Dynamic Characteristics of Dams Evaluated Using Earthquake Monitoring Data for Safety Assessment

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ABSTRACT:
Earthquake monitoring is normally conducted in high dams in Japan. The acceleration monitored is less utilized and is only accumulated to confirm the maximum values for further inspection. Detailed analysis of dam behaviour during an earthquake helps to identify the mechanical properties of the dam which could reflect its current soundness. This paper focuses on the effective utilization of earthquake monitoring data for the safety management of dams. Data on concrete gravity dams, arch dams and rockfill dams are examined so as to elaborate the management criteria in terms of the response characteristics and the predominant frequency. Such dynamic characteristics of concrete dams are formulated with influential factors, which are finally identified as the dam height, dam-reservoir interaction and mechanical properties of the transverse joints. In addition, the applicability of microtremor measurement is verified for another method of identifying the predominant frequency of dams through the in-situ measurement of an arch dam. It is concluded that the dynamic characteristics of the dam examined can be utilized as management indices to reveal an abnormal situation or degradation of the dam by detecting their deviations.

Keywords: Earthquake monitoring, Dynamic characteristic, Predominant frequency, Formulation, Management index

1. OUTLINE

Earthquake monitoring is conducted for the safety assessment of dams as well as monitoring of displacement, leakage etc. Seismometers are usually arranged to monitor the acceleration behaviour of dams due to earthquake impacts at the lowest gallery or the foundation and at the crest of each type of dam. Depending on the degree of earthquake response acceleration of the dam, a detailed inspection of the dam is occasionally necessary after an earthquake. Because of the difficulty in treating the earthquake monitoring data at the administration office of the dam, the maximum value of the acceleration response is only identified when the acceleration is not beyond the criteria for inspection. Many earthquake monitoring data on dams are accumulated and left for further analysis.

The earthquake behaviour of a dam is a structural response to a fluctuating load which depends on the mechanical properties of the dam and involves the interaction of the dam-foundation-reservoir system. Analysis of dam behaviour during an earthquake helps to identify the current mechanical properties of the dam and to understand the structural characteristics of the dam-foundation-reservoir system. Such results contribute to enhancing the numerical analysis method for dams during large earthquakes.

This paper focuses on the effective utilization of earthquake monitoring data for the safety management of dams. The acceleration response of dams owned by J-Power are analysed in order to prepare management criteria for the management personnel at the dam administration office. The dynamic characteristics of acceleration and the predominant frequency of dams are studied using the acceleration data during earthquakes. In addition, the factor of the predominant frequency of the arch dam is examined.

2. DAMS FOR EARTHQUAKE MONITORING

The basic characteristics and the locations of the dam studies in this paper are shown in Fig. 1 and Table 1. The acceleration behaviour of dams during earthquakes has been monitored at the lowest location and the crest at the highest section of the dam using seismometers. The downstream rock foundation instead of the lowest location of the dam is sometimes selected as the monitoring location.

Table 1. Earthquake monitoring in dams of J-Power

Dams	(1)	(2)	(3)	(4)
Nukabira	PG	76	1956	1987
Tagokura	PG	145	1959	1994
Sakuma	PG	155.5	1956	1981
Kazaya	PG	101	1960	2007
Ikehara	VA	111	1964	1987
Sakamoto	VA	103	1962	2007
Kuttari	ER	27.5	1987	1994
Ouchi	ER	102	1989	1985
Tadami	ER	30	1990	1990
Kassa	ER	90	1978	1977
Misakubo	ER	111	1969	1969
Kuzuryu	ER	128	1968	1968
Miboro	ER	131	1961	1969
Yanase	ER	115	1965	1965

(1) Type of dams, PG : Concrete gravity, VA : Concrete arch, ER: Rockfill (2) Dam height (m) (3) Year of Completion (4) Earthquake monitoring has been done since the year.

