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Effects of reservoir water level and temperature on Vibration characteristics of concrete gravity dam

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ABSTRACT

To evaluate seismic performance of dams against large earthquakes, it is necessary to select physical properties of each dam and its foundation appropriately so that their actual dynamic behaviors during earthquakes are accurately estimated. Focusing on vibration characteristics such as natural frequencies obtained from analysis results of earthquake motion records observed at each dam are one of the most popular and practical way to identify values of various properties such as the elastic modulus of dam body. The values estimated in this way, however, may be affected by fluctuations of the reservoir water level and the temperature.
The vibration characteristics, that reflect the stiffness of a dam, may also provide an effective barometer to monitor the structural soundness of the dam body. But the factors effecting the vibration characteristics, such as reservoir water level should be adequately considered to detect the sign of deterioration of the dam due to aging.
In this paper, the effect of reservoir water level and temperature on the vibration characteristics of a dam body such as natural frequency is investigated by analyzing seismic motion records including those obtained at the time of a large-scale earthquake and microtremor measurement result at a concrete gravity dam.
As a result, it is revealed that the natural frequencies of the dam are obviously affected by fluctuation of not only the reservoir water level but also the temperature. In addition, the reason for these behaviors is discussed based on analysis of displacement measurement data of transversal joints of a dam and numerical analysis of a model dam considering transversal joints.

Keywords: vibration characteristics, earthquake, microtremor, natural frequency, concrete dam

1. INTRODUCTION

Including The 2011 Tohoku Earthquake, large earthquakes occurs frequently in Japan. After The 1995 Kobe Earthquake of January 17, 1995, the seismic performance of various civil engineering structures including dams have been actively evaluated. To evaluate the seismic performance of dams against large earthquakes, it is necessary to appropriately reproduce the actual seismic behavior of each dam, and therefore also necessary to appropriately select dynamic material properties of the dam body. The identification of values of various properties such as the elastic modulus of the dam body to reflect in the analysis model is often conducted using seismic records actually observed at the dam.

However, these vibration characteristics are probably affected by fluctuations of reservoir water level and the temperature.

The vibration characteristics, that reflect the structural stiffness of a dam, may also provide an effective barometer to monitor the structural soundness of the dam body. The effects of reservoir water level and temperature should be taken adequately into consideration to detect the sign of deterioration due to aging.

Therefore, the effect of reservoir water level and temperature on the vibration characteristics of a dam body such as natural frequency was investigated by analyzing seismic motion records and microtremor measurement results at a concrete gravity dam, where many earthquakes had been observed.

2. OUTLINE OF ANALYSIS

Seismic motion records and microtremor measurement results obtained at a concrete gravity multipurpose dam with height of 65m completed in 1998 were analyzed. At this dam, which is located in the Tohoku Region of Japan, The 2011 Tohoku Earthquake and other many earthquakes including aftershocks of the earthquake were observed. Table 1 shows the specification of the dam.

Table 1. Specification of the Dam

Height	65	m
Crest Length	174	m
Catchment Area	226.4	km^2
Total Storage Capacity	42,800,000	m^3
Effective Storage Capacity	36,000,000	m^3

2.1 Seismic motion records

Seismometers were installed at the crest (inside gate room) and bottom (foundation inspection gallery) of the highest monolith (BL.6) as shown in Fig.1. Sampling frequency is 100Hz. 113 seismic motion records in total including The 2011 Tohoku Earthquake were analyzed.

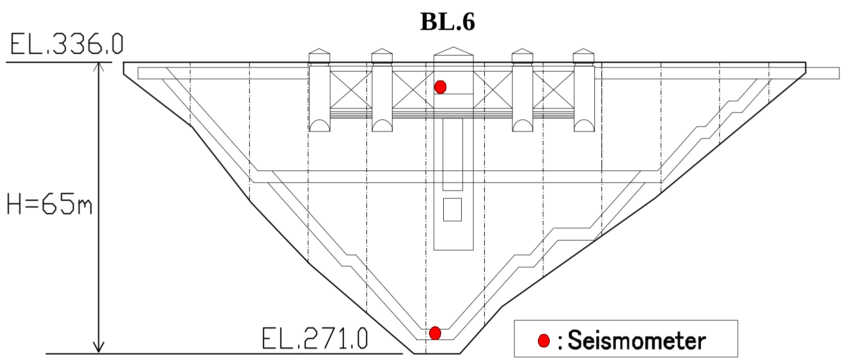


Figure 1. Location of seismometers

2.2 Microtremor measurement records

Microtremors of the dam were measured four times as shown in Table 2. The measurement locations were near above-mentioned seismometers, at the crest (inside gate room) and bottom (foundation inspection gallery) of the highest monolith. The sampling frequency was 250Hz.

