of the pier, a static pushover analysis is conducted for three models. The analyses are conducted in a displacement controlled mode. The horizontal loading sequence with displacement increment of 0.01m was imposed to the top of the pier until the limit point (again, very similar load capacity, but different displacements). Fig.6 and Fig.7 shows the load-displacement relationships and the variations of the maximum horizontal displacements along height of three models, respectively.

It can be seen that the load-displacement relationships is trilinear model with two obvious turning points. By analysis on response behaviors of BRBs and pier sections, it is observed that the former of two obvious points is BRB yielding point and the latter is the pier section yielding point. It has been confirmed by the phenomenon of quasi-static test. The load-displacement relationship curves shows that for the case assuming rigid foundation, the pier response becomes nonlinear earlier than the other cases considering pile foundation and PSSI. Therefore, the stiffness the whole structure becomes smaller after considering pile foundation, verified by the different displacements at the bottom of the pier in Fig.7. However, the case with pile foundation is very close to the case considering PSSI, which suggests pile-soil interaction has no significant effects on the seismic capacity of the pier.

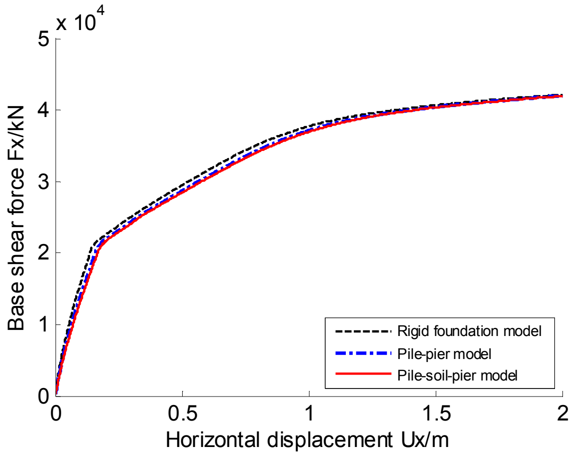


Fig.6: load-displacement relationships

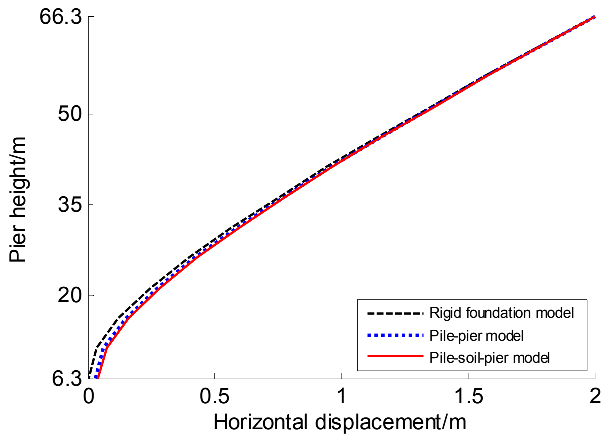


Fig.7: Distributions of the maximum horizontal displacements along pier height

4 Time history analysis

As it is well known, the seismic response of structure depends on the relationship between transfer function of structure and predominant frequency of seismic motion. Before discussing the results of the time history analyses, model analyses of three models were firstly performed. The fundamental periods of model 1 and model 2 are 1.996s and 2.298s, respectively. For the sake of different equivalent-linear soil properties under different earthquake actions, the fundamental periods of model3 under the cases of PGA =0.2g and PGA=0.4g, are 2.394s and 2.412s, respectively.