Figure 1. Large dams in J-Power

3. DYNAMIC CHARACTERISTICS OF DAMS

3.1. Response ratio

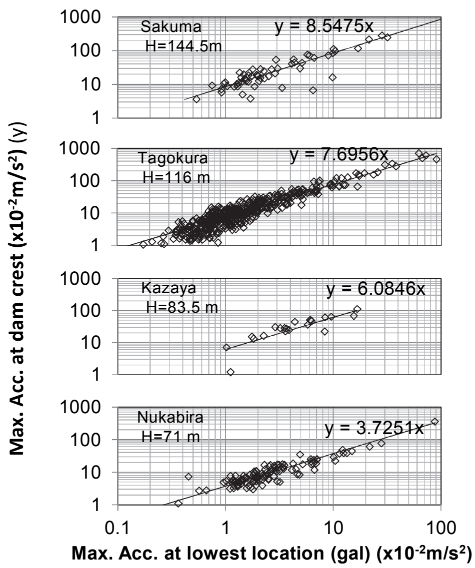
The acceleration behaviour of dams is frequently significant in the direction perpendicular to the dam axis of concrete gravity dams and rockfill dams and in the normal direction of the dam axis of arch dams due to the characteristics of these three-dimensional configurations. The acceleration data monitored in these significant directions are examined below. The response ratio is defined here as the ratio of the maximum accelerations at the crest and the lowest location of the dam. Both maximum values are not monitored rigorously at the same instant but are monitored almost simultaneously. It is considered that the maximum acceleration at the dam crest is excited by the maximum acceleration at the lowest location of the dam.

The acceleration response characteristics of the dams shown in Table 1 are illustrated in Fig. 2. The acceleration response characteristics of the lowest location and the crest of each dam show linear relations which are equivalent to the constant response ratios in the monitored range of acceleration. When a non-linear relation of these acceleration response or significantly different behaviour from a certain moment is found after an earthquake, damage to the dam or the dam foundation may be suspected due to the earthquake. However no facts described above are found in Fig. 2. It is suggested that non-linear characteristics of rockfill material cause the decline in the response ratio in the higher-acceleration range of as rockfill dam. The slight tendency of such phenomenon is found in Ouchi Dam shown in Fig. 2 (c).

The response ratios of the dams are summarized in terms of the height of the monitored locations in Fig. 3. Stronger dependency of the response ratio on the height of the monitored locations is found in concrete dams both of the gravity and the arch type, but not in rockfill dams. To further investigate this tendency, Eq. 1, by which the monitored acceleration at the crest is converted to acceleration of a dam of 100 m high, is introduced, assuming that the acceleration behaviour of the concrete dams is proportional to the dam height. The converted acceleration response is referred to as equivalent response acceleration in this paper.

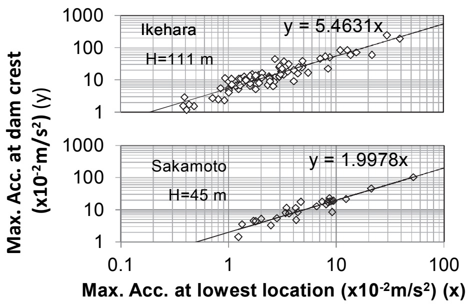
$$A_{Ni} = \alpha \cdot A_i \cdot 100/H' \qquad (1)$$

Where, A_{Ni} : Equivalent acceleration response corresponding to the height difference of 100 m, A_i: Monitored acceleration response, H': height difference, α: Constant

