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Lateral bearing capacity of embedded foundation under sinusoidal excitation

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ABSTRACT : There are three factors that affect resistance of the underground structure of building against seismic force, that is, (a) front and back earth pressure, (b) lateral face friction on the side walls and (c) resilient rigidity of piles. This study aims at clarifying the lateral bearing capacity of embedded foundation, and analyzing the characteristics of earth pressure in earthquake. To study, sinusoidal excitation tests were made under the restricted conditions using an oscillating soil bin, followed by the finite element analysis simulated with pseudo-three-dimensional models. The study of parameters was also made in analytical method under different conditions.

1 INTRODUCTION

During earthquake, the embedded foundation behaves in two different ways ; one is input facility of seismic force from ground to structure, the other is propagation of force from structure to ground. There are three factors that affect resistance of the underground structure of building against seismic force, that is , (a) front and back earth pressure, (b) friction on the side walls and (c) resilient rigidity of piles, as illustrated in Fig.-1. For more effective and economic seismic design of foundation , it is very important to clarify the dynamic facilities and characteristics and to indicate the distribution ratio of each factors.

In Japan it is recommended that seismic horizontal shear forces applied to pile heads is reduced up to 70% in accordance with $1 - 0.2 \times \sqrt{H} / \sqrt[4]{D_f}$, in which H is the height of the super structure, and D_f is the depth of structure in the ground. This study aims at confirming the recommendations, and at investigating the characteristics of the distribution ratio in the lateral resistance of embedded foundation in earthquake. For this purpose, sinusoidal excitation tests were made under the restricted conditions using an oscillating soil bin, followed by the finite element analysis simulated with pseudo-three-dimensional models. The study of parameters was also made in analytical method under different conditions.

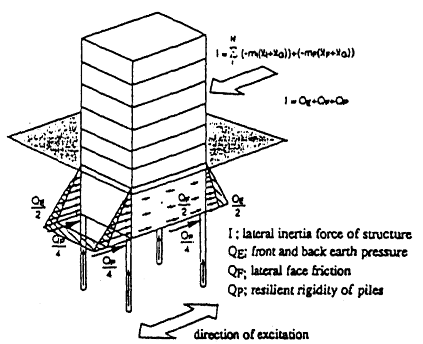

Figure. 1 Behavior in the lateral resistance of embedded pile foundation

2 MODEL TESTS

2-1 Oscillating soil bin and model ground

The oscillating soil bin was 197 cm long, 199 cm wide and 75 cm high and was supported with six plate springs from the retaining walls (see Fig.- 2) . The springs were made of steel, measuring 4.5 cm wide, 36 cm high and 218 cm long. They were rigid enough to produce oscillations only in horizontal direction. The bin was capable of generating stable sinusoidal excitation at a constant frequency of 3 Hz up to about 500 gal. In the boundary of four side wall urethan foam 10 cm thick was inserted in order to decrease the boundary effects. Before the sinusoidal excitation tests, air-dried Toyoura standard sand was filled and tightened enough by shaking whole the soil bin at the acceleration level of about 300 gal for about 20 minutes, whereby the level of the sand changes about from 70 cm to 64 cm.

2-2 Law of similarity and prototype

In the test using models, the model should represent the corresponding prototype as accurately as possible in term of geometry and kinetics. As a prototype assumed was a usual 6-story R/C building with the embedded foundation and piles, having 16m square of floor. For the scale of the soil bin, similitude factor of length is determined to 1/32. The density and the oscillating acceleration were in one-to-one correspondence to the actual ones. Other simulation factors were calculated and determined as listed in Table-1, together with the prototype data and the model test examples.

2-3 Test models

The models used in the tests consisted of three parts ; super structure, embedded box shaped walls and eight slender piles. The super structure was made of four aluminium columns and steel plates, and designed so that number of stories could be changed from zero to six by removing the steel floors. The test on a shaking table, using sweep loading, and free vibration tests were carried out for determination of the natural frequencies measured on superstructure having different number of stories under the two conditions; the first was that the model was fixed on the shaking table securely without piles, and the other that the model was settled on the ground with piles. The measured values are listed in Table-2 with the heights and the weights of foundation alone, 3- and 6- story buildings.

