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SCALE MODEL TESTS ON INERTIAL INTERACTION AND KINEMATIC INTERACTION OF PILE-SUPPORTED BUILDINGS

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SUMMARY

This paper reports on oscillator and shaking table tests of model building-pile-soil systems in accordance with a similitude law. The objectives of this study are to determine impedance functions of pile foundations in the oscillator test, and to examine the effects of inertial interaction and effective input motion due to kinematic interaction in the shaking table test. The experimental parameters are buildings of various natural frequencies, foundation types, backfill conditions, etc. In rotational input motions, pile effects are recognized. While horizontal base responses are affected mostly by horizontal input motion, rotational base responses are mostly affected by inertial interaction.

INTRODUCTION

During the last decade, scale model testing has developed rapidly in earthquake engineering. Some studies of scale model shaking table tests are intended to clarify soil-structure interaction of buildings and nuclear power plants instead of analysis, field tests and earthquake observations (Refs. 1, 2, 3 and 6). Advantages of scale model testing are to remove local inevitable conditions of field tests, to do parametric studies of earthquake-related specific phenomena under controlled conditions, and to obtain an insight into the problem in a comparatively short time.

At present, soil-structure interaction is, in principle, understood to be composed of inertial interaction and kinematic interaction. However, little detailed information exists to estimate soil interaction effects of existing buildings. Our intention is to evaluate impedance functions of pile foundations by oscillator tests and to examine the effects of inertial interaction and kinematic interaction of pile-supported buildings by shaking table tests. The study includes comparison of building types, foundation types, backfill conditions, etc.

MODEL AND SETUP

An eleven-story apartment building supported on cast-in-place piles was selected as the prototype. The pile caps are embedded to a depth of 8 percent of the building height. In the building, earthquake observation has been made. Similitude ratios of length, weight and time were 1/30, 1/36000 and $1/\sqrt{30}$, respectively, as shown in Table 1. In the modeling of the building, one of interior dwelling units was considered throughout the height of the building and treated as a single-degree-of-freedom system in the transverse direction. The embedded base (pile caps and girders) and the piles were modeled as a box and as plates with round edges, respectively. This model defined as the 'basic model', as shown in Fig. 1, has the fixed-base natural frequency of the building, f_b, higher than the predominant frequency of the ground, f_g. Two other buildings were selected: the case where f_b is nearly equal to f_g and the case where f_b is lower than f_g. Table 2 summarizes the fixed-base dynamic characteristics of the three model buildings. The elastic model soil was composed of polyacrylamide, bentonite, etc. The shear wave velocity of the cast model soil was 20.3 m/sec compared with the target shear wave velocity of 23 m/sec. Water-saturated urethane foam was set around the cylinder-shaped model soil to simulate the horizontally infinite condition (Refs. 1, 2 and 3).

In addition to the three types of building, the following experimental parameters were examined: 1) two types of foundation: pile foundation with fixed pile head and hinged pile tip, and mat foundation. 2) two types of base weight: standard weight in accordance with the similitude law, and 'light weight' of about two thirds of standard weight. The latter was used to check base inertia effects on the response. 3) three conditions of backfill soil: 'stiff (hard) soil' of 20 m/sec shear wave velocity, 'soft soil' of 15 m/sec shear wave velocity, and 'no backfill soil (trench)'. Note that trenches were excavated on both lateral sides of the base in all cases to remove friction at the base-soil interface, as shown in Fig. 1. The treatment was made to preserve the longitudinal condition of the prototype building.

Two types of excitation using an oscillator and a shaking table were carried out. In the former, a small oscillator with 0.358 $gf.sec^2$ exciting moment was set on the base without the building and sweep tests were performed from 1 to 20 Hz. In the latter, the table shook the complete setup in both sweep and seismic motion tests. In the sweep tests, excitation acceleration and frequency range were 50 gal and 1-30Hz, respectively. In seismic motion tests, the accelerogram recorded near the pile tip of the prototype during the Miyagiken-Oki Earthquake of 1978 was adopted and the maximum acceleration was 120 gal. The accelerations, earth pressures of the base embedment and bending moments in the pile were determined during the excitation.

