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CENTRIFUGE MODELING OF EARTHQUAKE RESPONSE OF EARTH DAMS

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ABSTRACT

Dynamic centrifuge modeling is performed to reproduce the response of a heterogeneous earth dam to actual earthquake shaking. The dam model was constructed in a laminar container with the inside dimensions of 41 *cm* in height, 23 *cm* in width and 80 *cm* in length along the shaking direction. It has been confirmed that: 1) dynamic centrifuge model tests could reproduce well the seismic response of the dam under the 1 *g* field and 2) both the natural frequency of first order and the response amplification decrease obviously with increasing confining pressures, indicating the significant influence of the confining pressures on the seismic behavior of the dam. The test results show that dynamic centrifuge modeling is an effective approach to examine the actual seismic behavior of the prototype earth dam, particularly for larger scale earth dams.

KEYWORDS

seismic response; centrifuge model test; heterogeneous earth dam; decomposed granite soil

INTRODUCTION

Sandy soils, silts and gravels, which are usually used as the materials of earth dams, exhibit strong non-linear deformation behavior during earthquake shaking. Their seismic behavior is also significantly dependent on the confining pressures. It is therefore believed to be difficult by using model tests at 1 *g* field to simulate the responses of actual earth dams to earthquake shaking, because these tests are conducted under the confining pressures quite smaller than those in the dams. In order to reproduce faithfully the true in-situ stress field, dynamic centrifuge model technology has recently attracted considerable attention as a potentially effective way. Several studies on the seismic stability of the dams, such as those by Arulanandan et al.(1988) and by Kutter et al. (1989), have been conducted based on dynamic centrifuge model tests. However, dynamic centrifuge modeling of the dams related to evaluation of their fundamental seismic response seems quite few.

The objective of this paper is to investigate the fundamental behavior of earth dams during earthquakes based on dynamic centrifuge model tests. At first, the tests are performed and then the obtained results are compared with the available data observed from the shaking table test of a large scale model earth dam at 1 *g* , in order to check whether the centrifuge model tests meet the similitude requirements. Subsequently, the shaking table tests on centrifuge are used to examine the basic non-linear behavior of the dams during earthquakes under the conditions having higher confining pressures.

TEST EQUIPMENTS

Centrifuge Equipment

Model tests were performed using a dynamic geotechnical centrifuge at the Institute of Technology, Shimizu Corporation. The specifications of the centrifuge have been described in details by Sato (1994). The arm radius of the apparatus to the basket platform 3.11 *m* for dynamic tests. The centrifuge is equipped with a 950-*mm* x 650-*mm* shaking table driven by an electro-magnetic shaker. The shaking table accommodates a maximum payload of 300 *kg* at 50 *g*. The input shaking acceleration can attain 5 *g* for sinusoidal waves and 10 *g* for random waves. In the shaking table test, a model can be shaken over a wide range of vibration frequencies from 50*Hz* to 350 *Hz*. In addition, a computer-controlled digital feedback correction system is used to make the shaking table motion reproduce various scaled earthquake time histories with satisfactory fidelity.

A Laminar Container

A laminar container was designed based on the proposal by Kokusyo et al. (1978) and used in the shaking table test under centrifuge. Its inside dimensions are 41-*cm* in height, 23-*cm* in width and 80-*cm* in length along the shaking direction. The container consists of 18 rectangular hollow frames. The frames are made of square steel tubes with the dimensions of 20-*mm* height, 35-*mm* width and 1.2-*mm* thickness. Linear bearings with a height of 2 *mm* were installed between these frames to reduce friction during shearing. The container was lined with 1-*mm* thick rubber membranes to provide waterproofing for saturated sand and to protect the bearings from the soil.