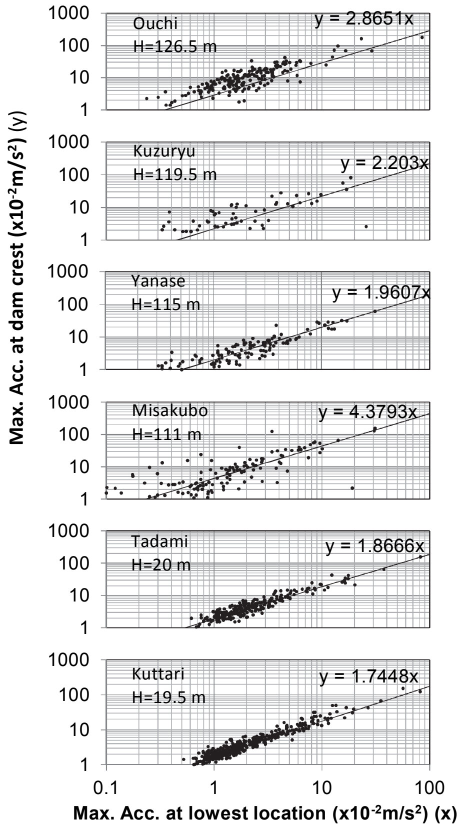


(a) Concrete gravity dams

Figure 2. Response ratio of dams



(b) Concrete arch dams



(c) Rockfill dams

Figure 2. Response ratio of dams

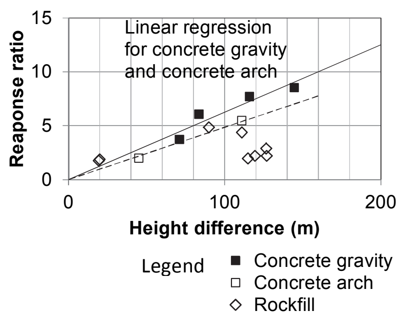


Figure 3. Summary of response ratio of dams

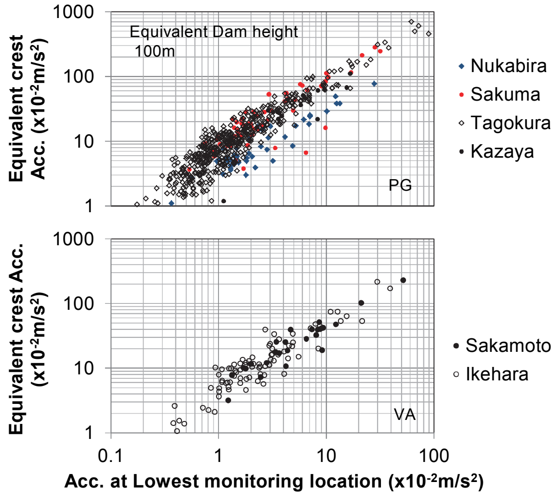


Figure 4. Equivalent response ratio of concrete dams

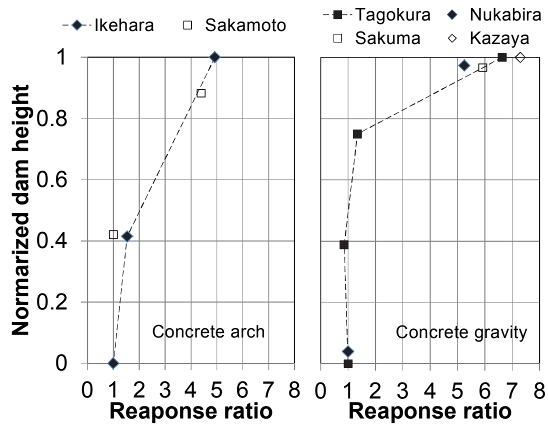


Figure 5. Response distribution of concrete dams

By applying Eq. 1 to the monitored acceleration response of the dam crest, the equivalent acceleration responses are plotted in terms of the dam types in Fig. 4. The converted data are closely plotted and show a closer tendency in the higher-acceleration range. This means that the acceleration response of the concrete dams significantly depends on the height of the dam or the monitoring location.

The distribution of the equivalent acceleration responses of concrete dams are examined as shown in Fig. 5. Both gravity dams and arch dams show specific distributions. These are roughly characterized by a sharp increase in the vicinity of the dam crest for a gravity dam and the a gradual increase along the dam height for an arch dam. The sectional shape is a major reason for the resulting specific response characteristics of each dam type, which are linear reduction of the sectional area of a gravity dam and the roughly constant section of an arch dam.

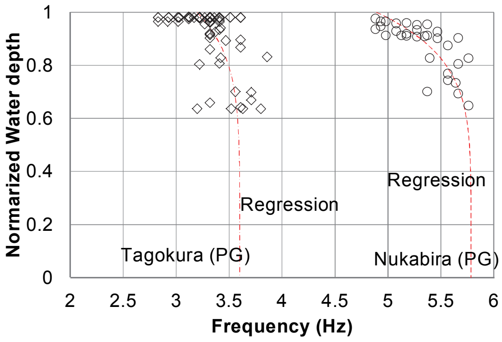
3.2. Predominant frequency

The predominant frequency of dams can be identified using several methods, which are broadly categorized into monitoring data analysis and numerical analysis. The transfer function which is estimated by the Fourier spectrum ratio at a certain two locations, is frequently utilized for monitoring data analysis. A numerical analysis method such as eigen frequency analysis and dynamic response analysis, requires an adequate calculation model involving the material properties of the dam at a certain moment, interactive behaviour due to the dam foundation and the reservoir, boundary conditions, etc. The material properties of the concrete dam inherently vary in respect to the concrete age, which corresponds to the moment of analysis. The methods of interaction between the dam and the reservoir affect the results of the analysis. However these conditions for numerical analysis are difficult to select, thus incurring difficulties in identifying the predominant frequency of the dam by numerical analysis.

