EARTHQUAKE RESISTANT EVALUATION OF DAM AND SPILLWAY GATE TO LARGE-SCALE EARTHQUAKES

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ABSTRACT

In recent years, large earthquakes have been observed frequently at dam sites in Japan and it is an imperative issue that seismic performance of dam should be evaluated. For the evaluation, it is important that an analytical model can reproduce the actual behavior. In this study, a three-dimensional composite analytical model consisting of a dam, gates, foundation rock and a reservoir was applied to evaluate seismic performance of dam. Presentation in this include: 1) trial application of a three-dimensional composite model and 2) seismic response analysis of dam against large-scale earthquakes using three-dimensional composite model.

INTRODUCTION

In order to ensure the safety of hydroelectric power facilities against large earthquakes, the Kansai Electric Power Co., Inc. has been evaluating their earthquake resistance since 2006. For the evaluation, the maximum scale earthquake motion which possibly occurs in the future, namely “Level 2 earthquake motion” was assumed. It is important that an analytical model can reproduce the actual behavior to evaluate structural safety against level 2 earthquake motion.

The seismic behavior of a concrete gravity dam is considered to be affected by such factors as the frictional resistance between dam blocks and the restraint of surrounding rock mass. These effects can not be reflected in two dimensional analysis, but three-dimensional ones. Building a three-dimensional model, however, requires the setting of several parameters, which are effectively obtained by reproduction analysis based on the results of seismological measurement.

In this study, seismological measurement was first performed for two years by using the measuring devices installed on a dam and a spillway gate. Further, a three-dimensional analytical model that could reproduce the response of the dam and spillway gate was developed by using multiple measurement results. Furthermore, we studied a difference in dam response between conventional 2-D and 3-D analysis when the level 2 earthquake motion acts on the dam and spillway gate. Then, a comparison was made between dam responses to level 2 earthquake motion expected at the site by conventional two-dimensional analysis and three-dimensional analysis.

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OUTLINE OF STUDY STRUCTURE

The dam used for study is outlined in Figure 1 and Figure 2. The concrete gravity dam is 35.2 m in height, 132.5 m in crest length, 1:0.85 in slope of downstream face and 44,750 m^3 in volume. Granite is exposed on both banks and throughout the bed at the dam site. Three radial gates are installed onto the spillway. The span is 9.0 m and the gate height is 13.2 m.

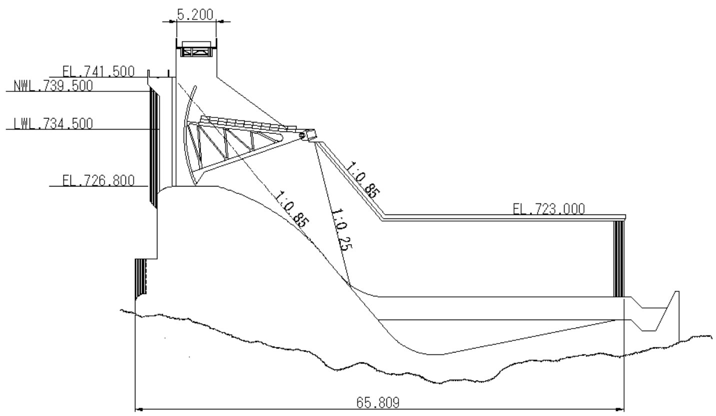


Figure 1. Cross section of the dam

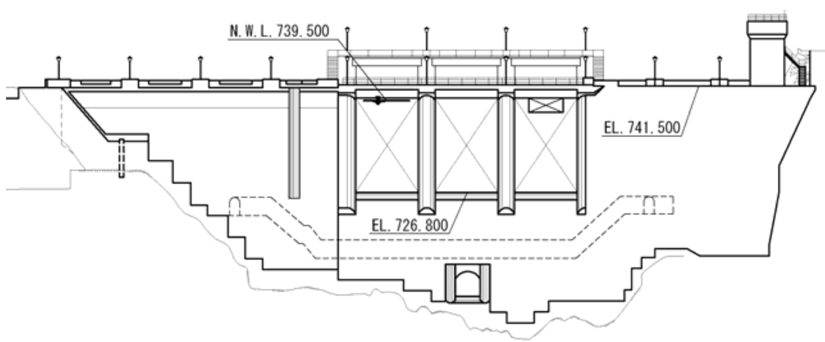


Figure 2. General view of upstream side of the dam

SEISMOLOGICAL MEASUREMENT

Outline of seismological measurement

Seismological measurement was commenced in October 2010 and has continued to date. Figure 3 shows the locations of measurement instruments.

Accelerometers were installed at four locations on the dam piers and in the dam body (on the crest and in the inspection gallery), and at three locations on the radial arm and horizontal main girder of the gate. The accelerometers on piers were installed at the location of gate pin to measure the acceleration input to the gate. The accelerometers were used to measure three elements of acceleration, in the flow direction, along the dam-axis and vertical elements.

