Prediction of seismic motion at engineering bedrock based on earthquake records and numerical analysis

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Abstract: *In Japan, dam safety against large-scale earthquakes is verified by numerical analysis. Seismic motion defined for verification of the 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 records to the stipulated lower-limit acceleration response spectrum. Generally, the input seismic motion for earthquake response analysis is prepared by pulling the seismic motion back to the engineering bedrock, hypothesized by a numerical analysis method. However, lack of precise criteria for setting engineering bedrock for earthquake response analysis, the appropriateness of the preparation method of the seismic motion, and of the prepared input seismic motion, are not necessarily clarified. This study predicts the seismic motion of deep bedrock using earthquake acceleration recordings from the Tokachi offshore earthquake of 2003 (M. 8.0) inside bedrock at a depth of 57m below the bottom of Satsunaigawa Dam, which is equipped with 8 seismographs. Based on the results from the research it was concluded that, in the case of concrete gravity dams, engineering bedrock should be set at a depth equal to approximately 1.5 times the dam's height, and where the shear wave velocity of the bedrock should be no less than 2000m/sec. Then, a procedure for preparing input seismic motion for earthquake response analysis is proposed.*

Keywords: Concrete dam, engineering bedrock, earthquake records, seismic motion.

1. Introduction

Earthquake response analysis of a dam in order to verify its seismic performance is often carried out using the following flow: firstly, estimating the seismic motion of the bottom surface of the dam, or open bedrock, by applying either the empirical method[1], or semi-empirical method[2,3,4], then predicting the seismic motion of the engineering bedrock, hypothesized by a pull-back calculation of the wave. Naturally, the predicted seismic motion of the engineering bedrock is dependent on conditions of the analysis model, and is nothing more than a numerical analysis. The earthquake response of the foundation bedrock, the

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surrounding natural ground, and the dam body, excited by the input seismic motion, are not necessarily clarified. Furthermore, verification of the seismic performance of the dam, based on the analysis results, has several matters to be resolved. Because, on the other hand, it is difficult to directly measure seismic motion in deep bedrock, almost no effort has been made in the field of dam engineering to verify the setting of seismic motion for engineering bedrock.

Satsunaigawa Dam is a concrete gravity dam with a height of 114m. Three-direction component seismographs have been installed at the locations shown in Figure 1, and have collected several sets of earthquake records since the dam was completed in 1996. The seismograph placed at a depth of 57m beneath the bottom surface of the dam has, in particular, obtained valuable records inside the bedrock. Seismographs are also installed inside the rim-tunnels of both banks. The dynamic properties and dynamic behaviour of the dam were studied based on numerical analysis using earthquake records[5]. This study aims to contribute to setting the input seismic motion in order to verify future seismic performances of dams. Based on earthquake records obtained at multiple monitoring points at 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 the preparation methods for inputting seismic motion for earthquake response analyses of a dam are investigated.

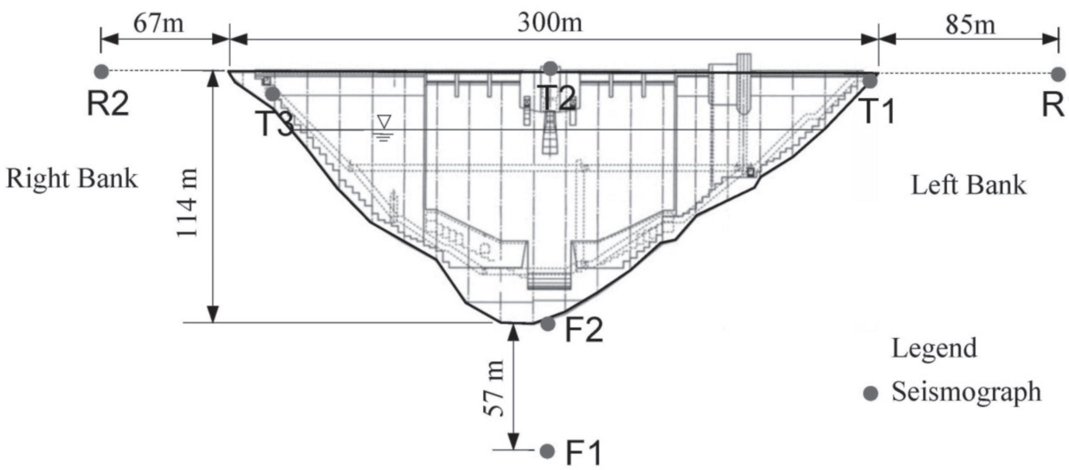


Figure 1. Location of the seismographs at Satsunaigawa Dam (downstream side)

