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Vibration model tests on the seismic characteristics of raised fill dams

H. Tagashira, Y. Hayashida, S. Kuroda & S. Masukawa
Incorporated Administrative Agency National Agriculture and Food Research Organization (NARO)
National Institute for Rural Engineering (NIRE), Tsukuba, Japan
tagataga@affrc.go.jp

ABSTRACT:
Dynamic centrifuge model tests and 1g shaking table model test were carried out in order to investigate the seismic characteristics of raised fill dams. Four types of dam body model were made: one was an existing dam, another was a trapezoidal embankment made of the raised new dam body material, another was a raise fill dam without the middle layer (transition layer) on the existing dam body, and the other was a raised one with the middle layer. They were made of No.6 silica sand with 5% of water content and three kinds of relative density: 50% for the existing dam body, 75% for the middle layer and 95% for the raised new dam body. Five sine waves with maximum acceleration of 100, 200, 300, 400 and 500 cm/s^2 were input in order. As a result, the following characteristic phenomena were recognized; larger settlement at the raised new dam body crest than that at the existing dam body crest, horizontal displacement of the raised new dam crest toward the existing dam crest, local intense change of displacement and acceleration amplification ratio at the boundary between the two dam bodies or at the middle layer, and the possibility of the middle layer function in the reduction of response acceleration.
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Keywords: Raised fill dam, Seismic characteristics, Centrifuge model test, 1g shaking table test

1. INSTRUCTION

Heightening of a dam is an effective means for recovery or increasing of the active storage capacity at low cost and at relatively low environmental burden. In the case of raising of fill dams, the newly raised part usually has higher rigidity than the existing one because of the differences in embankment material and compaction method. The difference in rigidity between the two parts is expected to cause the distinct behaviors in earthquakes from unraised fill dams to raised ones. They are not sufficiently clarified, though a few studies by numerical analysis (Tani et al., 2009) were carried out. In addition, the seismic effect of the middle layer, or transition layer, on the existing part, intended to suppress the local rapid material property change, is not fully understood either. The purpose of this paper is to elucidate the seismic characteristics of raised fill dam with particular focus on the effect of the middle layer using vibration model tests.

2. VIBRATION MODEL TESTS PROCEDURE

2.1. Selection of dam type

The heightening design of a fill dam can be categorized by the positional relationship of the two dam axes into three types: one is the design in which the dam axis of the raised dam body is downstream of that of the existing dam body, another in which the former is upstream of the latter, the other in which both the axes almost coincide with each other. In this research, homogeneous earthfill dam of the first type was selected as the examination target, taking into consideration that many of the aged fill dams consisted of a generally homogeneous soil material and that the type was often adopted in the raising of water utilization dams because of its advantage that the reservoir operation could be made during the construction work.

The existing part, the raised part except the middle layer, and the middle layer of a raised fill dam are reffered as "Zone Ⅰ", "Zone Ⅱ", and "Zone Ⅲ"), respectively hereafter.

