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ABSTRACT

Dynamic centrifuge tests were performed on a superstructure-footing model that was placed on a dry sand surface and subjected to two different input motions having peak accelerations of 60 cm/s^2 and 249 cm/s^2. Two simple analyses, equivalent linear analysis (SHAKE) and dynamic response of a structure using a sway-rocking model (SR-model) were performed. The following conclusions were drawn: (1) SHAKE and SR-model analyses can simulate the recorded response of the soil and superstructure. However, the shear wave velocity of the ground that can simulate the superstructure response by an SR-model for a_{max}=249 cm/s^2 is much smaller than that of the free field estimated using SHAKE. (2) The observed relation of the base friction force with relative displacement between the footing base and the ground surface shows strong nonlinearity when a_{max}=249 cm/s^2, which probably results from the large shear deformation of the thin layer beneath the footing.

INTRODUCTION

Extremely high peak ground accelerations and velocities (PGA and PGV) have been observed during recent earthquakes in Japan. These include a PGA of 1716 cm/s^2 at K-NET Tokamachi and a PGV of 146 cm/s at JMA Kawaguchi during the 2004 Niigataken-chuetsu Earthquake, as well as a PGA of 924 cm/s^2 and a PGV of 127 cm/s at KIK-net Hino during the 2000 Western Tottori Earthquake. Despite the extremely strong motions that were recorded, structural damage, especially to low-rise buildings, was slight. Apparently, the unexpectedly minor structural damage might have been the result of nonlinear soil-structure interaction.

To investigate the soil-structure interaction, many studies have used numerical analyses, observations of soil-structure response during earthquakes, shaking table tests, and dynamic centrifuge tests. The mechanism of nonlinear soil-structure interaction, however, remains elusive because of its great complexity.

This study is intended: 1) to evaluate the soil-structure interaction with different input acceleration levels using centrifuge shaking table tests; 2) to simulate the soil and superstructure response by simple numerical analyses; and 3) to elucidate the nonlinearity of soil-structure interaction effects based on results of tests and analyses. For those purposes, dynamic centrifuge tests on a superstructure-footing model were performed with two input acceleration levels, with examination using equivalent linear analysis (SHAKE) and dynamic response of a structure using a sway-rocking model (SR-model).

CENTRIFUGE TESTS PERFORMED

Centrifuge tests were performed at 40 × g centrifugal acceleration using the geotechnical centrifuge at the Disaster Prevention Research Institute, Kyoto University. Figure 1 portrays a footing-superstructure model and sensors prepared in a laminar shear box with inner dimensions of 450 mm (length) × 150 mm (width) × 200 mm (height). The soil model used for the dry sand deposit was Toyoura sand (D_{50}=0.21 mm) with Dr=90%. The sand was air pluviated. The soil model height was 148 mm.

The superstructure-footing model was set on the ground surface. Table 1 presents weights and dimensions of the footing-superstructure model in the model and prototype. The footing was modeled with aluminum alloy of 124 mm (shaking direc-

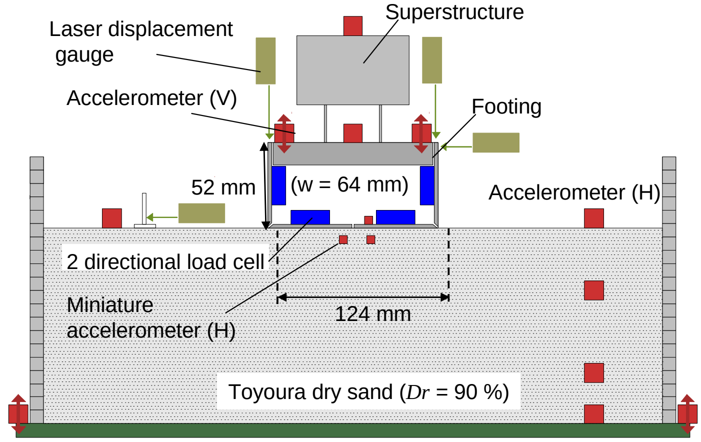


Fig. 1. Setup for centrifuge tests on footing-superstructure model.

