Experimental Study on Seismic Response Behavior of Fill Dams Influenced by Dam's Shapes and Input Wave's Directions

Y. Hayashida, S. MASUKAWA, I. ASANO & H. TAGASHIRA
National Institute for Rural Engineering, National Agriculture and Food Research Organization, Tsukuba, Japan.
fill@affrc.go.jp

ABSTRACT:
The characteristics of the seismic behaviour of fill-type dams were examined by shaking table tests, in which three shapes of dam models, namely, symmetric about both a maximum cross section and a dam axis, symmetric about only a dam axis, and asymmetric about both a maximum cross section and a dam axis, were shaken separately in the stream direction and in the dam axis direction, and then the effects of the dam's shape and the direction of the input wave on the seismic response behaviour were verified. From the results of the experiment, the point at which the maximum acceleration values were recorded during the shaking in the stream and the dam axis directions was found to be right above the deepest part of the dam's valley. It was clarified that the response orthogonal to the shaking direction could arise depending on the shapes of the dam, the direction, and the dominant frequencies of the input waves. In particular, in the case of shaking in the dam axis direction, the point at which no response could be incited appeared on the crest of the dam depending on the shape of the dam and the dominant frequencies of input waves.

Keywords: Fill dam, Seismic response, Shaking table test, Shape of dam, Direction of input wave

1. INTRODUCTION

After the Southern Hyogo Prefecture Earthquake in 1995, huge earthquakes have been occurred frequently in Japan, for example the Mid Niigata Prefecture Earthquake in 2004, the Iwate-Miyagi Nairiku Earthquake in 2008, the 2011 off the Pacific coast of Tohoku Earthquake and so on.

No fill dam designed by seismic coefficient method was utterly destroyed caused by such huge earthquake motion. However, damages such as settlement and longitudinal cracks at crest were observed (Kohgo,Y. 2016; Masukawa,S., et.al. 2000, 2002, 2005, 2009, 2012 and 2014). It is supposed that these damages are caused by the complicated three dimensional seismic behaviour of dam body. So it is considered that the complicated three dimensional seismic behaviour of dam body in higher seismic mode will be important factor to manage the safety of existing dams.

In this study, the characteristics of the seismic behaviour of fill type dams were examined by shaking table tests, in which three dam models with different shapes were shaken separately in the stream direction and in the dam axis direction, and then the effects of the dam's shapes and the direction of the input wave on the seismic response behaviour were verified.

2. TEST METHOD

2.1. Property of Dam Models

Three types of dam model which have different shapes are tested to evaluate the effect of dam's shapes to their seismic behaviour. A model consists of the dam body made of silicon rubber and abutment made of metal frames and wood board. Schematics of dam models are shown in Fig. 1.

The shape of Model A is symmetric about both a maximum cross section and a dam axis. The shape of Model B is symmetric about only a dam axis and the shape of Model C is asymmetric about both a maximum cross section and a dam axis. All models have same height, length of crest and slope gradient, their height are 300 mm, their lengths of crest are 1200 mm and their slope gradients are 1: 2.5. Accelerometers are set on the appointed place shown in Fig. 1 to record the acceleration during tests. Arrows on Fig. 1 show the direction of positive acceleration value.

2.2. Test condition

This study intends to verify the change of seismic behaviour according to shaking direction and frequency of input wave.

