Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Sway-rocking model for simulating nonlinear response of sandy deposit with structure

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ABSTRACT: The shaking table test of dense sand−structure system is conducted to investigate the nonlinear interaction under high intensive ground motion. The relationships of $G-\gamma$ and $h-\gamma$ under the condition of shear strain in the 10^{-3} can be obtained accurately by an inversion analysis for the test results. Using these relationships of $G-\gamma$ and $h-\gamma$, the equivalent linear analysis with a sway−rocking model can well represent the measured response of the sand−structure system.

1. INTRODUCTION

Although the two or three dimensional nonlinear analyses (Vaughan 1983, Finn 1985, Lacy 1987, Ohtsuki 1992, Fukutake 1990, 1991) are considered to be an effective tool to assess the nonlinear response of the ground including a structure, simplified methods such as the equivalent linear analysis with a sway−rocking model should be applied to examine the seismic resistance of structures against nonlinear ground motions from the design viewpoint. However, there have been a few studies in which their effectiveness for evaluating the nonlinear response of the soil−structure system has been confirmed by comparing numerical results with observed results. This is due to the luck of sufficient measured data for nonlinear soil−structure systems.

In the present paper, a series of shaking table tests is conducted for investigating the nonlinear response of a dense sandy deposit, on which a one−story structure stands. The verification of the sway−rocking model is discussed through the comparisons of the experimental data under the condition of shear strain in the 10^{-3}.

2. SHAKING TABLE TEST

The model ground is made of the dry Toyoura sand with a relative density of approximately 98 percent. As shown in Fig.1, the model ground has a depth of 98cm, a length of 200cm and a width of 150cm. The ground container is made from a stack of 18 aluminum rectangular rings, each ring being 5cm high and 3cm wide. Ball bearings are installed between the aluminum rings to reduce the shear friction. To suppress the vibration component of the container normal to the shaking direction and to satisfy one−directional shaking, side rollers are attached to the lateral wall of the container parallel to the shaking direction. In addition, guard rollers are installed on the top of the container to reduce its rocking mode.

The one−story structure is made of steel columns, plates, and a viscous damper using asphalt. Two models having different natural frequencies are considered. The first model, called structure−A, has a natural frequency of 33.6Hz and a damping factor of 4 percent. The natural frequency is measured under the condition that the basement of the structure is fixed on the shaking table. The other model, called structure−B, has a natural frequency of 15.1Hz and a damping factor of 4 percent. Both structures are embedded in 2cm below the surface.

The accelerations at different locations in the ground and the structure are measured by accelerometers (A−G1~A−G8). Displacement transducers (D−1~D−5) are attached to the lateral wall of the container to measure the horizontal displacement of the ground.

The sinusoidal waves and the EW component of the TAFT record in 1952 were considered as input motions. The time scale of the TAFT record was reduced to 1/4 times that of the real record by considering the similitude.

The experiments were conducted for three different models of the soil−structure system as shown in Table 1. In the T−1 case, the sinusoidal waves ranging from 10 to 100Gal were applied to study the dynamic characteristics of the dry sandy deposit, and the relationships of the shear modulus and the damping factor vs the shear strain. In the T−2 and T−3 cases, structure−A