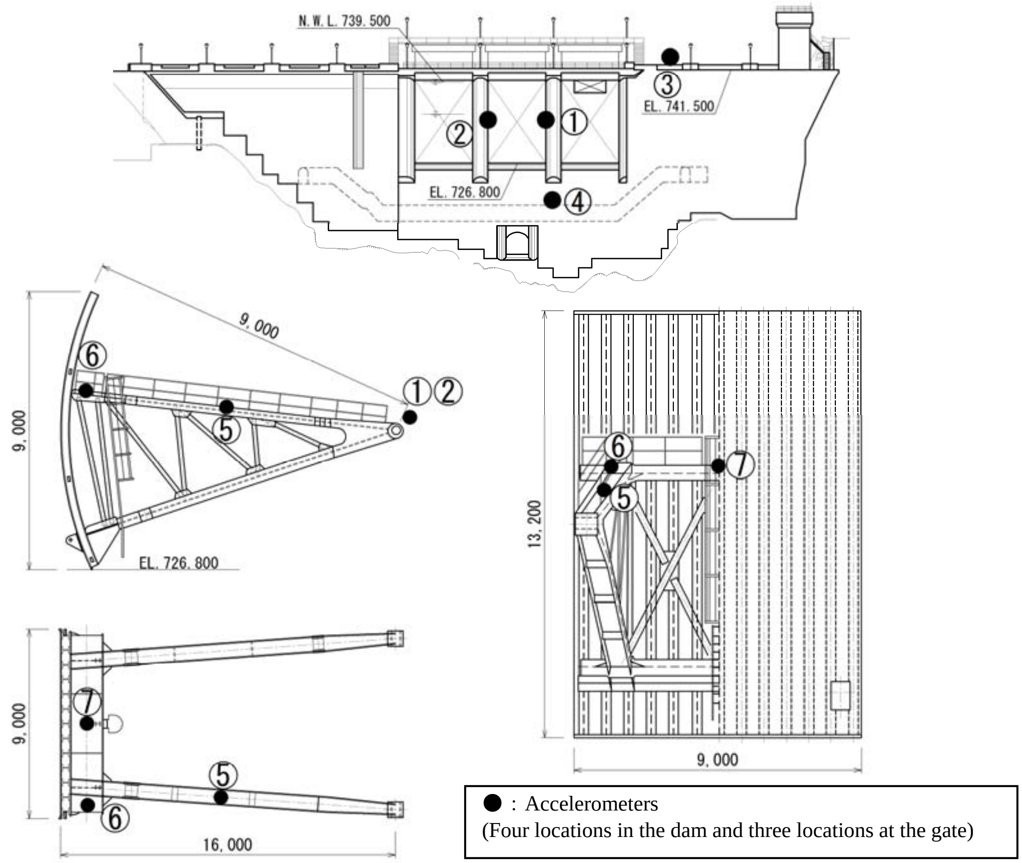


Figure 3. Locations of measurement instruments

Results of seismological measurement

We have obtained four seismic records, of which specifications and peak accelerations at each measurement locations are listed in Table 1. The reservoir water level during each earthquake was in the range between one (1) m and two (2) m below the normal water level, or nearly at the normal water level. No measurements were, however, made on the dam crest during earthquake No. 1 and in the flow direction on the pier on the left bank during earthquake No. 4 because of instrument malfunction.

Table 1. Specifications and peak accelerations of earthquakes

Earthquake No.		No.1			No.2			No.3			No.4		
Magnitude		3.7			3.1			3.2			5.1		
Distance from epicenter		14.7km			12.8km			4.4km			64.9km		
Peak acceleration (gal)	Measurement location	flow	dam axis	vertical	flow	dam axis	vertical	flow	dam axis	vertical	flow	dam axis	vertical
	①	22.6	56.0	26.5	43.5	33.1	7.4	20.1	30.8	18.2	10.3	17.4	14.3
	②	17.1	35.7	14.1	35.7	42.3	14.6	21.9	40.6	23.3	N. m.	17.1	4.2
	③	Not measured			51.7	14.3	16.8	25.6	13.9	11.7	11.4	10.8	14.9
	④	8.3	10.2	8.3	23.2	9.4	9.9	8.6	7.8	9.0	3.6	3.7	2.7
	⑤	41.5	99.1	94.8	33.8	170.3	138.6	32.2	160.9	79.6	22.7	50.9	36.7
	⑥	56.6	67.6	102.4	39.6	44.7	47.0	27.2	32.8	41.1	26.4	22.9	25.0
	⑦	50.4	82.4	72.3	66.6	59.9	53.9	30.9	37.2	27.0	44.5	49.2	70.2

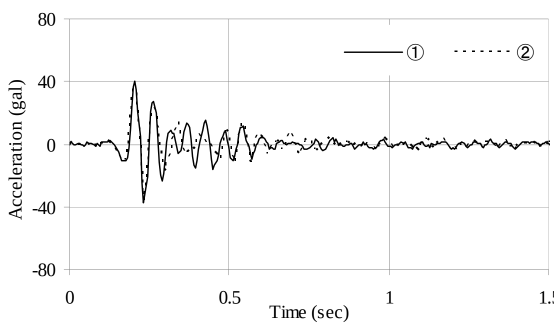
①Pier on the right bank ②Pier on the left bank ③Dam crest ④Inspection gallery
⑤Midpoint of radial arm ⑥End of horizontal main girder ⑦Midpoint of horizontal main girder

The epicenter was very close to the dam during earthquake No. 1 through 3 although the events were of small scale in the 3.1-to-3.7 magnitude range. Earthquake No. 4 was a magnitude-5.1 medium-scale earthquake but its epicenter was far from the dam unlike during the other earthquakes. The peak acceleration of No. 2 is the highest of four earthquakes in the flow direction of the inspection gallery.

