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SHAKING TABLE TESTS OF ELASTO-PLASTIC SOIL-PILE-BUILDING INTERACTION SYSTEM

Shinichiro TAMORI[1] and Yosikazu KITAGAWA[2]

[1]Department of Architecture, Shinshu University,
Nagano-shi, Nagano, Japan
[2]Building Research Institute, Ministry of Construction,
Tsukuba-shi, Ibaragi, Japan

SUMMARY

Previously, We had made a series of shaking table tests in order to study the effects of plastic deformation of soil on natural frequency, magnification ratio and energy absorption in swaying, rocking and building of soil-building interaction system without piles. This time, we conducted a series of shaking table tests of soil-building interaction system with piles. Results of two series of the tests were compared to evaluate the difference of the effects of a mat and a piled foundation models. Relative amount of energy absorbed in the building having a piled foundation was not decreased by plastic deformation of the soil beneath the building foundation so much as in the buildings having a mat foundation, because the piles prevented rocking motion of the foundation in case of piled foundation models.

INTRODUCTION

Many experimental studies have been conducted in order to evaluate the effects of plastic deformation of soils in the soil-foundation or soil-rigid structure interaction system (Refs. 1,2 etc.). These experiments were conducted with the structure resting on the ground under the harmonic loading on the shaking table or impulse loading. Experiments of soil-pile system or embedded rigid structure have been done also (Refs. 3,4 etc.). They were conducted with the structures embedded in the sand ground under the harmonic loading on the shaking table or by an actuator. Experimental studies for soil-building interaction system with artificial plastic soil material were very limited (Refs. 5, 6).

In order to estimate the effects of plastic deformation of ground soils on the natural frequency, response magnification factor and energy absorption of the system, the shaking table tests were carried out by 1/30 scaled soil-pile-foundation-building models using artificial plastic soil materials. The rigidity and damping factor of the material can be changed by adjusting the amount of oil contained in it.

PLASTIC MATERIAL FOR GROUND MODEL

The artificial plastic material for the ground model was made of PLASTICINE and oil. PLASTICINE, being a mixture of calcium-carbonate and oil, has been used as model materials for plastic deformation processing of steel, because it has similar restoring force curves as high-temperature steel.

Fig. 1 shows strain-shear modulus and strain-damping factor relationships of the soil material used in the present tests and the real cohesive soils (Ref. 7). The initial shear modulus , Gt (strain being 1.0 x10^{-5}), the shear modulus at large strain levels, Gs, and damping factor, hg, were obtained by tri-axial compression tests and hollow cylinder torsional shear tests, in which ambient stresses were kept to be 0.5 and 1.0 kg/cm2. Shear modulus of the soil material had similar strain dependency as the cohesive soils. The damping factors which were obtained by the compression tests for the soil material were 2 or 4 times lager than those obtained for the cohesive soils, but their strain dependency were similar as those obtained for the cohesive soils. The damping factors which were obtained by the torsional shear tests for the plastic soil material were close to those for the cohesive soils when strain levels were larger than 1.0x10^{-4} , but they were larger than those for the cohesive soils at the strain levels being less than 1.0x10^{-4}. Shear modulus ratio, Gs/Gt and the damping factor of the plastic soil material did not fluctuate very much for different ambient stresses.

Fig. 2 shows the strain-shear modulus and the strain-damping factor relationships of the soil material, used in the previous shaking table tests done by the authors (Ref. 6), which were also made of PLASTICINE and oil. In this case, the shear modulus and damping factor of the soil material has similar strain dependency as the cohesive soil. The difference of damping factors of the soil material used in the two series of the shaking table tests was made by the amount of oil contained in the soil material. As the amount of oil increased, the larger values takes the damping factor. Also, the initial shear wave velocity can be changed from 20 to 60 m/s by adjusting the amount of oil.

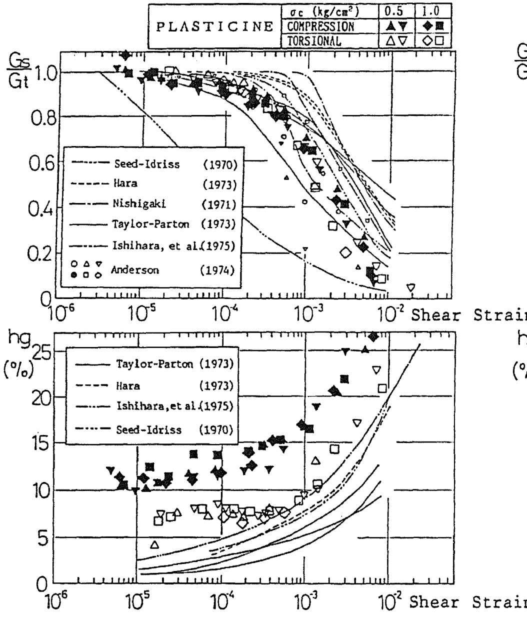

Fig.1 Shear Modulus and Damping Factor (for a Piled Foundation Models)