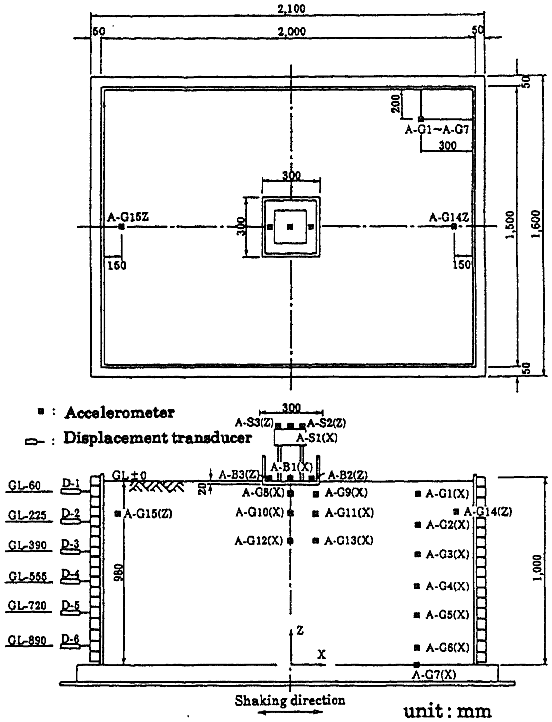
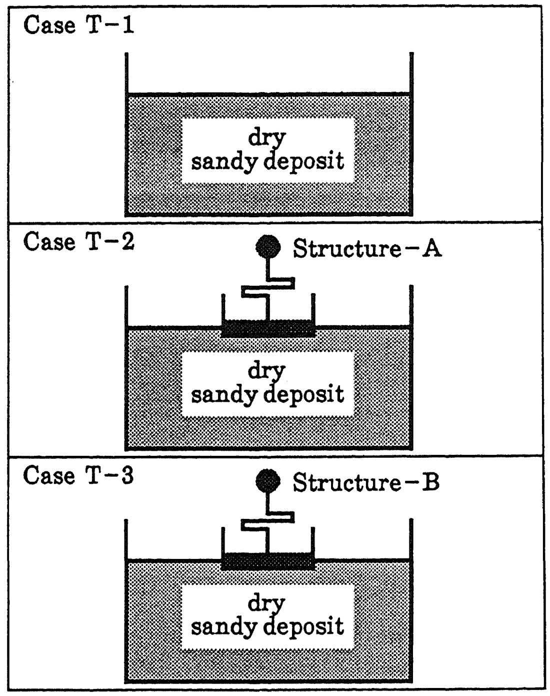


Figure 1. Experimental model

Table 1. Experimental cases



and B standing on the dry sandy deposit were considered to examine the characteristics of the soil-structure system under the nonlinear ground motion.

3. FUNDAMENTAL CHARACTERISTICS OF DRY SANDY DEPOSIT AND STRUCTURE

The mean unit weight of the Toyoura sand is $1.62tf/m^3$. The shear velocities, measured by the plank hammering test, at the upper part and the bottom part of the ground are approximately $104m/s^2$ and $155m/s^2$, respectively. The predominant frequency due to microtremor for the dry sandy deposit is about 30Hz. The predominant frequencies obtained from the transfer functions between the surface of the ground and the top of structure-A or B are 21.6Hz and 13.5Hz, respectively.

As shown in Figs.2 and 3, the nonlinear characteristics of the dry sandy deposit appears in the response of ground and the soil-structure system(Case T-2 and 3) due to the sinusoidal waves ranging from 10 to 100Gal. It is found from Figs.2(a) and 3(a) that the predominant frequency of the dry sandy deposit shifts to lower frequency range accompanying with increase of the amplitude of input motion. The sharp peak, which corresponds to the predominant frequency of 27Hz for the input motion of 10Gal, is converted to gently sloping peak under the incident wave of 100Gal. For the transfer function between the basement of the ground and the top of structure-A, as shown in Fig.2(b), the predominant frequency of structure-A shifts to lower frequency range and its amplitude becomes smaller as the amplitude of input motion increases. The predominant frequency becomes close to that of the ground, approximately 20Hz, when the input motion increases to 50 or 100Gal. On the other hand, the predominant frequencies of ground and structure-B differ significantly,as illustrated in Fig.3(b). Two peak values appear separately in the transfer functions for sinusoidal waves of 50 and 100Gal, and they shift to lower frequencies and their amplitudes become smaller.

Table 2. Ratios of sway, rocking and shear components

Amplitude of sinusoidal wave (Gal)	Structure-A			Structure-B		
	Sway (%)	Rock-ing(%)	Sheer (%)	Sway (%)	Rock-ing(%)	Sheer (%)
10	14	60	26	7	23	70
50	18	65	17	9	34	57
100	20	70	10	13	42	45

The ratios of sway, rocking, and shear components to the total movement at the top of the structure are calculated from the observed