OSCILLATOR TEST RESULTS

Base Response Figures 2 and 3 show horizontal and vertical base displacements (normalized by force) of the pile foundation with three backfill types in horizontal excitation. Horizontal displacements increase near the fundamental natural frequency of the soil, f_g*, due to resonance of the soil. At higher frequencies, horizontal and vertical displacements tend to increase with frequencies. The difference among the backfill types is larger in vertical response than in horizontal response.

Impedance Function Figure 4 presents the horizontal impedance functions of the pile foundation with three backfill types. At f_g*, the real part of the impedance has a big notch and the imaginary part has a big peak. These are derived from resonance of the soil by radiation wave. At higher frequencies, the real part tends to decrease slightly and the imaginary part tends to increase slightly. Figure 5 shows a comparison of the impedance between the pile foundation and the mat foundation. Both the real and the imaginary parts of the pile foundation are slightly larger than those of the mat foundation. But on the whole, the difference is small. The effect of piles on impedance is found to be relatively small.

SHAKING TABLE TEST RESULTS

Effective Input Motion to Base The effective input motion due to kinematic interaction is defined as the response of a massless rigid base. But the response of the base in the tests included base mass effects. In order to remove the effects from the base response and detect input motion, the impedance functions derived from the oscillator tests are utilized in the manner of Ref. 5. Figure 6 presents a comparison between the base response and the detected input motion. The difference is very small and negligible. Therefore we assume hereafter that the base response without the building is the effective input motion.

Figures 7 and 8 show horizontal and rotational components of the effective input motions of the pile foundation, respectively. These figures include the comparison of the backfill types. Horizontal and rotational input motions decrease in the order of stiff backfill, soft backfill and no backfill at frequencies lower than 13 Hz, including the fundamental natural frequency of the soil, f_g*. This results from the soil motion acting on the embedded base. The input motions increase with the existence of the backfill and with backfill stiffness. Figures 9 and 10 present the horizontal and rotational motions of pile and mat foundations. Rotational input motion of the pile foundation is smaller than that of the mat foundation. Horizontal input motion of the pile foundations is basically the same as that of the mat foundations. Effects of piles on the rotational input motion are distinguished.

Figure 11 compares the effects of the horizontal input motion U_{fi} with those of rotation input motion U_{ri} at the model building height. A solid line represents the sum of the both motions, U_{ti}. At frequencies lower than 10 Hz, the horizontal component is larger than the rotational one. On the other hand, at frequencies higher than 10 Hz, the rotational component increases and becomes comparable to the horizontal one.

Effects of Kinematic Interaction and Inertial Interaction Figure 12 depicts the ratios of building response U_t, which includes inertial interaction effects, and the sum of the horizontal and rotational effects at the building height, U_{ti}, which excludes inertial interaction effects. By arranging the data, we can accurately determine the sum of building damping and radiation damping due to inertial interaction. The total damping ratios of the three buildings are 4 to 5 percent, and damping of the fixed-base buildings was adjusted as 1 percent. As a result, radiation damping is evaluated at 3 to 4 percent.

Figure 13 shows the horizontal base response of the buildings and horizontal input motion. The difference between the response and input motion is due to inertial interaction and is somewhat large near the resonant frequencies of the buildings, f_b*. On the whole, inertial interaction effects are small, and the response is profoundly affected by horizontal input motion due to kinematic interaction. Figure 14 presents rotational base response of the buildings and rotational input motion. The difference between the response and the input motion is large, particularly near the frequencies f_b*, in comparison with the horizontal case. At frequencies lower than f_b*, the building and the base oscillate in the same phase. The rotational response of the base increases due to inertial interaction. At frequencies higher than f_b*, they vibrate in the reverse phase. As a result, inertial interaction decreases the rotational response of the base. Figure 15 compares the base responses of the pile-supported and mat foundation buildings, and includes horizontal input motion. The difference is very small. Figure 16 similarly presents the rotational base responses of the two foundation types. The response of the mat foundation is larger than that of the pile foundation, especially near f_b* and f_g*. Consequently, the presence of piles decreases the rotational response of the base.

CONCLUSIONS

The main concluding remarks of the study are summarized as follows; 1)

Existence of backfill slightly increases the effective input motion and horizontal impedance in pile foundations. 2) Piles have significant effects on the rotational responses of the base in both inertial interaction and kinematic interaction. Pile effects on the horizontal responses of the base, however, are small. 3) While horizontal base responses are affected mostly by horizontal input motion, rotational base responses are affected mostly by inertial interaction.