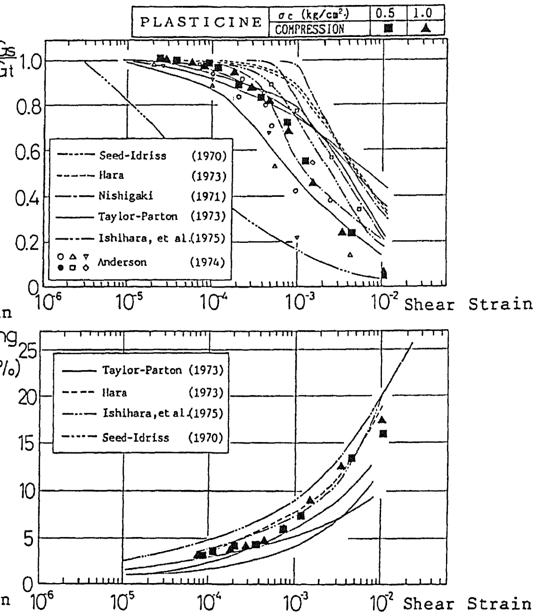

Fig. 2 Shear Modulus and Damping Factor (for a Mat Foundation Models)

OUTLINE OF SHAKING TABLE TESTS

Similarity The similarity of Buckingham was used in modeling the building and the ground soils. The scale factors calculated from this theory are summarized in Table 1. This similarity is

Table 1 Scale Factors

ITEM	RATIO(MODEL/PROTOTYPE)	
DENSITY	$1/\eta$	1/0.88*
LENGTH	$1/\lambda$	1/30
ACCELERATION	1	1
DISPLACEMENT	$1/\lambda$	1/30
MASS	$1/\eta\lambda^3$	$1/(2.38\text{x}10^4)$
SHEAR MODULUS	$1/\eta\lambda$	1/26.5
FREQUENCY	$\sqrt{\lambda}$	$\sqrt{30}$
VELOCITY	$1/\sqrt{\lambda}$	$1/\sqrt{30}$
STRESS	$1/\eta\lambda$	1/26.5
STRAIN	1	1

*Soil density of prototype is 1.5 g/cm³

applicable to non-linear soil dynamics when the soil model material has a similar shear modulus-strain and a damping factor-strain relations to those of the prototype. Under this condition, the ratio of shear forces in the model and the prototype was kept approximately equal to that of damping forces for wide strain levels (Ref. 8).

Building and Ground Model and Measurement Apparatus Fig. 3 shows a outline of the building and the ground models together with measurement apparatus. One dwelling unit of the 11, 14 and 24-story buildings in the transverse direction were modeled into a single-degree-of-freedom system. Their fixed-base natural frequencies are 2.2, 1.3 and 0.6 Hz, respectively. The top mass and foundation were made of steel weight and steel box, and building columns were made of steel plates, on which rubber plates were attached in order to produce the damping effects of the building. Piles were made of steel plates being hinged at the both ends. The building model with a mat foundation had the same superstructure as the model with a piled foundation. Table 2 shows the natural frequency and damping factor of the building models. The fixed-base natural frequency, fb, for model 1 was higher than the predominant natural frequency of the ground model, fg. it was close to fg for model 5 and lower than fg for model 6.

Water-saturated urethane form was set around the cylinder-shaped ground model in order to absorb the propagating wave from the building foundation (Fig. 3). Central part of the upper layer of the ground model was made from PLASTICINE and oil. The other part of the model were composed of polyacrylamide and bentnite, which remained elastic throughout the tests. Table 3 shows the shear wave velocities and density of each part of the ground model. The shear wave velocities were obtained from the free torsional vibration tests.