2.2. Centrifuge model test

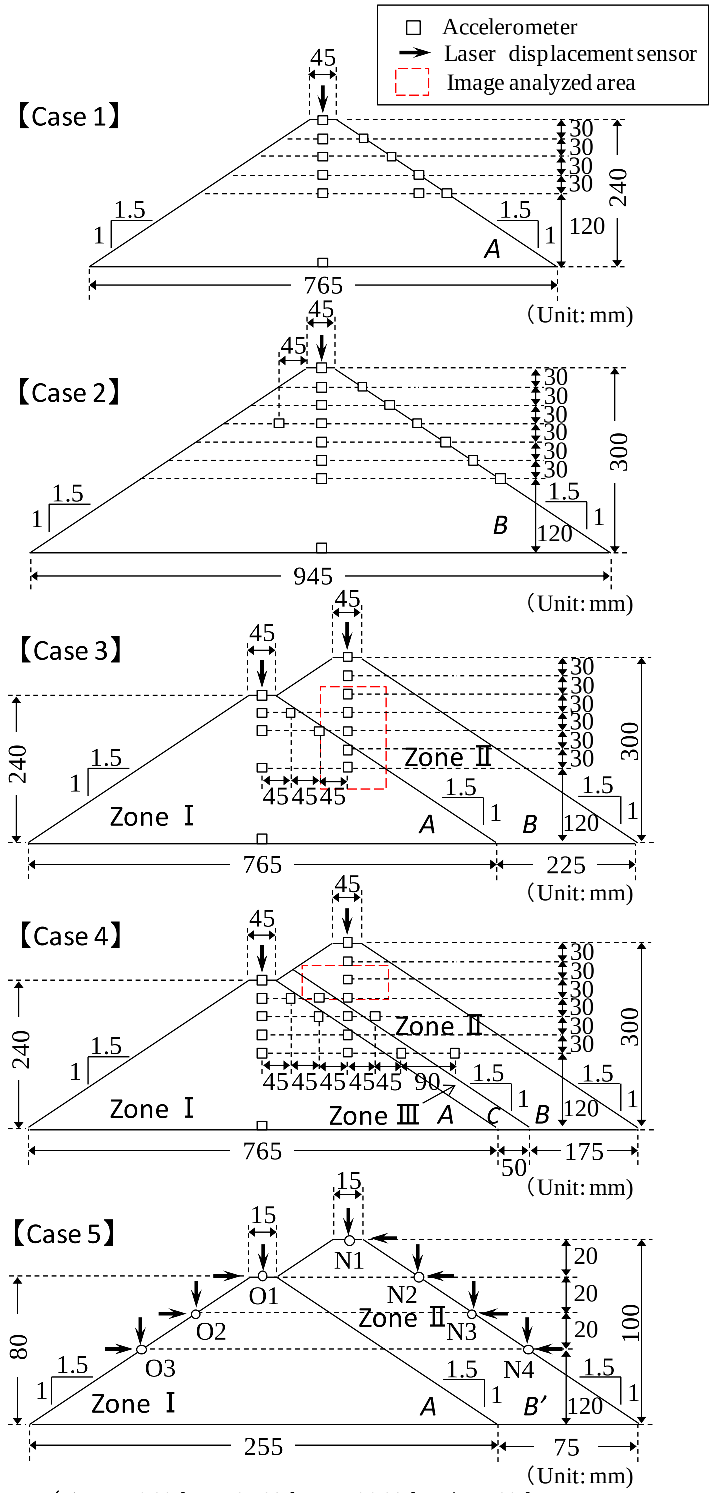
2.2.1. Specifications of the centrifuge

The centrifuge of beam type equipped with a swing up platform was used in this research. The arm radius was 2.60 m for dynamic test. The excitation apparatus had a shaking table of 700 mm long and 400 mm wide and could provide a maximum amplitude of ±3.0 mm, a maximum dynamic acceleration of 25 *g*, a maximum shaking force of 118 kN, and a maximum frequency of 400 Hz. The model container was shaken in the direction perpendicular to the rotation plane, in other words, in the vertical direction. Acrylic resin plates were fitted and fixed to the one side of the aluminum sidewall of the container so that we may watch and take pictures of the side face of a model.

2.2.2. Model geometries

Four kinds of models shown in Figure 1 were constructed. All of them have the crest length of 295 mm. The slope gradients are set to 1:1.5 at the upstream and the downstream sides, which is considerably steep for fill dams, in order the deformation by shaking to become larger. The ratio of the height of Zone Ⅱ to that of Zone Ⅰ was 1.25. Case 1 simulated an existing fill dam. Case 2 corresponded to a new dam with the same height as Zone Ⅱ. Case 3 and Case 4 had the same outer shape and imitated a raised fill dam without Zone Ⅲ and one with Zone Ⅲ respectively.

All models consisted of No.6 silica sand with the density of soil particle of 2.653 g/cm^3, the coefficient of curvature of 2.11, the particle size at 50% accumulated weight of 0.324 mm, and 5% of water. The minimum and maximum densities Obtained from the minimum and maximum densities test of sands were 1.384 g/cm^3 and 1.666 g/cm^3 respectively. Three kinds of relative density were prepared: 50% for Case 1 and Zone Ⅰ in Case 3 and Case 4, 75% for Zone Ⅲ and 95% for Case 2 and Zone Ⅱ in Case 3 and Case 4.



