Statistics in Dynamic Characteristics of Existing Dams Evaluated by Earthquake Monitoring Data

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Abstract

More than 4000 earthquake data have been accumulated in approximately 20 major dams of J-Power in past several decades. Based on these data, dynamic characteristics of dams are analyzed statistically aiming the safety assessment of these dams as well as the understanding of comprehensive dam behavior during earthquakes. Major parameters are estimated on response characteristics between the dam foundation and the dam crest. Comparing these parameters among each dam type, typical dynamic characteristics of dams are extracted. The predominant frequency/period of concrete dams possesses the high dependency on the water depth and the temperature acting on the dam. While it is widely recognized as the interaction between the dam and the reservoir water, it could attribute to the condition of the transverse joints altered by the temperature change. Little dependency on the reservoir water depth is found in ones for embankment dams. Earthquake responses in perpendicular to the dam axis are selectively predominant in concrete dams. In contrast to these, the three-dimensional dynamic behaviors are common in embankments dams. These characteristics are essential for the validation of dynamic analysis methods and the identification of current material properties of existing dams. It demonstrates the importance of the earthquake monitoring in dams.

Keywords: Statistics, Dynamic behavior, Earthquake, Dynamic characteristics, Frequency.

1. INTRODUCTION

Earthquake monitoring for dams is conducted for the safety assessment during and after earthquakes along with the monitoring of displacement, leakage etc. Seismometers are usually arranged to monitor the acceleration behavior of dams due to earthquake impacts at the lowest gallery or the foundation and at the crest, and additionally at the both abutments of each type of dams. Depending on the degree of earthquake response acceleration of the dam, a detailed inspection of the dam is occasionally necessary after the earthquake. Because of some difficulties in treating the earthquake monitoring data at the in-situ office of the dam immediately after the earthquake, the maximum values of the acceleration response of the dam are only identified when the accelerations are relatively small, not exceeding the criteria for inspection. It makes that many earthquake monitoring data on dams are accumulated and left for the further analysis.

The behavior of a dam to anoscillating load such as an earthquake is a structural response which depends on the current mechanical properties of the dam and involves the interaction of the dam-foundation-reservoir system. It might be assumed a vibrating experiment of the dam with afull-scale model. Therefore, the interpretation of adam behavior during an earthquake can provide valuable information on the structural characteristics of dams, such as current mechanical properties of the dam, interaction of the dam-foundation-reservoir system and so on. It is commonly implemented by the numerical reproduction analysis using finite element method (FEM).

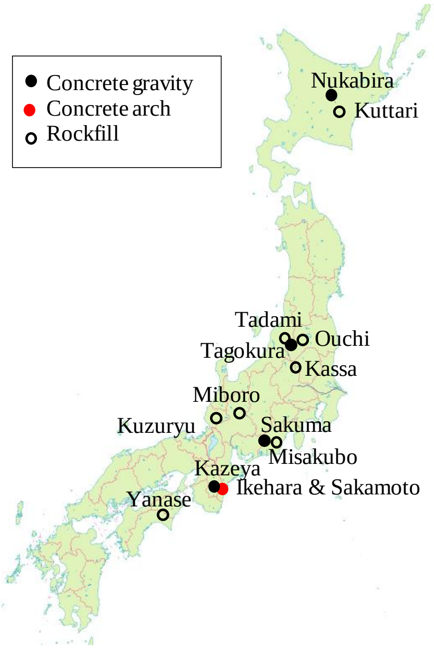
Approximately three thousand records of earthquakeresponse of 14 dams operated by J-Power (Electric Power Development Co., Ltd.) are accumulated so far. Almost of all are low responses below the acceleration of 0.1 m/sec^{2}and classified in ones to small earthquakes, while a few high acceleration responsesup to several m/sec^2 at the dam crest are monitored. The high responses are adequate as a reference behavior to the reproduction analysis of the dam behavior during earthquakes. The statistic characteristics of these data involving small responses of the dam are useful to understanding comprehensively dynamic characteristics of dams. In addition, these statistics areassumed to be a good index to the soundness of the dam during an earthquake for detecting the abnormality of the dam behavior. Authors studied, in this context, on the dynamic behaviors of specific dams [1], [2]. By adding the number of dams and dam types, the statistics on dynamic behavior of dams were studied using the earthquake monitoring data of dams [3], which are updated in this paper. Kondo et. al. [4] examined the characteristics of predominant frequency of concrete gravity dams using the earthquake monitoring data and introduced the physical assumption that the predominant frequency of concrete dams relates to the reservoir water depth, acting on the dam surface and the ambient temperature. According to this, the predominate frequency clearly correlates the reservoir water depth in concrete gravity dams. Authors confirmed similar behavior in arch dams as well as concrete gravity dams [2], [3]. The technical committee of Japan Commission on Large Dams compiled major earthquake monitoring data at dams in Japan. Using these data, dynamic behavior is studied for each type of dams [5].