A COMPARISON OF CENTRIFUGE MODEL TEST RESULT WITH LARGE SIZE SHAKING TABLE TEST RESULT AT 1 *g* FIELD

A Large Size Shaking Table Test of Earth dam at 1 g Field

Shaking table test was conducted on a model earth dam with the dimensions of 2.5-*m* height, 2-*m* width and 12-*m* length by Watanabe (1980). The heterogeneous dam model, which was treated as a plane strain problem, was constructed in a large rigid container. A decomposed granite soil, whose grain size distribution is shown in Fig. 1, was used as the model material. The other physical indices of the soil are: maximum grain diameter, 63.5 *mm* ; moisture content, about 7%; and dry density, 1.62 g/cm^3 .

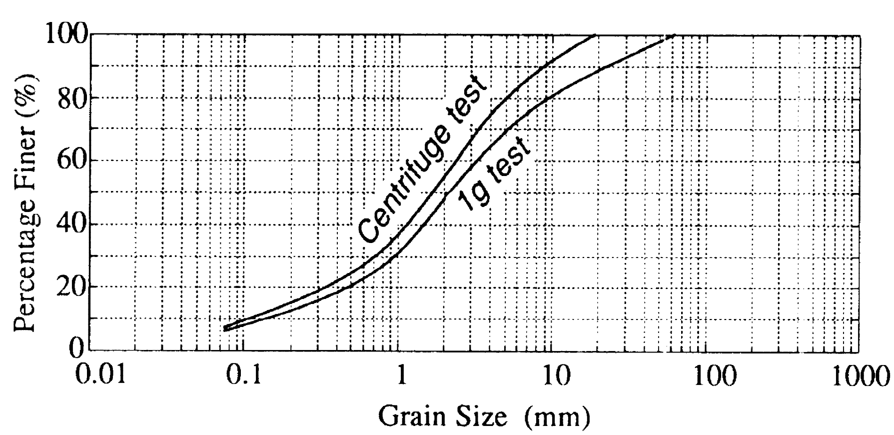

Fig.1 Grain size distribution curves of the soils used as the model material

The dam model was shaken over a wide range of frequency under a specified input acceleration level. The sinusoidal wave was adopted as input excitaion. Similar shaking table tests were conducted for five acceleration levels of 49 *Gal*, 74 *Gal*, 101*Gal*, 126 *Gal*, and 147 *Gal*. Fig.2 shows the frequency transfer functions of the dam measured at its crest as well as inside up-stream and down-stream soil zones for the case of acceleration levels of 49 *Gal* .

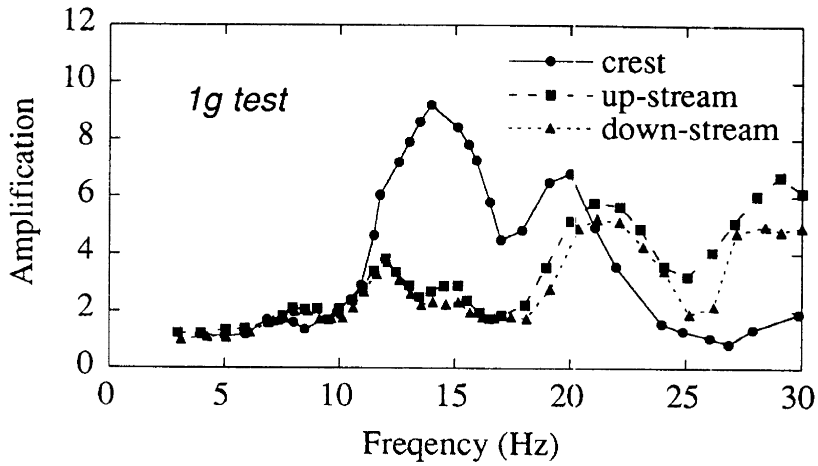

Fig.2 Frequency transfer functions of the dam measured at the crest and inside the upstream and downstream soil zones

A Dam Model Used in Dynamic Centrifuge Test

The dam model was used as the prototype of the dam for the dynamic centrifuge test. The similitude ratio of model to prototype used in the centrifuge modeling was adopted as 1 : 14.7. The similitude requirements corresponding to this ratio is listed in Table 1. The shaking table tests on the centrifuge model were conducted under 14.7 *g*. It should be noted that the data shown in the following figures indicate those of the prototype except particular instruction.

