A FEW CONSIDERATIONS ON EARTHQUAKE MONITORING OF DAMS

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ABSTRACT

A few considerations on earthquake monitoring of dams are introduced in terms of enhancement of earthquake monitoring and safety assessment of dams. These are based on examinations on thousands of earthquake data monitored in major dams of J-Power in more than 50 years in Japan. (1) Transfer function matrix clearly demonstrate that dams under earthquake load behave in a distinctive manner according to material, configuration and foundation condition. While concrete gravity dams behave selectively in upstream-downstream direction as 2D (two-dimensional) structures due to the high stiffness of dam concrete and rock foundation, the behavior of embankment dams is 3D (three-dimensional), attributing to dilatancy characteristics and the relatively low stiffness of materials and rock foundation. (2) Predominant frequencies of dams are various in earthquakes. Analyzing independent monitored data in short time segments clarified that the predominant frequencies decrease relative to the degree of acceleration of dam crest. It is considered that the interaction between the dam and reservoir works stronger in the higher response acceleration of dam. (3) Spillways arranged in the middle section could disturb the earthquake monitoring at the highest section of the dam due to adjoined piers and/or walls of the spillway. The numerical examinations using numerical models with and without spillway structures suggest that the disturbance is slight in acceleration response, but crucial in the stress around spillway. (4) The authors have proposed the new method of GPS (Global Positioning System) self-relative single positioning for the dynamic deformation monitoring of dams. When the new method using high frequency GPS receiver is combined with conventional accelerometers, earthquake monitoring of dams will be easily upgraded to monitor the deformation process during an earthquake simultaneously as well as the acceleration response.

1. INTRODUCTION

An earthquake is a control load in the design of a dam. The earthquake monitoring of dams is considered for the validation of the design of dams and its method. In addition, the dynamic behaviors of dams during earthquakes are analyzed to diagnose the soundness and assess the safety of existing dams. Therefore, the earthquake monitoring of dams is inevitable in all dams.

The accelerations are frequently monitored at the representative locations in the dam. Using the acceleration responses during earthquakes, the dynamic characteristics such as amplification, propagation in the dam are examined and compared to the past records to identify abnormality of the dam. The frequency characteristics of dams during earthquakes are representative indexes of the current state of the existing dams. The reproduction analysis is conducted to evaluate quantitively the dam response of acceleration, stress and safety everywhere in the dam under the major earthquakes. It is utilized to estimate the current properties of dams as well. The numerical dynamic analysis of dams indicates the significance of the interaction among dam, foundation and reservoir in understanding the behavior characteristics of dams during earthquakes.