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REFERENCES

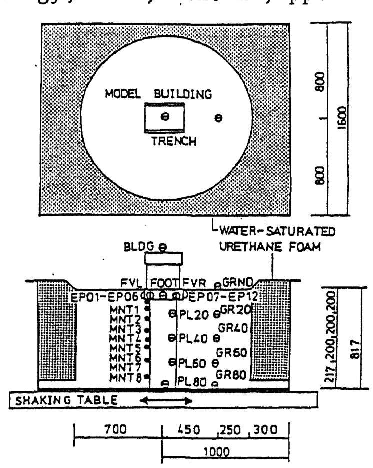
1. Mizuno, H., "Model Experiments of Building-Pile-Soil Systems With Emphasis on Selection and Modelling," Annual Report of BRI, Fiscal Year 1978, pp.147-154 (in Japanese) **2.** Mizuno, H. and Iiba, M., "Shaking Table Testing of Seismic Building-Pile-Soil Interaction," Proceedings of the 6th Japan Earthquake Engineering Symposium, 1982, pp. 1713-1720 **3.** Mizuno, H., Iiba, M. and Kitagawa, Y., "Shaking Table Testing of Seismic Building-Pile-Two-Layered-Soil Interaction," Proceedings of the 8th World Conference on Earthquake Engineering, 1984, Vol. 3, pp. 649-656 **4.** Mizuno, H. and Iiba, M., "Experimental Study of Dynamic Building-Pile-Soil Interaction," Proceedings of the 7th Japan Earthquake Engineering Symposium, 1986, pp. 1713-1720 (in Japanese with English Abstract) **5.** Wong, H. L. and Luco, J. E., "Dynamic Response of Rectangular Foundation to Obliquently Incident Seismic Wave," Earthquake Engineering and Structural Dynamics, Vol.6, 1978, pp3-10 **6.** Matsushima, Y., Mizuno, H., Machida, N, Sato, k. and Okano, H., "Shaking Table Test and Analysis of Embedded Structure Soil Interaction Considering Input Motion," Transactions of the 9th International Conference on Structural Mechanics in Reactor Technology, 1987, Vol. K1, pp. 305-310

Table 1 Similitude Ratios

Items	Dimension	Similitude ratio
Length	L	1/30
Weight	MLT^{-2}	1/36000
Time	T	$1/\sqrt{30}$
Bending Rigidity	ML^3T^{-2}	$1/324\times10^5$
Density of Ground	ML^{-3}	3/4
Velocity	LT^{-1}	$1/\sqrt{30}$
Acceleration	LT^{-2}	1

Table 2 Dynamic Properties of Model Buildings

TYPE OF BUILDING	RELATION BETWEEN fb and fg (fb : base-fixed nat. freq. of bldg. fg : predominant freq. of ground)	DIMENSION OF BUILDING: WEIGHT (kg)	DIMENSION OF BUILDING: HEIGHT (cm)	BASE-FIXED CHARACTERISTICS OF BUILDING: FREQUENCY (Hz)	BASE-FIXED CHARACTERISTICS OF BUILDING: DAMPING (%)
1	$f_b > f_g$	12.73	23.8	11.85	1.08
2	$f_b = f_g$	16.33	32.4	5.98	1.07
3	$f_b < f_g$	21.72	40.4	3.53	1.09