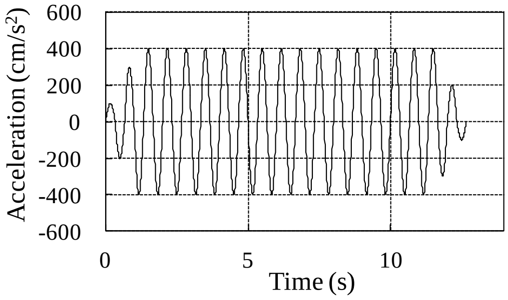
(*) D_r : 50 % for *A*, 95 % for *B*, 100 % for *B'*, 75 % for *C*

Case 1~4: for centrifuge test Case5: for 1*g* shaking table test

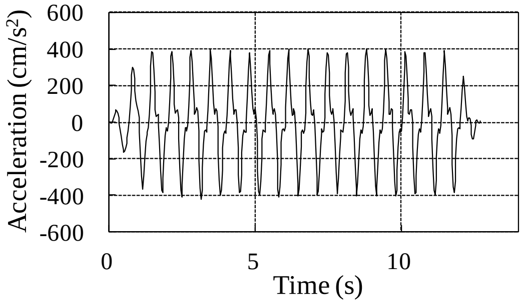
Figure 1. Outline of models

2.2.3. Input motion and measurements

All models were consolidated and shaken at a 60*g* gravitational acceleration field. They were subjected to similar input motion as shown in Figure 2 along the upstream and downstream direction, which was a sine wave of 1.5Hz (converted value into a 1*g* field) and 16 cycles with front and rear taper waves of 1.5 cycles. In each case, the input motion



(a) Target input motion



(b) Observed input motion

Figure 2. Example of input motion for centrifuge tests (converted into a 1g field)

was set 100, 200, 300, 400, 500 cm/s^2 (converted values into a 1*g* field) incrementing in order, and the test was finished without switching to the next acceleration level if a slip occurred in the model.

The response during shaking of the acceleration in the upstream and downstream direction and the vertical displacement at the crests were monitored at an interval of 5 ms (converted value into a 1g field). The transducers were installed as shown in Figure 1. After shaking at each acceleration level, a picture of the one side of the model on the acrylic resin plates was taken for later use in the displacement measurement by image analysis with CCIP method (Ueno et al., 2000). Each model was cut and the outline of the central cross section was sketched after the test finishing.

2.3. 1*g* shaking table test

A 1*g* shaking table test was performed in order to complement centrifuge tests. Centrifuge tests have the large advantage of simulating the stress levels in real dams but have the disadvantages that they cannot satisfy the similarity laws on the soil grain size, that they have some difficulties in the visual inspection because of their small size and that the number of the monitoring points is decreased by their spatial restriction. On the other hand, 1*g* shaking table tests are free from the problems, though they have the demerit of low stress level.

2.2.1. Specifications of the apparatus
A tri- axial shaking table of 6 m long and 4 m wide was used. In this test, the model was shaken only in one horizontal direction. The apparatus could provide a maximum amplitude of ±15.0 mm in the horizontal directions and a maximum frequency of 40 Hz.

The horizontal maximum dynamic acceleration ranged from 0.5 g with a maximum load (= 50t) to 1.0 *g* without load.

2.2.2. Model geometries, input motion and measurements
The model for this test is shown in Figure 1. It had the cross section similar to that of Case 3 and the crest length of 400cm. The input motion was a sine wave of 10 Hz and 290 cycles with front and rear taper waves of 5 cycles. The other shaking procedures were similar to the above centrifuge tests. The vertical displacement and horizontal displacement in the upstream and downstream direction were monitored at an interval of 2 ms by the transducers installed as shown in Figure 1. The model was cut and the outline of the central cross section was sketched after finishing the test.

3. RESULTS

3.1. Deformation

Figure 3 shows the final deformed models for all cases. Slips occurred at the maximum acceleration level of 400 cm/s^2 in Case 1, Case 3 and Case 4, and at that of 500cm/s^2 in Case 2 and Case 5. In Case1 and Case 2, slips appeared in both slopes and the destruction forms of the models were almost similar to each other. On the other hand, a slides occurred only in Zone Ⅰ with its top being at the crest in Case 3~5, which simulated raised fill dams.

While many cracks other than the slip line were recognized in Case 5, no cracks could be found out in the other cases. It is thought that one of the reasons for this was the fact that the distance between the lighting incandescent lamp and the model was short and the surface area was heated and dried by the lamp in the centrifuge tests.

In Case 3~5, the boundary between the zones bent toward Zone Ⅰ in the upper area. The curvature amount of the line in Case 4 was smaller than that in Case3. It indicates that Zone Ⅲ might reduce the displacement near the boundary area. The low stress level in Case 5 is considered to be the reason that the bending amount of the borderline in Case 5 is smaller than that in that in Case3.