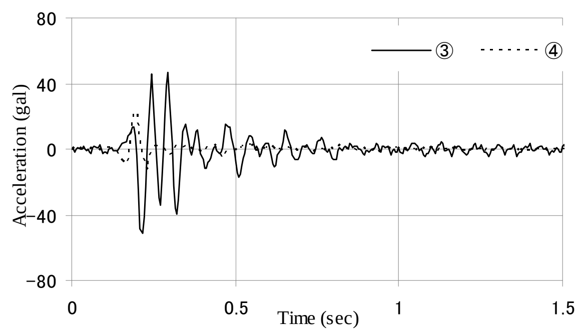
As a result of comparison in acceleration between the inspection gallery and the other measurement locations, it was found that all acceleration amplified at the measurement locations. In the dam, the mean rate of amplification of the dam piers and the inspection gallery during the four earthquakes was high, approximately 4.5 times, along the dam axis though the rate varied depending of each earthquake. This may be attributable to the structure of the pier with a smaller thickness along the dam axis than in the direction of flow. Then, the response of the gate amplified as compared with the pier, which indicates that acceleration at the gate amplified inside. The mean rate of amplification of gate response as compared with the pier during the four earthquakes was approximately two times both in the flow direction and along the dam axis, and approximately 5.5 times in the vertical direction.

Analysis of seismological measurements

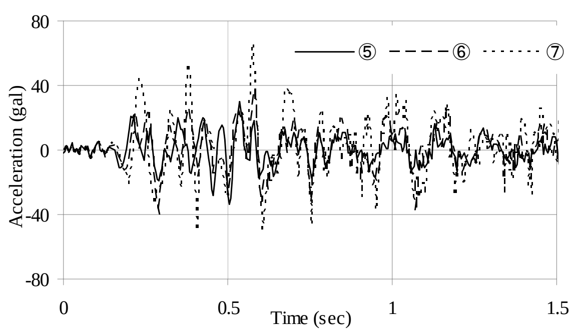
Figure 4 shows acceleration time histories of upstream/downstream element in the dam and at the gate during earthquake No. 2 with the highest peak acceleration of the flow direction in the inspection gallery. A slight phase difference was confirmed in acceleration in piers on both banks and in the gate.