Table 2. Dates and conditions of microtremor measurement

	Date	Reservoir water level (EL.m)	Temperature* (°C)
1st	2013/3/12	325.60	3.50
2nd	2013/6/20	317.79	21.60
3rd	2013/8/22	318.04	25.90
4th	2013/10/17	316.94	12.1

*At nearest Meteorological Agency observation station

2.3 Vibration characteristics analysis method

The analysis of vibration characteristics was conducted in the following steps: [1] collecting vibration data, [2] calculating the Fourier amplitude spectra, [3] calculating the frequency response function (FRF), and [4] estimating the natural frequency.
FRF between the dam crest and the foundation was calculated as the ratio of the Fourier Spectra obtained from the acceleration time history at the dam crest and dam foundation by using Eq.(1).

$$Z(\omega) = \frac{\int_{-\infty}^{\infty} f(t) e^{-i\omega t} dt}{\int_{-\infty}^{\infty} g(t) e^{-i\omega t} dt} \qquad (1)$$

Where, $Z(\omega)$: FRF, ω: frequency, $f(t)$: acceleration time history at the dam crest, $g(t)$: acceleration time history at the dam foundation
The natural frequencies of the dam body were estimated based on the lowest frequency at which the dam shows the resonant behavior of the FRFs.

3. ANALYSIS RESULTS

3.1 Relationship of reservoir water level and temperature with natural frequency

It has already been pointed out that the natural frequency of the dam body of a concrete gravity dam changes under the effects of the reservoir water level and temperature because the higher the reservoir water level, the greater the added mass effects, and the temperature can change the state of transversal joints as the volume of the concrete changes (Kondo. et.al, 2013). To confirm this, the relationship between first-order (lowest) natural frequency estimated at the dam and reservoir water level were analyzed as shown in Fig.2. It reveals that as the reservoir water level rises, the natural frequency tends to decrease, although even at almost identical reservoir water levels, near reservoir water level EL. 326m and EL. 318m, scattering of about 1.0Hz are seen, and near reservoir water level of EL. 320m, scattering of about 1.5Hz are seen. In addition, no clear difference was revealed between the first-order natural frequencies estimated based on seismic motion records and based on the microtremor measurement records.

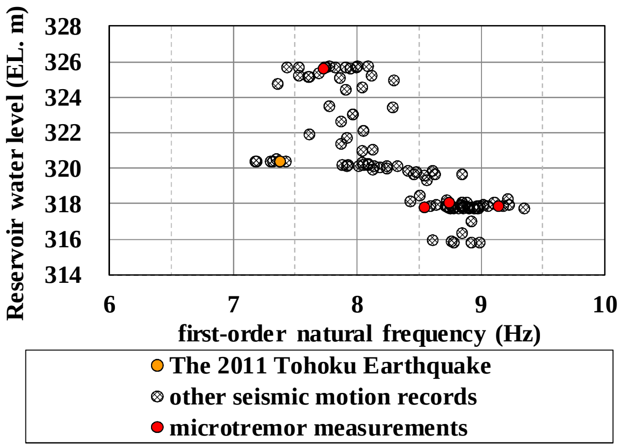


Figure 2. Relationship of reservoir water level and first-order natural frequency

Fig.3 shows the relationship of first-order natural frequency and the daily average temperature at the nearest Meteorological Agency observation station. It reveals that as the temperature declines, first-order natural frequency tends to decrease although both the seismic motion records and the microtremor measurement records are scattered overall. Here too, no clear difference was revealed between first-order natural frequencies estimated based on seismic motion records and based on the microtremor measurement records.

As shown above, a certain level of correlation of reservoir water level and air temperature with first-order natural frequency can be seen at the dam which was analyzed.