Table 1. Conditions of footing-superstructure model in prototype and model scale.

		Unit	Prototype	Model
Footing	Mass	kg	64,000	1.0
	Length (L×B×H)	m	4.96×2.56×2.08	0.124×0.064×0.052
Structure	Mass	kg	128,000	2.0
	Natural frequency	Hz	3.8	105

Table 2. Earthquake events.

ID	Earthquake	Max. acc. (Prototype)
EQ1	Rinkai92	60 cm/s^2
EQ2	Rinkai92	249 cm/s^2

tion) × 64 mm (width) × 52 mm (height). Toyoura sand was pasted on the base plates to simulate the prototype's roughness. The superstructure was modeled with rigid brass and supported by two plate springs. The superstructure was 2.0 kg; the footing was 1.0 kg. The natural frequency of the superstructure and damping constant under the fixed footing condition were about 105 Hz and 0.5%.

To evaluate the friction between the footing base and the soil underneath accurately, the base of the footing was made of two separate plates of equal size, each supported by small load cells, as presented in Fig. 1. The load cells were capable of separate measurements from the two orthogonal forces acting on the base plates, i.e., the horizontal shearing and vertical compressive forces. During the shaking table test, horizontal accelerations of the superstructure, footing and soil, vertical accelerations of the footing, and horizontal and vertical displacement of the footing were measured in addition to the forces acting on the base plates.

This paper describes results from the single centrifuge model subjected to two different levels of input motions, EQ1 and EQ2 as presented in Table 2. The excitation used for the test was Rinkai92, which is a synthesized ground motion for the Tokyo Bay area. All data presented in the following sections are of prototype scale.

CENTRIFUGE TEST RESULTS

Figures 2 and 3 respectively depict the acceleration time histories of the acceleration of input, ground surface, footing and superstructure for EQ1 and EQ2. The maximum accelerations of the ground surface for EQ1 and EQ2 are 100 cm/s^2 and 422 cm/s^2, respectively, which are about 1.7 times that of the input in both cases. The maximum accelerations of the superstructure for EQ1 and EQ2 are 151 cm/s^2 and 514 cm/s^2, respectively, which are about 2.5 and 2.1 times those of the input, respectively.

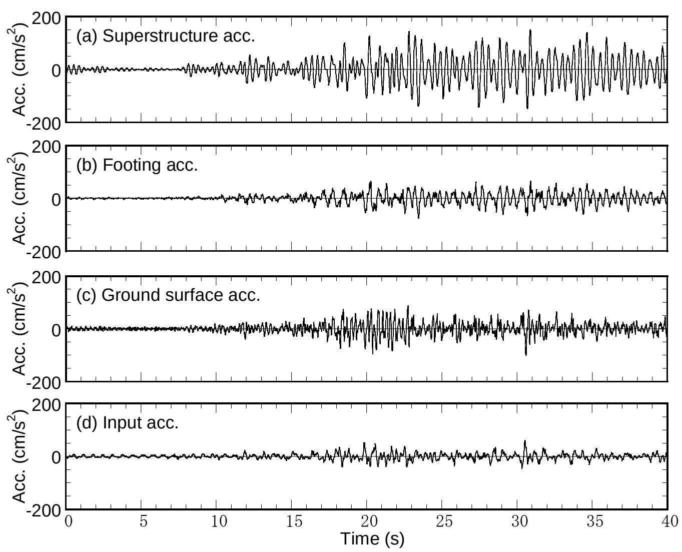


Fig. 2 Time histories of acceleration for EQ1.