2. Investigation Method and Conditions

2.1 Investigation method

The following points must be considered when setting engineering bedrock:

(1) Seismic motion in engineering bedrock is almost immune to the effects of the dynamic behaviour of the upper ground structure and the dam, so 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 engineering bedrock based on these records. Inversely, when the estimated seismic motion of engineering bedrock has been input, the dynamic response at all monitoring points must be reproduced.

According to these premises, in this study the earthquake response analysis of a 3D dam-foundation bedrock-reservoir system was performed in order to reproduce the behaviour of Satsunaigawa Dam and its foundation bedrock during the Tokachi offshore earthquake, which occurred on 26th September 2003. Four items were considered concerning reproducibility, i.e. maximum acceleration, accelerogram, Fourier spectrum, and transfer function. To improve the reproducibility of the observed dynamic behaviour, the physical properties of the dam and foundation bedrock were repeatedly adjusted. Through this process the seismic motion of the engineering bedrock, which was assumed to be 171m below 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 the criteria and appropriate method for creating seismic motion at the engineering bedrock in order to retrieve the earthquake response analysis of a dam was proposed.

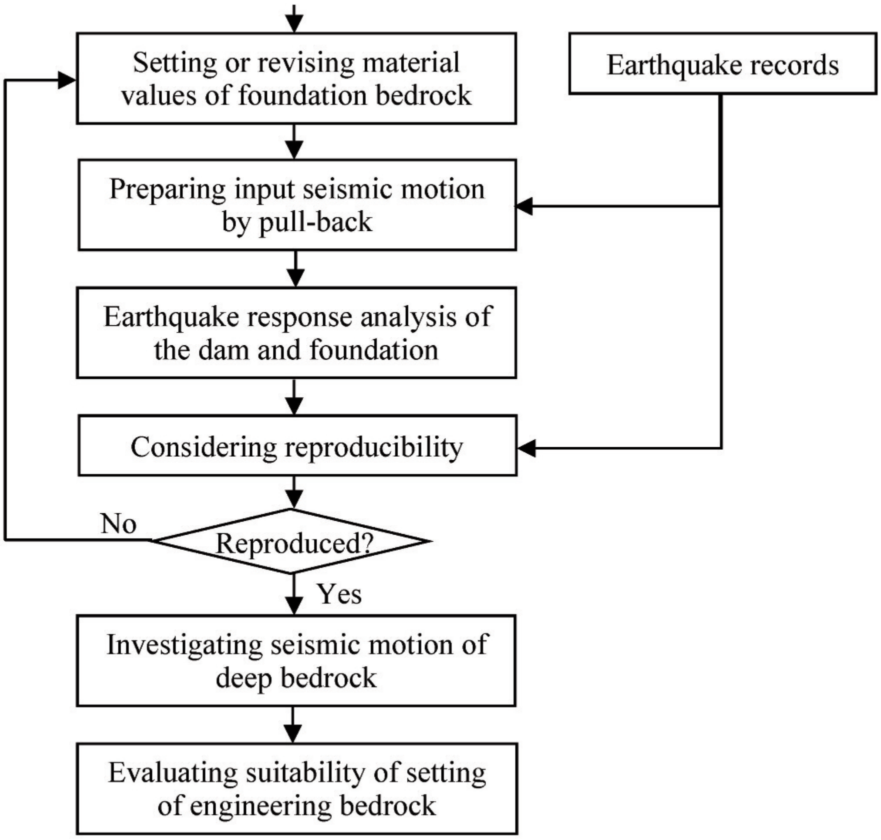


Figure 2. Investigation flow

2.2 Investigation conditions

(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 and Figure 4, respectively, as examples.

(2) Model used for the investigation: Figure 5 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[6] 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.