3.2. Response Displacement
Figure 4 shows the measured vertical displacements at the centers of the crests in the centrifuge tests, converted into a 1g field. While the subsidence amount rose steeply and became unmeasurable at the maximum acceleration level of 400cm/s^2 in Case 1, those on Zone Ⅰ in Case 3 and in Case 4 were smaller than that in Case 1. It means that the heightening of a fill dam might decrease the settlement in Zone Ⅰ. It is consider that Zone Ⅱ and Zone Ⅲ acted as a counterweight fill. The settlement on Zone Ⅱ was larger than that on Zone Ⅰ in both Case 3 and Case 4. It is believed that the long distance from the bottom to the crest of Zone Ⅰ and the sudden decrease of the sectional width at the Zone Ⅰ crest level caused large vibration and deformation in the top area of Zone Ⅱ. From the comparison between Case 3 and Case 4, it seems that Zone Ⅲ has the function of making the settlement at Zone Ⅰ crest smaller and that at Zone Ⅱ one larger.

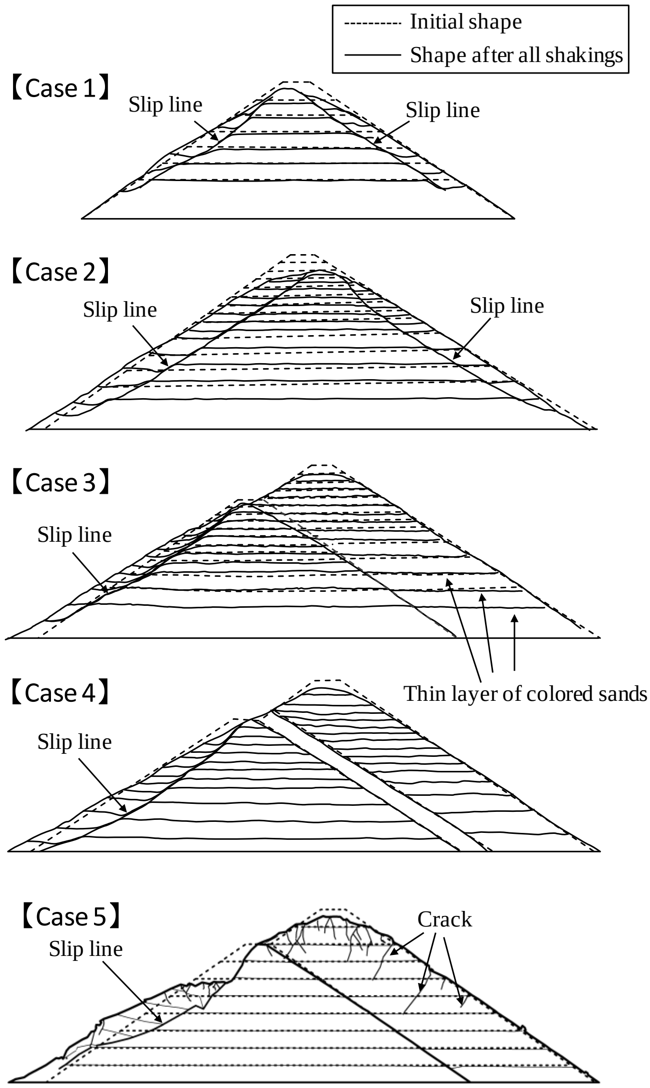


Figure 3. Deformation of the central cross section

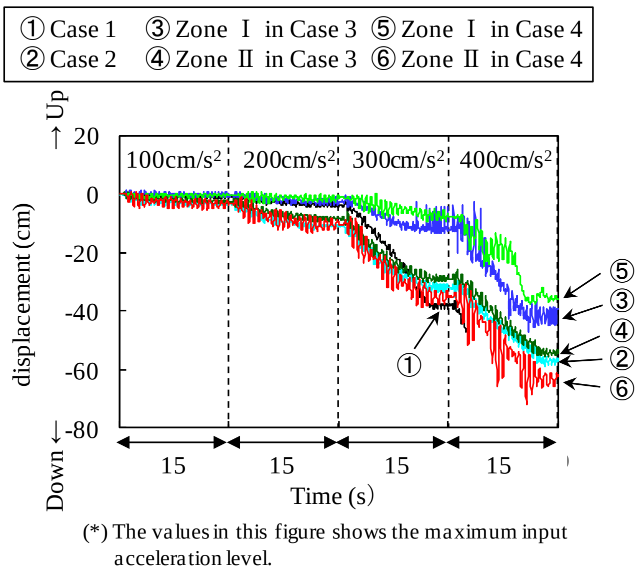
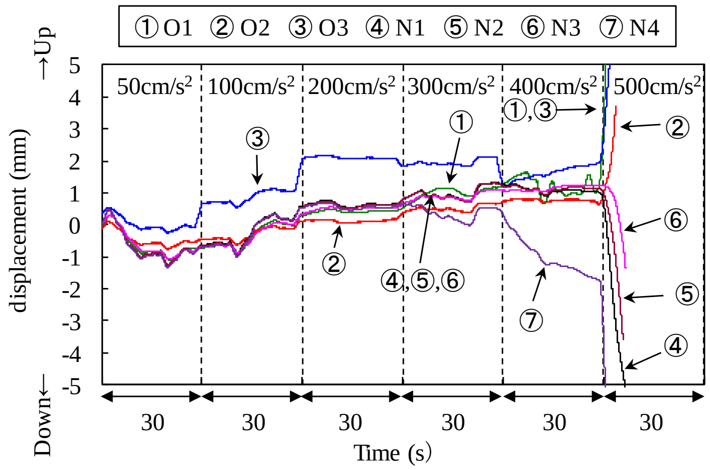


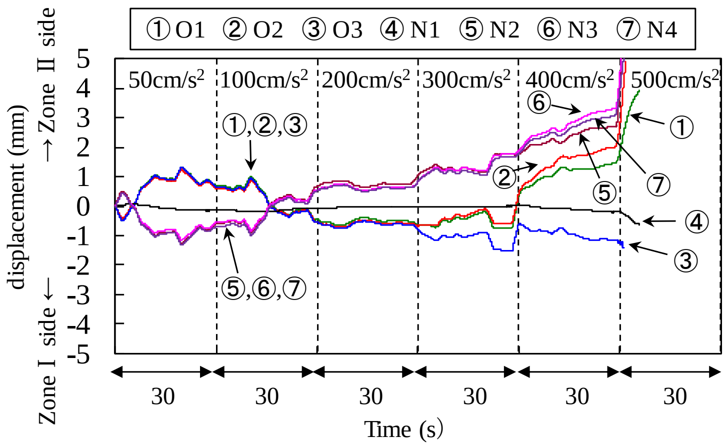
Figure 4. Observed vertical displacement at the crests in the centrifuge tests (converted into a 1g field)