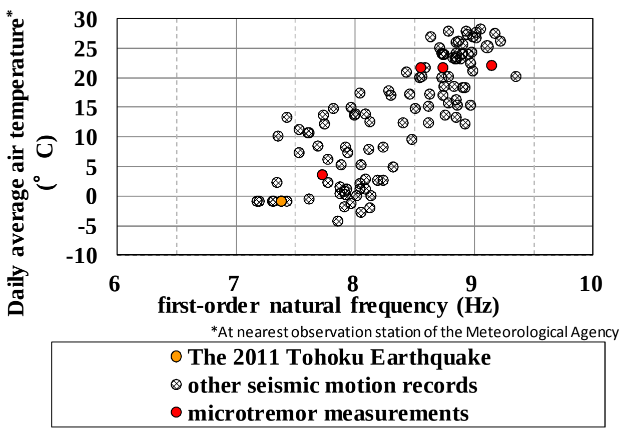


Figure 3. Relationship of the temperature and first-order natural frequency

3.2 Separation of the effects of reservoir water level fluctuation and temperature change

As stated above concerning the relationship of the reservoir water level and temperature with the natural frequency, as the temperature declines, the natural frequency tends to decrease. However, in the summer, when the temperature at the dam is high, at the same time there is a period when the reservoir water level is lowered to prepare for flood control, and these combine to have effects in a direction which increases the natural frequency. Inversely, in the winter when the temperature is low, the reservoir water level is high, and its effect decreases the natural frequency. Therefore, a study was conducted to separate the effects of each of these factors on change of the natural frequency.

First, eigenvalue analyses (natural vibration analyses) using the 2D-FEM model considering of the reservoir water were conducted to estimate the effects of water level on the natural frequency. The highest monolith (BL6) has spillway, but analysis model ignored it as shown in Fig.4. With seismic motion records obtained at the time of measurement in the summer (August 12, 2012), when it is assumed that the temperature was high and transversal joints were adequately closed, the elastic modulus of an analysis model that reproduces first-order natural frequency (8.64Hz) was identified. As a result of a trial calculation, the elastic modulus of the dam concrete was estimated to be 54,000N/mm^2. This value might be higher than the elastic modulus of usual dam concrete. However, when considering the effects of constraint by adjoining monoliths, which cannot be represented by two-dimensional definition analysis, the result can be recognized to be not necessarily contradictory.

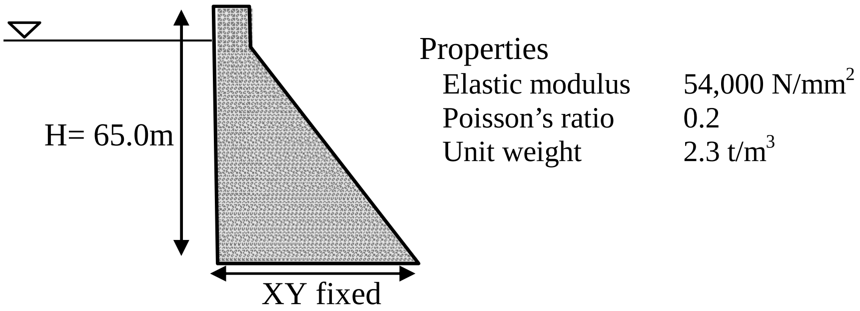


Figure 4. Eigen Value analysis model (2D)

Fig.5 shows the relation between reservoir water levels and the first-order natural frequency of the dam obtained from measurement and calculation (eigenvalue analysis). According to results of the analysis, from the water level rate of 0% to 50%, the frequencies are almost equal. But, from the ratio of 50%, as the water level becomes larger, the frequency rapidly becomes smaller. The diminution range in the value of natural frequency is about 1.5Hz. The range of fluctuation of the natural frequency obtained by actual measurements (about 2.0Hz) is larger than the range of fluctuation according to the analysis (1.5Hz). This suggests the existence of some other factor effecting the natural frequency of the dam.