(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's behaviour during the earthquake. The damping coefficient was obtained by the half power method using the earthquake records[5], and the elastic modulus of the dam's concrete was adjusted, starting with 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 dam execution.

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

Table 1. Physical properties of the dam concrete

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

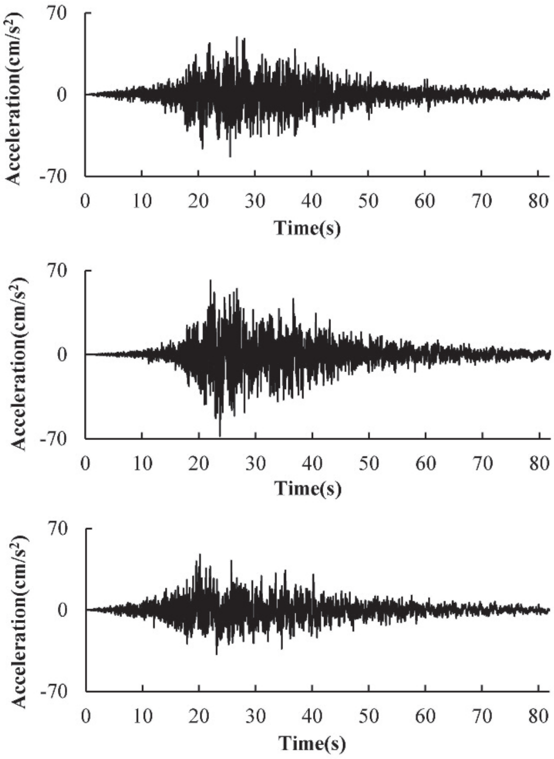


Figure 3. Earthquake records below the bedrock (F1)

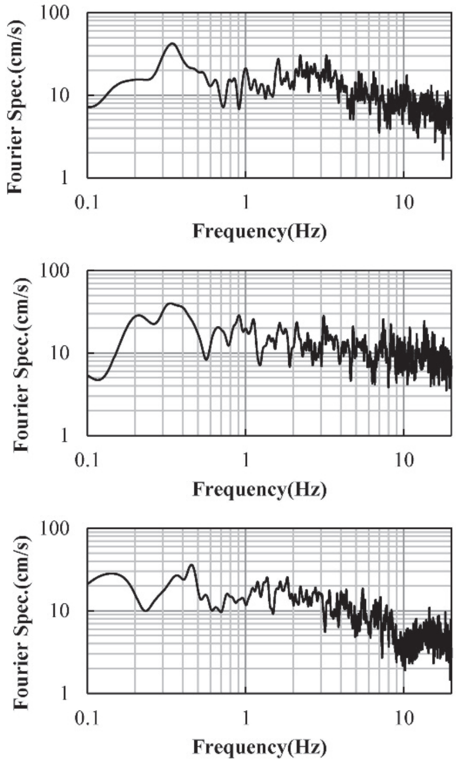


Figure 4. (F1) Fourier spectra bedrock

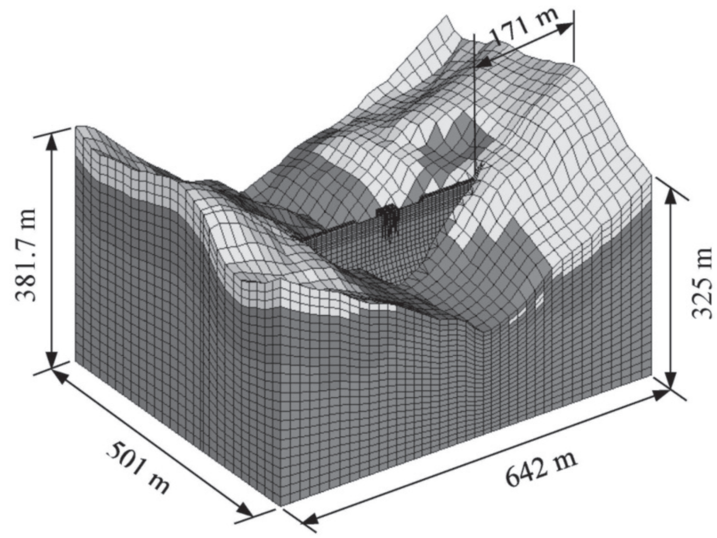


Figure 5. Model used for the study

Rock class	Elastic modulus (N/mm^2)	Density	Poisson's ratio (g/cm^3)	Damping coefficient
CM	13620			5%
CH	29180	2.74	0.28	2%
B	52530			1%
Grounds	PS logging	Rock testing	PS logging	By analysis