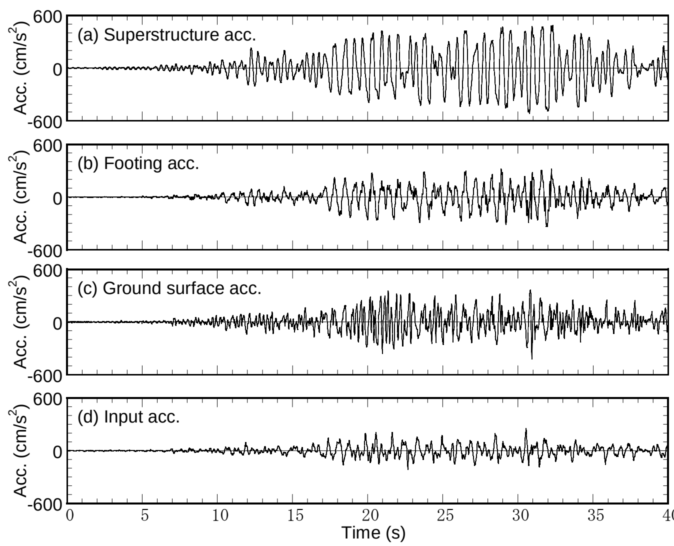


Fig. 3 Time histories of acceleration for EQ2.

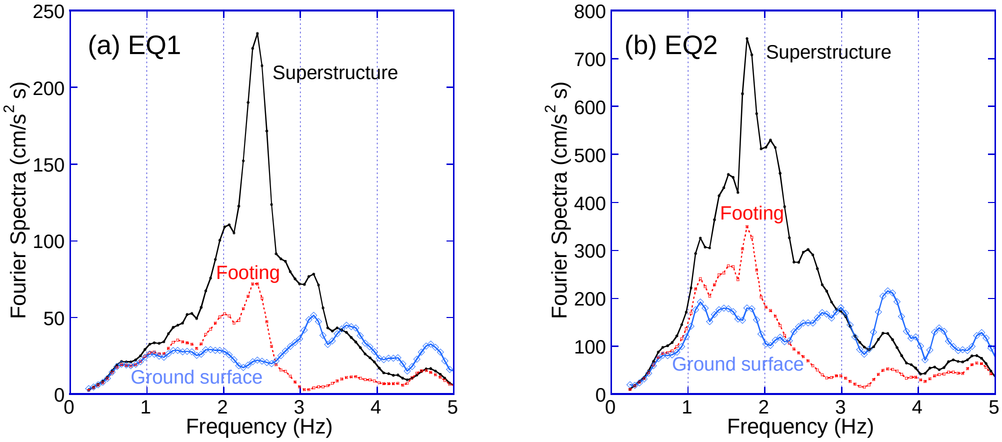


Fig. 4. Fourier amplitude spectrum of the ground surface, footing and superstructure acceleration.

Figure 4 shows Fourier amplitude spectra of the ground surface, footing and superstructure acceleration for EQ1 and EQ2. The predominant frequencies of the superstructure are 2.4 Hz and 1.8 Hz for EQ1 and EQ2, respectively, which are lower than the natural frequency of the superstructure under the fixed footing condition: 3.8 Hz. The predominant frequency of the superstructure for EQ2 is lower than that for EQ1, indicating the nonlinear soil-structure interaction. The Fourier amplitude of the footing is smaller than that of the ground surface in the frequency range higher than 2.7 Hz and 2.3 Hz for EQ1 and EQ2, respectively, suggesting the input loss effect, which is considered to be dominant at frequencies greater than the natural frequency of the soil-structure system.

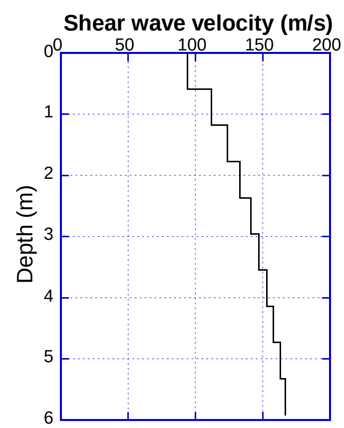


Fig. 5. Initial V_S profile.

