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Dynamic response of a shaft in dry sands

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ABSTRACT: In order to study the dynamic behavior of a shaft in soil during earthquakes, dynamic centrifuge tests were carried out. Two types of models were taken up;(1)level ground of sand; and (2) a hollow shaft of two different depth embedded into the level ground. An effective boundary treatment method was presented so that the semi-infinite ground condition can be satisfied approximately. The effects of input level and shaft geometry on the response of shaft-soil system were discussed.

1 INTRODUCTION

The behavior of underground structures during earthquakes can be simulated on a centrifuge much more realistically compared with conventional model test. In view of the above, the seismic behavior of hollow shaft embedded in a dry sand deposit was modeled experimentally on a centrifuge at 1/50 scale in order to investigate the dynamic behavior of shaft-soil system during earthquakes. Main attention were given to the following two aspects: (1) to propose a boundary treatment method; (2) to study the effects of input motion level and shaft geometry on the response of shaft-soil system.

2 PRELIMINARY CENTRIFUGE TEST ON THE BOUNDARY TREATMENT

One of the problems in physical modeling of dynamic phenomena is that the model is bounded by the container walls, and the artificial boundaries at the end and side walls can significantly affect the response of ground model. Thus it is important to reduce both the end wall effects and the friction between side wall and the ground model[1]. In this section, a method to treat the boundary at the container walls is proposed. The verification of the proposed boundary treatment method is also presented through both dynamic centrifuge tests and the 1-D numerical analysis[2].

2.1 Experiment arrangement

Silicone rubber was placed between sands and end wall, as shown in Fig.1, so that the shear deformation of the ground model would not be greatly affected by the end wall. The stiffness of silicone rubber is determined by preliminary numerical analysis. The Young's modulus of silicon rubber is 2.4kgf/cm^2, and the damping ratio is 4.8%(at the first peak). These values

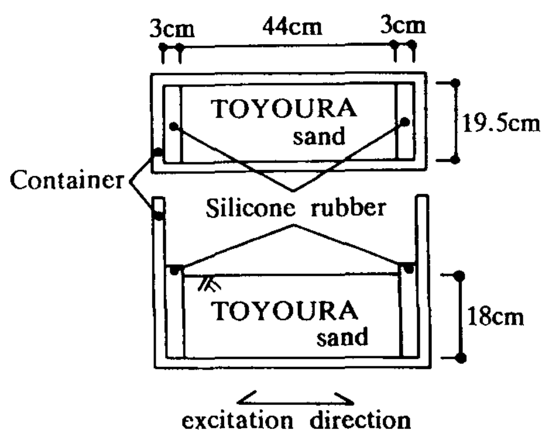

Fig.1 Outline of preliminary test

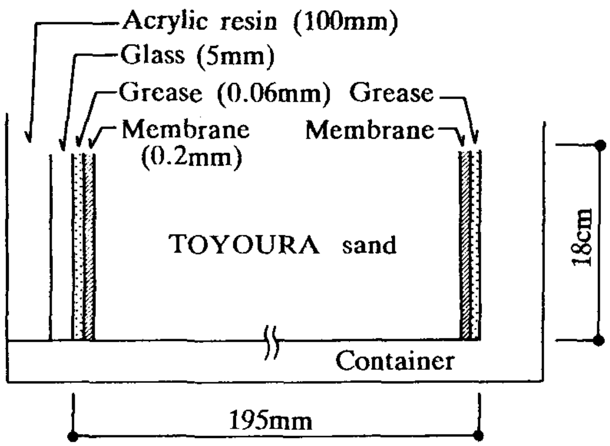

Fig.2 A section of container

Table.1 Preliminary test condition

	height of ground model h	relative density of ground model Dr	maximum acceleration of input motion
with boundary treatment	18.4cm	95.2%	1.5g
without boundary treatment	17.4cm	97.9%	1.8g

were obtained from 1g excitation tests of the silicone rubber. Rubber membrane was set up between sands and side walls with grease pasted along the interface between them, as shown in Fig. 2. The rubber membrane is supposed to move with the ground model, and the grease reduces the friction between rubber membrane and side walls.

To verify the proposed boundary treatment method, two types of the boundary conditions(with treatment and without treatment) were considered. Fig.1 shows the cut view of the experiment model. Table 1 shows the model condition and the maximum acceleration of input motion for two test cases with different boundary conditions. All tests were carried out under 50g centrifugal condition. The input signal for the shaker was intended to simulate the 1940 El Centro NS wave. The TOYOURA standard sand was pluviated through air directly into the container to be the model ground. Fig. 3 and Table 2 show the physical properties of TOYOURA standard sand.