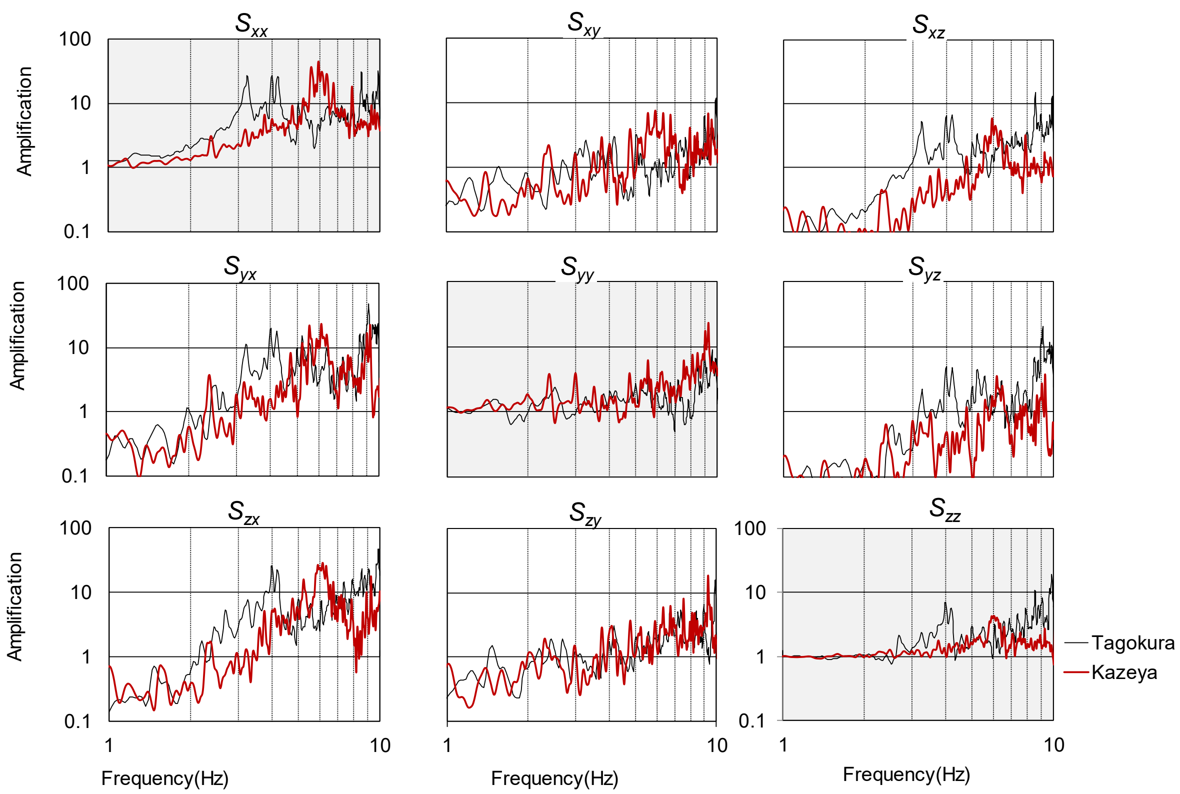
This paper describes a few considerations in terms of the enhancement of the earthquake monitoring and the safety assessment of dams. These are based on the examinations on thousands of earthquake data monitored in the major dams of J-Power in more than 50 years in Japan. The applicability of GPS self-relative single positioning method newly invented by authors is considered for the dynamic deformation monitoring of dams during earthquakes.