ACCELEROMETER (Horiz., Verti.)
STRAIN GAUGE
EARTH PRESSURE TRANSDUCER

Fig. 1 Model and Instrumentation

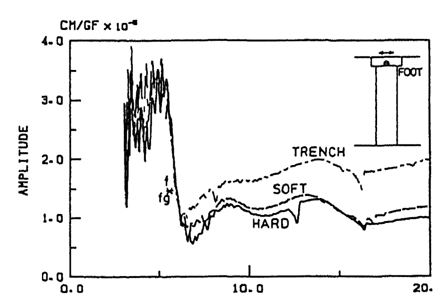


Fig. 2 Horizontal Displacement of Base with Backfill Types

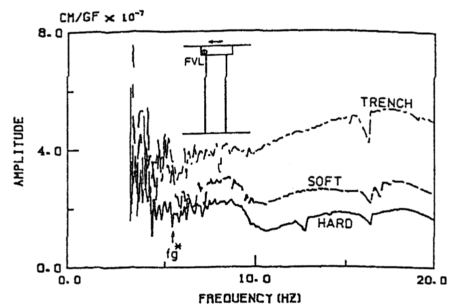


Fig. 3 Vertical Displacement of Base with Backfill Types

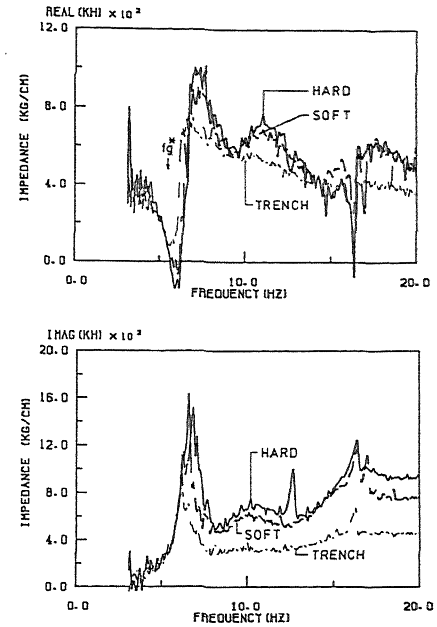


Fig. 4 Horizontal Impedance with Backfill Types

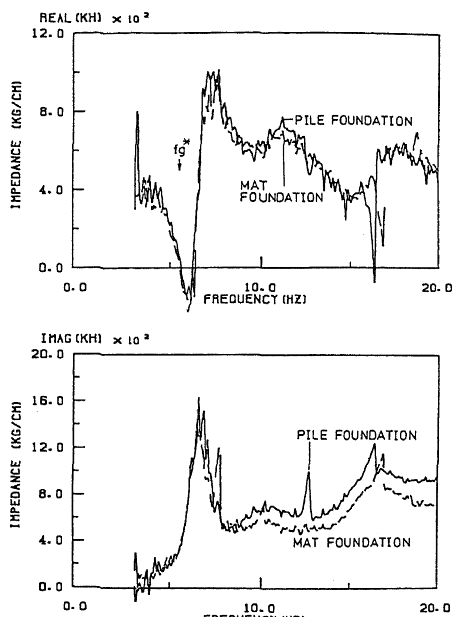


Fig. 5 Horizontal Impedance with Foundation Types

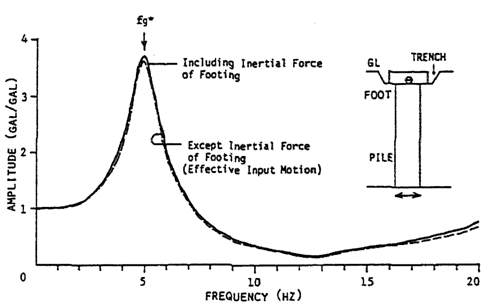


Fig. 6 Effect of Inertial Force on Base Response

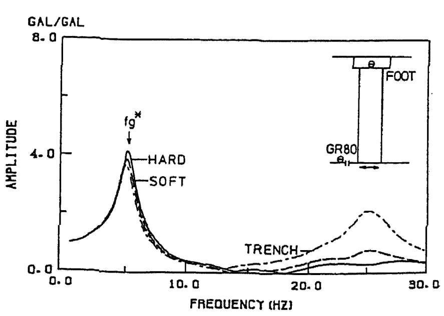


Fig. 7 Horizontal Effective Input Motion of Pile Foundation with Backfill Types

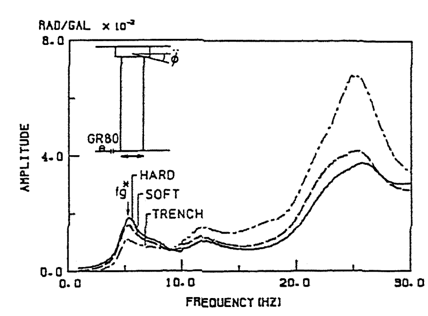


Fig. 8 Rotational Effective Input Motion of Pile Foundation with Backfill Types

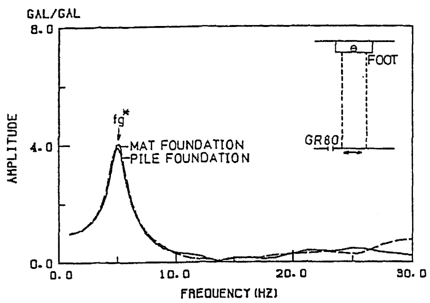


Fig. 9 Horizontal Effective Input Motion with Foundation Types

