

2. Investigation of the material and vibration properties of a heightened concrete gravity dam

## Investigation of the material and vibration properties of a heightened concrete gravity dam

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**ABSTRACT:** In recent years, flood disasters due to climate change have become more frequent and severe, and increasing the flood control capacity of existing dams by heightening them is one of the countermeasures. In this study, the material properties of a 65-year-old concrete gravity dam were investigated as a case study, and the material test results were verified through an analysis that reproduces the seismic behavior of the dam. It was found that the compressive strength of the 65-year-old concrete was the same or slightly higher than that at the time of dam construction and that the elastic modulus had not decreased. In addition, by analyzing the seismic records of the dam, changes in the vibration characteristics of the dam before, during, and after its heightening were clarified. Furthermore, the elastic modulus and damping ratio of the concrete of the new body were estimated by analyzing the reproduced seismic behavior of the heightened dam. The following conclusions are obtained. The mechanical properties of concrete in its present condition were clarified by reviewing the results of material tests using core specimens of dam concrete 65 years after its completion. Compared to the data published in the Standard Specifications for Concrete Structures by JSCE, it was determined that the elastic modulus of the dam concrete has not decreased after 65 years since its completion and has increased to some extent. The test results also revealed the relationship among the tensile strength, compressive strength, and elastic modulus of the dam concrete, as well as the relationship between the static and dynamic elastic moduli. The test results, including the elastic modulus, were verified by an analysis that reproduced the seismic behavior of the dam. The elastic modulus and damping ratio of the concrete of the newly constructed dam were identified after conducting a reproduction analysis of the seismic behavior of the dam after heightening and reverifying the physical properties of the existing dam. Notably, the mechanical properties of the concrete of the heightened dam were confirmed to be slightly smaller than those of the existing dam due to the early age of the materials.

## 1 INTRODUCTION

Recently, large-scale flood disasters have been occurring frequently due to an increase in abnormally strong rainfall exceeding the planned scale and the increasing size of typhoons. In 2019, the amount of flood damage in Japan reached 2.18 trillion yen (MLIT, 2021), and it is expected that climate change will cause more frequent and severe water-related disasters in the future. Although dams are effective in controlling floods in their watersheds, suitable sites for dam construction are limited. Under these circumstances, there is a growing need to increase the flood control capacity of existing dams, or so-called dam upgrading. Among these, heightening a dam is an effective countermeasures of dam upgrading. In this study, using the Shin-Katsurazawa Dam (To distinguish it from the existing Katsurazawa Dam, the dam heightened is called Shin-Katsurazawa Dam. Table 1 shows the specifications before and after dam heightening), which is a case of the coaxial heightening of a concrete gravity-type dam, the following issues were examined:

- 1) The mechanical properties (elastic modulus, unit weight, compressive strength, and tensile strength) of the existing dam concrete, which was 65 years old since completion, are determined by material testing of core specimens (Yamada, et al., 2004), and the results were verified through an analysis that reproduces the seismic behavior of the dam during an earthquake.
- 2) The analysis of seismic records revealed changes in the vibration characteristics of the dam before, during, and after heightening construction. The elastic modulus of the new dam body was also estimated by analyzing the reproduced seismic behavior of the dam after its heightening.

Table 1. Specifications of the Shin-Katsurazawa dam before and after heightening construction.

Item	Before heightening construction	After heightening construction
Location	Katsurazawa, Mikasa City, Hokkaido	
Type	Concrete gravity dam	
Height	63.6 m	75.5 m
Crest length	334.25 m	397.0 m
Crest width	5.5 m	5.5 m
Crest elevation	EL.188.6 m	EL. 200.5 m
Slope	Upstream side: <EL.153 1:0.10, >EL.153 1:0.08	
	Downstream side: 1:0.77	Downstream side: 1:0.88
Volume	350,000 m <sup>3</sup>	646,000 m <sup>3</sup>
Basin area	298.7 km <sup>2</sup>	298.7 km <sup>2</sup>
Total water storage	92,700,000 m <sup>3</sup>	147,300,000 m <sup>3</sup>