2. DISTINCTION OF BEHAIVIORS DURING EARTHQUAKES AMONG DAMS

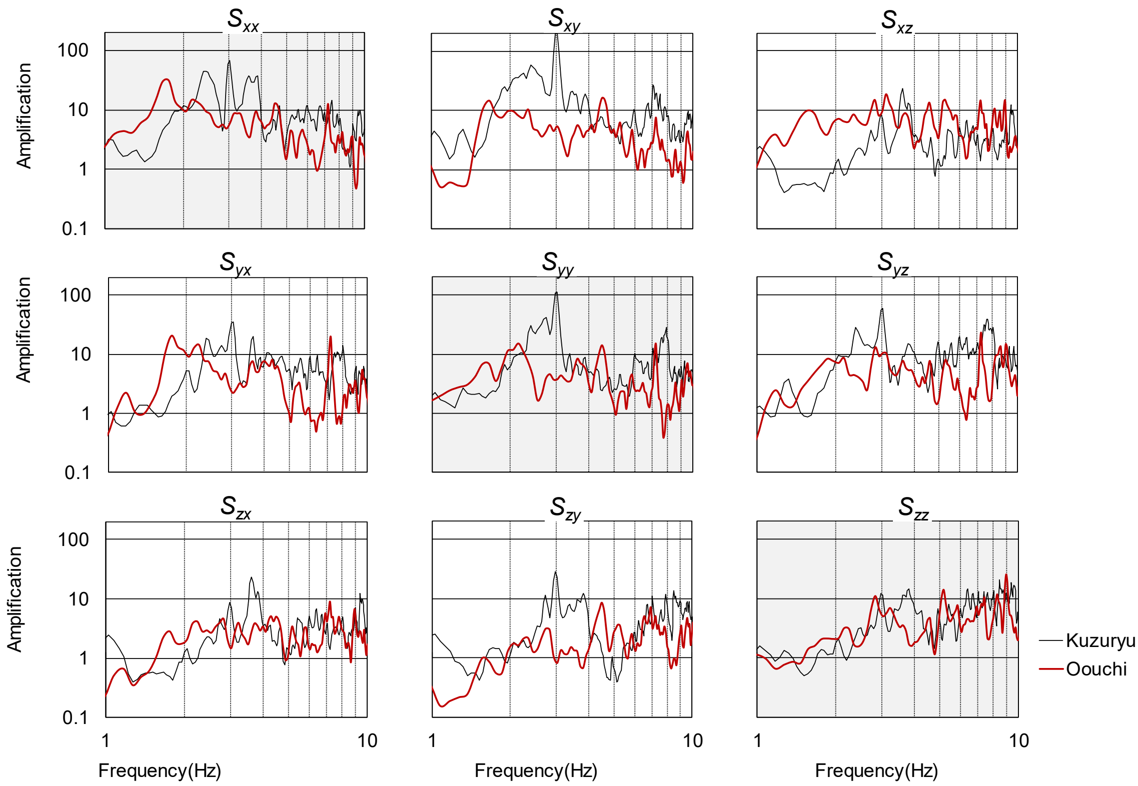
The amplification characteristics of dams is commonly evaluated by the transfer function. Here, these are analyzed in detail using the transfer function matrix (TFM) (Kashiwayanagi & Cao 2018), which consists of nine independent transfer functions (represented by S_{ij}, i is response direction, j is input direction) in 3-dimensional coordinates. While only one set of input and its response waves 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 how to work on dam behavior is put to be a future issue here. Several sets of three earthquake data are selected for TFM calculation for concrete gravity dams (Tagokura (145 m high) and Kazeya (101 m high)) and rockfill dams (Kuzuryu (128 m high) and Ohuchi (102 m high)) with a little effort on the conformity of these data. The results are illustrated in Figure 1, in which X, Y and Z denote the directions of upstream-downstream, longitudinal and vertical directions, respectively.

Some outstanding peaks in the amplification are clearly observed in S_{xx} and S_{yy}. These correspond to the dominant 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 1 (a) and 1 (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 1 represent the specific amplification characteristics of each dam and each dam type.

The characteristics of TFM shown in Figure 1 are interpreted as follows. Concrete gravity dams behave to the earthquake input in selectively upstream-downstream 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 gravity dams is 2D. The behavior of embankment dams is 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 gravity dams, Kazeya dam and Tagokura dam



(b) Embankment dams, Kuzuryu dam and Ohuchi dam

* Hatched figures are transfer functions equivalent to ones estimated by conventional method. X, Y and Z denote the directions of upstream-downstream, longitudinal and vertical directions, respectively.

Figure 1 : Dynamic response characteristics of dams. (Kashiwayanagi & Oonishi 2020)

3. CONSIDERATION OF DOMINANT FREQUENCIES OF CONCRETE GRAVITY DAMS

A dominant frequency (referred to as predominant frequency) of a concrete gravity dams is designated as the lowest peak frequency in the spectrum distribution of the acceleration or the transfer function of the dam behavior during an earthquake, micro-tremor measurement, etc. The consistent predominant frequency of the dam is a confident evidence of the soundness of the dam after earthquakes. However, these spectra inherently involve several spikes even after the smoothing processing. It makes difficulties in the identification of the predominant frequency of the dam. An example on the concrete gravity dam (145m high) is shown in Figure 2 (Kashiwayanagi et al. 2016). Predominant frequencies estimated by the transfer functions during earthquakes show wide scatter, even though the correlation is clear to the water depth, indicating the interaction between the dam and the reservoir.

