STUDY ON THE ENGINEERING BEDROCK AND SEISMIC MOTION AT IT IN THE EARTHQUAKE RESPONSE ANALYSIS OF A CONCRETE DAM

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ABSTRACT

In Japan, the dam safety against large-scale earthquakes is verified by numerical analysis. Seismic motion defined for verification of seismic performance of a dam is set based on the distance attenuation formula which is obtained by statistical analysis of the earthquake records of many dams, the empirical Green's function method, and a method of adjusting ground motion record to the stipulated lower-limit acceleration response spectrum for verification. Generally, the input seismic motion for the earthquake response analysis is prepared by pulling the seismic motion back to the engineering bedrock hypothesized by numerical analysis method. However, lacking precise criteria for setting engineering bedrock for earthquake response analysis of a dam, the appropriateness of the preparation method of the seismic motion and of the prepared input seismic motion are not necessarily clarified. This study predicted seismic motion of deep bedrock using earthquake acceleration records during the Tokachi-oki Earthquake in 2003 (M. 8.0) inside bedrock at a depth of 57 m below the bottom of the Satsunaigawa Dam which is equipped with 8 seismographs. Based on the research results, it was pointed out that in the case of concrete gravity dams, the engineering bedrock should be set at a depth equal to about 1.5 times the dam height, and where the shear wave velocity of the bedrock should be no less than 2,000 m/s. Then, a procedure of preparing input seismic motion for earthquake response analysis is proposed.

1 INTRODUCTION

Earthquake response analysis of a dam done to verify the seismic performance of the dam is often carried out using the following flow: first estimating the seismic motion of the bottom surface of the dam or of the open bedrock applying the empirical method (Matsumoto et al. 2003) or the semi-empirical method (Irikura1986, Boore 1983, Kamae et al. 1991) then predicting the seismic motion of the engineering bedrock that was hypothesized by a pull-back calculation of the wave. Naturally, the predicted seismic motion at the engineering bedrock is dependent on conditions of the analysis model, and it is nothing more than a numerical analysis. The earthquake responses of the foundation bedrock, the natural ground and dam body excited by the input seismic motion are not necessarily clarified. Furthermore, the verification of seismic performance of the dam based on the analysis result has several matters to be resolved. Because, on the other hand, it is difficult to directly measure seismic motion in deep bedrock, almost no efforts have been made in the field of dam engineering to verify the setting of seismic motion for engineering bedrock.

The Satsunaigawa Dam is a concrete gravity dam with height of 114 m. Three-direction component seismographs installed at the locations shown in Figure 1, have collected several earthquake records since the dam was completed in 1996. The seismograph at a depth of 57 m (equals to half of the dam height) underneath the dam base in particular, has obtained valuable records inside the bedrock. Besides, seismographs are also installed inside the rim-tunnels of both banks.

The dynamic properties and dynamic behavior of the dam were studied based on numerical analysis using earthquake records (Yasuda et al. 2007). This study aims to contribute to setting input seismic motion in order to verify seismic performance of dams in the future. Based on earthquake records obtained at multiple monitoring points on the Satsunaigawa Dam site, the seismic motion of the deep bedrock is predicted by a numerical analysis method. Simultaneously, the criteria for setting engineering bedrock and preparation methods of input seismic motion for earthquake response analyses of the dam are investigated.

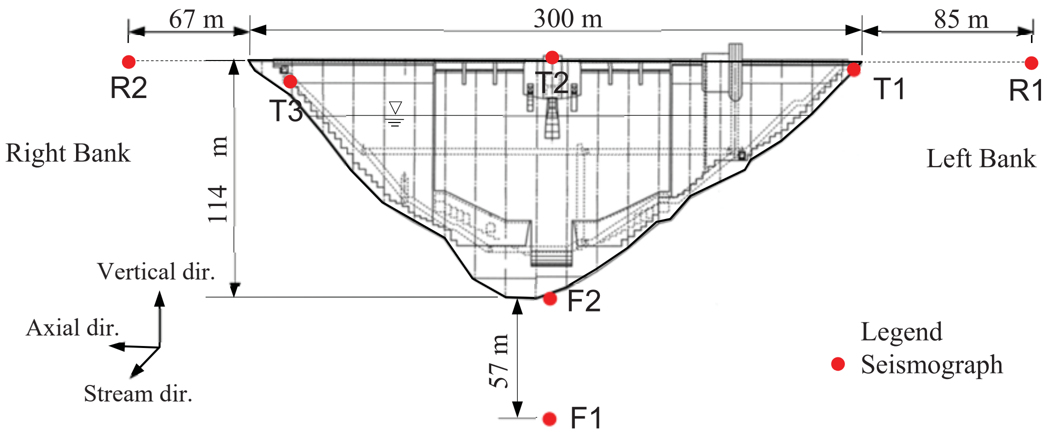


Figure 1. Locations of seismographs at the Satsunaigawa Dam (downstream side).

2 INVESTIGATION METHOD AND CONDITIONS

2.1 *Investigation Method*

The following two points must be considered when setting the engineering bedrock.

(1) Seismic motion in engineering bedrock is almost immune to the effects of the dynamic behavior of the upper ground structure and the dam, so that seismic motion at any location on the same elevation of the foundation bedrock is almost identical.

