1-G Model Test with Digital Image Analysis for Seismic Behavior of Earth Dam

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ABSTRACT: This paper proposes a new experimental method using small 1-G shaking table tests to investigate the seismic behavior of an earth dam. In this research, a digital image analysis was applied to observe strain distributions during excitation. White gauge points were placed on the surface of the model and the movements of these points were analyzed via successive digital image pictures. From the displacements of the gauge points, the distributions of shear strain and volumetric strain were examined as the functions of the acceleration response of the dam body. As a result of the volumetric strain distributions, it was found that vertical tension and compression zones exist in turn, and that tensile stress was observed at the top of the model. It was estimated that the crack at the crest of the earth dam, brought about by the earthquake, was attributed to the tensile stress.

1. INTRODUCTION

In Japan, there are approximately 200 thousand small earth dams, which have been very important sources of water supply for irrigation for a long time. These small earth dams are shorter than 15 m in height and are called irrigation tanks in Japanese. However, many of these irrigation tanks were constructed over one hundred years ago. Thus, details of the irrigation tanks are unknown and the strength of these small earth dams has been deteriorating with time. Kato (2005) reported that there are 20,000 irrigation tanks in need of repair. Of course, Japan also has many earth dams higher than 15 m, which have been subjected to past strong earthquakes. As for these earth dams, damage such as cracks at the crest, induced by earthquakes, has been reported. Nevertheless, most of the dams are manageable and have maintained their reservoir function, according to Masukawa *et al*. (2012) and Tani (2000). After the Great East Japan Earthquake, however, it was reported by Ono *et al*. (2011) that the earthquake-induced failure of the embankment of the Fujinuma Dam, a homogeneous earth dam with a height of 17.5 m, resulted in eight deaths in a village downstream.

One of the most important factors in the seismic safety of dams is the dynamic response. The difference in properties, including the water content of the material and the shape of the dam, influences the seismic response. Investigations of the seismic behavior of dams have been conducted mostly based on numerical analyses. However, the seismic behavior of dams is still not well understood.

Two types of dynamic tests have been used for the dynamic model tests, namely, dynamic centrifuge tests and 1-G shaking table tests. Dynamic centrifuge tests utilize the gravity force to simulate a prototype scale dam. Kim *et al*. (2011) conducted dynamic centrifuge tests to simulate an earth-core rock-fill dam (ECRD) and a concrete-faced rock-fill dam (CFRD). In these tests, the amplification of the acceleration and the residual horizontal and vertical deformations of the dam body were analyzed. Sharp and Adalier (2006) studied the seismic response of an earth dam with a clay core at the center on a foundation having a loose liquefiable layer. The acceleration, the excess pore pressure and the deformation of the dam body were measured, while varying the depth of the liquefiable layer. Ng *et al*. (2004) performed centrifuge model tests on a loose fill embankment to investigate its dynamic response and liquefaction when subjected to uni-axial and bi-axial earthquakes. The following previous studies include the performance of 1-G shaking table tests. Torisu *et al*. (2010) studied the residual displacement of a fill dam model with a clay core and a homogeneous sandy dam model using medium-sized 1-G shaking table tests. Lin and Wang (2006) studied the seismic behavior of a slope model with large-scale shaking table tests. They focused on the acceleration amplification and concluded that its effect appears to be quite significant. Masukawa *et al*. (2004) experimentally studied a homogeneous earth dam in order to examine cracks on the slopes in a longitudinal direction. They concluded that the cracks were brought about by the tensile stress in the slopes, and that the tensile forces with both horizontal and vertical shaking motion became larger than those with only horizontal shaking motion.

The study presented in this paper includes the performance of 1-G shaking table tests with a digital image analysis. Since most of the previous studies have focused on the acceleration response or the residual deformation, such as slide failure and the settlement after an earthquake, the objectives of this paper are to propose a new experimental method using small shaking table tests with a digital image analysis and to investigate the seismic behavior of earth dams in terms of the shear strain and the volumetric strain during earthquakes based on this method.