Table 2. Physical properties of the foundation bedrock

(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[7,8] of the 3D seismic motion using earthquake records from the lower points of the bedrock (F1), which is immune to the effects of the vibration of the dam and surrounding natural ground. Figure 6 shows the procedure image, and a detailed description is given in references [7] and [8].

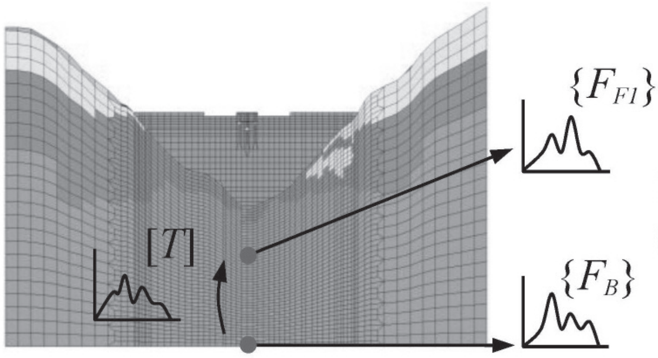


Figure 6. Preparing the input seismic motion

3. Results of Reproduction Analysis of Dynamic Behaviour 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 with relatively good precision. The maximum accelerations at each monitoring point are summarized in Table 3. As examples, Figure 7 shows the acceleration response time histories at the dam crest (T) and upper point of the bedrock (F2), and Figure 8 shows the Fourier spectra and transfer functions of these acceleration responses.

The differences between 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 7, the accelerograms generally coincide with each other. Figure 8 shows that the Fourier spectra and transfer functions of the calculated acceleration response, and the recorded accelerations at these two locations, are extremely close. The calculated and recorded results for the left bank (T1) and right bank (T3) also closely conform and, from the results these generally reproduced, both the natural ground on the left bank (R1) and the right bank (R2) were obtained. The reasons for 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.

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

Table 3. Maximum accelerations at each monitoring point resulting from reproduction analysis
*Note: *Error = (analysis value – observed value)/observed value*