(2) When there are earthquake records at multiple monitoring points including natural ground, it is possible to predict the seismic motion of the engineering bedrock based on the earthquake record. Inversely, when the estimated seismic motion of the engineering bedrock has been input, the dynamic response at all monitoring points must be reproduced.

According to the above premises, in this study, earthquake response analysis with a 3-D dam–foundation bedrock–reservoir system was performed to reproduce the behaviors of the Satsunaigawa Dam and its foundation bedrock during the Tokachi-oki Earthquake in 2003 (September, 26). Four items were considered concerning reproducibility: the maximum acceleration, accelerogram, Fourier spectrum, and the transfer function. To improve the reproducibility of the observed dynamic behavior, the physical properties of the dam and the foundation bedrock were repeatedly adjusted. Through this process, the seismic motion of the engineering bedrock that was assumed to be 171 m underneath the bottom surface of the dam was sequentially estimated. Figure 2 shows the investigation flow. By considering the seismic motion inside the bedrock when the earthquake record for each monitoring point was reproduced, setting criteria and appropriate method of creating seismic motion at engineering bedrock for the earthquake response analysis of a dam was proposed.

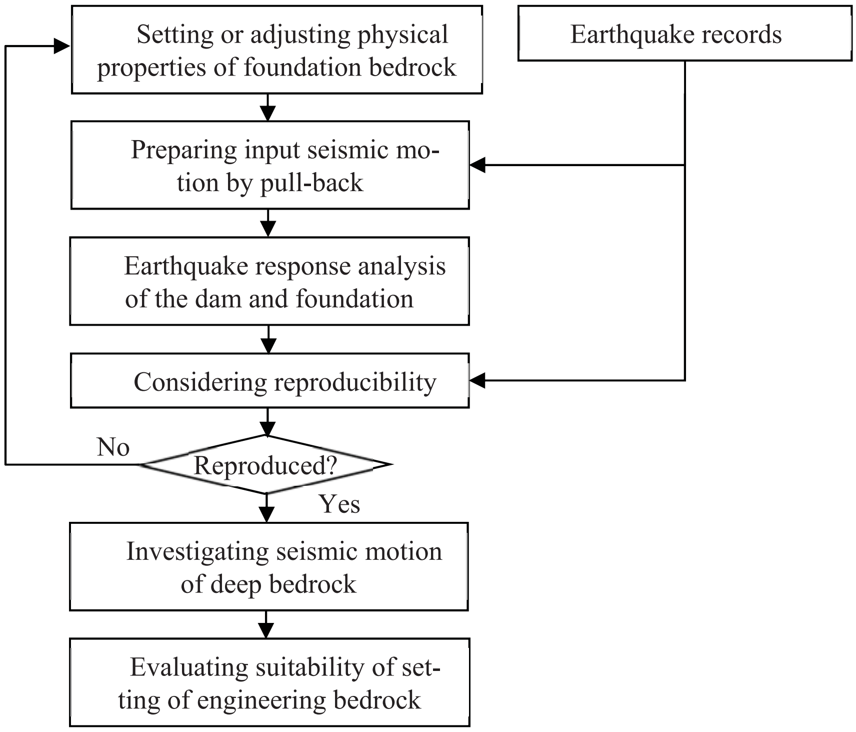


Figure 2. Investigation flow.

2.2 *Investigation Conditions*

2.2.1 *Earthquake record*

During the earthquake, acceleration records were obtained from each seismograph shown in Figure 1. The accelerations and Fourier spectra at the lower point of the bedrock (F1) are shown in Figure 3(a) and Figure 3 (b) respectively as examples.

2.2.2 *Model used for the investigation*

Figure 4 shows the model used for this study. The geology and detailed topography of the foundation bedrock are taken into account in the analysis model. Viscous boundaries (Cao et al. 2012) were set as the side and bottom surface boundaries of the foundation bedrock model, and the extent of ground spreading infinitely outside the analysis range was considered.