The transient characteristics of the behavior during an earthquake of the dam monitored is examined to investigate the causes of the scatter of the predominant frequency of the dam. The frequency of the acceleration monitored at the dam is separately analyzed in segments of the major response (referred to as main wave) and the minor response (referred to as coda wave) far after the main wave as shown in Figure 3 (a). The spectra are calculated using MEM (Maximum entropy method) program, which is available to waves of smaller wave numbers. The predominant frequencies are designated as the peak of the MEM spectrum as shown in Figure 3 (b) as an example. The earthquake response data of the dam in Figure 2 are selected as higher acceleration and longer duration of responses. The results are shown in Figure 4.

The peak frequencies of the segments are distinct in the MEM spectra, which make easier designation of the predominant frequencies of the dam. However, the scatter ranging approximately 0.3 Hz in plus and minus are found in Figure 4. The predominant frequencies in the main wave inversely relate to the maximum acceleration of the wave. It is less in the coda wave. It is considered that the predominant frequency of the dam is not constant and relates the behavior intensity of the dam as a whole.

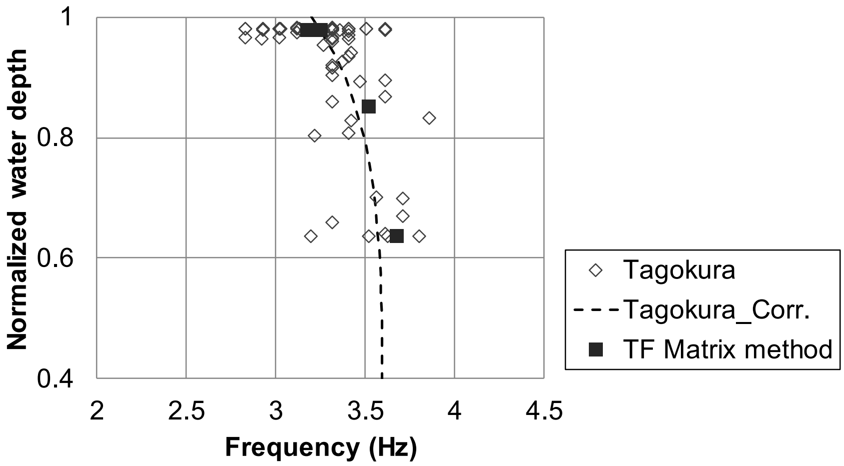
The predominant frequency of the concrete gravity dams could non-lineally vary depending on many factors. Major factors are an interaction among dam, foundation and reservoir, and related damping as well as the aging of the dam material. The behavior of transverse joints is considered as an influential factor. Regarding this issue, Kondo et.al. (2015) proposed the Equation (1) taking the reservoir water depth and the joint behavior which relates to the ambient temperature into consideration. Based on this, the existing dams are analyzed for the soundness diagnosis of dams.

$$f_1(h,\theta) = c_0 + c_1(h/H)^{\beta} + \frac{c_2}{\sqrt{\theta^* - \theta}} + e \qquad ...(1)$$

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

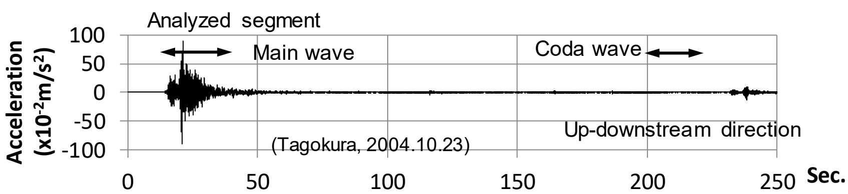
As shown in Figure 2, the predominant frequencies of concrete dams apparently relate the reservoir water depth. It is resulted by the action of the hydrodynamic pressure caused by the interaction between the dam and the reservoir. Considering the growth of the hydrodynamic pressure acting on the dam, the fall of the frequency as shown in Figure 4 may conform to the increase of the acceleration of the dam. Hydrodynamic pressure on the dam surface relates to both the water depth and the acceleration based on Westergaard's equation. Taking the relation between the frequencies and the acceleration in Figure 4 into consideration, the scatter ranging 0.3 Hz in plus and minus of the frequencies could be compensated by the acceleration of 10m/s^2. However, such strong response of the dam has not been observed yet at the relevant dam. In addition, the adjustment of the frequency shown in Figure 2 taking the same relation to the acceleration is failed in the slight change of the figure.