Figure 5 and Figure 6 show the histories of the vertical and lateral displacements in the 1*g* shaking table test. Moving averages for 100 data are plotted in the figures because of the large fluctuation in a short period. The disappearance or dramatic change of the lines at the maximum acceleration level of 500 cm/s^2 means the rapid movement or removal of the target plate for the laser displacement sensor caused by the occurrence of a slip or a crack. In Figure 5, the settlements at all observation points increases gradually from the beginning but decreases from the middle of the maximum acceleration level of 50 cm/s^2. The target plate mounted an inserting plate to the model surface on the rear face. It is supposed to that there was a weak point in the integration property of the target and the surrounding soils due to the very low lateral confining pressure, which is supported by the fact that the fluctuation of the vertical displacement was much larger than that of the horizontal one. Turning our attention to Figure 6, it is noted that the crest on Zone Ⅱ (N1) slightly moves toward Zone Ⅰ side.



(*) The values in this figure shows the maximum input acceleration level.

Figure 5. Observed vertical displacement in the 1*g* shaking table test

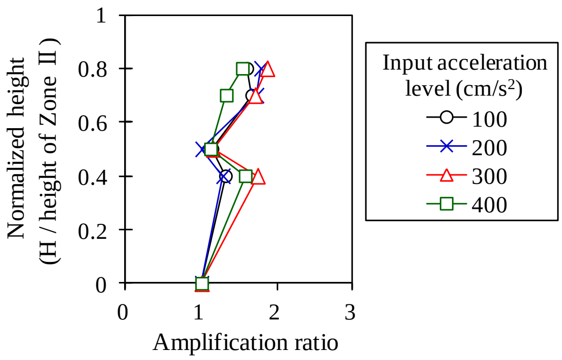


(*) The values in this figure shows the maximum input acceleration level.