This paper focuses the statisticson the dynamic characteristics of dam behavior independently. Both amplification characteristics and predominant frequencies are studied for concrete gravity dams, arch dams and embankment dams. The features of the dynamic behavior are clarified and discussed in terms of the dam type.The statistics are examined for the utilization of the safety management of dams. Finally, comments on earthquake monitoring of dams are prepared.

2. EARTHQUAKE MONITORING IN DAMS

The earthquake monitoring is conducted in almost all large dams operated by J-Power. Among these dams, 14 major dams are studied in this paper. These basic characteristics and the locations are summarized in Figure. 1. The acceleration behavior of dams during earthquakes has been monitored at several locations in the dam, indispensably at the lowest location or the dam foundation, the crest and additional both abutmentsusing seismometers. The downstream rock foundation instead of the lowest location of the dam is sometimes selected due to the malfunction of the devices embedded in the dam. Three directions of acceleration are independently monitored by servo acceleration meters normally in stream, dam axis and vertical directions.

The earthquake monitoring is implemented by the following manner. Once a certain acceleration beyond a specified value, normally 0.01 m/sec^{2}is detected at the lowest monitoring location, all devices simultaneously workwith the sample frequency of 100 Hz. The synchronized data at each location as well as the data of several 10 seconds prior to the occurrence are stored temporally in the digital memory in the seismometer. All monitored accelerations are transmitted through the independent lines or micro-waves to the data storage device located in the administration office near the dam promptly after the earthquake. The data are come on the display as waves with an alert for the examinationby the stuff of the dam management for the further action such as detailed inspection of dams. The example of the earthquake monitoring is shown in Figure 2 in Ikehara dam. Due to the complex behavior of the arch dam, the monitoring locations are additionally arranged in middle parts of the dam crest and the vertical dam section. The horizontal accelerations are monitored in perpendicular directions to the dam surface considering the configuration of the arch dam.



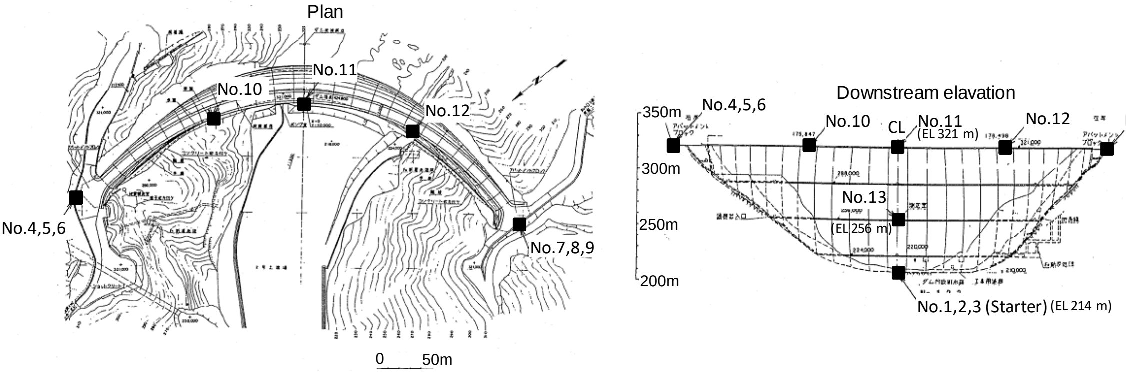
Dams	(1)	(2)	(3)	(4)
Nukabira	PG	76	1956	1987
Tagokura	PG	145	1959	1994
Sakuma	PG	155.5	1956	1981
Kazaya	PG	101	1960	2007
Ikehara	VA	111	1964	1987
Sakamoto	VA	103	1962	2007
Kuttari	ER	27.5	1987	1994
Ouchi	ER	102	1989	1985
Tadami	ER	30	1990	1990
Kassa	ER	90	1978	1977
Misakubo	ER	111	1969	1969
Kuzuryu	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. Earthquake monitoring in dams of J-Power