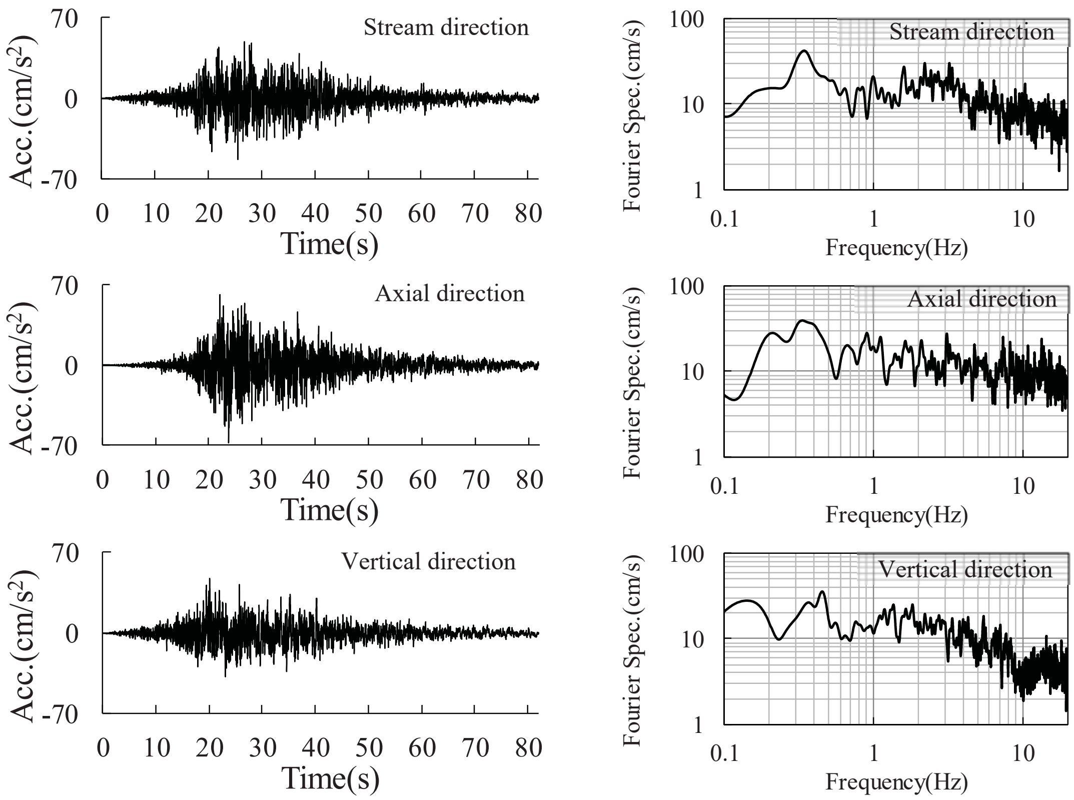
2.2.3 *Physical properties*

For the dam concrete, as a linear material, its elastic modulus and damping coefficient were adjusted to most accurately reproduce the dam behavior during the earthquake. The damping coefficient was obtained by the half power method using the earthquake records (Yasuda et al. 2007), and the elastic modulus of the dam concrete was adjusted starting from the design value. Table 1 shows the physical properties of the dam concrete defined conclusively. Of these, the density and Poisson's ratio are the results of quality control testing during the dam execution.

Table 1. Physical properties of dam concrete.

Elastic Modulus (N/mm^2)	Density (g/cm^3)	Poisson's ratio	Damping coefficient
31200	2.4	0.2	2%

The foundation bedrock is also considered to be linear material. Its physical properties were obtained from the seismic velocity (PS) logging and rock testing, but the damping coefficient was finely adjusted so that it would be possible to most accurately reproduce the behavior of the monitoring points of the concerned foundation bedrock during the earthquake. Ultimately the physical properties were defined as shown in Table 2.



(a) Earthquake records (b) Fourier spectra

Figure 3. Earthquake records and Fourier spectra at the lower point of the bedrock (F1).

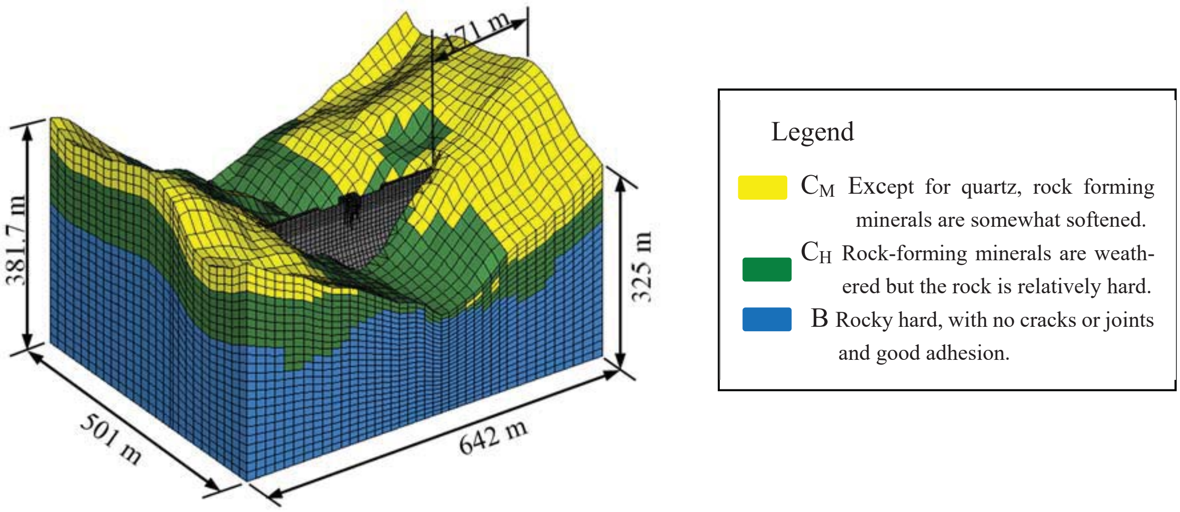


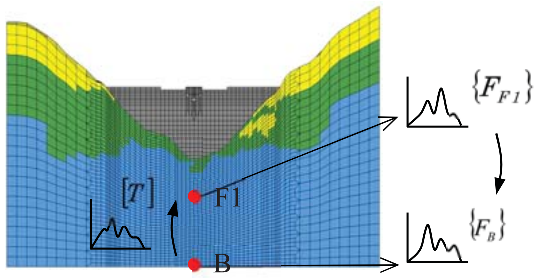
Figure 4. Model used for the study.