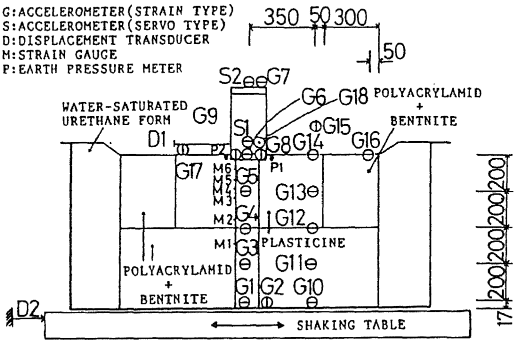

Fig. 3 Tests Model

The measurement apparatus consisted of 20 accelerometers (9 buried in the ground, 4 on the surface and 7 in the building), 2 displacement transducers for measuring the displacement of the shaking table and one between the foundation of building model and the shaking table, and 6 strain gauges on the pile.

Table 2 Dynamic Characteristics of Building Models

SPECIMEN	RELATION BETWEEN fb AND fg	FOUNDATION		BUILDING		CHARACTERISTICS OF FIXED-BASE BUILDING	
		SIZE (cm)	WEIGHT (kg)	HIGHT (cm)	WEIGHT (kg)	FREQ. (Hz)	DAMPING (%)
model 1	f b>f g	27.0	6.9	32.1	12.2	11.62	0.91
model 5	f b≒f g	X		35.4	12.0	6.65	0.99
model 6	f b<f g	17.3		44.4	19.7	3.58	1.29

fb:Fixed-base Natural Freq. of Building   fg:Predominant Freq. of Ground (7.32 Hz)

Table 3 Ground Model

ITEM	UPPER LAYER		LOWER LAYER
	CENTER	EDGE	
Vs	21.8*	14.9	25.3
h	9.90*	4.46	4.81
ρ	1.71	1.07	1.34

Vs: S-wave Velocity (m/s)
h : Damping Factor (%)
ρ: Density (g/cm^3)
* Shear Strain $\gamma = 5.0 \times 10^{-4}$

Table 4 Tests Program

SPECIMEN	INPUT WAVE	MAX. ACC.(gal)
0 : GROUND 1 : MODEL 1 5 : MODEL 5 6 : MODEL 6	H : HACHINOHE EW 1968 M : MURORAN EW 1968 (OFF TOKACHI EARTHQ.) P : PACOIMA DAM S74W 1971 E : EL CENTRO NS 1940 S : SWEEP	S : 100 L : 400 L L : 800

TEST NUMBER :
E 1 H S 1: Model 1, HACHINOHE EW, where the max. acc. is 100 gal.
SPECIMEN
INPUT WAVE
MAX. ACC.

Tests Program The tests program is shown in Table 4. Four earthquake records, in which the time length was corrected according to the similarity, were used for the input ground motions : Hachinohe EW , Muroran EW (1968 Off Tokachi Earthquake), Pacoima Dam S74W (1971 San Fernando Earthquake) and El Centro NS (1940 Imperial Valley Earthquake) together with the sweep wave. The sweep wave contained the frequency components between 0 and 30 Hz and has the length of 30 sec. The maximum accelerations of input wave were set 100, 400 and 800 gal on the shaking table.

TESTS RESULTS

Natural Frequency of Interaction System Figs. 4, 5, and 6 show the natural frequency ratios (f_{ip}/f_{ie}), where f_{ip} stands for the natural frequency of soil-building systems in the shaking table tests and f_{ie} for the natural frequency obtained from the free vibration tests, for the different maximum accelerations measured on the ground surface (G14 in Fig. 3). Since the maximum acceleration at the top of the building model in the free vibration tests was so small as 50 gal., f_{ie} can be considered to be the natural frequency of soil-building system within elastic range.

As shown in Figs. 4, 5 and 6, the natural frequency, f_{ip}, was decreased 16% for the model 1 at most, and by 10% for the models 5 and 6. The smaller the height-width ratio is, the more the natural frequency decreases. The same quantities for the building with a mat foundation are shown in Figs. 5 and 6. The decrease in the natural frequencies for the building with a mat foundation were 4 to 6 times larger than that for the building with a piled foundation.

Acceleration Response Magnification Ratio Figs. 7, 8 and 9 show the acceleration response magnification ratios (G7/G14), where G7 stands for the maximum acceleration at the top of the building model and G14 for the ground surface. The magnification ratios for the models 1, 5 and 6 were decreased by 35%, 57% and 35%. Figs. 8 and 9 shows the same quantities for the models with a mat foundation. The rate of the decreasing magnification factors for the buildings with a piled foundation is 58% to 76% smaller than that obtained for the buildings with a mat foundation. This may due to the facts that the piles prevents rocking motion significantly.