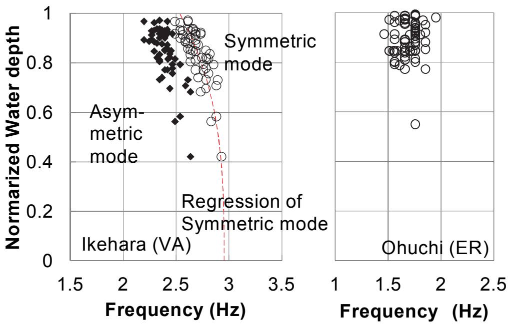
Earthquake monitoring data are analysed to identify the predominant frequency of each dam type using the transfer function between the crest and the lowest location of the dam. The result in respect to the normalised water depth is shown in Fig. 6 for each dam type. Regression curves, estimated using the method by Kondo (Kondo et al., 2015), are added to the concrete dam cases. The predominant frequency of concrete dams clearly depends on the water depth and decrease according to the increase in water depth. It shows the mass effect of water fluctuating with the dam due to interaction of the dam and the reservoir during an earthquake. These predominant frequencies are scattered in a certain range at the same water depth. It shows something else in addition to the water interaction affecting the predominant frequency of the concrete dams. The rockfill dam shows a relatively constant tendency against the water depth, which means that the water interaction has less influence on the dam behaviour of a rockfill dam.
In the next section, the factors that affect the dynamic behaviour of an arch dam are examined in detail in terms of the characteristics of predominant frequency.

4. STUDY ON PREDOMINANT FREQUENCY OF A CONCRETE ARCH DAM

The predominant frequency of concrete dams is a fundamental parameter that reveals the dynamic properties of a dam at the time of monitoring. The diagnosis method for concrete dams has been studied by taking advantage of such characteristics of the predominant period (Sasaki et al., 2012). Factors affecting the dynamic characteristics of the dam can be selected from below:
(1) Elastic modulus of the dam concrete
(2) Mechanical characteristics of the transverse joints
(3) Reservoir water interaction
(4) Ambient temperature



(a) Concrete gravity (PG)



(b) Concrete arch (VA) and rockfill (ER)

Figure 6. Predominant frequency of dams estimated using earthquake monitoring data

The ambient temperature (item (4)) makes the volumetric change of the dam monolith, which induces alteration of the mechanical characteristics of the transverse joints (item (2)) by movement of the monoliths of the concrete gravity dam. Though the transverse joints of the arch dam are usually close due to the hydrostatic pressure on the upstream surface, the arch action of an arch dam may be affected by the condition of the transverse joints due to ambient temperature fluctuation. As cited above, the reservoir water interaction (item (3)) gives an additional load of hydrodynamic pressure on the dam and results in a shift in the predominant frequency due to the dam-reservoir interaction. It is well known that the physical properties of dam concrete continuously increase (item (1)) in terms of not only strength but also elastic modulus over a certain number of years due to hydration reaction. Imaoka et al.(2014) reported such results on the concrete of an arch dam by testing the cored concrete. The impacts of these factors can be observed as the shift in the predominant frequency of concrete dams.
To take the impacts due to items (2), (3) and (4) into account, Eq. 2 is introduced in this paper, referring to Kondo et al.(2015). The impact due to item (4) is examined hereinafter.

$$f_1(h,\theta) = c_0 + c_1(h/H)^{\beta} + \frac{c_2}{\sqrt{\theta^{*}-\theta}} + \mathrm{e} \qquad (2)$$

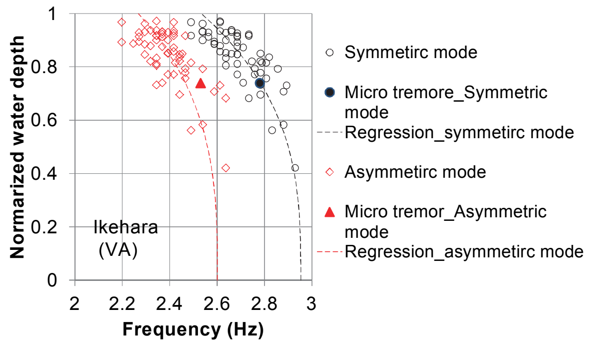
Where, $f_1(h,\theta)$: predominant frequency, h : water depth of the reservoir, H : full depth of the reservoir, β :

