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Dynamic response of soil-pile-building interaction system in large strain levels of soil

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ABSTRACT: A series of shaking table tests of scaled soil-pile-building(SPB) models were performed in order to study effects of plastic deformation of soil on dynamic characteristics of the SPB interaction system. Results show that ratios of lateral forces applied to the piles and the inertial force caused by a building were in proportional to the inertial force. Stiffness and damping factors for swaying motion determined using an analytical method were compared with those obtained using the shaking table in order to check the accuracy of the analytical model. Stiffness obtained by analyses agreed well with those obtained by the tests. However, the analytical method overestimates the damping factors of piles and embedment.

1 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 (Henke et. al. (1983), Vaughan et. al. (1983), etc.). These experiments were conducted with the structure resting on the ground either under harmonic loading on the shaking table or under impulse loading. Experiments involving soil-pile system or an embedded rigid structure have also been done (Goto et. al. (1973), Hakuno et. al. (1972)). These experiments were conducted with the structures embedded in the sand ground either under the harmonic loading on the shaking table or by an actuator. Experimental studies that involve soil-pile-building interaction system using plastic material as an artificial soil are very limited (Yoshikawa et. al. (1982)).

In order to estimate the effects of plastic deformation of ground soils on the natural frequency and force applied to piles, the shaking table tests were carried out on 1/30 scale soil-pile-foundation-building models using plastic soil materials. The rigidity and damping factor of the artificial soil can be changed by adjusting the amount of oil contained in the plastic material. In order to check the accuracy of the analytical models, stiffness and damping factor for swaying motion obtained by the shaking table were compared to those determined by the analytical model.

2 PLASTIC MATERIAL FOR GROUND MODEL

The plastic material for the artificial ground model used in this study was made of Plasticine and oil. Plasticine , being a mixture of calcium-carbonate and oil, has been used as a model material for plastic deformation processing of steel, since it has restoring force curves similar to high-temperature steel (Cook (1953)).

Figure 1 shows the soil characteristics, strain-shear modulus and strain-damping

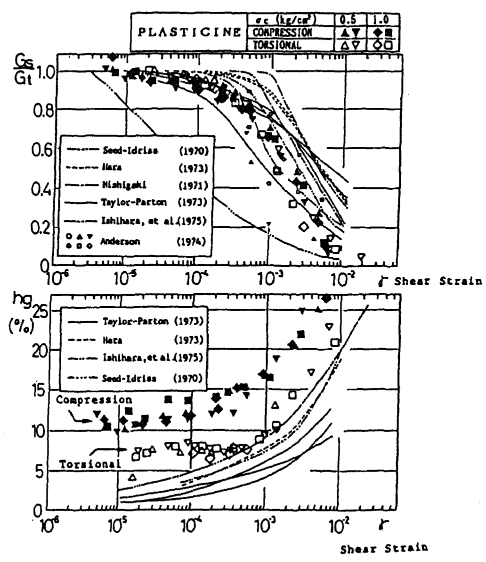

Figure 1. Soil characteristics

factor relationships, for actual cohesive soils and the plastic soil material used in the shaking table tests. The initial shear modulus, G_t (strain being 1.0×10^{-5}), the shear modulus at large strain levels, G_s, and damping factor, h_g, were obtained by tri-axial compression tests and hollow cylinder torsional shear tests, in which ambient stresses were kept at either 0.5 or 1.0 kg/cm^2. Shear modulus of the plastic soil material, Plasticine, had similar strain dependency as actual cohesive soils. The damping factors for Plasticine, obtained by the compression tests, were 2 to 3 times lager than those for the cohesive soils; strain dependency for Plasticine was similar to that obtained for the cohesive soils. The damping factors for Plasticine, obtained by torsional shear tests, were comparable to those for the cohesive soils when strain levels were larger than 1.0×10^{-4}, greater than those for the cohesive soils when the strain levels were less than 1.0×10^{-4}. Shear modulus ratio, G_s/G_t, and the damping factor, h_g, of Plasticine did not fluctuate greatly for different ambient stresses.

3 OUTLINE OF SHAKING TABLE TESTS

3.1 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 applicable to non-linear soil dynamics when the soil model material has a shear modulus-strain and a damping factor-strain relations similar to those of the prototype(Kagawa (1987)). Under these conditions, the ratio of shear forces in the model and the prototype were kept approximately equal to that of the damping forces for wide strain levels .