The image-processing technique or the digital image analysis was used to be utilized to observe strain localization due to shear banding within triaxial test specimens. Sachan and Penumadu (2007) tested a cylindrical clay specimen on which a latex membrane with dots, marked in a grid pattern, was placed. Pictures of this specimen were taken during the triaxial tests and the strain localization was calculated. Oka *et al*. (2005) studied the strain localization of rectangular clay specimens, having a rubber membrane on which 2-mm-square meshes were drawn. In this paper, the new experimental method, which combines shaking table tests with the above digital image analysis technique, is proposed.

2. TEST PROGRAM

2.1 Shaking table

In the present study, shaking table tests were carried out on earth dam models in a 1-G gravity field. A small shaking table, 610 mm in length, 480 mm in height and 250 mm in breadth, was used in this study, as shown in Figure 1. Using this shaking table, the frequency and the amplitude of the shaking motion can be adjusted. A horizontal acceleration up to approximately 280 gal can be provided.

2.1 Model preparation

In this study, two types of dam models with different cross-sections were investigated. The first type, the small model, with a height of 150 mm and upstream and downstream gradients of 1:0.545, and the second type, the large model, with the same height and a gradient of 1: 1.5, were used in order to produce a qualitative picture of the effect of the difference in model shape, especially the gradient of the slope, on the dynamic behavior. The sizes of the models are very small compared to those in previous studies and to the sizes of actual dams because of the limited shaking table size and acceleration capacity. However, preparations for the experiment are so simple that many experiments can be performed. The uncertainty caused by a small number of experiments is resolved and a parametric study can be easily performed. Therefore, this paper aims to propose a new experimental method and to qualitatively evaluate the seismic behavior of earth dams during earthquakes.

The effect of hydrodynamic pressure on the dam body was examined using the special water tank shown in Figure 2. Its surface, which faces the slope of the dam body, is made of a rubber membrane in order to prevent water from penetrating into the dam body and allowing water to be contained on the upstream side. The special water tank with rubber membrane could avoid surplus wave of contained water and dam overtopping. Therefore, hydrodynamic pressure was applied on the upstream slope during the earthquake simulation. The seepage flow into the dam body was not considered because the study aims to investigate the seismic response of the dam body. Shaking table tests were performed in the full reservoir state and then in the empty reservoir state. At the same time, four pressure gauges were installed on the slope of the dam body and an acceleration transducer was attached to the water tank. Then, the time histories of the hydrodynamic pressure and the input accelerations were simultaneously measured to survey their correlation to each other. Schematic views of the experimental set-ups of the small and the large models are shown in Figures 3 and 4, respectively.

Figure 5 shows the grain size distribution curve for the sand used in the construction of the models for the dam body. The other physical properties of the sand were an optimal water content of about 11% and a maximum dry density of 1.88 g/cm^3. Although the seismic behavior of the full-scale dam could not be investigated because the method could not satisfy the similarity rule, the qualitative picture of the seismic response could be investigated. Preparations for the experiment were as follows. For the dam model, the sand was mixed with water at the designed water content. In order to investigate the effect of the water content on the seismic behavior of the dam body, the water content levels of the examined dam models were 8%, 10%, 12%, 14% and 16%, as shown in Table 1. Then, the mixture was placed in a mould, made by the authors, and was compacted by a rammer at an approximate compaction energy level of 550 kJ/m^3. The dam model was placed directly on the shaking table. In order to generate enough friction between the dam model and the shaking table, a rubber sheet was laid on the shaking table. Since the dam model was fixed with the shaking table and the table was shaken in upstream and downstream direction, it resulted in a two-dimensional condition.