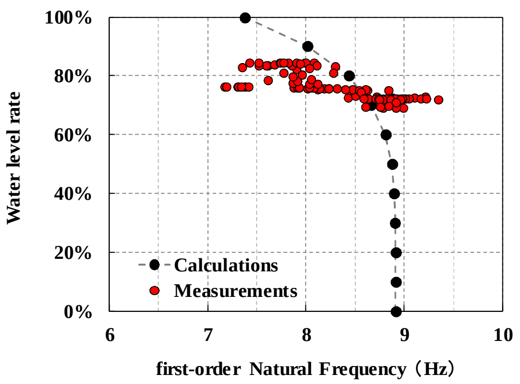


Figure 5. Comparison of Calculated and Measured natural frequency

Fig.6 shows the time series fluctuation of the measured value of first-order natural frequency. In the figure, "○" (without considering reservoir water level fluctuation) show the first-order natural frequency estimated by seismic motion records and microtremor measurement records , "×" (considering reservoir water level fluctuation) show the first-order natural frequency ignoring the effect of the reservoir water level fluctuation according to the eigenvalue analysis results (Fig. 5). It hypothesizes change of the natural frequency as a sine curve based on the temperature change curve, and also shows the approximate curves obtained by the least square method. This reveals that the change of the natural frequency considering reservoir water level fluctuation also correlates closely with change of the temperature. It also reveals a phase difference of about 1 month between temperature change and change of first-order natural frequency.

In addition, the maximum fluctuation range of 8m of the reservoir water level at the dam (reservoir water level rate: 85%—73%) corresponds to the range of fluctuation of 0.35Hz of the natural frequency according to the eigenvalue analysis results (Fig. 5). The range of fluctuation of the natural frequency caused by change of temperature corresponds to about 1.16Hz according to the amplitude of the approximate curve that considered reservoir water level. This means the temperature has a greater effect on the natural frequency than the reservoir water level at this dam.

