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LONG-TERM FLUCTUATION IN DYNAMIC CHARACTERISTICS AND PROPAGATING BEHAVIORS OF SEISMIC MOTION IN A ROCKFILL DAM-FOUNDATION SYSTEM

Norihisa MATSUMOTO[1], Nario YASUDA[2] and Zengyan CAO[3]

[1]Fellow member of JSCE, Advisor, Japan Dam Engineering Center
(2-9-7 Ikenohata, Taito-ku, Tokyo 110-0008, Japan)
E-mail: matsumoto@jcold.or.jp
[2]Member of JSCE, Dam Technology Research Institute, Japan Dam Engineering Center
(2-9-7 Ikenohata, Taito-ku, Tokyo 110-0008, Japan)
E-mail: yasuda@jdec.or.jp
[3]Member of JSCE, Social and Environmental Eng. Dept., JP Business Service Corporation
(2-2-18, Fukagawa, Koto-ku, Tokyo 135-8451, Japan)
E-mail: sou@jpbs.co.jp

With the earthquake records obtained during the last 23 years, analyses of transfer function, cross-spectrum and coherence function have been performed for a rockfill dam named Aratozawa dam (74.4m high and with central clay core). Based on analysis results, the fundamental frequencies and acceleration amplification factors of the dam were investigated. It was found that the fundamental (first natural) frequencies and the acceleration amplification factors of the dam sharply decreased temporarily, after being struck by the Iwate-Miyagi Nairiku Earthquake on June 14, 2008. However, these characteristics recovered almost to their original status about a week after the main shock. By investigating the propagating behavior of seismic motion in the dam-foundation system, it has been pointed out that in the low frequency range up to the fundamental frequency of the dam, the response of the dam crest mainly depends on the seismic motion of the subjacent bedrock. On the other hand, in the higher frequency ranges, the contribution of the seismic motion of both banks may become dominant depending on frequency.

Key Words: *rockfill dam, earthquake record, dynamic characteristics, propagating behavior, cross spectrum, coherence function*

1. INTRODUCTION

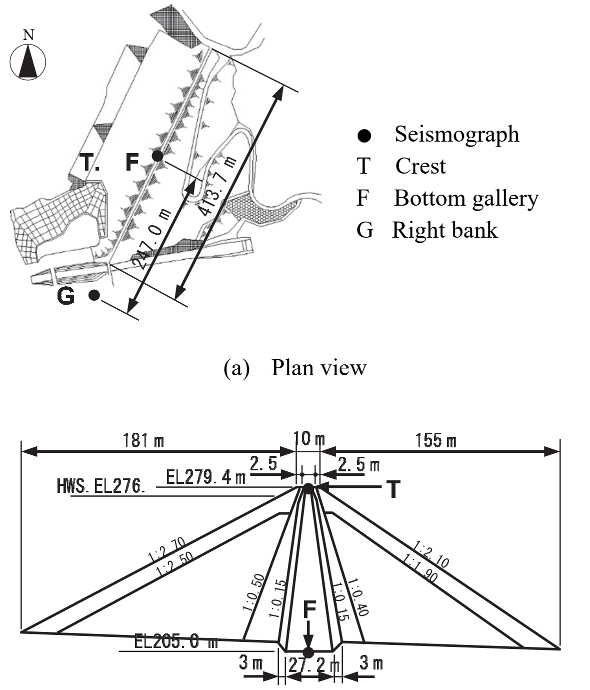
To ensure the seismic safety of dams, which are essential infrastructure facilities, monitoring the seismic behavior of dams during earthquakes and relevant researches on applying such monitoring data for maintenance and operation of dams are becoming increasingly important. In recent years, spectral analyses or statistical processions of earthquake records have been performed to evaluate the dynamic characteristics such as fundamental (first natural) frequency, acceleration amplification factors and damping properties, or to assess the soundness of dams. Matsumoto et al.[1)] obtained the fundamental frequencies of dams based on earthquake records, and presented these in their relationship to dam type, dam height, and the maximum acceleration of the foundation bedrock. Omachi and Tahara[2)] investigated the variation in shear wave velocity and shear elastic modulus of the embankment materials of the Aratozawa Dam based on earthquake records. They also examined the variation in excessive pore water pressure during and after the Iwate-Miyagi Nairiku Earthquake in 2018 to study the nonlinear dynamic properties of embankment materials. Mogi et al.[3)] performed normalized input-output minimization analysis (NIOM) on the earthquake records of the dam. The results clearly showed that shear wave transmission time in the dam body increased abruptly during the main motion of the earthquake, and the time decreased as the amplitude declined after the main motion. Sato et al.[4)] evaluated the dynamic deformation properties of a rockfill dam by analyzing earthquake records and used the results to perform reproduction analysis of the dynamic behaviors of the dam during the earthquake. Kondo et al.[5)] presented an approximate equation to show the relationship between the fundamental frequency of concrete gravity dam and the maximum acceleration of foundation bedrock and water level, etc. Ueshima et al. [6] clarified the effects of air temperature and reservoir level on the predominant frequency of an arch dam by analyzing the monitoring data of microtremors and seismic motions for a period of three-and-a-half years. This study demonstrates that it is possible to evaluate the soundness of a dam with such monitoring data.

However, most of the studies concerning earthquake monitoring and relevant analyses so far mainly survey with specific earthquakes or statistically survey the seismic events of large number of dams. This study has investigated the long-term fluctuation in the dynamic characteristics (fundamental frequency, acceleration amplification factor) of the Aratozawa Dam by analyzing its earthquake records over 23 years. Meanwhile, the influence of the Iwate-Miyagi Nairiku Earthquake on the dynamic characteristics of the Aratozawa Dam has been also clarified.

Traditionally, the aseismic design of dams on the other hand, premises that seismic motion vertically propagates uniformly from the bedrock under the dam. It does not consider the phase shifting at each elevation of abutments and its effects on earthquake responses of the dam. Therefore, in this study, analyses of transfer function between earthquake monitoring points, cross-spectrum and coherence function were performed based on earthquake records of the Aratozawa Dam, to investigate the correlation of the earthquake response of the dam crest with the seismic motion of subjacent bedrock and those of both banks. As a result, the contribution of the seismic motion of the subjacent bedrock and those of both banks to the earthquake responses of the dam crest has been clarified.

Table 1 Main features of the Aratozawa dam.

Dam location	Aratozawa, Miyagi Prefecture
Dam type	Rockfill dam with central clay core
Dam height	74.4 m (Lowest ground elevation: EL205.0 m)
Crest length	413.7 m
Crest width	10.0 m
Crest elevation	EL.279.4 m
Slope gradients	Upstream: 1:2.7 Downstream: 1:2.1
Dam volume	3,048,000 m^3
Basin area	20.4 km^2
Reservoir capacity	13,850,000 m^3
Design seismic coefficient	0.15 (dam body), 0.16 (spillway)



(a) Plan view

(b) Typical cross-section

Fig. 1 Locations of seismographs at the Aratozawa Dam.