Table 1 Testing program

	Model	Water content (%)	Gradient of slope
Case 1	SA,SB	8	1:0.454 (Small model)
	SC,SD	10	
	SE,SF	12	
	SG,SH	14	
	SI,SJ	16	
Case 2	LA,LB	8	1:1.5 (Large model)
	LC,LD	10	
	LE,LF	12	
	LG,LH	14	
	LI,LJ	16	

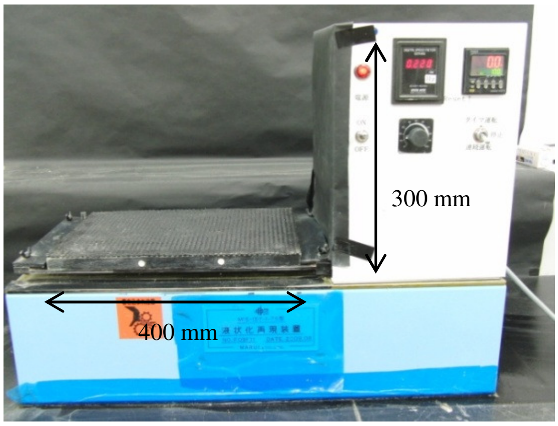

Figure 1 Shaking table

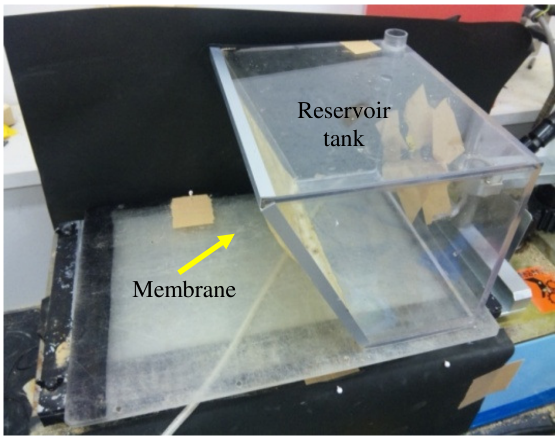

Figure 2 Special water tank with rubber membrane

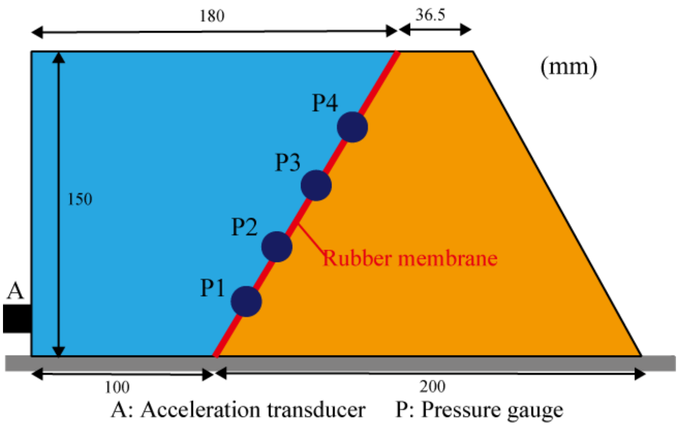

Figure 3 Schematic view of experimental set-up (Model with slope gradient of 1:0.545)

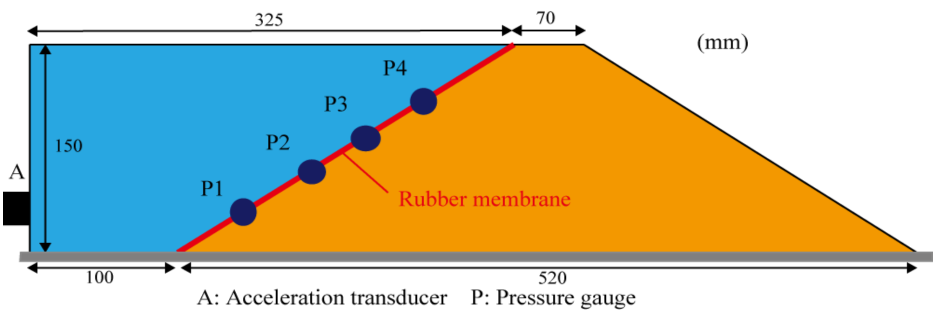

Figure 4 Schematic view of experimental set-up (Model with slope gradient of 1:1.5)