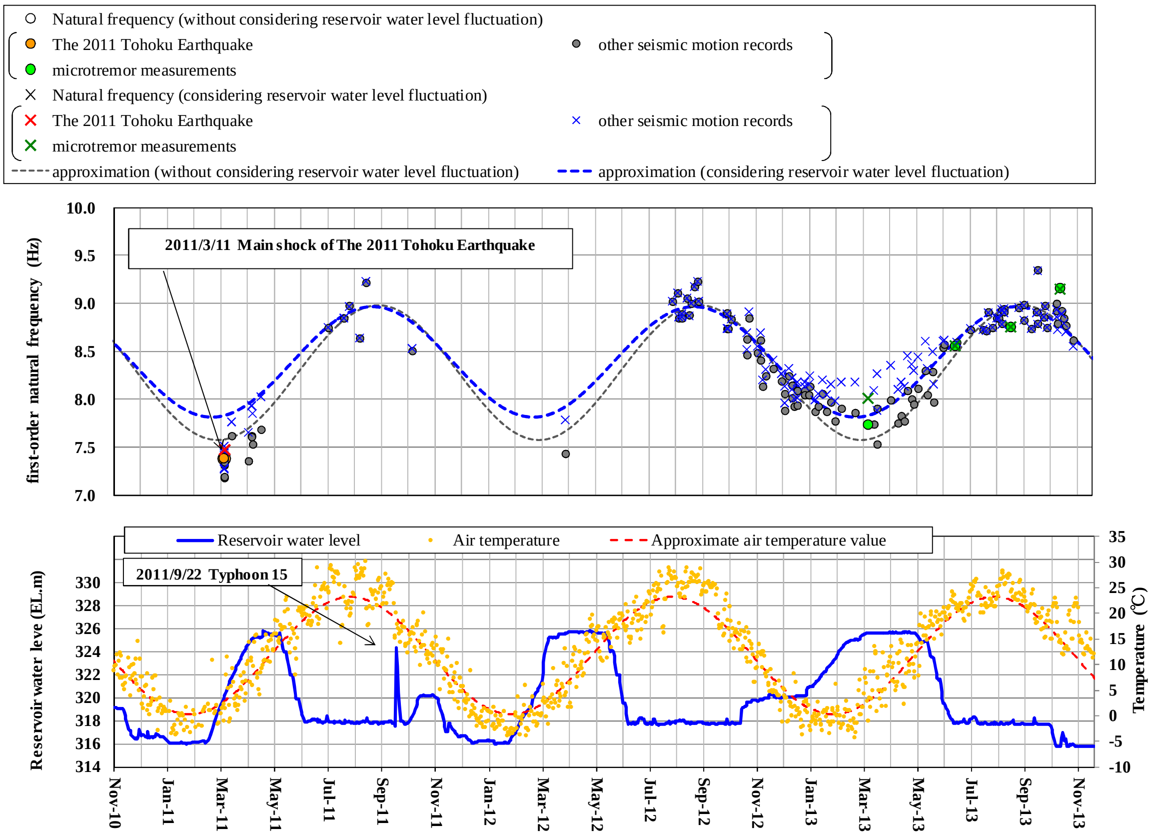


Figure 6. Seasonal Change of first-order natural frequency

4. CAUSES OF VIBRATION CHARACTERISTICS CHANGE DUE TO TEMPERATURE FLUCTATION

The analysis of the seismic motion records and the measurements of microtremors have shown that the temperature clearly effects the natural frequency of the dam body. In order to clarify the cause of this phenomenon, the relationship between the temperature of dam concrete and displacement of transversal joints was investigated. In addition, three-dimensional FEM analysis considering the transversal joints was performed to study the effect of change of constraint conditions of transversal joints on the natural frequency of the dam body.

4.1 Analysis of measured behavior

At the dam, transversal joint displacement gauges with thermometer functions are installed at joints between monoliths in the inspection gallery. Near the highest monoliths, they are installed in the middle level inspection gallery, and at the monoliths near the left and right banks, they are installed in the upper inspection gallery. Displacement data measured by the transversals joint displacement gauge 5JD6, which is installed in the middle level inspection gallery and 9JD10, which is the one located in the upper inspection gallery as shown in Fig.7 to the analysis.

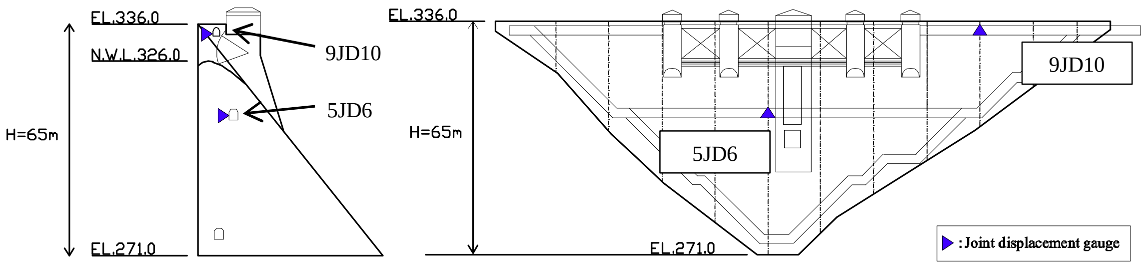


Figure 7. Locations of the selected joint displacement gauges

Fig.8 shows the time histories of joint displacement, outside air temperature and dam body temperature. Fig.9 is a figure which shows the relationship between the dam body temperature and joint displacement at the locations of the joint displacement gauges. At the location of 9JD10 joint displacement gauge installed at the upper inspection gallery relatively close to the dam body surface, temperature of the dam concrete fluctuates in almost the same phase as the outside air temperature, and the joint displacement tends to open at the time the dam body temperature is low. At 5JD6 displacement gauge installed near the center of the dam body on the other hand, the temperature and displacement both fluctuate cyclically, but the dam body temperature is about 3 months behind the outside air temperature fluctuation, and the fluctuation range of inside temperature of about 5°C is narrower than the range of fluctuation of the outside air temperature, which is about 30°C. The joint displacement is also far smaller than that at the upper inspection gallery, and is almost constant. Even a correlation chart of the temperature and joint displacement at the location of the joint gauge shown in Fig.9 indicates high correlation with 9JD10 joint displacement gauge in the upper inspection gallery. And at 5JD6 installed in the middle level inspection gallery, the correlation of the temperature and joint displacement at the installation locations is not high. Near the dam body surface, the opening and closing of transversal joints is closely linked to the outside air temperature, and there is a strong possibility that the effect of seasonal fluctuation of the natural frequency is governed by the opening/closing of transversal joints that are near the dam body surface.

