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EEFFECTS OF PILE-FOUNDATION-SOIL INTERACTION ON DEMANDED STRENGTH OF HIGHWAY BRIDGE PIER

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SUMMARY

In this study, effects of dynamic interactions between pile-foundations and soils on strength demand spectra of highway bridge piers were investigated. Demanded strengths determined by the strength demand spectra control the ductility of structures. The strength demand spectra, therefore, becomes a useful tool for aseismic design taking into account inelastic behaviors of structures. The strength demand spectra are obtained from results of response analysis for given ground motions. In order to calculate the strength demand spectra taking into account the dynamic pile-foundation-soil interaction, a highway bridge pier was modeled as a simple 3-degree-of-freedom (3DOF) system including sway and rocking motions. Stiffness of the sway and rocking motions were calculated by pushover analysis. Two surrounding soil conditions and two input ground motions were used in the analysis. The strength demanded spectra considering pile-foundation-soil interactions were calculated and compared with those of rigid based SDOF models. The dynamic interactions between pile-foundation and soil had a marked effect on the strength demand spectra. Especially, the demanded strengths obtained by 3DOF model were greater than those of SDOF when natural periods of piers were short. A range of natural period, where the demand strength markedly decreased, existed when considering the pile-soil interaction. The effects of pile-soil interaction on the strength demand spectra of piers depended on not only natural period of piers but also input ground motions. It is concluded that the dynamic pile-soil interactions should be considered in inelastic aseismic design procedures of highway bridge piers.

INTRODUCTION

After the 1995 Hyogo-ken Nanbu Earthquake, elastic design procedures of structures are replaced by those taking into account inelastic behavior because the design ground motions became large. In inelastic design procedures, the inelastic behavior of piers is only considered with the assumption that foundations of those structures are fixed rigidly and no deformation of the pile-foundation is considered. However if the acceptable inelastic deformation of the foundation is clearly defined within the range of no serious

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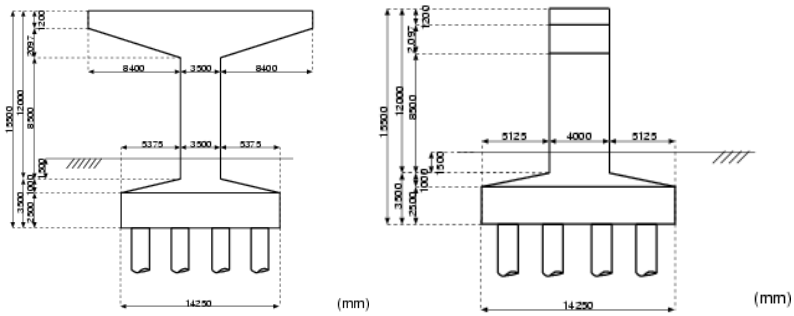


Figure 1: Road Bridge Pier

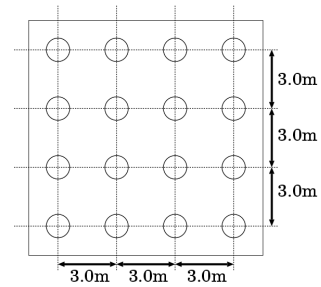


Figure 2: Pile arrangement

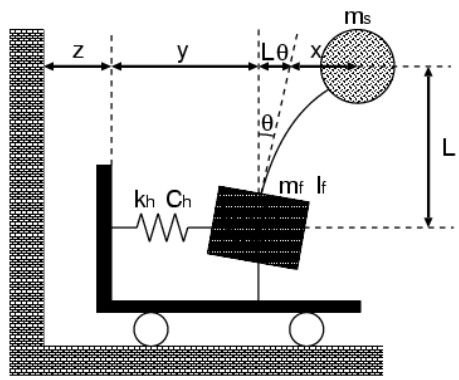


Figure 3: 3DOF Sway-Rocking Model

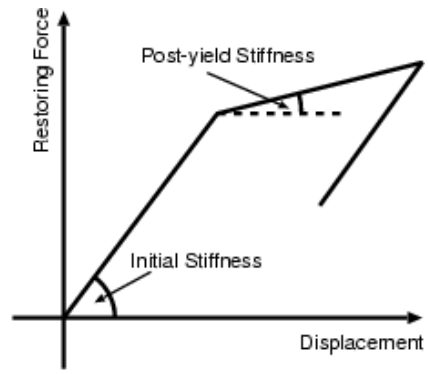


Figure 4: Bilinear Model

damage to their functions, the rational aseismic design procedures, in which the deformation distribution are properly considered, can be established.