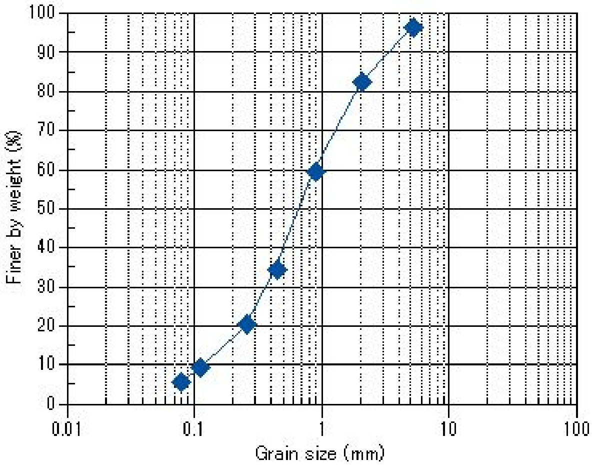

Figure 5 Grain size distribution curve for material

2.1 Testing and monitoring program by digital image analysis

All dam models were subjected to an input of 1.4 Hz to 2.4 Hz horizontal harmonic shaking, and accelerations were recorded with the acceleration transducer attached to the reservoir tank. The amplitude of the shaking motion was approximately 100 gal. The dam model was shaken over a wide range of frequencies under specified input acceleration levels. Two samples, with mostly the same water contents, were prepared. The results were evaluated using their average value.

Most of the previous studies have focused on the acceleration response or the residual deformation, such as the slide failure and the settlement after an earthquake. In this study, we investigated the strain value or the strain distribution in the cross-section of the dam. However, the model used in the tests was so small that the measurement instruments, such as the acceleration transducer and the displacement transducer, could not be installed. Therefore, a digital image analysis was performed. The analysis in this study used 28 white gauge points for the small model tests and 66 gauge points for the large model tests. The gauge points were placed on the surface of each dam model, as shown in Figures 6 and 7. Then, the gauge points on the surface of the models were tracked using high resolution images. A digital camera (CASIO EX-F1) with approximately 6 million pixel resolutions (2112 H: 2816 V) was used to obtain the digital images of each dam model. The following steps show the digital image analysis proposed in this paper.

Firstly, one static image was taken before each model was excited. While the model was shaken, continuous images were taken, as shown in Figures 6 and 7. The dynamic situation was observed by the temporal resolution of 60 images per second. Next, these images were downloaded into a personal computer. The downloaded images were transformed into black and white binary images in order to make the image process quick and easy. In these binary images, not only the white gauge points, but also the noise was found as white elements. Thus, it was necessary to remove this noise, as shown in Figure 8. After that, by calculating the center of each white element, representing the gauge points, the coordinates of the gauge points were measured in the unit of pixels. Finally, the observed distance between two points on the surface of the shaking table, which was exactly 100 mm, could also be measured in the unit of pixels. The scale calibration was carried out by the observed distance in pixels and the known value in mm. Consequently, all the coordinates of the gauge points in each image could be measured in the unit of mm. By repeating this procedure on the static image and 60 dynamic images, the displacement trace for each image could be obtained.

The velocity of each gauge point was calculated by dividing the difference in displacements by the serial shoot duration time, and the acceleration was obtained by dividing the difference in velocity by the time. The relative displacement of a gauge point was calculated by subtracting the absolute displacement of the gauge point on the shaking table from the absolute displacement of the gauge point on the surface of the dam body. The relative displacements of three gauge points were used to evaluate the shear strain and the volumetric strain of the triangular element made by connecting the three points under a two-dimensional condition. In this research, the vertical and the lateral length of each element were almost the same. Considering the gauge points as nodes, the shear strain and the volumetric strain of each element were evaluated. In this research, the positive value is an extension and the negative value is compression for the volumetric strain.