NUMERICAL MODELING

<u>Amplification of seismic wave</u>

Numerical analysis of the soil response was performed using SHAKE, equivalent linear seismic response analyses of horizontally layered soil deposits. To simulate the soil response by SHAKE, the initial V_S profile is important. The average shear velocity of the soil model was estimated through experimentation as

$$V_{SA} = 4H / T_g\,, \qquad (1)$$

in which H is the soil model thickness and T_g represents the measured natural period of the soil model during slight shaking. The average shear velocity of the soil model was also estimated as

$$V_{SA} = \Sigma(V_S \times \Delta H) / H, \qquad (2)$$

in which V_S and ΔH respectively denote the shear wave velocity and thickness of each sublayer. The V_S of each layer increases concomitantly with increasing depth, considering that the variation of shear modulus $G_0(=\rho V_S^2)$ with depth is approximated as a square root function of the effective confining stress levels. Consequently, the shear velocity at each depth, V_S, can be determined using Eqs. (1) and (2). The soil model is divided into 10 layers. The estimated initial shear velocity profile is presented in Fig. 5.

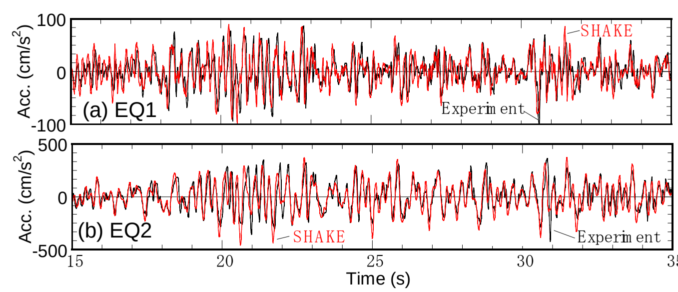


Fig. 6. Time histories of observed and computed acceleration for EQ1 and EQ2.

The G/G_0-γ curve, where G is the shear modulus for a certain strain level and γ is a shear strain, and the h-γ curve, where h

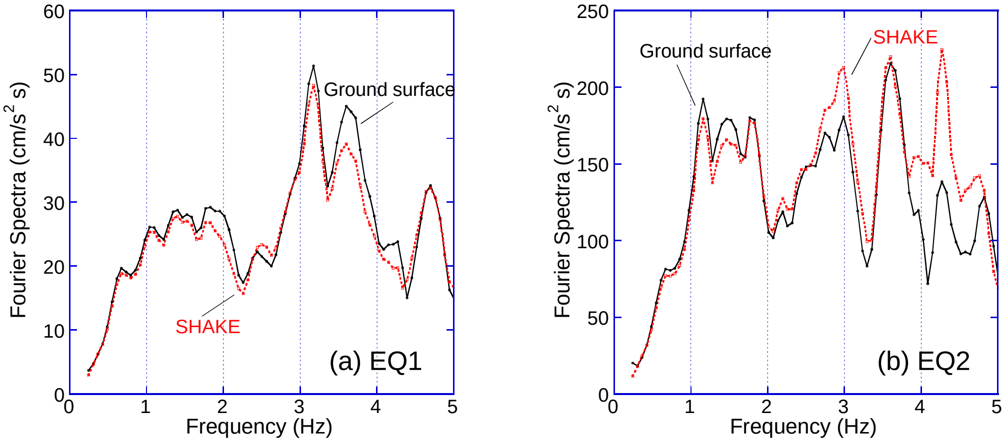


Fig. 7. Fourier amplitude spectrum of the ground surface, footing and superstructure acceleration.

is damping ratio, are based on the cyclic triaxial test results of Toyoura sand (Kokusho, 1980). The value of the effective strain is assumed to be 0.65 times that of the maximum strain obtained in the analysis.

