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Characteristics of seismic motions at a concrete gravity dam site and suggestions for setting the engineering bedrock

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Abstract

The earthquake records of a concrete gravity dam with eight seismographs were spectrally analyzed to clarify the characteristics of the seismic motions at each monitoring station. Based on the analysis results, whether it is appropriate to use such earthquake records to generate the input ground motion in assessments of the seismic performance of dams was discussed. It was found that the earthquake records at the dam base show reduced amplitudes at frequencies corresponding to the natural vibration modes of the dam. When these earthquake records are used to generate the input ground motion in an assessment of the seismic performance of a dam, sufficient consideration should be given to this feature. Suggestions on where to install seismographs at dam sites are presented. Based on the numerical simulation of the seismic response of the dam, it is suggested that the engineering bedrock should be considered to be located at a depth of at least 1.5 times the dam height, and the shear wave velocity of the rock at that depth should preferably be 2000 m/s or more. Since this study uses seismic motions recorded across the entire dam site, including the deep rock, which is globally rare, it is considered that the basic conclusions obtained in the article can provide a reference for other concrete dams.

Keywords

Seismic motion, concrete gravity dam, engineering bedrock, seismograph, dynamic analysis

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Introduction

Seismographs installed at dam sites play an important role in monitoring the seismic behavior of dams and improving dam safety during earthquakes. Generally, seismographs are installed at the dam crest and dam base (e.g. the inspection gallery). For the convenience of maintenance, they are sometimes set inside the banks or abutment instead of at the dam base.

The Satsunaigawa Dam is a concrete gravity dam with a height of 114 m located in Hokkaido, Japan (Figure 1). Seismographs with three directional components are installed at the locations shown in Figure 2 to monitor the dynamic behavior of the dam, its foundation, and the rock masses in both banks. Approximately 300 sets of earthquake records have been collected since the dam was completed in 1996. Particularly, earthquake records obtained through the seismograph placed at a depth of 57 m beneath the dam base (hereafter referred to as "lower bedrock," F1) and those located inside the rim tunnels in both banks (R1 and R2) are of significant value since it is generally difficult to install seismographs at such positions. These earthquake records provide an opportunity to understand the seismic motions at dam sites, not only in the dam and at the ground surface but also deep inside the bedrock. Furthermore, based on the analysis of the characteristics of seismic motions at each monitoring station, suggestions on the installation of seismographs at dam sites are presented in this article.

In Japan, assessments of the seismic performance of existing dams under the influence of large earthquakes are being carried out (National Institute for Land and Infrastructure Management (NILIM), 2005). Choosing the input ground motion (in this article, this term is used to express the seismic load in response analysis) at the dam site (Point F, G, or Q in Figure 3) is a conventional and important issue in response analysis. In practice, one of the most frequently used methods is adjusting the amplitude of an earthquake record to a certain peak ground acceleration (PGA) or peak ground velocity (PGV), which is determined by ground motion prediction equations (GMPEs). Earthquake records at dam sites, especially at the dam base, are practically used as an original waveform when setting the input ground motion. However, the characteristics of earthquake records at dam sites and their applicability to setting the input ground motion are not yet fully understood. In addition, instead of the ground motion at Point F or G in Figure 3, the ground motion at the engineering bedrock (Point Q) is usually used in the earthquake response analysis of dams. Therefore, this raises a fundamental question, "Where should the engineering bedrock be set?" Unfortunately, there is no definite criterion or common method for identifying the engineering bedrock in practice. Consequently, earthquake response results based on incorrect assumptions about the location of the engineering bedrock are not necessarily valid.

Therefore, the main objectives of this study are as follows:

1. To clarify the characteristics of the seismic motions at each monitoring station and investigate whether it is appropriate to use the earthquake records to generate the input ground motion in assessments of the seismic performance of dams;
2. To propose reasonable locations for installing seismographs for monitoring the seismic behavior of existing dams; and
3. To provide a suggestion for setting the engineering bedrock and present a method for generating input ground motion at the engineering bedrock.

Figure 1. Location of the Satsunaigawa Dam.

In this study, the characteristics of the seismic motions at the Satsunaigawa Dam site were investigated by Fourier spectral analysis and a comparison of the analysis results. Based on the analysis results, the earthquake records of each monitoring station were examined to determine whether it is appropriate to use these records to generate the input ground motion in the assessment of the seismic performance of dams. Through three-dimensional (3D) seismic behavior simulations of the dam during strong earthquakes, the validity of the location of the assumed engineering bedrock was examined. In the simulation, the input ground motion at the engineering bedrock was generated by inverse analysis of the earthquake records obtained at the lower bedrock (F1 in Figure 2) and dam base (F2 in Figure 2). The satisfactory reproducibility of the dynamic behaviors of multiple seismographs suggests the validity of the numerical model and the generated input ground motion. By examining the seismic motions of the deep bedrock in the above analyses, a suggestion is provided for setting the engineering bedrock in the earthquake response analysis of concrete gravity dams. Simultaneously, a procedure and method are presented for use in preparing the input ground motion at the engineering bedrock.

Outline of the dam and earthquake monitoring

Features of the Satsunaigawa Dam

The Satsunaigawa Dam is a concrete gravity dam constructed by the roller compacted dam concrete (RCD) method and was completed in 1996. The design PGA at the dam site is 0.12 *g*. The main features of the dam are shown in Table 1. Figure 2 shows the plan and downstream views of the dam.

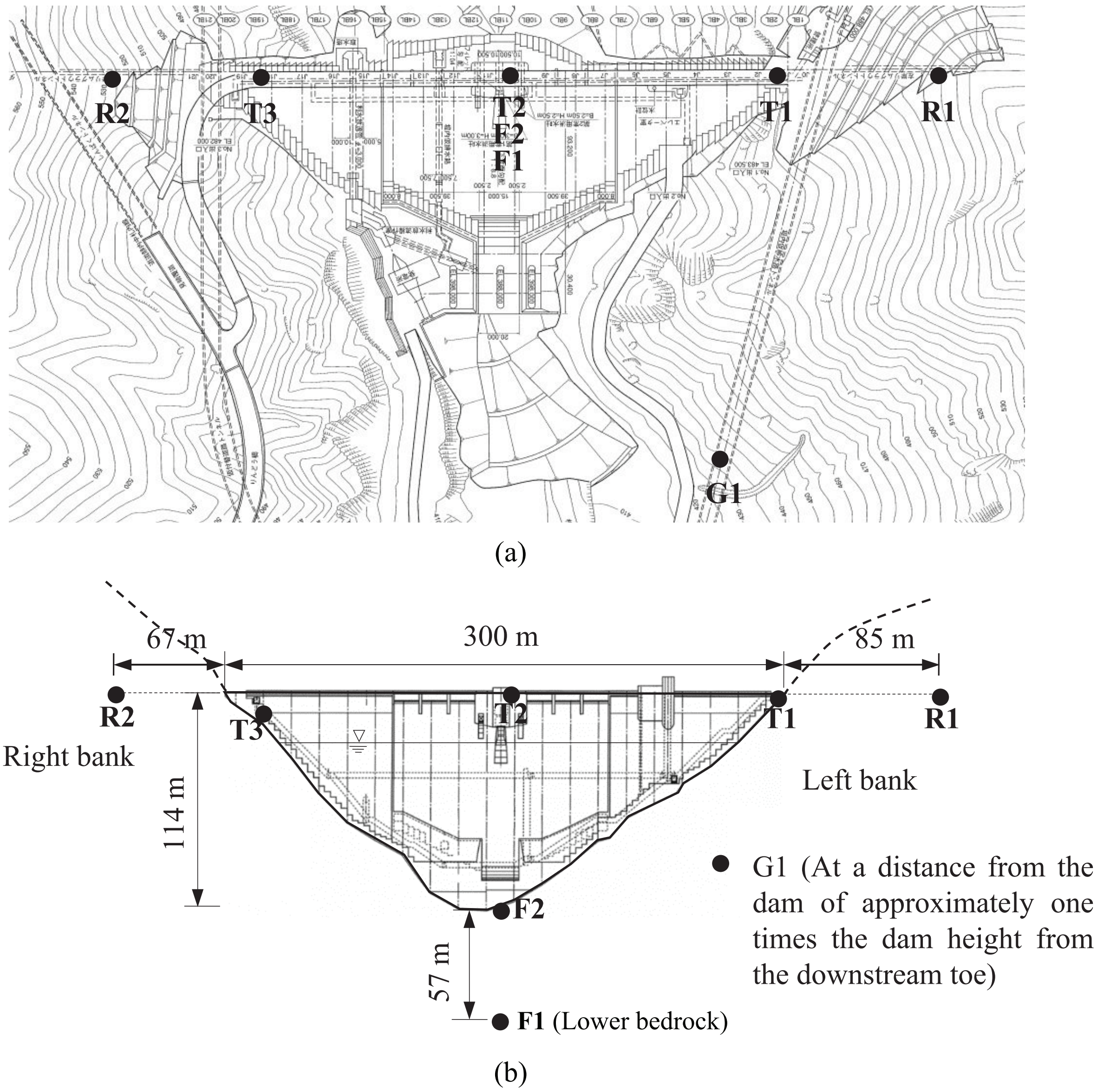


Figure 2. (a) Plan and (b) downstream views of the Satsunaigawa Dam and locations of seismographs.

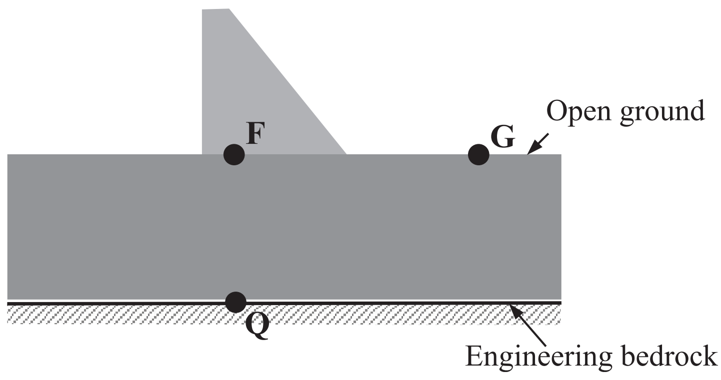


Figure 3. Schematic of the dam, foundation, and engineering bedrock.