The heterogeneous model with height of 17*cm* , up-stream gradient of 1:2.6 and down-stream gradient of 1: 2.1 should be prepared based on the similitude requirements shown in Table 1. It was found from the experimental comparison that, if the dam model was constructed in a rigid container, the influence

Table 1 Similitude requirements of centrifuge and 1 *g* model test

		Scale	*Centrifuge test*	*1 g test*
Dam height	H	$1/\lambda$	17cm	250cm
Density	ρ	1	1.62 g/cm^3	1.62 g/cm^3
Stress	σ	1	1.0 kPa	1.0 kPa
Strain	ε	1	1×10^{-6}	1×10^{-6}
Frequency	f_0	λ	204 Hz	14 Hz
Shaking acceleration	α	λ	0.7 *g*	49 Gal
Centrifuge acceleration	*g*	λ	14.7 *g*	1 *g*

・Scale=Model/Prototype=1/14.7
・ *g* =980Gal

of the friction existing between the model and the container during shearing could not be neglected, because the height of the model was relatively small. Therefore, the model was prepared in the laminar container stated above.

The soil shown in Fig.1 was adopted as the model material, after its coarse grains more than 19.1 *mm* were removed. The model was filled and compacted to the specific density and moisture content, using the same method as used in the 1 *g* model test. The moisture content was measured to be about 6% and dry density, about 1.65 g/cm^3.

Fig. 3 shows the plan and side view of the dam model constructed in the container. Transducers were placed in the different positions of the model as described in the same figure.

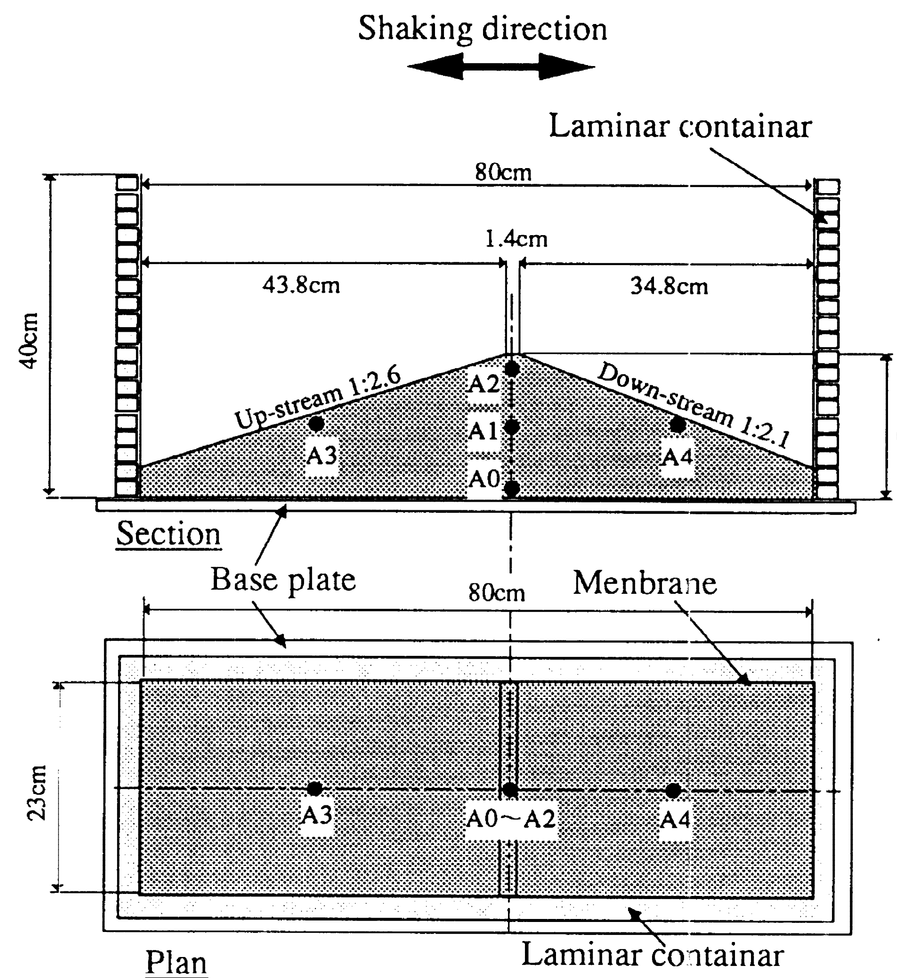

Fig.3 Plan and side view of the dam model and transducers locations

Comparison between the Results Obtained from Dynamic Centrifuge and 1 g Model Tests