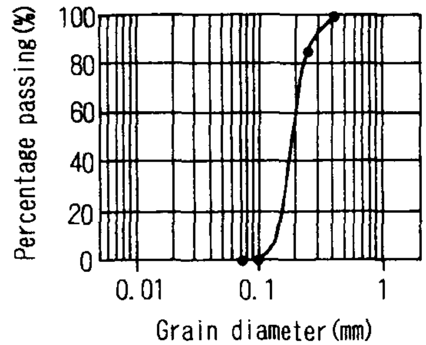

Fig.3 Grain size distribution of TOYOURA standard sand

Table.2 Physical properties of TOYOURA standard sand

Specific gravity	2.648
Bulk density - compacted	1.645 g/cm^3
- uncompacted	1.335 g/cm^3

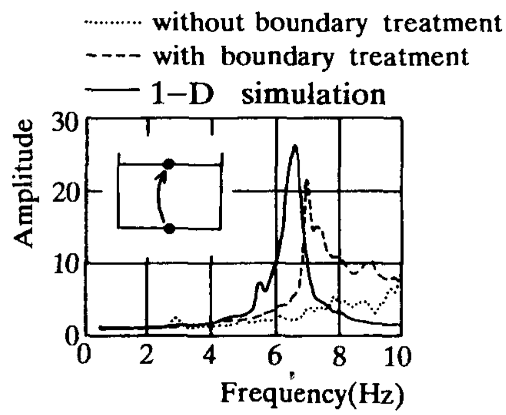

Fig.4 Effects of boundary condition on transfer function

2.2 Test results

Fig.4 for the preliminary test shows the transfer functions for two cases of different boundary condition computed from the ratio of Fourier spectra of response at the surface to those at the bottom. The frequency shown in these figures is at prototype scale. The result of 1-D non-linear simulation using lumped mass model is also shown in the same figure. The input motion in 1-D simulation is the acceleration observed at the bottom.