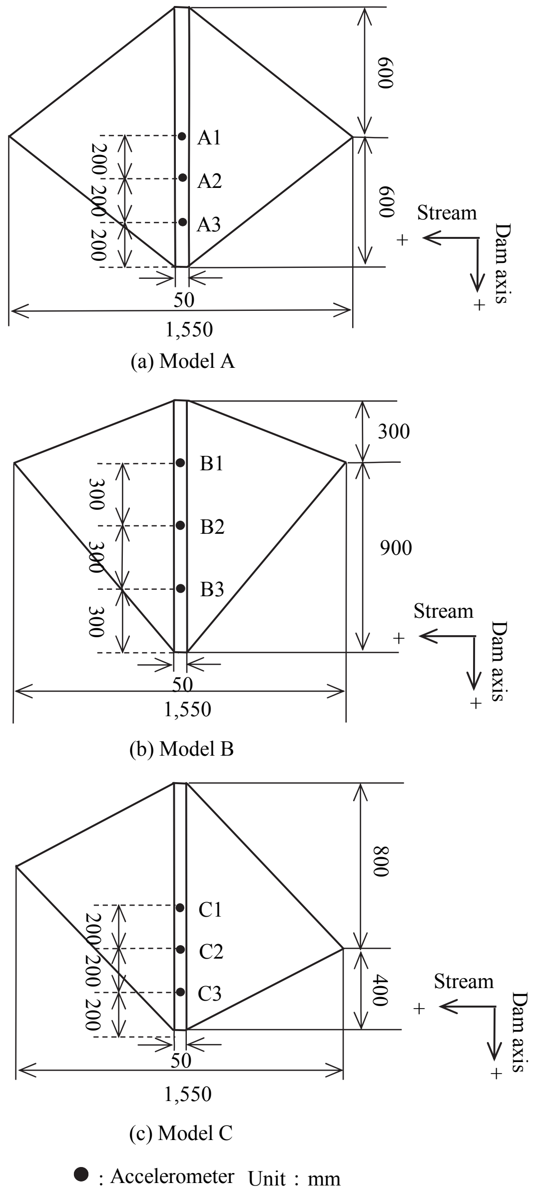


Figure 1. Shape of models

Shaking directions are stream and dam axis direction, the former is called as Case 1, and the latter is called as Case 2. Input waves used in tests are sine waves whose frequency are swept from 0.6 Hz to 14.0 Hz and their amplitude are 1.0 m/s^2. However, the shaking table test device used in test cannot sweep the frequency from 0.6 Hz to 14.0 Hz thoroughly because of the limitation of data volume in a test. So two waves are adopted as input waves. Wave 1 sweeps the frequency from 0.6 Hz to 9.3 Hz, and Wave 2 sweeps the frequency from 4.7 Hz to 14.0 Hz. Amplitude of each wave is 1.0 m/s^2.

Table 1 shows the specification of the experiment cases. Fig. 2 shows results of acceleration records measured at the shaking table in an experiment. As shown in Fig. 2, it is found that amplitudes of input waves are almost 1.0m/s^2 and the shaking table test device represented the prescribed amplitude value of input waves.

Table 1. Specifications of experiment cases

	Experiment case	Frequency (Hz)	Amplitude (m/s^2)	Shaking direction
Frequency sweep	Case 1	0.6 ～9.3 (WAVE 1) 4.7～14.0 (WAVE 2)	1.0	Stream
	Case 2	0.6 ～9.3 (WAVE 1) 4.7～14.0 (WAVE 2)	1.0	Dam axis

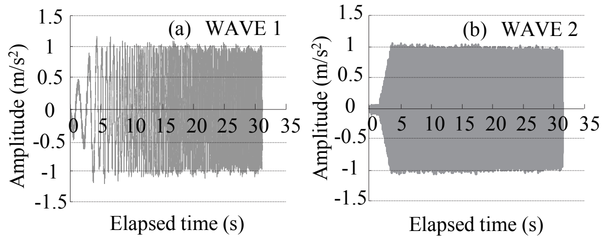


Figure 2. Input waves

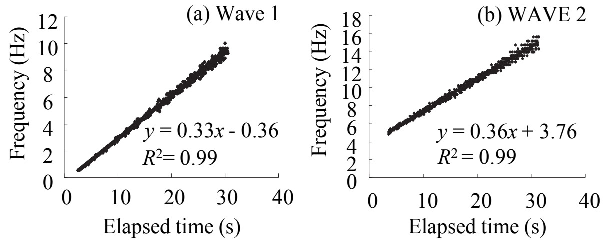


Figure 3. Frequencies of input waves changing with elapsed time

Fig. 3 shows the relation between frequencies of acceleration records measured at the shaking table and elapsed time. As shown in Fig. 3, frequency of both waves increase lineally between prescribed frequency ranges, in WAVE 1 at a rate of 0.33 Hz/s and in WAVE 2 at a rate of 0.36 Hz/s. From these results, it is confirmed that shaking table device can reproduce the required amplitude and frequency of input waves.