The underground walls are made of aluminium plates of 8 mm thick and equipped with several measuring devices (later described).

The pile model was also made of aluminium sticks measuring 1.0 cm wide, 0.5 cm depth and 40 cm long and seated on pressed plinth with the pin type joint.

2-4 Measuring devices

To measure the earth pressures, four earth pressure cells were attached on the front and the back walls of the foundation. The four cells allowed us to measure the vertical earth pressure distribution in static state as well as under vibration.

To measure the frictional force applied to the underground side walls and the bottom wall, measuring devices were newly developed (see Fig.-3). The devices could provide lateral force applied to each pile head if enough open space is available between the bottom wall and the ground for pile foundation.

The bottom wall and one of side wall were divided into nine sections and three sections respectively and supported with two (for bottom wall) and three (for side wall) acrylic sticks. If the frictional force is applied horizontally along the wall, the sticks will be bent, like a beam held in position at both ends. Two strain gauges were placed vicinity of the structure so that they gave the bending strain response values. From these values and the formula representing the relationship between the frictional force and the bending strain obtained from the static loading tests (Fig.- 4), we determined the lateral face friction on the side wall and resilient rigidity of piles indirectly. To verify the the behavior of the structure under vibrations, the shaking table test was made and we could verify that the values measured with the measuring devices met those determined theoretically.

Table 1. Data pertaining to prototype and model

Item	Dimension	Similitude Factor	Prototype	Model
Length	L	1/32	Width 16m	Width 0.5m
Acceleration	LT^{-2}	1.0	100 gal Input	100 gal Input
Velocity	LT^{-1}	1/5.7	Vs=656 m/s	Vs=115 m/s
Time	T	1/5.7	2 sec. Input	0.33 sec. Input
Density	ML^{-3}	1.0	1.6 g/cm^3	1.6 g/cm^3
Weight	MLT^{-2}	$1/32^3$	301.5 t/story	9.2 kg/story
Story-Stiffness	$MT^{-2}L^{0}$	$1/32^2$	865.7 t/cm	845.4 kg/cm
BendingStiffness	ML^3T^{-2}	$1/32^5$	2.52×10^8 t/cm^2	7500 kg/cm^2

Table 2. Data pertaining to superstructure model

Structure model	Height (cm)	Weight (kg)	Natural Frequency (Hz)	
			Fixed on shaking table	Planted in ground with piles
Foundation	1.0	36.94	-	-
3-story	40.0	64.54	21.6	19.0
6-story	79.0	92.14	11.5	10.3

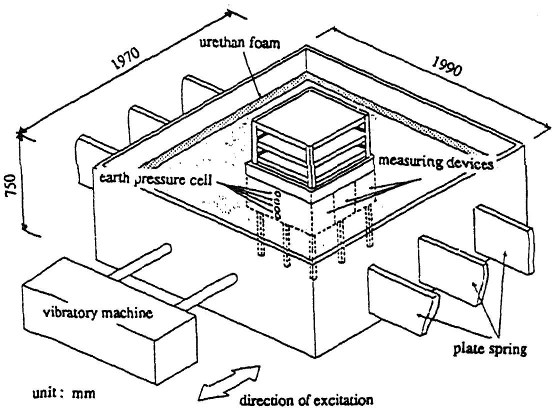

Figure. 2 Oscillating soil bin test system

2-5 Test Parameters

The major parameters used in the tests as follows ;

a) Number of stories of superstructure (ranging from foundation alone to six stories)

b) Depth of embedded section (0 - 6 - 12 - 18- 24 cm)

c) Input acceleration (50 - 200 gal)

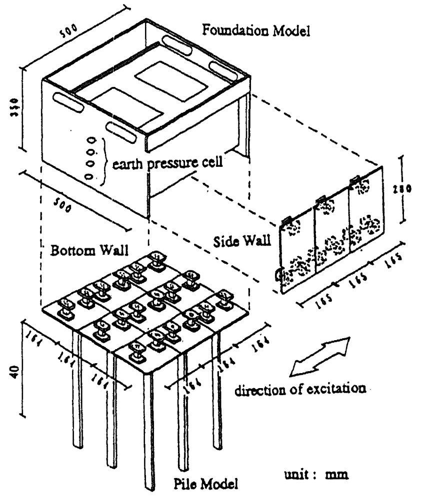

Figure. 3 Foundation model and measuring devices

The change of number of stories of the superstructure was necessary to vary the specific vibration frequency of the structure and the amount of rocking. The input acceleration slightly affected the amplification of vibration because of tightly packed ground and did not significantly affect the lateral force distribution.

