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THREE-DIMENSIONAL BEHAVIOR PROPERTIES AND REPRODUCTION ANALYSIS OF AN ARCH DAM DURING LARGE-SCALE EARTHQUAKES*

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SUMMARY

This study analyzed the following earthquake records at the Yagisawa Dam, which is managed by the Japan Water Agency, in order to clarify the three-dimensional behavior of arch dams during large-scale earthquakes: (a) microtremor records measured simultaneously at 14 points, (b) small earthquake measurement records obtained simultaneously by seismographs installed at 6 points, and (c) maximum earthquake records ($6.56 m/s^2$ at center of dam crest). The behavior at the Yagisawa Dam found in (c) during a $6.56 m/s^2$ earthquake record was difficult to reproduce based on three-dimensional FEM analysis, which is generally used in Japan, but were reproduced with high precision by analysis using revised foundation ground – dam body – reservoir coupling conditions.

** La façon dont réagit un barrage voûte lors d'un tremblement de terre expliquée en 3 points, et nouvelle analyse proposée*

Keywords: arch dam, yagisawa dam, response spectrum, three-dimensional, analysis, seismic resistance.

RÉSUMÉ

Dans cette recherche, afin d'expliquer sur 3 niveaux différents la façon spécifique dont un barrage voûte réagit lors d'un tremblement de terre, nous avons relevé de façon précise et analysé tous les tremblements de terre enregistrés, comme indiqués dans les points suivants (a) ~ (c). Nous avons procédé en nous basant sur des observations effectuées au barrage Yagisawa, un barrage voûte sous le contrôle de la « Japan Water Agency ». Cela nous a permis de rendre explicites, sur 3 niveaux différents, les caractéristiques des secousses au barrage Yagisawa. (a) Relevé des micro-secousses enregistrées simultanément dans 14 endroits différents, (b) relevé des tremblements de terre mineurs enregistrés simultanément par des sismographes placés dans 6 endroits différents, (c) relevé des plus grands tremblements de terre mesurés au barrage Yagisawa (656cm/s^2 au centre du sommet de la digue du barrage). En outre, pour les caractéristiques de la réaction du barrage Yagisawa dans « le relevé des tremblements de terre de 656cm/s^2 observés au barrage Yagisawa » mentionné ci-dessus au point (c), il était difficile de reproduire la méthode d'analyse utilisant le système d'analyse MÉF sur 3 niveaux, méthode utilisée habituellement au Japon. Nous nous avons cependant réussi à reproduire avec une bonne précision les spécificités de la réaction du barrage Yagisawa grâce à une analyse révisée en reliant entre elles les données pour la base, le bâtiment et le réservoir du barrage.

1. INTRODUCTION

There are few earthquake records of arch dams during large-scale earthquakes worldwide, and therefore many aspects of the behavior of arch dams during such earthquakes remain unclear.

This study analyzed the following earthquake records at the Yagisawa Dam, which is managed by the Japan Water Agency, in order to clarify the three-dimensional behavior of arch dams during large-scale earthquakes: (a) microtremor records measured simultaneously at 14 points, (b) small earthquake measurement records obtained simultaneously by seismographs installed at 6 points, and (c) maximum earthquake records (6.56m/s^2 at center of dam crest). The behavior at the Yagisawa Dam found in (c) during a 6.56m/s^2 earthquake record was difficult to reproduce based on three-dimensional FEM analysis, which is generally used in Japan, but was reproduced with high precision by analysis using revised foundation ground – dam body – reservoir coupling conditions.

2. GRASPING THE BEHAVIOR OF THE DAM BODY

2.1. MICROTREMOR RECORDS

Table 1 shows the specifications of the Yagisawa Dam. Fig. 1 shows the layout of the seismographs and the positions of the speed indicators used to measure microtremors at the dam. This study defined the tangent line of the arch at the center of the upper inspection gallery (location T1) as the direction of the dam axis and its normal line as the upstream-downstream direction. The sampling frequency of the microtremor measurements was 200Hz. Fourier analysis was done using 30 minutes of measurement data. On the measurement day (October 8, 2014), the reservoir level was EL. 849.4m.