(a) Ikehara dam

(b) Seismometer (Servo acceleration meter)



(c) Arrangement of monitoring locations in Plan

(d) Arrangement of monitoring locations in Downstream elevation

Figure 2.Example of earthquake monitoring

3. STATISTICS OF EARTHQUAKE RESPONSE OF DAMS

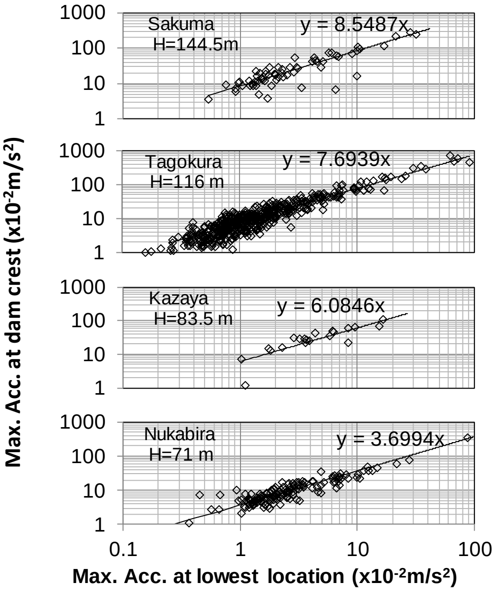
Response characteristics of dams to earthquakes are examined based on many earthquake monitoring data in various dams in terms of dam types and dam height. The amplification ratio and the frequency characteristics are examined based on the accelerations monitored at the dam foundation and the dam crest. The results are statistically shown in Figures 3 and 4 for the amplification and the predominant frequency of dams, respectively.

(a) AMPLIFICATION BEHAVIOR OF DAMS

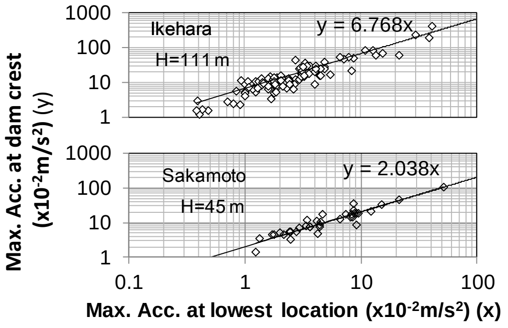
The amplification ratio of dams is estimated by the ratio of the peak accelerations monitored at the dam crest and at the lowest monitoring location, frequently the dam foundation (It is referred to as dam foundation). These shown in Figure 3are more stable in higher acceleration range and apparently prevail the linear relation between the dam crest and the dam foundation. Its tendency is clearer in concrete dams and lower height of embankment dams. Noise of the monitored acceleration may be influential in lower acceleration range less than 0.1 m/s^2.

These amplification behaviors are considered as the structural response as an integrated structure of a dam, its foundation and impounded water facing to the dam. In addition, the environment surrounding dams such as meteorological conditions, aging of dams and so on could be influential on these behaviors. In other words, the amplification behavior should involve all these factors. Therefore, the statistic amplification behavior must be the comprehensive index of the dam behavior to the earthquake to access the present soundness of the dam.