The purpose of this study is to examine the effects of the inelastic behavior of the pile-foundations on the aseismic performance by comparing the strength demand spectra. We investigated the relationship between the inelastic deformation of the pier and the pile-foundation on the aseismic performance of the structure systems.

PILE-FOUNDATION-SOIL INTERACTION SYSTEM

Road bridge pier and foundation

In this paper, we consider the RC road-bridge pier supporting by pile-foundation as shown in Figure 1. The height of the pier is about 12m. Figure 2 shows the arrangement of the piles. The diameter of each pile is 1.2m and its length is 20m. The number of piles is assumed as 16 and the pile spacing is 3.0m in order to eliminate the group pile effects.

Three Degree of Freedom Sway-Rocking Model

In this study, the 3-Degree-of-Freedom Sway-Rocking model was used for the pile-foundation-soil interaction system. Figure 3 shows the 3DOF system with sway and rocking motions. In Figure 3, k_s and k_h

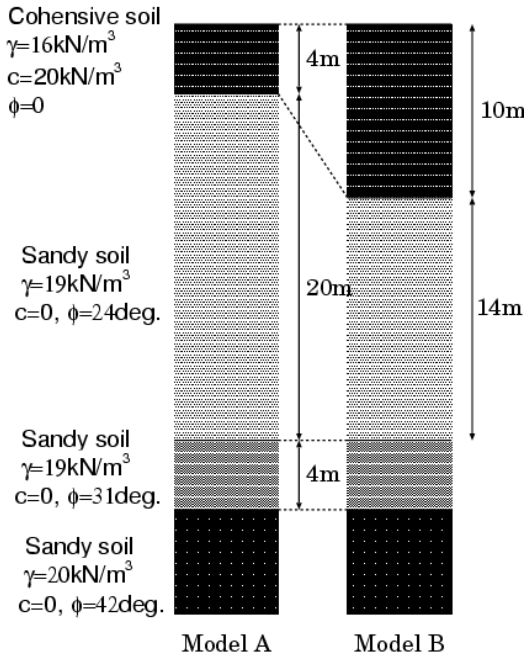
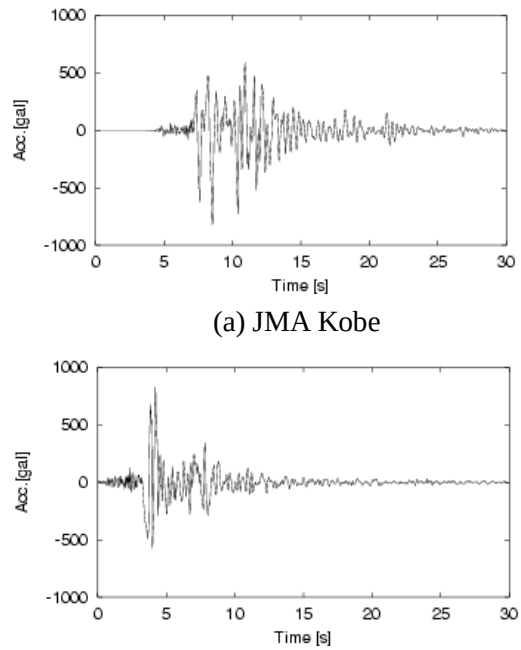


Figure 5: Soil profile model



(a) JMA Kobe

(b) Sylmar

Figure 6: Input ground motions

represent the stiffness of pier and sway motion, and m_s, m_f and I_f are the mass of superstructure, foundation and the rotational inertia, respectively. The equation of 3DOF model shown in Figure 3 is