The time histories of the observed and computed ground surface acceleration for t=15–35 s are depicted in Fig. 6. Fourier amplitude spectra of the observed and computed ground surface acceleration are also portrayed in Fig. 7. The time histories and corresponding Fourier spectra of the computed ground surface acceleration show good agreement with the experimental results for EQ1 and EQ2, which indicates that the estimated V_S values at various depths are reasonable.

The V_S profiles evaluated by SHAKE for EQ1 and EQ2 are presented in Fig. 8(a). The shear wave velocity values at any depth are smaller than the initial values at the same depth. The average of the equivalent shear wave velocity of the soil model is, respectively, 137 m/s and 106 m/s for EQ1 and EQ2. The equivalent shear strain profiles of the free field soil evaluated using SHAKE are presented in Fig. 8(b). The averages of the equivalent shear strain of the soil model are, respectively, 8.6×10^{-5} and 6.7×10^{-4} for EQ1 and EQ2.

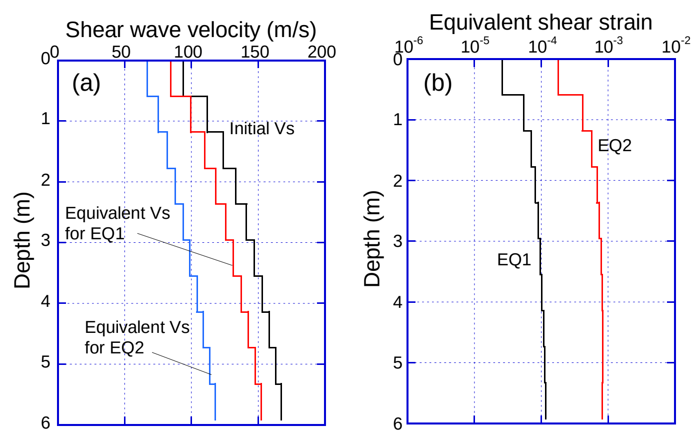
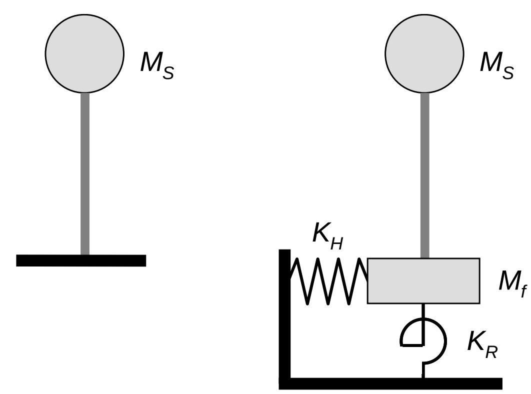


Fig. 8. Initial and equivalent V_S profiles and equivalent shear strain profiles.

Response of superstructure

Dynamic response analysis of a superstructure is performed under either constraint or sway and rocking motions of the footing (AIJ, 2001). The analytical models are presented in Fig. 9. The superstructure has a single degree of freedom (DOF) with sway motion and the footing is two-DOF with sway and rocking motions. To include a Soil-Structure Interaction (SSI) effect, dynamic springs for sway and rocking motions are connected to the footing mass. The dynamic springs for sway and rocking motions were evaluated according to the Dynamical Ground Compliance of a rectangular foundation on semi-infinite elastic medium (Kobori et al., 1967). The soil model's Poisson ratio is assumed to be 0.3.



(a) Fixed footing model *(b) SR-model*

Fig. 9. Model for analysis.

The damping constants of the soil model are 0.03 and 0.15 for EQ1 and EQ2, respectively, which are the averages of the equivalent damping constant computed by SHAKE. The input motions are the ground surface acceleration computed using SHAKE.