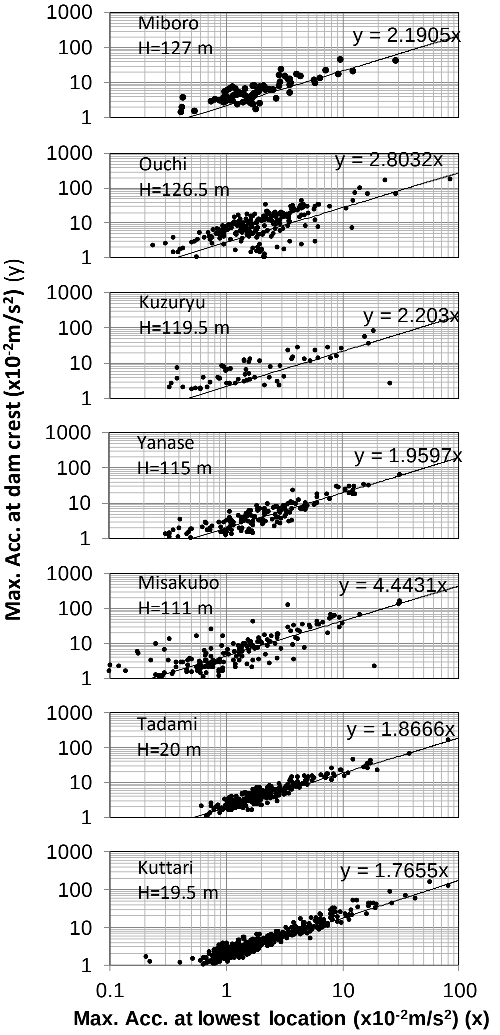
The ratios of the amplification are shown in Figure 3 as the linear regression formula. The ratios in concrete dams are proportional to the dam height as shown in Figure 3 (d), while less relation between the ratio and the dam height are found in embankment dams. It is considered that variety of embankment material isthe reason. In addition, non-linear properties of stiffness in high shear strain of embankment material is not detected clearly so far.