2. DAM USED IN THE STUDY

(1) Dam specifications

The Aratozawa Dam is a rockfill dam with a central clay core 74.4 m high and completed in 1998. **Table 1** shows the main features of the dam. **Figure 1** is the plan view and the typical cross-section of the dam, and the locations of seismographs are shown in the figure. Seismographs are installed in three directions (stream, dam-axial, and vertical directions) at each monitoring point of the foundation (F), dam crest (T) and natural ground on the right bank (G), respectively.

(2) Outline of earthquake monitoring

A total of about 1,700 earthquakes from 1992 immediately after the completion of the dam embankment to 2015 were recorded. Of these, in the foundation bedrock, earthquakes with maximum acceleration 10 cm/s^2 or more and earthquakes with 100 cm/s^2 or more were recorded 500 times and 37 times, respectively. Particularly, the Iwate-Miyagi Nairiku Earthquake (M7.2, below referred to as “the main shock”) occurred on June 14, 2008, a maximum acceleration of 1,024 cm/s^2 in the stream direction at the foundation bedrock was recorded. This is the biggest earthquake record at dam foundation bedrock in Japan so far.

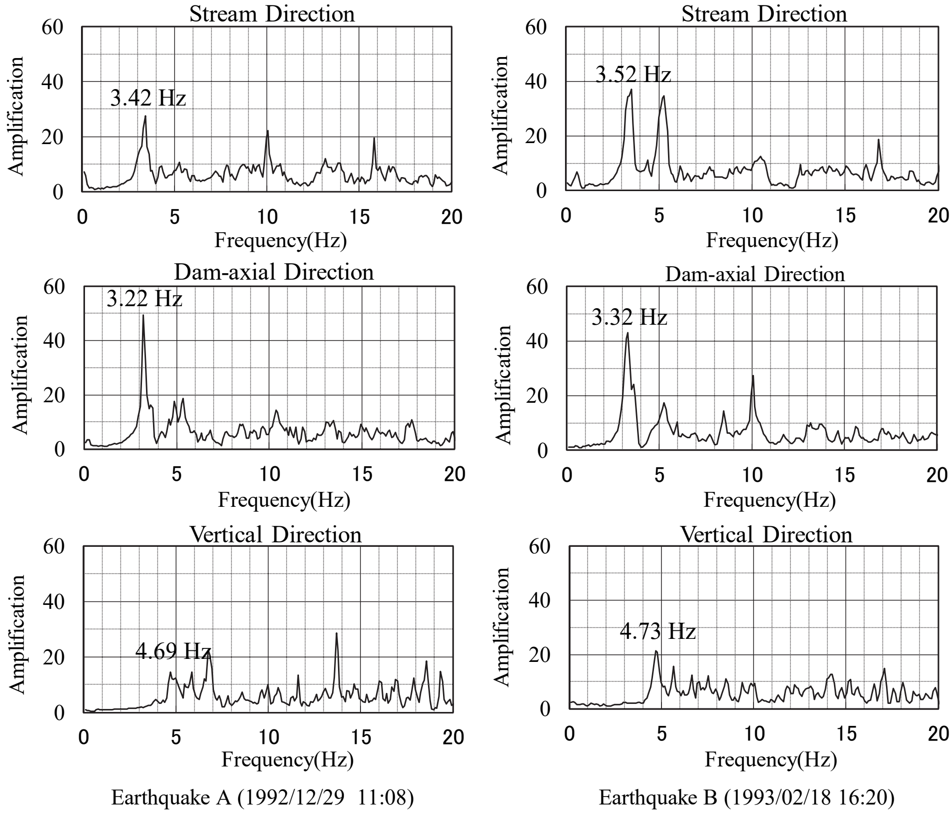


Fig. 2 Examples of transfer functions based on earthquake records.

3. LONG-TERM FLUCTUATION IN THE DYNAMIC CHARACTERISTICS OF THE DAM

The earthquake records of a dam reflect the dynamic characteristics (fundamental frequencies, acceleration amplification factors) of the dam. Therefore, it is possible to clarify the long-term fluctuation in the dynamic characteristics of the dam by analyzing the earthquake records of about 23 years mentioned above. The investigation focuses on the long-term fluctuation in fundamental frequency and acceleration amplification factor of the dam in each direction based on the analysis of earthquake records.

(1) Fluctuation in fundamental frequencies

Based on acceleration records at the foundation bedrock (F) and crest (T) of the dam, acceleration transfer functions of the dam were found. By examining the variation in the transfer functions, the fluctuation, if any, in the fundamental frequency of the dam in each direction and the trends of this fluctuation were studied. It is important to appropriately select the earthquake records to be used for finding the transfer function. With the consideration of microtremors (max. 1 cm/s^2 is assumed) and the resolution of measurement instruments (0.01cm/s^2), if the amplitude of the acceleration record is not sufficiently large, inaccuracy in analysis results will be relatively large. On the other hand, if the amplitude of the acceleration record is too large, nonlinear properties of the embankment materials, i.e., the decrement of the stiffness and the shift of the fundamental frequency of the dam will appear. Therefore, in this study, the records with maximum acceleration in the stream direction at the dam crest within the range of 10 to 20 cm/s^2 were selected. The measurement is thought to be precise, and the nonlinearity of the materials can be neglected. A total of 38 earthquake records were selected from earthquake records covering 23 years with consideration of their distribution in time. However, there was no earthquake record that satisfied the above selection criteria during the two days immediately after the main shock. As an exception, two earthquake records with the maximum acceleration in the stream direction at the crest of 123 cm/s^2 and 139cm/s^2 were selected as the objects of analysis.