3 TEST RESULTS

3-1 Superstructure

Fig.-6 shows the vertical distributions of static earth pressure, dynamic earth pressure and differential earth pressure, which is defined as the difference in earth pressure on the front wall and the back wall. From these test results, it is obvious that phase difference between the wave at the bottom cell and the wave at the top cell is equal to half of wavelength for structure of foundation alone, that is, the differential earth pressure acts as an additional stress. In the case of 6-story building, however, all the differential earth pressure provides a resistant action. Fig.-7 shows the relationships between number of stories and the amplification magnitude (response to input excitation), and the lateral force distribution ratio. When the amplification magnitude at the top of the structure exceeds the limited level, the lateral force distribution ratio of the earth pressure exceeds 50% and that of the piles decrease to about 25%. The lateral frictional resistance ratio is about 25 - 30% and does not significantly depend on the superstructure.

3-2 Depth of embedment

Fig.-8 shows the relationships between depth of embedment and the amplification magnitude, and the

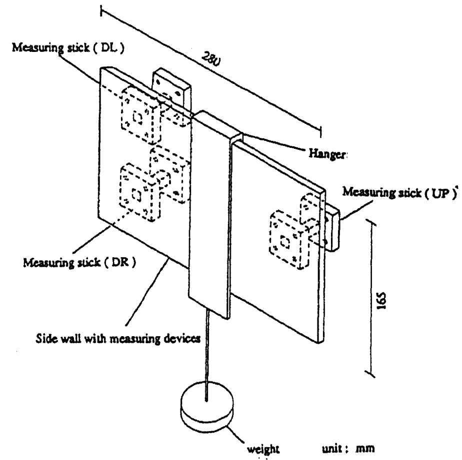

Figure. 4 Static loading test
(for determination the relationship between frictional force and bending strain)

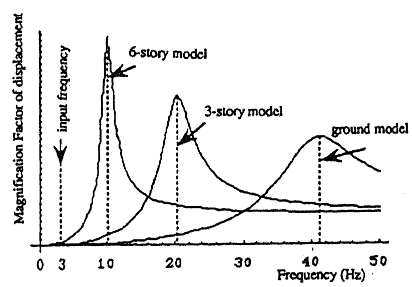

Figure. 5 Curves of resonance in structure and ground used in this tests

lateral force distribution ratio. The deeper the embedment, the larger are the restrain effects, so the amplification magnitude of the structure decreases. Then the lateral resistance is distributed from the piles to the earth pressure and the side wall friction.

4 SIMURATION ANALYSIS

4-1 Analytical model

The soil bin and the structure model were simulated by two planes shown in Fig.-9 ; one was soil-structure model, and the other free ground model. To represent the three-dimensional behavior, each one node is connected to the corresponding node through each shear spring element. The ground was assumed to consist of rectangular elements and triangle elements and the structure was assumed to be beam elements. We assume the whole elements are homogeneous visco-elastic.