3. TEST RESULTS AND CONSIDERATION

3.1. Acceleration Response

The direction and maximum value of acceleration response are focused on. The maximum values of acceleration response (absolute values) measured in the test are shown in Table 2. Acceleration loci on the horizontal plane (stream and dam axis plane) are shown in Fig. 4. Herein, results of Wave 1 (frequency is from 0.6 Hz to 9.3 Hz) and Wave 2 (frequency is from 4.7 Hz to 14.0 Hz) are merged into a graph, so each graph shows the acceleration loci at the frequency swept from 0.6 Hz to 14.0 Hz. Two direction arrow in each graph shows shaking direction.

As shown in Fig. 4 (a), all points of Model A response to only shaking direction in both cases. As shown in Fig. 4 (b), all points of Model B response to only shaking direction in Case 1. But, in Case 2, B1 and B2 response to shaking direction (dam axis) and its orthogonal direction (stream) like drawing a ellipse on the horizontal plane. At B1 which is right above the deepest part of the valley, the maximum absolute value of acceleration response to shaking direction (dam axis) is 6.9 m/s^2 and that to its orthogonal direction (stream) is 3.0 m/s^2 (see Table 2). At B2 which is on the centre of crest, the maximum value of acceleration response to shaking direction (dam axis) is 6.5 m/s^2 and that to its orthogonal direction (stream) is 3.7 m/s^2. Thus, in Model B, it is found that the acceleration response orthogonal to the shaking direction will arise and the acceleration loci will show the ellipse shape on the horizontal plane when dam body is shaken to dam axis direction.

As shown in Fig. 4 (c), C1 which is right above the deepest part of the valley and on the centre of crest shows different behaviour from other points of Model A and Model B in Case1. The maximum value of acceleration response to shaking direction (stream) is 10.3 m/s^2 and then the value of acceleration response to its orthogonal direction (dam axis) shows -1.2 m/s^2 simultaneously. The minimum value of acceleration response to orthogonal direction (dam axis) is -2.0 m/s^2 and then the value of acceleration response to shaking direction shows 3.1 m/s^2 simultaneously. Thus, in Model C, C1 which is right above the deepest part of the valley and on the centre of crest will response to not only the shaking direction but also the direction orthogonal to input wave when the shaking direction is stream. In Case 2, C1 and C2 show the acceleration response orthogonal to shaking direction (stream). At C1, the minimum value of acceleration response to shaking direction (dam axis) is -9.3 m/s^2 and then the value of acceleration response to its orthogonal direction shows -1.2 m/s^2. At C2 the maximum value of acceleration response to shaking direction is 5.8m/s^2 and the value of acceleration response to orthogonal direction shows -1.1 m/s^2 simultaneously. The dominant response directions of C1 and C2 are opposite.

Table 2. Measured maximum acceleration values (Absolute values)

	Case 1 (Stream direction)			Case 2 (Dam axis direction)		
	Stream (m/s^2)	Dam axis (m/s^2)	Vertical (m/s^2)	Stream (m/s^2)	Dam axis (m/s^2)	Vertical (m/s^2)
A1	11.8	0.7	1.1	0.6	9.7	2.4
A2	5.5	1.4	0.6	0.5	5.3	3.9
A3	3.1	0.3	0.3	0.5	2.9	1.4
B1	8.6	0.7	0.6	3.0	6.9	4.4
B2	5.7	1.0	0.7	3.7	6.5	4.1
B3	4.2	0.7	0.3	0.6	2.3	1.2
C1	10.3	2.0	0.9	2.1	9.3	0.8
C2	4.3	1.3	0.9	2.4	5.8	3.8
C3	2.4	0.5	0.4	0.7	2.5	0.9