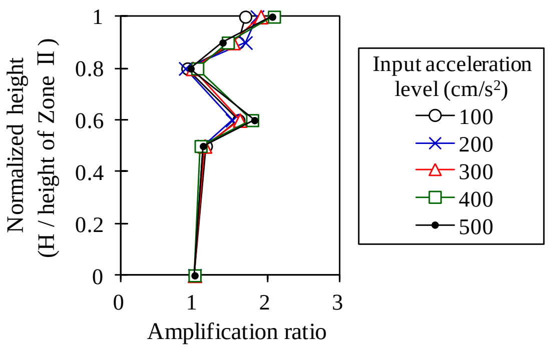
Figure 6. Observed horizontal displacement in the 1*g* shaking table test

3.3. Response acceleration

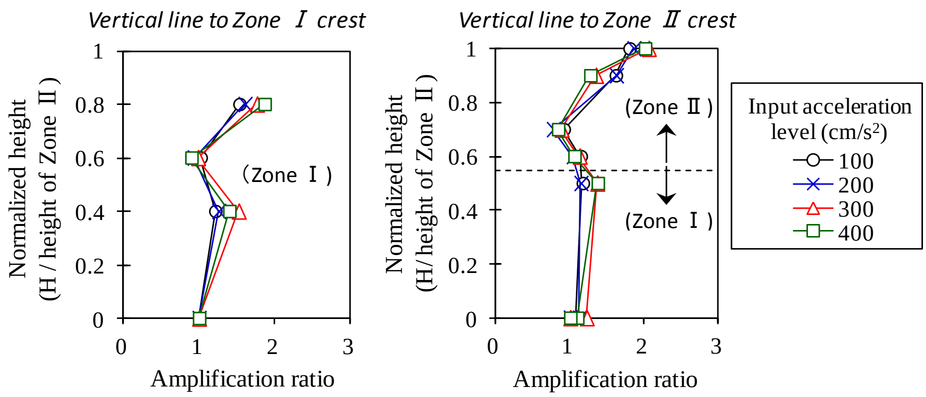
The observed acceleration data were corrected by the parabolic method. Figure 7 plotted the distributions of acceleration amplification ratio at the vertical line to the crest. The



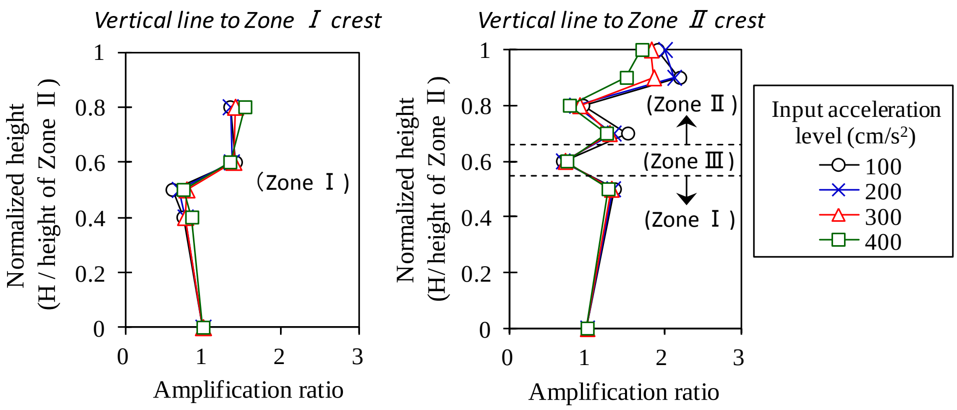
(a) Case 1



(b) Case 2



(c) Case 3



(d) Case 4

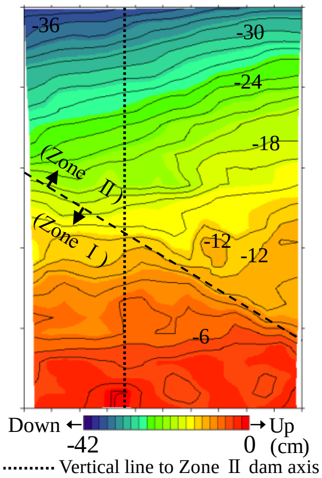
Figure 7. Distributions of acceleration amplification ratio at the vertical line to the crest

value at each maximum acceleration level is determined to be the largest one among the amplification ratio at each cycle. While the acceleration amplification ratio, generally speaking, increases gradually from the bottom to the top at the center in a homogeneous dam body like Case 1 and Case 2, some monitoring points are not consistent with this tendency in the two cases. There was the possibility of the local disturbance near the sensors or stiffness dispersion.