Table 2. Physical properties of foundation bedrock.

Rock class	Elastic modulus (N/mm²)	Density (g/cm³)	Poisson's ratio	Damping coefficient
CM	13620			5%
CH	29180	2.74	0.28	2%
B	52530			1%
Grounds	PS logging	Rock testing	PS logging	by analysis

2.2.4 *Input seismic motion*

The input seismic motion at the bottom surface of the model (hypothesized engineering bedrock) was prepared based on the pull-back method (Yasuda et al. 2018, Cao et al. 2016) of the three-dimensional seismic motion using earthquake records of the lower points of the bedrock (F1) which is immune to the effects of the vibration of the dam and natural ground. Figure 5 shows the procedure image, and the detailed description is given in references (Yasuda et al. 2007, Yasuda et al. 2018).



$\{F_{F1}\}$, $\{F_B\}$ is the Fourier spectrum of F1 and B, respectively.
$[T]$ is the transfer function between F1 and B.

Figure 5. Preparing the input seismic motion.

3 RESULTS OF REPRODUCTION ANALYSIS OF DYNAMIC BEHAVIOR OF THE DAM AND FOUNDATION BEDROCK

The earthquake motions at each monitoring point on the dam body and foundation bedrock were successfully reproduced by numerical analysis at relatively good precision. The maximum accelerations at each monitoring point are summarized in Table 3. Here, as examples, Figure 6 shows the acceleration response time histories at the dam crest (T2) and upper point of the bedrock (F2), and Figure 7 shows the Fourier spectra and transfer functions of these acceleration responses.

The differences of the maximum acceleration responses and recorded accelerations at the dam crest (T2) and upper point of the bedrock (F2) are scattered according to direction, but as shown in Figure 6, the accelerograms generally are similar. Figure 7 shows that the Fourier spectra and transfer functions of calculated acceleration response and recorded accelerations at these two locations conform extremely closely. The calculated and recorded results for the left bank (T1) and the right bank (T3) conform closely, and calculated results those generally reproduced both the natural ground on the left bank (R1) and the right bank (R2) were obtained. The reasons for the good reproducibility of the analysis are assumed to be the fact that the analysis model reflects detailed topographical and geological information, and the physical properties were precisely defined.

4 SEISMIC MOTIONS INSIDE BEDROCK AND AT ENGINEERING BEDROCK

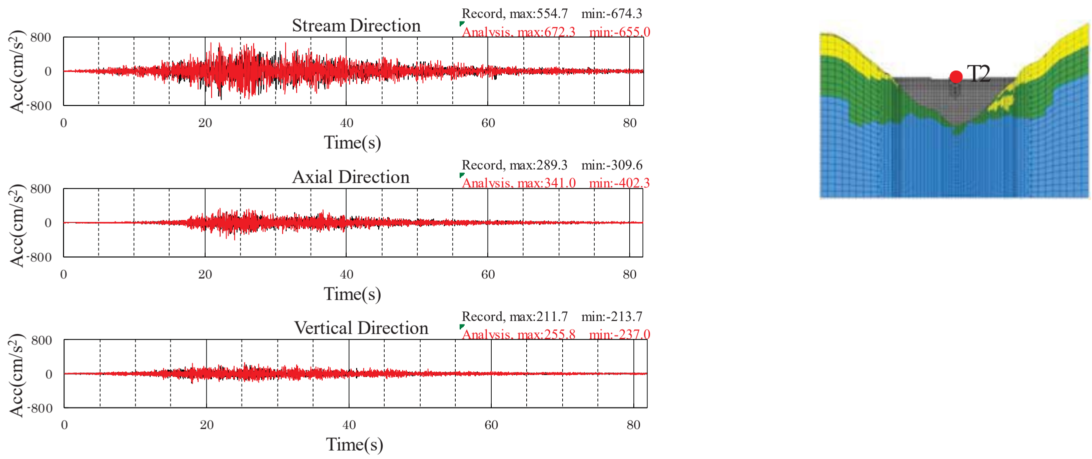
4.1 *Seismic motions inside bedrock*

When the earthquake motions of all monitoring points on the dam body and inside the foundation bedrock had been reproduced by numerical analysis, it is assumed that the earthquake response deep in the foundation bedrock model approximated the actual seismic motion without effects of the vibrations of dam body and natural ground. Accelerations at a total of 18 points on two horizontal planes shown in Figure 8 were calculated. The time histories and Fourier spectra of calculated accelerations at each location considered in the stream direction and axial direction (see Fig. 8(b)) were compared on each plane. Since the seismic motion inside the bedrock includes the wave propagates from the lower layer and the reflection from above layer, it is marked as E+F wave in Figure 8. The seismic motion at the engineering bedrock is obtained by inverse analysis using the earthquake records of monitoring points. The seismic motion is defined at an open ground, so it is marked to be 2E wave in Figure 8.