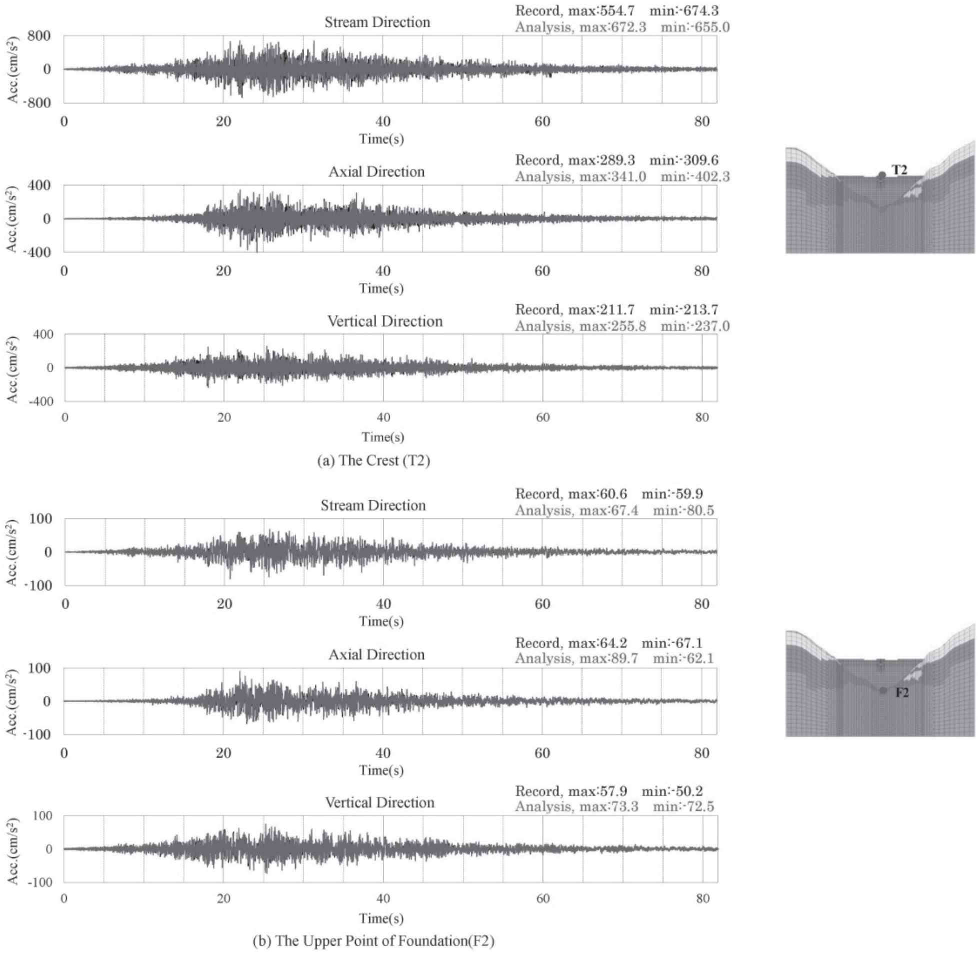


Figure 7. Comparison of acceleration at dam crest and dam base during reproduction analysis

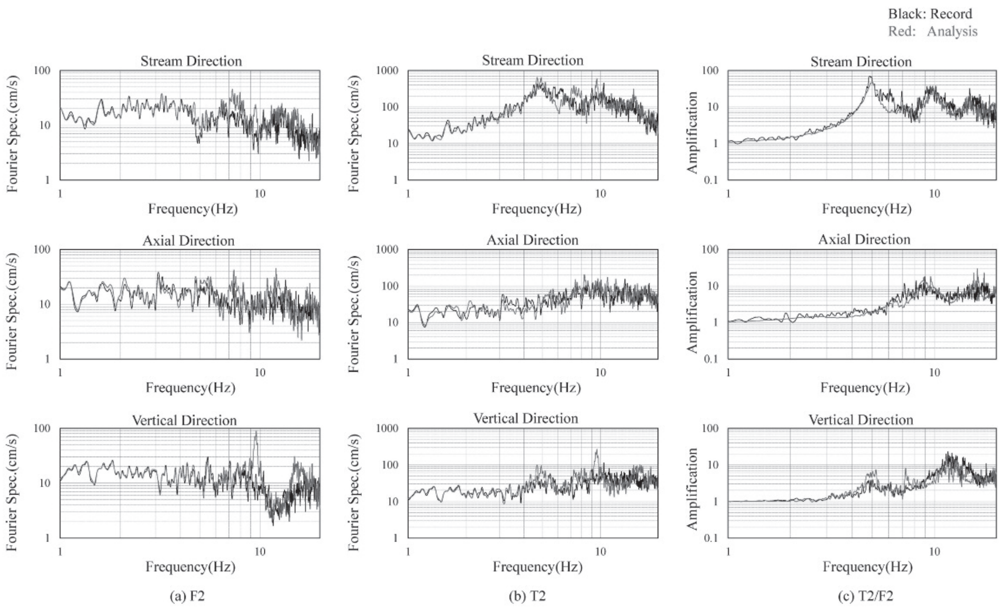
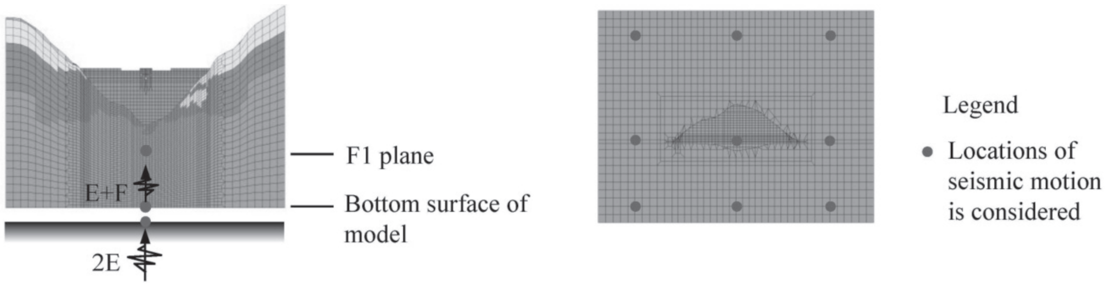