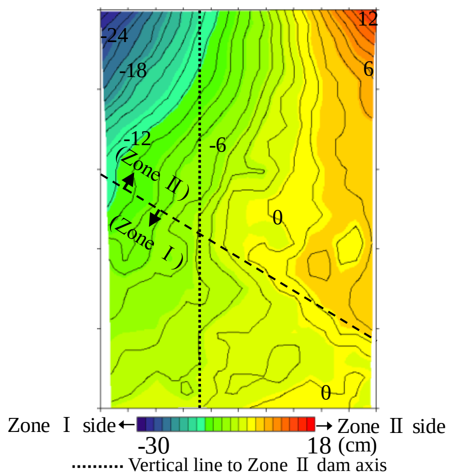
The ratio in Zone Ⅱ increased rapidly from the crest level of Zone Ⅰ, which supported the supposition about the large settlement of Zone Ⅱ in Figure 3. The decrease of the ratio in Zone Ⅲ in Case 4 indicates the possibility of the response acceleration reducing function of Zone Ⅲ, though careful attention should be paid to the influence of the local disturbance and stiffness dispersion mentioned above.

3.4. Displacement Distribution

Figure 8 and Figure 9 show the displacement distribution near the boundary after all the shakings obtained from image analysis in Case 3 and Case 4 respectively, converted into a 1g field. The analyzed areas are shown in Figure 1. It is clear that the local change at the boundary is more remarkable in the upstream and downstream direction than in vertical

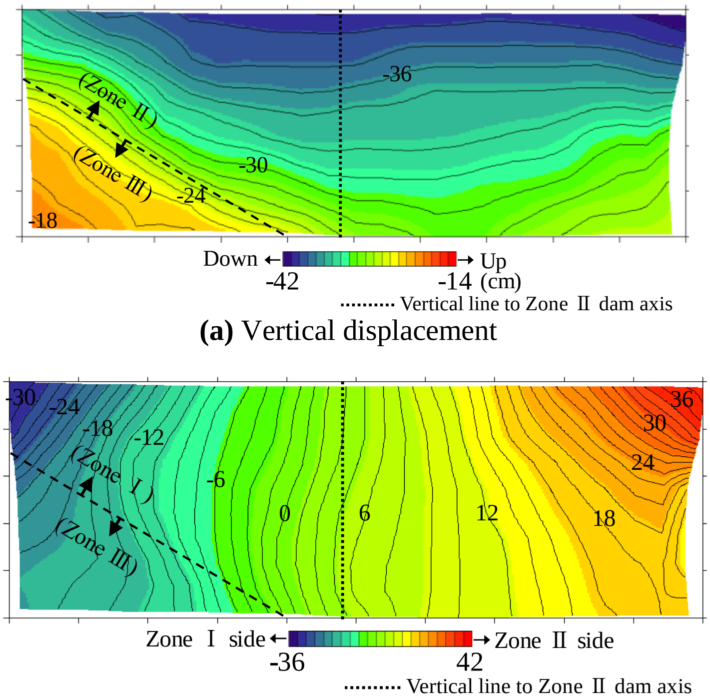


(a) Vertical displacement



(b) Horizontal displacement

Figure 8. Distributions of displacement in Case 3



(a) Vertical displacement

(b) Horizontal displacement

Figure 9. Distributions of displacement in Case 4

direction and that the settlement in the upper part of Zone Ⅱ is not symmetrical with the dam axis face as a center but larger in the Zone Ⅰ side than in Zone Ⅱ side except the slope surface area.

4. CONCLUSIONS

In this study, some characteristics of raised fill dams and the effects of the mille layer have been made clear by the centrifuge tests and 1g shaking table test, namely,larger settlement at the raised new dam body crest than that at the existing dam body crest, horizontal displacement of the raised new dam crest toward the existing dam crest, local intense change of displacement and acceleration amplification ratio at the boundary between the two dam bodies or at the middle layer, and the possibility of the middle layer function in the reduction of response acceleration, and so on. It needs further investigation with additional tests and numerical analysis in order to solve the problems found in a part of the measured data.

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