The solid and dotted lines shown in Fig. 4 show the frequency transfer functions of the dam near the crest observed respectively from the centrifuge and 1 *g* model tests under the conditions with the nearly same input acceleration levels. As seen from the figure, the natural frequency of first order, which corresponds to the peak response, was about 13 *Hz* for the centrifuge test and about 14 *Hz* for the 1 *g* test. In addition, the amplification ratio of response acceleration reached nearly eight times for the former case and nine times for the latter. The good agreement in the two shows that the centrifuge model test could successfully reproduce the dynamic response of the dam observed in the 1 *g* field.

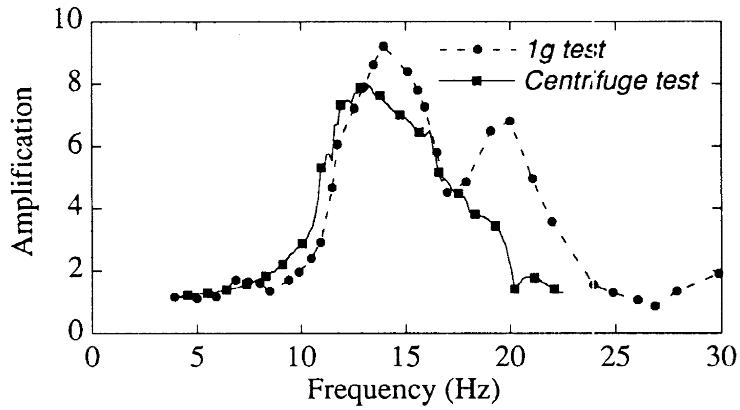

Fig.4 Frequency transfer functions of the dam near the crest observed respectively from the centrifuge and 1 g model tests

Fig.5 shows the frequency transfer functions of the crest measured from the centrifuge model tests under the different input accelerations of 0.6 g, 1.0 g, and 2.0 g were taken respectively, corresponding to 40 *Gal*, 67 *Gal*, and 132 *Gal* under the prototype. It can be found that both the natural frequency of first order and the amplification ratio of response acceleration decrease with increasing input acceleration, showing the non-linear response of the dam. Made in Fig. 6 is the comparison between the degradation of the amplification ratios obtained respectively from the centrifuge and 1 g

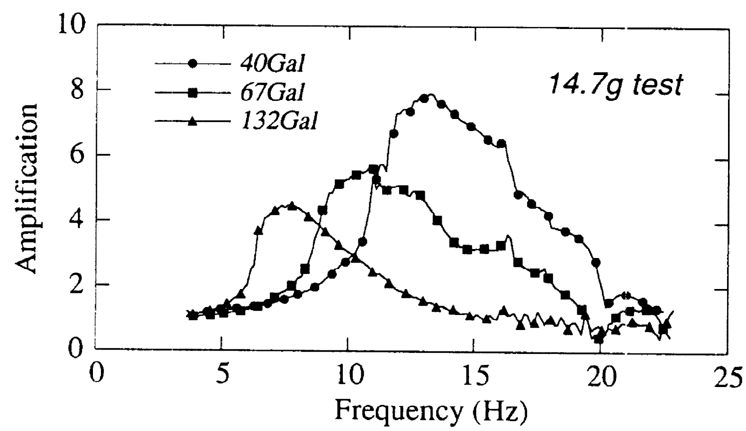

Fig.5 Frequency transfer functions of the crest measured from the centrifuge model tests under three input accelerations