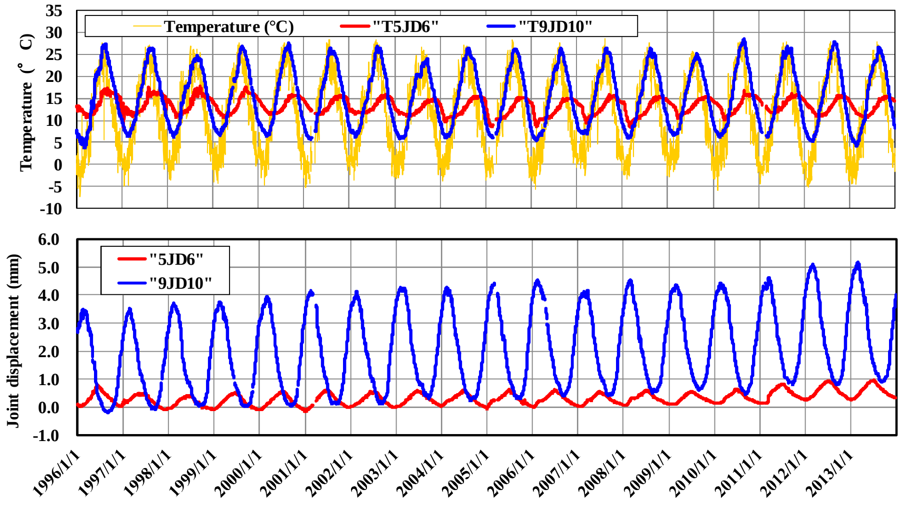


Figure 8. Time History of Transversal Joint Displacement

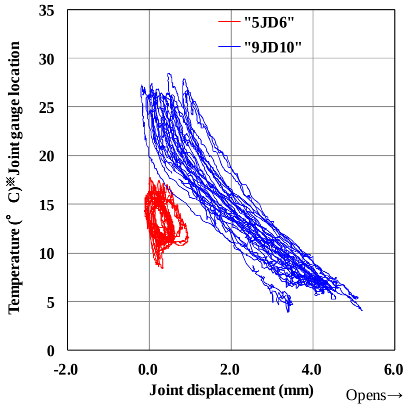


Figure 9. Temperature of dam concrete and Transversal Joint Opening/Closing

4.2 Numerical analysis

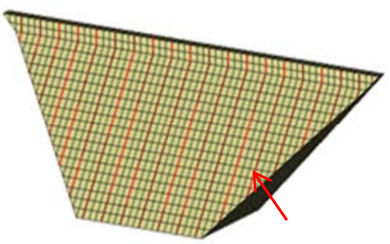
Three-dimensional dynamic analysis considering transversal joints in the model dam (dam height 100m, reservoir water level at 90% of dam height) was conducted to clarify the effects of the state of transversal joints on the natural frequency.

Analysis conditions were set for three cases: Model 1 hypothesizing a high temperature state with the dam body concrete expanded so the transversal joints are tightly closed and transversal joints are not modeled in the FE model, Model 2 and Model 3 hypothesizing low temperature and considering the opening of transversal joints. Transversal joints are considered by using joint elements. The stiffness of the joint elements are considered to be equal that of the concrete in Model 2. In Model 3, the stiffness of the joint elements are considered for the perpendicular direction of the joint surface, but not considered in the shear direction (sliding in the upstream-downstream direction was considered).

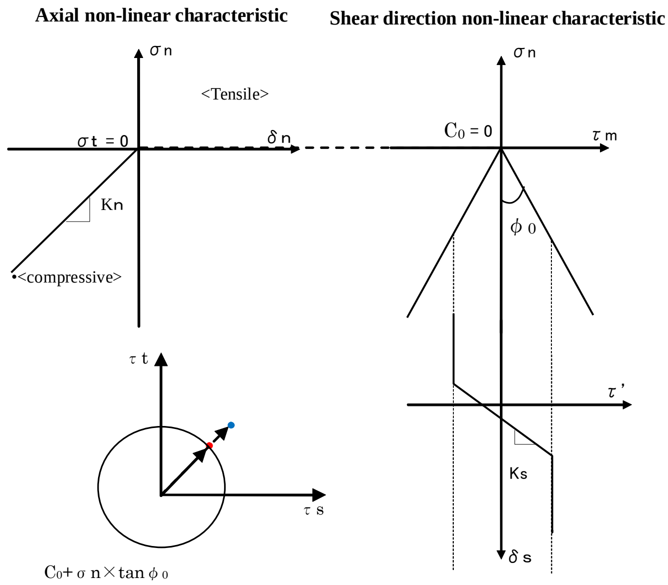
The analysis model and the values of material properties are shown in Table 3 and Fig.10 respectively. The input seismic motion records were set for two cases—an inland earthquake and a subduction-zone earthquake—and for 3 direction shaking (2 horizontal directions and 1 vertical direction).