4.1 Seismic inputs

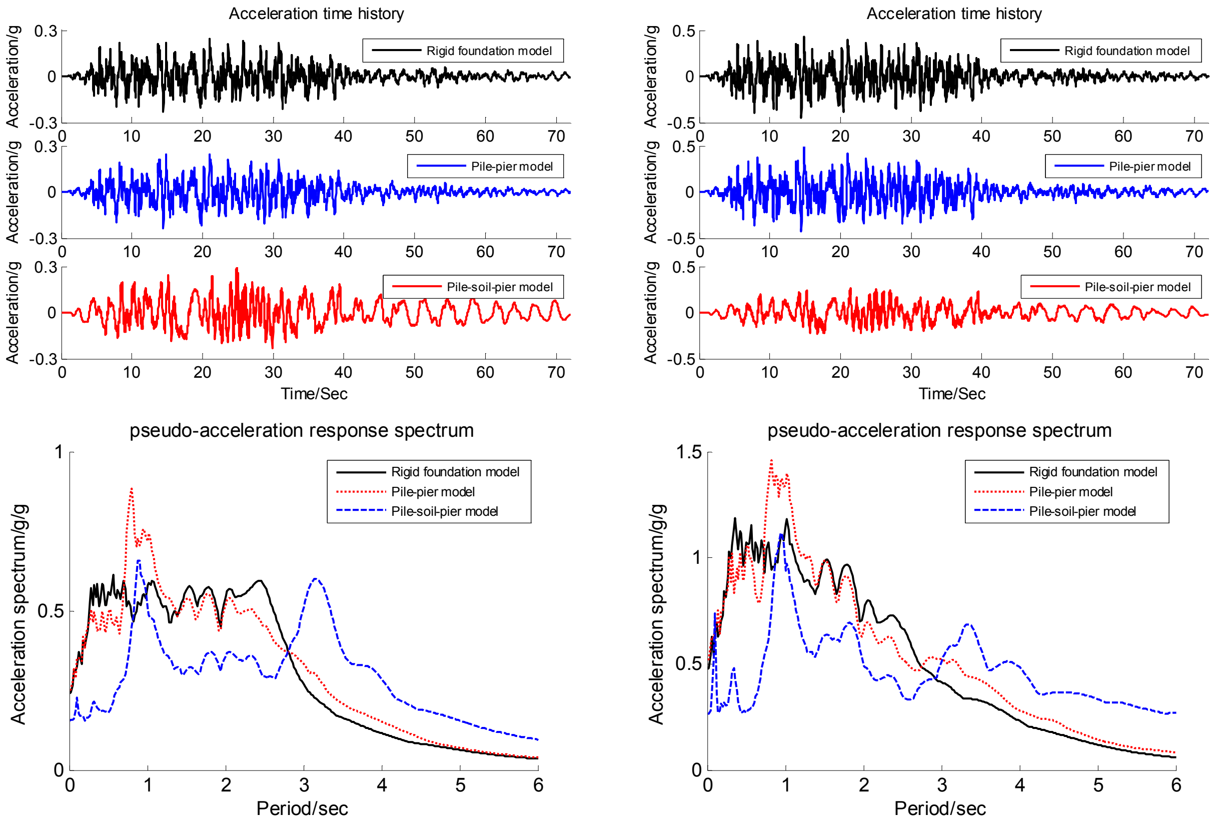
In the seismic response analysis, different modes of the earthquake motion were adopted in different models. The original surface acceleration history was inputted at the pier base of model1 and at the pile base of model 2, but model1 was based on the hypothesis that the pier base is in the surface. In the model 3, dynamic excitation is applied as a force time history to the base of the soil column. This force history is obtained by multiplying the velocity time history of above inversed bedrock motion by the mass density and shear wave velocity of the underlying bedrock layer and the area of the base of the soil column. This technique considers the finite rigidity of the underlying layer by allowing energy to be radiated back into the underlying material. The original surface motion and inversed bedrock motion were shown in above Fig. 3.

4.2 Results of seismic analysis

In this section, dynamic response simulation of three models under the cases of PGA =0.2g and PGA=0.4g are analyzed. Some representative results for three models o are presented.

1). Acceleration response

Fig. 8 shows the horizontal acceleration histories and pseudo-acceleration response spectrum of the pier top. It is seen that the acceleration amplitude of pile-soil-pier system is significantly smaller than ones of pile-pier system and rigid foundation model. For the sake of the structural natural period prolonged considering the foundation, PSSI decreases obviously the acceleration amplitude. However, smaller difference between the acceleration amplitude of rigid foundation model and that of pile-pier system illustrates that the massive mass of the pile cap alters the ground motions transmitted to the pier. The influence of massive pile cap is nonnegligible in the seismic response analysis and seismic design of the pier.