(a) ① and ② on the piers



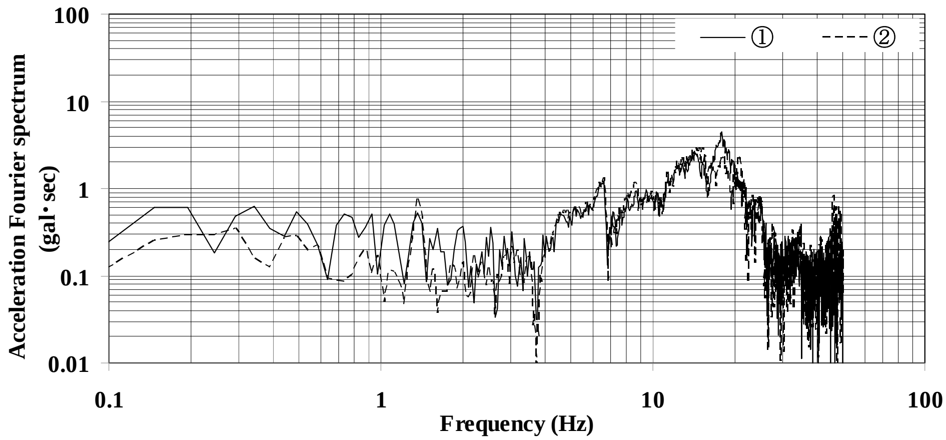
(b) ③ and ④ in the dam body



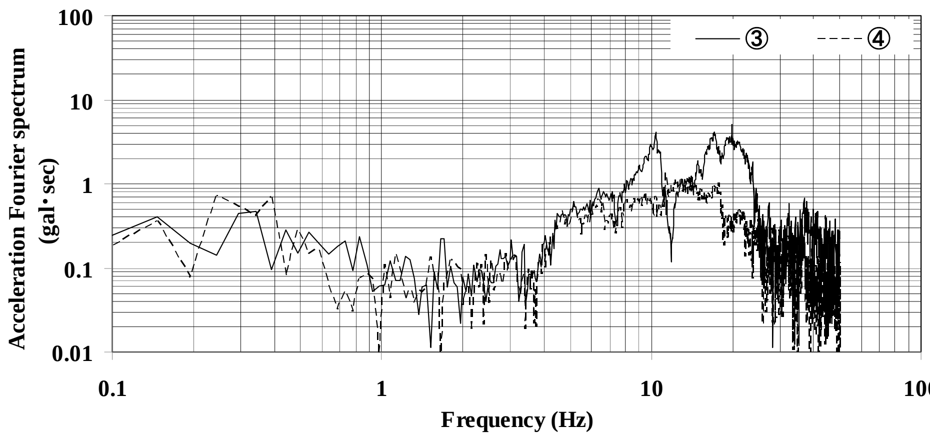
(c) ⑤, ⑥ and ⑦ at the gate

Figure 4. Acceleration time histories during earthquake No.2

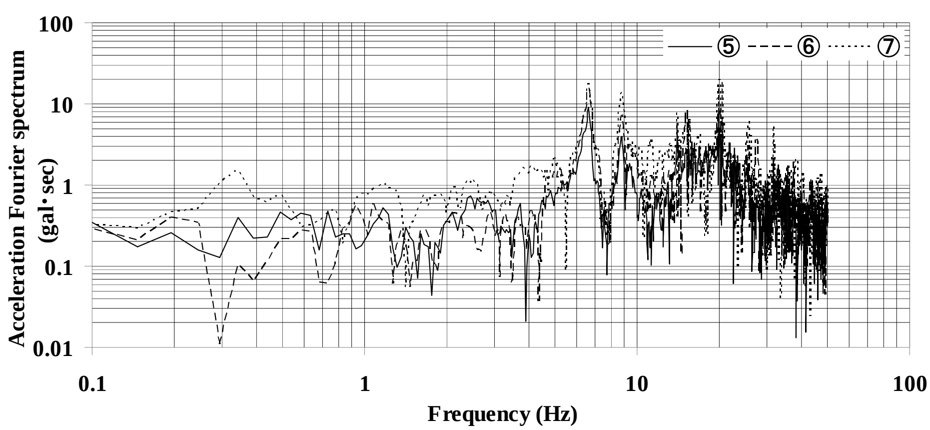
Figure 5 shows acceleration Fourier spectra during earthquake No. 2. Dominant frequencies were confirmed near 10 Hz on dam crest, 14 and 17 Hz on the piers and 7, 9 and 14 Hz at the gate. The dominant frequencies were nearly in agreement with the results of the eigenvalue analysis and excitation tests conducted separately.



(a) measurement locations ① and ② on the pier



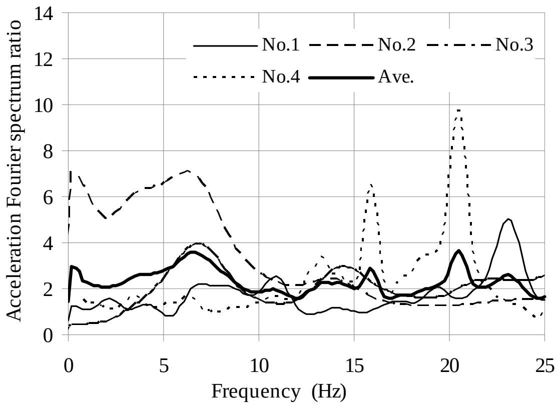
(b) measurement locations ③ and ④ in the dam



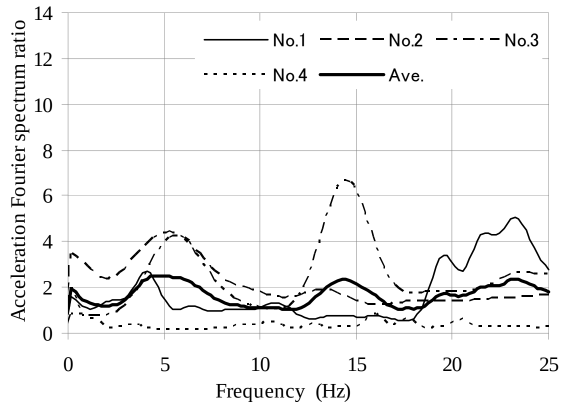
(c) measurement locations ⑤, ⑥ and ⑦ at the gate

Figure 5. Acceleration Fourier spectrum during earthquake No.2

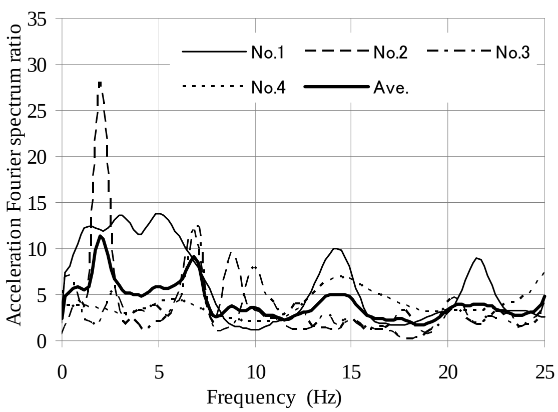
Figure 6 shows the ratios of acceleration Fourier spectrum of the upstream/downstream element during earthquake No. 1 through 4 to verify dominant frequencies on the piers and at the gate. Arranging the acceleration Fourier spectrum enables the identification of dominant frequencies of the study structure except the characteristics of response along the vibration transmission path. The mean ratios of acceleration Fourier spectrum of all the measurements were also organized because dominant frequencies varied from earthquake to earthquake. Slight difference was recognized in dominant frequency on the piers on the left and right banks. The phase difference for accelerations may be attributable to the difference in dominant frequency. Judging from the mean ratios of spectrum at the gate and on the piers, it was assumed that the first natural frequency at the gate was close to 7 Hz. In the acceleration Fourier spectrum at the gate shown in Figure 6, dominant frequencies were confirmed also at 9 and 14 Hz, which is assumed to be the effects of dam vibration.