## 2 MECHANICAL PROPERTIES OF DAM CONCRETE USING CORE SPECIMENS FROM EXISTING DAM BODIES

### 2.1 Outline of the existing Katsurazawa Dam and heightening work

The Katsurazawa Dam was completed in 1957 as the first multipurpose dam in Hokkaido and has been responsible for flood control, water supply, and hydropower generation. Figure 1(a) shows the location of the dam. The dam was upgraded using a coaxial heightening method to enhance its flood control and

water utilization functions, and the heightening work was completed in March 2023. The standard cross sections of the dam before and after heightening are shown in Figures 1(b) and 1(c). By heightening the dam by 11.9 m, it was possible to increase the water storage capacity by approximately 1.6 times.

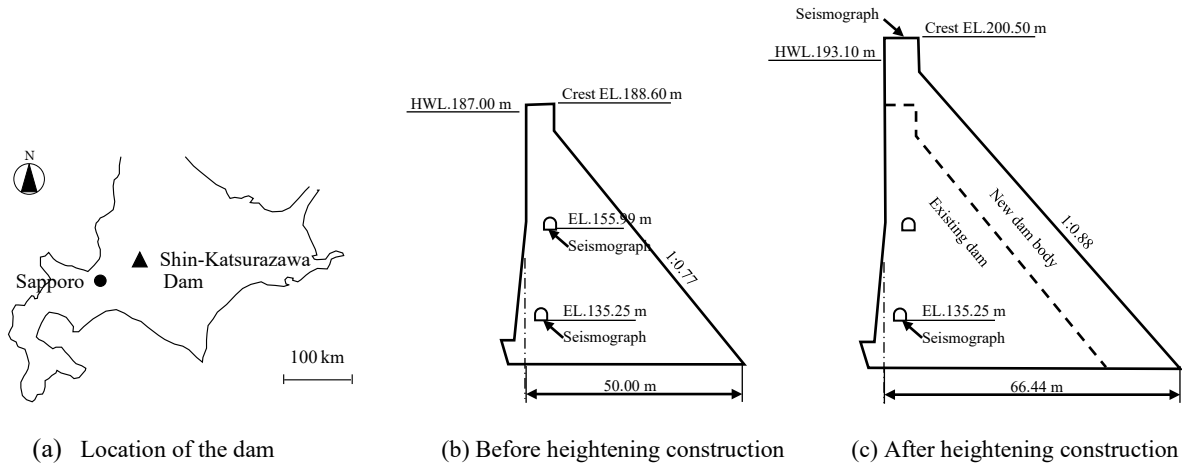


Figure 1. Location and cross sections before and after the heightening construction of the dam.

### 2.2 Compressive and tensile strength of dam concrete

Uniaxial compression tests were performed on the sampled core specimens taken from each mix and each depth position. Figure 2 shows the relationship between the compressive strength of the existing dam concrete and the unit weight as a single correlating parameter. The figure shows that the compressive strength of the core specimens increased as the unit weight of concrete increased and that there was a relatively good correlation between the two, although there was some variation between them. The same figure also shows the uniaxial compression test results obtained from the quality control test of the concrete during the construction of the existing dam body (material age of 91 days). This comparison shows that the compressive strength of the core specimens is generally equal to or greater than the test results of the quality control during the construction of the existing dam.

### 2.3 Elastic modulus of dam concrete

In the uniaxial compression test of the core specimen described in the previous section, the initial tangential slope of the stress–strain curve is taken as the static elastic modulus of concrete. The relationship between the static elastic modulus and the compressive strength of the specimen is shown in Figure 3. The result in this figure is compared with the correlation between the compressive strength and the static elastic modulus from the nationwide surveyed results, as shown in the Standard Specifications for Concrete Structure (Design). Although there is variation in the test results of the core specimens, the elastic modulus is maintained at the same level as that of ordinary concrete if the unit weight is  $2.3 \text{ gf/cm}^3$  or more. This indicates that the elastic modulus does not deteriorate even after 65 years. Core specimens with a unit weight of  $2.3 \text{ gf/cm}^3$  or less were taken from the internal concrete and were found to have an average static elastic modulus of  $15,000 \text{ N/mm}^2$  or higher. Figure 4 shows the test results of the static and dynamic elastic moduli conducted on core specimens taken from another dam body which used the same aggregate as the Katsurazawa Dam. This figure shows that the dynamic elastic modulus is 1.0-1.4 times the static modulus, with an average value of 1.22 times.