Figure 8. Comparison of Fourier spectra and transfer functions at dam crest and the upper point of bedrock (recorded and calculated)

4. Seismic Motions Inside Bedrock and at Engineering Bedrock

4.1 Seismic motions inside bedrock

When the earthquake motions at all monitoring points on the dam body and inside the foundation bedrock had been reproduced by numerical analysis, it was assumed that the earthquake response deep in the foundation bedrock model approximated the actual seismic motion without the effects of the vibrations of the dam body and surrounding natural ground. Accelerations at a total of 18 points on two horizontal planes, as shown in Figure 9a, were calculated. The time histories and Fourier spectra of the calculated accelerations at each location considered in the stream direction and axial direction (see Figure 9b) were compared on each plane.



(a) Depth of the plane considered

(b) Points on each plane considered

Figure 9. 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 were extracted from the total time history (length 81.92 seconds). Figure 10 shows the main motions of three components at three locations on the F1 plane (depth of 57m from the bottom surface of the dam) of the dam axis section. Comparing with the lower point of the bedrock (F1), the accelerations at both sides (L1 and R1) are slightly 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 behaviour of the dam and natural ground on both sides.

Figure 11, on the other hand, shows the main motion at three locations on the bottom plane of the model (depth of 171m 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 (171m in this model), and that the seismic motion at this location will be almost unaffected by the behaviour of the dam and natural ground during the earthquake.

4.2 Seismic motion at engineering bedrock

As stated in the previous section, seismic motion on the bottom surface of the model, at a depth of 171m, is almost immune from the influence of the dynamic behaviour of the dam or natural ground, so this depth (Figure 9a) can be set as the engineering bedrock. Figure 12 shows waves (E+ F waves) at the intra-layer at this location, obtained by reproduction analysis. This is considered to be similar to the actual seismic motion generated in deep bedrock by the Tokachi offshore earthquake. Figure 13 shows the outcrop waves (2E waves) on the open bedrock surface (Figure 9a) at this location. It is possible to reproduce the dynamic behaviour at each monitoring point on the dam body, and on the foundation bedrock, by inputting this wave so it can be considered to be the seismic motion at the engineering bedrock.