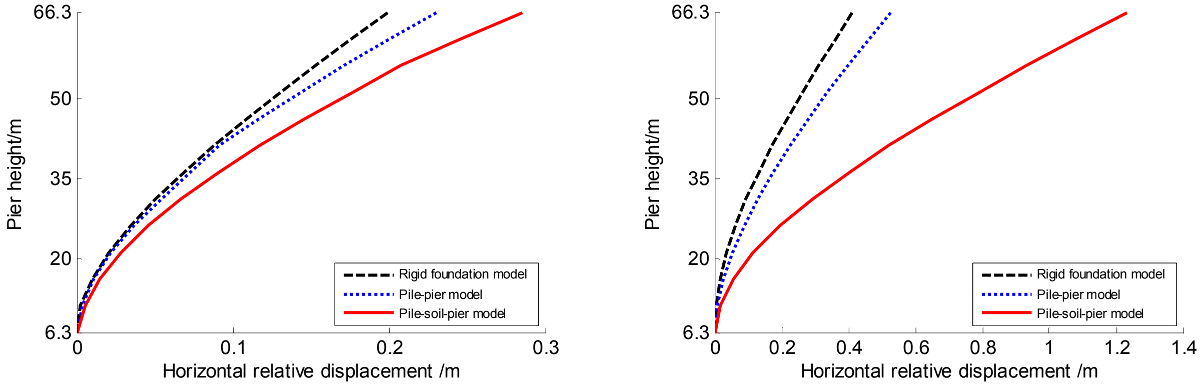


(a) PGA=0.2g **(b) PGA=0.4g**

Fig. 8: Acceleration time histories and pseudo-acceleration response spectrum of the pier top

2). Displacement response

Displacement response is an important factor for assessing damage levels of bridges. The excessive displacement may cause unseating of superstructures, which is the primary failure leading to bridge collapse. Fig.9 shows the distributions of maximum displacements along the pier. Fig.10 indicates that the pile -pier model is subjected to roughly 25% larger deformation than the rigid foundation model. The elevated pile foundation and the inputting position of the surface motion have a slight effect on the displacement response of the pier. The displacements of the pier models without consideration of PSSI are significantly underestimated, by upper to 100% under the case of PGA=0.4g, leading to the conclusion that PSSI markedly increases the displacements response of the pier, especially under the strong earthquake.

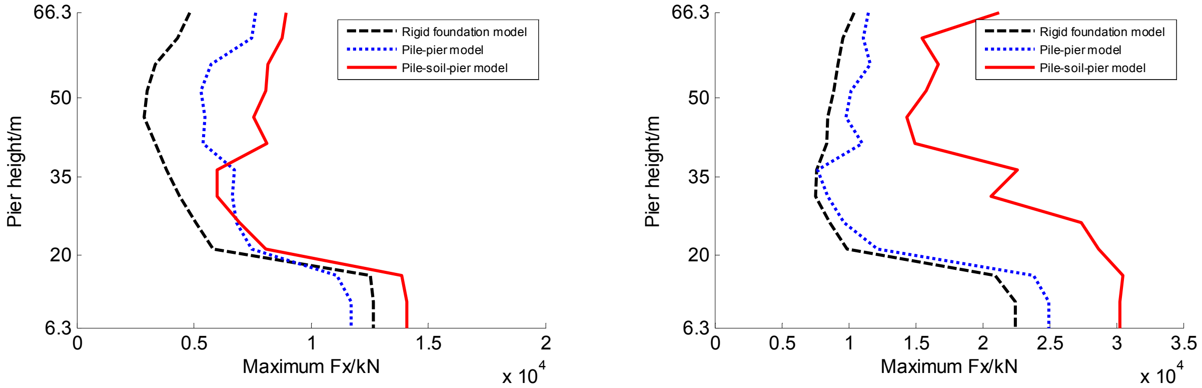


(a) PGA=0.2g **(b) PGA=0.4g**

Fig. 9: Distributions of maximum relative displacements along with the pier height

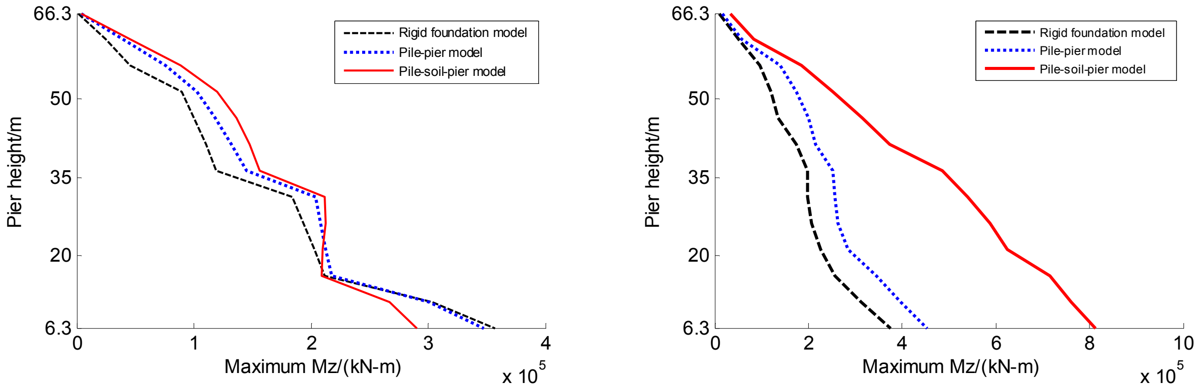
3). Internal forces

The internal force and curvature are criterions judging structural members yielding. Fig. 10 and Fig. 11 shows the distributions of maximum shear forces and maximum bending moments along the pier under two cases, respectively. It can be observed that the effect of PSSI on internal forces is comparatively complex. Under the case of PGA=0.2g, the internal forces of the upper pier considering PSSI are increased while those of the lower pier reduced. However, under the case of PGA=0.4g, the internal forces of the whole pier are significantly increased considering PSSI.