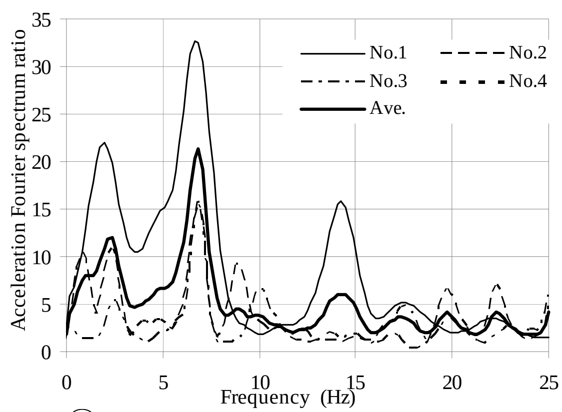
(a) ①pier of the right bank
④inspection galley



(b) ②pier of the left bank
④inspection galley



(c) ⑦midpoint of horizontal main girder
①pier of the right bank



(d) ⑦midpoint of horizontal main girder
②pier of the left bank

Figure 6. Acceleration Fourier spectrum ratio during respective earthquakes

REPRODUCTION ANALYSIS

Analytical model

For reproducing the measurement records, a composite analytical model consisting of a dam, gate, foundation rock and reservoir was adopted. Dam concrete, steel members and foundation rock were represented by elastic body models. The reservoir was represented by an incompressible fluid model. Viscous boundaries were created at the bottom and on the sides of the foundation rock. Figure 7 gives a general view of the composite model used for reproduction analysis. The following two points were taken into consideration in particular to accurately reproduce actual behavior.

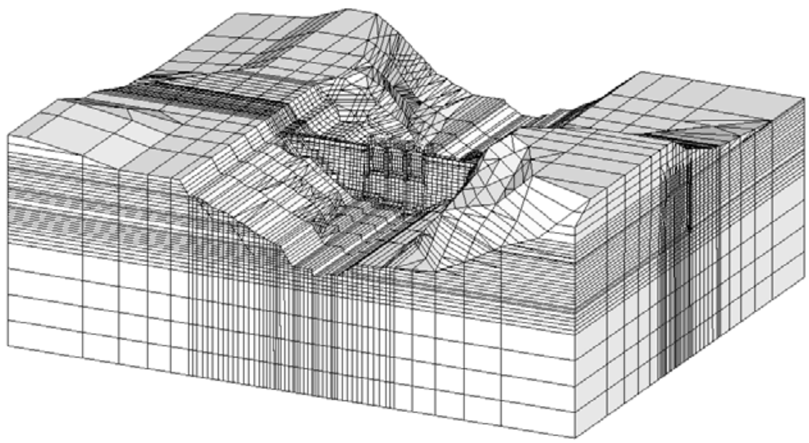


Figure 7. Composite model used for reproduction analysis

Friction between dam blocks The concrete gravity dam is divided into blocks along the dam axis. It is, however, assumed that each block does not behave independently but blocks behave cohesively somewhat as mass concrete because of the restraint of the foundation rock and the friction between concrete blocks.
When building a model, therefore, joint elements were created between concrete blocks and stress transmission due to friction was taken into consideration. Specifically, the shear strength of the joint element was set as $\tau=0.587\ \sigma n$ as a function dependent on the axial stress. The coefficient of internal friction used here was obtained by conducting a laboratory test in which the joints in a concrete dam were simulated (e.g., Nishiuchi et al. 1995 in Japanese).

Modeling of the gate The composite model used for reproduction analysis was complicated because the dam body and foundation rock were also modeled. Incorporating a detailed model of the gate was therefore impractical. Simplifying the gate model for incorporation into the composite model was considered. Specifically, eigenvalue analysis was implemented first using a detailed model of the gate that employed shell elements shown in Figure 8. Then, the gate model was simplified as long as the compatibility with the results of the eigenvalue analysis was ensured. As a result, the members except skin plates and horizontal girders were simplified using a beam element. The gate model incorporated into the composite model is shown in Figure 9.