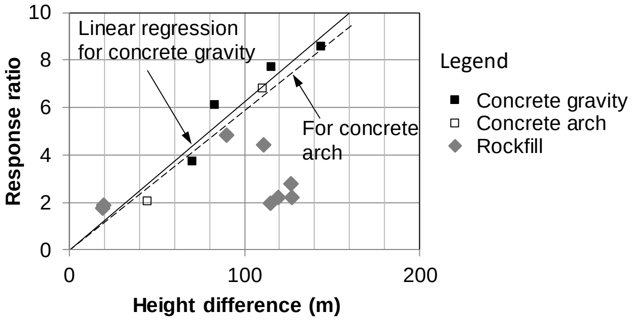
(a) Concrete gravity dams



(b) Arch dams



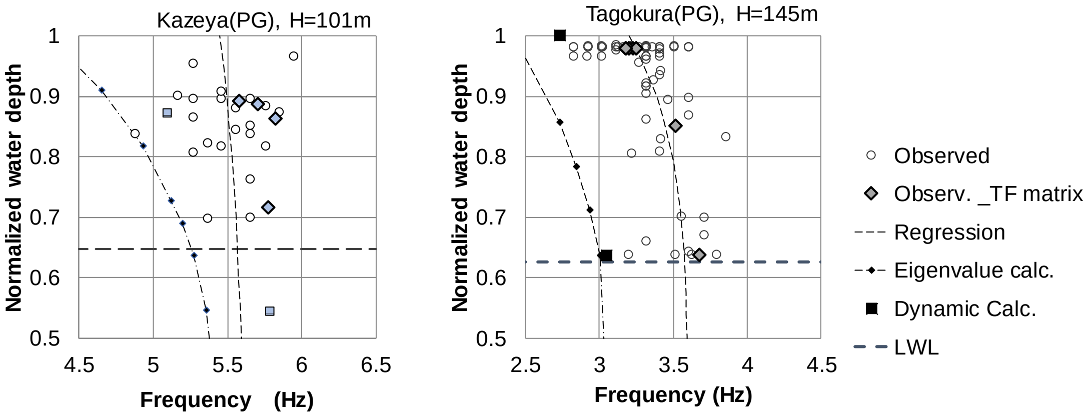
(c) Embankment dams



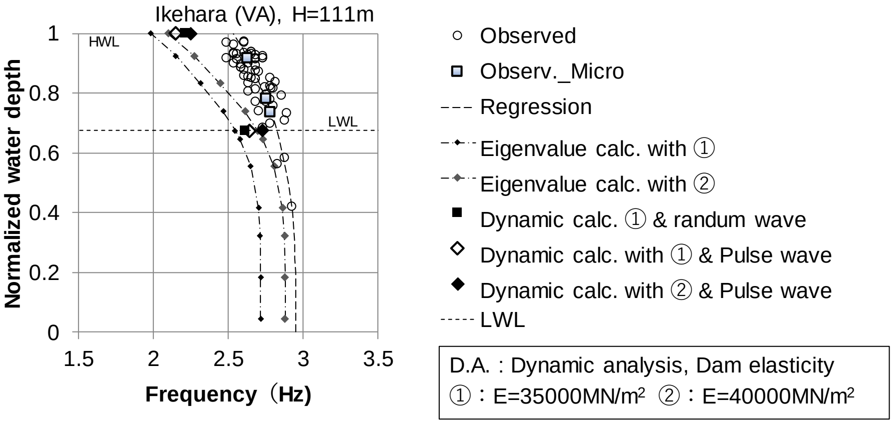
(d) Amplification ratio of dams

Note: H in each figure shows the height between the dam crest and the dam foundation or the lowest monitoring location. The formula shows the linear regression of data.

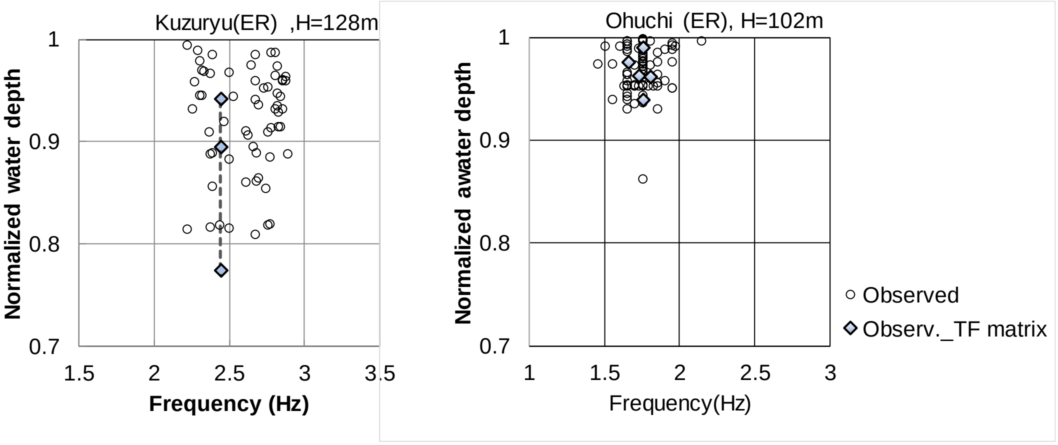
Figure 3. Amplification behavior of dams



(a) Concrete gravity dams



(b) Arch dam



(c) Embankment dams

Note: Observ._TF matrix: Estimated by method of transfer matric function based on observed data, Observ._Micro: Frequency based on micro tremor measurement, Regression: Refer to [3]

Figure 4. Predominant frequencies of dams

(b) PREDOMINANT FREQUENCY OF DAMS

Predominant frequency is examined for all dams listed in Figure 1 based on the transfer function between the dam crest and the lowest location of each earthquake monitoring data and in-situ data by micro tremor measurement. In addition, numerical simulations on the monitored behavior are conducted to consider the interaction among the dam, the foundation and the reservoir. These studies are summarized as predominant frequencies of dams higher than 100 m in Figure 4.