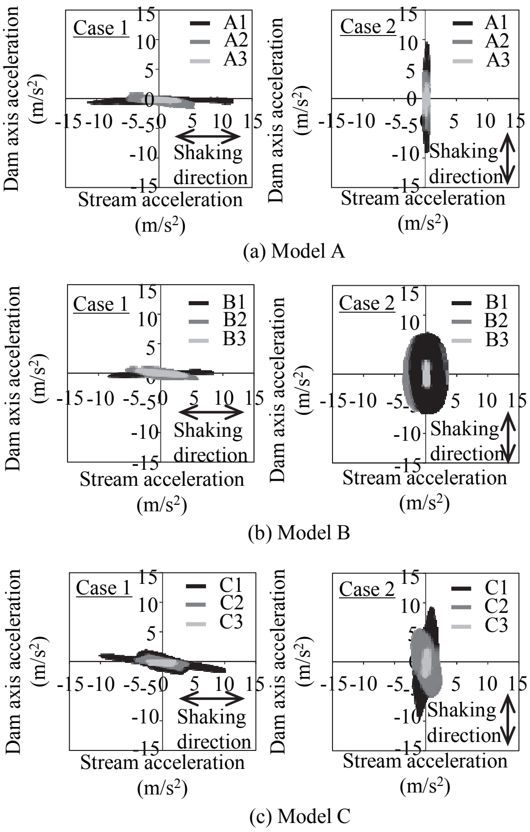


Figure 4. Loci of measured acceleration in stream and dam axis plane

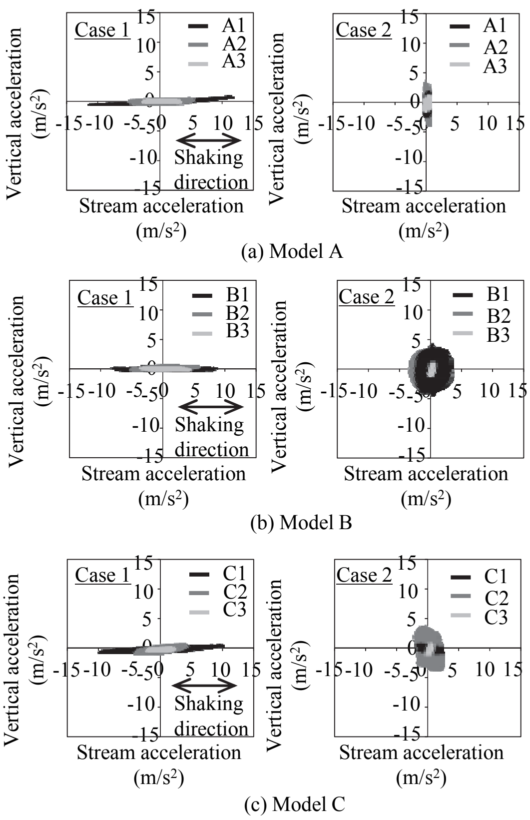


Figure 5. Loci of measured acceleration in stream and vertical plan

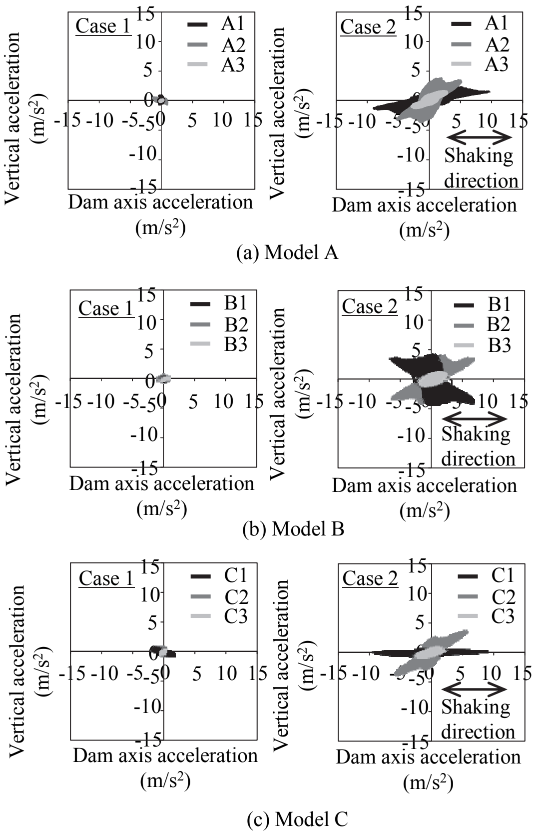


Figure 6. Loci of measured acceleration in dam axis and vertical plane

The acceleration loci of each model on stream and vertical plane and dam axis and vertical plane are shown in Fig. 5 and Fig. 6 respectively. In a graph without two direction arrow, shaking direction is perpendicular to the plain. All points of three models show little response to the vertical direction in Case1, but show remarkable response to the vertical direction in Case 2. In the case of Model A, the maximum value of acceleration response to the vertical direction are 2.4 m/s^2 at A1 which is right above the deepest part of the valley and on the centre of crest, 3.9 m/s^2 at A2 and 1.4 m/s^2 at A3 which is near to abutment. Thus, remarkable response to the vertical direction arise at all points of Model A. In the case of Model B, the maximum absolute values of acceleration response to the vertical direction are 4.4 m/s^2 at B1 and 4.1 m/s^2 at B2. The dominant response directions of B1 and B2 are opposite (see Fig. 6 (b) Case 2). In the case of Model C, the acceleration response to vertical direction at C1 and C3 are not remarkable but the maximum absolute value of acceleration response to vertical direction at C2 is 3.8 m/s^2.

From these results, it is found that the tendencies of acceleration response will be different at each point on dam's crest. When shaking direction is stream, points which is right above the deepest part of the valley (A1, B1 and C1) show the maximum value of acceleration response. Here, the value