Table 1
Specifications of Yagisawa Dam

Item	Specifications
Dam type	Concrete arch dam
Dam height	131.0m
Dam crest length	352.0m
Dam crest width	7.9m
Dam body volume	570,000m^3
Dam crest elevation	EL.856.0m
Foundation elevation	EL.725.0m
Surcharge water level	EL.854.5m
Full reservoir level	EL.850.0m
Lowest water level	EL.796.5m

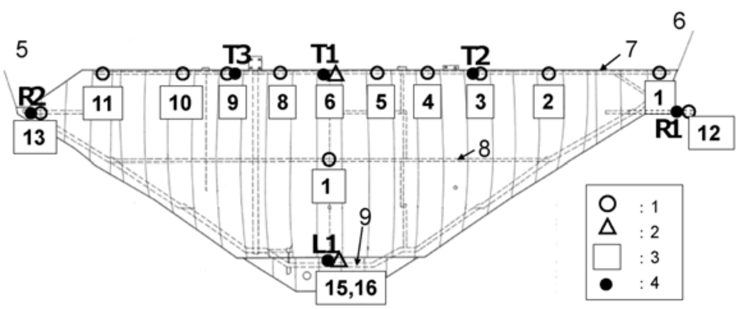

Fig. 1
Yagisawa Dam seismograph and accelerometer layout diagram
Plan d'agencement du sismographe et du compteur de vitesse pour le barrage Yagisawa

1	Speed indicator locations (upstream-downstream direction)	*1*	*Lieux d'emplacement des compteurs de vitesse (en direction de l'aval et de l'amont)*
2	Speed indicator locations (upstream-downstream and dam axis directions)	*2*	*Lieux d'emplacement des compteurs de vitesse (en direction de l'aval et de l'amont – en direction de l'axe du barrage)*
3	Accelerometer number	*3*	*Numéro du compteur de vitesse*
4	Seismograph (3 constituents)	*4*	*Sismographes (composant 3)*
5	Right bank	*5*	*Rive droite*
6	Left bank	*6*	*Rive gauche*
7	Upper inspection gallery	*7*	*Couloir d'inspection supérieure*
8	Middle inspection gallery	*8*	*Couloir d'inspection intermédiaire*
9	Lower inspection gallery	*9*	*Couloir d'inspection inférieure*

2.2. Earthquake records

Seismographs were installed at the dam as shown in Fig. 1. Of these, seismographs in the upper inspection gallery (T2, T3) and in the right bank abutment (R2) were added in September 2014. An earthquake (M6.7) occurred in northern Nagano Prefecture on November 22, 2014 after these seismographs were added, and the maximum acceleration in the upstream-downstream direction at the center of the dam crest (T1) was approximately $0.2 m/s^2$. This paper reports the results of analyzing this earthquake record (hereinafter, "small earthquake record"). The maximum earthquake record observed at the dam was the maximum aftershock (M6.5) of the Mid Niigata Prefecture Earthquake in 2004, which was recorded at 18:34 on October 23, 2004. In this record, the maximum acceleration in the upstream-downstream direction at the center of the dam crest (T1) was approximately $6.6 m/s^2$ (hereinafter, "Chuetsu Earthquake"). The dam was not damaged by the Mid Niigata prefecture Earthquake in 2004. The reservoir level and maximum acceleration of the small earthquake record and the Chuetsu Earthquake are shown in Table 2.

2.3. Eigenvalue analysis

We conducted eigenvalue analysis using a model prepared for reproducing the behavior of the dam body. The analysis was conducted by extracting the dam body part of the reproduction analysis model as discussed later. The eigenvalue analysis model is shown in Fig. 2, and the physical properties used for the eigenvalue analysis are shown in Table 3.

Fig. 3 and 4 show Fourier spectra of the small earthquake record at the upper inspection gallery T1 and microtremors measured at the location corresponding to T1. The spectra have the following characteristics.