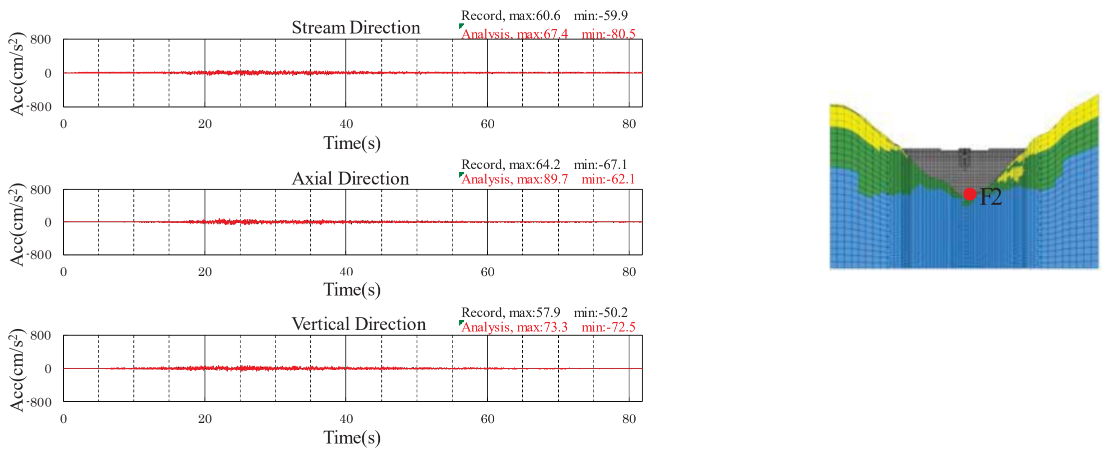
Table 3. Maximum accelerations at each monitoring point found by reproduction analysis.

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

Note: *Error = (analysis value – observed value)/observed value

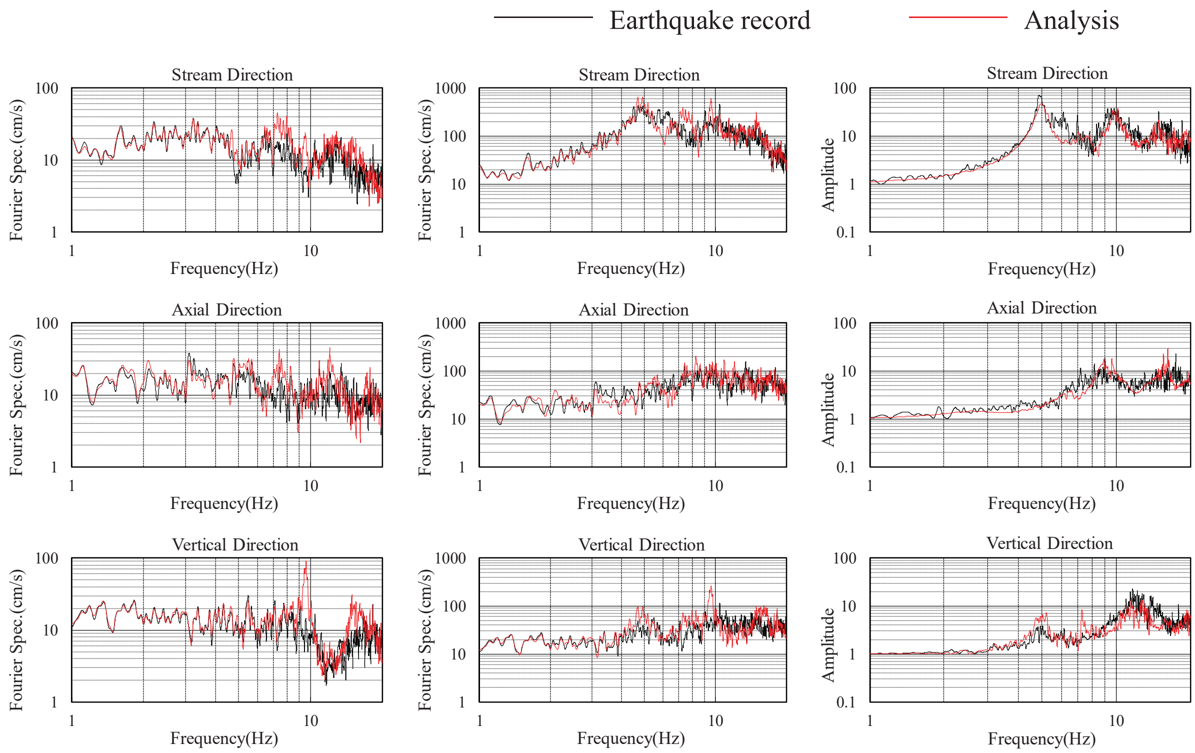


(a) The Crest (T2)