$$[M]\{\ddot{Y}\}+[C]\{\dot{Y}\}+[K]\{Y\}=-[M]\{1\}\ddot{z}\,, \tag{1}$$

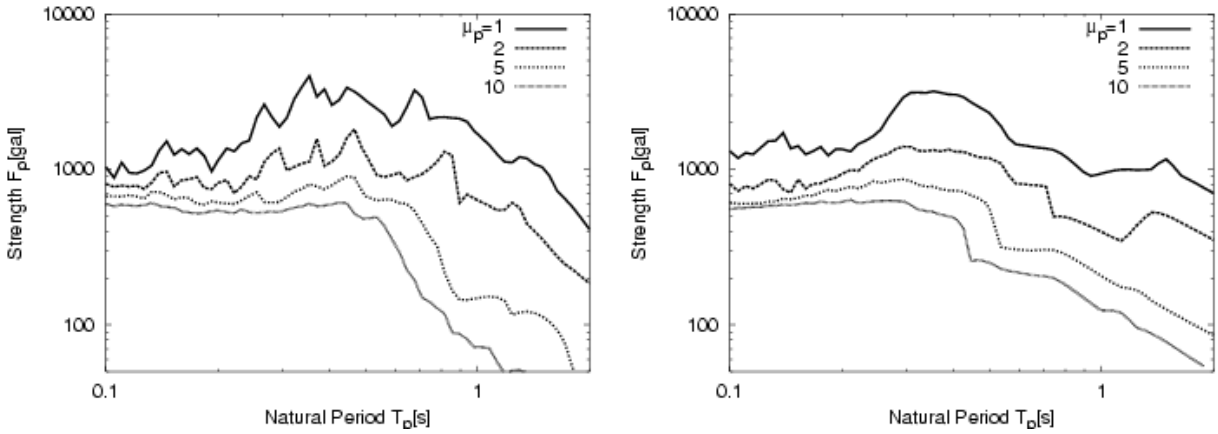
where

$$[M]=\begin{bmatrix} m_s & m_s & m_s L \\ m_s & m_s+m_f & m_s L \\ m_s L & m_s L & m_s L^2+I_f \end{bmatrix} \tag{2}$$

$$[C]=\begin{bmatrix} c_s & 0 & 0 \\ 0 & c_h & 0 \\ 0 & 0 & c_r \end{bmatrix} \tag{3}$$

Table 1: Parameters of 3DOF system

Mass of superstructure	Mass of foundation	Height of pier	Rotational Inertia
7.81E+05 (kg)	2.08E+06 (kg)	12.0 (m)	3.64E+07 (kg m2)



(a) JMA Kobe (b) Sylmar

Figure 7: Demanded strength spectra of SDOF

$$[K]=\begin{bmatrix} k_s & 0 & 0 \\ 0 & k_h & 0 \\ 0 & 0 & k_r \end{bmatrix} \tag{4}$$

$$\{Y\}^t=\{x \quad y \quad \theta\} \tag{5}$$

$$\{1\}^t=\{0 \quad 1 \quad 0\}. \tag{6}$$

The restoring force characteristic of the pier is modeled as the bilinear shown in Figure 4. The post yield stiffness is assumed as 1% of the initial stiffness. In the following analysis, the initial stiffness is calculated with the natural period and the mass. The properties of the 3DOF system are shown in Table 1. In this study, the non-iterative computation scheme developed by Sakai et al [1] was used to solve the equation (1)

Soil Model

Two soil models supporting the pier were assumed. Figure 5 shows the soil models. The soil model A has a clay stratum on the rigid bedrock. On the other hands, the soil model B has the sand layer on the clay. The shear wave velocity of this clay stratum is 125 m/s in both models and the sand stratum is 200 m/s. The other properties of each soil models are described in Figure 5.

Input ground motion

Figure 6 shows the input ground motions we used in the following analyses. The upper is the observed record at JMA Kobe Marine Observatory during the 1995 Hyogo-Ken Nanbu Earthquake and the bottom one is recorded acceleration at Sylmar during the 1994 Northridge Earthquake.