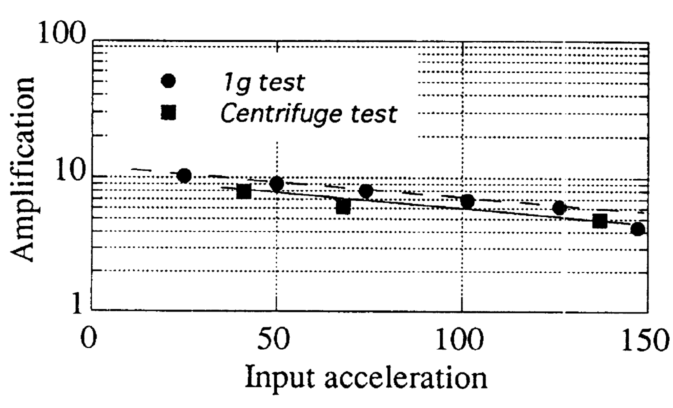

Fig.6 Comparison between the degradation of the amplification ratios obtained respectively from the centrifuge and 1 g model tests

model tests. The amplification ratio corresponding to the specified input acceleration is seen to be slightly smaller for the centrifuge test than for the 1 g test; however, the slopes of the two curves are nearly the same, and the amplification ratios, resulted from the non-linear response characteristics of the dams, tends to degrade conspicuously.

CENTRIFUGE MODELING OF SEISMIC CHARACTERISTICS OF THE DAM

Effect of Confining Pressures on Seismic Characteristics of the Dam

In order to examine the influence of the confining pressure level on the seismic characteristics of the dam, sinusoidal-wave-sweep shaking table tests on the dam model were performed under a centrifuge acceleration of 30 g. In the tests, the specified amplitude of sinusoidal acceleration wave was input, while the vibration frequency was swept from 60 Hz to 350 Hz for the model, which corresponds to 10 Hz - 11.7 Hz for the prototype. The smaller input accelerations of 0.5 g, 1.0 g, and 2.0 g were taken respectively, corresponding to 17 Gal, 35 Gal, and 67 Gal under the prototype.

Fig. 7 provides the frequency transfer functions of the dam near crest obtained from such sinusoidal-wave-sweep shaking table tests. Comparing Fig. 7 with Fig. 5, the natural frequency of first order is seen to be 6 - 8 Hz for the case of the shaking table tests under the centrifuge acceleration of 30 g, but it is 8 - 13 Hz for the case of 14.7 g. This shows that the dynamic characteristics of the dam are significantly different due to the difference in confining pressure level. Similarly, in the shaking table tests under 30 g, the predominant frequency decreases as the input acceleration increases.

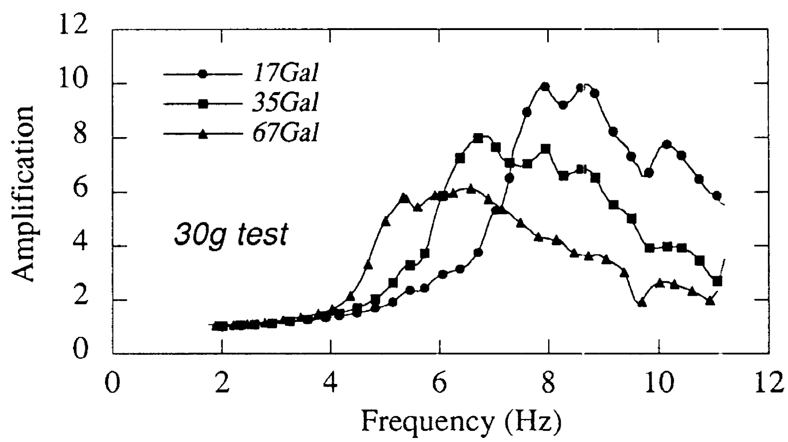

Fig.7 Frequency transfer functions of the dam near crest obtained from sinusoidal-wave-sweep shaking table tests

Response of the Dam to Earthquake Shaking

The El Centro earthquake record was adopted as an input seismic wave after the seismic time was compressed on a scale of one-thirtieth and the peak acceleration was adjusted proportionally to 6.2 g which corresponds to the peak prototype acceleration of 210Gal. The shaking table test was performed under the centrifuge acceleration of 30 g. Fig. 8 shows the response acceleration time histories measured at three locations inside the dam. The acceleration is found to increase from the base to the crest, indicating the amplification characteristics of the dam. In addition, Fig. 9 shows the frequency transfer functions of the crest response with respect to the base input which was obtained through the Fourier transformation of the data shown in Fig.8. Comparing Fig. 9 with Fig. 8, there is the difference in response characteristics of the dam due to the difference in input acceleration time history.