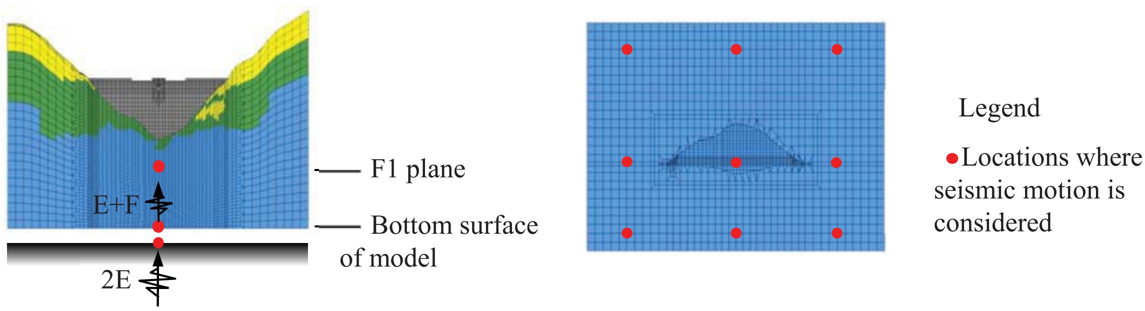
(b) The Upper Point of Foundation(F2)

Figure 6. Comparison of acceleration at dam crest and dam base in reproduction analysis.



(a) F2 (b) T2 (c) T2/F2

Figure 7. Comparison of Fourier spectra and transfer functions at dam crest and the upper point of bedrock (Recorded and calculated).



(a) Depth of the plane considered (b) Points on each plane considered

Figure 8. Locations of calculated accelerations inside the bedrock.

In order to clearly compare the accelerograms at different locations, 10 seconds (20.01 to 30.0 seconds) of main motion was extracted from the total time history (length 81.92 seconds). Figure 9 shows the main motions of three components at three locations on the F1 plane (depth of 57m from bottom surface of dam) of the dam axis section. Comparing with the lower point of the bedrock (F1), the accelerations at both sides (L1 and R1) are a little larger in three directions, and the phase difference appeared partially in time histories. This result is assumed to be the disturbance of the seismic motion in the bedrock of this depth by the influence of the dynamic behavior of the dam and the natural ground on both sides. Figure 10, on the other hand, shows the main motion at three locations on the bottom plane of the model (depth of 171 m below the bottom surface of the dam). At this depth, the relative error of the maximum acceleration at three locations was quite small, and its phases conformed throughout almost the entire time history. For this reason, it is assumed that the depth of the engineering bedrock for analysis should be set at least 1.5 times the dam height (in this model, 171 m), and that the seismic motion at this location will be almost unaffected by the behavior of the dam and natural ground during the earthquake.

4.2 ***Seismic motion at engineering bedrock***

As stated in the previous section, the seismic motion on the bottom surface of the model at a depth of 171 m is almost immune from the influence of the dynamic behavior of the dam or natural ground, so this depth (Fig. 8(a)) can be set as the engineering bedrock. Figure 11 shows the responses of this location obtained by reproduction analysis. This is considered to be similar to seismic motion actually generated in deep bedrock by the Tokachi-oki Earthquake in 2003. Figure 11(a) shows the ground motion on the open bedrock surface (Fig. 8(a)) at this location. It is possible to reproduce the dynamic behavior at each monitoring point on the dam body and on the foundation bedrock by inputting this wave, so this wave can be considered to be the seismic motion at the engineering bedrock.

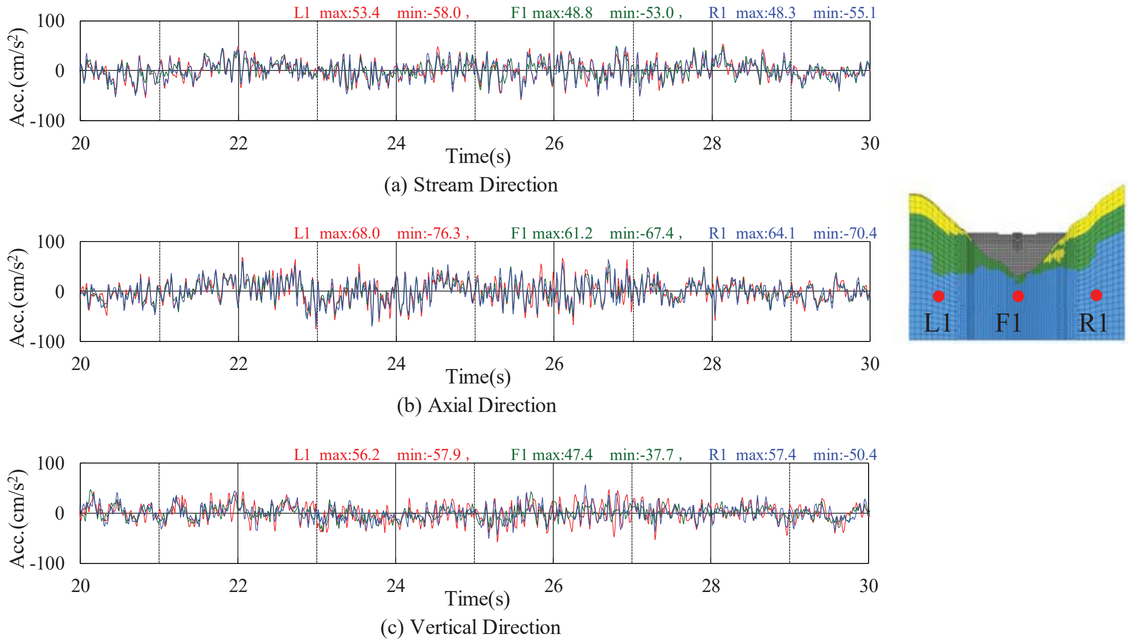


Figure 9. Comparison of seismic motion on F1 plane.