Table 2: Cases for the analysis

Case	Soil Model	Pile Model
LA	A	Linear
NA	A	Nonlinear
LB	B	Linear
NB	B	Nonlinear

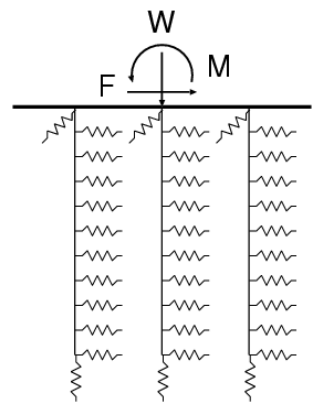


Figure 8: pile-soil model

The strength demand spectra of SDOF are shown in Figure 7. For these diagrams, the damping ratio is assumed as 2%. The response ductility factor μ_p is defined as

$$\mu_p = x^p{}_{\max} \Big/ x^p{}_{yield} \tag{7}$$

where, $x^p{}_{max}$ and $x^p{}_{yield}$ are the maximum and the yield deformation of pier, respectively. In Figure 7, it can be seen that the demanded strength is not changing in the short period. On the other hand, the demanded strength becomes small when the natural period increases in the long period. These figures also show that the demanded strength of pier could be reduced if the capacity of deformation is large enough.

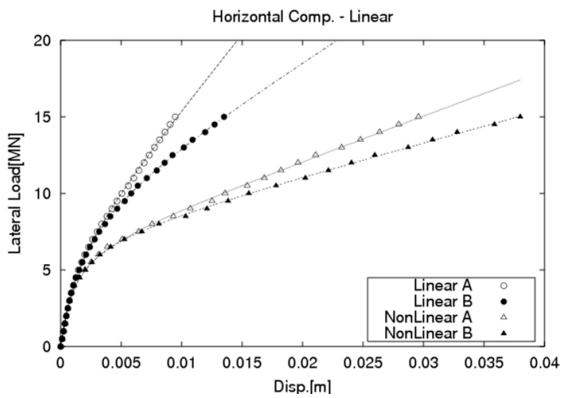
Cases for the analysis

In this study, two soil models and two pile models were considered. As it is already mentioned, the soil models are shown in Figure 2. The linear and tri-linear models were used for the pile. All cases are summarized in Table 2.

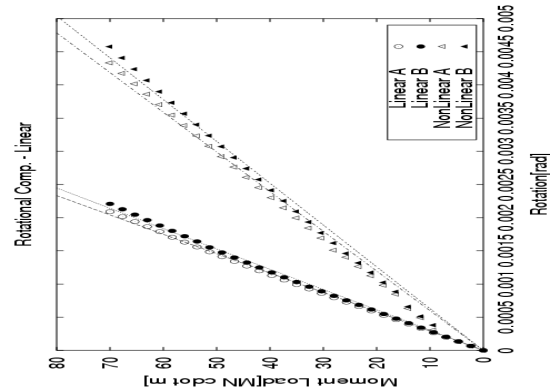
PUSHOVER ANALYSIS ON SOIL-PILE INTERACTION SYSTEM

In this study, to determine the model parameters for the sway and rocking motions, the Pushover analysis was conducted[2]. In the Pushover analyses, beam element and soil spring were used to represent the pile foundation as shown in Figure 8. The initial stiffness and the yield strength of the soil springs were decided according to the references[3, 4]. The lateral soil springs were assumed as elastic-plastic and vertical springs were elastic.

The pushover analysis was done for sway and rocking motions, separately. The force (moment) acting on the footing was increased incrementally. In each step, the acting force (moment) and the response displacement (rotation angle) of the footing were plotted. Then, the relationship between the force (moment) and displacement (rotation angle) were obtained as shown in Figure 9. Figure 9(a) and (b) are corresponding to the results for the sway motion and the rocking motion, respectively. It was clear that the sway motion had a non-linear characteristic and the rocking motion is almost linear. In considering these results, the restoring force characteristics of sway motions were modeled as a bi-linear type and the rocking motion was assumed as a linear.



(a) Sway



(b) Rocking

Figure 9: Results of Pushover analyses

To describe the characteristics of the restoring force $K_h(x)$ for the sway motion, the hyperbolic type model was used. $K_h(x)$ is defined as,