Table 1. Main features of the Satsunaigawa Dam

Location	Nakasatsunai Kawamura, Kasai-gun, Hokkaido, Japan
Dam type	Concrete gravity dam (RCD)
Height	114 m
Crest length	300 m
Crest elevation	488.0 m
Dam volume	770,000 m^3
Basin area	117.7 km^2
Reservoir capacity	54,000,000 m^3
Design peak ground acceleration	0.12 *g*
Year of completion	1996

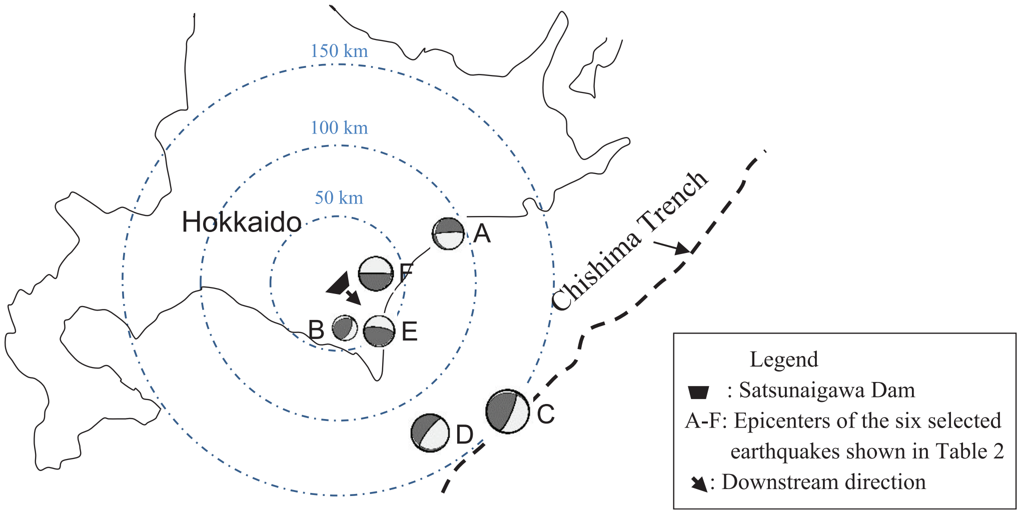


Figure 4. Epicenters of the earthquakes and location of the Satsunaigawa Dam.

Earthquake monitoring

Before the 1990s, the technology used to install seismographs in the deep foundation rock of a dam site was not advanced in Japan. Based on the idea that the foundation rock of a dam is massive and behaves as a single unit during an earthquake, seismographs were occasionally installed in a rim tunnel used for curtain grouting of the foundation and ground during dam construction. The seismic records from such sites were sometimes used to generate the input ground motion in the response analysis of dams. Therefore, clarifying the vibration characteristics of the dam and foundation rock was an urgent issue at that time. The site of the Satsunaigawa Dam in the Tokachi region of Hokkaido is in an earthquake-prone area, so it was highly possible that many earthquake records could be obtained. Thus, prior to construction, the first author of this article provided the dam construction office with instructions on the arrangement of seismographs in the dam body and the foundation. Seismographs with three directional components were installed at eight locations, as shown in Figure 2. To obtain a comprehensive understanding of the seismic motions at the dam site, seismographs were also installed in the lower bedrock (F1 in Figure 2) at a depth of 57 m below the dam base, inside the rim tunnels on both banks (R1 and R2 in Figure 2), at a downstream open-ground site (G1 in Figure 2), and at the dam crest and abutments. The seismographs can measure up to a maximum acceleration of 1000 cm/s^2, and the signals are recorded in digital format with a sampling frequency of 100 Hz. To date, more than 300 sets of earthquake records have been collected. Table 2 shows the maximum acceleration values recorded at the dam site during six relatively strong earthquakes as examples.

In this study, to ensure analytical accuracy, earthquake records with a minimum acceleration of 15 cm/s^2 or larger in the stream direction at the dam base (F2 in Figure 2) were selected for the analysis. Figure 4 shows the epicenters of the six selected earthquakes and the location of the Satsunaigawa Dam. The features of the selected earthquakes and the maximum acceleration values of the seismographs are summarized in Table 2. Among the earthquakes, the Tokachi-Oki earthquake occurred on 26 September 2003, and a maximum acceleration of 677 cm/s^2 was recorded at the dam crest (T2) in the stream direction.

Characteristics of seismic motions at the dam site

Analysis method

The characteristics of seismic motions at the dam site were analyzed by Fourier spectral analysis of the records of the six selected earthquakes. The similarities and differences among the Fourier spectra of the seismic motions at the monitoring stations were investigated, and the analysis was carried out from the following two viewpoints:

1. Similarities of different earthquake records at each monitoring station: The maximum acceleration values at the dam site differed greatly during these six earthquakes, as did their Fourier spectra. Therefore, the analysis was performed based on normalized spectra, with the maximum values of the Fourier spectra taken as a unit.
2. Characteristics of different monitoring stations during an earthquake: By comparing the Fourier spectra of the earthquake records during the Tokachi-Oki earthquake (No. C in Table 2), the characteristics of the seismic motions at different monitoring stations were clarified.

Prior to the above analysis, the transfer functions of the dam body were determined based on the Tokachi-Oki earthquake records at the dam crest (T2) and dam base (F2). The results are shown in Figure 5, and they are referred to in the analyses here.

Similarities of different earthquake records at each monitoring station

The normalized Fourier spectra of the selected earthquake records at each monitoring station are compared in Figure 6. The characteristics and similarities of the earthquake records were examined as follows:

1. At the dam crest (T2): Fourier spectra in each direction (Figure 6a), especially in the stream direction, show maximum values around the natural frequencies (indicated by circles in Figure 5) of the dam. Naturally, the vibration characteristics of the dam are clearly observed in the earthquake records at the dam crest.
2. At the dam base (F2): An important feature is that the normalized Fourier spectra (Figure 6b) of each earthquake are reduced at certain frequencies, namely, 5 and 9.5 Hz in the stream direction, 9.5 Hz in the dam axis direction, and 12 Hz in the vertical direction. According to the transfer functions shown in Figure 5, these

Table 2. Maximum acceleration in the earthquake records (Unit: cm/s^2)

No.		A	B	C	D	E	F
Epicenter		Middle Southern Kushiro	Southern Tokachi	Tokachi-Oki	Tokachi-Oki	Southern Tokachi	Southern Tokachi
Occurrence		1999/05/13	2003/01/07	2003/09/26	2003/09/26	2012/08/25	2013/02/02
time		02:59	03:27	04:50	06:08	23:16	23:17
Magnitude		M6.3	M4.7	M8.0	M7.1	M6.1	M6.5
Middle of crest (T2)	Stream	296.0	223.0	676.7	182.8	528.1	442.5
	Dam axis	246.2	48.5	303.5	81.3	199.3	358.9
	Vertical	98.8	30.9	206.8	40.9	120.3	158.0
Dam base (F2)	Stream	37.9	15.0	61.5	22.8	35.5	46.2
	Dam axis	40.9	10.3	67.0	15.8	54.7	48.6
	Vertical	22.1	6.9	56.3	17.1	27.4	39.7
Lower bedrock (F1)	Stream	23.6	12.1	51.0	18.6	28.8	50.9
	Dam axis	41.1	9.4	68.9	13.7	48.1	38.4
	Vertical	26.4	6.0	46.6	14.2	20.7	23.9
Left rim tunnel (R1)	Stream	37.8	13.9	66.1	22.9	41.3	47.9
	Dam axis	44.1	9.2	64.7	18.5	36.0	58.2
	Vertical	23.5	6.7	72.1	23.6	39.5	40.2
Left abutment (T1)	Stream	118.6	35.5	199.3	41.5	118.6	144.8
	Dam axis	153.6	25.4	216.2	38.6	100.8	159.4
	Vertical	83.4	15.3	116.9	33.4	109.5	98.0
Right abutment (T3)	Stream	95.6	43.8	214.1	55.0	104.5	149.0
	Dam axis	125.8	36.6	195.6	52.6	133.4	183.5
	Vertical	63.5	22.3	151.5	34.0	75.5	90.2
Right rim tunnel (R2)	Stream	41.2	20.3	79.1	28.6	64.1	59.6
	Dam axis	46.5	15.4	98.2	29.6	74.3	53.3
	Vertical	35.6	11.0	103.3	25.3	53.4	52.2
Downstream open ground (G1)	Stream	31.1	11.7	59.1	17.7	35.0	47.8
	Dam axis	50.9	8.8	74.8	15.5	30.2	62.3
	Vertical	32.7	10.8	69.0	21.3	31.1	36.0

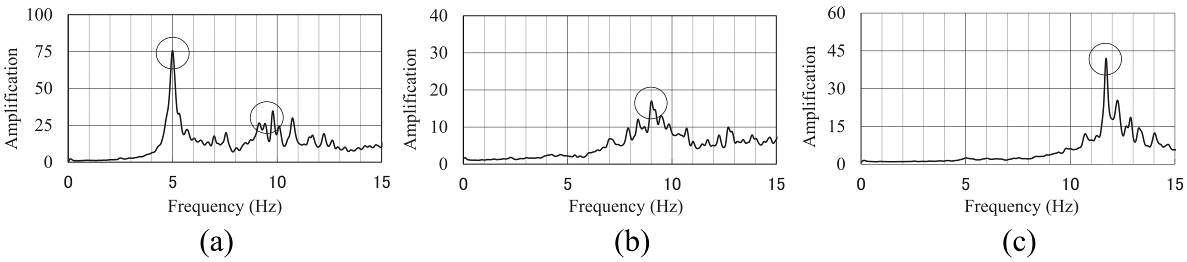


Figure 5. Transfer functions found from Tokachi-Oki earthquake records. (a) Stream direction. (b) Dam axis direction. (c) Vertical direction.

