REPRODUCTION OF A LARGE-SCALE 1G TEST ON UNSATURATED SAND DEPOSITS AND PILE FOUNDATIONS USING CENTRIFUGE MODELING

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SUMMARY

A dynamic centrifuge test on the behaviour of a soil-pile system was conducted to simulate that of a large-scale shaking table test as a prototype. For the large-scale shaking table test, a model consisting of a pile-supported rigid structure and an unsaturated sand deposit was constructed in an ultra laminar container with the inside dimensions of 6m in height, 3.1 m in width and 11.6 m in length along the shaking direction. The pile foundation consisted of four (2x2) steel piles with an outer diameter of 0.3 m and a length of 6 m. The dynamic centrifuge test was performed under 15 g centrifuge acceleration. The model was geometrically similar to its prototype. The sand layer was prepared using the method employed in the large-scale shaking table test. The natural frequency of the soil model in the centrifuge test was equal to that in the large-scale test, so that the response acceleration of the sand deposit as well as the distribution of the bending moment of the piles could be reproduced almost exactly by the centrifuge test.

INTRODUCTION

Dynamic centrifuge model test technology has recently attracted considerable attention in the field of geotechnical earthquake engineering, mainly because it has the obvious advantage in reproducing the dynamic response of actual soil ground under conditions which satisfy the similitude requirements concerning confined stress of soil. However, when soil models are prepared for centrifuge tests, it may not always be perfectly consistent with the actual soil ground. It is important to establish test procedures and techniques to reproduce the behaviour of an actual soil-pile-structure system during earthquakes. Therefore, it is necessary to improve experimental techniques in order to settle some problems for the reproduction. Previously, dynamic centrifuge tests satisfying the similitude requirements were conducted in reference to unprecedented large-scale tests with laminar containers [1, 2] using dry sand [3], saturated sand [4], and a pile foundation in liquefied soil [5], and the challenges in reproducing the dynamic behaviour of actual ground were discussed. In this paper, a test with reference to the past studies is reported to reproduce the dynamic behaviour of a pile foundation and unsaturated sand.

LARGE-SCALE SHAKING TABLE TEST

Test apparatus

A shaking table test using a large laminar container was conducted in the National Research Institute for Earth Science and Disaster Prevention Science and Technology Agency. The table has a size of 15.0 m x 14.5 m and its maximum payload is 500 tons.

Laminar container

The laminar container has inner dimensions of 11.6 m in length, 6 m in height, and 3.1 m in width. The container was constructed of 29 rectangular frames made of H-shaped steel members (200 mm x 200 mm). The

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inner face of the container was lined with a 3 mm thick rubber membrane to provide waterproofing and to protect the rollers from the soil. Steel pipes with an outer diameter of 200 mm as rollers and Teflon sheets were placed between each of the container frames to reduce the shear stiffness of the container.

Preparation ground

A large-scale shaking test model and the locations of the transducers are shown in Fig.1. The soil material is ρmax=1.74t/m3, ρmin=1.39t/m3, D50=0.27mm, Uc=3.4, Fc=3%, the river sand collected from Hokota, Ibaraki Prefecture. After being dried naturally, the sand was conditioned to be slightly wet. The test sand was poured through a funnel from a height of 1 m. The sand deposit had an average density of ρt=1.69t/m3 and a water content of w=11% at the beginning of the test.

Pile foundation

The foundation is a rigid structure, consisting of stacked rectangular steel plates, which has a length of 3.0 m, a width of 2.5 m, a height of 0.26 m, and a weight of 15.6 tons. The piles used were four (2x2) actual steel piles with an outer diameter of 318.5 mm, a thickness of 6.9 mm, and a length of 6 m with a center-to-center spacing 6 times that of the diameter. The top of each pile was firmly fixed to the structure, and the bottom of each pile was pin-connected to the container base. Accelerometers were buried in the sand deposit, and strain gauges were attached to the steel pile surfaces to measure the bending moment.