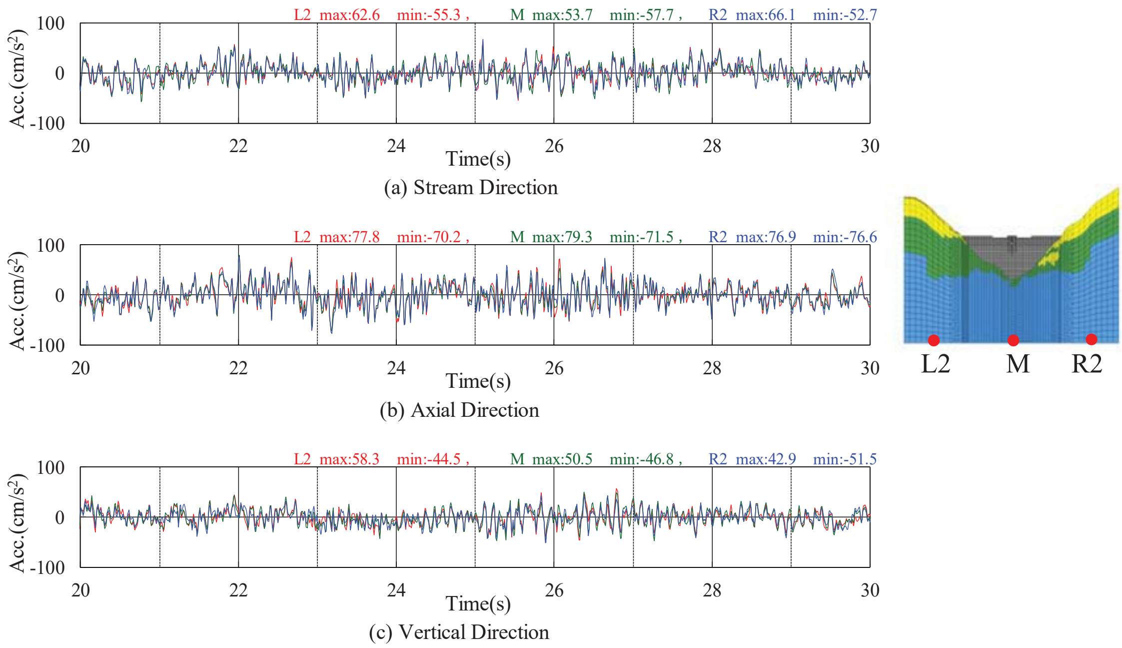
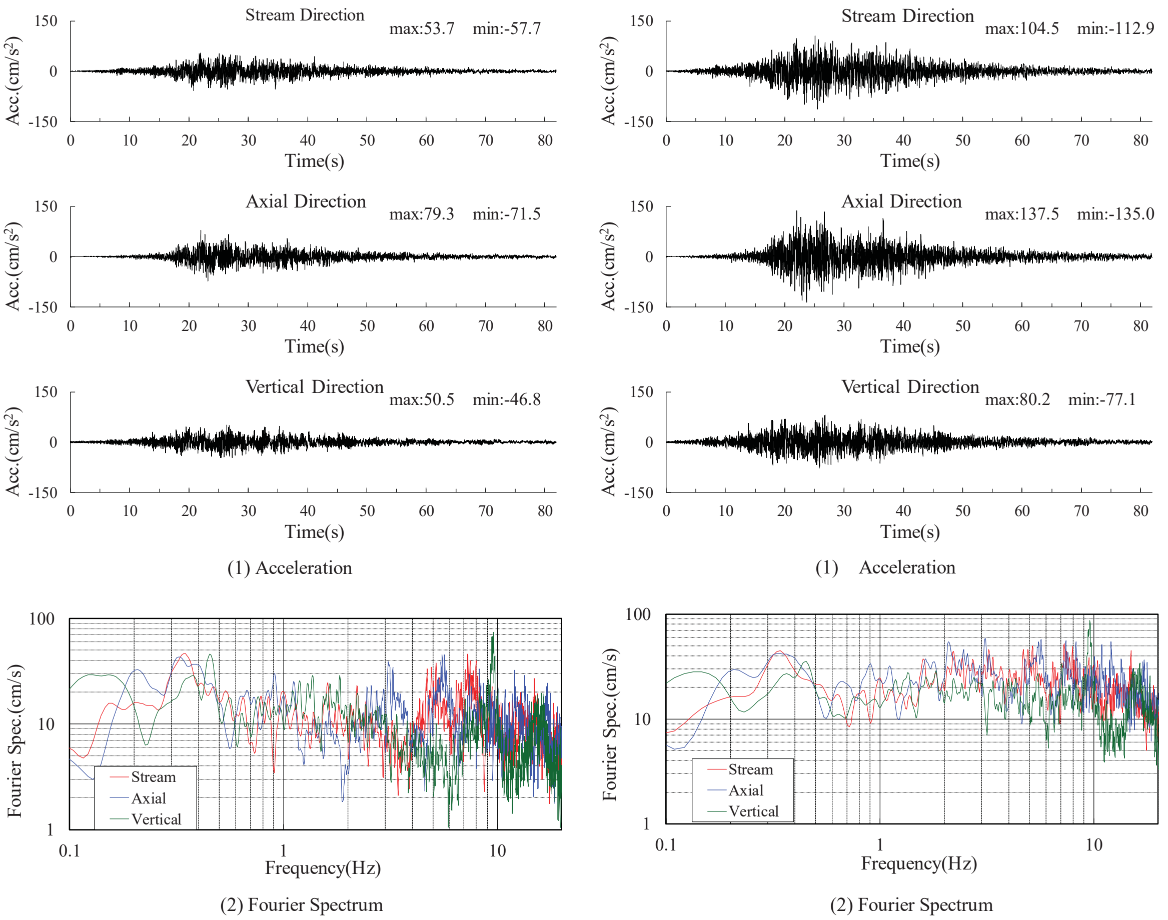