which is normalized the acceleration response value at each point by the amplitude of input wave is defined as response ratio. Maximum response ratios at A1, B1 and C1 are 11.8, 8.6 and 10.3 respectively (see Table 2). In Model A and Model C, the point which is right above the deepest position of valley corresponds to the centre of crest. But in Model B, the point which is right above the deepest part of the valley is near to abutment. Then, it is supposed that the value of response ratio at B1 is smaller than that at A1 and C1 because B1 is more strongly influenced by the abutment than the others.

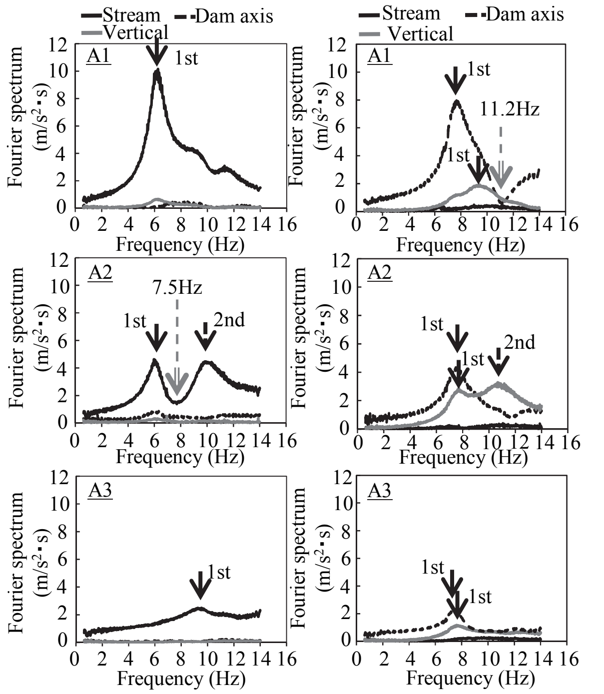
When the shaking direction is dam axis (Case 2), points which are right above the deepest part of the valley (A1, B1 and C1) show the maximum value of acceleration response. This tendency corresponds to that in Case 1. Maximum response ratio at A1, B1 and C1 are 9.7, 6.9 and 9.3 respectively. However, in Model B, B2 which is the centre of crest shows comparatively high response ration 6.5 which is almost same as B1. In Case 2, it is supposed that all models show the remarkable response perpendicular to the direction of input wave because deformation of dam body toward dam axis is restricted by the abutment and then dam bodies show the complicated three dimensional behaviour.

It is concluded that the point at which the maximum acceleration values were recorded during the shaking in the stream and the dam axis directions is right above the deepest part of the valley. It is clarified that the response orthogonal to the shaking direction could arise depending on the shapes of the dam, the direction of the input waves. Especially, when the shaking direction is dam axis, dam body will show the complicated three dimensional behaviour.