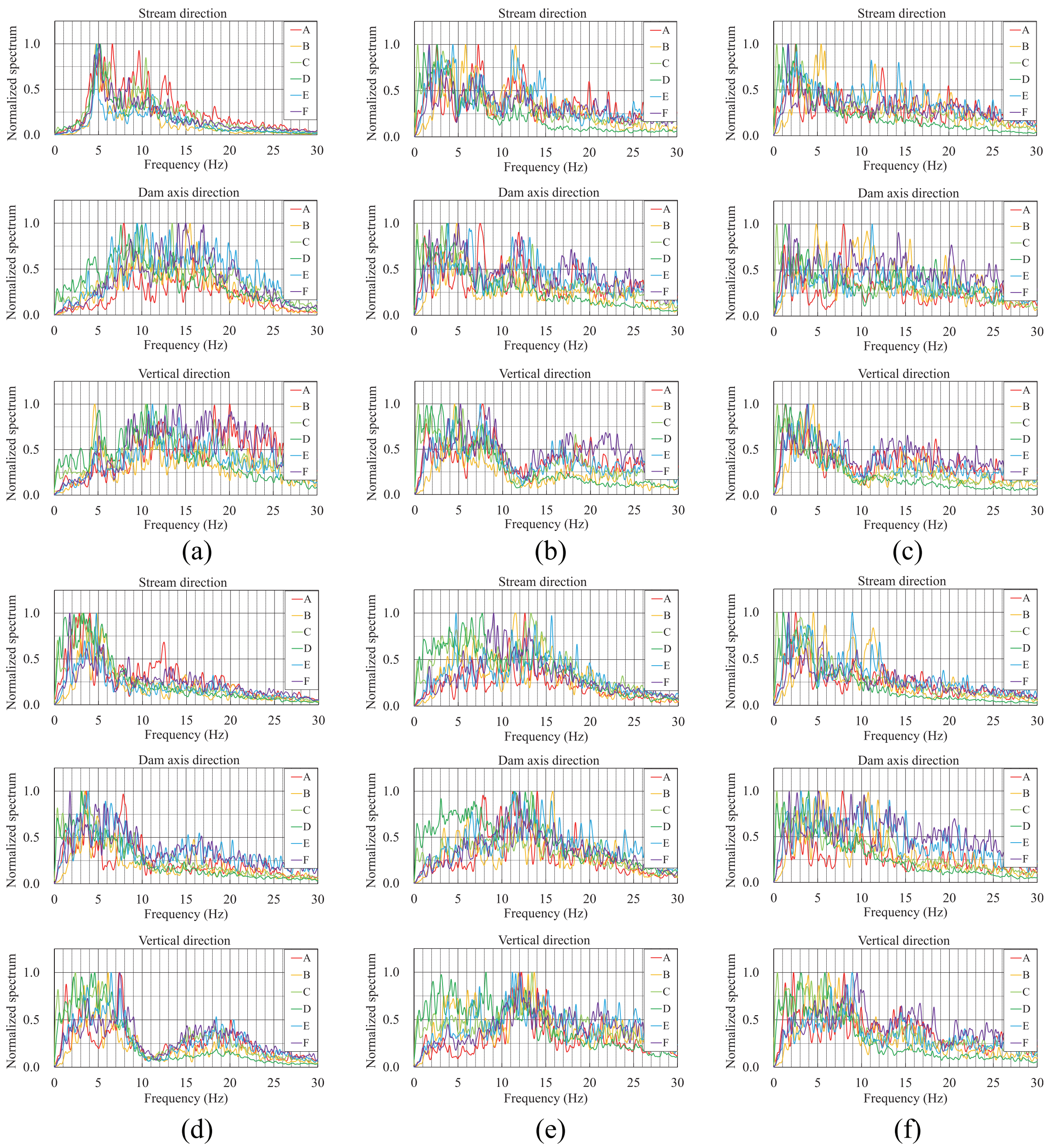


Figure 6. Normalized Fourier spectra of earthquake records. (a) Crest (T2). (b) Dam base (F2). (c) Lower bedrock (F1). (d) Left bank (R1). (e) Left abutment (T1). (f) Downstream open ground (G1).

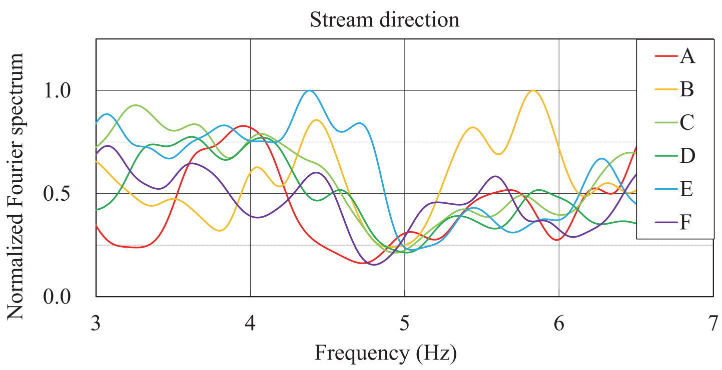


Figure 7. Enlarged view of the normalized Fourier spectra at approximately 5 Hz (stream direction component).

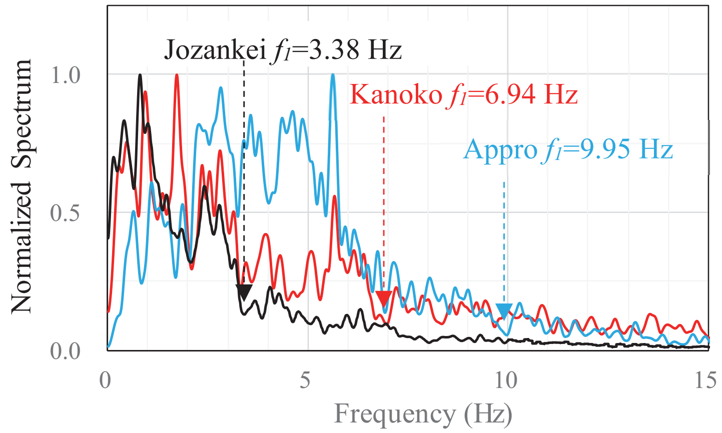


Figure 8. Fourier spectra of different earthquake records at the bases of other dams.

frequencies are the individual natural frequencies of the dam in the stream, dam axis, and vertical directions. For clarity, as an example, the normalized Fourier spectra around the frequency of 5 Hz in the stream direction are enlarged in Figure 7. It is thought that during earthquakes, the dam base (F2) under the influence of the natural vibration mode of the dam body becomes a node in the vibration mode at these natural frequencies, and the amplitude of the vibration at this position is suppressed. This phenomenon can also be recognized in other concrete dams during other earthquakes. A few examples are shown in Figure 8, in which the names of the dams and the fundamental frequencies of the dams are annotated. Earthquake records at the dam base (F2) are frequently used to set the input ground motion for assessments of the seismic performance of dams. In some cases, the input ground motion is set by adjusting such recordings to a separately determined acceleration spectrum (Matsumoto et al., 2003; Sasaki and Ito, 2016). If there is an earthquake record at the dam site or nearby area stronger than the ground motion set by other methods, the earthquake record can be directly used for the assessment of the seismic performance of the dam (NILIM, 2005). Therefore, it is highly recommended that sufficient consideration should be given to this feature. If the earthquake record at the dam base (F2) is used in the evaluation of the seismic performance of a similar type of dam, it is recommended that the frequency components corresponding to the natural frequencies of the dam be corrected to obtain an appropriate evaluation. Another feature is that in the low frequency range up to 1.0 Hz, the Tokachi-Oki earthquake (No. C in Table 2) and its aftershock (No. D) show large peaks in each direction. Since these are both subduction zone earthquakes (Chishima Trench shown in Figure 4), long-period components are predominant.

3. At the lower bedrock (F1): Although the amplitude of the Fourier spectrum (Figure 6c) in the vertical direction decreases near the frequency of 10 Hz, there is no sharp drop in any of the directions akin to that at the dam base (F2). The influence of the vibration of the dam body is not as strong as that at the dam base (F2), since the seismograph is at a depth of 57 m below the dam base (F2).
4. At the banks (R1 and R2): Since the results of the right bank (R2) are similar to those of the left bank (R1), only the normalized Fourier spectra of the left bank (R1) are shown in Figure 6d. The spectral amplitudes in the frequency ranges up to 6 Hz in the stream direction and 8 Hz in the dam axis direction and vertical direction are obviously larger than those in the higher-frequency ranges. This is presumably due to the influence of the vibration of the rock mass above the seismograph. Moreover, like the other monitoring stations except the dam crest, this site features predominant components in the low frequency range below 1 Hz for subduction-zone earthquakes (Nos. C and D in Table 2).
5. At the abutment (T1 and T3): The representative normalized Fourier spectra of the left abutment (T1) are shown in Figure 6e. In the low frequency range up to approximately 8 Hz, the subduction-zone earthquakes (Nos. C and D in Table 2) show large Fourier spectra in each direction. For the other earthquakes, the maximum values of the normalized Fourier spectra appear at approximately 12 Hz in each direction. This may be due to the influence of the scattered waves resulting from the interaction between the dam body and the natural ground.
6. At the downstream open-ground site (G1): A slight reduction in the spectral amplitude can be found around the natural frequencies of the dam, as shown in Figure 6f. This implies that the seismic motion at this location is slightly affected by dam vibration. The seismograph is installed at a distance nearly equal to the dam height from the downstream toe of the dam, which may not be far enough. Another possible cause is that the valley here is relatively narrow (crest length/height = 2.63), and the earthquake record of this seismograph may be influenced by the vibration of the rock masses in the banks. Hence, the earthquake record here cannot be regarded as that of real open ground. In other words, the vibration of the dam body and the rock masses in both banks had some influence on the earthquake records. However, compared with that of the dam base (F2), the influence is much smaller. Therefore, it is considered that the earthquake record of the downstream open-ground site (G1) is reasonably applicable as an original waveform for setting the input ground motion for assessments of the seismic performance of dams.