Table 2
Earthquake record specifications

Earthquake		Small earthquake record (earthquake on Nov. 22, 2014)	Chuetsu Earthquake record ((earthquake on Oct. 23, 2004)
Magnitude		6.7	6.5
Reservoir water level		EL.847.9m	EL.845.3m
Measurement location		Max. acceleration (m^2/s)	Max. acceleration (m^2/s)
L1 (Foundation)	Upstream-downstream	0.014	0.848
	Dam axis	0.013	0.462
	Vertical	0.013	0.714
T1 (Center of crest)	Upstream-downstream	0.208	6.563
	Dam axis	0.034	1.445
	Vertical	0.034	1.523
T2 (Left bank at crest)	Upstream-downstream	0.141	-*
	Dam axis	0.030	
	Vertical	0.017	
T3 (Right bank at crest)	Upstream-downstream	0.158	
	Dam axis	0.033	
	Vertical	0.019	
R1 (Drift on left bank)	Upstream-downstream	0.012	0.545
	Dam axis	0.011	0.311
	Vertical	0.013	0.389
R2 (Natural ground on right bank)	Upstream-downstream	0.034	-*
	Dam axis	0.025	
	Vertical	0.019	

* The Chuetsu Earthquake occurred before supplementary seismographs were installed.

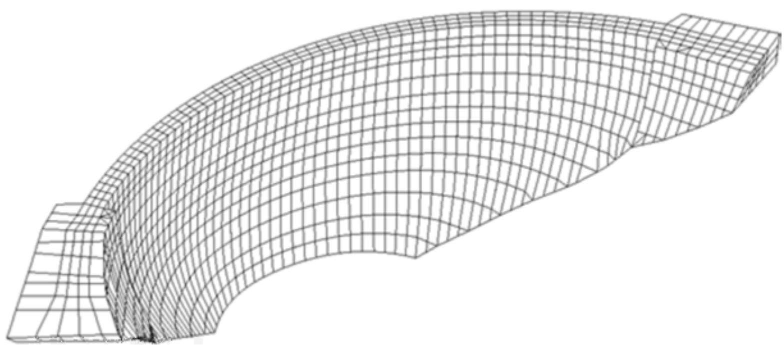

Fig. 2
Eigenvalue analysis model
Modèle d’analyse de la valeur proper

Table 3
Physical properties used for Eigenvalue analysis

Item	Physical property
Unit weight by volume	23.03kN/m^3
Modulus of elasticity	34,400N/mm^2
Poisson's ratio	0.20
Attenuation constant (Rayleigh)	5.0% 1st (2.5Hz), 14th (10.0Hz)

Dominant frequencies of the fourier spectrum (measured)

1) In the upstream-downstream direction, dominance at approximately 2.3Hz, 2.5Hz, and 3.4Hz was confirmed in both the small earthquake record and microtremor record, but the peak of 2.3Hz in the microtremor record is unclear.

2) In secondary mode (approximately 2.5Hz), dominance of the upstream-downstream direction was greatest at T1 (center of dam crest) in both the small earthquake record and microtremor record. Accordingly, it is presumed that the secondary mode (approximately 2.5Hz) is the major response mode of the dam.

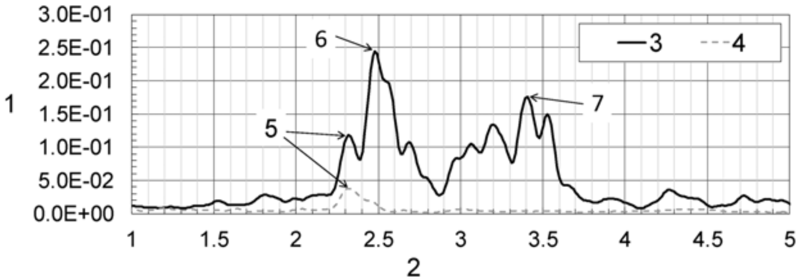

Fig. 3
Fourier spectrum of small earthquake record (Nov. 22, 2014) (T1)
Spectrum Fourier (T1) pour le suivi des tremblements de terre mineurs (22.11.2014)

1	Fourier spectrum ((m/s^2)$_*$s)	*1*	*Spectrum Fourrier ((m/s^2)$_*$s)*
2	Frequency (Hz)	*2*	*Fréquence (Hz)*
3	T1 (upstream-downstream direction)	*3*	*T1 (en direction de l'aval et de l'amont)*
4	T1 (dam axis direction)	*4*	*T1 (en direction de l'axe du barrage)*
5	Primary mode: 2.32Hz	*5*	*Mode 1er degré : 2.32Hz*
6	Secondary mode: 2.48Hz	*6*	*Mode 2ème degré : 2.48Hz*
7	Tertiary mode: 3.41Hz	*7*	*Mode 3ème degré : 3.41Hz*