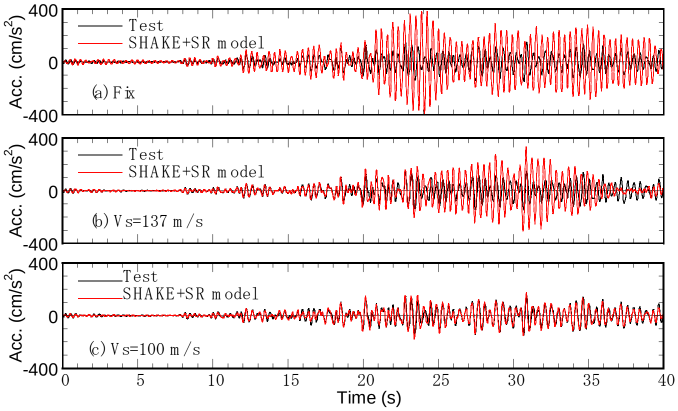


Fig. 10 Time histories of observed and computed acceleration for EQ1.

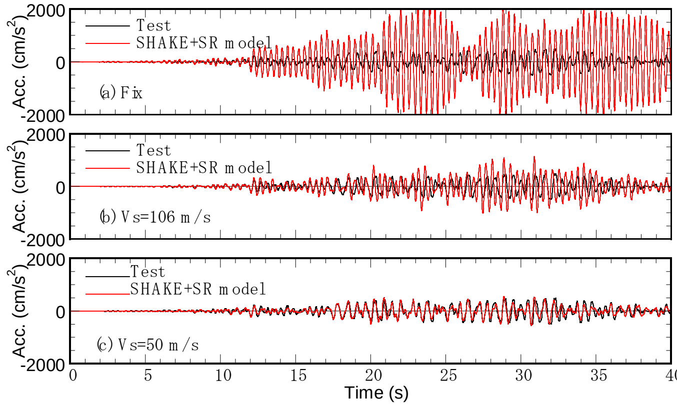


Fig. 11 Time histories of observed and computed acceleration for EQ2.

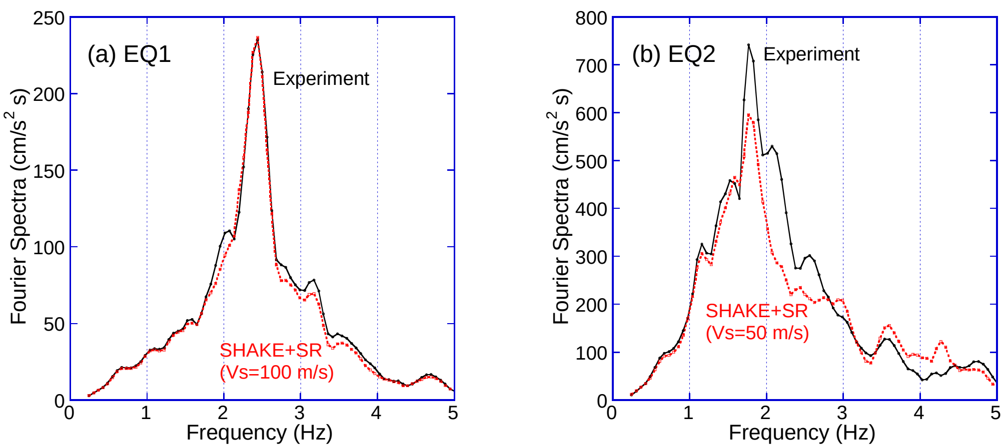


Fig. 12. Fourier amplitude spectrum of observed and computed superstructure acceleration.

Figures 10 and 11 present the time history of the superstructure acceleration computed with three different footing conditions. The computed acceleration under the fixed condition for EQ1 and EQ2 (Figs. 10(a) and 11(a)) are much larger than the measured data. The maximum theoretical accelerations are 2.6 times and 4.8 times larger than those of the measured value for EQ1 and EQ2, respectively, which indicates that soil-structure interaction strongly affects superstructure responses.