3.2 Building and ground model and measurement apparatus

Figure 2 shows a outline of the building and the ground models together with the location of the measurement apparatus. Each scale dwelling unit, 11, 14, and 24-story buildings, were modeled by a single-degree-of-freedom system in the transverse direction. Their fixed-base natural frequencies were 2.2, 1.3, and 0.6 Hz, for the 11, 14, and 24-story building, respectively. The top mass and foundation were made of steel weight and steel box, respectively, and the 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 hinged at both ends. Table 2 shows the natural frequency and damping factor of each of the building models. The fixed-base natural frequency, f_b, for model 1 (the 11-story building) was higher than the predominant natural frequency of the ground model, f_g, it was comparable to f_g for model 5 (the 14-story building) and lower than f_g for model 6 (the 24-story building). Model 5B had no embedment, and model 5C had no embedment and also had a gap between base of the foundation and the ground surface. These two models have a same superstructure as model 5 had.

Water-saturated urethane form was set around the cylindrical ground model in order to absorb the propagating wave from the building foundation. The central part of the upper layer of the ground model was made from Plasticine and oil. The remaining portions of the model were composed of polyacrylamide and bentnite, and remained elastic throughout the tests.

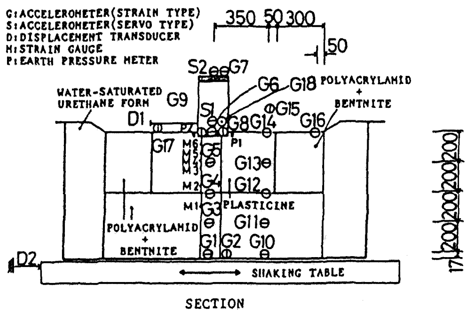

Figure 2. Test model and measurement apparatus

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	$1/\eta\lambda^3$	$1/(2.38 \times 10^4)$
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/cm^3

Table 2. Dynamic characteristics of building models

SPECIMEN	RELATION BETWEEN f_b AND f_g	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 x 17.3	6.9	32.1	12.2	11.62	0.91
model 5 5B 5C	$f_b \fallingdotseq f_g$			35.4	12.0	6.65	0.99
model 6	$f_b < f_g$			44.4	19.7	3.58	1.29

f_b:Fixed-base Natural Freq. of Building f_g:Predominant Freq. of Ground (7.32 Hz)

Table 3 shows the shear wave velocities and density of each part of the ground model. The shear wave velocities were obtained from free torsional vibration tests. The measurement system (see Figure 2) 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 with one of the transducers placed between the foundation of building model and the shaking table, and 6 strain gauges placed on the pile. Two earth-pressure meters were set on walls of the embedment of the foundation.

Table 3. Characteristics of 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/cm³)
* Shear Strain $\gamma = 5.0 \times 10^{-4}$

Table 4. Test strategy

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

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

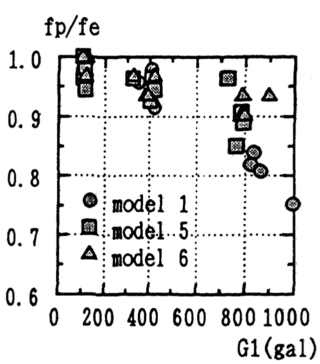

Figure 3. Natural frequency ratios

3.3 Tests strategy

The test strategy is shown in Table 4. Together with the sweep wave, four earthquake records, in which the time length was corrected according to the similarity of Buckingham, 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). The sweep wave contained the frequency components between 0 and 30 Hz with a duration 30 sec. The maximum acceleration of input wave were set at 100, 400 , and 800 gal on the shaking table.

4. TEST RESULTS

4.1 Natural frequency of the interaction system

Figure 3 shows the natural frequency ratios, f_p/f_e, where f_p is the natural frequency of soil-pile-building systems in the shaking table tests and f_e is the natural frequency obtained from the free vibration tests, for the different maximum accelerations measured at the bottom of the model ground (G1 in Figure 2). Since the maximum acceleration at the top of the building model in the free vibration tests was so small (50 gal), f_e was considered to be the natural frequency of soil-building system within the elastic range.

As shown in Figure 3, f_p was decreased by, at most, 20% for model 1, by 15% for model 5, and by 10% for model 6; the smaller the height-width ratio is, the greater the decreases in the natural frequency. This is caused by the fact that the piles prevented rocking motion significantly.

4.2 Lateral force ratios

Prediction of the lateral force applied to piles is quite important for an earthquake resistance design of piles in the case of an embedded foundation with the piles. A prediction method was proposed in an Japanese recommendation (The Building Center of Japan (1989)), but was mainly derived by studies for the case when base shear coefficient of a building was 0.2; the method to estimate the lateral force, when base shear was larger, was not clarified.