Table 3. Input Material Properties

		Item	Value
Dam body	Model 1, 2, 3	Elastic modulus	29,000 N/mm^2
		Poisson's ratio	0.2
		Unit weight	2.3 t/m^3
		Damping constant	10 %
Foundation		Elastic modulus	40,000 N/mm^2
		Poisson's ratio	0.3
		Unit weight	2,300
		Damping constant	5 %
Transversal joint (Non-linear joint)	Model2	Tensile strength	0 N/mm^2
		Stiffness perpendicular to surface	29,000 N/mm^2
		Shear stiffness	12,000 N/mm^2
		Pure shear strength	0 N/mm^2
		Internal friction angle	45°
	Model3	Tensile strength	0 N/mm^2
		Stiffness perpendicular to surface	29,000 N/mm^2
		Shear stiffness	0 N/mm^2
		Pure shear strength	0 N/mm^2
		Internal friction angle	0°



Analysis Model (Dam Body)



Non-linear joint element (Model 2)

Figure 10 3D Analysis Model

Fig. 11 shows the frequency response functions between the crest and foundation of the highest monolith as obtained from analysis. It shows that the effect of the input earthquake motion on the frequency response function is small, and for all input earthquake motions, considering the transversal joints reduces the natural frequency of the dam body, and if sliding of the joint is allowed, the natural frequency is further decreased. For these reasons, it is considered highly possible that the opening of the transversal joints due to decline of the concrete temperature, following decline of air temperature lowers the natural frequency of the dam body.

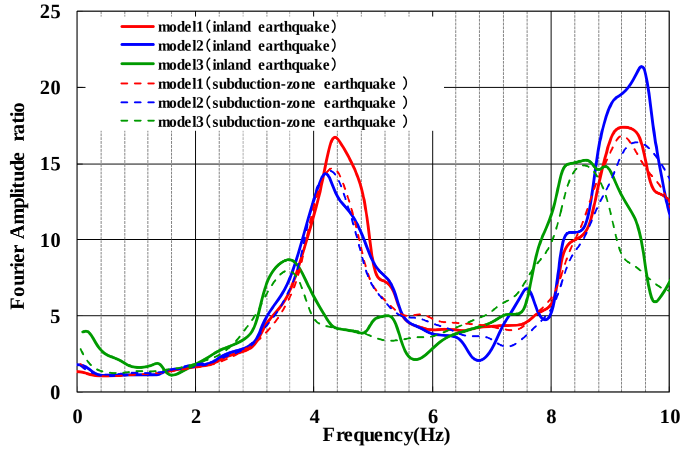


Figure 11. Differences in Frequency response functions (With/without of Transversal Joints)

5. CONCLUSIONS

Seismic motion records and microtremor measurement records obtained at concrete gravity dam were analyzed. From the results of the analysis, the following knowledge was obtained.

1) According to the analysis of natural frequency, the vibration characteristics of the dam are affected both by reservoir water level fluctuation and temperature change.

2) According to the analysis of transversal joint displacement and temperature inside the dam body, as well as the three-dimensional FEM analysis considering transversal joints, the factor causing the natural frequency to fall as the temperature declines is highly likely to be the fall of stiffness caused by opening of the transversal joints due to contraction (shrinkage) of dam concrete.

To establish a method of accurately separating the effect of various factors on the vibration characteristics of a dam, performing similar studies of other dams shown in this paper, would help accurately identify properties of the dam body for seismic performance evaluation, and to evaluate structural soundness of aging dam in the future.

REFERENCES

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