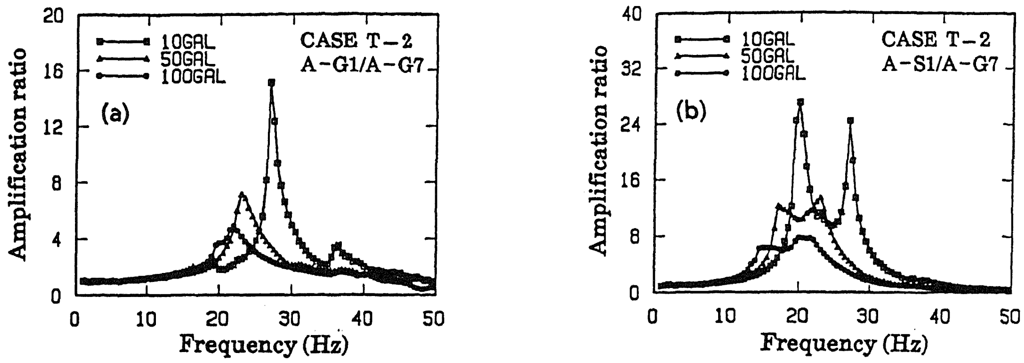


Figure 2. Transfer function for soil−structure A system due to sinusoidal waves

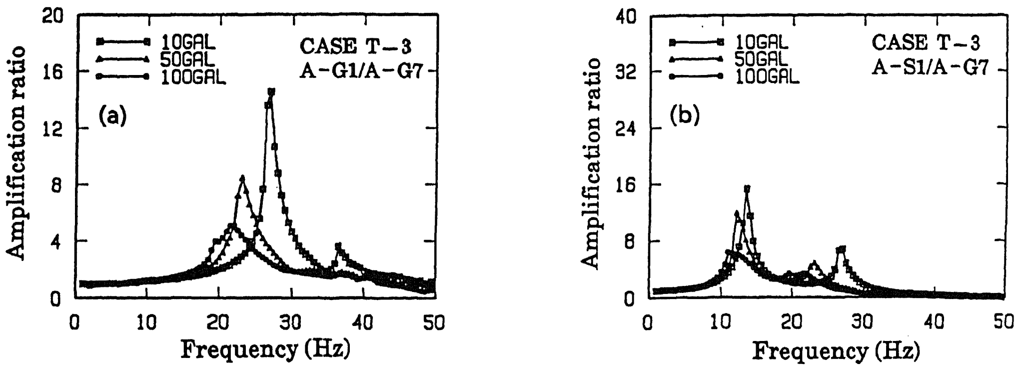


Figure 3. Transfer function for soil−structure B system due to sinusoidal waves

responses of the structures for the sinusoidal waves ranging from 10 to 100Gal. As shown in Table 2, the rocking mode is predominant in the response of structure−A compared with structure−B.

4. RELATIONSHIPS OF G−γ AND h−γ FOR GROUND MODEL

Since the relative density of the dry sandy deposit is about 98 percent, the present shaking table test can reproduce the same nonlinear response of the ground due to the same amplitude of the input motion. Thus, the relationships of G−γ and h−γ are obtained directly from the resonance curve of the dry sandy deposit for the sinusoidal waves by the inverse analysis (Matuda 1986). The ground is modeled by the multi−degree of freedom system featuring shear springs and lumped masses. As a result, the shear modulus and the damping factor for each layer are obtained from the calculated complex stiffness for the above model. For instance, the values of the shear modulus and the damping factor for the layer between A−G3 and A−G4 are shown by circular plots in Fig.4, together with the solid lines indicated as the mean curves for the relationships of G−γ and h−γ. Those lines are determined to represent the nonlinear relationships of G−γ well under the condition of the shear strain ranging from 10^{-5} to 10^{-3}. An initial shear modulus, G_0, an initial reference shear strain, $\gamma_{0.5}$ and a maximum damping factor, h_{max} are read off from the curves of G−γ and h−γ.

5. SIMULATION OF GROUND MOTION

The equivalent linear analysis is carried out by SHAKE with the reduction coefficient of 0.5 for obtaining the effective strain to assess the equivalent shear modulus and damping. Since the relationships of G−γ and h−γ are estimated accurately by the inverse analysis applied to the resonance curves of the sandy deposit, the amplitude and the phase of those time histories obtained from the equivalent linear analysis agree quite well with those from the experiment as shown in Fig.5. It is found from Fig.6 that the computed Fourier spectra ratio also agrees well with the observed one.

The applicability of the equivalent linear analysis can be recognized to be effective for simulating the nonlinear response of the ground under the condition of the shear strain ranging from 10^{-4} to 10^{-3}.