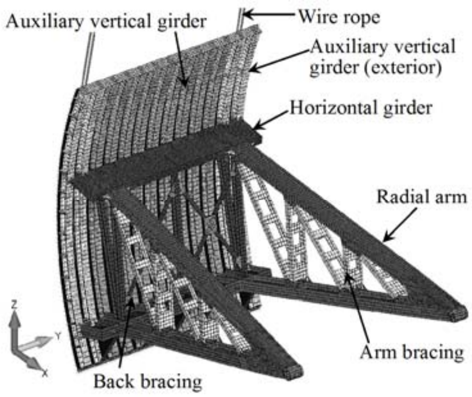


Figure 8. Detailed shell model

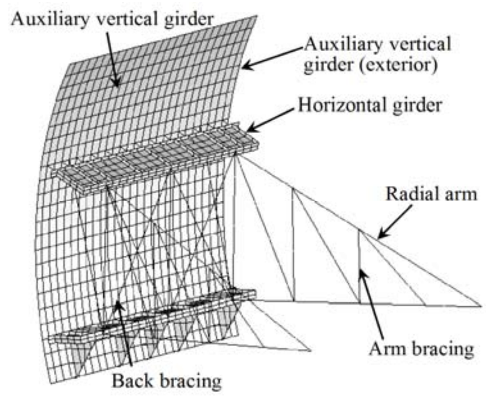


Figure 9. Simplified model

Results of reproduction analysis

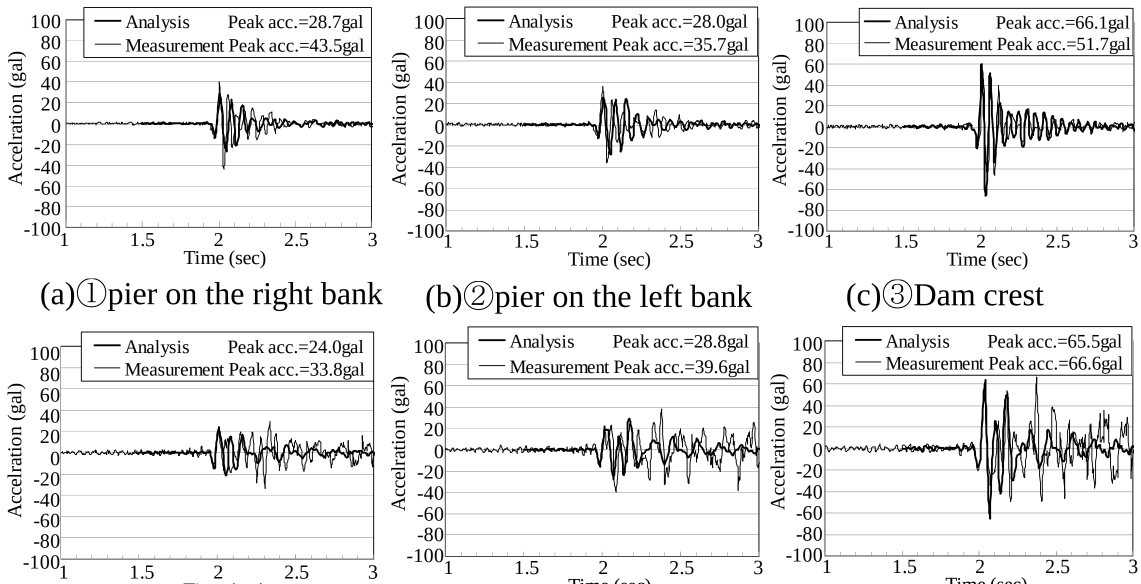
Analysis conditions are listed in Table 2. For input ground motions for analysis, the acceleration time histories of three elements in the direction of upstream/downstream, along the dam axis and in the vertical direction were pulled back from the location of the seismograph installed in the inspection gallery to the bottom of the analytical model, and then they was used as vertically upward waves.

Table 2. Analysis conditions

Parameter	Set value		
	Dam	Gate	Foundation rock
Densityρ(t/m^3)	2.35	Set as the equivalent mass	2.63
Dynamic modulus of elasticity E_d(N/mm^2)	21,182	206,000	38,344
Dynamic Poisson's ratiov_d	0.2	0.3	0.292
Damping coefficient h(%)	10	10	5

The damping coefficients for the dam body and gate were set by conducting parameter studies. Reproduction analysis was made for earthquake No. 2 during which the highest peak acceleration was recorded in the inspection gallery, at varying damping coefficients in the dam body and at the gate, 2, 5 and 10%. As a result, measurements were well reproduced both in the dam body and at the gate in the case where the damping coefficient was set at 10%. Thus the damping coefficient was set at 10%. The damping coefficient of the foundation rock was set at 5% based on existing examples (e.g., Ariga 2007). The damping coefficient of the gate exceeded a damping coefficient of ordinary steel of 1 to 2%. This increase of the damping coefficient may be attributed to such factors as the water cut off rubber or the friction of the bottom end of the gate.

Figure 10 compare the results of analysis of peak acceleration in the upstream/ downstream direction obtained by reproducing earthquake No.2, with the results of actual measurement. The accelerations not only in the dam body but also at the gate were roughly reproduced, though the results of analysis were slightly lower.