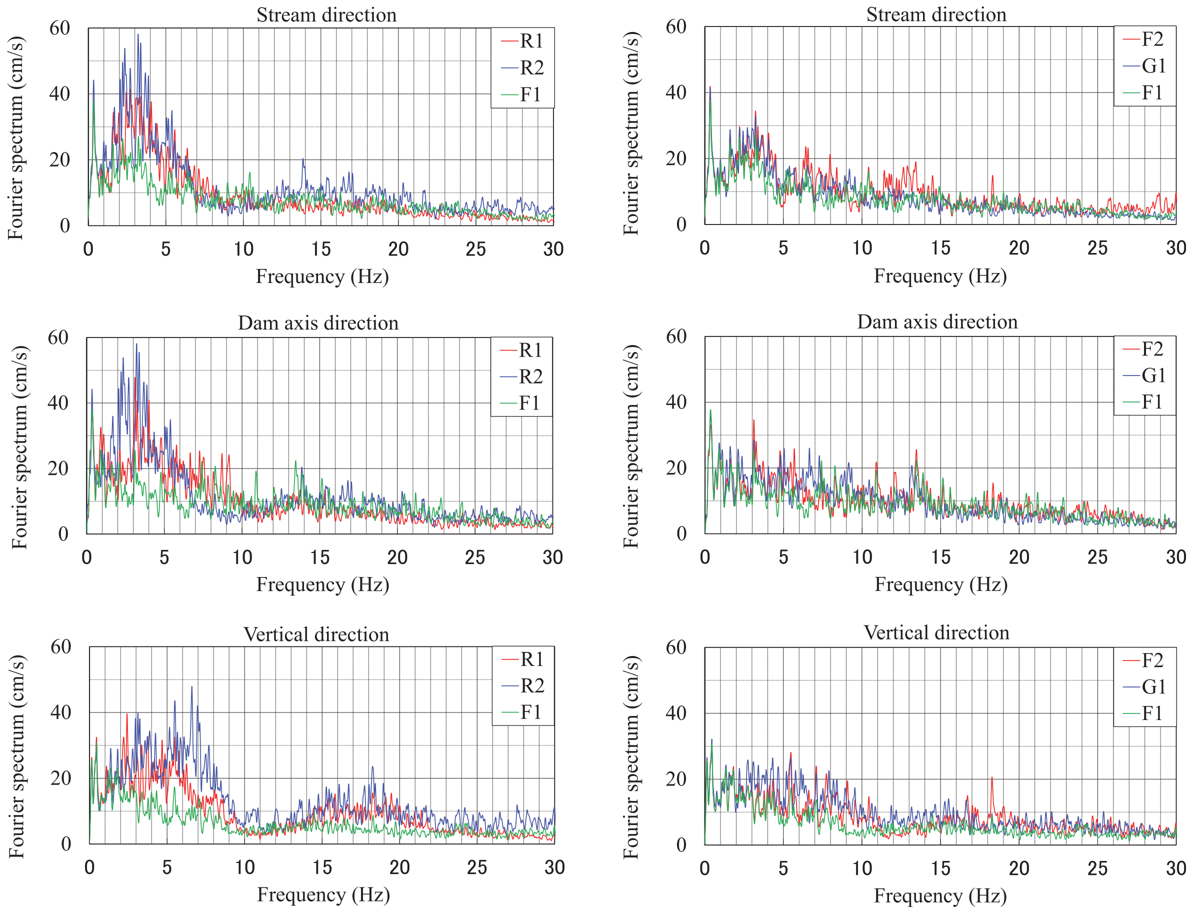
From the above, when planning the installation of seismographs at a dam site, it is recommended to install seismographs in deep bedrock and on open ground if possible. When the installation of seismographs is restricted due to cost, seismographs at the crest and the dam base are indispensable for monitoring the dam behavior. If a seismograph is to be installed at an open-ground site near a dam, it is strongly recommended that the site be at a distance equivalent to at least 1 time the dam height from the downstream toe of the dam and located in a relatively wide valley. Regarding the applicability of earthquake records for generating the input ground motion in the assessment of seismic performance of dams, records from deep bedrock or an open-ground site are the best choice. The earthquake record from the dam base is preferable to those from the abutments and inside the rock masses in the banks because the latter are influenced by interactions between the dam and the ground and by the rock mass itself, as mentioned above.

Characteristics of different monitoring stations during an earthquake

Here, the characteristics of the seismic motions at the dam site are examined from a different viewpoint than that in the previous section. During the Tokachi-Oki earthquake (M8.0) on September 26, 2003, strong seismic motions were recorded at the dam site, with a maximum acceleration of 677 cm/s^2 at the dam crest in the stream direction. The Fourier spectra of the earthquake records at different monitoring stations are compared. From the strain response of the dam in the behavior simulation of the Tokachi-Oki earthquake, it was found that the maximum tensile strain was 36×10^{-6} and the maximum compressional strain was 34.4×10^{-6}. According to Hatano's (1969) research, the ultimate tensile strain on the dam concrete was approximately 100×10^{-6}. The maximum tensile strain that occurred during the earthquake was slightly greater than one-third of the limit value of the dam concrete; therefore, it can be presumed that the dynamic characteristics of the dam were in the linear stage during the earthquake. On the contrary, it is difficult to judge the dynamic characteristics of the foundation rock because of the complex geological distribution. The axial strain reaches a maximum of 31.2×10^{-6} in a limited area near the right shoulder of the dam, which is less than 20×10^{-6} in most other rocks. Therefore, even if slight non-linearity occurred in the foundation rock of the dam during the earthquake, it is judged that there was no significant effect on the analysis results, even with a linear analysis.

From the discussion in the previous section, it is known that the earthquake records of the abutment (T1 and T3) are not suitable for generating the input ground motion. Therefore, the discussion here concentrates on the earthquake records other than those from these monitoring stations. The monitoring stations are grouped according to their locations (the group of stations within the ground and the group of stations on the riverbed). Their Fourier spectra are compared with that of the lower bedrock (F1), which is regarded as a reference.

1. The group within the ground (R1, R2, and F1): Figure 9a shows the Fourier spectra of the earthquake records of both banks and that of the lower bedrock. In the low frequency range up to 10 Hz, the amplitudes of the Fourier spectra of both banks are larger than that of the lower bedrock in each direction. In the frequency range higher than 10 Hz, the Fourier spectra of the three monitoring stations show no large difference in the horizontal directions. On the contrary, in the vertical direction, the seismic motions of both banks show larger spectra in the range of 13–23 Hz. From these results, it is obvious that the characteristics of the seismic motions inside the rock masses in both banks (R1 and R2) differ greatly from those of the lower bedrock (F1).
2. The group on the riverbed (F2, G1, and F1): Figure 9b shows the Fourier spectra of the earthquake records at the dam base (F2), the downstream open ground (G1), and the lower bedrock (F1). In any direction, in the low frequency range below 2 Hz, the three monitoring stations show almost the same Fourier spectra. This indicates that the foundation bedrock moves almost rigidly in the low frequency



(a) (b)

Figure 9. Comparison of the Fourier spectra of earthquake records. (a) Group containing R1, R2, and F1. (b) Group containing F2, G1, and F1.

range. Except for individual frequencies in the frequency range from 2 to 15 Hz, the Fourier spectra of the dam base (F2) and the downstream open-ground site (G1) are larger than that of the lower bedrock (F1). This means that the seismic motions were amplified in the foundation bedrock shallower than the lower bedrock (F1). However, in the frequency range above 15 Hz, there is no large difference among the three monitoring stations in any of the directions. On the contrary, compared with that of the downstream open ground (G1), the Fourier spectrum of the dam base (F2) in the stream direction is obviously smaller around the frequencies of 5 and 9.5 Hz. As mentioned in the previous section, it is thought that the dam base (F2) becomes a node in the natural vibration modes of the dam at 5 and 9.5 Hz, at which the vibration at the dam base was restricted. Moreover, in the lower bedrock (F1), the Fourier spectral amplitude decreases somewhat around the frequency of 4.5 Hz. This is estimated to be due to the influence of the dam vibration, since the seismograph of the lower bedrock (F1) is located at a depth of half the dam height, which is not deep enough below the dam base.

From the above findings, it can be confirmed that the earthquake records inside the rim tunnels (R1 and R2) strongly reflect the vibration characteristics of the rock masses in

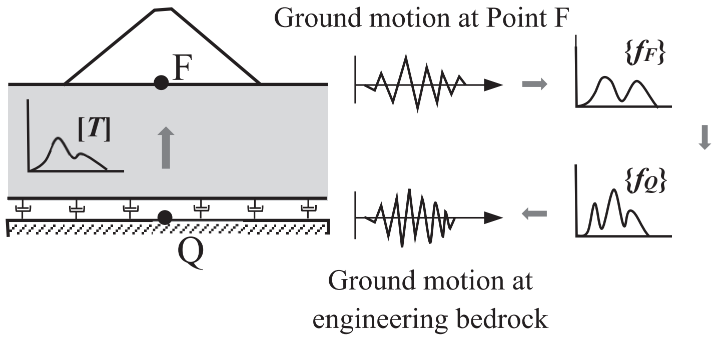


Figure 10. Preparation of the input ground motion at the engineering bedrock.

both banks. These earthquake records are not the pure seismic motions arising from the lower bedrock but include the strong reflected waves resulting from the vibration of the rock mass. In addition, the dam base (F2) becomes a node of the natural vibration modes of the dam during earthquakes, and the component corresponding to the natural frequency of the dam is significantly reduced. Therefore, in the case of using the earthquake record at the dam base (F2) as an original waveform to set the input ground motion for assessments of the seismic performance of dams, it is necessary to pay full attention to such characteristics. On the contrary, since the influence of the dam vibration on the earthquake records of the lower bedrock (F1) and the open-ground site (G1) is small, it is desirable to use such earthquake records to generate the input ground motion. However, it is difficult and expensive to install seismographs deep within the rock, and finding a proper position for an ideal open-ground site (G1) is not easy; thus, it is realistic in practice to use earthquake records at the dam base (F2) as the input ground motion with comprehensive consideration of their deficiencies.

Method for preparing the input ground motion at the engineering bedrock

It is assumed that the ground motion at the dam base (Point F in Figure 3) or an open-ground site (Point G in Figure 3) is defined to assess the seismic performance of an existing dam, and an earthquake response analysis of the dam-foundation system is needed. The input ground motion at the assumed engineering bedrock (Point Q in Figure 3) can be prepared based on the following inverse analysis method with the above-defined ground motion.

The main point of this method is to determine the transfer function of the foundation model. This method is described in the following steps using Figure 10.

Step 1: to obtain the temporary responses of the foundation at Point F in Figure 10

A 3D earthquake response analysis is carried out with the coupled dam-foundation (or further coupled with the reservoir) model. Since the purpose of this step is only to create the input and output waves needed to determine the transfer function between Point Q and Point F, there are many options for selecting the input waves. For convenience, the earthquake records or defined ground motions at Point F are used as the input waves. These waves are input below the bottom viscous boundary (i.e. these waves are used as 2E waves). The three directional components of the input waves are input separately for each direction. Hence, the following three sets of response results can be obtained:

$$\{R_{xx} \quad R_{yx} \quad R_{zx}\}\text{when } W_x \text{ is input,}$$

$$\{R_{xy} \quad R_{yy} \quad R_{zy}\}\text{when } W_y \text{ is input,}$$

$$\{R_{xz} \quad R_{yz} \quad R_{zz}\}\text{when } W_z \text{ is input,}$$

where W_x, W_y, and W_z are the directional components of the earthquake records or defined ground motions at Point F, but they are temporarily used as input waves at Point Q. $R_{ij}(i,j=x,y,z)$ is the response at Point F in the i direction when $W_j(j=x,y,z)$ is input here.