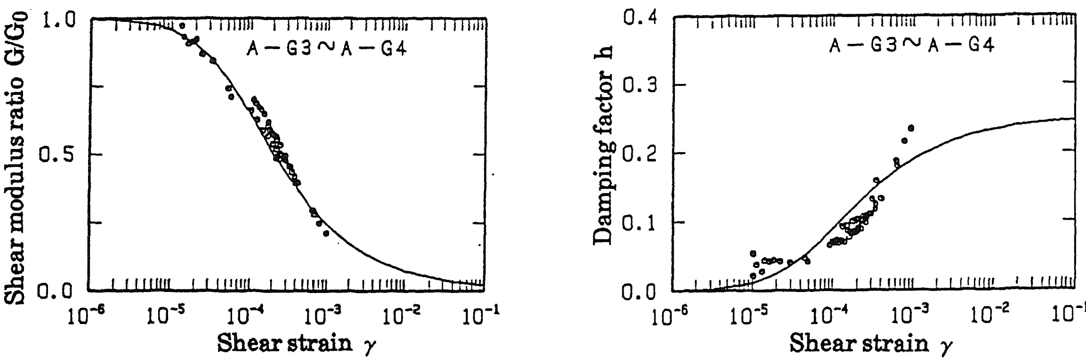


Figure 4. Relationship of $G\sim\gamma$ and $h\sim\gamma$ for layer between (A−G3) and (A−G4)

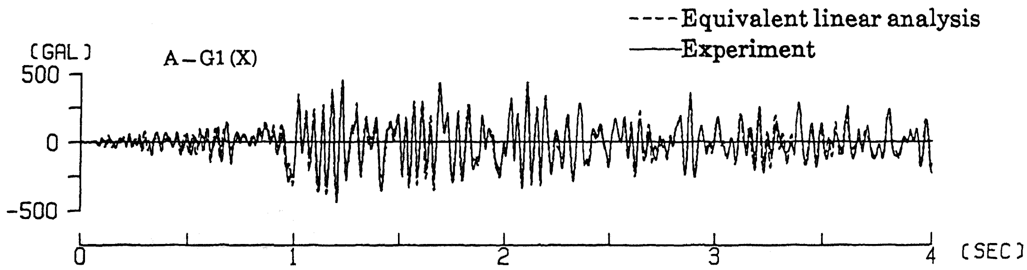


Figure 5. Computed and measured accelerations

6. EQUIVALENT LINEAR ANALYSIS WITH SWAY−ROCKING MODEL

The effectiveness of the simplified method is discussed with the comparison of the experimental data. The interaction between the soil and the structure is represented by sway−rocking springs and dashpots based on the equivalent shear modulus and the equivalent damping factor which are obtained from the equivalent linear analysis for the ground. The values of springs and dashpots are calculated from the following procedure.

(I) The equivalent shear modulus Geq and the equivalent damping factor heq for each layer and the input motion for the structural model are obtained by SHAKE.

(II) The mean shear velocities V_S, used for assessing the stiffness of sway and rocking springs, are obtained by averaging the values of the equivalent shear modulus G_{eq} for each layer.

(III) The value of the stiffness for the sway spring K_S is calculated from the equation (Yamahara 1965):

$$K_S=\frac{8b\rho V_S^2}{2-\nu}A_X \tag{1}$$

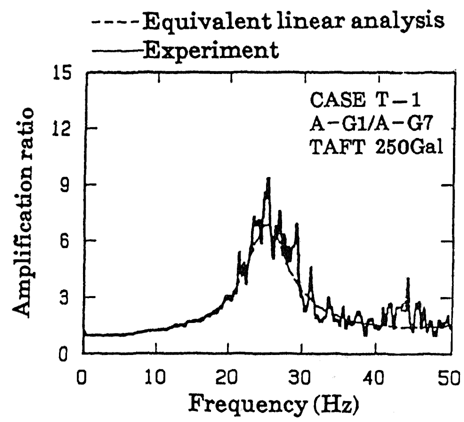


Figure 6. Computed and measured Fourier spectra ratios

where

$$A_X=\frac{2}{\Pi}\left\{\log\tan\left(\frac{\Pi}{4}+\frac{1}{2}\tan^{-1}\frac{c}{b}\right)+\frac{c}{b}\log\tan\left(\frac{\Pi}{4}+\frac{1}{2}\tan^{-1}\frac{b}{c}\right)\right\} \tag{2}$$