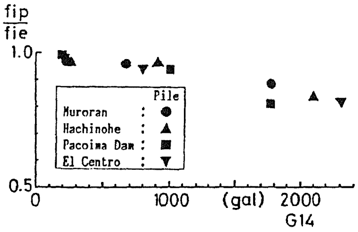

Fig. 4 Natural Frequency Ratios (Model 1)

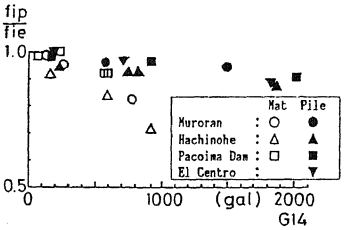

Fig. 5 Natural Frequency Ratios (Model 5)

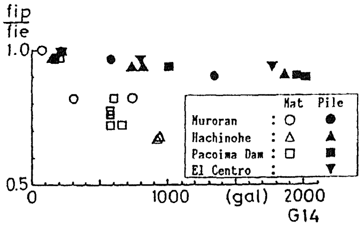

Fig. 6 Natural Frequency Ratios (Model 6)

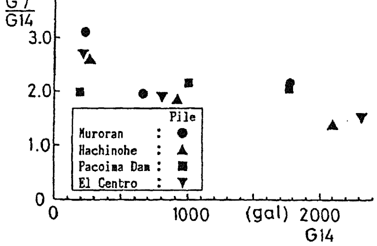

Fig. 7 Magnification Ratios (Model 1)

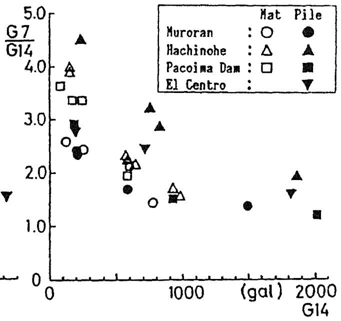

Fig. 8 Magnification Ratios (Model 5)

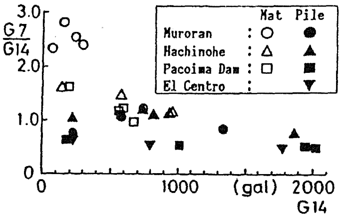

Fig. 9 Magnification Ratios (Model 6)

Energy Response The energy response was defined as the total area of hysteresis loops experienced during the whole excitation. It was calculated for swaying, rocking and deformation of the columns independently. Energy response ratios, being ratios of energy for swaying, rocking and building to the total energy response, are shown in Figs. 10, 11, and 12. The total energy response is the sum of energy responses for swaying, rocking and building deformation. The total energy response increased as the maximum input acceleration increased.

For model 1, the energy response ratio for rocking has been decreased and those for swaying and building deformation increased as the total energy increased. In contrast, the ratios of energy response took almost constant values for model 5, unless the total energy response exceeded 10 kgcm. As the total energy response became larger than 10 kgcm, the ratio for building deformation increased. This fact was caused by 1) the increased damping factor due to large deformation in rubber plates on columns and 2) the large plastic strain energy consumed in the columns. In case of model 6, the energy response ratio for rocking increased and that for building deformation was decreased as the total energy increased, unless the total energy response exceeded 10 kgcm.

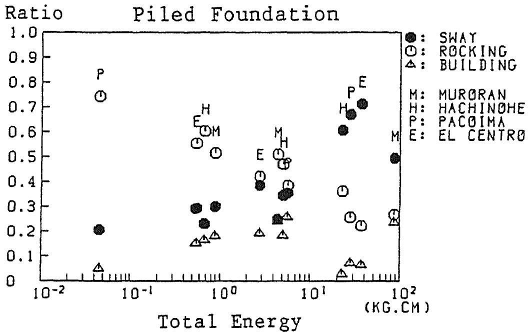

Fig. 10 Energy Response
(Model 1)

Figs. 13 and 14 show the cases for the buildings with a mat foundation, in which the building models were the same as those in the models 5 and 6. The energy ratios of rocking were increased and those of building deformation were decreased as the total energy increased.