Fourier spectra of the selected earthquake records were found and transfer functions of the dam (Fourier spectrum ratio between the crest (T) and foundation bedrock (F)) were obtained. **Figure 2** shows the examples obtained from the first two earthquake records in time series. The frequency corresponding to the first peak of the transfer function in each

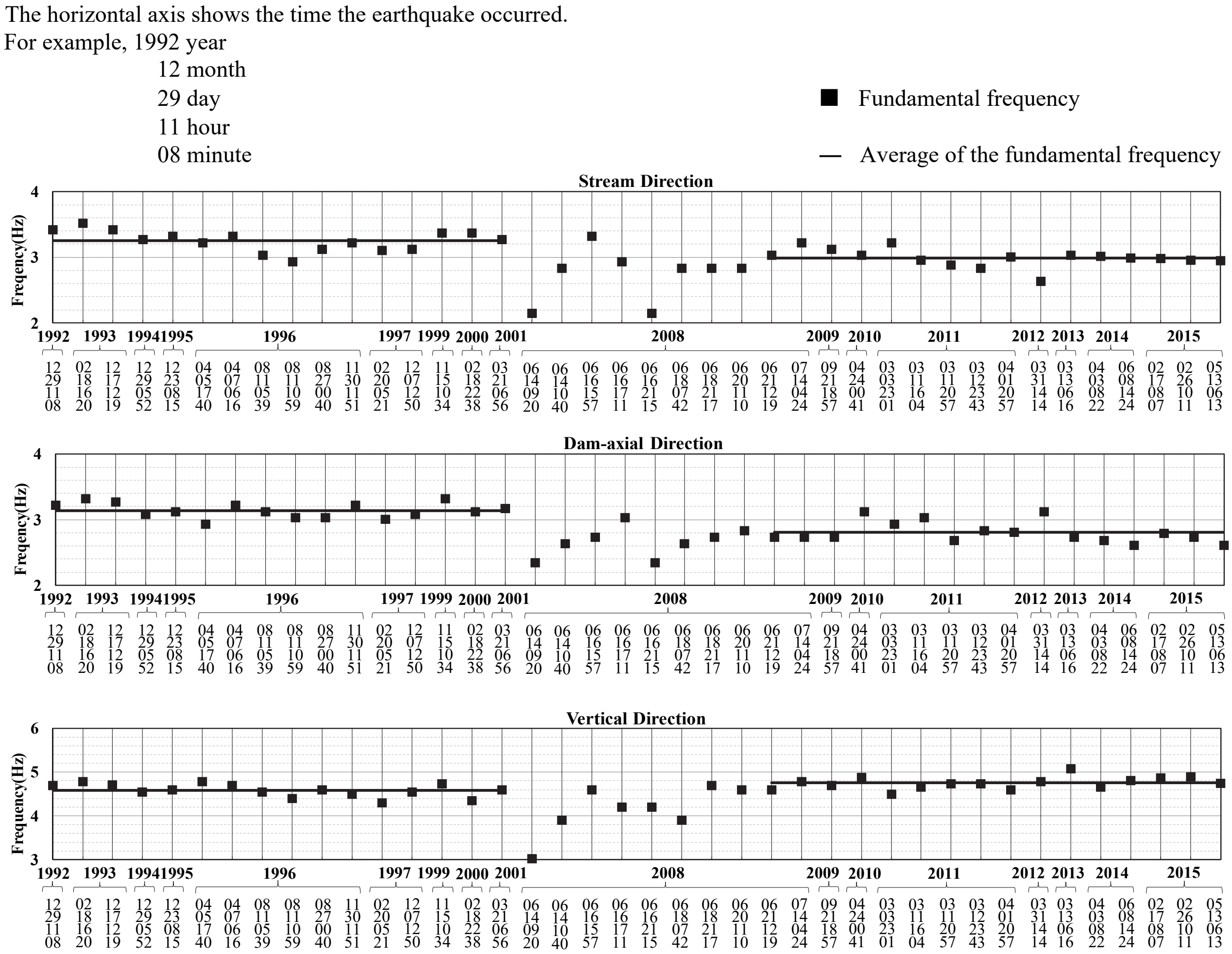


Fig. 3 Variation in the fundamental frequencies of the dam.

Table 2 Variation in the fundamental frequencies.

Direction	Before(Hz)	After(Hz)*[1]	Variation*[2]
Stream	3.2	3.0	-6.2%
Dam-axial	3.1	2.8	-9.7%
Vertical	4.6	4.8	+4.3%

Note: *[1] a week after the main shock
*[2] Variation = (After – Before) / Before

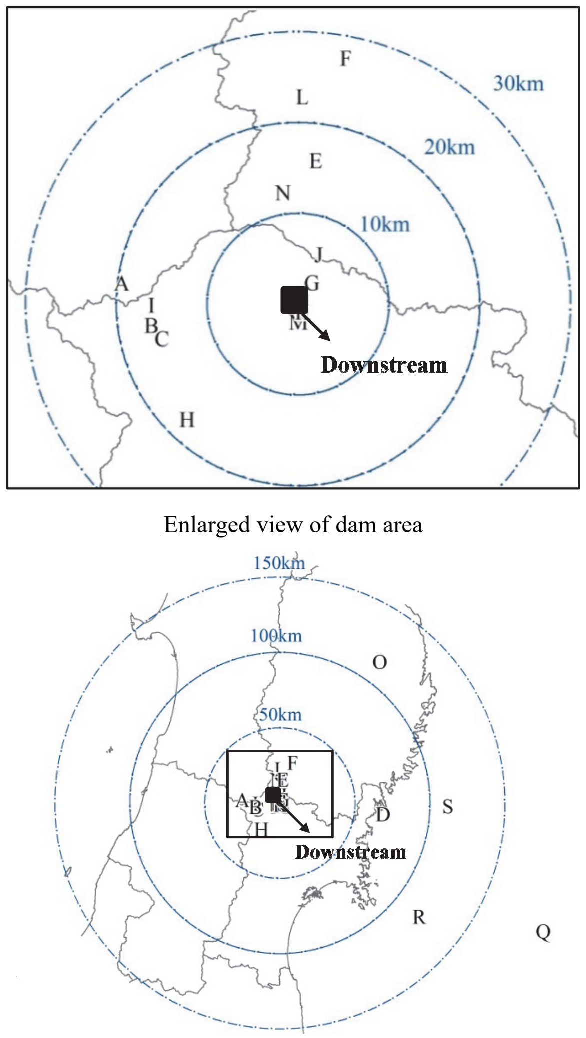
direction (stream, dam-axial, and vertical direction) is considered as the fundamental frequency of the dam, and the results were organized in order of time of occurrence of the earthquakes in each direction as shown in **Fig. 3**.

a) Decrement of the fundamental frequency caused by strong ground motion

The main shock occurred at 8:43 on June 14, 2008. As shown in **Fig. 3**, the fundamental frequency of the dam in the stream direction obtained from the earthquake record of an aftershock at 9:20 on the same day shows a sharp decrement from 3.2 Hz before the main shock to 2.2 Hz. This decreasing trend is similar for all three directions. At the next aftershock of 10:40, the fundamental frequencies recovered slightly, but in the stream direction, it was 2.8 Hz, which is much lower than that before the main shock. It should be kept in mind that the acceleration amplitude of these two aftershocks were slightly larger than those of the other earthquakes and the stiffness softening caused by nonlinearity of the embankment materials is included. During the two days immediately after the main shock, aftershocks exceeding 200 cm/s^2 at the foundation bedrock occurred several times. About one week until June 20 of the same year, the fundamental frequencies in three directions fluctuated, but decreased significantly from those before the main shock. This reveals that because of the main shock, the fundamental frequencies of the dam decreased sharply.

b) Recovery of the decreased fundamental frequency

Then, from June 18 until June 20, a recovery tendency was seen in the horizontal fundamental frequencies. The average values before and after the main shock and its aftershocks are summarized in **Table 2** and shown by the solid line in **Fig. 3**. After



■ Aratozawa Dam
A–S: Epicenter of earthquakes

Fig. 4 Epicenters of earthquakes analyzed.