4-2 determination of constants used in analysis

The weight of the analytical model was same as that of

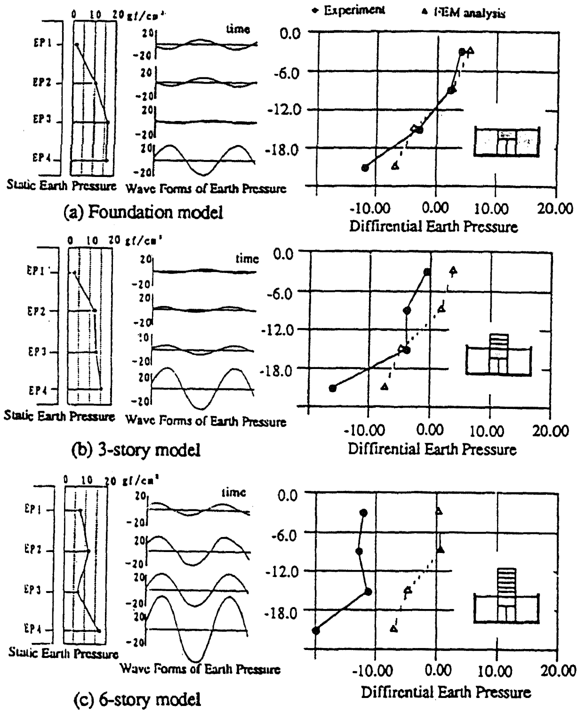

Figure. 6 Static earth pressure and its wave forms during vibration and Diffirential Earth Pressure

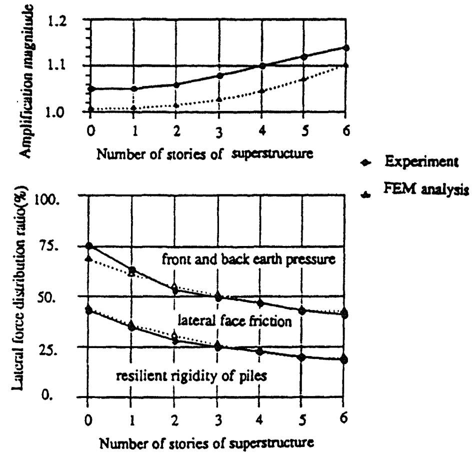

Figure. 7 Amplification magnitude and lateral force distribution ratio versus superstructure

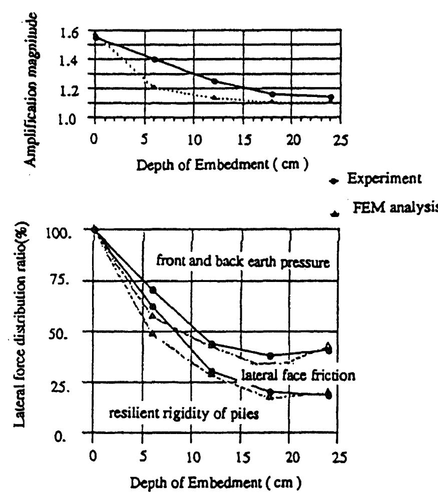

Figure. 8 Amplification magnitude and lateral force distribution ratio versus depth of embedment

the experimental model. As for the determination of elastic constants and damping factors, the results of free vibration tests were used efficiently under the first conditions that the model was fixed on the shaking table securely without piles. And from the results of the other free vibration test that the model was planted on the ground with piles, the spring constants between pile and soil were determined. The shear wave velocity inherent in the model ground was determinated from propagation speed of impact test on the free ground model, but for the soil-structure model we thought the shear wave velocity was smaller than the free ground model and determined the value from amplitude factors of the tests.

4-3 Method for lateral force distribution ratio

For the frequency domain analysis, the finite elements matrices are formed from total matrices as follows.

$$\{[K]+i\omega[K]-\omega^2[M]\}\{x\}=\omega^2[M]\{j\}x_g \qquad (1)$$

where $[K]$ $[C]$ $[M]$ *is the spring matrices, the damping* matrices and the mass matrices respectively, and $\{x\}$ is the displacement vector and $\{j\}$ is the unit vector when the displacement is in vibration direction. And ω is the circular frequency and x_g is the amplitude of input wave.

We can take the inertia force of the structure from,

$$I=\sum_s\left(\omega^2[M]\{x+x_g\}\right) \qquad (2)$$

and determine the time in which the inertia force is maximum from,

$$t=-\frac{1}{\omega}\tan^{-1}\left(\frac{Img\{I\}}{Re\{I\}}\right) \qquad (3)$$

At that time we regard the lateral force distribution ratio as the total force of each resistant factor of embedment , determined from,

$$D_E=\frac{Q_E}{I},\ D_F=\frac{Q_F}{I},\ D_P=\frac{Q_P}{I} \qquad (4)$$

where D_E,D_F and D_P are the lateral force distribution ratio of each factor which can be explained in Fig.- 10.