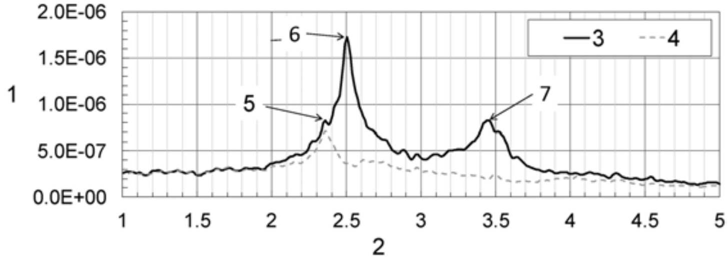

Fig. 4
Fourier spectrum of microtremors (T1)
Spectrum Fourier (T1) pour le suivi des micro-secousses

1 Fourier spectrum ((m/s^2)*s)
2 Frequency (Hz)
3 T1 (upstream-downstream direction)
4 T1 (dam axis direction)
5 Primary mode: 2.36Hz
6 Secondary mode: 2.50Hz
7 Tertiary mode: 3.45Hz

*1 Spectrum Fourrier ((m/s^2)*s)*
2 Fréquence (Hz)
3 T1 (en direction de l'aval et de l'amont)
4 T1 (en direction de l'axe du barrage)
5 Mode 1er degré : 2.36Hz
6 Mode 2ème degré : 2.50Hz
7 Mode 3ème degré : 3.45Hz

2.4. Vibration mode

Fig. 5 shows the vibration modes at the primary, secondary, and tertiary natural frequencies (approximately 2.3Hz, 2.5Hz, 3.4Hz) in the small earthquake record and microtremor record confirmed by Fig. 3 and 4. Fig. 5 refers to the natural frequencies and vibration mode diagrams obtained from the eigenvalue analysis. The vibration modes are determined on the basis of the Fourier amplitude of each measurement point at the dominant frequency. From Fig. 5, it can be presumed that the vibration modes of the small earthquake record and the microtremor record conform closely and that the major natural vibration mode during an earthquake can also be clarified precisely even from microtremors. A comparison of the eigen-value analysis results with actual measurements shows that although the natural frequencies obtained from analysis are slightly higher than actual measurements, the vibration mode can accurately reproduce the measurements. Therefore, the analysis model and analytical physical properties were evaluated as suitable.

2.5. Comparison with records of the Chuetsu Earthquake

Fig. 6 shows the Fourier spectra of the Chuetsu Earthquake observed at the Yagisawa Dam. From Fig. 6, even during the earthquake, spectrum peaks can be

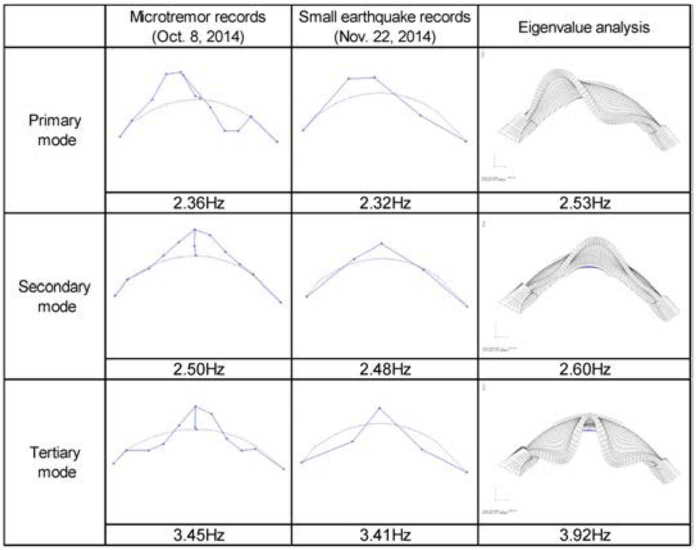

Fig. 5
Vibration mode at natural frequency
Modes de vibration dans les fréquences naturelles