Parameter, θ : ambient temperature, θ^* : ambient temperature corresponding to zero opening of the transverse joint (40℃ is adopted.), c_0, c_1, c_2 : constant, e : residual

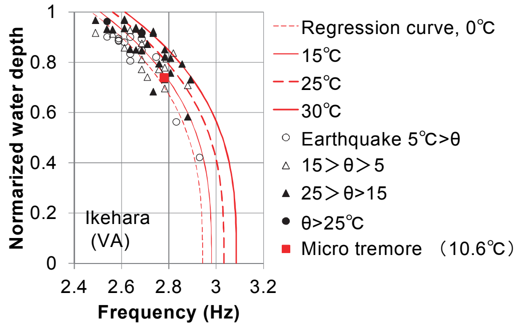
The examination of Eq. 2 is conducted by regression analysis based on the monitored predominant frequency of an arch dam, as shown in Fig. 6(b). As a result, parameter β is set as 3.0 and the average temperature over 30 days with a lag of 30 days is used for the ambient temperature. Multiple regression analysis for the predominant frequency of the arch dam provides a high regression coefficient of 0.81 and each constant of c_0, c_1 and c_2. The correlations between the monitored values and water depth or ambient temperature are shown in Fig. 7(a) and Fig. 7(b), respectively.

A parameter β of 6.0 was adopted for concrete gravity dams (Kondo et al., 2015). In this case, the influence of the parameter is limited to shallower-water-depth region. The regression curve with a smaller β which is applied to an arch dam, affect the shift in the predominant frequency to deeper-water region. These characteristics of the shift in the predominant frequency indicate good agreement with the vertical distribution of the response acceleration of the concrete dams as shown in Fig. 5. The concrete gravity dam shows significant response in a limited area of the crest vicinity, in which great impact is observed on the shift of predominant frequency. The arch dam shows a gradual increase in acceleration response from the middle to the crest. Its profile matches the profile of the shifted predominant frequencies of the arch dam. This phenomenon is interpreted to be caused by the difference of the degree of the dam-reservoir interaction between a concrete gravity dam and an arch dam.
The scatter appearance of the predominant frequency due to temperature fluctuation, shown in Fig. 7(b), indicates good quantitative correlation with the estimated frequency by Eq. 2. The influence of the temperature on predominant frequency is originally formulated for concrete gravity dams by Eq. 2, where the shear characteristic of transverse joints is incorporated in the manner of a simple mass-spring model instead of the opening of transverse joints due to temperature fluctuation. Because the transverse joints of the arch dam are subject to compression force due to hydrostatic pressure and the resulting arch action in the dam axis direction, little opening of the transverse joints is expected. However the alteration of the shear characteristic is certainly happened in the transverse joints of arch dams as well as concrete gravity dams due to temperature fluctuation. It is considered that the situation in Fig. 7(b) verifies indirectly the influence of temperature fluctuation on the shear characteristic of transverse joints.

As for another method to identify the predominant frequency of structures, microtremor measurement as well as the analytical method described in Section 3.2 is sometimes applied. Microtremor measurement requires simple devices, i.e., a servo-type velocity meter and data logger, which can be transported manually. The applicability of these methods is examined hereinafter. Dam-reservoir interaction is considered for eigen value analysis and dynamic time history analysis using added mass and FEM interaction analysis, respectively. The results of these methods are shown in Fig. 8.
A significantly great decline in predominant frequency in the higher-water-level region is found through analytical methods than through earthquake monitoring. This tendency is clearer in eigen frequency analysis. The deviation in estimated frequency of each analytical method is caused by the difference in hydrodynamic pressure distributions, even though dam-reservoir interaction is considered in both analytical methods. The excessive decline found through analytical methods in the high-water-level region should be addressed.