Ones of concrete gravity dams and arch dams are a contrast to ones for embankment dams in a dependency on the reservoir water depth. A certain dependency on the water depth is clearly found in predominant frequencies estimated by various methods in concrete dams. It is an evidence of the interaction between the dam and the water. Even though a little data in a lower water depth, it is hard to find similar dependency in embankment dams. It is understood that the upstream embankment absorbs the interaction with the water due to its high permeability. Predominant frequencies of dams scattered respect to the water depth in all types of dams. It suggests that there are other parameters on the dam behavior besides the water depth. Kondo et. al. [4] indicate the ambient temperature is influential parameter on the behaviors of concrete gravity dams. Kashiwayanagi et. al. [3] confirmed similarly its influence on the arch dam. However, no influential parameters have been considered for ones of embankment dams as long as the behavior of the embankment dam is linear to the earthquake intensity. These are left to the future study.

A reproduction analysis is commonly conducted to identify the material properties of a dam and its foundation for the safety assessment of dams during earthquakes. The frequency characteristics obtained by dynamic analysis and eigenvalue analysis as shown in Figure 4 can be adjusted to fit to ones based on the monitored data by the modification of the material properties used in the analyses. Therefore, the statistics of predominant frequencies as well as the amplification characteristics shown in Figures 3 and 4 are suitable references for the identification of the present material properties of existing dams. The frequencies of arch dams analyzed by the numerical simulation are decreased more rapidly than ones based on the monitored data as increasing the water depth. It is considered that the interaction with water is assumed to be excessively stronger in the shallow water depth region in the simulations. The simulated interaction with water is treated by FEM involving fluid elements for the water. Therefore, the simulation of the water interaction should be studied more to adjust the inconsistency in frequencies above-mentioned in the future.

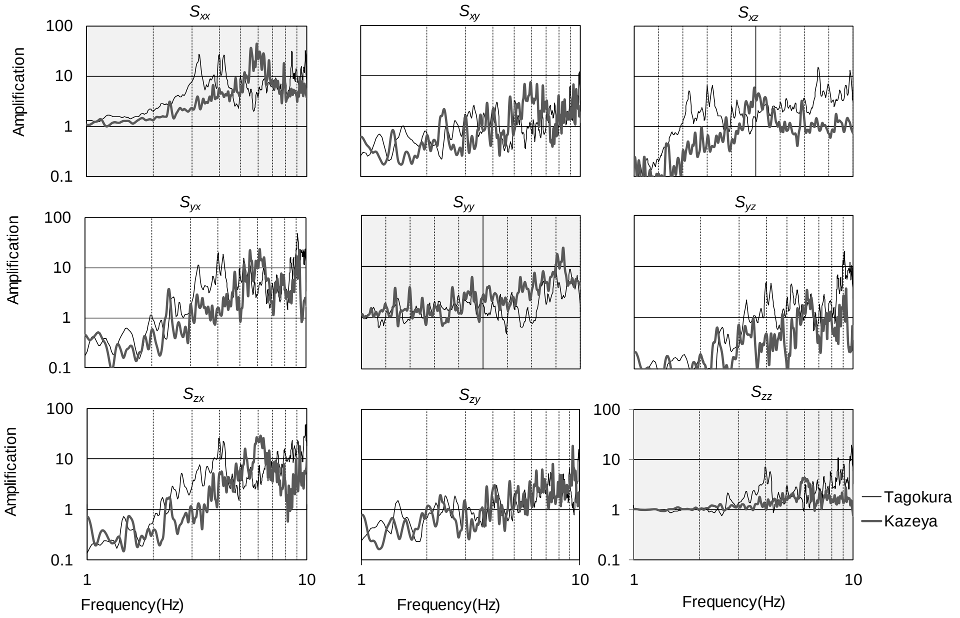
All methods for the identification of frequency characteristics applied here are almost equivalent as shown in Figure 4. Micro tremor measurement is preferable to easily acquire the present situation of dams due to its convenience which require portable measuring instruments and can be conducted manually anytime.