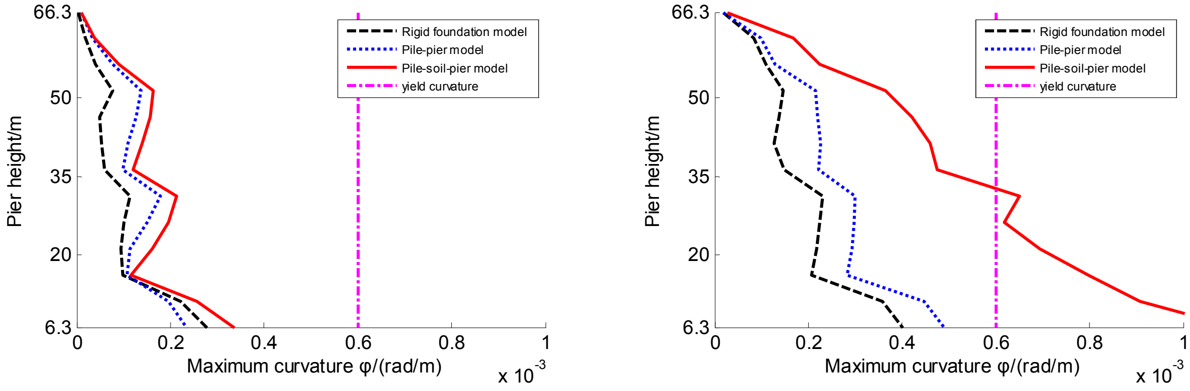
(a) PGA=0.2g **(b) PGA=0.4g**

Fig. 10:Distributions of maximum shear force along with the pier height



(a) PGA=0.2g **(b) PGA=0.4g**

Fig. 11:Distributions of maximum moment along with the pier height



(a) PGA=0.2g **(b) PGA=0.4g**

Fig. 12: Distributions of maximum curvature along with the pier height

The curvature is often used to judge whether the pier enters into the plastic state. The distribution of maximum sectional curvature along the pier shown in Fig. 12 demonstrates that the branch columns of the pier were not damage except under the strong earthquake action considering PSSI. Table.1shows most of energy dissipation elements BRBs yield, especially ones locating at the upper pier.

Table 1: Damage of BRBs

Number	B1		B2		B3		B4		B5		B6	
PGA	0.2g	0.4g	0.2g	0.4g	0.2g	0.4g	0.2g	0.4g	0.2g	0.4g	0.2g	0.4g
Model1	Yield	Yield	Yield	Yield	Yield	Yield	Yield	Yield	Elastic	Yield	Elastic	Elastic
Model2	Yield	Yield	Yield	Yield	Yield	Yield	Yield	Yield	Elastic	Yield	Elastic	Elastic
Model3	Yield	Yield	Yield	Yield	Yield	Yield	Yield	Yield	Yield	Yield	Yield	Yield

5 Conclusion

In this paper, the influence of PSSI on the seismic performance of an energy dissipation subsidiary pier was evaluated. A significant feature of the study is the systematic methodology employed for analyzing the pile-soil-pier system. First, the seismic analyses of free-field was performed to obtain the equivalent-linear properties of soil and the bedrock motion by using SHAKE2000, the seismic response of the pier by using OpenSees. The analysis process avoids a large-scale nonlinear calculation of the soil, so that the non convergence problem can be overcome and the computing time can be shorten.

Based on this study, the following conclusions can be drawn:

1) For the energy dissipation subsidiary pier with pile foundation, assuming rigid foundation is unreasonable. The stiffness of the piles and the mass of pile caps has significant influence on the seismic performance of energy dissipation subsidiary pier. The inputting position of the ground motion also has a slight effect on the displacement response of the pier. Considering pile foundation will increase the seismic responses of the pier.

2) Pile-soil interaction has no significant effects on the seismic capacity of the pier.

3) PSSI prolongs the natural period of the structure, in small acceleration response and large displacement response, especially under strong earthquake. The effect of PSSI on internal forces is comparatively complex. Under small earthquake some internal force responses will be increased and some reduced. While the internal force responses will be generally increased under strong

earthquake.

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