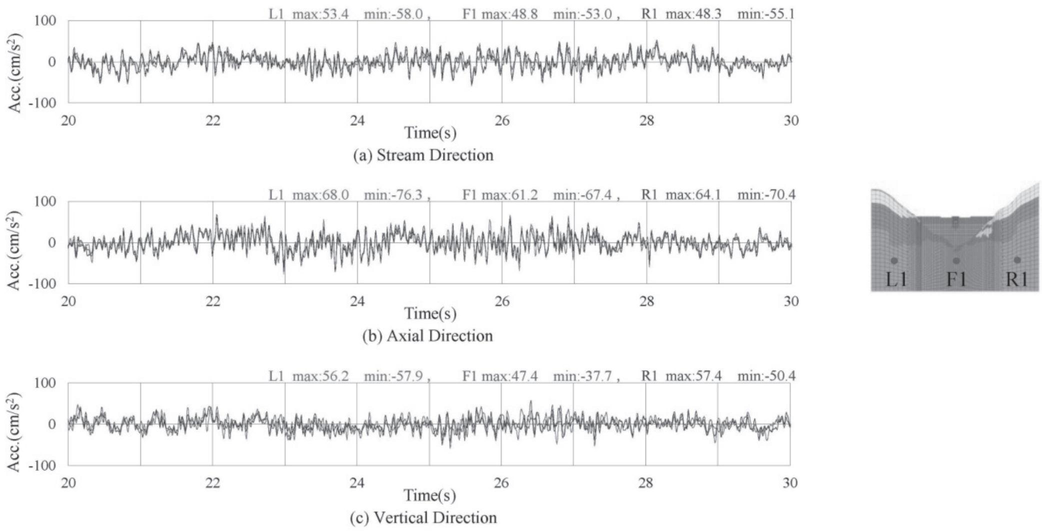


Figure 10. Comparison of seismic motion on F1 plane

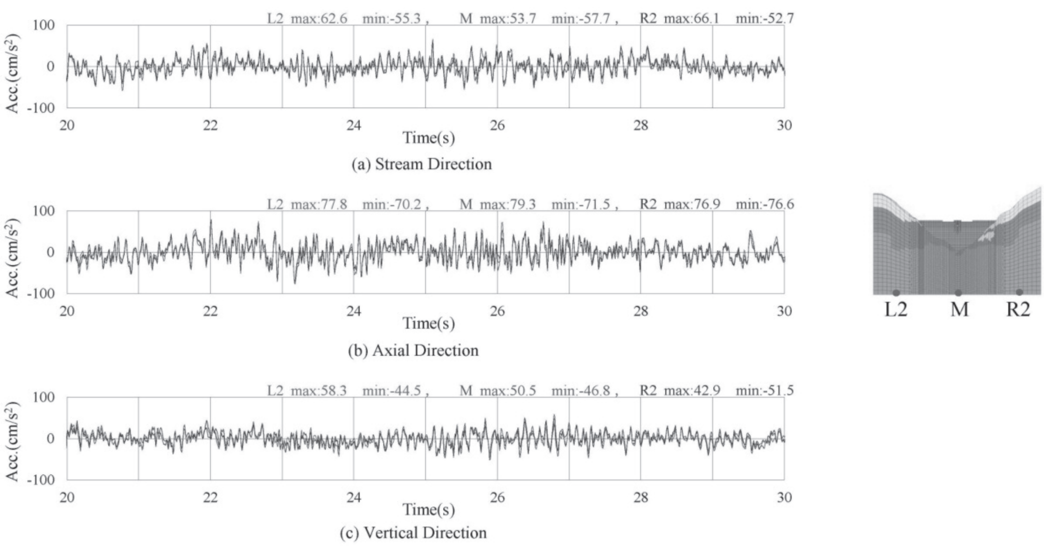


Figure 11. Comparison of seismic motion on bottom of model

The hypocenter of the 2003 Tokachi offshore earthquake was 45km deep, at an epicentral distance of 150km downstream of Satsunaigawa Dam. Figure 14 shows the relative locational relationship of the hypocenter and the 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 12 and Figure 13, the main seismic motion in the stream direction and vertical direction at Satsunaigawa Dam appear to have arrived a little earlier than the axial direction component. On the other hand, the amplitude of the seismic motion in the 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 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 about 2000m/sec. The preparation method of the hypothesized seismic motion at the engineering bedrock 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.