$$K_h(x) = \frac{a \cdot x}{|1 + b \cdot x|} + c \cdot x \tag{8}$$

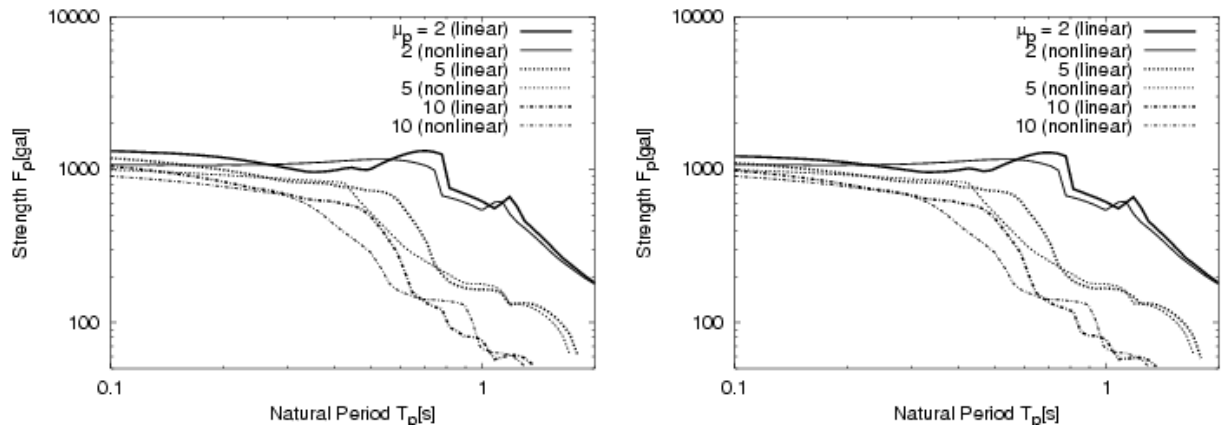
On the other hand, the rocking motions were described by the linear model as follows,

$$K_r(x) = d \cdot x\,. \tag{9}$$

The curves approximated by the result of the Pushover analysis are also shown in Figure 9, and the parameters determined by the least-square technique are summarized in Table 3.

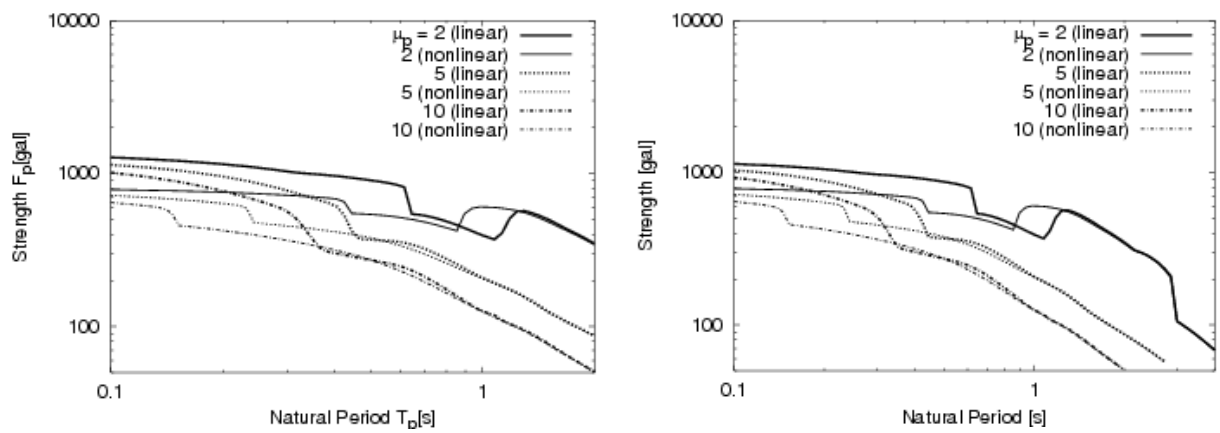
Table 3: Parameters for sway and rocking springs determined by the pushover analysis

Case	a(MN/m)	b(m)	c(MN/m)	d(MN)
LA	5.01E+03	7.64E+02	9.56E;02	3.34E+04
NA	6.50E+03	9.88E+02	2.90E+02	1.67E+04
LB	4.93E+03	5.16E+02	4.89E+02	3.27E+04
NB	6.15E+03	8.60E+02	2.13E+02	1.59E+04



(a) soil A (b) soil B

Figure 10: Demanded strength spectra taking into account soil-pile interaction (JMA Kobe)