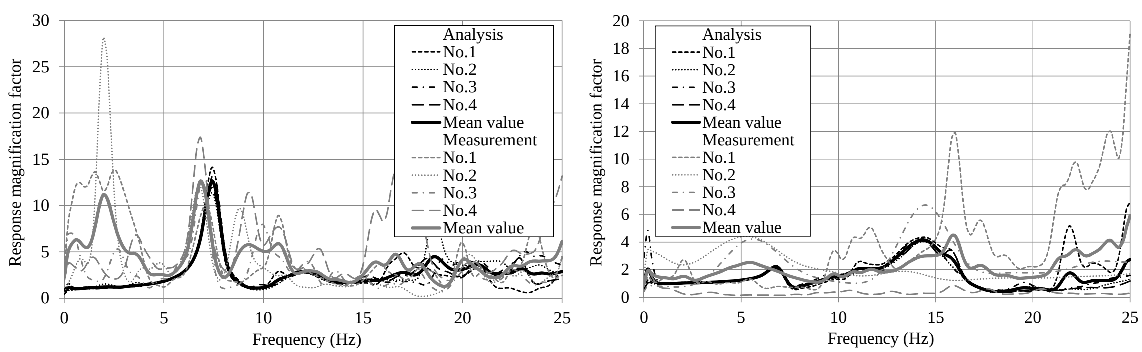


(a)①pier on the right bank (b)②pier on the left bank (c)③Dam crest

(d)⑤mid point of radial arm (e)⑥End of horizontal main girder (f)⑦mid point of horizontal main girder

Figure 10. Acceleration time histories in the flow direction

Figure 11 gives a comparison between the ratios of acceleration Fourier spectrum and the results of measurement. As shown in Figure 7, the characteristics of response varied from earthquake to earthquake. For comparison, therefore, the mean ratio of acceleration Fourier spectrum in all the measurements was used. As a result of comparison, it was confirmed that the characteristics of frequency response reproduced in the analysis were well in agreement with the tendency represented by the mean measurement in all of the earthquakes and that the three-dimensional analytical model developed in this study was valid.



(a)⑦main girder of the gate / ①pier on the right bank (b)②pier on the left bank / ④inspection gallery

Figure 11. Comparison of Fourier spectrum ratio

COMPARISON OF THE RESULTS OF TWO- AND THREE-DIMENSIONAL ANALYSES

Outline of two-dimensional analytical model

The two-dimensional analytical model used for comparison is shown in Figure 12. The cross section of the pier with the largest sectional area was used as the typical cross section of the model. For the physical property values used for analysis, same values as those in Table 2 were used to verify the effect of the modeling for two- and three-dimensional analyses. The gate, which could not be incorporated into the two-dimensional model, was considered by causing the self weight and inertia force of the gate and the hydrostatic and hydrodynamic pressures acting on the gate to act on the gate support.

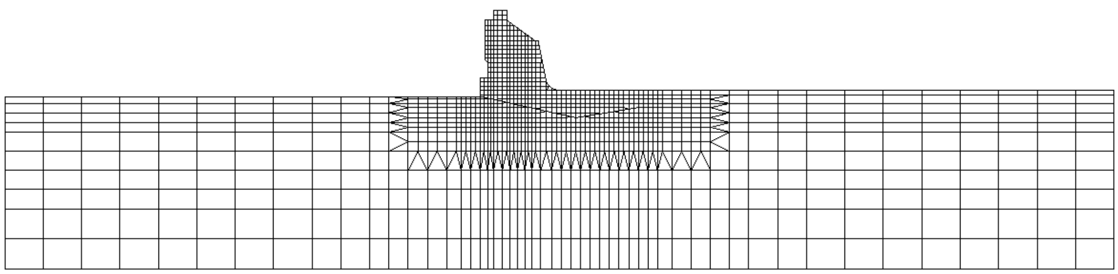
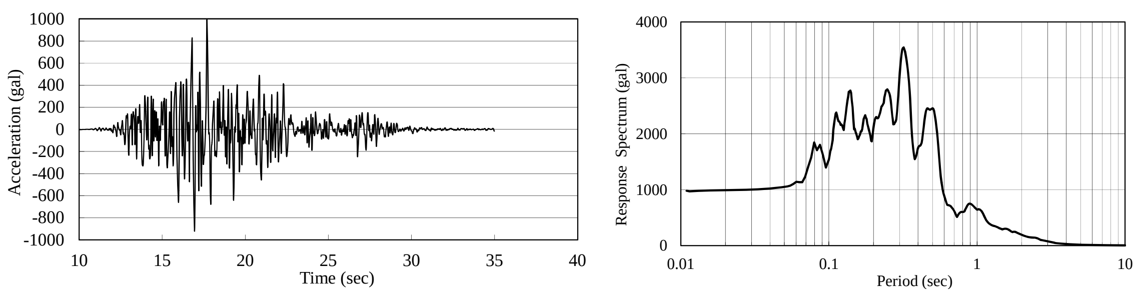


Figure 12. Two dimensional analytical model

Input ground motions

The time history of acceleration and response spectrum of level-2 ground motion to be studied are shown in Figure 13. The peak acceleration in the flow direction was 992 gals. The ground motion was estimated based on the scale of an active fault near the dam.