Step 2: to obtain the transfer functions of the foundation model

The transfer functions of the foundation model can be obtained from the Fourier spectra of the input waves at Point Q and the output waves at Point F with the following equations:

$$\begin{aligned} T_{xx} &= F_{R_{xx}}/F_{W_x}, \quad T_{yx} = F_{R_{yx}}/F_{W_x}, \quad T_{zx} = F_{R_{zx}}/F_{W_x} \\ T_{xy} &= F_{R_{xy}}/F_{W_y}, \quad T_{yy} = F_{R_{yy}}/F_{W_y}, \quad T_{zy} = F_{R_{zy}}/F_{W_y} \\ T_{xz} &= F_{R_{xz}}/F_{W_z}, \quad T_{yz} = F_{R_{yz}}/F_{W_z}, \quad T_{zz} = F_{R_{zz}}/F_{W_z} \end{aligned} \tag{1}$$

where $T_{ij}(i,j=x,y,z)$ indicates the transfer function, $F_{Wi}(i=x,y,z)$ is the Fourier spectrum of the input wave at Point Q, and $F_{R_{ij}}(i,j=x,y,z)$ indicates the Fourier spectrum of the output wave at Point F.

Step 3: to obtain the input ground motions at the engineering bedrock

Fourier spectra of the input ground motions at the engineering bedrock can be obtained with the following equation:

$$\begin{Bmatrix} F_{W_x} \\ F_{W_y} \\ F_{W_z} \end{Bmatrix} = \begin{bmatrix} T_{xx} & T_{xy} & T_{xz} \\ T_{yx} & T_{yy} & T_{yz} \\ T_{zx} & T_{zy} & T_{zz} \end{bmatrix} \begin{Bmatrix} F_{W_{Qx}} \\ F_{W_{Qy}} \\ F_{W_{QZ}} \end{Bmatrix}, \tag{2}$$

where $F_{W_{Qi}}(i=x,y,z)$ indicates the Fourier spectrum of the input ground motion at the engineering bedrock. Equation 2 is solved by the Gaussian elimination method. Usually, at least 512 frequencies are needed to reconstruct the Fourier spectrum. Finally, by inverse Fourier transformation of the Fourier spectra $F_{W_{Qi}}(i=x,y,z)$, the input ground motions at the engineering bedrock $W_{Qi}(i=x,y,z)$ can be obtained.

The engineering bedrock and the input ground motions at this location

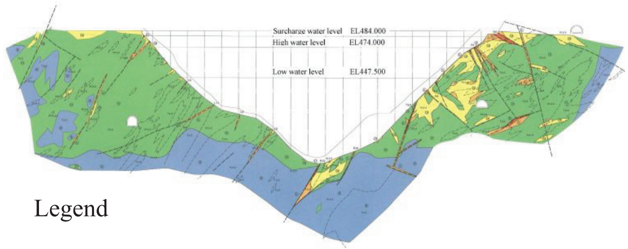
One of the essential issues in the earthquake response analysis of dams is choosing where to set the engineering bedrock. In practice, this depends on the analyst's experience. When the ground motion at the dam base (Point F in Figure 3) or open ground (Point G in Figure 3) is defined, the input ground motion at the assumed engineering bedrock can be generated by the method discussed in the previous section. If the assumed engineering bedrock is not properly set, even if the ground motion defined at the dam base or open ground can be reproduced in the response analysis, the response of the abutments will be incorrect, and the analysis results for the dam will not be reliable. Therefore, the following parts of this study aim to clarify the conditions that should be satisfied in setting the engineering bedrock.

Investigation method and conditions

The engineering bedrock and the input ground motion at this location should satisfy at least the following two assumptions:

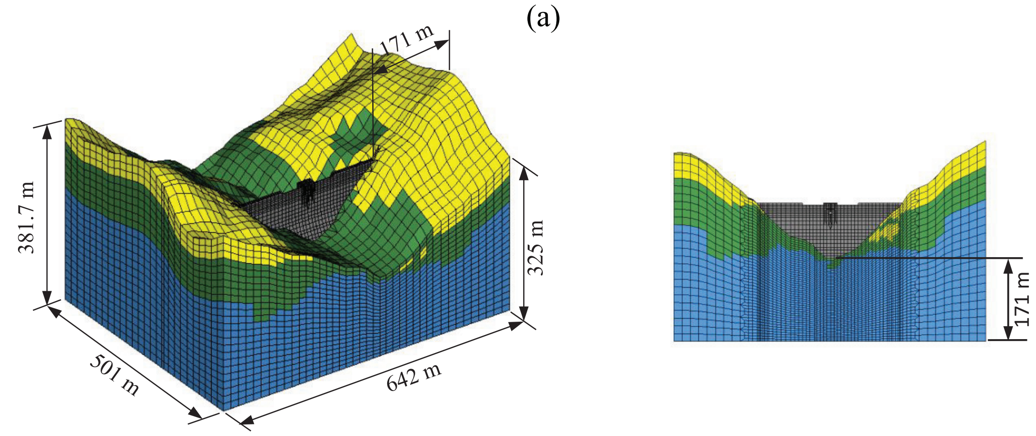
1. The input ground motion at the engineering bedrock should be almost immune to the influence of the dynamic behavior of the upper ground structure and the dam. Therefore, the seismic motion at any location at the same elevation should be almost identical (neglecting the time interval in wave propagation over the model range).
2. There is a dependency relationship between the seismic motions of the dam-foundation system and the input ground motion at the engineering bedrock. When earthquake records are available at multiple monitoring stations, it is possible to regenerate the input ground motion at the engineering bedrock based on the earthquake records. Conversely, when the input ground motion is input from the engineering bedrock, the earthquake records at all the monitoring stations should be reproduced.

To investigate the appropriate position of the engineering bedrock, reproduction analyses of the dynamic behaviors of the Satsunaigawa Dam during earthquakes are performed with an assumed position. By examining the seismic responses of the foundation according to the above two assumptions, whether the assumed engineering bedrock position is appropriate is judged. If not, the depth of the assumed engineering bedrock is adjusted, and the reproduction analyses of the dam and foundation system are performed again. It is thought that if one of the conditions, such as the position of the assumed engineering bedrock, the input ground motion at this position, or the material properties of the analysis model, is incorrect, the earthquake records of all eight monitoring stations will not be reproduced, even if the other conditions are appropriate. The geology and topography of the dam site and the conditions of the reservoir during the earthquakes should also be considered in the model when generating the input ground motions at the engineering bedrock position. The responses of the deep foundation rock are examined to judge whether the above two assumptions are satisfied.



	Rock classification	S-wave velocity (m/s)	Shear strength (MPa)	Friction angle (degree)
(yellow)	CM	1200 – 1700	5 - 20	35 - 45
(green)	CH	1800 – 2400	10 - 30	40 - 50
(blue)	B	2700 – 3000	20 - 50	45 - 55

(a)



(b) (c)

Figure 11. Model used in the study. (a) Geological condition in the dam axis section. (b) Elevated view of the model. (c) Dam axis section.

In the following sections, the reproduction analyses of the Tokachi-Oki earthquake (No. C in Figure 4 and Table 2) are described as an example. The conditions and methods used in the analyses are as follows:

1. Numerical model: Figure 11 shows the finite element model used in the reproduction analyses. The engineering bedrock, as the first trial, is supposed to be at a depth of 1.5 times the dam height (171 m) based on previous studies (Yasuda et al., 2007, 2018) and analysis experience with similar concrete gravity dams. The geology and detailed topography of the foundation bedrock are considered in the model. Viscous boundary conditions (Cao and Saotome, 2012; Miura and Okinaka, 1989) are applied at the side and bottom boundaries of the foundation. Under these conditions, the effects of the ground spreading infinitely outside the model range can be considered.
2. Physical properties: The foundation rock is mainly sandstone with no large faults or fracture zones. Detailed information on the physical properties of the bedrock is known. Because the bedrock is not horizontally stratified, the deep bedrock is relatively sound and homogeneous, with a shear wave velocity greater than 2700 m/s. The rock classification is shown in Figure 11. However, the detailed geotechnical

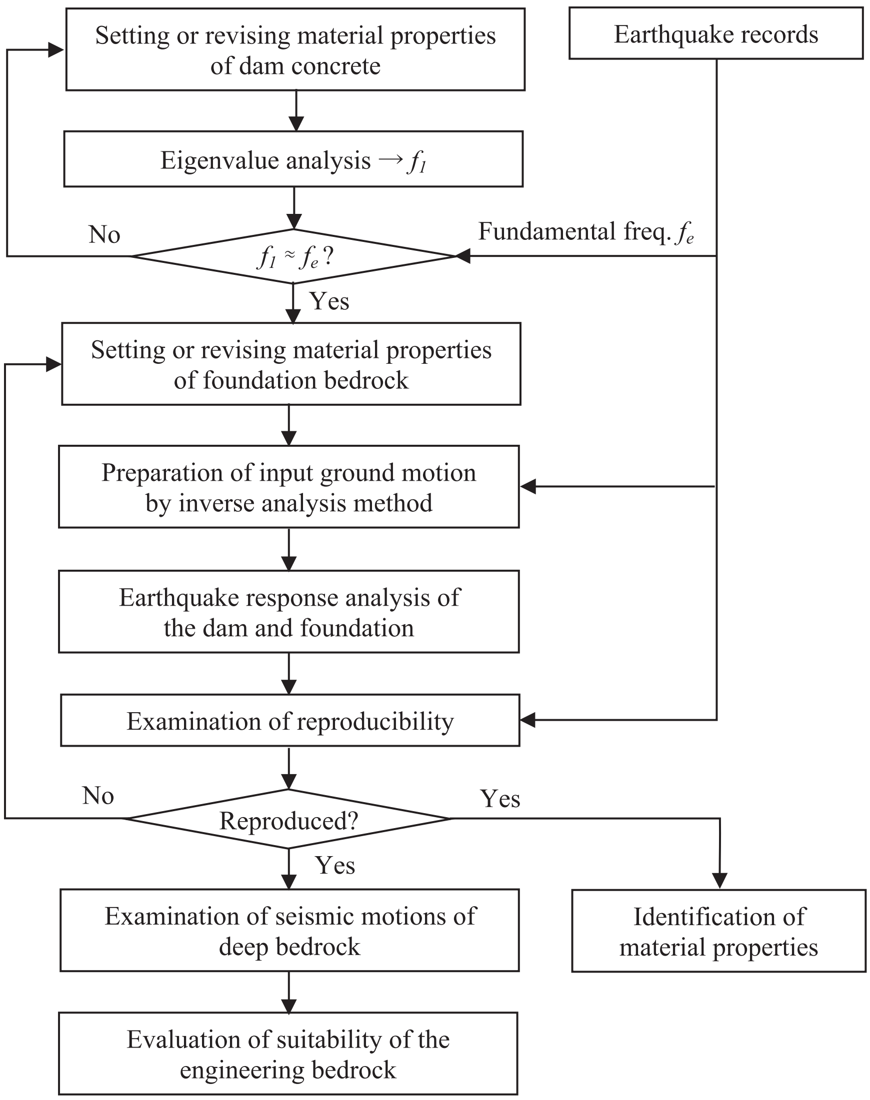


Figure 12. Procedure for the identification of material properties and setting of the engineering bedrock.