June 21st, the situation was relatively stable at 3.0 Hz in stream direction, 2.8 Hz in dam-axial direction, which are 0.2 Hz and 0.3 Hz lower, respectively, than those before the main shock.

c) Fluctuation in the vertical fundamental frequency

On the other hand, the vertical fundamental frequency of the dam also decreased temporarily. It recovered about a week after the main shock, and even increased by 4.3% from the average value before the main shock. It is thought that the stiffness of the embankment materials softened because of the strong ground motion, then recovered due to restoration effect. However, the recovery of the stiffness caused by the restoration effect differed between the horizonal and vertical directions and was remarkable in the vertical direction. This indicates that the influence of the strong ground motion differed according to its direction.

Table 3 Specifications of the earthquakes analyzed.

No.	Time of occurrence	M	Depth (km)	PGA*1 (cm/s^2)
A	1996/08/11 03:12	6.1	9	28
B	1996/08/11 08:10	5.8	10	36
C	1996/08/11 15:01	4.9	10	30
D	2003/05/26 18:24	7.1	72	114
E	2008/06/14 08:43	7.2	8	1024
F	2008/06/14 09:00	4.2	11	99
G	2008/06/14 09:01	4.0	7	482
H	2008/06/14 09:14	3.6	4	151
I	2008/06/14 09:20	5.7	7	76
J	2008/06/14 10:40	4.8	7	120
K	2008/06/14 12:09	4.1	8	92
L	2008/06/14 12:10	4.8	9	79
M	2008/06/14 19:11	4.1	8	229
N	2008/06/16 23:14	5.3	7	76
O	2008/07/24 00:26	6.8	108	27
P	2008/09/25 15:04	4.1	6	119
Q	2011/03/11 14:46	9.0	24	102
R	2011/04/07 23:32	7.2	66	120
S	2015/05/13 06:13	6.8	46	18

Note: *1 The maximum acceleration of the three directional components of the foundation

Table 4 Average of the amplification factor.

Direction	Before the earthquake	Mainshock & aftershocks	After the earthquake*1
Stream	3.33	1.29 (-61.3%)*2	3.36 (0.9%)
Dam-axial	4.89	1.85 (-62.2%)	4.30 (-12.1%)
Vertical	2.85	2.11 (-26.0%)	3.23 (13.3%)

Note: *1 a week after the main shock
*2 Values in parentheses = (Current – Before) / Before

The above reveals that, as a result of the main shock, the fundamental frequencies of the Aratozawa Dam in each direction, or in other words its stiffness, temporarily decreased sharply. The fundamental frequencies recovered to nearly their original status about a week after the main shock. On the other hand, restoration effect is anisotropic and the vertical fundamental frequency of the dam recovered to even higher than its original value.

(2) Fluctuation in the acceleration amplification factor

Earthquake records with relatively large acceleration amplitudes were selected before and after the main shock of June 14, 2008 and its aftershocks. With these earthquake records, the fluctuation in the acceleration amplification factor of the dam and its fluctuation process were investigated. **Table 3** shows the selected earthquakes, and **Fig. 4** shows the epicenter position of each earthquake and the location of the Aratozawa Dam.

The ratios of the maximum acceleration of the crest (T) and that of the foundation bedrock (F) in each direction were found as the amplification factors, and their temporal fluctuation is shown in **Fig. 5**. In this figure, the fundamental frequencies of the dam before May 26, 2003 and those after July 24, 2008 are the values shown in the **Table 2**, respectively, as the average values before and after the main shock. The average values of the fundamental frequencies of the dam during the main shock and approximately a week afterwards are obtained from records of aftershocks during this period shown in **Fig. 3**. The following can be mentioned based on **Fig. 5**.

a) Decrement of the acceleration amplification factor caused by the strong ground motion

As a result of the main shock at 8:43 on June 14, the acceleration amplification factors of the dam in each direction decreased sharply. In the aftershocks that occurred a few days, although the maximum acceleration of the ground motion of the aftershocks was much smaller than that of the main shock, the acceleration amplification factor in each direction overall, remained low. The average values of the acceleration amplification factors in two horizontal directions during this period dropped to less than half of their values before the main shock. And in vertical direction, it was also lower than that before the main shock. One cause of this decrement is, as shown in **Fig. 5**, that the predominant frequency (frequency corresponding to the peak of the Fourier spectrum of the acceleration record at the foundation bedrock (F)) of earthquakes during this period was higher than those of other periods, and the average value of the fundamental frequency of the dam (in this figure, shown by the dotted lines) decreased as described above. Another cause is the nonlinearity that reduced the stiffness and increased the damping of the embankment materials, with the occurrence of large strain of the materials under the strong ground motion during this period.

Figure 6 shows the relationship of the acceleration amplification factor and the maximum acceleration (the maximum value of three direction components) of the foundation bedrock (F). This figure reveals that as one of the effects of material nonlinearity (decline in stiffness and increase in damping due to strain increment), the higher the maximum acceleration of the foundation bedrock, the lower the acceleration amplification factor of the dam.

b) Recovery of the reduced acceleration amplification factor

The average values of the acceleration amplification factors in each direction before and after the main shock and aftershocks are found, and the results are shown by the dash-dotted line in **Fig. 5**. The average values of each period are summarized in **Table 4**. Although the acceleration amplification factors in the two horizontal directions are scattered after the earthquake, the average values recovered almost to their original levels before the earthquake.

c) Different fluctuation tendency of the amplification factors in the horizontal direction and the vertical direction

As shown in **Table 4** and **Fig. 5**, as a result of the main shock, the acceleration amplification factors of the dam reduced about 61% horizontally, but only about 26% vertically. Moreover, compared with the recovery condition of the acceleration amplification factors in the two horizontal directions after the earthquake, the amplification factor in the vertical direction completely recovered to the state before the main shock. This shows a similar fluctuation trend like that of the fundamental frequency of the dam in the vertical direction as described in Section **(1)**.