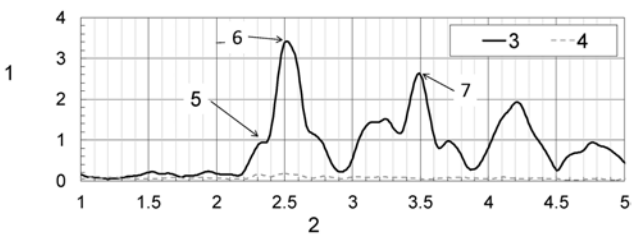

Fig. 6
Acceleration Fourier spectrum of maximum earthquake record observed at Yagisawa Dam
Spectrum Fourier d'accélération pour le suivi des tremblements de terre majeurs mesurés au barrage Yagisawa

1 Fourier spectrum ($(m/s^2)*s$)	*1 Spectrum Fourrier ($(m/s^2)*s$)*
2 Frequency (Hz)	*2 Fréquence (Hz)*
3 T1 (upstream-downstream direction)	*3 T1 (en direction de l'aval et de l'amont)*
4 T1 (dam axis direction)	*4 T1 (en direction de l'axe du barrage)*
5 Primary mode: 2.33Hz	*5 Mode 1er degré : 2.33Hz*
6 Secondary mode: 2.54Hz	*6 Mode 2ème degré : 2.54Hz*
7 Tertiary mode: 3.50Hz	*7 Mode 3ème degré : 3.50Hz*

confirmed at approximately 2.5Hz (secondary) and 3.5Hz (tertiary). Small dominance is also seen at 2.33Hz (primary). At approximately 4.2Hz, dominance that could not be confirmed in the microtremor record and small earthquake record was seen. The major response modes which are dominant in the earthquake response of dams are identified in Yagisawa Dam under the Chuetsu Earthquake.

3. REPRODUCTION ANALYSIS

In order to reproduce the three-dimensional behavior of the Yagisawa Dam during a large-scale earthquake which were confirmed in Section 2, a three-dimensional dynamic FEM analysis was performed.

3.1. Analysis model

The reproduction analysis model is shown in Fig. 7 and the physical properties used for the analysis are shown in Table 4. The range of the foundation rock

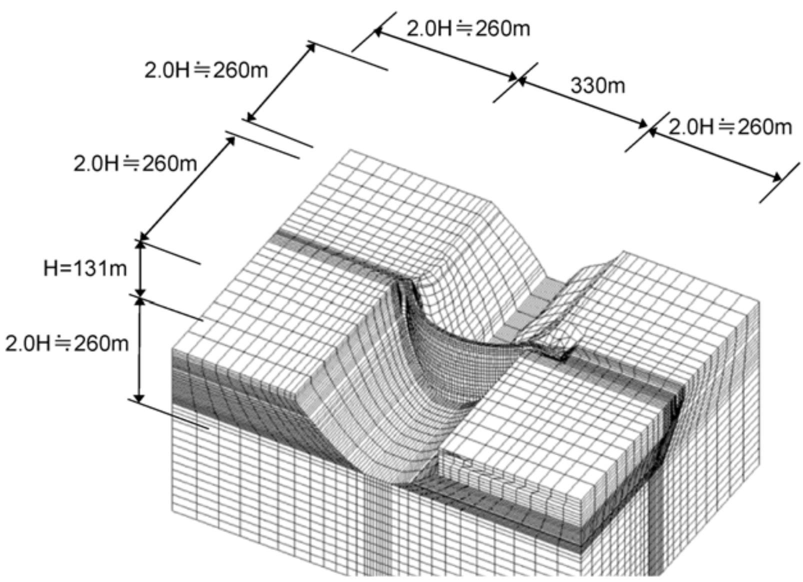

Fig. 7
Analysis model
Modèle d'analyse

that was modeled was set as shown in Fig. 7 with reference to past research results [1]. H in Fig. 7 denotes the length of dam height. Elements in the model of the dam body were divided as shown in Fig. 2. The reservoir was modeled by adopting velocity potential compressible fluid elements and modeling to a range of 2H matched to the foundation rock on the upstream side of the dam body. Boundary conditions were a viscous boundary with the bedrock used on the bottom surface, while a viscous boundary based on the principle of virtual work was used on the side.