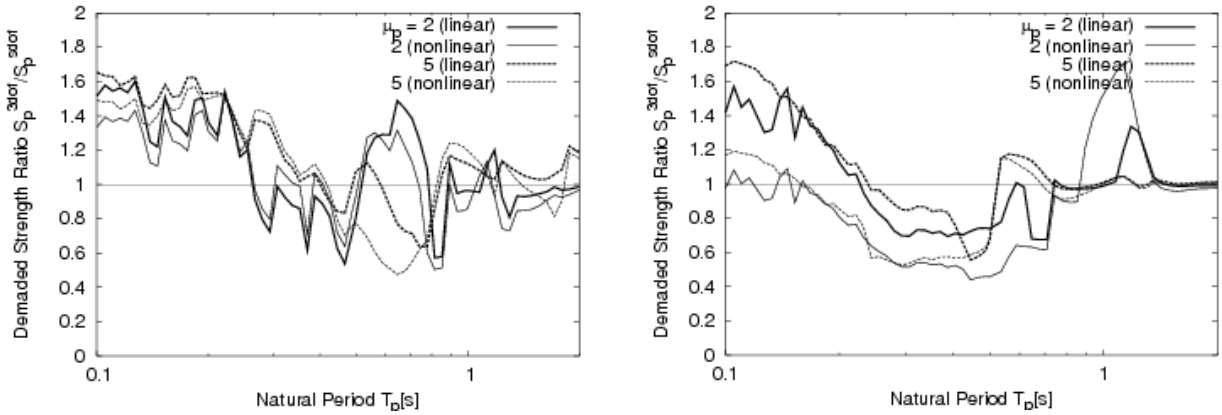
(a) soil A (b) soil B

Figure 11: Demanded strength spectra taking into account soil-pile interaction (Sylmar)

STRENGTH DEMAND SPECTRA TAKING INTO ACCOUNT SOIL-STRUCTURE INTERACTION

The strength demand spectra of 3DOF system are shown in Figure 10 and 11. Figure 10 is corresponding to the case of the JMA Kobe input and Figure 11 is the case of Sylmar. In these figures, the horizontal axis T_p indicates the natural period of the pier. The words linear and nonlinear in the legend mean the case of the linear and nonlinear pile models used in the pushover analysis.

As compared with the case of the SDOF system shown in Figure 7, what is the evident is that the forms of the spectra become gentle and the peak values in the middle period disappear. It means that the soil-pile interaction has a smoothing effect on the strength demand spectrum and decreases the maximum value of the demanded strength. As compared with the case of the soil A and B in each figure, the difference



(a) JMA Kobe (b) Sylmar

Figure 12: Spectrum ratio between 3DOF and SDOF models

caused by the soil model is hardly seen. Thus, the results with the soil model B are mentioned in the following study.

Figure 12 shows the spectrum ratio between 3DOF and SDOF systems. The spectrum ratio varies from 0.4 to 1.8. The horizontal solid line is corresponding to the ratio 1.0. The demanded strength of 3DOF system is larger than that of SDOF system in the short period. In the middle period, the spectra have a hollow where the demanded strength is reduced by the interaction. This effect is shown clearer in the case of Sylmar input than JMA Kobe. On the other hand, in the long period, it can be seen that the curves approach to the 1.0 and the effect of the interaction is rather small.

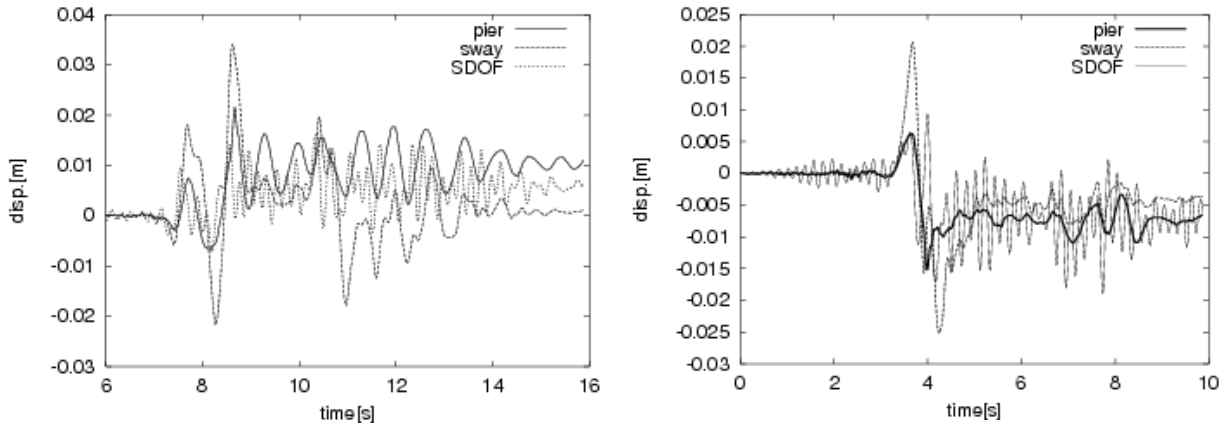
From Figure 12(a), with respect to the case of μ_p=2, the demanded strength of the 3DOF system becomes larger than that of the SDOF system at T_p=0.20s in the both input motions. Figure 13 shows the horizontal displacement responses of the pier and footing when μ_p =2 and T_p=0.20. The displacement caused by the rocking motion is excluded in these figures because it is quite small. The response of the SDOF system is also shown in Figure 13. From these figures, it is clear that the displacement of the foundation is larger than the deformation of the pier. This means that the demanded strength is increased by the displacement of the foundation.