information cannot be used directly in the foundation model, and it must be simplified geometrically and numerically. Here, the physical property parameters are given for each classified geology. Similarly, since the construction joints in the dam are not modeled, their effects should be considered in terms of the material properties instead. In the reproduction analyses, the physical properties of the dam and foundation bedrock are iteratively adjusted to improve the reproducibility of the earthquake records. Four items, that is, the maximum acceleration, accelerogram, Fourier spectrum, and transfer function, are examined with respect to reproducibility. Figure 12 shows the identification procedure of the material properties. For the dam concrete, as a linear material, an initial value of the elastic modulus of the dam concrete is set up based on the design value. The value is identified by comparing the fundamental frequency of the dam obtained from eigenvalue analysis and that obtained from earthquake records (the frequency corresponding to the first peak of the transfer function of the dam body). The initial value of the damping ratio of the dam concrete is obtained by the half power method using

Table 3. Material properties of the dam and foundation bedrock

Items		Shear modulus[a] (N/mm^2)	Density[b] (g/cm^3)	Poisson's ratio[c]	Damping ratio[d]
Dam concrete		13,000	2.44	0.20	2%
Foundation rock	CM	5,320	2.74	0.28	5%
	CH	11,400	2.74	0.28	2%
	B	20,520	2.74	0.28	1%

[a]The shear modulus of the dam concrete is identified by reproduction analysis of earthquake behavior of the dam, and the shear modulus of the foundation rock is the result of a geophysical survey.
[b]Test results for quality control in dam construction.
[c]Converted from material test results for the dam concrete and foundation rock.
[d]Identified by reproduction analysis of the earthquake behavior of the dam and foundation in a strong earthquake.

earthquake records (Yasuda et al., 2007). The foundation bedrock is also treated as a linear material. The shear modulus and Poisson's ratio values of these materials are obtained from the shear wave velocities determined from PS logging and rock testing during the construction stage of the dam. A general value of the damping ratio for the foundation bedrock is given by Yoshinaka et al. (2012). However, it is also iteratively adjusted so that it is possible to accurately reproduce the dynamic behaviors of the monitoring stations of the dam and foundation bedrock during earthquakes. The physical properties finally identified are shown in Table 3.

3. Earthquake records: The acceleration records obtained during the Tokachi-Oki earthquake on 26 September 2003 are used. The acceleration records and their Fourier spectra at the lower bedrock (F1) are shown in Figure 13. The input ground motion at the engineering bedrock is calculated based on the inverse analysis method discussed in the previous section using the earthquake records at the lower bedrock (F1).

Results of reproduction analyses

The 3D earthquake response analyses of the dam and foundation system are carried out using UNIVERSE, which is a program designed for the analysis of dams (Ariga et al., 2004).

Acceptable reproduction results are obtained when the material properties shown in Table 3 are used. The earthquake responses at each monitoring station are compared between the analysis results and the earthquake records. The maximum accelerations at each monitoring station are summarized in Table 4. The differences between the maximum acceleration responses and those recorded at the dam crest (T2) and dam base (F2) are scattered in terms of direction. However, as shown in Figure 14, the accelerograms generally coincide with each other. For clarity, only the 3-s main motions (from 22 to 25 s) of the accelerograms are shown in the figure. Figure 15 shows that the Fourier spectra and transfer functions of the calculated acceleration responses and the recorded responses at these two locations match very well. The analysis results of the left abutment (T1) and right abutment (T3) also coincide well with the earthquake records. It is considered that the recorded accelerations at the left and right banks (R1 and R2) are generally reproduced, although the maximum relative error in the stream direction is over 30%, which is

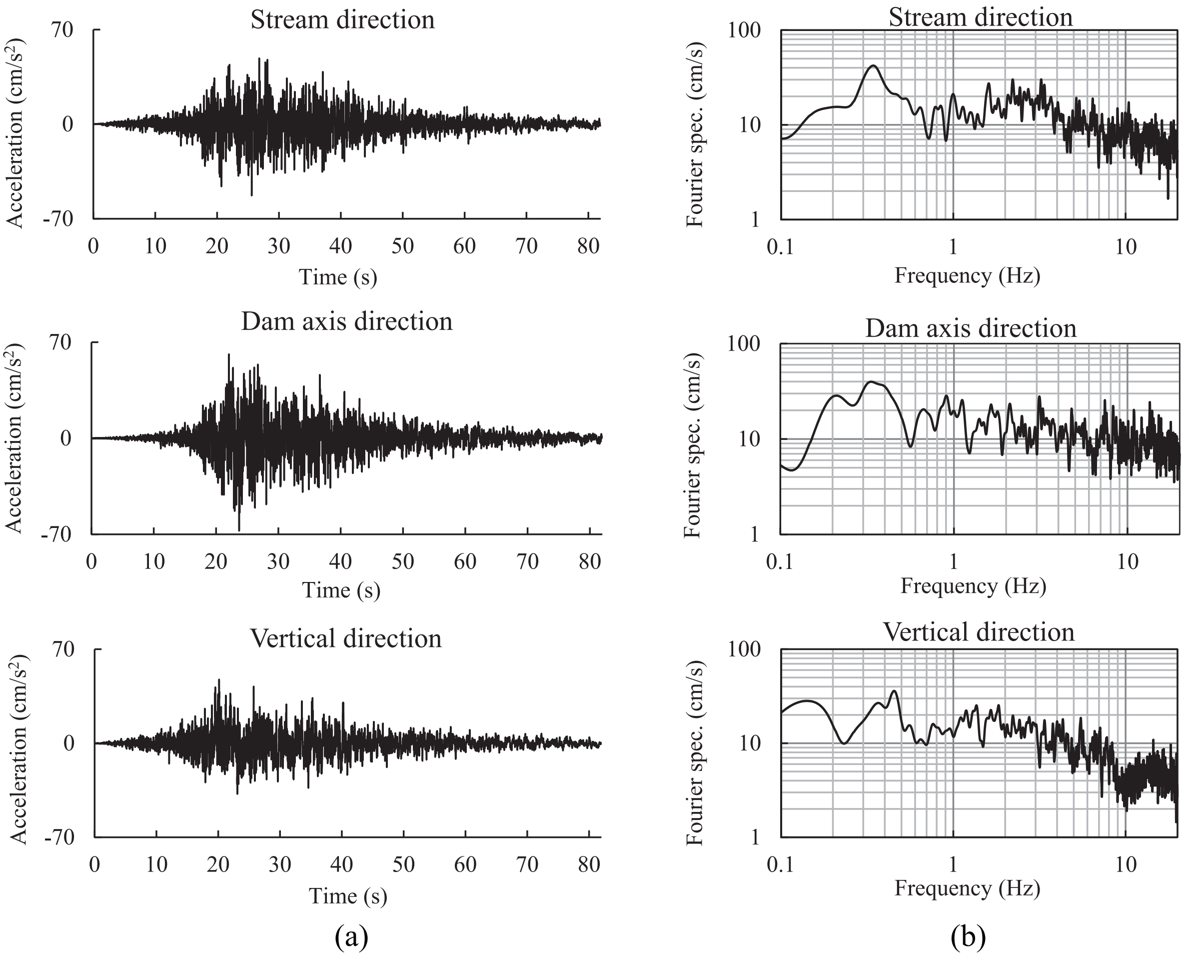


Figure 13. Acceleration records and Fourier spectra at the lower-bedrock monitoring station (F1). (a) Acceleration records. (b) Fourier spectra.

thought to be due to the uncertainty of the geological conditions. As PS logging was only carried out at the foundation bedrock below the dam area, the geological information from the vicinity of the dam is limited. The reasons for the good reproducibility of the analysis are considered to be that the analysis model is based on generally detailed topographical and geological information and that the physical properties are precisely identified through the process shown in Figure 12.

Suggestions for setting engineering bedrock

When the dynamic behaviors of all monitoring stations at the dam site are reproduced by the numerical analysis, it can be considered that the earthquake responses, including those of the foundation bedrock in the analysis model, approximate the actual seismic motions during the earthquake. For the seismic motions inside the foundation bedrock, acceleration responses are examined at a total of 18 points on two horizontal planes, as shown in Figure 16. The acceleration time histories and Fourier spectra of all the points are compared. To clearly show the differences among the points, the 3-s main motions are extracted from the entire time history (81.92 s). Figure 17 shows the main motions of the three points along the intersection line between the F1 plane (with a depth of 57 m below the dam base) and the dam axis section. Compared with the acceleration at monitoring

Table 4. Maximum accelerations at each monitoring station

Seismograph	Direction	Recorded (cm/s^2)	Analyzed (cm/s^2)	Error (%)[a]
T2	Stream	674	672	0
	Dam axis	310	402	30
	Vertical	214	256	20
F2	Stream	61	80	33
	Dam axis	67	90	34
	Vertical	58	73	27
F1	Stream	53	53	0
	Dam axis	67	67	0
	Vertical	47	47	0
R1	Stream	68	94	39
	Dam axis	68	86	26
	Vertical	71	83	16
T1	Stream	202	161	−20
	Dam axis	222	182	−18
	Vertical	114	110	–3
T3	Stream	213	191	−10
	Dam axis	195	204	5
	Vertical	157	149	−5
R2	Stream	79	106	35
	Dam axis	98	90	−8
	Vertical	99	110	11

[a]Error = (analysis value − recorded value) / recorded value.

station F1, the acceleration on both sides (FL and FR of Figure 17) is slightly higher in all three directions, and phase differences can be observed in parts of the time histories. This is presumed to be due to the disturbance resulting from the seismic motions of the dam and natural ground since the plane is at a depth of only half the dam height. Figure 18 shows the main motions of the three points along the intersection line between the bottom plane (with a depth of 171 m below the dam base) and the dam axis section. At this depth, the relative errors of the maximum acceleration values are quite small, and the phases conform throughout almost the entire time history. In other words, the seismic motions at this depth are hardly affected by the vibration of the dam and natural ground during earthquakes. Therefore, it seems reasonable to set the position of the engineering bedrock to this depth. Based on the conditions used in this analysis and the analysis results, it is suggested that the engineering bedrock should be set at a depth of at least 1.5 times the dam height. At this depth, the shear wave velocity of the foundation bedrock should be 2000 m/s or higher (although, in this study, this value is 2700 m/s, a value of 2000 m/s or higher is recommended as a general value for setting the engineering bedrock for concrete gravity dams). It is considered that this value is not a very high hurdle for the bedrock at a depth of 1.5 times the dam height in the case of concrete dams. Furthermore, it is desirable to set the position of the engineering bedrock in a uniform rock mass.