The model piles in this study had a hinged head, so that lateral force applied to the pile head was not measured directly. The lateral force was estimated; by first filtering the time history of moments along a pile. Lower and higher frequency of the band-pass filter was $0.9f_p$, and $1.1f_p$, respectively, where f_p is the natural frequency of the interaction system. Next, the lateral force applied to the pile head was estimated by the moment distribution at a certain time along the pile. This method was an application of Chang's theory (1937). By this method, the lateral force caused by the inertial force of the building was mainly evaluated.

Figure 4a shows the lateral force ratio, Q_p/Q_i, where input motion is Hachinohe EW, for models 1,5 and 6. Q_p is the force applied to the pile head, and Q_i is the inertial force caused by the mass of the building and the foundation, when acceleration at top of the building is at a maximum. Results show that the lateral force ratio was proportional to the inertial force. When Q_i was less than 30 kg, the lateral force ratio for models 5 and 6 were 1.5 to 2 times as large as those for model 1.

Figure 4b shows the lateral force ratio, Q_e/Q_i, where Q_e, the earth pressure, is the applied force to the walls of the embedment. It is apparent that this ratio was inversely-proportional to the inertial force, Q_i. The ratios for models 1 and 5 is larger than those for model 6, when Q_i was less than 30 kg. In this range of inertial force, maximum acceleration at the ground surface was ranged from 200 to 1000 gal. Therefore, in a realistic range of acceleration for an actual earthquake, the smaller the height-width ratio, the larger the lateral force ratio of the earth-pressure.

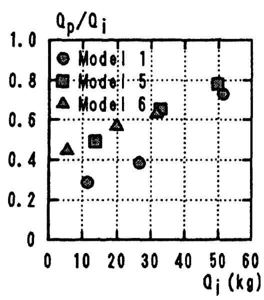

Figure 4a. Lateral force ratios of piles

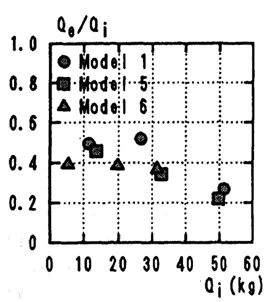

Figure 4b. Lateral force ratios of earth-pressure

5. EQUIVALENT STIFFNESS AND DAMPING FACTOR

5.1 Theoretical model

Dynamic stiffness and damping factor of a embedded foundation, proposed by Novak (1974), and that of a pile, proposed by Novak and Nogami (1977), were employed in this study. Dynamic stiffness of bottom of foundation proposed by Kobori et. al.(1970) was employed also. Applicability of Kobori's method to evaluating the stiffness and damping factor for soil-building interaction system has previously been examined (Tamori et. al. (1987)). In this study, the dynamic stiffness of soil-pile-foundation system was calculated by root sum square of the dynamic stiffness of the piles and that of the embedded foundation.

Equivalent shear modulus, G_s, and damping factor, h_g, of the soil were determined by the torsional shear tests according to the following equation modified by the Hardin-Drnevich model(Hardin and Drnevich (1972)):

$$\frac{G_s}{G_t} = \frac{1}{1 + 1.1(r_s/r_a)^{1.2}} \qquad (1)$$

$$h_g = 0.150(1 - G_s/G_t) + 0.070 \qquad (2)$$

where G_t is the initial shear modulus of the soil, r_s is the shear strain of soil, and r_a is the standard shear strain (1.7×10^{-3}).

The soil strain was estimated from acceleration at the foundation and beneath the foundation: accelerometers G5 and G6, respectively shown in Figure 2. Dynamic stiffness of the embedment and the piles were calculated by determining shear modulus and equivalent damping factor of the soil. The dynamic stiffness has frequency dependence, so that those at the natural frequency of the interaction system, f_p, were employed.

In order to estimate dynamic stiffness and damping factor for the tests, a simple approximation of soil-pile-building system , which had a sway-rocking spring beneath a building foundation, was used. Time history of the force and displacement, represented by a hysteresis loop as shown in Figure 5,

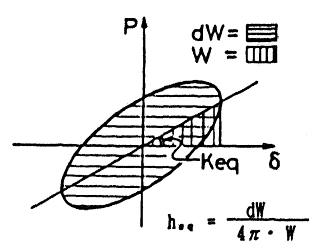

Figure 5. Hysteresis loop

occurring at the swaying spring, were used to calculate the stiffness and damping factor for swaying motion. The band-pass filter, as mentioned previously, was also incorporated in this process.