Table 4
Physical properties obtained by analysis

ITEM	UNIT	DAM	BEDROCK	RESERVOIR
Static modulus of elasticity	N/mm^2	34,410	24,000	
Dynamic modulus of elasticity	N/mm^2	34,410	24,000	
Poisson's ratio	-	0.2	0.25	
Unit weight by volume	t/m^3	2.35	2.60	1.00
Attenuation constant	%	5-8	5	

3.2. Reservoir – bedrock – dam body coupling

This study initially set and analyzed the boundary conditions of the reservoir and surrounding bedrock based on impedance ratio β = 2 to 5. As shown later, while the analysis under this condition represented the monitored acceleration in the upstream-downstream direction dominating at 2.5 Hz of the Fourier spectrum, it could not obtain the dominance at 3.5Hz or 4.2Hz. On the other hand, the natural frequency (f=V/4h) of the reservoir based on the water depth h of the Yagisawa Dam and the propagation velocity V of the water was confirmed at 3.5Hz under water level conditions during the earthquake. The discrepancy of the analysis is thought that to be due to the effect of the dynamic interaction of the reservoir and bedrock. Consequently, in this study, the boundary conditions of the reservoir and foundation bedrock were revised so as to reproduce the dominance around 3.5Hz. An attempt was made to adopt conditions such that a certain range of the boundary of the reservoir and bedrock are coupled under the conditions similar to the boundary of the reservoir and dam body.

In past analyses [2], the coupling of the dam body and reservoir was considered by placing double nodes in the boundary nodes of the dam body and reservoir and setting boundary conditions in Eq. [1], and the coupling of the bedrock with the reservoir was considered by setting the penetration and reflection of the wave based on the impedance ratio.

$$\frac{\partial \varphi}{\partial n} = \frac{\partial u_n}{\partial t} \qquad [1]$$

ϕ : velocity potential of a fluid
u_n : n direction displacement of a solid body
$\frac{\partial}{\partial n}$: differentiation in the direction normal to the boundary

In this study the analysis was done under coupling conditions based on Eq. [1] also at the boundary coupling points of the foundation rock and the reservoir. In the range in which the coupling of the foundation bedrock and reservoir is considered similarly to the dam body (below, "coupling range"), preliminary analysis was done by setting the coupling range to 1.2H, 1.0H, and 1.5H from the upstream surface of the dam body. The coupling range of 1.0H is adopted where the reproduction of the Fourier spectrum dominant at 3.5Hz is favorable. On other boundaries of the reservoir and bedrock, the penetration and reflection of the wave was set based on an impedance ratio β = 2.0. Figure 8 shows the coupling range that was adopted.

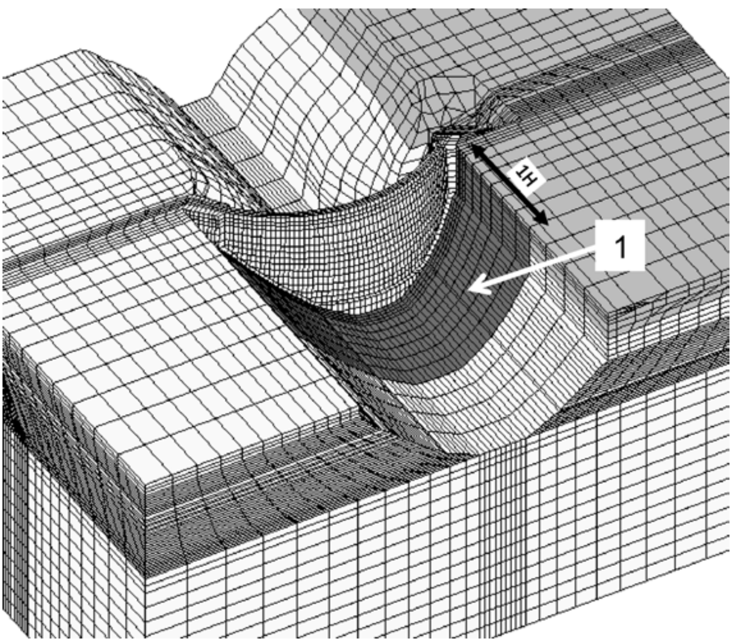

Fig. 8
Coupling range in reproduction analysis
Partie du réservoir pour l'analyse préliminaire

1 Reservoir – bedrock coupling range

1 Zone du Réservoir d'eau et du fond rocheux

Fig. 9 shows the results of preliminary analysis. In Fig. 9, the transfer functions at the center of the crest in the measurement and analysis results are normalized based on the maximum values of each case. Based on Fig. 9, in the case where the coupling of the foundation and the reservoir is not considered, it is impossible to confirm the dominance near 3.5Hz that can be confirmed by measurements, but it is possible to confirm reproduction of dominance near 3.5Hz by considering the coupling of the foundation and the reservoir. Even for dominance near 4.2Hz, the tendency of the dominance is reproduced while the absolute value is low. When a past analysis method [2] was applied to reproduction analysis of the Yagisawa Dam, the low reproducibility of the mode of 3.5Hz or higher was a problem, but this point is improved in the present study.