4. INVESTIGATION ON PROPAGATION BEHAVIOR OF SEISMIC MOTION IN DAM-FOUNDATION SYSTEM

In aseismic design and earthquake response analysis of a dam, it is usually assumed that seismic motion propagates vertically from subjacent bedrock. In other words, seismic motion propagates while varying its phase in the abutment and the influence of this on the earthquake response of the dam is neglected. It will be significant for the aseismic design and analysis of dams to clarify the propagation behavior of seismic motion of the dam site. Therefore, the contribution of the seismic motion propagating from the subjacent bedrock and that transmitted through the natural ground of both banks on the earthquake response of the dam crest are investigated here. In this study, transfer function analysis, cross-spectral analysis and coherence function analysis[7)] are performed on the earthquake records of the Aratozawa Dam shown in **Fig. 4** and **Table 3**. Based on the analysis results, the propagating behavior of seismic motion in dam-foundation system and the influence of the main shock are investigated.

(1) Analysis method

In a dam-foundation system, because of irregular natural topography and complex distribution of rock geology as well as zoned non-uniform embankment materials and so on, seismic motion overlaps with the disturbance of scattered waves. Hence, the propagation of seismic motion is extremely complex. However, investigating the correlation of the earthquake

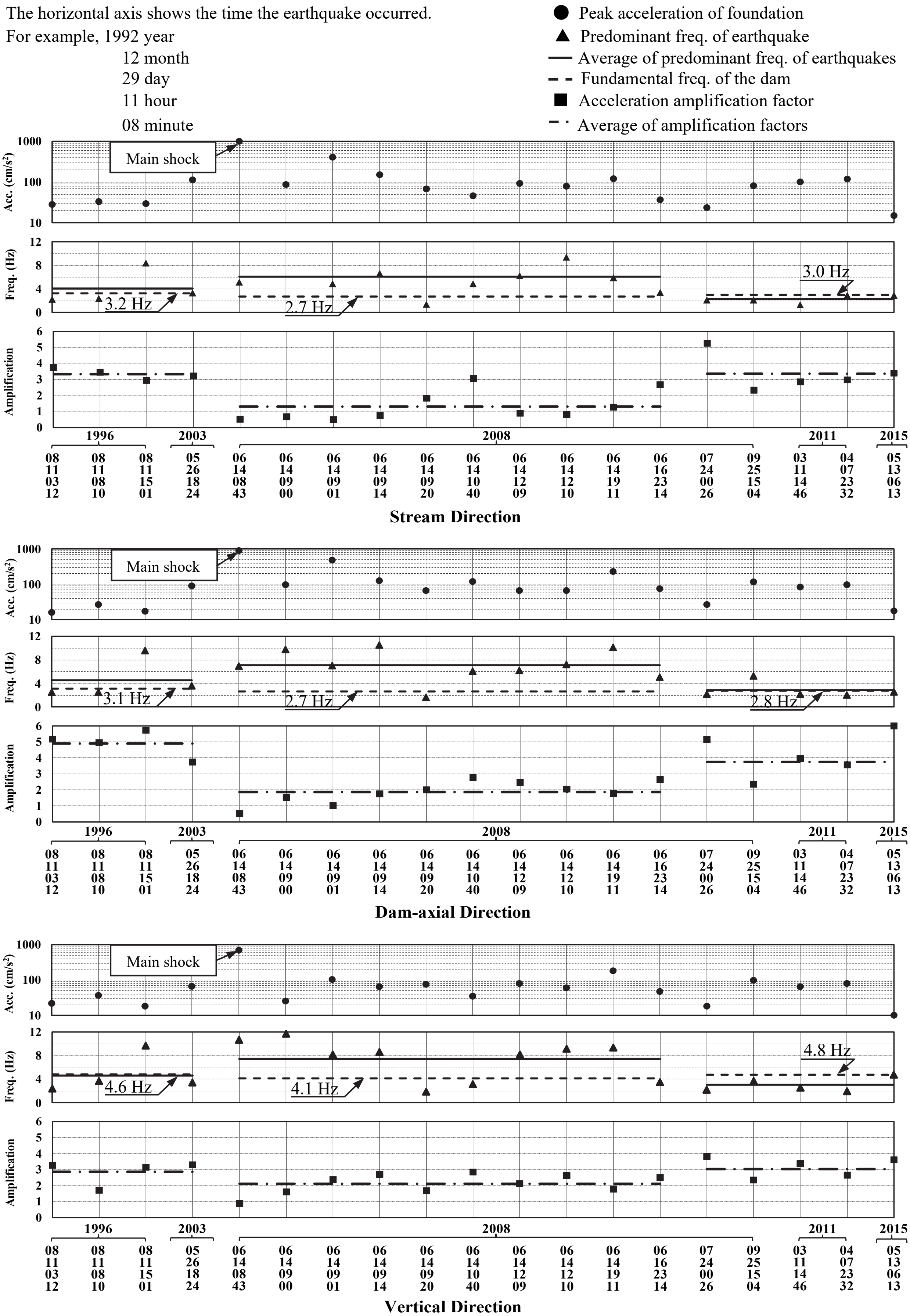


Fig. 5 Fluctuation in acceleration amplification factors.