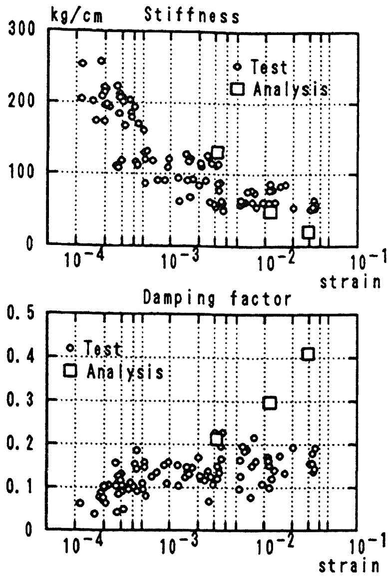

Figure 6. Dynamic stiffness and damping factor(model 5C, Hachinohe EW)

5.2 Results of analyses

Figure 6 shows the stiffness and damping factors of swaying for model 5C. This model had no embedment and also had a gap between base of the foundation and the ground surface, so that horizontal resistance was cased by the piles only. The theoretical stiffness and the experimental stiffness agreed well with each other when soil strain was from 1.0×10^{-3} to 1.0×10^{-2}. However, the damping factor was over estimated by the analyses. The larger the strain of the soil, the larger the difference between the tests values and the theoretical values.

Figure 7 shows the stiffness and damping factors of swaying for model 5B. This model had no embedment, so that horizontal resistance was caused by the base of the foundation and the piles. The stiffness determined by the analyses and those by the tests agreed well with each other. Again the damping factor was overestimated by the analyses when the strain of the soil was larger than 4.0×10^{-3}.

Figure 8 show examples of the stiffness and damping factor of swaying for model 5, which had the embedded foundation with piles. Relation between the theoretical and test values can be summarized as follows:

1. The stiffness obtained by the analyses and those by the tests agreed well with each other.

2. In the case of the damping factor, the larger the soil strain, the larger the difference between the test values and the theoretical values. The theoretical values

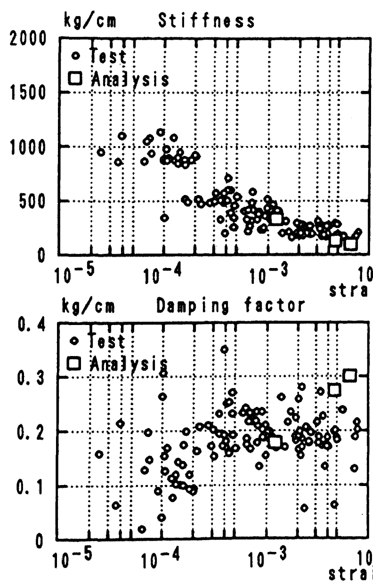

Figure 7. Dynamic stiffness and damping factor(model 5B, Hachinohe EW)

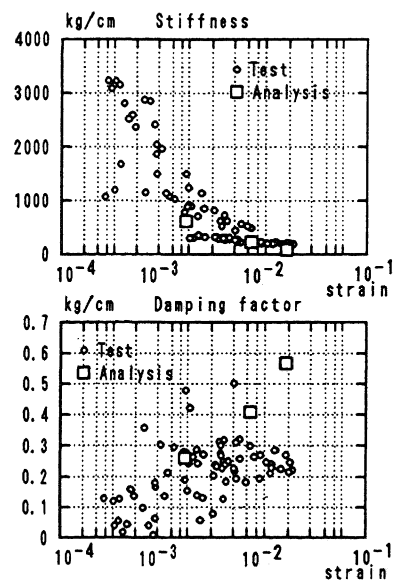

Figure 8. Dynamic stiffness and damping factor(model 5, El Centro NS)

were 2 times as large as the test values in larger strain levels of the soil. In the case of mat foundation (Tamori et. al. (1987)), the damping factor was not so greatly overestimated as in this case. Therefore, the damping factor of the embedment and piles were overestimated by the analyses.

6 CONCLUSION

This study involved performing shaking table tests on elasto-plastic soil material to investigate the soil-pile-building interaction system. Along with these tests, an analytical method, that incorporates Novak's and Kobori's method, were used to determine stiffness and damping factors for swaying motion, and then compared the resulting analytical values to those obtained by the shaking table tests.

The shaking table tests showed that the natural frequency was decreased 10 to 20 % by plastic deformation of soils; the smaller the height-width ratio, the more the natural frequency decreased. This is due to the fact that the piles prevented rocking motion significantly.

The shaking table tests also showed that the lateral force ratios applied to the piles and the inertial force caused by the building and the foundation were changed from 30% to 90%, and were proportional to the inertial force of the building and the foundation; the larger the height-width ratio, the larger the lateral force ratios.

Lastly, stiffness of swaying motion obtained by the analyses and those by the tests were agreed well. However, damping factors of swaying motion were overestimated by the analyses when soil strain was greater than 4.0×10^{-3}. These last results were caused by overestimation of the damping factor of the embedment and the piles.

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