The compressive strength, tensile strength, and elastic modulus of the concrete of the Katsurazawa Dam 65 years after its completion were determined by material tests using the above core specimens. The data necessary for verifying the seismic performance of the dam were thus obtained.

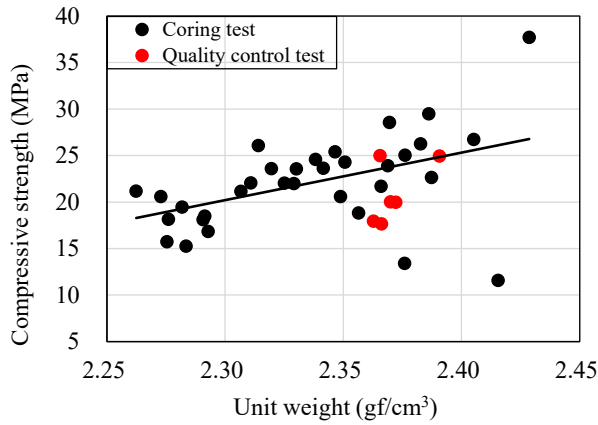


Figure 2. Relationship between the unit weight and compressive strength.

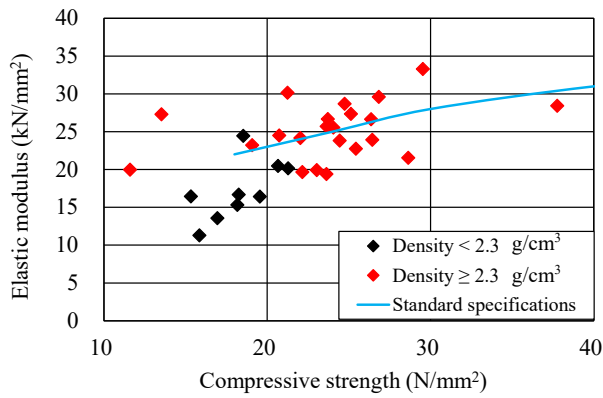


Figure 3. Relationship between the elastic modulus and compressive strength.

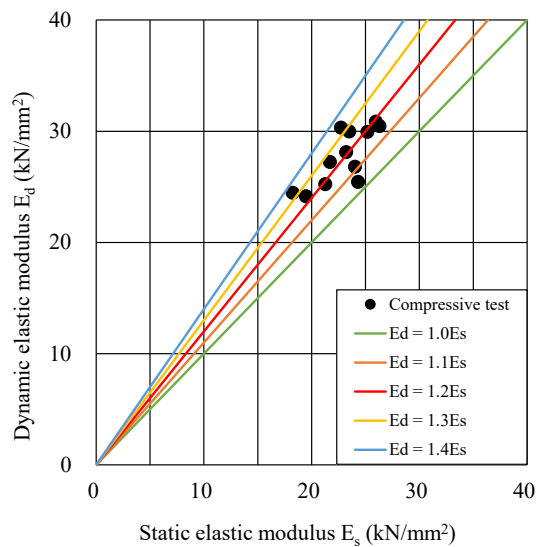


Figure 4. Relationship between the static and dynamic moduli.