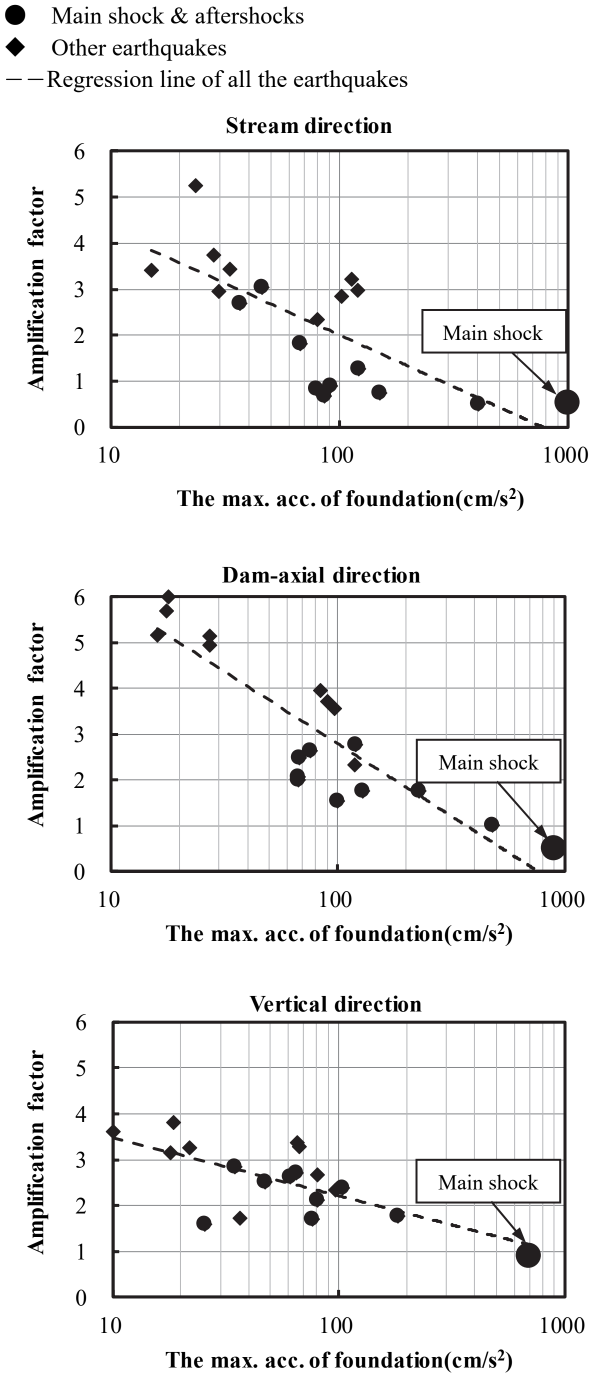


Fig. 6 Relationship between the acceleration amplification factor and the maximum ground acceleration.

records of any two monitoring points may clarify the causal relationship or the magnitude of the mutual influence of the seismic motion between the two points. Cross-spectrum shows the correlation of two signals for each frequency. Coherence function quantitively shows the correlation of two waveforms for each frequency. Coherence function takes a value from 0 to 1, and in case of 1 it indicates that output signals are all due to input signals in this frequency. In this study, cross-spectral analysis and coherence function analysis were carried out to analyze the

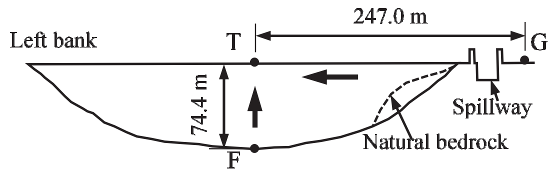


Fig. 7 Axial cross-section of the dam and schematization of the propagation path of seismic motion.

influence of the seismic motion propagated from the subjacent bedrock and that transmitted through the natural ground of both banks on the earthquake response of the dam crest. The analysis results were comprehensively examined in comparison with the results of transfer function analysis between any two monitoring points.

During an earthquake, seismic motion propagates through arbitrary position of abutment to a dam. However, in order to clearly distinguish the propagating path, the path from the monitoring point (F) of the foundation bedrock to the monitoring point (T) of the dam crest shown in **Fig. 7** (below referred to as Path "F-T") and the path from the monitoring point (G) of the natural ground on the right bank to the monitoring point (T) of the dam crest (below referred to as Path "G-T") were schematized. The following analyses were performed on the earthquake records of each propagating path.

Transfer function:

$$D_{Ti} = S_T/S_i \quad (i = F, G)$$

Cross-spectrum:

$$W_{Ti} = S_T \cdot S_i \quad (i = F, G)$$

Coherence function:

$$C^2_{Ti} = | W_{Ti} |^2 /(W_{TT} \cdot W_{ii}) \quad (i = F, G)$$

where, S represents the Fourier spectra of the acceleration records of each monitoring point, and D indicates the transfer function between the monitoring points of the propagating path. W and C^2 represent cross-spectrum and coherence function, respectively. T, F, and G indicate the monitoring points: crest (T), foundation bedrock (F), and right bank (G) in turn.

The study in the previous section reveals that the dam showed different vibration characteristics during the three periods, i.e., before the main shock, about one week beginning at the main shock, and from then to 2015. Therefore, the 19 earthquake records shown in **Table 3** were analyzed and the results were examined by grouping them according to the variation timing of the vibration characteristics of the dam as follows.

Group 1: From completion of the dam construction to just before the main shock

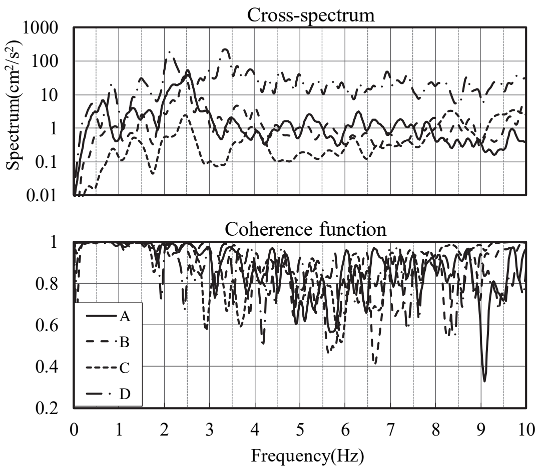


Fig. 8 Example of cross-spectrum and coherence function (Group 1, Path “F-T”, in stream direction).

Table 5 Earthquakes selected for investigation.

No	Occur-rence time	State of the dam	Reason for selection
A	1996/8/11 03:12	From completion of the dam construction to just before the main shock	Record showing the initial state of the dam
K	2008/6/14 12:09	From the main shock to about a week later	Just after the main shock
S	2015/5/13 06:13	From about a week after the main shock to 2015	Record showing the current state of the dam

Group 2: From the main shock to about a week later
Group 3: From about a week after the main shock to 2015

(2) Analysis results

As an example, **Fig. 8** shows the results of the cross-spectrum and coherence function of the path “F-T” of Group 1 in the stream direction. Because the acceleration of the foundation bedrock of Earthquake D is the highest in this group, the cross-spectrum also shows a relatively high value. However, the four earthquakes show generally common features. For example, in the frequency range of 2.1 - 2.6 Hz, all the earthquakes show their respective large spectrum values. Common features of the coherence functions are even clearer. For example, in the frequency range of 0.2 - 1.6 Hz, the coherence functions are almost 1 for all the earthquakes. In the frequency range up to 2.6 Hz, except a few individual frequencies, the values are 0.9 or larger. To show the results clearly, for each group one earthquake is chosen here, with the consideration of the time of occurrence of the earthquake and the number of data in the record (long duration time). Earthquake A is chosen from Group 1 since it reflects the original status of the dam. Earthquake K is chosen from Group 2 since it is the aftershock that occurred on the same day as the main shock. Earthquake S is chosen from Group 3 since it is the most recent earthquake record available. **Table 5** lists the chosen earthquakes and indicates the reasons for their selection.

Figure 9 shows the analysis results of the chosen earthquakes.