The superstructure response estimated using the SR-model depends on the shear wave velocity of the soil. Figures 10(b) and 11(b) show SR-model results computed with the average of the equivalent shear-wave velocity estimated using SHAKE, i.e., 137 m/s for EQ1 and 106 m/s for EQ2. The computed structural acceleration is also larger than the measured one in both cases, which indicates that the SR-model with the equivalent shear velocity estimated by SHAKE might overestimate the superstructure response. Figures 10(c) and 11(c) portray the SR-model results computed with V_S=100 m/s for EQ1 and 50 m/s for EQ2. The time histories of the computed ground surface acceleration show good agreement with the experimental data in both cases. The Fourier spectra of the computed ground surface accelerations also show good agreement with the experimental results for EQ1 and EQ2, as presented in Fig. 12. The assumed V_S=100 m/s for EQ1 corresponds the average shear velocity from the ground surface to GL-2 m for EQ1, while that for EQ2, V_S=50 m/s, is smaller than that of the top thick layer for EQ2. Based on the facts presented above, the SR-model analyses are reasonably capable of simulating the recorded response of the superstructure. However, the suitable shear wave velocity of the soil is much smaller than that of the free field estimated by SHAKE for the strong shaking, which suggests that the shear wave velocity of the soil beneath the footing might be smaller than that of the free field soil.

NONLINEAR SOIL-STRUCTURE INTERACTION

Footing base friction

The time histories of the observed ground surface, footing base displacement, and friction force between the footing base and the soil model are shown in Figs. 13 and 14 to show the soil and footing interaction. The base friction is evaluated

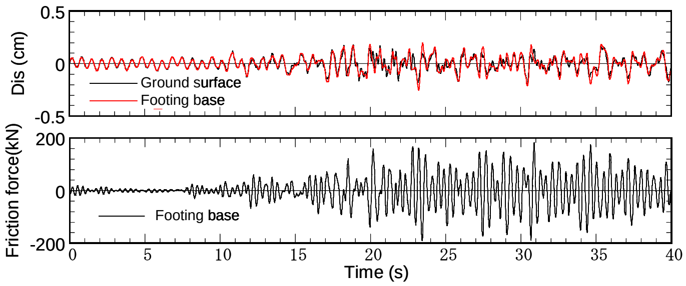


Fig. 13. Time histories of observed ground surface and footing base displacement, and friction force at footing base for EQ1.

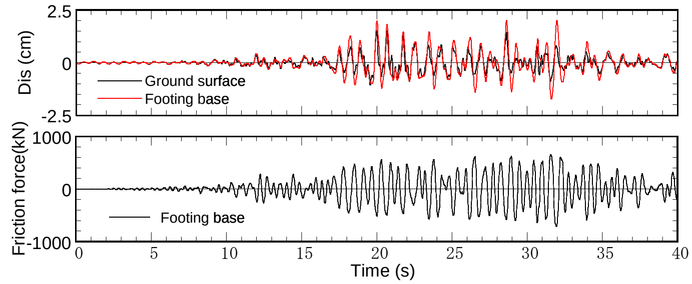


Fig. 14. Time histories of observed ground surface and footing base displacement, and friction force at footing base for EQ2.

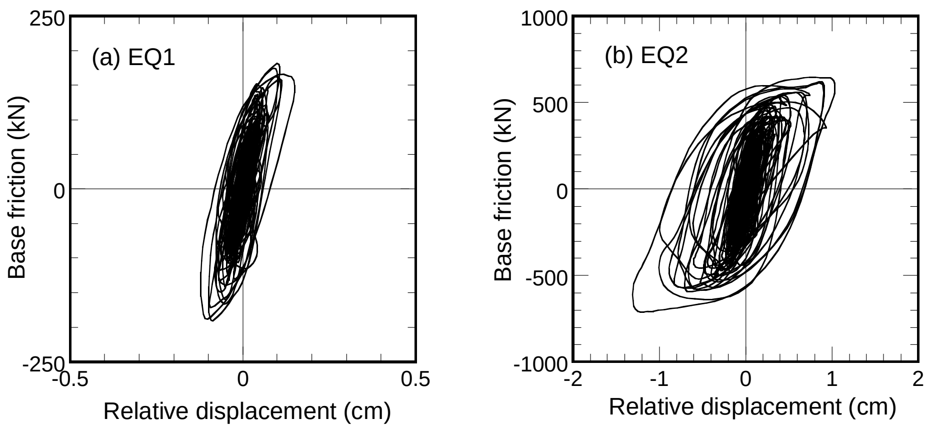


Fig. 15. Relation between relative displacement and base friction (observed).