The value of the stiffness for the rocking spring K_R is calculated from a following equation:

$$K_R=\frac{8b^3\rho V_S^2}{3(1-\nu)}A_\Phi \qquad (3)$$

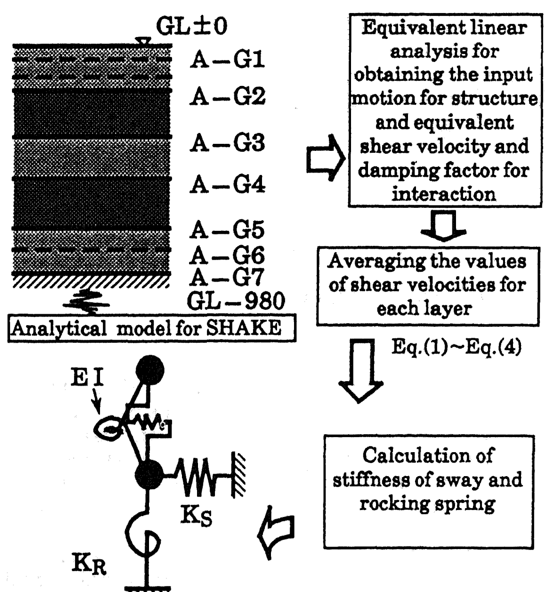
where

$$A_\Phi=\frac{4}{\Pi}\left\{\log\tan\left(\frac{\Pi}{4}+\frac{1}{2}\tan^{-1}\frac{c}{b}\right)+\right.$$

$$\left.\left(\frac{c}{b}\right)^3\left\{\frac{b}{2c}\sqrt{1+\left(\frac{c}{b}\right)^2}-\frac{1}{2}\log\tan\left(\frac{\Pi}{4}+\frac{1}{2}\tan^{-1}\frac{b}{c}\right)\right\}\right\} \qquad (4)$$

Here, 2b and 2c denote a length and a width of a rigid rectangular foundation; ρ is a unit weight of soil; ν and V_S correspond to a Poisson's ratio and a shear velocity of a half space. Equations (1) and (3) are often used in Japan for obtaining the values of interaction springs in seismic design. The sway spring K_S of 5t/cm and the rocking spring K_R of 1475 t cm/rad are used in earthquake response analyses for the TAFT record of 250Gal.

(Ⅳ) The dashpot for the sway and rocking springs is considered to be internal damping. The value of the damping factor for 250Gal is 11 percent, which is equal to the value of heq for the first layer obtained from the equivalent linear analysis.



Amplitude of input motion	K_s (t/cm)	h_s (%)	K_R (t·cm/rad)	h_R (%)
250 Gal	5.035	11.08	1475	11.08

Fig.7 Modeling of sway−rocking model

The modeling of sway−rocking model is shown in Fig.7.

7. SIMULATION OF RESPONSE OF STRUCTURES

The computed and observed Fourier spectra ratio between the basement(A−G7) and the top of structure−A(A−S1) is shown in Fig.8(a). The figure confirms that the amplification ratio and the predominant frequency of the structure are represented well by the sway−rocking model.

The computed and observed accelerations at the top of the structure are illustrated in Fig.9(a). It is noticed that although both results agree well, the acceleration obtained from the sway−rocking model is larger than that of the observation after one second, and the phase of the computed acceleration differs slightly from that of the experiment around the main shock.

The computed and observed Fourier spectra ratio between the basement(A−G7) and the top of structure−B(A−S1) is also shown in Fig.8(b). The figure confirms that the computed Fourier spectra ratio agrees well with the observed one. The amplification and the predominant frequency of structure−B are simulated reasonably by the sway−rocking model as well as the two dimensional nonlinear analysis.

The computed and observed accelerations at the top of the structure are illustrated in Fig.9(b). The computed acceleration is clearly seen to agree well with the observed one.

These simulations demonstrate that the equivalent linear analysis with the sway−rocking model can well represent the nonlinear response of the ground including the structure under a shear strain of 10^{-3} in the ground.