Seismic motion of the deep bedrock

As mentioned in the previous section, the seismic motion at the bottom plane of the analysis model is almost immune to the influence of the vibration of the dam and natural ground. Figure 19 shows the responses at the center of the bottom plane of the foundation model. These results can be regarded as the seismic motion during the Tokachi-Oki

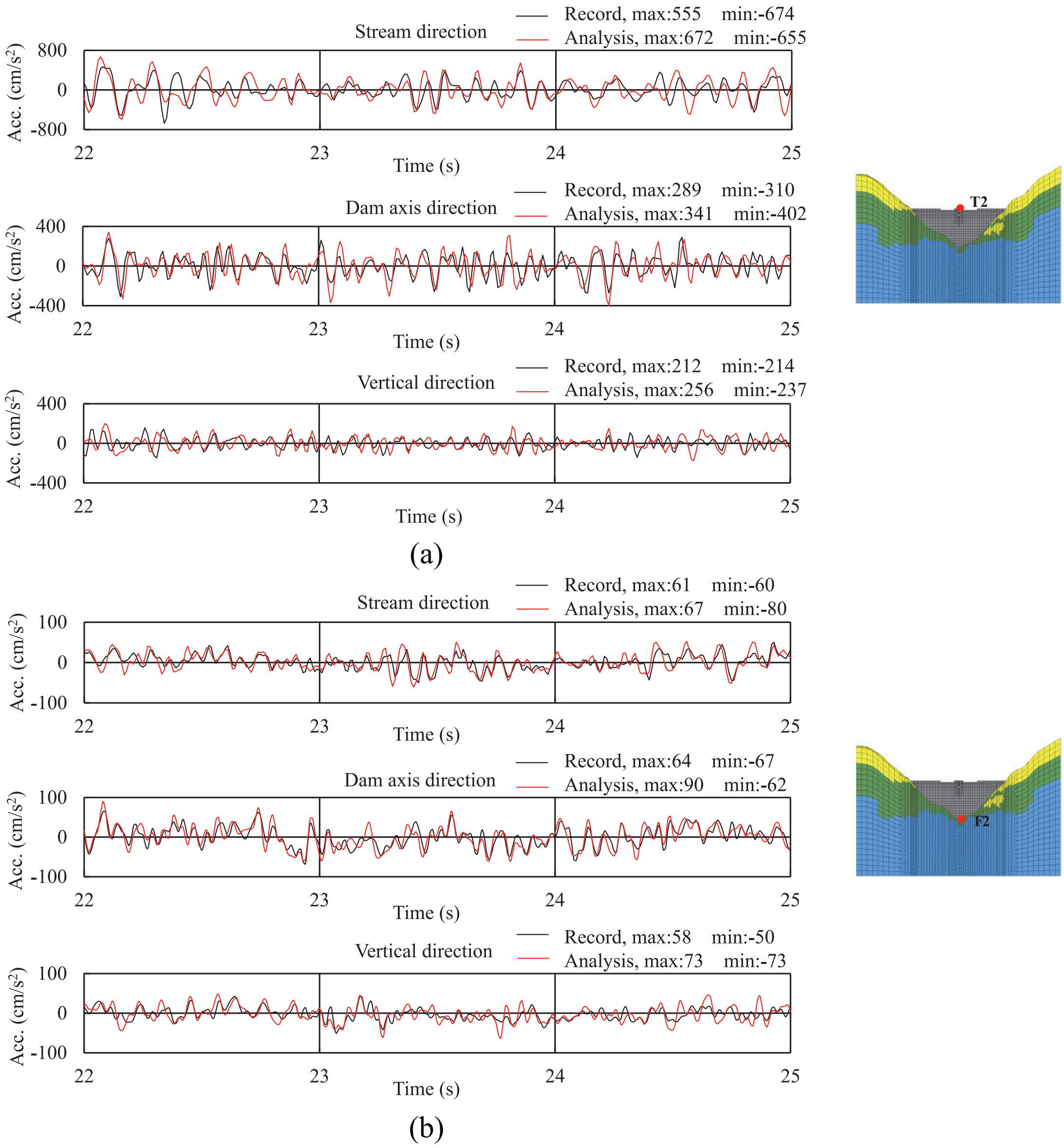


Figure 14. Comparison of accelerations at the (a) dam crest (T2) and (b) dam base (F2).

earthquake. To date, there are no reported records of seismic motion in deep bedrock at depths greater than 170 m; therefore, the analysis results obtained here should be helpful for understanding the seismic motion of deep bedrock. In addition, in analyses related to assessments of the seismic performance of dams, the input ground motions for the engineering bedrock can be calculated via various methods, such as prediction equations or empirical Green's functions (Irikura, 1989). The seismic motions obtained here can be used to verify these methods.

Comparison of the input ground motions created with different earthquake records

The above discussions have demonstrated that for earthquake response analysis, the engineering bedrock should be set at a depth 1.5 times the dam height, and it is desirable that the shear wave velocity of the rock at that depth be 2000 m/s or more. To create the input ground motion at the engineering bedrock, a numerical model reflecting the actual geology

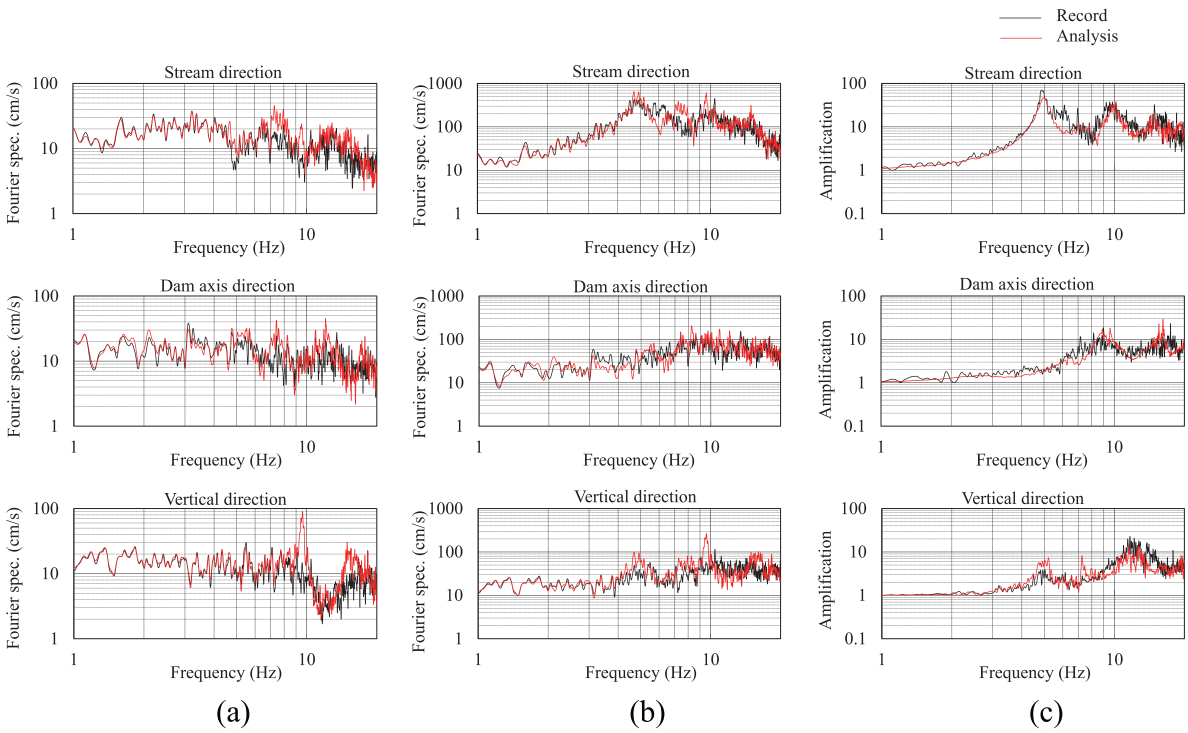


Figure 15. Comparison of Fourier spectra and transfer functions at the dam crest (T2) and dam base (F2). (a) F2. (b) T2. (c) T2/F2.

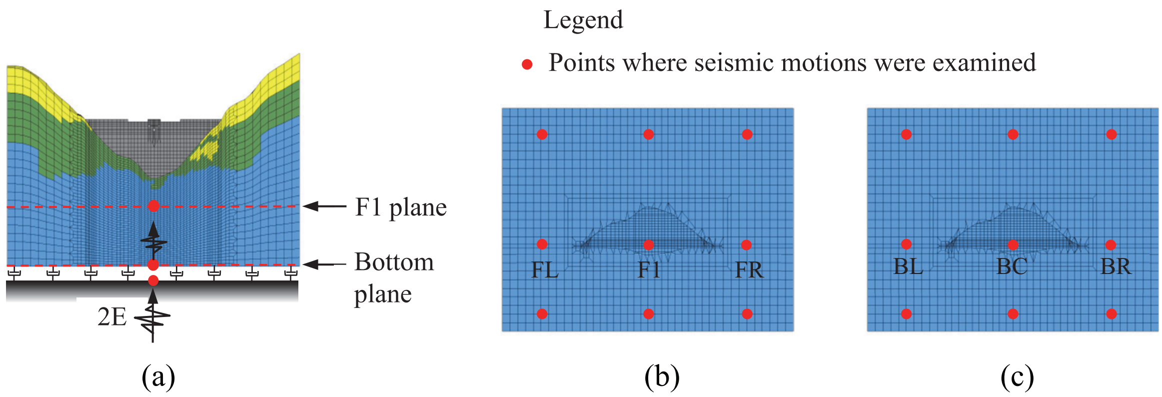


Figure 16. Planes and points where seismic motions were examined. (a) Locations of the planes. (b) Points within the F1 plane. (c) Points within the bottom plane.

and topography of the foundation rock should be used, and the material properties should be identified by reproducing the past earthquake records from multiple monitoring stations (if such data are available) using the procedure shown in Figure 12.