These are summarized as follows. Even though the predominant frequencies of concrete gravity dams relate to the reservoir water depth apparently and the acceleration of dams, the frequencies of dams scatter in a certain range which should be compensated by other unknown factors. The further investigation on the characteristics of the dynamic behavior of dams is mandatory to diagnose the soundness and access the safety of the existing concrete dams. The enhancement of the earthquake monitoring is inevitable to secure the data quality monitored and provide more information of the behavior of dams during earthquakes. One of the idea is proposed in chapter 5 in this regard.

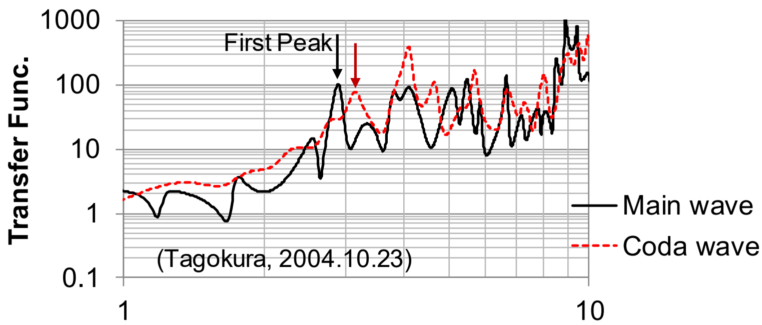


* TF Matrix method: Transfer function matrix method (Kashiwayanagi & Cao 2018)

Figure 2 : Predominat frequency of Tagokura (concrete gravity) dam based on earthquake monitoring (Kashiwayanagi et al. 2016, Partly modified).



(a) Analysed wave



(b) Tansfer functions with MEM spectra

Figure 3 : Example of the analysis.

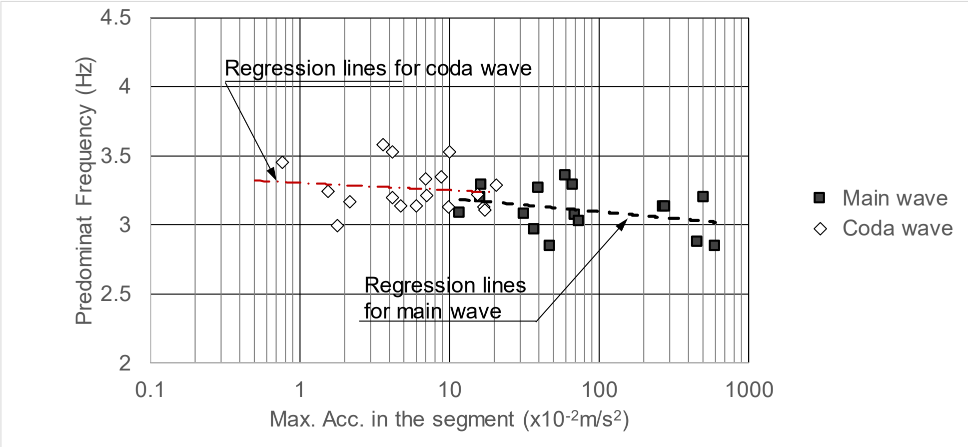


Figure 4 : Predominant frequency of concrete gravity dams over the response acceleration at the dam crest