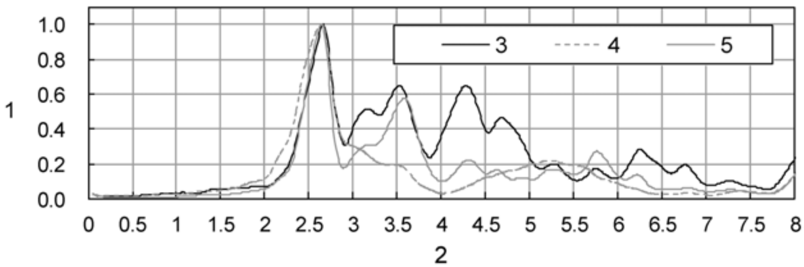

Fig. 9
Preliminary analysis results, normalized transfer function
(Crest/foundation, upstream-downstream direction)
Fonction de transmission régularisée pour les résultats de l'analyse préliminaire
(sommet de la digue/base de la digue, en direction de l'amont et de l'aval)

1 Transfer function (crest/ foundation)
2 Frequency (Hz)
3 Actual value
4 Analysis value : Bedrock and reservoir not coupled (β= 2)
5 Analysis value : Bedrock and reservoir coupled (coupling range=H)

1 Fonction de transfert (sommet de la digue/base du barrage)
2 Fréquence (Hz)
3 Onde des mesures effectives
4 Sans la base du barrage et du réservoir (β=2)
5 Base du barrage et réservoir (en aval et en amont H)

3.3. Analysis physical values

Table 4 shows the physical values obtained by the analysis. Values other than the damping ratio of the dam body are identical to the physical values obtained by the preliminary analysis. The damping ratio of the bedrock was 5%, and the damping ratio of the dam body was adjusted so that the peak of the transfer function of measurements in each case could be reproduced. In this study, the aperture of the joints and non-linearity of the materials were not considered.

3.4. Analysis case

The earthquake record of the Chuetsu Earthquake was used for the reproduction analysis. Because this study considers the coupling of the reservoir and foundation rock by the same method as the coupling of the reservoir and the dam body, it was thought that the small damping ratio of the reservoir model and the resonance phenomenon of 4H/C could cause successive integration analysis to diverge, so reproducibility was confirmed by performing a complex response analysis first. The damping ratio was set by adopting a constant damping ratio. The damping ratio hc of the dam body was set by sensitivity analysis using hc as the variable, so the transfer function of the analysis results (dam crest/foundation) matches the measured values.

3.5. Analysis results

The analysis results are compared with the monitored ones for the acceleration time histories in the upstream-downstream direction, those Fourier spectrum and the transfer function between the dam foundation and the crest in Figs. 10

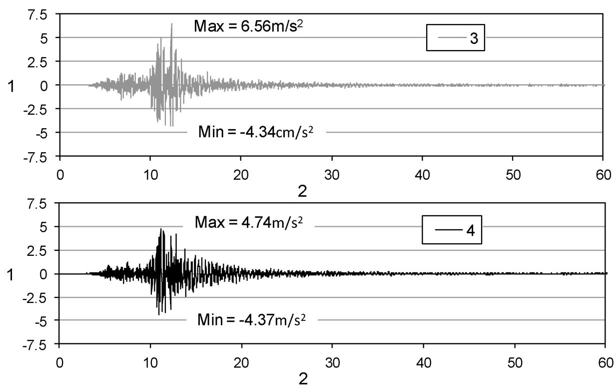

Fig. 10
Acceleration time history
(Seismograph at center of crest T1, upstream-downstream direction)
Relevé du temps d'accélération(sismographe T1 placé au centre du sommet de la digue, en direction de l'amont et de l'aval)