## 2.4 Verification of test results by reproduction analysis of the existing dam during the earthquake

Observation and analysis of the seismic behavior of a dam during an earthquake can be regarded as a kind of nondestructive inspection, from which the physical properties of dam concrete and the vibration characteristics of the dam through the analysis can be understood. To verify the test results of the core specimens and to clarify the seismic behavior of the dam, a reproduction analysis of the seismic behavior of the dam was conducted based on the seismic observation results of the existing Katsurazawa Dam. The analysis was conducted using the coupled dam-bedrock-reservoir model shown in Figure 5, based on a two-dimensional model of a cross section of the existing dam with seismographs (Fig. 1(b)). The earthquake used for reproduction analysis was the aftershock of the September 26, 2003 (time of occurrence 06:08) Tokachi-oki earthquake, which had a relatively large acceleration amplitude. Since the water level during the earthquake was 171.18 m, a reservoir corresponding to this reservoir level was also simulated in the analysis using the finite difference method. Viscous boundary conditions (Miura & Okinaka, 1989) were used at the bottom and lateral boundaries of the bedrock model to account for the vibration influence of the surrounding ground on the analytical model and for the dissipation of scattered waves due to the vibration of the dam and the bedrock foundation. At the upstream end of the reservoir, the complete absorption boundary condition (Hatano, 1966) of wave energy was applied, and at the bottom of the reservoir, the partial reflection condition (Hatano, 1966) (impedance ratio of 1.5 between sediment and water at the bottom of the reservoir) was established. At the surface of the reservoir, the effect of surface gravity waves was considered. The static elastic modulus of the dam concrete used in the analysis was estimated to be 23,000 N/mm<sup>2</sup> based on Figures 2 and 3 since the average unit weight of the core specimens was 2.3 gf/cm<sup>3</sup>. The dynamic elastic modulus was set to 28,060 N/mm<sup>2</sup>, which is 1.22 times the static modulus, according to Figure 4. This value was set as the initial value of the dynamic elastic modulus and adjusted to improve the reproducibility of the analysis. The input seismic motion in the analysis was generated by pulling back the seismic record at the lower seismometer position to the bottom of the bedrock model. The reproducibility of the analysis was determined by comparing the acceleration response, the Fourier spectrum and its transfer function between the recorded and calculated results. The analysis was performed as a linear problem using the dedicated dam analysis program "UNIVERSE" (Watanabe, 2002).

The reproduction analysis results show that the seismic record of the seismograph at the upper inspection gallery is best reproduced when the physical properties shown in Table 2 are used.

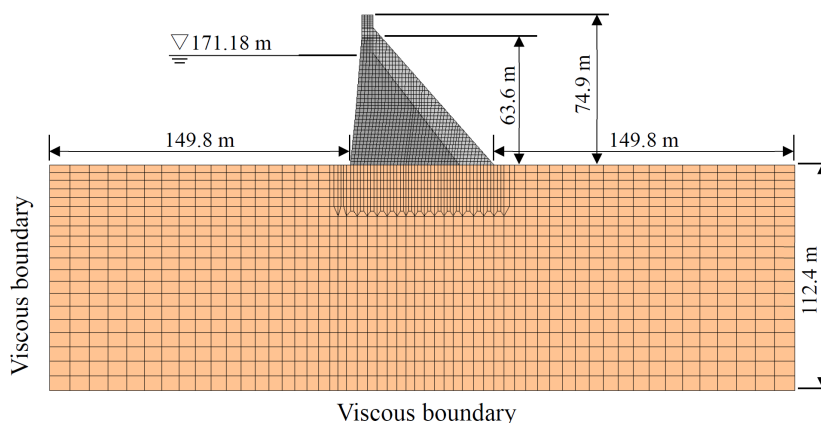


Figure 5. Analysis model.

Figure 6 shows the acceleration time history, and Figure 7 shows the Fourier spectrum of the acceleration and the transfer function between the upper and lower seismograph positions. The dynamic

Table 2. Material properties identified by reproduction analysis.

	Dynamic elastic modulus (N/mm <sup>2</sup> )	Poisson's ratio	Density (gf/cm <sup>3</sup> )	Damping ratio
Dam concrete	36,480 Based on and 1.22 times the results of core tests. Further increased by 30% to consider the restraint effect of the ground on both banks.	0.2 General value	2.3 Result of the core test	2.0% Estimated by analyses of seismic records
Foundation rock	26,300 Converted by the measured Vs	0.3 General value	2.45 Mean value of the rock tests	3.0% Based on the values of a similar rock mass