(a) Water depth



(b) Ambient temperature (for symmetric mode)

Figure 7. Dependence of predominant frequency of an arch dam

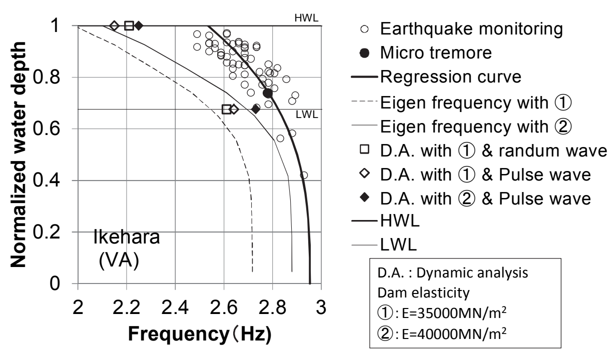


Figure 8. Comparison of estimation method of predominant period (Symmetric mode)

The analytical methods provide closer estimation to the monitored values in the case of an elastic modulus of 40000MN/mm^2. The current static modulus of an arch dam which more than five decades has passed is estimated to be 44000MN/mm^2 and 40000MN/mm^2 for a specimen extracted from the dam recently and a specimen molded at the construction site and cured in the laboratory, respectively. The analytical evaluation shall be equivalent to the monitored evaluations and the regression curve by Eq. 2 in the lower-water-depth region when the dynamic modulus is applied, considering the dynamic condition under earthquakes.

The temperature fluctuates in the range of 30 degrees centigrade at the arch dam site studied. The temperature fluctuation influence corresponds to a variation in the elastic modulus of approximately 5000MN/m^2 in terms of variation of the predominant period (refer to Fig. 7(b) and Fig. 8). The alteration of the shear characteristic of the transverse joints due to temperature fluctuation could be replaced by modification of elastic modulus of the dam. In other words, considerable dependence on ambient temperature is expected in the behavior of a dam during an earthquake at the time. This fact should be kept in mind regarding assessment of safety of dams against large earthquakes.

The frequency estimated by the data of microtremor measurement shows good agreement with the data of earthquake monitoring. Noise due to traffic, operation of a powerhouse situated near the dam, etc. could affect the measurements. However, little impact on the identification of the predominant frequency of the dam was found through the in-situ measurements. An example of the measurement conducted at Ikehara Dam is shown in Fig. 9. This feature enables easier continuous measurements, which can depict more clearly the influence of dam-reservoir interaction and temperature fluctuation on the frequency of arch dams.

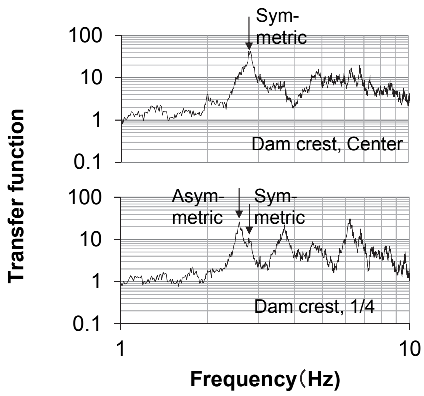


Figure 9. Example of micro tremor measurement at Ikehara dam

5. CONCLUSIONS

Earthquake monitoring data on dams are examined to evaluate the dynamic characteristics of the acceleration response and the predominant frequency for accessing the soundness and the current properties of dams. The conclusions are summarized below.

(1) The response acceleration at the dam crest during an earthquake has the characteristics of a linear relation and an independent response ratio to the bottom acceleration of the dam. Because of the dependence on the dam height of the response ratio of concrete dams, the acceleration response ratio is unified in terms of normalized dam height. Little tendency is found in the response ratios of rockfill dams, which each show a unique figure and a little non-linearity of acceleration response where the crest acceleration is greater.

(2) The vertical distribution of the response acceleration is figured identically in a concrete gravity dam and an arch dam using the equivalent response acceleration in respect to the dam height.

(3) The predominant frequency of concrete dams has a clear dependence on reservoir water depth and ambient temperature, while the predominant frequency of rockfill dams is almost constant without dependence on reservoir water depth and ambient temperature. The dependence on reservoir water depth and ambient temperature is caused by the dam-reservoir interaction during an earthquake and mechanical property alteration of transverse joints due to temperature fluctuation.

(4) Additionally considering the ageing of the elastic modulus of the dam concrete, the characteristic of the predominant frequency of arch dams is well formulated in terms of reservoir water depth and ambient temperature at the time. The applicability of microtremor measurement is verified for the method of identifying the predominant frequency of dams through in-situ measurement of an arch dam.

(5) The dynamic characteristics of dams examined in this paper can be utilized as management indices to reveal an abnormal situation or degradation of a dam by detecting their deviation. In this context, it is essential to accumulate data on all aspects relating to dam operation and its behavior and to periodically examine on these data.

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