The cross-spectrum and coherence function results show that there are generally common features in Group 1 and Group 3, respectively. However, regarding Group 2, i.e., the main shock and aftershocks during the week immediately after the main shock, the variation in the results is relatively large.

a) From completion of the dam construction to just before the main shock

Figure 9(A) shows the analysis results of an earthquake that occurred on August 11, 1996 shortly after the completion of the construction of the dam. In the stream direction, up to the primary predominant frequency (2.93Hz) of the transfer function, both the cross-spectrum and coherence function of path “F-T” were higher than those of path “G-T,” and hence, it is thought that within the low frequency range up to this first predominant frequency, the contribution of the seismic motion of the subjacent bedrock to the earthquake response of the dam crest was larger than that of the seismic motion of the natural ground of both banks. In the frequency range higher than the first predominant frequency, the magnitude relationship of coherence functions between the two paths varied alternately according to the frequency, but the cross-spectrum was always a higher value in path “G-T.” This suggests that the seismic motion of the natural ground of both banks is, as a result of amplification of ground acceleration, larger than the seismic motion of the subjacent bedrock. Therefore, at the frequency (where both the coherence function and cross-spectrum are large), the contribution of the seismic motion of the natural ground of both banks may be larger than that of the subjacent bedrock. In other words, for the earthquake response of the dam crest in the stream direction, in the low frequency range up to the fundamental frequency of the dam, the contribution of the seismic motion of the subjacent bedrock is relatively large. Whereas in the higher frequency range, the influence of the seismic motion of the subjacent bedrock and the natural ground of both banks varies according to frequency. There are also cases where the contribution of the seismic motion of the natural ground of both banks is relatively larger than that of the subjacent bedrock.

The mechanism of the above phenomena is considered as follows. Using the three-dimentional

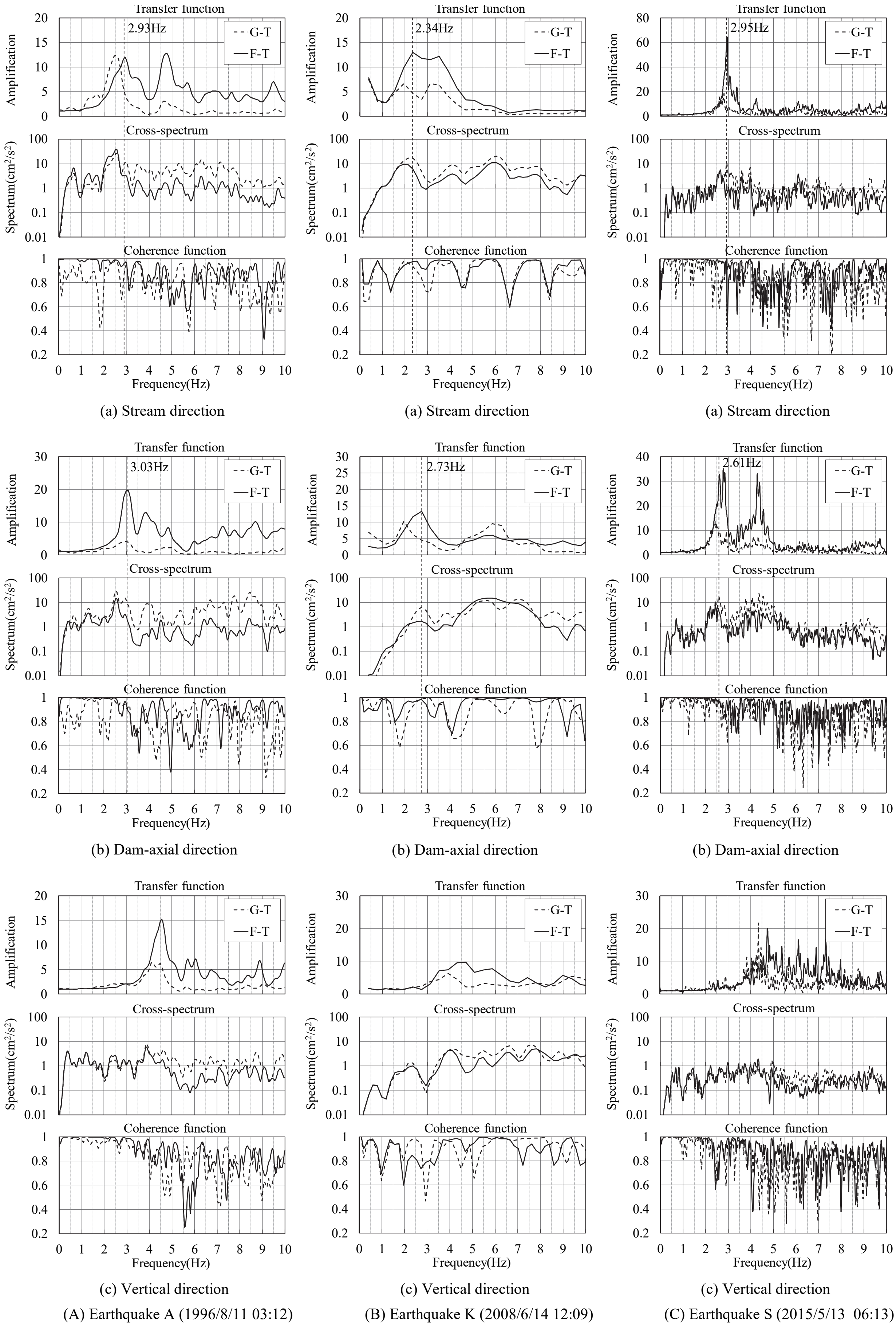
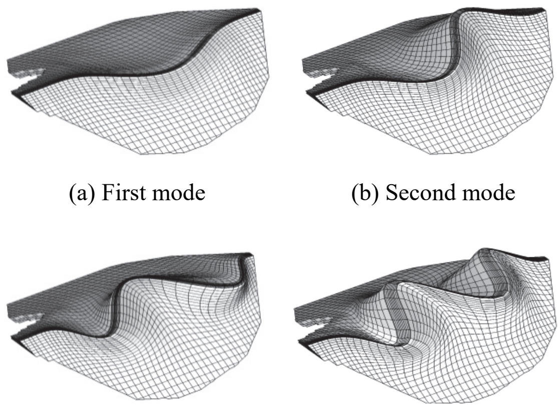


Fig. 9 Transfer functions, cross-spectra and coherence functions before and after the main shock.

eigenvalue analysis of the dam including the natural ground, the first mode as shown in **Fig. 10** reflects the overall shaking of the dam body and can be represented two-dimensionally in each direction. It can be easily understood that the restriction effect of the abutment is relatively weak in the first mode. In addition, the length of the path "F-T" is relatively short. These factors indicate that within the low frequency range up to the fundamental frequency, the contribution of the seismic motion of the subjacent bedrock is larger than that of the natural ground of both banks to the earthquake response of the dam. On the other hand, the restriction effect of the abutment on the secondary and higher modes becomes larger as the mode order increases. In higher mode, the seismic motion of the natural ground of both banks may propagate more easily than that from the subjacent bedrock. In addition, as shown in **Fig. 1** and **Fig. 7**, a spillway exists on the right bank side, and a part of the dam on the right bank side is composed of original natural ground. Thus, the real propagation path of seismic motion from the right bank to the middle of the dam crest is thought to be much shorter than "G-T."