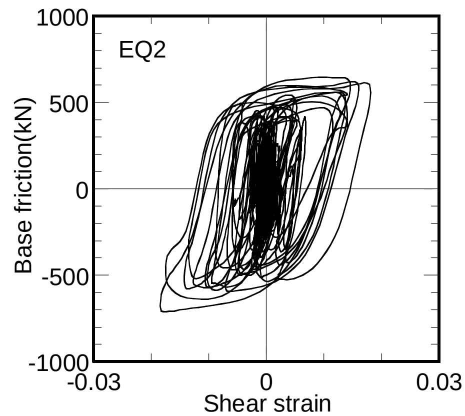


Fig. 16. Relation between soil shear strain beneath footing and base friction (observed).

by the load cells. The respective displacements were calculated according to the double integration of the accelerometer recordings. The footing displacement amplitudes tend to be slightly larger than the ground surface displacement for EQ1. The maximum friction force is about 200 kN. The footing displacement amplitudes tend to be larger than the ground surface displacement for EQ2. The maximum friction force is about 700 kN.

Figure 15 presents the base friction force and the relative displacement between the footing base and the ground surface. The footing did not slide for either case, considering that the base friction tends to increase concomitantly with increasing relative displacement. The friction-displacement loop is elliptical for EQ1, indicating that the soil-structure interaction can be simulated using viscoelasticity theory. The friction-displacement loop, in contrast, shows strong nonlinear behavior in which the relative displacement increases dramatically along with increasing base friction of more than 500 kN for EQ2.

Shear strain of soil beneath the footing

To investigate the nonlinear soil-structure interaction for EQ2, the shear strain of the soil beneath the footing, γ is evaluated as

$$\gamma = (D_1 - D_2) / \Delta H, \qquad (3)$$

in which D_1 signifies the ground surface displacement beneath the footing, D_2 stands for the soil displacement beneath the footing at GL-0.4 m, and ΔH denotes the distance of the two points (=0.4 m). Actually, D_1 is assumed as equal to the footing base displacement because the footing did not slide. The displacements were calculated using double integration of the miniature corresponding accelerometer recordings. Figure 16 depicts the relation between the shear strain and the base friction force for EQ2. The shear strain is greater than 1.5%, which is much larger than the shear strain of the free field evaluated by SHAKE, as presented in Fig. 8(b). In addition, the friction-shear strain loop shows significant nonlinearity. The findings described above indicate that the nonlinearity of soil-structure interaction might depend mainly on the shear deformation of the thin layer beneath the footing and that the shear wave velocity that can simulate the superstructure response by the SR-model might be much smaller than that of the free field subjected to strong shaking.

CONCLUSION

Dynamic centrifuge tests were performed on a superstructure-footing model that was placed on the dry sand surface and subjected to two different input motions having peak accelerations of 60 cm/s^2 and 249 cm/s^2. Two simple dynamic analyses, equivalent linear analysis (SHAKE) and dynamic response of a structure using a sway-rocking model (SR-model) were then performed. The following conclusions were drawn.

(1) SHAKE and SR-model analyses can simulate the recorded response of the soil and superstructure. However, the shear wave velocity of the ground that can simulate the superstructure response by SR-model for a_{max}=249 cm/s^2 is much smaller than that of the free field estimated using SHAKE.
(2) The observed relation of the base friction force with the relative displacement between the footing base and the ground surface shows strong nonlinearity when a_{max}=249 cm/s^2, which probably results from the large shear deformation of the thin layer beneath the footing.

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