3.2. Relationships between Acceleration Response and Frequency

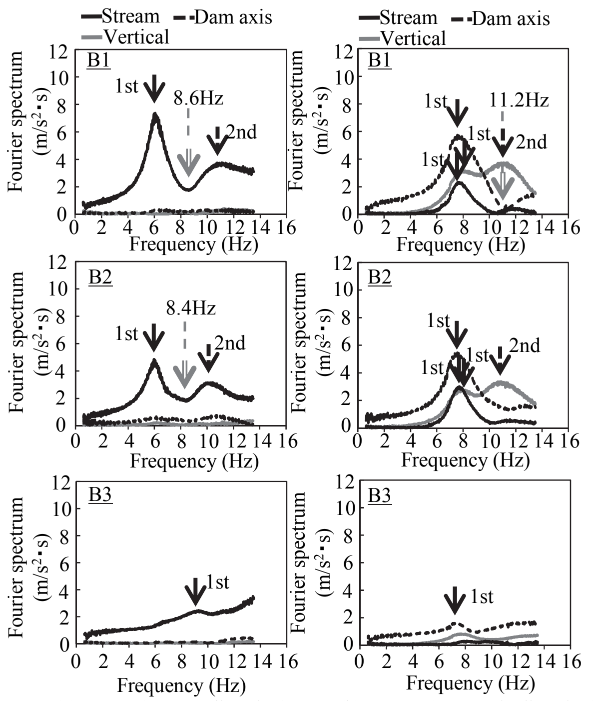
Fourier spectra analysed from the three components of acceleration response at each point of models by Fast Fourier Transform (FFT) are shown in Fig. 7, Fig. 8 and Fig. 9. Here, Fourier spectra analysed form the data of WAVE 1 and WAVE 2 are merged into a graph. In these figures, solid arrow shows 1st predominant frequency and broken arrow shows 2nd predominant frequency. Double arrow shows inflection point at which Fourier spectrum changes decrease to increase and its frequency value is shown too. Dominant frequencies at each point are shown in Table 3.

As shown in Fig. 7 (a), Fig. 8 (a) and Fig. 9 (a), in Case 1, all points except C1 response to only stream direction through targeted range of frequency. Dominant frequency at A1, B1 and C1 which are right above the deepest part of the valley show the maximum acceleration response value are 6.3 Hz, 6.1 Hz and 6.0 Hz respectively and these values are almost same (see Table 3). The shapes of Fourier spectra at A1 and C1 seems almost same and show a single peak remarkably. But the shape of Fourier spectrum at B1 is different from the others and show the double peak among targeted range, 1st predominant frequency is 6.1 Hz, 2nd predominant frequency is 11.5 Hz and frequency of inflection point at which Fourier spectrum changes decrease to increase is 8.6 Hz (see Table 3 and Fig. 8(a)).



(a) Case1 (Stream direction) (b) Case 2 (Dam axis direction)

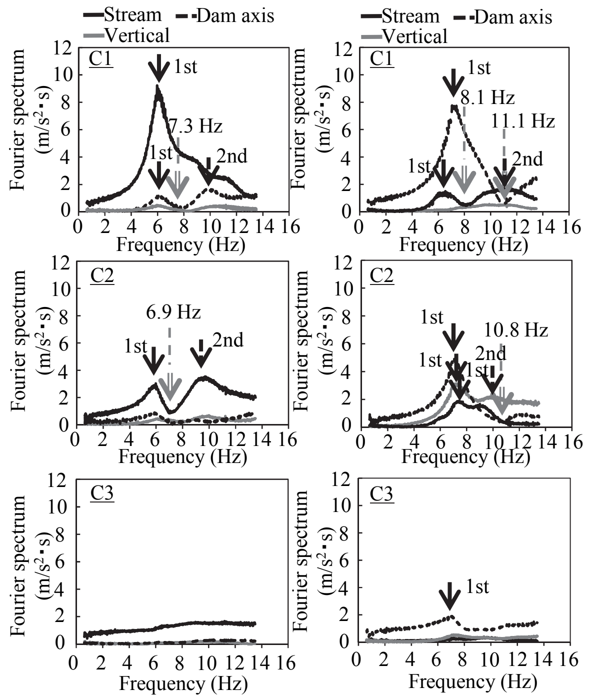
Figure 7. Fourier spectra of the amplitudes at each point in Model A



(a) Case1 (Stream direction) (b) Case 2 (Dam axis direction)

Figure 8. Fourier spectra of the amplitudes at each point in Model B

A1 and C1 are just above the deepest part of the valley and on the centre of crest, so they are less influenced by the abutment. On the other hands, B1 is just above the deepest part of the valley but near to abutment and B2 is on the centre of crest but depth is lower, so these points are affected by the restriction of abutment. The shapes of Fourier spectra at A2, B2 and C2 show the double peak same as B1 and B2. So, it is considered that shape of Fourier spectrum at the point which is less influenced by abutment shows remarkable single peak, but shape of Fourier spectrum at the point which is affect by the restriction of abutment shows double peaks or no remarkable peak.