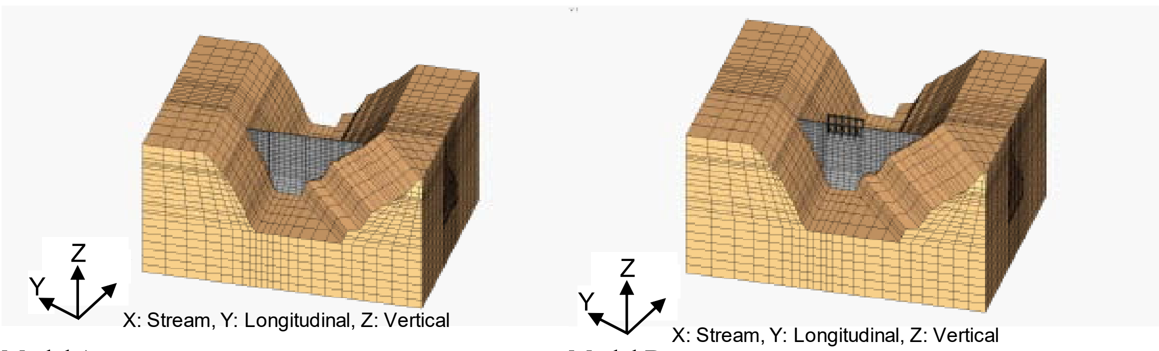
4. IMPACTS OF SPILLWAY SITUATED ON A DAM CREST ON DAM BEHAVIOR DURING EARTHQUAKES

Many concrete gravity dams are designed so that the spillway is arranged in the middle sections of the dam for adequately discharging flood. The earthquake monitoring devices are frequently arranged on the adjacent area of the spillway in these dams. It makes a concern on disturbance to the seismic monitoring at the dam crest due to the spillway response during an earthquake. The numerical examination is conducted to quantify the adverse impact of the spillway arranged on the dam crest in terms of the seismic monitoring of the dam.

An existing concrete gravity dam of approximately 150 m high is selected for the study. Sixty earthquake responses of the dam have been accumulated in past 40 years. The dynamic responses of the numerical model with and without spillway are compared in the acceleration and the stress. These numerical models are shown in Figure 5. The models consisting of the dam, the foundation and the reservoir are elaborated with simulating adequately the monitored responses of the past major earthquake. The properties used for the models are summarized in Table 1. Three dimensional dynamic behaviors are simulated under the assumed large earthquake and the full water level using the finite element program of UNIVERSE (Ariga et.al. 2004).

Table 1 : Simulation parameters

	Shear modulus (MPa)	**Unit weight (t/m^3)**	**Poisson's ratio**	**Damping coefficient (%)**
Foundation	12000	2.6	0.25	5.0
Dam / Spillway	13412	2.4	0.20	5.0
Reservoir	Velocity: 1440m/s	1.0	-	-



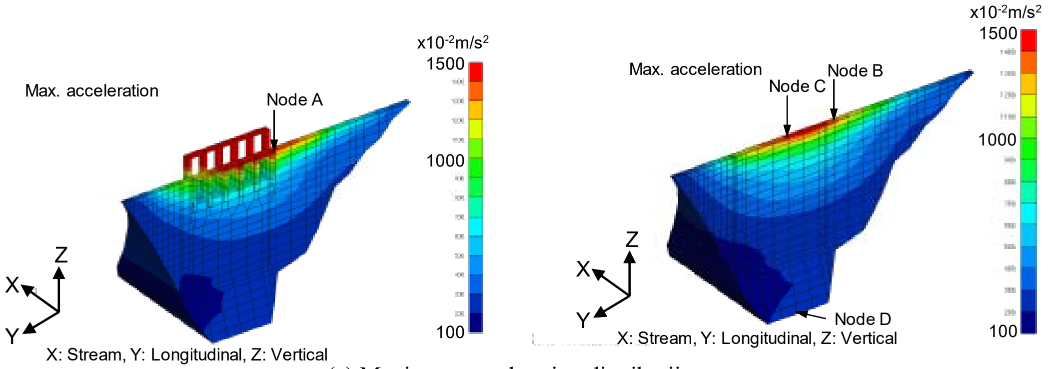
Model A Model B

Figure 5 : Numerical model with and without spillway structures, Upstream view.