To examine the possible influence of earthquake records when they are used for setting the input ground motions at the engineering bedrock, input ground motions based on the earthquake records of two monitoring stations (F1 and F2 in Figure 2) are calculated and compared. Briefly, the input ground motion obtained using the earthquake records from the lower bedrock (F1) is named "Wave F1," and that obtained using the earthquake

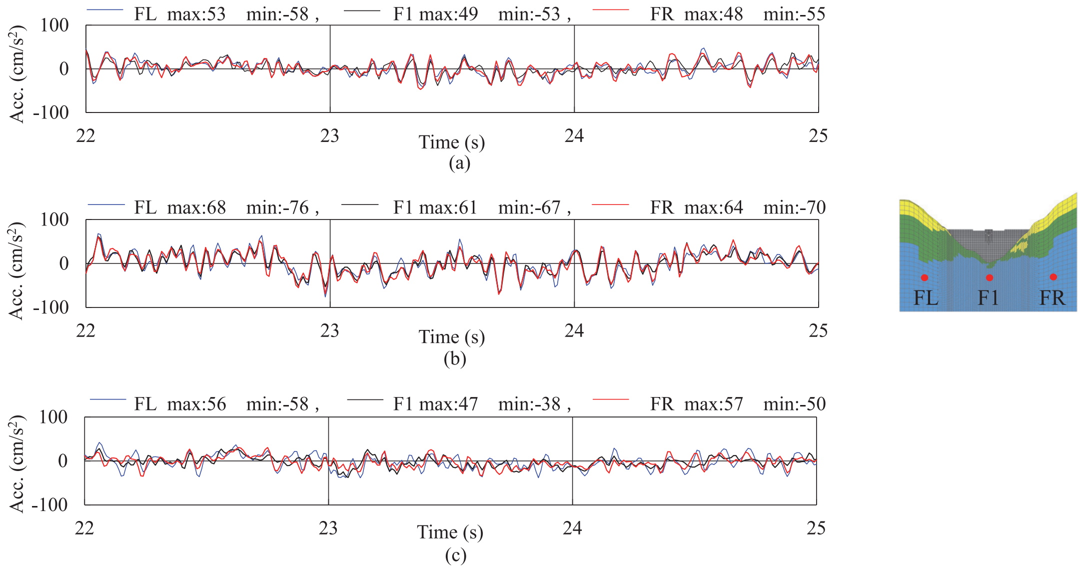


Figure 17. Comparison of seismic motions on the F1 plane. (a) Stream direction. (b) Dam axis direction. (c) Vertical direction.

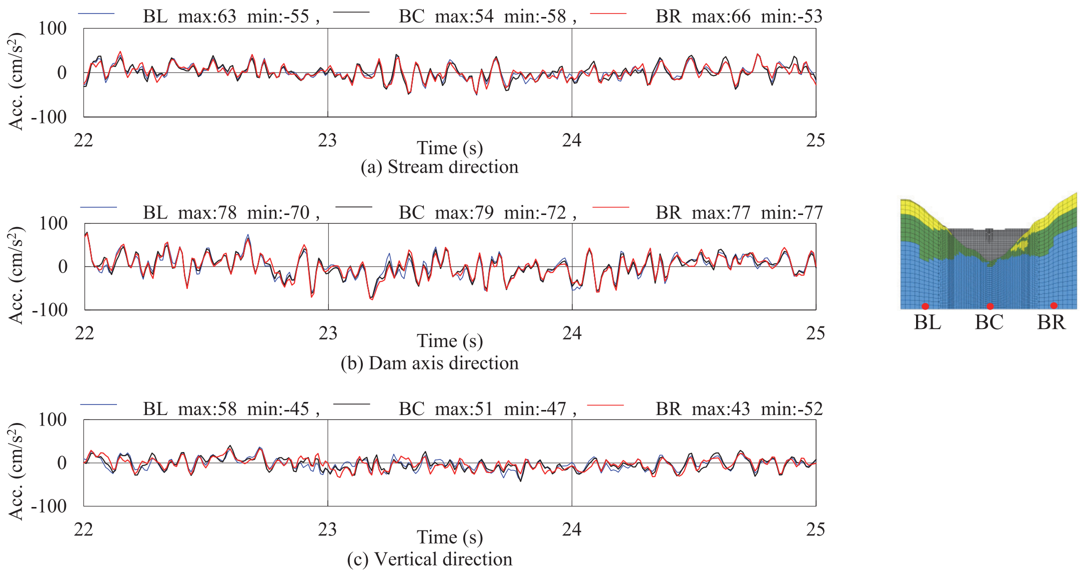


Figure 18. Comparison of seismic motions on the bottom plane. (a) Stream direction. (b) Dam axis direction. (c) Vertical direction.

records from the dam base (F2) is named "Wave F2." The stream direction components of the Fourier spectra of these two waves are compared in Figure 20 as an example. In the low frequency range up to 4.6 Hz, the Fourier spectra of the two waves are almost the same. This means that in the frequency range lower than the fundamental frequency of the dam, the input ground motions based on the earthquake records of the different monitoring stations are almost the same. In the frequency range of 4.7–9.5 Hz, the Fourier spectra of Wave F2 are lower in magnitude than those of Wave F1. As mentioned earlier, in this frequency range, the earthquake records at the dam base (F2) are affected by the natural vibration modes of the dam. The frequency components corresponding to this range are suppressed in the earthquake records. As a result, Wave F2 shows the same

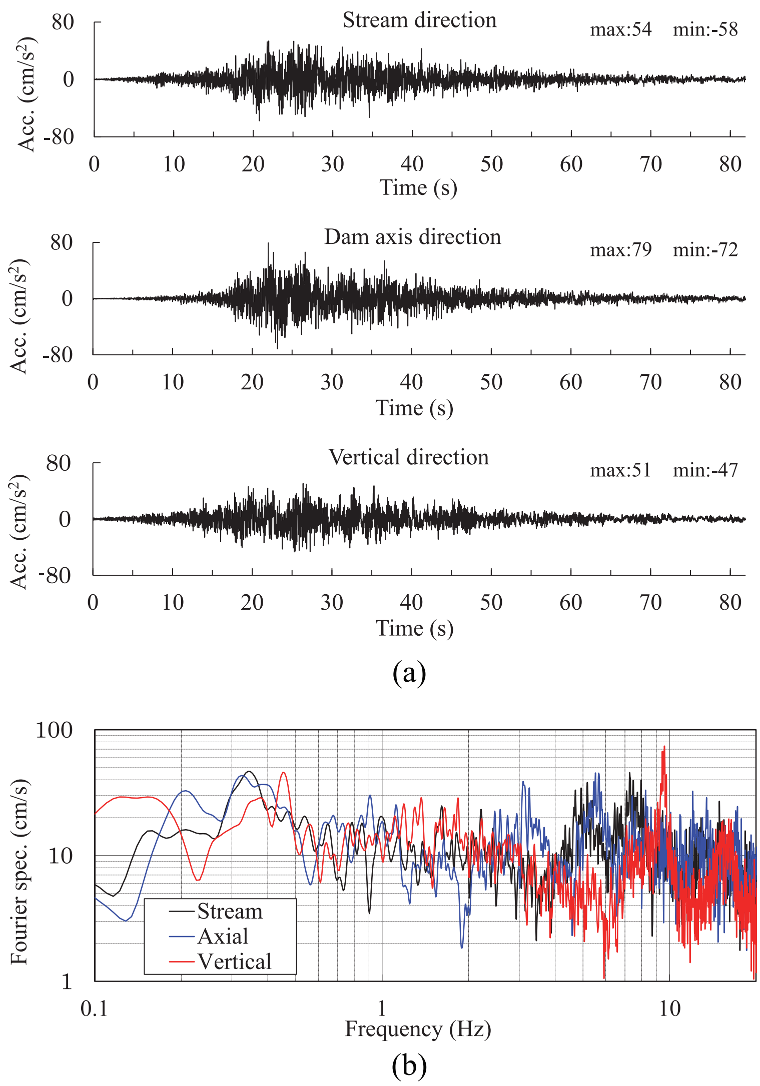


Figure 19. Ground motions at the center of the bottom plane of the foundation model. (a) Acceleration. (b) Fourier spectrum.

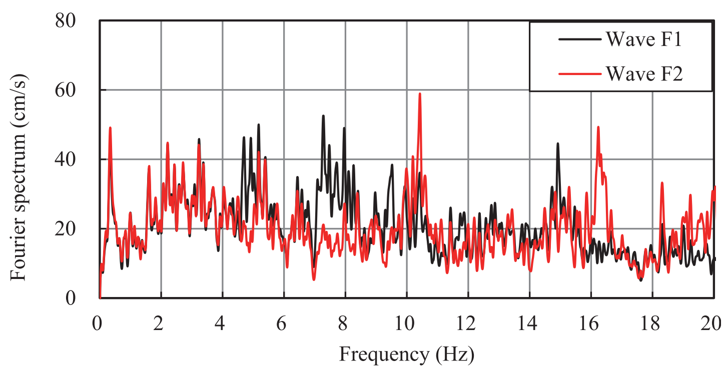


Figure 20. Comparison of the Fourier spectra of the input ground motions (stream direction).

tendency. In the frequency range of 10–15 Hz, the magnitude relationship between Wave F1 and Wave F2 changes depending on the frequency. In the frequency range higher than

15 Hz, the Fourier spectrum of Wave F2 is generally higher in magnitude than that of Wave F1.

In the dam axis and vertical directions, generally similar tendencies can be found, although they are not as clear as those found in the stream direction. Therefore, it is necessary to compensate for the frequency suppression before using the earthquake records of the dam base (F2) to generate the input ground motion at the engineering bedrock. This issue will be addressed in future studies.

Conclusions

The following conclusions were obtained from this study.

1. In the earthquake records at the dam base, the frequency components corresponding to the natural vibration modes of the dam are suppressed because of the influence of the dam vibration. In the case that such an earthquake record is used as an original waveform for setting the input ground motion in the assessment of seismic performance of a dam, these characteristics may lead to a potentially hazardous evaluation. Therefore, it is necessary to carefully consider such characteristics, and appropriate compensation of the earthquake records is desirable before using them for this purpose.
2. To understand the seismic motions of dam sites, it is desirable to install seismographs at a depth no less than half the dam height or at an open-ground site at a distance no less than the dam height. When the installation of seismographs is restricted due to cost or other conditions, seismographs at the crest and the base are indispensable for monitoring the dam behavior.
3. A procedure and method for creating the input ground motion at the engineering bedrock when the ground motion at the dam base or at an open-ground site is defined are proposed. When setting the engineering bedrock in a numerical analysis, in the case of concrete gravity dams, the engineering bedrock should be set at a depth no less than 1.5 times the dam height, and the shear wave velocity of the rock mass at such depth should preferably be 2000 m/s or more.

Investigations based on seismic motions across the whole dam site, including in the deep bedrock, are rare globally. Therefore, the basic conclusions obtained in the study are considered to have value as a reference for other concrete dams. On the contrary, it is difficult to apply the conclusions of this article to earthfill dams and rockfill dams because the vibration characteristics of dams and foundation rocks differ generally depending on the dam type.

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