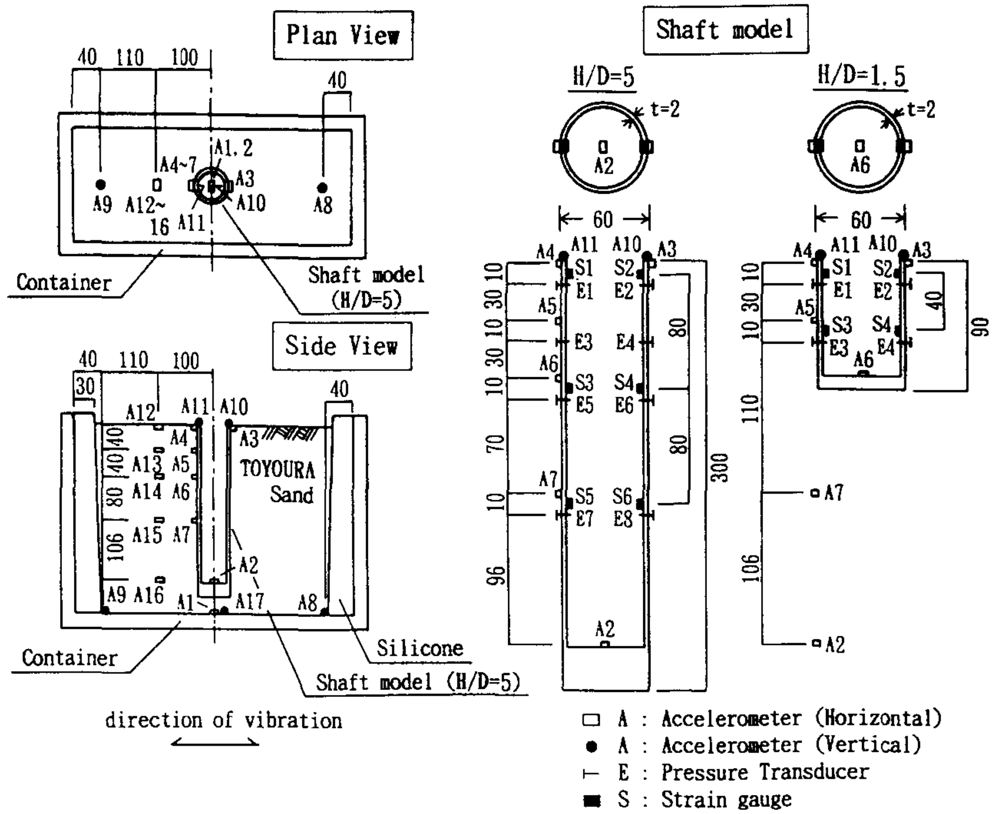

Fig.5 Outline of experiment model

In comparison between the case with and without boundary treatment(silicone rubber and rubber membrane), large difference could be observed around 7Hz in the amplitude of the transfer function. In the case without treatment, there is not a clear peak. On the contrary, the transfer function in the case of boundary treatment is very similar to that computed by 1-D simulation, which demonstrates the value of the proposed boundary treatment method.

Table.3 Test condition

	shaft condition	input wave	max. input accel. (g)	height of model (cm)	relative density of ground model Dr (%)
case 1	without	El Centro	1.2	33.0	82
case 2			9.2	33.0	83
case 3	short (H/D=1.5)		1.1	32.7	87
case 4			9.8	32.6	88
case 5	long (H/D=5)		1.2	33.0	83
case 6			10.0	32.9	85
case 7	short (H/D=1.5)	Sine100Hz	4.8	32.9	88
case 8		Sine250Hz	6.8	32.9	89
case 9	long (H/D=5)	Sine100Hz	4.5	32.8	86
case10		Sine250Hz	7.3	32.8	87

3 CENTRIFUGE TESTS OF A SHAFT IN DRY SANDS

The dynamic centrifuge tests with three sorts of arrangements(only ground model, ground model with long shaft and ground model with short shaft) were carried out. In this section, the effects of the shaft condition and input amplitude level on the response of acceleration are discussed. In addition, the influence of shaft geometry on the dynamic earth pressure and bending moment of the shaft are studied by analyzing the test results.

3.1 Experiment arrangement

Fig.5 shows the outline of the experiment model. Test cases with different shaft conditions are shown in Table 3. The parameter for the shaft geometry is the length/diameter ratio(H/D) with the diameter and wall thickness being kept the

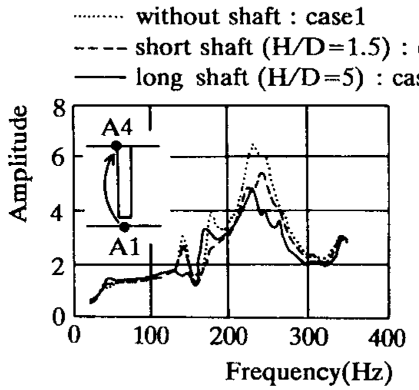

Fig.6 Transfer function at A4 in the case with small amplitude input

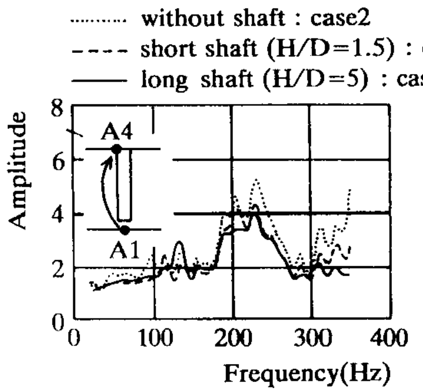

Fig.7 Transfer function at A4 in the case with large amplitude input

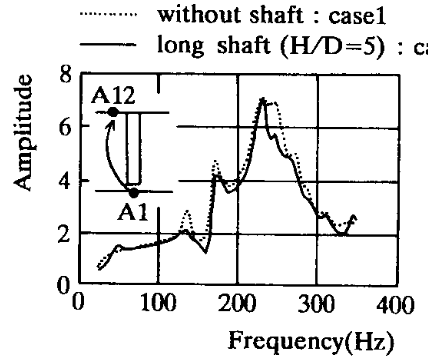

Fig.8 Transfer function at A12 in the case with small amplitude input

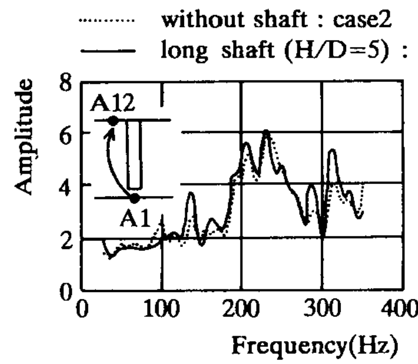

Fig.9 Transfer function at A12 in the case with large amplitude input

same. Two types of shaft conditions, short shaft(H/D=1.5) and long shaft(H/D=5), are considered. The shaft models are made of aluminum. Table 3 also shows the density of ground model and the maximum acceleration of input motion. All tests were carried out under 50g centrifugal condition. The model ground, composed of the dry TOYOURA standard sand, was made by air-pluviation.