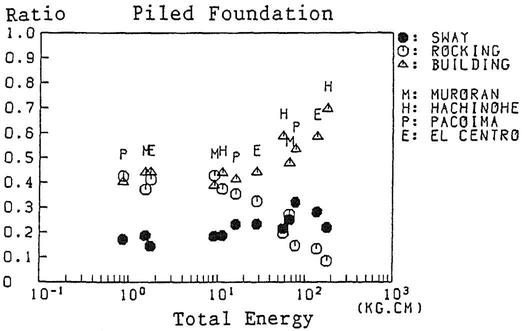

Fig. 11 Energy Response
(Model 5)

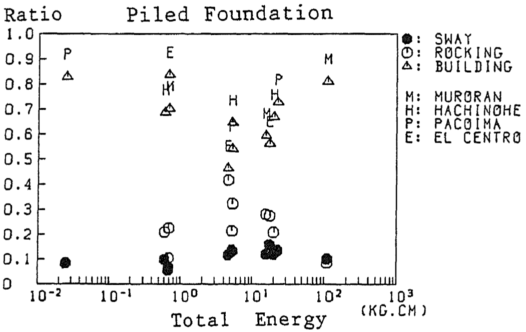

Fig. 12 Energy Response
(Model 6)

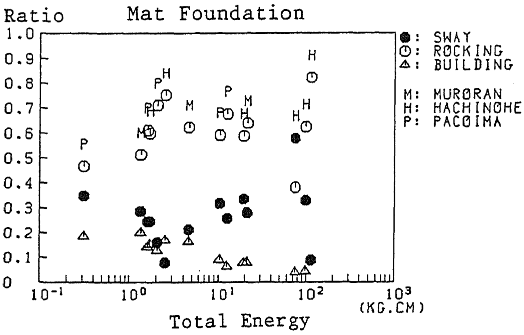

Fig. 13 Energy Response
(Model 5)

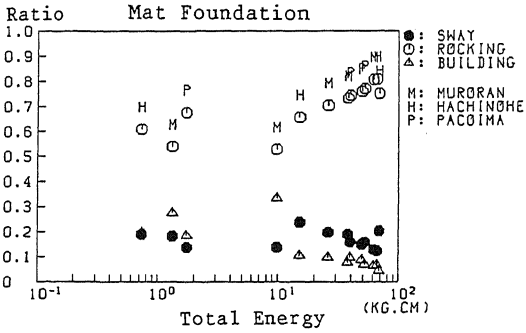

Fig. 14 Energy Response
(Model 6)

We summarized the forgoing discussions as follows: 1) In case of a mat foundation, plastic deformation beneath the foundation caused by rocking motion reduced the energy which should be absorbed in the building otherwise, thus reducing the damages of buildings. 2) In case of of a piled foundation, energy response ratio of building deformation did not decreased as a large plastic deformation of soil took place, because piles prevented rocking of the foundation significantly. But an energy response ratio-total energy response relationships similar as to that for a mat foundation was observed for model 6. This may reflected the fact that the deformation in piles by larger over-turning moment for for model 6 was greater than for the other models.

CONCLUSION

The ratios of energy response for swaying, rocking and building deformation varied with the magnitude of plastic deformation beneath the foundation. In case of a mat foundation, plastic deformation of soils for rocking motion beneath the foundation will reduce the energy which should be consumed in the buildings. In case of a piled foundation, the energy ratio for building deformation did not decrease so much as for the case of a mat foundation, because the piles prevented rocking motions of the foundation.

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REFERENCES

1. Henke, A.M., Richart, F.E. and Woods, R.D., "Nonlinear Torsional Dynamic Response of Footing", Journal of Geo. Eng. of ASCE, 109, 72-88,(1983).
2. Vaughan, D.K. and Iseberg, J., "Non-linear Rocking Response of Model Containment Structure", Earthquake Eng. and Struct. Dynamics, 275-296,(1983).
3. Goto, H., Kitaura, M. and Miyawaki, K., "Experimental Study on The Dynamic Behavior of The Structure Foundation Embedded in Sand Layer", Proc. of Japan Society of Civil Engineering, 219, 15-25,(1973), (in Japanese).
4. Hakuno, M., Yokoyama, K. and Sato, Y., "Real Time Dynamic Test on A Model Pile Foundation", Proc. of Japan Society of Civil Engineering, 200, 85-91,(1972), (in Japanese).
5. Yoshikawa, M. and Abe, I., "Model Vibration Test of Tower-pile Foundation-Soil System," Proc. of the 6th Japan Earthquake Engineering Symposium, 1705-1711,(1982), (in Japanese).
6. Tamori, S., Kitagawa, Y. and Mizuno, H.," Shaking Table Tests of Elasto-Plastic Soil-Building Interaction System", Proceedings of The Pacific Conference of Earthquake Engineering, 3, 95-106,(1987).
7. Ishihara, K., Doshitu Dourikigaku no Kiso, Kajima Inst. Publishing Co., Ltd.,(1978), (in Japanese).
8. Kagawa, T., "On The Similitude in Model Vibration Tests of Earthquakes", Proc. of Japan Society of Civil Engineering, 275, 69-77,(1978), (in Japanese).