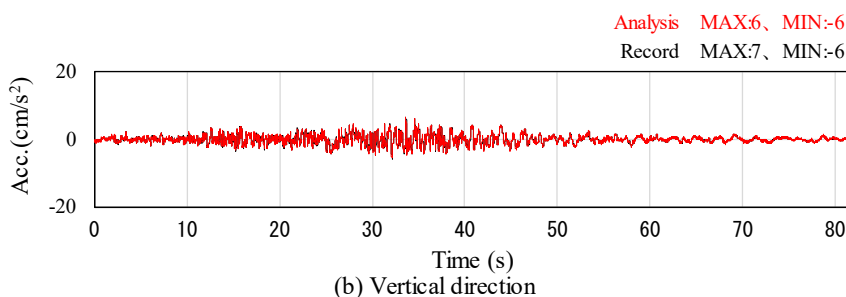
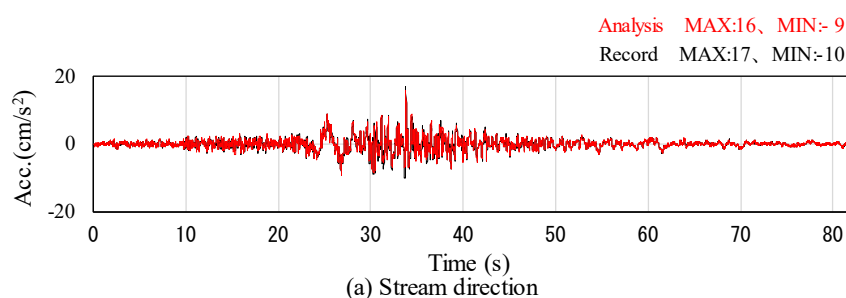


Figure 6. Acceleration response at the location of the upper seismograph.

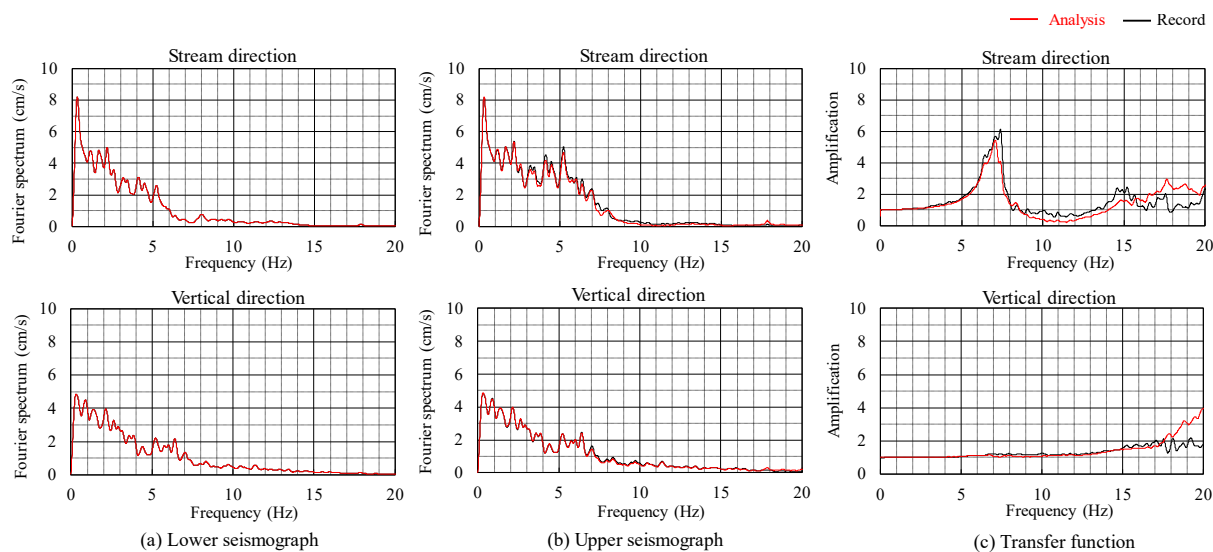


Figure 7. Fourier spectra and transfer functions.

elastic modulus of the identified dam concrete is  $36,480 \text{ N/mm}^2$ , which is approximately 30% higher than the initial value of  $28,060 \text{ N/mm}^2$ . This difference can be attributed to two factors. First, the material test of the core specimen, which is the basis for setting the elastic modulus, was a uniaxial compression test, but the concrete in the actual dam was in triaxial compression, and the elastic modulus may have increased due to the confining pressure (Yasuda, et al., 2023). Second, the analysis was performed using a two-dimensional model with approximately the maximum cross section, but the actual dam has a lower cross-sectional height in the dam axis direction, which is thought to increase the apparent stiffness due to the resulting constraining effect of the ground. Therefore, it can be concluded that the elastic modulus of dam concrete identified by the reproduction analysis is generally consistent with the results of the material tests using the core specimens described above.