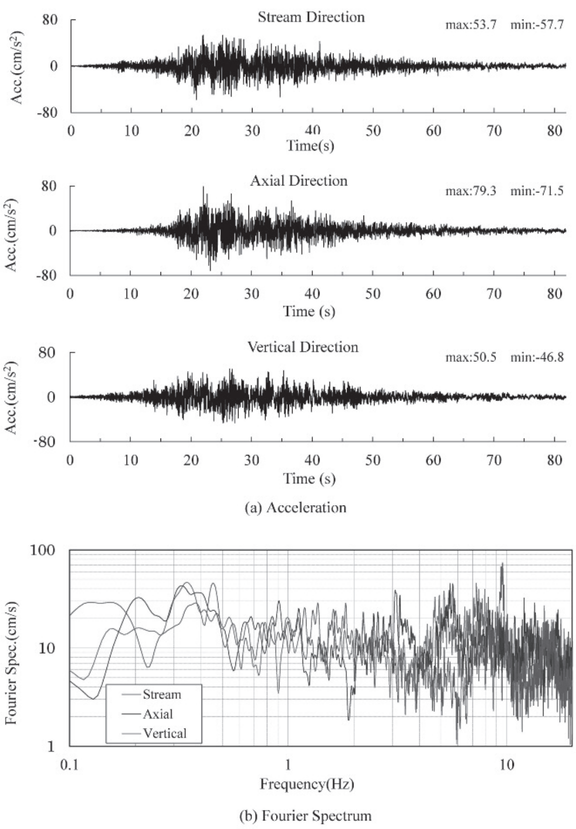


Figure 12. Seismic motion at intra-layer, 171m deep

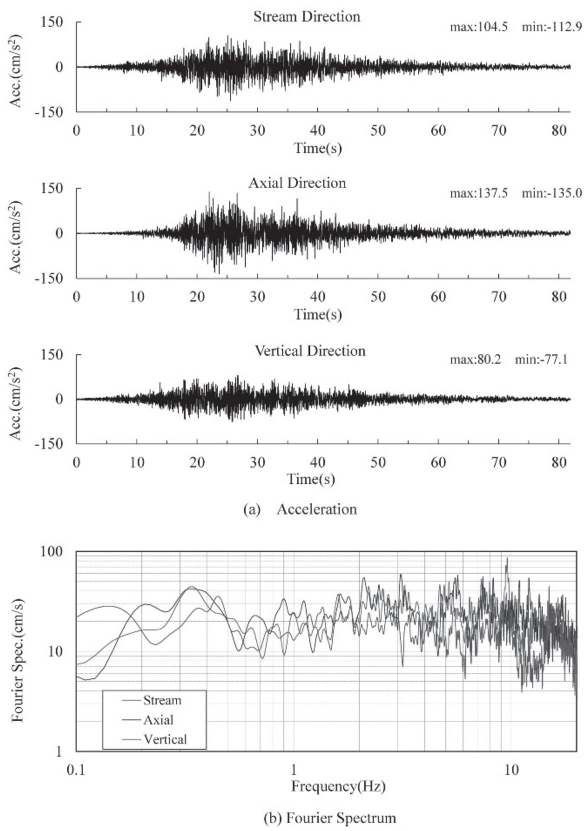


Figure 13. Seismic motion at engineering bedrock, 171m deep

For past analysis relating to the verification work of the seismic performance of a dam, the input seismic motion was prepared by a method of the dam distance attenuation formula, 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 for input seismic motion.

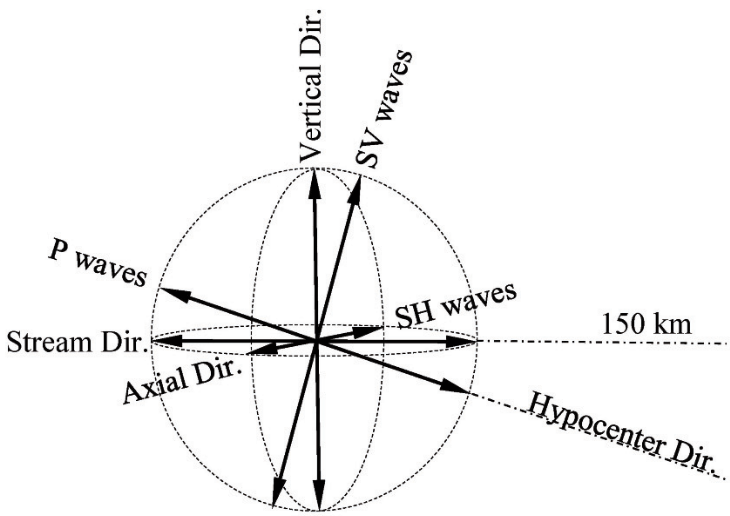


Figure 14. Relationships of seismic motion directions and orientations of the dam

5. Summation

This study clarifies the following:

(1) The physical properties of Satsunaigawa Dam were identified by preparing an analysis model based on detailed topographical data and geological information in order to perform reproduction analysis of the dam's dynamic behaviour during the Tokachi offshore earthquake of 2003. The analysis succeeded in precisely reproducing the earthquake records at multiple monitoring points on the dam body and foundation bedrock, and predicting the seismic motion in deep bedrock, particularly at engineering bedrock.

(2) As a criteria for setting the position of engineering bedrock, in the case of a concrete gravity dam, 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 2000m/sec.

(3) Seismic motion at engineering bedrock should be prepared using the pull-back calculation method 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 seismic motion preparation methods that have been widely-used for the verification of the seismic performance of dams.

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