Excitation

Excitation cases of the large-scale shaking tests are described in reference [6]. In this paper, the test results for the following conditions are reported: a structure weight of 15.6 tons, a sinusoidal wave incremental acceleration, an excitation frequency of 3 Hz, and a maximum acceleration of 600 gal.

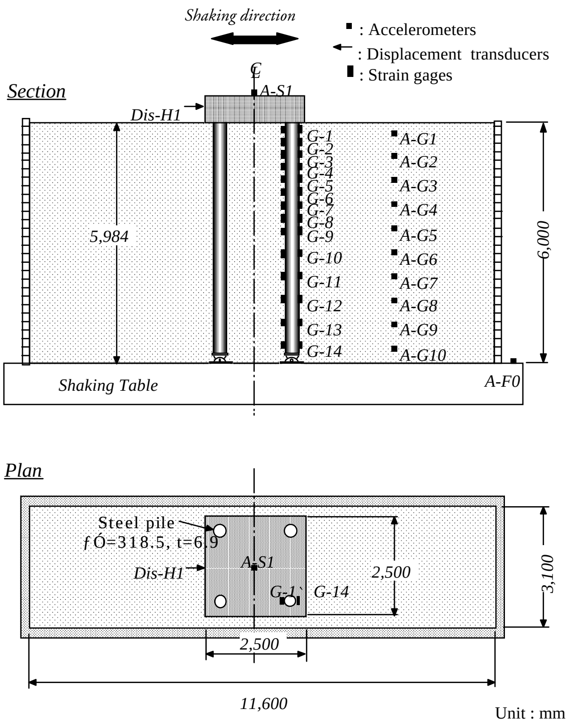

Fig.1 A large-scale shaking test model and the location of the transducers

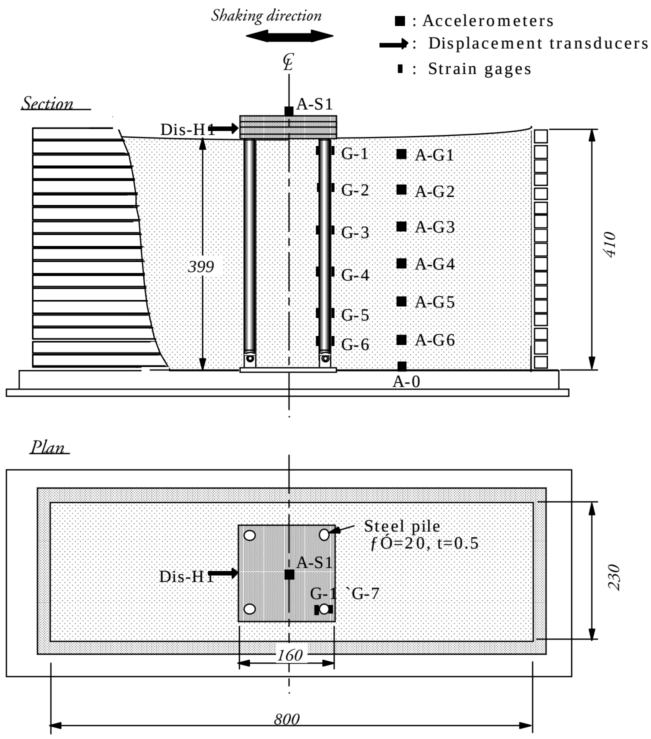

Fig.2 A centrifuge shaking test model and the location of the transducers

Table 1 Similitude requirements used in the experiments

		Symbol	Scale ratio	Unit	1 g	Centrifuge
Sand Stratum	Thickness	H_r	$1/\lambda$	m	5.984	0.399
	Density	ρ_r	1	g/cm^3	1.69	1.69
Pile	Length of pile	L	$1/\lambda$	m	6.0	0.4
	Diameter	D	$1/\lambda$	mm	318.5	20(21.4)
	Thickness	t	$1/\lambda$	mm	6.9	0.5(0.46)
	Young's modulus	E	1	MN/m^2	206,000	206,000
	Geometrical moment of inertia	I	$1/\lambda^4$	cm^4	8,200	0.162
	Bending stiffness	E·I	$1/\lambda^4$	MN/m^2	16.9	0.000300 (0.000334)
	Area	A	$1/\lambda^2$	cm^2	67.55	0.300
	Normal stiffness	E·A	$1/\lambda^2$	MN	1,392	6.18
Footing	Mass	m_r	$1/\lambda^3$	kg	15,600	4.62
	Length	L_r	$1/\lambda$	m	2.5	0.167
Exciting acceleration		α	λ	g	0.4	6.1

$1/\lambda$ = model / prototype = 1 / 15

CENTRIFUGE SHAKING TABLE TEST

Test apparatus

Model tests were performed using a dynamic centrifuge at the Institute of Technology, Shimizu Corporation. The specifications of the centrifuge have been described in detail by Sato [7]. The arm radius of the centrifuge to the shaking table is 3.1 m, and is equipped with a shaking table of 950 mm x 650 mm. The table accommodates a maximum payload of 300 kg at a centrifuge acceleration of 50 g. The maximum acceleration of excitation is 5 g when the frequency of sinusoidal vibration is continuously changed in the frequency range of 50-350 Hz, and 10 g in the case of arbitrary waveforms, such as a seismic wave. Excitation is driven by an electromagnetic system so that seismic waves can be precisely reproduced by the stable control of the waveforms even in a wide frequency range.

Laminar container

The laminar container which is geometrically similar to the one used in the large-scale shaking test, has inner dimensions of 80 cm in length, 41 cm in height, and 23 cm in width. The container consists of 18 stacked frames of rectangular hollow steel pipes of 20 mm in height, 40 mm in width and 1.2-mm in thickness. The inner face of the container was lined with a 0.5 mm thick