8. CONCLUSION

The verification of the the equivalent linear analysis with the sway−rocking is discussed through the comparisons of the experimental data for the structure standing on the dry sandy deposit. Since the relationships of $G-\gamma$ and $h-\gamma$ under the condition of the shear strain ranging from 10^{-5} to 10^{-3} can be obtained accurately by an inversion analysis for the resonance curve of the sandy deposit, the the sway−rocking model can represent well the observed nonlinear response of the sand−structure system. However, further study is needed to confirm the effectiveness of the sway−rocking model for real problems through comparison of the analysis and observation results.

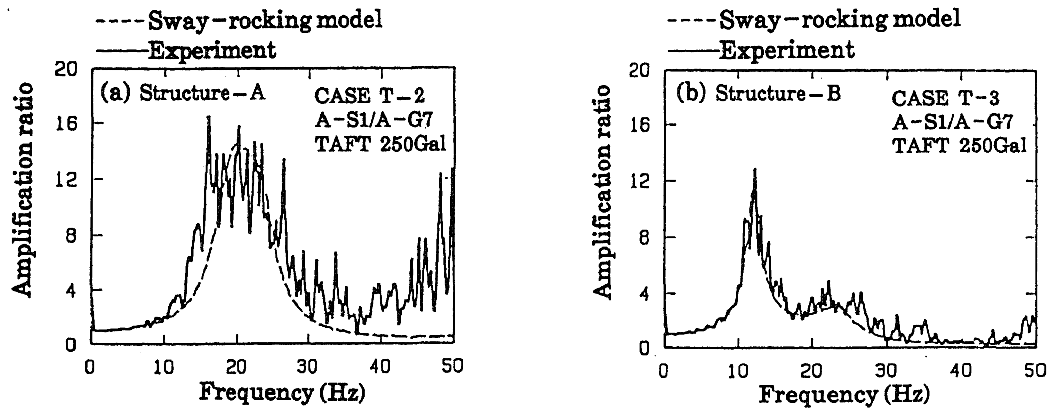
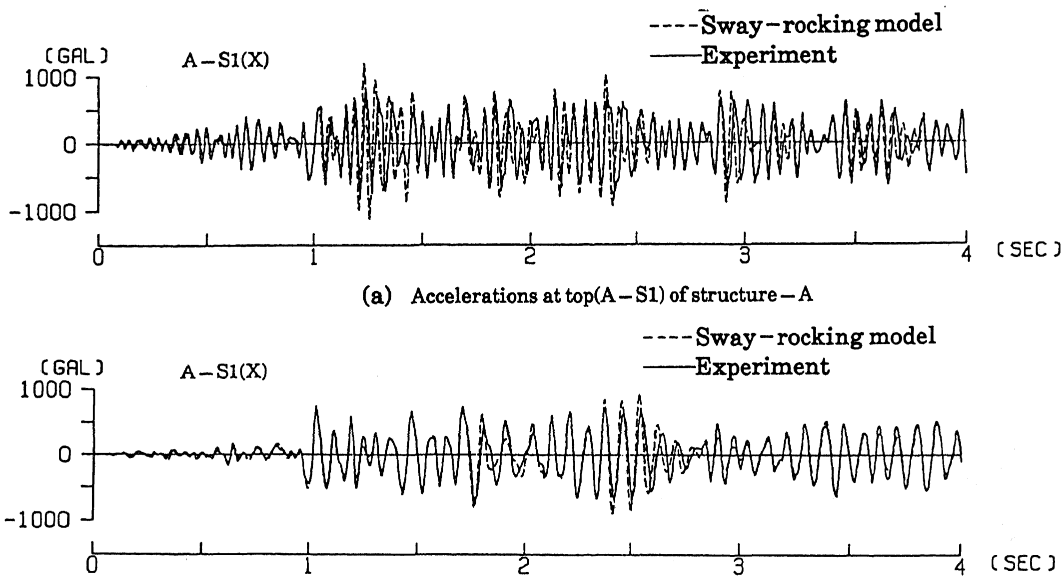


Figure 8. Computed and measured Fourier spectra ratios



(a) Accelerations at top(A-S1) of structure-A

(b) Accelerations at top(A-S1) of structure-B

Figure 9. Computed and measured accelerations

9. ACKNOWLEDGEMENT

The authors are indebted to Mr. Isao Tanabe, Mr. Masanori Hirota of Tokyo Electric Power Company for their valuable suggestions. They also thank Masayoshi Sato and Yasuhiro Shamoto of Shimizu Corporation for their corporation in conducting the shaking table test.

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