### 3 SEISMIC CHARACTERISTICS AND REPRODUCTION ANALYSIS OF THE HEIGHTENED DAM

After the completion of the heightening of the Shin-Katsurazawa Dam, many earthquakes were observed. By analyzing the seismic behavior of the dam before, during, and after the heightening construction, changes in the vibration characteristics and seismic performance of the dam can be understood.

#### 3.1 *Changes in the vibration characteristics of the dam before and after heightening*

Using the recorded seismic acceleration of the dam (see Fig. 1 for the location of the seismograph), its Fourier spectrum and transfer function were obtained. The first-order natural frequency of the dam body is considered to correspond to the low-order first-order peak of the transfer function. Figure 8 shows the transfer functions between the lower and upper seismographs in the stream direction, and the accelerations used are before, during, and after the construction work. Note that the seismograph at the upper inspection gallery was moved to the crest of the new dam body after the completion of the heightening. The first-order natural frequencies of the dam body in the stream direction indicated in Figure 8 are arranged in a time series, and the changes are shown in Figure 9. Although there is some variation, the first-order natural frequency of the dam clearly decreased after the heightening of the dam compared to that before the heightening construction. Although the length of the dam base has increased and the downstream slope has become more extended after the construction, the change in the natural frequency of the dam can be attributed to the effect of the heightening of the dam. On the other hand, the first-order natural frequency of the dam became slightly higher during the heightening construction than before the construction for the following two reasons: first, the rigidity of the dam as a whole increased due to the addition of the new dam body downstream of the existing dam, and second, the dam height did not change for most of the time during the heightening construction (the crest elevation of the new dam body does not exceed that of the existing dam). The above indicates that the vibration characteristics of the dam have changed due to the heightening of the dam. The effect of these changes on the seismic performance of the dam is discussed in the next section.

#### 3.2 *Reproduction analysis of the seismic behavior of the dam after heightening*

After the completion of the heightening, the seismograph installed in the upper inspection gallery of the existing dam was moved to the new dam crest (see Fig. 1(c)). A magnitude 5.4 earthquake occurred on January 27, 2021, in the central Iburi district in Hokkaido, and this earthquake was recorded at the Shin(new)-Katsurazawa dam. To identify the physical properties of the concrete of the newly constructed

dam and to understand the vibration characteristics of the whole dam after heightening, the seismic behavior of the dam observed during this earthquake was reproduced and analyzed.

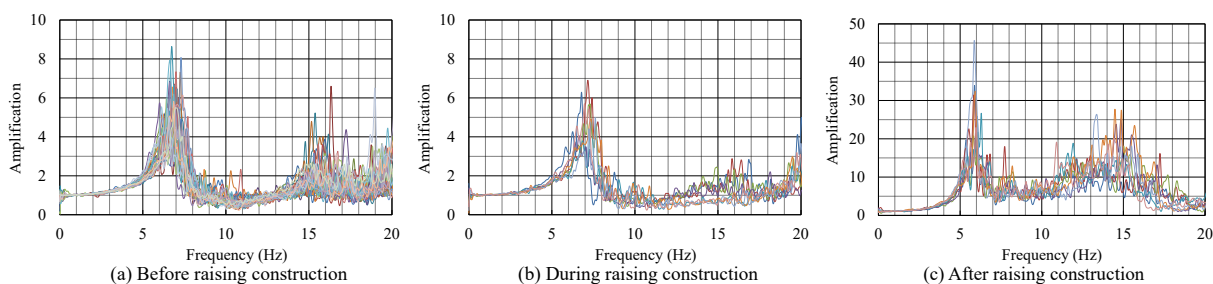


Figure 8. Transfer functions before, during and after the heightening construction.