Figure 10. Comparison of seismic motion on bottom of model.

The hypocenter of the Tokachi-oki Earthquake in 2003 was 45 km deep at an epicentral distance of 150 km downstream from the Satsunaigawa Dam. Figure 12 shows the relative locational relationship of the hypocenter and the Satsunaigawa Dam. The vibration components of stream direction and vertical direction at the dam site are based on a synthesis of P waves and SV waves of the seismic motion, and the axial direction is almost exactly parallel to the vibration direction of the earthquake's SH wave. Thus, as shown in Figure 11(a) and Figure 11(b), the seismic main motion in the stream direction and vertical direction at the Satsunaigawa Dam appear to have arrived a little earlier than the axial direction component. On the other hand, the amplitude of seismic motion of axial direction, or in other words of the SH wave component, was a little larger than the other two components.

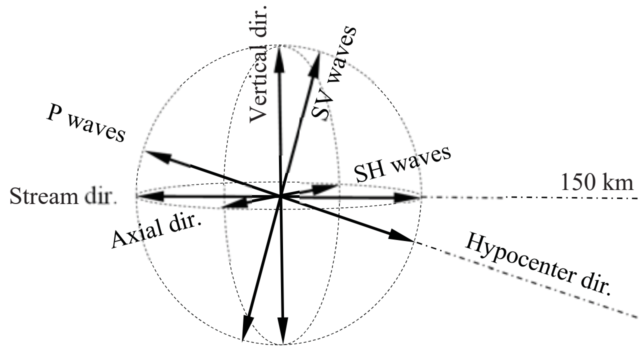
From the above, it is assumed that at the Satsunaigawa Dam, the appropriate location of the engineering bedrock for earthquake response analysis is in deep bedrock at a depth 1.5 times the dam height, and where the shear wave velocity is approximately 2,000 m/s (the elastic modulus of rock class CH in Table 2 is calculated with Vs = 2000 m/s). The preparation method of the seismic motion at the engineering bedrock hypothesized is to identify the analysis model by reproducing the earthquake records at multiple monitoring points following the investigation flow in Figure 2, then performing the pull-back calculation of the seismic motion as explained in Section 2.2.4. Rightly, the analysis model used must reflect the geology and topography of the foundation bedrock.

For the past analysis related to verification work of seismic performance of a dam, the input seismic motion was prepared by a method of the dam distance attenuation formula, or the empirical Green's function method, or the method of adjusting an earthquake record to the lower-limit acceleration response spectrum for verification. Seismic motion at foundation bedrock obtained through this study can contribute to the verification of these preparation methods of input seismic motion.



(a) at intra-layer of 171 m deep (b) at engineering bedrock

Figure 11. Seismic motion at intra-layer of 171 m deep and engineering bedrock.



P waves are longitudinal waves that oscillate in the direction in which the waves travel and transmit expansion and contraction.

SH waves are the shear components that oscillate parallel to the ground surface.

SV waves are shear components perpendicular to SH waves.

Figure 12. Relationships of seismic motion directions and orientations of the dam.

5 CONCLUSIONS

This study clarified the followings.

(1) The physical properties of the Satsunaigawa Dam were identified by preparing an analysis model based on detailed topographical data and geological information to perform reproduction analysis of dynamic behavior during the earthquake. The analysis succeeded in precisely reproducing the earthquake records at multiple monitoring points on the dam body and the foundation bedrock, and in predicting the seismic motion at deep bedrock, particularly at the engineering bedrock.

(2) As the criteria for setting the position of the engineering bedrock, in the case of a concrete gravity dam, the engineering bedrock should be set at a depth equal to 1.5 times the dam height, and where the shear wave velocity is at least 2,000 m/s.

(3) The seismic motion at the engineering bedrock should be prepared by pull-back calculation of the seismic motion using an analysis model identified by the reproduction of the earthquake records at multiple monitoring points.

(4) The seismic motion at engineering bedrock produced by this study can help verify the seismic motion preparation methods that have been in wide use for the verification of seismic performance of dams.

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