rubber membrane to provide waterproofing and to protect the bearings from the soil. The inertia effect of the container frames was minimized because of the light weight of the frames. Flat bearings of 2 mm in bearing thickness were installed between the rectangular frames to reduce the shear stiffness of the container. Acrylic plates were installed between the container frames to prevent the insertion of the membrane into the gaps between each frame.

Similitude requirements

The similitude requirements used in the centrifuge test are summarised in Table 1. The ratio of the centrifuge and the large-scale test is 1/15. The value of centrifugal acceleration was set to 15 g. In the time history and strain diagrams shown in this paper, the values of the centrifuge test were translated to the actual size based on the similitude requirements.

Preparation model ground

Some information was previously known as the necessary data to execute the centrifuge experiment reproducing the large-scale test result. There were soil density, the natural frequency of the ground, the specifications of the pile foundation, and the input wave of the large-scale shaking test, to enable the centrifuge test to be conducted as a prediction experiment of actual sand deposit.

The centrifuge shaking test model and the locations of the transducers are shown in Fig.2. The same sand used was that in the large-scale test, and the soil model used was constructed using the same preparation method. The natural frequency of the model ground in the centrifuge test was made equal to that in the large-scale test. Although it was reported in a previous study [3] that the behaviour of a dry sand deposit could roughly be reproduced by using the same average soil density for large-scale and centrifuge tests, there is another concern in that the response behaviour of sand deposits may be affected by nonhomogeneity. It was therefore considered that a sand deposit having the same elastic response behaviour would be more appropriate to investigate overall behaviour of an actual sand deposit.

A soil model with a slightly lower density than that of the large-scale test was prepared. The natural frequency was investigated by swept sinusoidal vibration with a small acceleration of 0.1 g and a frequency range of 30-150 Hz, corresponding to 6 gal and 2-10 Hz under the prototype. Through vibrating compaction, a target value of 75 Hz, corresponding to 5 Hz under the prototype, was attained as the natural frequency of the model sand deposit.