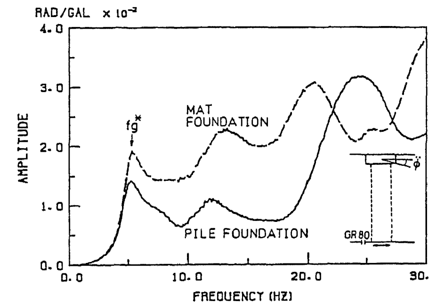


Fig. 10 Rotational Effective Input Motion with Foundation Types

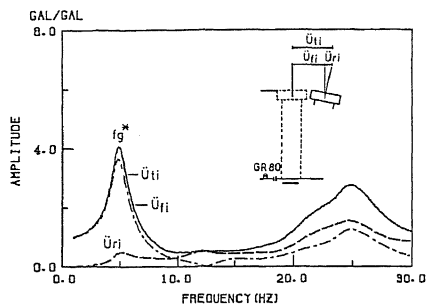


Fig. 11 Effective Input Motion at Building Height

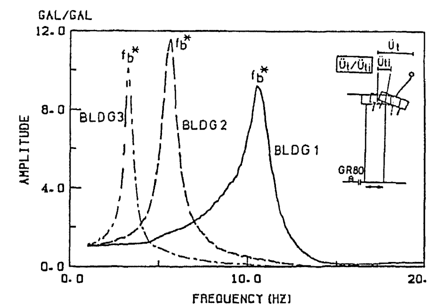


Fig. 12 Building Response due to Inertial Interaction

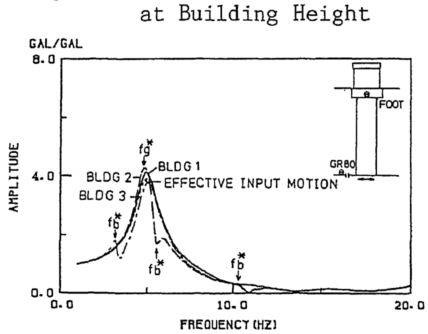


Fig. 13 Horizontal Response of Base with Building Types and Horizontal Effective Input Motion

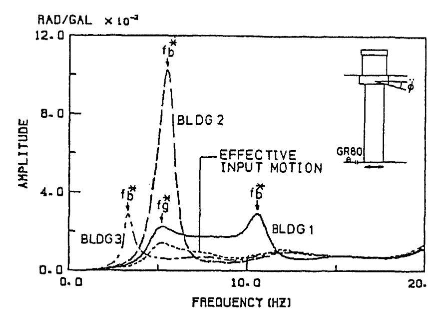


Fig. 14 Rotational Response of Base with Building Types and Rotational Effective Input Motion

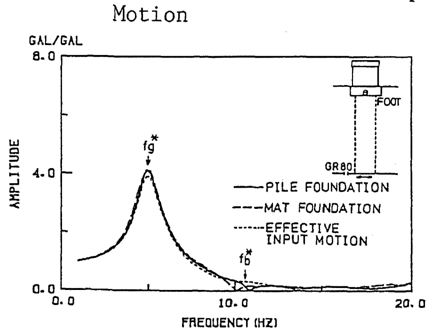


Fig. 15 Horizontal Response of Base with Foundation Types and Horizontal Effective Input Motion of Pile Foundation

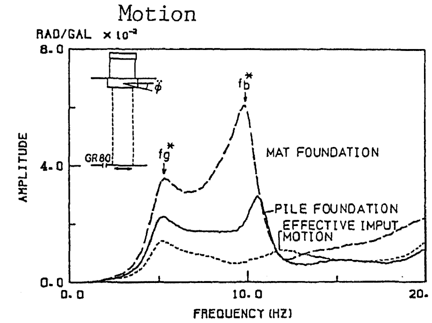


Fig. 16 Rotational Response of Base with Foundation Types and Rotational Effective Input Motion of Pile Foundation