(a) Acceleration time history (b) Response spectrum

Figure 13. Input ground motion

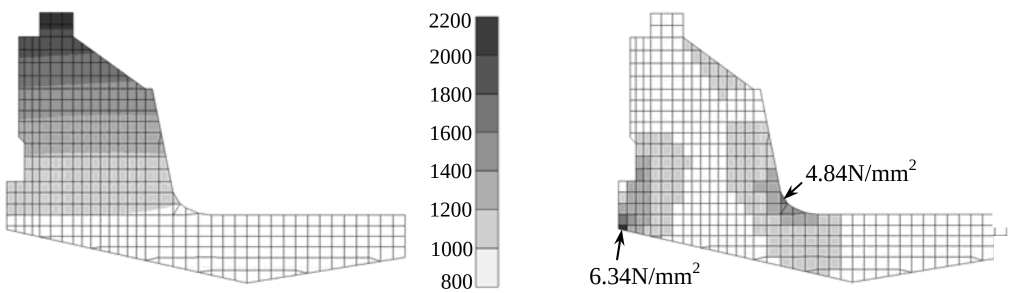
Comparison of analysis results

Figure 14 shows the distributions of accelerations and tensile stresses obtained by two-dimensional analysis. Figure 15 shows the distributions of accelerations and tensile stresses obtained by three-dimensional analysis in the cross section in the pier section, the same location as in two-dimensional analytical model.

The acceleration on dam crest was slightly higher in three-dimensional analysis. The result suggests that damping coefficient was lower in the three-dimensional analytical model. This may be because the damping coefficient in the three-dimensional analytical model was set by conducting reproduction analysis for small-scale earthquakes although the damping coefficient of structures is generally considered to increase as the input ground motion increases. There was, however, no adequate reason for setting a damping coefficient higher than 10% because no greater ground motions had been measured in current seismological measurement. A damping coefficient of 10% was considered an optimum level that could currently be set for checking the resistance to large-scale earthquakes to ensure safety.

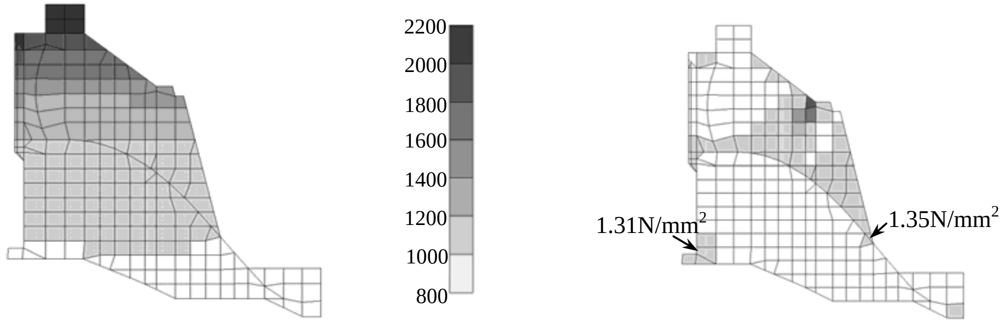
Very large tensile stress occurred according to the results of two-dimensional analysis. The maximum tensile stress was 6.34 N/mm^2 on the upstream side of the dam at the bottom end of the dam and 4.84 N/mm^2 on the downstream side.

In the three-dimensional analysis, tensile stress was reduced greatly. The maximum tensile stress was 1.35N/mm^2 on the upstream side of the dam at the bottom end of the dam and 1.31 N/mm^2 on the downstream side. This is assumed to be ascribable to the monolithic behavior of the dam, which could not be considered in conventional two-dimensional analysis.



(a) Acceleration (gal) (b) Tensile stress (N/mm^2)

Figure 14. Results of two-dimensional analysis



(a) Acceleration (gal) (b) Tensile stress (N/mm^2)

Figure 15. Results of three-dimensional analysis

CONCLUSION

In this study, seismological measurements were made in the dam body and on the spillway gate, analysis was conducted by reproducing the results of measurement and a three-dimensional model was developed that can reproduce the behavior of the dam body and the spillway gate. A comparison was also made of the results of two- and three-dimensional analyses of a large-scale earthquake.

As a result of the seismological measurement, the dynamic behaviors of the dam and the gate were verified. A three-dimensional analytical model was used to reproduce the measurements and it was found that the measurements were well reproduced when the damping coefficients of the dam and the spillway gate were set at 10%.

The results of two- and three-dimensional analyses were compared. It was verified that the stress that occurred in the dam body based on the results of three-dimensional analysis was greatly smaller than that based on the results of two-dimensional analysis in the case where level-2 input ground motion was applied in both analyses. This is assumed to be ascribable to the monolithic behavior of the dam, which was not considered in conventional two-dimensional analyses.

In future, we will implement the following tasks through continuous seismological monitoring.

1) Clarification of the characteristics of structural response during earthquakes: the characteristics varied from earthquake to earthquake in the seismological measurements currently available.

2) Verification of the damping coefficient for large-scale earthquakes in the three-dimensional analytical model: the result of a comparison with two-dimensional analysis suggests that the damping coefficient set by conducting reproduction analysis of small-scale earthquakes was lower.

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