El Centro 1940 NS record was used as the input signal for shaker. The shaking time was shortened to 1/50 of the original one in accordance with similitude. The sine acceleration waves with frequency of 100Hz and 250Hz were also used as input motions in separate tests. The first natural frequency of the ground model is 225Hz(see Fig.6).

Fig. 5 shows the location of the sensors. In order to observe the acceleration response of the ground model and shaft, accelerometers were set up at various locations. To measure the horizontal earth pressure acting on the shaft, pressure transducers were instrumented at the outer face of shaft. Eight and four pressure transducers were used at long and short shafts, respectively. In order to observe the strain in axial direction of the shaft during excitation, pairs of strain gauges were bounded at both ends of a diameter to the inner face of shafts. Eight and six gauges were used at long and short shafts, respectively.

3.2 Test results and analysis

Responses of shaft and ground are first investigated through the analysis of transfer function. In order to study the effects of the input amplitude level, the transfer functions subjected to input motions of small and large amplitudes are compared. Fig.6 and Fig.7 show the transfer functions at the A4(see Fig.5)for the case with short shaft, long shaft and without shaft under low and high excitation levels. All the transfer functions are computed from the ratio of Fourier spectra of acceleration response at A4 to those at the bottom. It can be seen that, the predominant period becomes longer and the amplification ratio decreases with the input level. As this tendency does not depend on the shaft condition, it is believed to be due to soil non-linearity.

To study the effects of the shaft conditions, the transfer functions for the cases with different shaft conditions are compared. It can be seen from Fig.6 and Fig.7 that the transfer functions of the shaft(at the surface, point A4) have smaller amplitudes compared with that of the ground at the same position at the non-shaft case. Fig.6 and Fig.7 show that the transfer functions for the case with long shaft have smaller amplitude compared with that for the case with short shaft. These tendencies don't depend on the input level. Hence, the shaft, which is much stiffer than the ground, restrains the shear deformation of the ground model, and the long shaft has a stronger effect than the short one. Fig.8 and Fig.9 show the transfer functions at the point A12 for the cases with and without shaft, under low and high excitation levels. Transfer functions of the ground point A12, which is 100mm away from the shaft center, are quite similar in all cases. This tendency doesn't depend on the input level. Therefore, it could be concluded that the extent of the ground to which the shaft could restrain is less than 1.5D(D:diameter of the shaft) from the shaft center.

The distribution of relative displacement amplitude(peak to peak) between shaft and ground, which could be calculated from accelerations, is also studied. Fig.10 shows the results for the cases under sine wave excitation. The relative displacement is very small in the case of 100Hz wave excitation regardless of the shaft condition. This excitation frequency is lower than f_0 (the natural frequency of the ground model), which is around 225Hz (see Fig.6). Therefore the shaft and ground move together when the excitation frequency is lower than f_0. However, in the case of 250Hz wave excitation, which is close to f_0, relative displacement in the region near the ground surface is large, and the relative displacement in the case with long shaft is larger than that in the case with short shaft. Thus, when the excitation frequency is close to the f_0, the response at ground surface is largely amplified, resulting in