4. SPECIFIC AMPLIFICATION CHARACTERISTICS

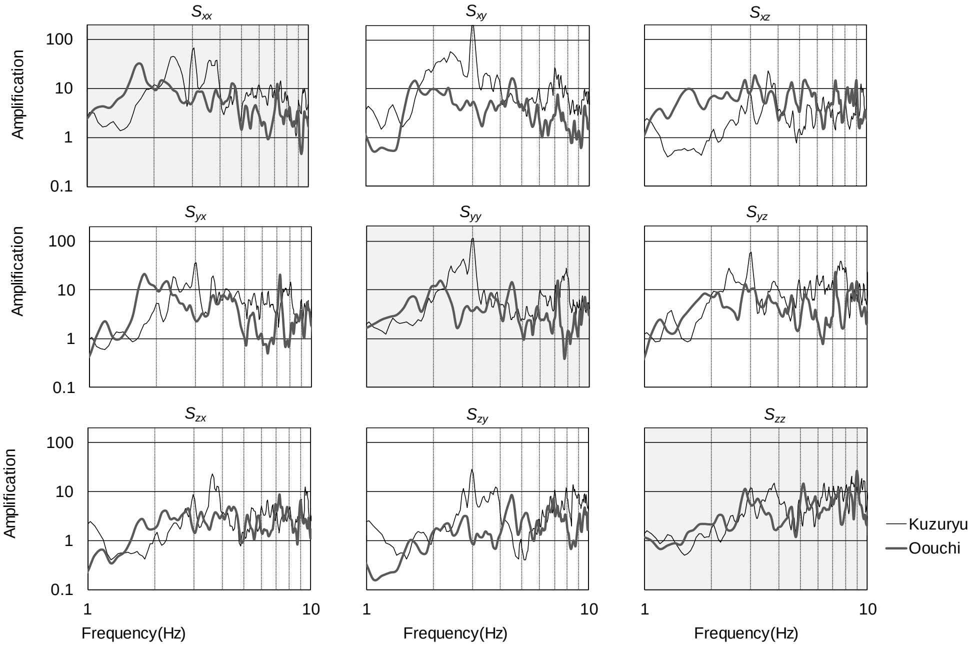
The amplification of dams is commonly characterized by the transfer function. Here, these are analyzed in detail using the transfer function matrix (TFM) [6], which consists of nine independent transfer functions (represented by S_{ij}, j is input direction, i is response direction) in 3D coordinates. While only one set of the waves of input and its response is necessary for the estimation of the conventional transfer function, an analysis of TFM requires three set of waves corresponding to the number of estimated components. Because various parameters are considerable on dam behavior during earthquakes, some effort is necessary in selecting three set of earthquake records which are monitored at similar conditions, for example reservoir water depth, ambient temperature, earthquake characteristics and so on. However, clear understanding on these parameters in dam behavior is put to be a future issue. Several sets of three earthquake data are selected for TFM calculation for concrete gravity dams and rockfill dams with a little effort on the conformity of these data. The results are illustrated in Figure 5.

Some outstanding peaks in the amplification are clearly observed in S_{xx} and S_{yy}. These correspond to the predominant component of the response behavior of dams to the earthquake vibration at the dam foundation. Comparing comprehensively figures of TFM between dam types in Figures 5 (a) and 5 (b), these show own characteristics. In concrete gravity dams, S_{xx} is eminently dominant, while other components show relatively low values in especially frequency range lower than the predominate frequency of S_{xx}. In embankment dams, both S_{xx} and S_{yy} possess unique outstanding peaks and other components show corresponding peaks to S_{xx} and $S_{yy}$and higher values of amplification than 1.0. The similar characteristics are found in TFM calculated based on the different data sets, even though the above-mentioned condition on dams and earthquakes are not consistent. It is considered that TFM shown in Figure 5 represent the specific amplification characteristics of each dam and each dam type.