Pile foundation

Model iron piles satisfying the similitude requirements regarding the bending stiffness were adopted. Each pile had a diameter of 20 mm, a wall thickness of 0.5 mm, and a length of 40 cm. The same conditions as those in the large-scale test were adopted regarding the number of piles, pile arrangement, and the fixing method of the pile top and bottom.

Excitation

The time scale of the input wave was reduced in relation to used in the large-scale test to 1/15. Although the input waveforms of both tests were virtually identical, the maximum acceleration in the centrifuge test results in a smaller value of 400 gal.

COMPARISON OF EXPERIMENTAL RESULTS

Natural frequency of sand deposits

Microtremoros were measured to investigate the characteristics of the sand deposit before the start of the large-scale shaking test, and the natural frequency was found to be 5 Hz as shown in Fig.3. Because microtremors could not be measured in the centrifuge test, a swept vibration test with a very small level of excitation was conducted. As started in (4) of 3 and shown in Fig.4, the natural frequencies of both sand deposits showed a good correspondence.

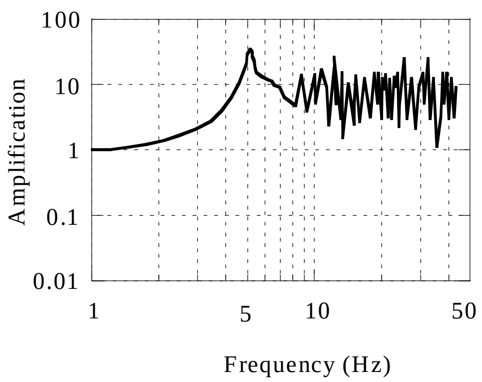

Fig.3 Frequency transfer function of soil in in the large-scale shaking table test

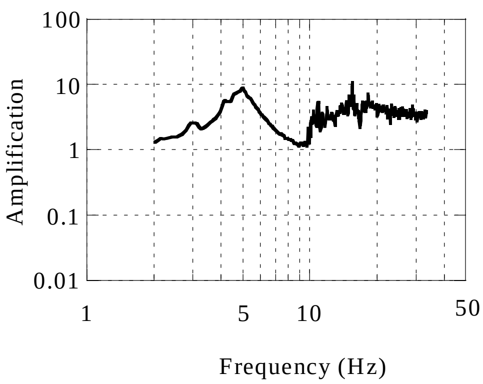

Fig.4 Frequency transfer function of soil the centrifuge shaking table test

Acceleration response of the soil and the pile foundation structure

The time history of acceleration in the large-scale shaking test is shown in Fig.5, and that in the centrifuge shaking test is shown in Fig.6. The centrifuge test resulted in lower response acceleration at the footing because of the lower input acceleration of the shaking table. The two tests resulted in similar soil response acceleration even though the input waves had different amplitudes. A trend of decreased response at the intermediate height of about 4.5-m was observed in both tests. The similarity of response accelerations in both tests, in spite of different inputs implies to what degree the soil nonlinearity in the large-scale test was larger than that in the centrifuge test.

Bending strain of piles

The time histories of the bending strain of piles in the large-scale and centrifuge tests are shown in Figs. 7 and 8, respectively. The relationship between the bending strain and the bending moment can be expressed by the following equation,

$\varepsilon = My/EI$ where ε : bending strain, M : bending moment, y : radius of pile, E : Young's modulus, I : geometrical moment of inertia.

Although similar results were obtained in both tests, the large-scale test generally resulted in slightly greater values, which may reflect the greater input acceleration. The decreased bending strain of piles at the intermediate height of about 3.5 m was well reproduced by the centrifuge test.

The distributions of bending strain for the two tests are shown in Fig.9. Although the distributions of both tests are roughly the same, the large-scale test generally resulted in greater strain values. The small values of bending strain at the intermediate height of about 3.5 m correspond to the transition from positive to negative values. Small bending strain values are also observed near the pile bottom because of its hinged structure.