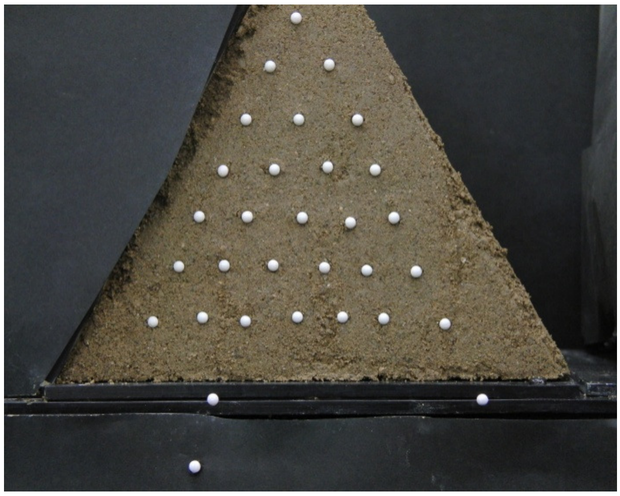

Figure 6 Small model with gauge points

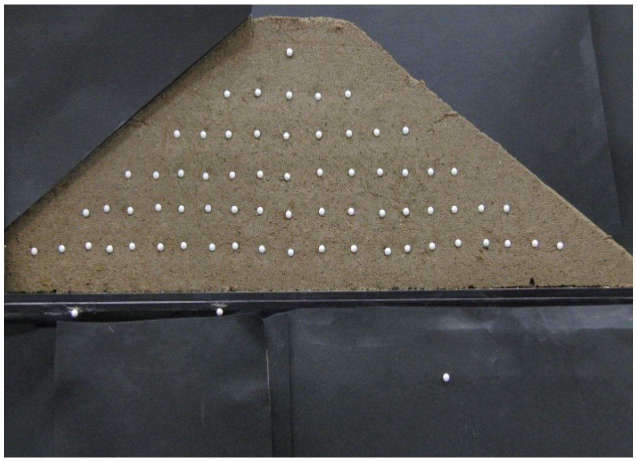

Figure 7 Large model with gauge points

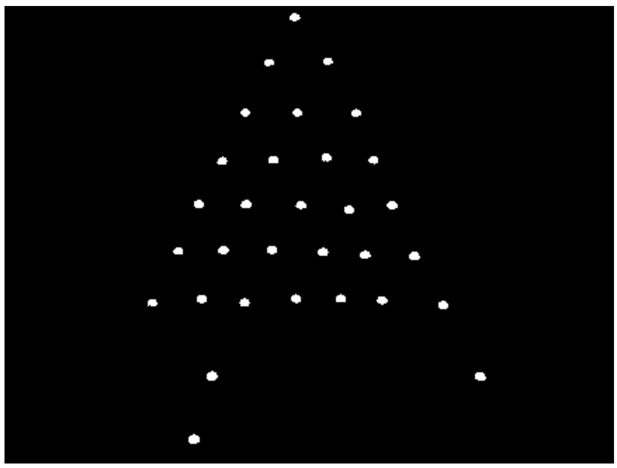

Figure 8 Binary image for digital image analysis

3. RESULTS AND DISCUSSION

3.1 Hydrodynamic pressure

The hydrodynamic pressure applied to the upstream slope of the dam model was measured by the pressure gauges on the slope. At the same time, the acceleration of the input motion was measured by the acceleration transducer on the reservoir tank. In this way, the time histories of the acceleration and the hydrodynamic pressure were obtained, as shown in Figure 9. The period when the peak acceleration was measured is different from that when the peak hydrodynamic pressure was measured. The hydrodynamic pressure reached its maximum, or minimum, after the peak acceleration.

The input acceleration, measured by the acceleration transducer on the reservoir tank, and the hydrodynamic pressure, measured by the pressure gauges, were obtained simultaneously. However, the values computed by the digital image analysis from successive images, such as the displacement of each gauge point, the shear strain or the volumetric strain, and the values obtained by the measurement instruments, such as the acceleration or the hydrodynamic pressure, could not be obtained simultaneously. To resolve this problem, the acceleration was calculated by the difference in the observed displacement of each gauge point and, in turn, the difference in velocity. By synchronizing the computed acceleration and the measured acceleration, as shown in Figure 10, the correlation between the hydrodynamic pressure and the other parameters could be investigated. Moreover, the measured acceleration and the computed acceleration were mostly comparable. Thus, the digital image analysis was successfully conducted.