On the other hand, Figure 14 shows the results of μ_p =2 and T_p=0.47. The demanded strength is reduced by the soil-pile interaction in these cases. The displacement of foundation is smaller than the deformation of the pier. In addition, the deformation of the pier becomes smaller than that of the SDOF system. In these cases, the soil-pile interaction reduces the demanded strength.

CONCLUSIONS

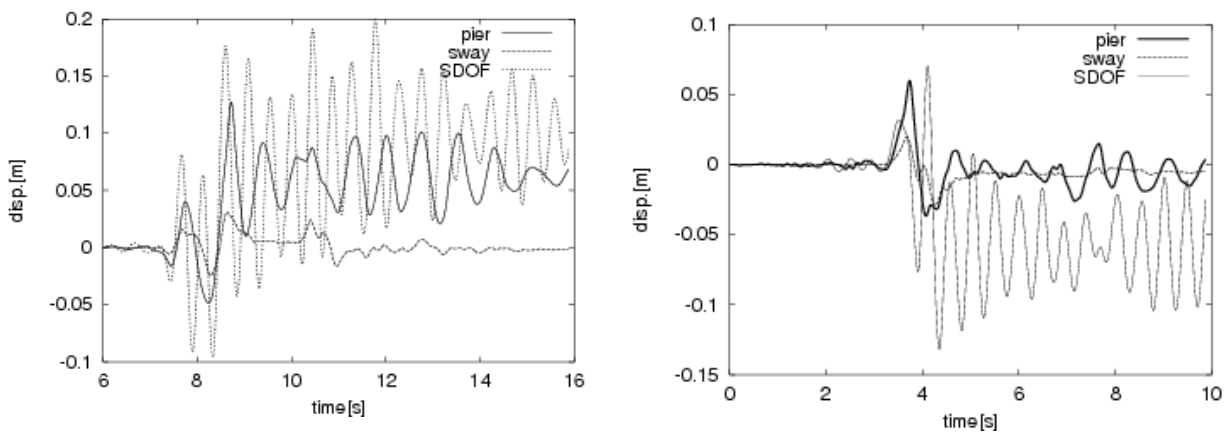
In this paper, we discussed the influence of the soil-pile interaction on the strength demand spectra of a highway bridge pier. The conclusions are summarized as follows.

- The dynamic interaction between soil and pile-foundation has large effects on the demanded strength spectra of the highway bridge pier.



(a) JMA Kobe (b) Sylmar

Figure 13: Displacement responses in the case of demanded strength increasing (T_p=0.20s)



(a) JMA Kobe (b) Sylmar

Figure 14: Displacement responses in the case of demanded strength decreasing (T_p=0.47s)

- The spectrum ratio of the demanded strength for the 3DOF system to those of the SDOF system varied from 0.4 to 1.8 dependent on the natural period.
- The demanded strength spectrum of a highway bridge pier is smoothed and the peak value of the spectrum is removed by the dynamic soil-pile interaction.
- The effect of the dynamic pile-soil interaction on the demanded strength of the highway piers is affected not only by the system parameters but also by the input motion.
- When the displacement of the foundation becomes larger than the deformation of the pier, the demanded strength of the pier increases. On the other hands, if the deformation of the pier becomes larger than that of the foundation, the dynamic interaction has the demanded strength of the pier reduced.

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