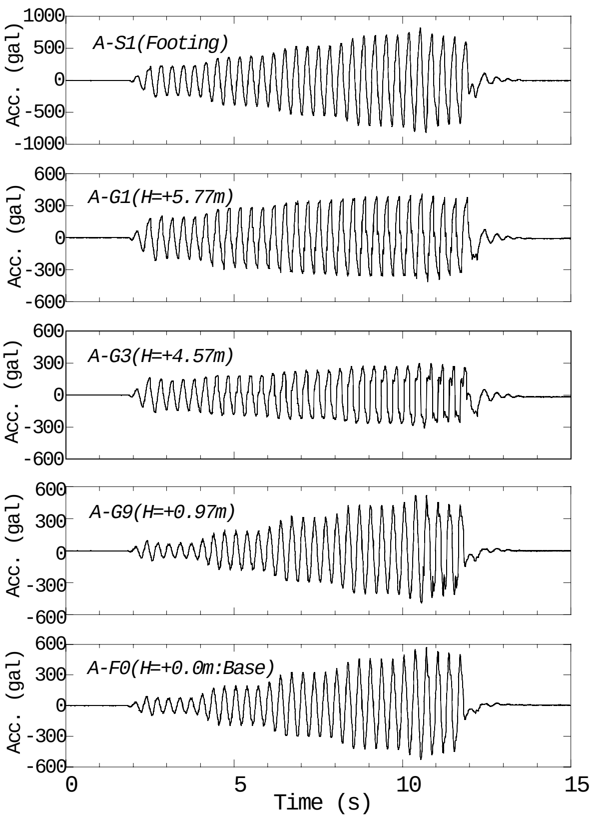

Fig.5 Time history of the acceleration of footing footing and soil in the large-scale shaking table test

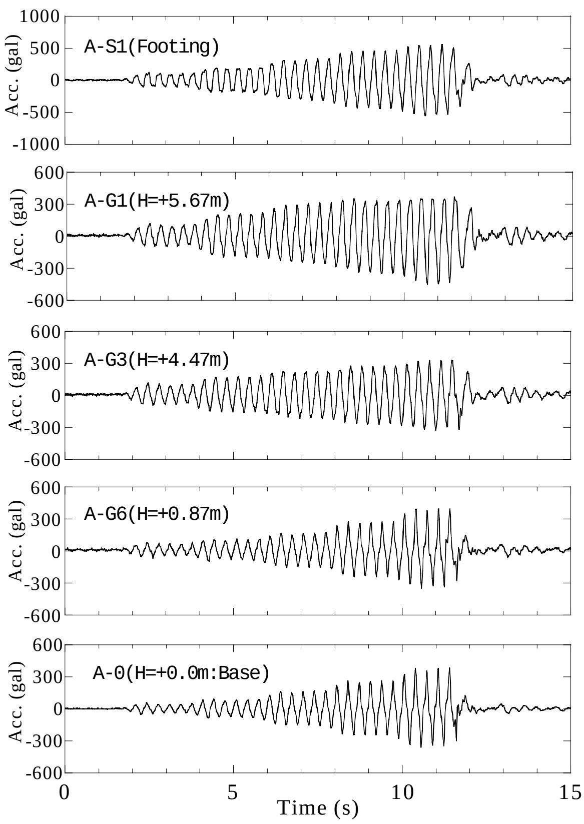

Fig.6 Time history of the acceleration of and soil in the centrifuge shaking table test