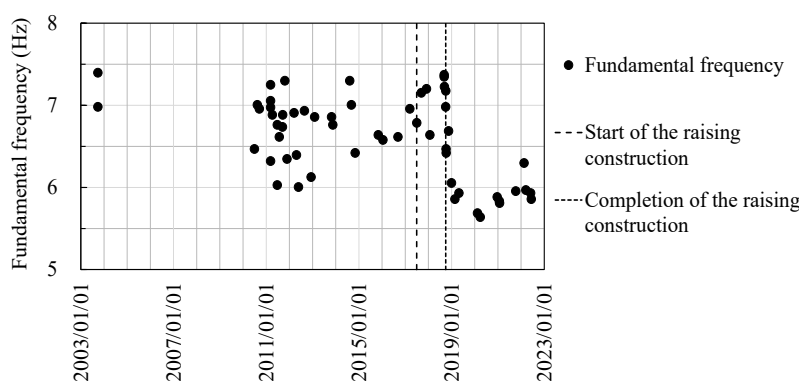


Figure 9. Variation in the fundamental frequency before, during and after the heightening construction.

### 3.2.1 Reproducible analysis conditions

The model used in the reproduction analysis is shown in Figure 5 above. The reservoir level in the analysis was set as EL.179.7 m during the earthquake. The dam and foundation bedrock were assumed to be linear elastic materials, and a coupled dam-bedrock-reservoir analysis was conducted. For the properties of the analytical model, the existing dam and foundation bedrock were identified from the reproduction analysis of the seismic behavior before heightening (shown in Table 2), and the same properties as those of the existing dam were used as the initial values for the new dam body, with minor adjustments to improve the reproducibility of the analysis. As a result of the adjustment, the elastic modulus of the newly placed concrete is  $30.000 \text{ N/mm}^2$  and the damping ratio is 1.0% when the observed seismic behavior of the dam is best reproduced. The elastic modulus is approximately 18% lower than that of the concrete of the existing dam shown in Table 2. It is assumed that the mechanical performance of the new dam body is not yet fully revealed because the concrete of the new dam body is younger in age than that of the existing dam. The damping ratio of the identified concrete of the newly constructed dam is lower than that of the existing dam concrete by 2.0%, but this difference is thought to be within the range of variation. The boundary conditions of the foundation bedrock and reservoir in the analytical model are those used in the reproduction analysis of the seismic behavior before heightening the dam. The input seismic motion in the analysis was generated by pulling back the acceleration record at the lower seismograph to the bottom of the bedrock of the analytical model. The reproducibility of the analysis was determined by comparing the acceleration response and the Fourier spectrum and its transfer function between the seismic record

and the analysis results.

### 3.2.2 Reproduction analysis results

The acceleration response time history at the dam crest corresponding to the seismograph position is obtained from the analysis, as shown in Figure 10. The acceleration record during the earthquake is shown in the same figure, and the record indicates that the maximum acceleration value at the crest and the acceleration waveform are generally reproduced. Figure 11 shows the Fourier spectra and their transfer functions of the accelerations of seismographs at the lower position and the crest. These figures show that the seismic behavior of the dam was well reproduced by the analysis. Although the

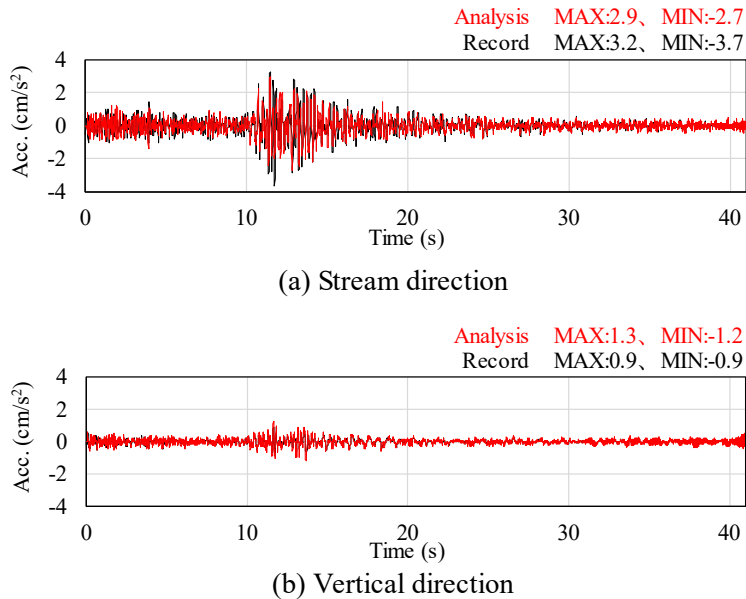


Figure 10. Acceleration response at the location of the crest seismograph.