1 Acceleration (m^2/s)
2 Time (seconds)
3 Actual values
4 Monitored values (hc = 8%)

1 Accélération (m^2/s)
2 Temps (secondes)
3 Onde des mesures effectives
4 Résultat de l'analyse (hc=8%)

to 12, respectively. While the instantaneous acceleration peaks are under-estimated in the analysis, the overall acceleration behavior is generally reproduced. These reproductions in the frequency domain are favorable. These are consistent to the monitored ones form 3.5 Hz to 10 Hz, especially at the major modes of 2.5Hz and 3.5Hz. The damping ratio of 8% is obtained to reproduces the peak of the transfer function of the major mode near 2.5Hz. It is higher than the value of 5% used for earthquake resistance studies of common civil engineering structures in Japan [3].

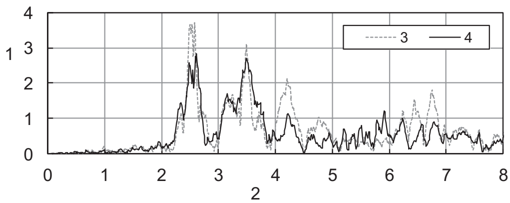

Fig. 11

Acceleration Fourier spectra (Seismograph at center of crest T1, upstream-downstream direction)

Spectrum Fourier d'accélération (sismographe T1 placé au centre du sommet de la digue, en direction de l'amont et de l'aval)

1 Acceleration Fourier spectrum	*1 Spectrum Fourrier d'accélération*
2 Frequency (Hz)	*2 Fréquence (Hz)*
3 Monitored values	*3 Onde des mesures effectives*
4 Analysis values (hc = 8%)	*4 Résultat de l'analyse (hc=8%)*

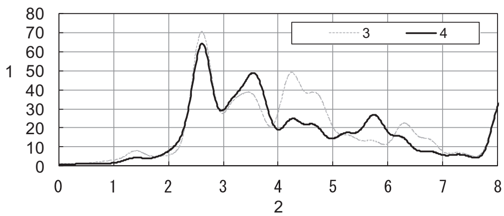

Fig. 12

Transfer function (Crest/foundation, upstream-downstream direction)

Fonction de transmission (sommet de la digue/base de la digue, en direction de l'amont et de l'aval)

1 Transfer function	*1 Fonction de transfert*
2 Frequency (Hz)	*2 Fréquence (Hz)*
3 Monitored values	*3 Onde des mesures effectives*
4 Analysis values (hc = 8%)	*4 Résultat de l'analyse (hc=8%)*

4. CONCLUSION

A reproduction analysis of the three-dimensional behavior of an arch dam during large-scale earthquakes was conducted based on measurements, and the damping ratio of the dam body was studied. The following results were obtained.

1) A comparative analysis of the vibration modes in the acceleration Fourier spectra and dominant frequency of the microtremor record, small earthquake record, and Chuetsu Earthquake at the Yagisawa Dam was conducted, and the vibration characteristics during an earthquake were clarified.

2) The results of the comparative analysis confirmed that the major dominant frequency and vibration mode during large-scale earthquakes can be estimated based on microtremor measurements, even for small earthquake records.

3) The earthquake response of the dam body of the Yagisawa Dam during the Chuetsu Earthquake was reproduced with high precision by revising the reservoir and bedrock coupling method.

4) According to the reproduction analysis of the Chuetsu Earthquake, the damping ratio of the dam body was obtained by complex response analysis as hc = 8%.

In the future, successive integration analysis will be used to consider the non-linearity of joints when applying seismic safety evaluation to large-scale earthquakes.

REFERENCES

[1] M. UEDA, H. OKUDA, H. SHIOJIRI, AND C. TAMURA. Earthquake simulation of an arch dam. *Collected papers of the JSCE*, NO. 501/1-29, PP.203-212, 1994. (IN JAPANESE)

[2] Y. ARIGA, Z. SOU AND H. WATANABE. Research on three-dimensional analysis of arch dams considering discontinuous behavior of joints during earthquakes. *Collected papers of the* JSCE, No. 759/1-67, pp.53-67, 2004. (in Japanese)

[3] S. Kataoka. Design earthquake motion of civil engineering structures (No. 2) – Expressing design earthquake motion--, *Civil Engineering Technology Reports*, 49-11, pp.15-16, 2007. (in Japanese)