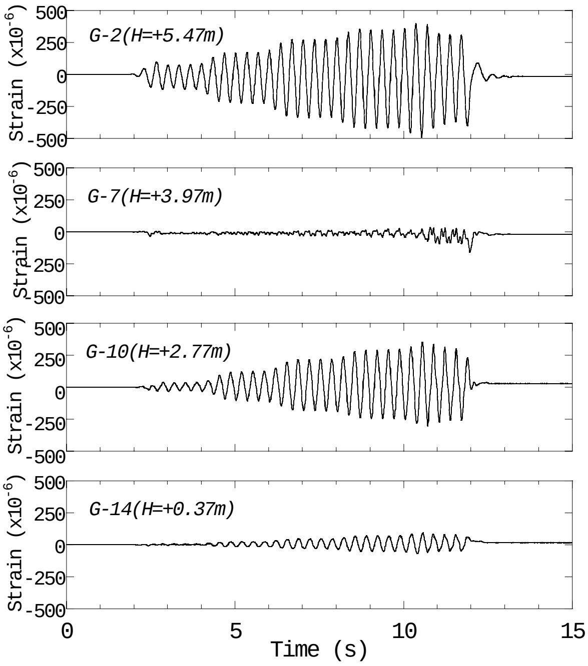

Fig.7 Time history of the bending strain of pile pile in the large-scale shaking table test

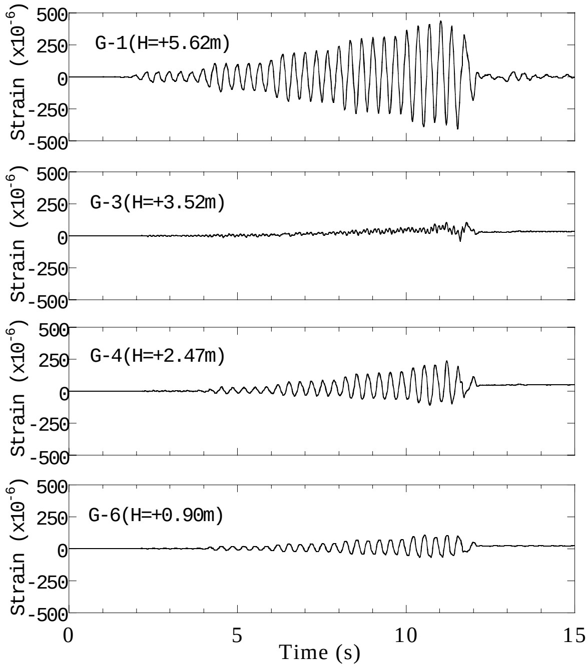

Fig.8 Time history of the bending strain of in the centrifuge shaking table test

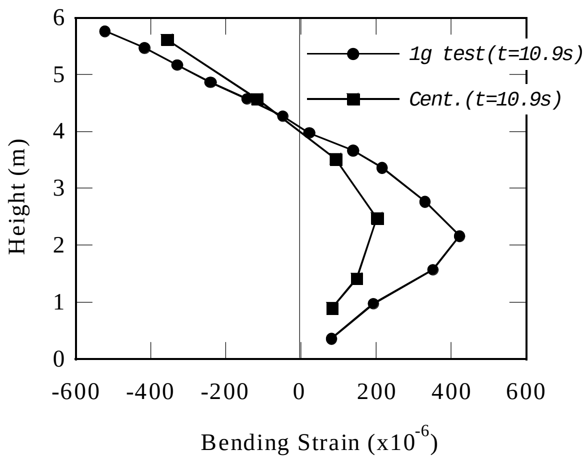

Fig.9 The Distribution of the bending strain of piles

CONCLUSION

The behaviour of a pile foundation structure in unsaturated sand could be reproduced by a centrifuge test, while considering a large-scale test as a prototype. The natural frequency of the soil model in the centrifuge test was equal to that in the large-scale test, so that the response acceleration of the sand deposit as well as the distribution of the bending strain of the piles could virtually be reproduced by the centrifuge test.

To verify the results obtained in this study, the effect of input acceleration levels and the nonlinearity of soil on the response acceleration and the bending strain of piles need to be further investigated by numerical analysis.

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