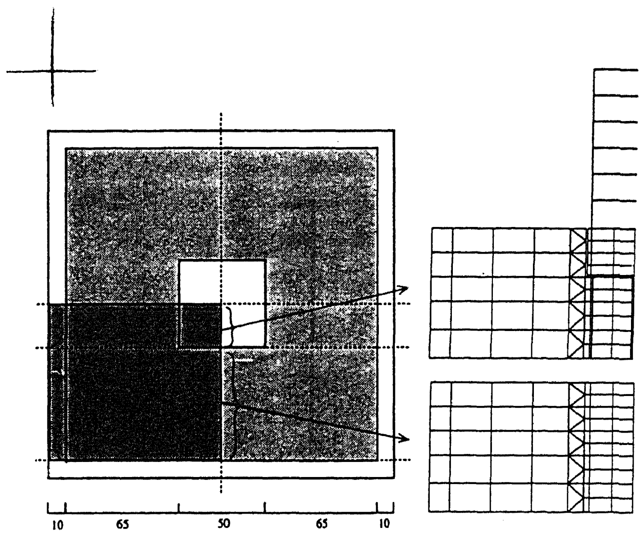

Figure. 9 Analytical model used in pseudo-three-dimensional FEM analysis

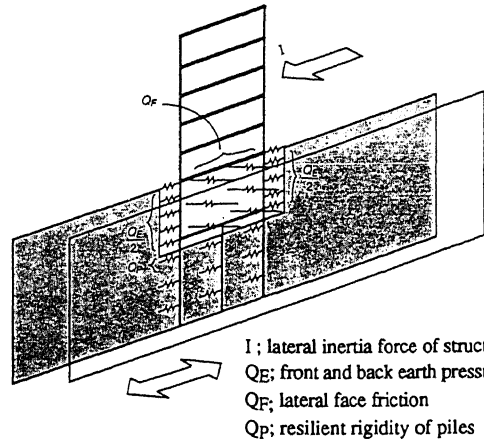

Figure. 10 Measurement of elements for lateral resistance

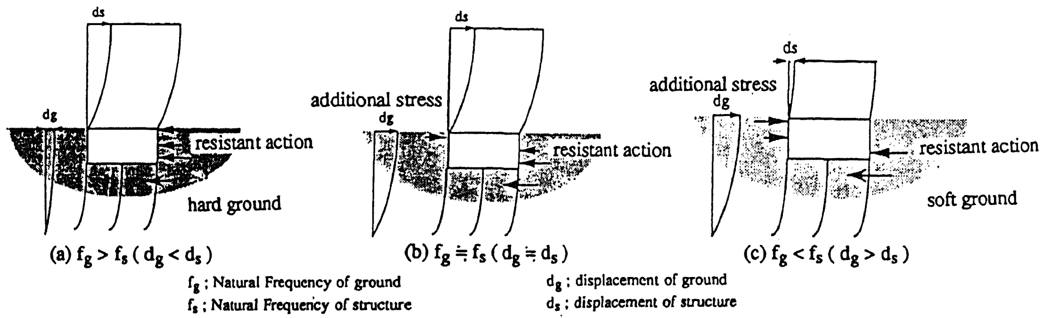

Figure. 11 Relation between soil-structure behavior and differential earth pressure