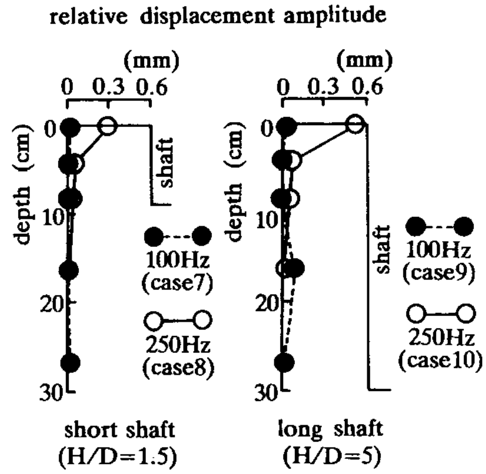

Fig.10 Distribution of relative displacement amplitude

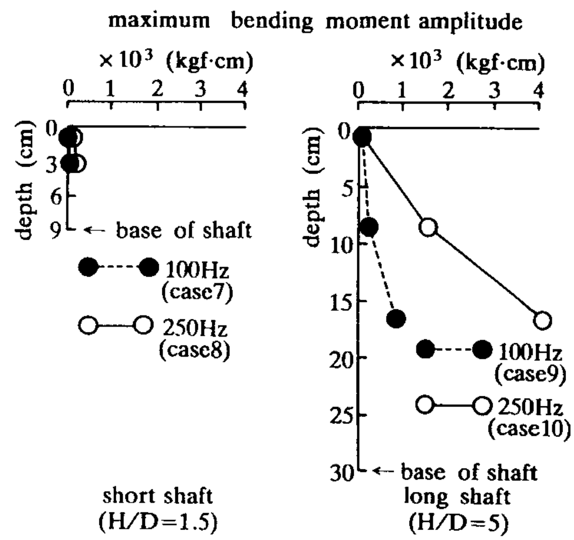

Fig.11 Distribution of dynamic bending moment amplitude

significant different response between shaft and ground. As the shaft is longer, the difference between responses of ground and shaft tends to be larger.

The bending moments of shaft during shaking are calculated using the record of the strain gauges. Fig 11 shows the distributions of dynamic bending moment amplitude (peak to peak) during sine wave excitation. In the case of short shaft, bending moment is very small, which suggests that the short shaft vibrates as a rigid body during shaking. In the case of long shaft, on the other hand, as the depth of shaft increases, the bending moment becomes larger, and bending moments at each depth change all in phase. Therefore, the vibration mode of the long shaft could be considered as the deformation of a

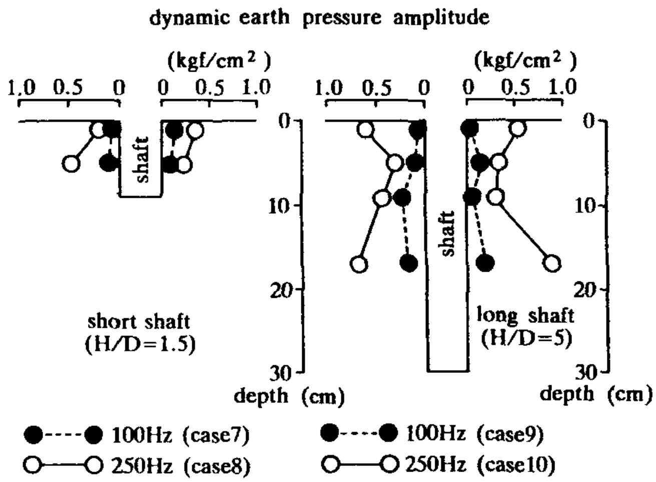

Fig.12 Distribution of dynamic earth pressure amplitude

cantilever under distributed load around tip.

The distribution of dynamic earth pressure amplitude(peak to peak), observed in the experiment under sine wave excitation, is shown in Fig.12. In the case with long shaft under 250Hz sine wave excitation, the dynamic earth pressure acting on the top and middle part of the shaft have larger amplitudes. This distribution tendency results from the distribution of the relative displacement between shaft and ground. At the depth near the ground surface, the relative displacement between ground and shaft becomes significant, which results in large earth pressure. To balance the large pressure at the top, large reaction force is needed at around the middle of the shaft where the soil is stiffer. It can be also seen that the distribution pattern of dynamic earth pressure amplitude varies as shaft condition is changed. Therefore, the distribution of dynamic earth pressure depends on the shaft vibration mode and the distribution pattern of the relative displacement, which is determined by the shaft geometry.

4 CONCLUSIONS

In order to reveal the earthquake response characteristics of a shaft in dry sand, dynamic centrifuge tests have been successfully carried out. Following are the main conclusions drawn from this study:

1)The proposed boundary treatment method is shown to be very promising through both dynamic centrifuge test and the 1-D numerical analysis;

2)The acceleration response of shaft-ground system is significantly affected by the amplitude level of input motion;

3)Shaft condition has large effect on the transfer function at the shaft, but little effect on that at the ground surface;

4)Short shaft vibrates in almost the same way as ground. However, in the case of long shaft, large response difference between the shaft and ground is observed near the ground surface;

5)Short shaft vibrates as a rigid body. Long shaft deforms during shaking, and its vibration mode is very similar to the deformation mode of a cantilever under distributed load around tip;

6)The distribution of dynamic earth pressure depends on the shaft vibration mode, which is determined by the shaft geometry.

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