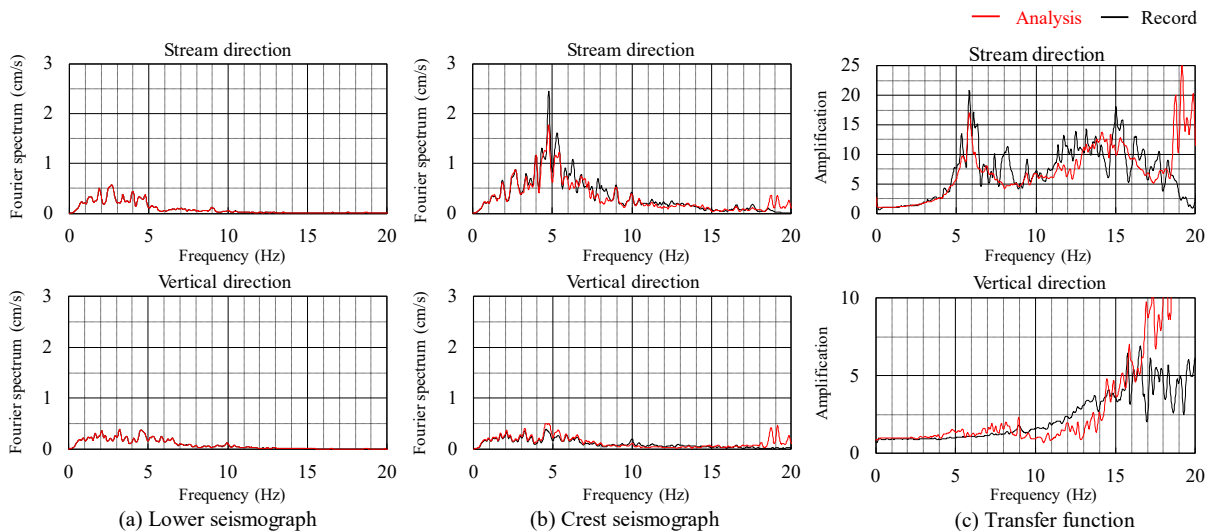


Figure 11. Fourier spectra and transfer functions.

difference between the analysis and observation results is relatively large in the frequency range of the transfer function above 17 Hz, the high-frequency range is not considered important for the evaluation of the dam seismic response. The well-reproduced seismic behavior of the dam allows us to determine the elastic modulus and damping ratio of the existing dam.

The elastic modulus and damping ratio of the existing dam were again verified, and the elastic modulus and damping ratio of the concrete in the new dam body were also identified. It can be inferred that the strength and elastic modulus of the concrete increase to some extent as the material ages and that in the long term, the concrete of the new dam body becomes equivalent to that of the existing dam concrete.

#### 4 CONCLUSIONS

- (1) The mechanical properties of concrete in its present condition were clarified by reviewing the results of material tests using core specimens of dam concrete 65 years after its completion. Compared to the data published in the Standard Specifications for Concrete, it was found that the elastic modulus of the dam concrete has not decreased after 65 years since its completion and has increased to some extent. The test results also revealed the relationship among the tensile strength, compressive strength, and elastic modulus of the dam concrete, as well as the relationship between the static and dynamic elastic moduli. The test results, including the elastic modulus, were verified to reproduce the seismic behavior of the dam.
- (2) The elastic modulus and damping ratio of the concrete of the newly constructed dam were identified after conducting a reproduction analysis of the seismic behavior of the dam after heightening and reverifying the physical properties of the existing dam. Based on the results, it was noted that compared to those of the existing dam, the mechanical properties of the concrete of the heightened dam could not be fully revealed due to the young age of the materials.

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