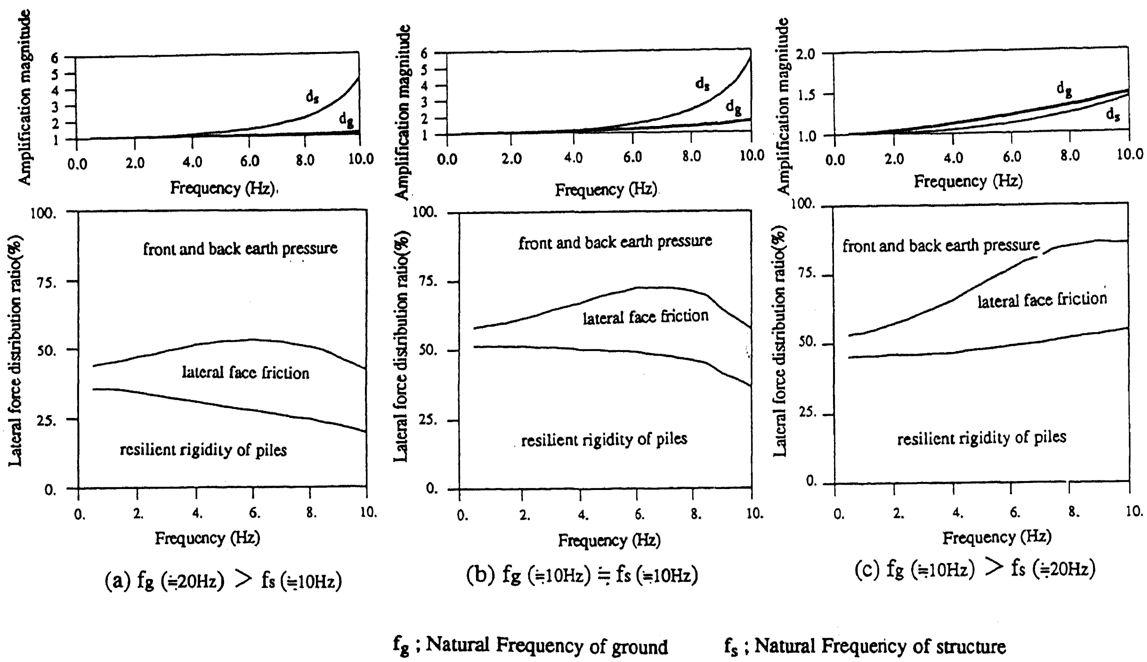

Figure. 12 Amplification magnitude and lateral force distribution ratio versus frequency

4-4 Results by simulation analysis

Fig.-6,7,8 show the comparison between the measured values and the analytical values. It was found that the observed results met the results obtained for such a model analysis.

5 PARAMETER STUDY

5-1 Parameters used in numerical study

Taking the law of similarity between prototype and the model into consideration this ground is thought to very hard and input period is thought to be very long(see Table-1). So we can make up these restricted conditions through numerical parameter study. In Fig.-5, resonant frequency in the 6-story structure model was about 10 Hz, so the input frequency was set up to 10 Hz because if input frequency is over the resonant frequency of the structure, the total inertia force will be decreased. Shear wave velocity of the ground was set up to 60 m/s and 35 m/s because when Vs equals to 35 m/s, resonant frequency of the ground would be 10 Hz.

5-2 Influences of natural frequency

Fig.-11 shows the relationship between the soil-structure behavior and the differential earth pressure, and Fig.-12 shows the lateral force distribution ratio, in the form of different three cases as follows;

(a) Natural frequency of the structure is smaller than that of the ground

The amplification magnitude of the structure is so large that the differential earth pressure entirely acts as a resistant stress and the earth pressure resistant ratio is 50 - 60(%), and the lateral force distribution ratio of piles is about 20 - 35(%).

(b) Natural frequency of the structure is close to that of the ground

The amplification magnitude of both the structure and the ground is large and the differential earth pressure acts as a resistant stress near the bottom, and the earth pressure resistant ratio is 30 - 40(%), and the lateral force distribution ratio of piles is about 35 - 50(%).

(c) Natural frequency of the structure is larger than that of the ground

The amplification magnitude of the ground is larger than that of the ground, and the differential earth pressure acts as an additional stress near the top and the earth pressure resistant ratio is 10 - 45(%) and the lateral force distribution ratio of piles is about 50(%).

6 CONCLUSIONS

From the sinusoidal excitation tests using an oscillating soil bin and the finite element analysis simulated with pseudo-three-dimensional models, it was found that the lateral bearing capacity of embedded foundation could be easily explained through the behavior of both foundation and soil. When the amplification magnitude of the structure was larger than that of the ground, the lateral force distribution ratio of the earth pressure exceeded 50% and that of the piles decreased to about 25%. Lateral face friction ratio is about 10 - 30% and does not significantly depend on the superstructure.

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