The characteristics of TFM shown in Figure 5 are interpreted as follows. Concrete gravity dams behave to the earthquake input in selectively river flow direction, which is perpendicular to the dam axis, and somewhat vertical direction. The behavior in dam axis direction is strongly restrained due to high stiffness of the dam concrete and the rock foundation. The behavior of concrete dams is of two-dimension (2D).The behavior of embankment dams is of three-dimension (3D). It is considered that 3D behavior of embankment dams attributes to dilatancy characteristics and relatively low stiffness of these materials and rock foundation. The behavior of arch dams will be analyzed similarly by TFM in future. However,3D behavior will be anticipated in arch dams due to these structural features.



(a) Concrete dams, Kazeya dam and Tagokura dam



(b) Embankment dam, Kuzuryu dam and Ohuchi dam

Note: Hatched figures are transfer functions equivalent to ones estimated by conventional method.

Figure 5. Dynamic response characteristics of dams

5. DISCUSSION ON EARTHQUAKE MONITORING OF DAMS

The acceleration-based seismometers are standard devices for the earthquake monitoring of dams in Japan. These have high performance in resolution, versatility, easy installation, applicability to the numerical analysis and so on. The deformation monitoring during earthquakes is scarcely implemented. The residual deformation is occasionally identified at dams excited significantly by the large earthquake through the survey, the deformation monitoring using GPS (Global Positioning System) and/or the pendulums in concrete dams, while the deformation behavior during the earthquake is unknown. However, the deformation behaviors of dams during earthquakes are great concerns not only to assess the safety of dams but also to validate the current simulation methods of the dam behavior during earthquakes. For example, once the maximum deformation during an earthquake could be monitored, the stress state inside of concrete dams would be estimated. It is essential for the concrete dams to verify the safety.

Some of authors have proposed a new method using GPS [7] to monitor the oscillating behavior of structures and ground surface during earthquakes. The method is characterized by a three-dimensional dynamic displacement that can be measured with high accuracy. It is based on a carrier phase observation technique, like GPS relative positioning, and takes a temporal difference of the carrier phase, while it requires only one sensor as in GPS single positioning. Thus, it is called GPS self-relative single positioning. It is promising monitoring method for the behavior of dams during earthquakes. Replacing existing GPS receivers on dams with high frequency GPS receivers, the dynamic behavior of the dam is possibly and directly monitored by applying GPS self-relative single positioning technique, while the long-term behavior including the residual deformation of dams after the earthquake is evaluated by the conventional GPS relative positioning. The new method is being studied as in-situ examinations to implement to dams and will be reported in near future.

6. CONCLUSIONS

Authors studied the dynamic behavior of dams during earthquakes using a great number of earthquake response data monitored of dams, which are updated since the previous study. These characteristics are summarized statistically in the amplification ratio and the predominant frequency. The specific dynamic behaviorsin terms of dam types are discussed based on TFM.The conclusions extracted from these studies are summarized below.

1) Statistics of the dynamic behavior during earthquakes are specific in each dam and in each dam type. These are useful index for the prompt assessment on the soundness of dams after earthquakes.

2) The amplification ratios are of a linear to the earthquake intensity and these dam heights in concrete dams. The dependency on the earthquake intensity is similarly found in embankment dams, while height dependency is not found.The predominant frequency of dams features that the dependency on the water depth facing to the upstream surface is clearly confirmed in concrete dams, but not in embankment dams. However, scattering in 0.5 to 1.0 Hz of these frequencies suggests that there could be other influential factors on the dynamic behavior of dams, such as the ambient temperature on concrete dams.

3) Methods used in this paperbased on the monitoring data or the numerical simulations are all equivalent in the evaluation of the predominant frequency of the dam. The proper adjustment of the model and its properties is necessary in the numerical methods. Micro tremor measurement is preferable to easily acquire the present situation of dams due to its convenience which require portable measuring instruments and can be conducted manually anytime.

5) The analyses using TFM on the dynamic behavior of dams highlight the 2-D behavior of concrete gravity dams and the 3-D behavior of embankment dams.GPS self-relative single positioning technique is promising in tracing the deformation behavior of dams during earthquakes for the advanced earthquake monitoring.

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