Figure 11 shows the time histories of the hydrodynamic pressure and the acceleration response near the crest. The acceleration response was defined by subtracting the computed acceleration of the shaking table from of the gauge point near the crest. As can be seen in the Figure 11, the acceleration response became the maximum just after the peak hydrodynamic pressure. Therefore, according to Figures 9 and 11, the input acceleration influenced the hydrodynamic pressure, in turn, the hydrodynamic pressure affected the acceleration response.

Figure 12 presents the time histories of the hydrodynamic pressure and the displacement of the shaking table for model LA with a frequency of 2.43 Hz, respectively. The positive value means the displacement toward the downstream side, while the negative value means the displacement toward the upstream side. As seen in the figure, when the hydrodynamic pressure became the maximum, or minimum, the displacement of the shaking table was zero, which means the shaking table was located at the center.

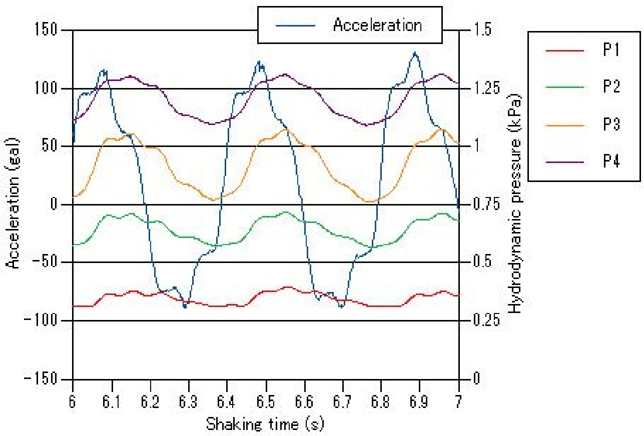

Figure 9 Time histories of measured acceleration and hydrodynamic pressure

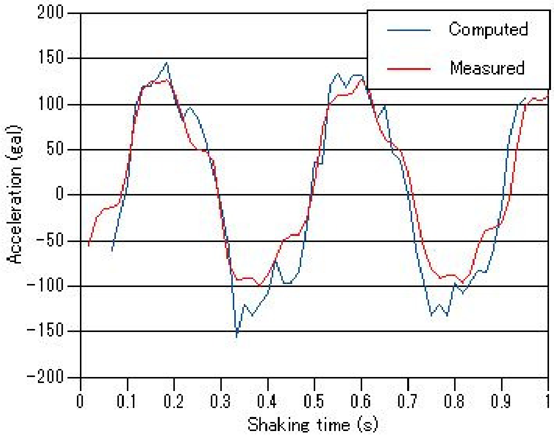

Figure 10 Measured and computed accelerations

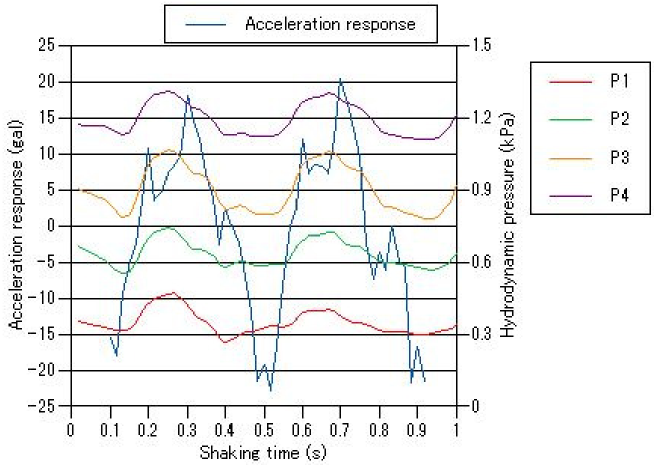

Figure 11 Time histories of acceleration response and hydrodynamic pressure (Large model)

Figure 12 Time histories of displacement of shaking table and hydrodynamic pressure (Large model)

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