In the dam-axial direction, the coherence function of path "F-T" in the low frequency range up to 2.5 Hz shows a high value (approximately 1), indicating high agreement between the earthquake response of the crest and the seismic motion of the subjacent bedrock. At the frequency near the fundamental frequency (3.0Hz) in the dam-axial direction, the coherence functions of the two paths show similar values, but the cross-spectrum shows a larger value in the path "G-T." Based on this, it is presumed that near the fundamental frequency of the dam in the dam-axial direction, the contribution of the seismic motion of the natural ground of both banks to the earthquake response of the dam crest in the dam-axial direction is probably larger than that of the subjacent bedrock. In the frequency range higher than the fundamental frequency, the cross-spectra and coherence functions of both paths show tendencies like those in the stream direction. That is, the cross-spectrum of path "G-T" was always a higher value and the magnitude relationship of coherence functions between the two paths varied alternately depending on frequency. It can be stated that the contribution of the seismic motion of the subjacent bedrock and that of the natural ground of both banks to the earthquake response of the dam crest in the dam-axial direction are alternately dominant depending on frequency.

In vertical direction, in the low frequency range up to nearly the first predominant frequency of the transfer function, the cross-spectra of both paths



(a) First mode (b) Second mode

(c) Third mode (d) Fourth mode

Fig. 10 Natural vibration modes of the dam by eigenvalue analysis.

show similar values, and the coherence function of the path "F-T" is a little higher. Therefore, it is thought that in the low frequency range, the contribution of the seismic motion of the subjacent bedrock to the earthquake response of the dam crest is a little larger than that of the path "G-T." In the frequency range higher than this, the cross-spectrum and the coherence function of both paths show tendencies generally the same as those in the results for the stream direction and dam-axial directions described above.

Based on the above investigation, it can be concluded that the contribution of the seismic motion of the subjacent bedrock and that of the natural ground of both banks to the earthquake response of the dam crest varies depending on the vibration direction. However, generally, in the low frequency range up to the fundamental frequencies of the dam, the contribution of the seismic motion of the subjacent bedrock is larger, and in the higher frequency range, the contribution of the seismic motion of the natural ground of both banks may become dominant according to frequency.

b) From the main shock to about a week later

Figure 9(B) shows the analysis results of the aftershock at 12:09 just after the main shock. Up to the first predominant frequency (2.34Hz) of the transfer function in the stream direction, the coherence function of path "F-T" is obviously lower than that before the main shock, and the cross-spectrum increases approximately in proportion to the frequency from an extremely low value. From this fact, it is presumed that in the low frequency range, the contribution of the seismic motion of the subjacent bedrock to the earthquake response of the dam crest in stream direction decreased sharply, compared with that before the main shock. In the frequency range higher than the first predominant frequency of the transfer function, except those near 3.0Hz (2.2 – 3.5Hz), the coherence functions of the two paths show similar values. Whereas, the cross-spectrum of path “G-T” is a little larger, it indicates that in the frequency range of 3.5Hz and higher, the contribution of the seismic motion of the natural ground of both banks is a little larger.

In the dam-axial direction, up to the first predominant frequency of the transfer function, the cross-spectrum and coherence function show similar trends like those in the stream direction, revealing that the contribution of the seismic motion of the subjacent bedrock to the earthquake response of the dam crest has changed because of the influence of the main shock. In the frequency range higher than this, the cross-spectra of both paths are in the same order, but the magnitude relationship of the coherence functions of the two paths varies depending on frequency.

The results in the vertical direction show similar trends with those in the dam-axial direction. Compared with the analysis results of the original status of the dam, the dependency of the earthquake response of the dam crest on the seismic motion of the subjacent bedrock and that of the natural ground of both banks is obviously weakened by the main shock.

c) From about a week after the main shock to 2015

Figure 9(C) shows the analysis results of the most recent aftershock (06:13 on May 13, 2015). This shows that compared with **Fig. 9**(A), the propagation characteristics of seismic motion in the dam under present conditions shows almost the same trends in all directions as before the main shock. In the low frequency range up to the fundamental frequency of the transfer function, for example, the coherence function of path “F-T” is almost 1, and in the higher frequency range, the magnitude relationship with path “G-T” alternates according to frequency. The cross-spectra tend to change in a similar way to those of the results before the main shock.

5. CONCLUSIONS

The following conclusions are obtained from this study.

1) Based on the earthquake records over a 23-year period, long-term fluctuation of the fundamental frequency of the dam was investigated. After being struck by the Iwate-Miyagi Nairiku Earthquake on June 14, 2008, the fundamental frequencies of the dam dropped sharply. Whereas, about a week after the main shock, the horizontal fundamental frequencies of the dam were, on the average, slightly lower than those before the main shock, but they had recovered to a stable status. The vertical fundamental frequencies, on the other hand, dropped temporarily immediately after the main shock, but later completely recovered, and even rose about 4% higher than that before the main shock. In other words, strong seismic motion caused the stiffness of the dam to decline, but later, as time passed, the stiffness of the dam recovered under restoration effect. However, the state of this recovery was more remarkable in the vertical direction than in the horizontal directions.
2) After being struck by the main shock of the Iwate-Miyagi Nairiku Earthquake, the acceleration amplification factors of the dam in each direction also decreased temporarily. It is thought that this phenomenon resulted from the fact that the predominant frequencies of the main shock and of the aftershocks were relatively high. Also, the nonlinearity of the stiffness decrement and damping increment of the embankment materials occurred as a result of large strain.
3) Regarding the propagation characteristics of seismic motion in a dam-foundation system, in the low frequency range up to approximately the fundamental frequency of the dam, the contribution of seismic motion of the subjacent bedrock to the earthquake response of the dam crest is larger than that of the natural ground of both banks. In the frequency range higher than this, the contribution of seismic motion of the natural ground of both banks may be larger than that of the seismic motion of the subjacent bedrock according to frequency. Also, as a result of the Iwate-Miyagi Nairiku Earthquake, the correlation of the earthquake response of the dam crest and the seismic motion of the subjacent bedrock and that of the natural ground of both banks temporarily weakened. According to the analysis results of the earthquake records of 2015, it can be judged that the propagation characteristics of seismic motion in the present dam-foundation system recovered to its original status before the main shock.

In future studies, the relationship between vibration intensity and compaction effect of embankment materials should be clarified with material testing. And based on wave theory, the influence of seismic motion of the dam site on the earthquake response of the dam should be studied.

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