(a) Case1 (Stream direction) (b) Case 2 (Dam axis direction)

Figure 9. Fourier spectra of the amplitudes at each point in Model C

Table 3. Measured dominant frequencies of each model

	Case 1			Case 2		
	Stream	Dam axis	Vertical	Stream	Dam axis	Vertical
A1	6.3	-	-	-	7.6	9.4
A2	6.0 (9.9)	-	-	-	7.6	7.7 (10.7)
A3	9.2	-	-	-	7.5	7.6
B1	6.1 (11.5)	-	-	7.6	7.6	8.2 (11.3)
B2	6.0 (10.0)	-	-	7.7	7.6	8.0 (10.8)
B3	9.3	-	-	-	7.2	-
C1	6.0	6.2 (9.7)	-	6.5 (11.1)	7.8	-
C2	6.0 (9.7)	-	-	7.4	7.0	7.1 (10.0)
C3	-	-	-	-	7.0	-

Unit: Hz, ( ): secondary predominant frequency, - : undetected

As shown in Fig. 7 (b), Fig. 8 (b) and Fig. 9 (b), in Case 2, the points at which the maximum Fourier spectrum are recognized is right above the deepest part of the valley (A1, B1 and C1) and the 1st predominant frequencies at A1, B1 and C1 are 7.6 Hz, 7.6 Hz and 7.8Hz respectively and these values are almost same (see Table 3). In Model B and Model C, the maximum response to the direction orthogonal to input wave on the horizontal plane arise at B2 and C2 and the dominant frequency of stream direction at their points are 7.7 Hz and 7.4 Hz respectively (see Table 3) . As shown in these figures, it is recognized that the response to the shaking direction (dam axis) at A1, B1 and C1 which show the maximum Fourier spectrum are none on the frequency at about 11.2 Hz shown by double arrows. Especially, at A1 and B1, no response to orthogonal direction on horizontal plane (stream) are recognized on this frequency. So it is considered that these points are nodes of horizontal vibration on this frequency. Thus it is confirmed that response property at the points on crest will change according to the frequency of input wave and the seismic behaviour of dam body shows the complicated three dimensional behaviour on a specific frequency. In Case 2, the vertical response orthogonal to input wave direction arise remarkably at A2, B1, B2 and C2, these values exceed the horizontal response on the 2nd predominant frequency of the vertical direction (A2: 10.7 Hz, B1: 11.3 Hz, B2: 10.8 Hz and C2: 10.0 Hz, see Table 3).

From these results, it is found that response toward the orthogonal direction to the shaking direction will arise in the complex shape of dam body such as Model C when shaking direction is stream. It is verified that complicated three dimensional response will arise in not only the complex shape of dam body like Model B and Model C but also the simple shape of dam body such as Model A when the shaking direction is dam axis on a specific frequency.

4. CONCLUSIONS

In this study, the characteristics of the seismic behaviour of fill type dams were examined by shaking table tests, in which three dam models with different shapes were shaken separately in the stream direction and in the dam axis direction, and then the effects of the dam's shapes and the direction of the input wave on the seismic response behaviour were verified.

From test results, it is concluded that the points at which the maximum acceleration values were recorded during the shaking in the stream and the dam axis directions are right above the deepest part of the dam's valley. It is clarified that the response orthogonal to the shaking direction could arise depending on the shapes of dam body, the direction and the dominant frequency of input waves. Especially, when the shaking direction is dam axis, dam body shows the complicated three dimensional behaviour. In particular, in the case of shaking in the dam axis direction, the point at which no response could be incited appeared on the crest of the dam depending on the shape of the dam body and the frequency of the input waves. So it is important to pay attention about the relation between seismic modes of dam body and dominant frequency of input wave when the data recorded by seismometers installed in real dams are analysed and the cause of dam's damage is examined

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