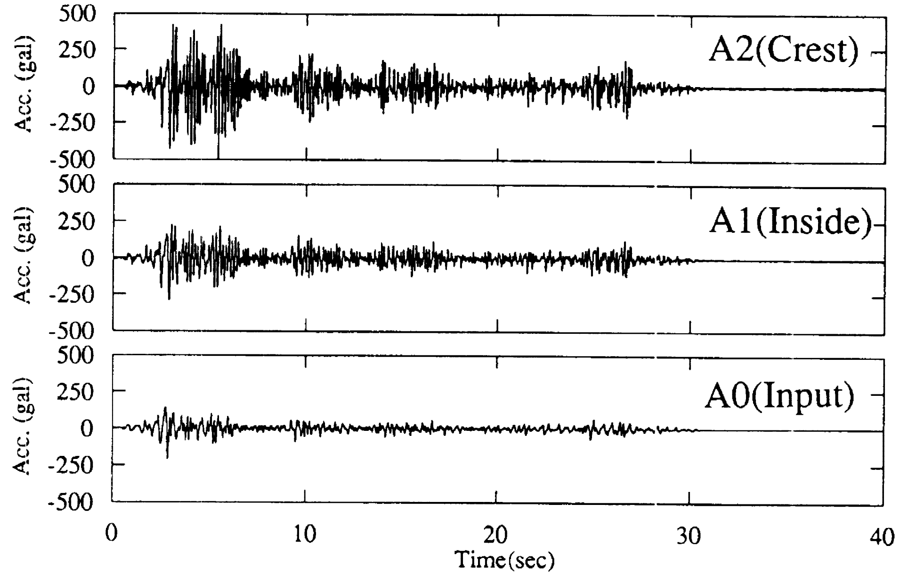

Fig.8 Response acceleration time histories measured at three locations inside the dam

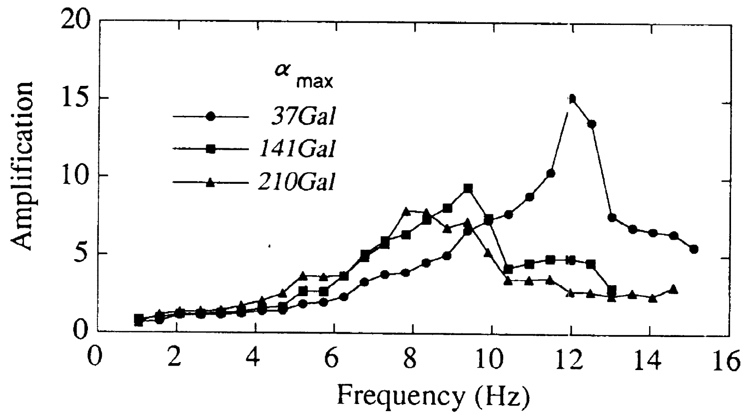

Fig.9 Frequency transfer functions of the crest response with respect to the base input

CONCLUSIONS

Dynamic centrifuge modeling has been performed to reproduce the seismic behavior of earth dam. Based on the experimental results, the following facts have been confirmed: 1) Dynamic centrifuge model tests could reproduce well the seismic response of the dam under 1 g field; 2) With increasing confining pressures, both the natural frequency of first order and the response amplification decrease obviously, indicating the significant influence of the confining pressures on the seismic behavior of the dam. These show that dynamic centrifuge modeling is an effective approach to examine the actual seismic behavior of the prototype earth dam, particularly for larger scale earth dams.

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