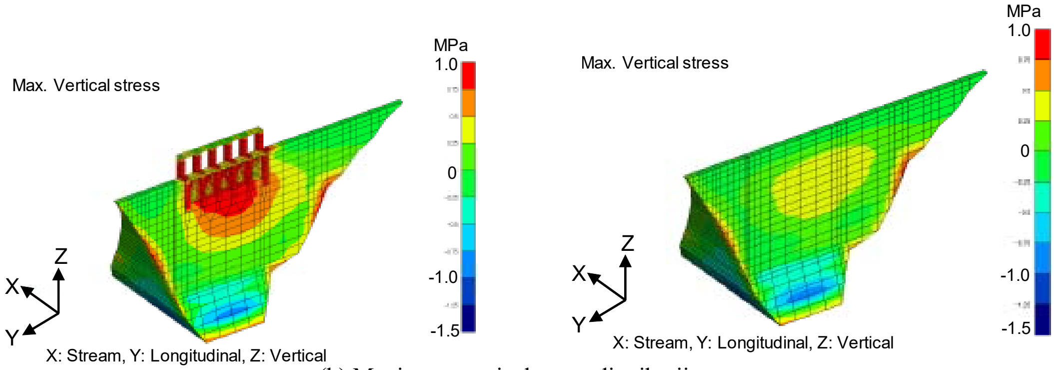
The results are shown in terms of the distribution of the maximum responses of acceleration and stress in Figure 6. Noticing the adjacent area of the spillway at the dam crest, the differences are slight in the acceleration response and recognizable in the stress response (See Figs 6(a), (b)). The response of the spillway is prominent and alternate the stress distribution of the dam beneath the spillway.

The above results are considered from the standpoint of the earthquake monitoring of dams. The propagation characteristics of the seismic wave at the dam crest is examined with and without the spillway. The acceleration spectra at the dam crest of the next block of the spillway are calculated at the nodes A and B (See Fig. 6 (a)) corresponding to with and without spillway, respectively, using the simulated results. Similarly, the transfer functions between the foundation and the crest of the dam are evaluated at nodes B and C respect to node D (See Fig. 6 (a)). Both nodes C and D are located at usual representative section for the earthquake monitoring, which is the highest dam section. These results are shown in Figure 7. Little differences of the spectrum characteristics of the acceleration response at the dam crest are found in both with and without spillway cases at nodes A and B. It conforms to the results in Figure 6 (a). The transfer functions are identical at nodes B and C, even though node B is in the section apart a few blocks from node D.

These are interpreted as follows. It is considered as the adequate practical method that the earthquake monitoring is conducted at the dam crest in the adjacent monolith of the spillway and not in the highest section of the dam when the spillway is arranged in the middle section. Little consideration for the analysis of the earthquake monitoring data is necessary on the disturbance of the spillway behavior during earthquakes. A few devices for the earthquake monitoring of the concrete dams are found on the piers of the spillway instead of the dam crest. These are susceptible to the independent behavior of the spillway.

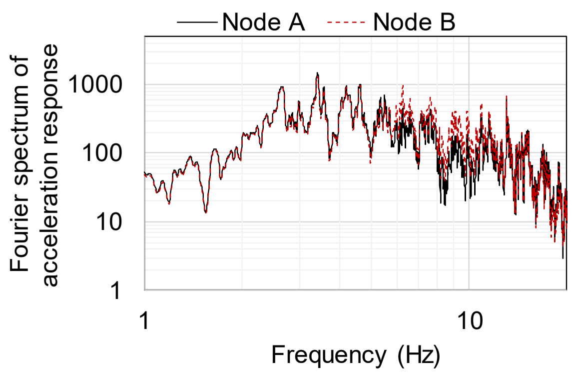


(a) Maximum acceleration distributiion

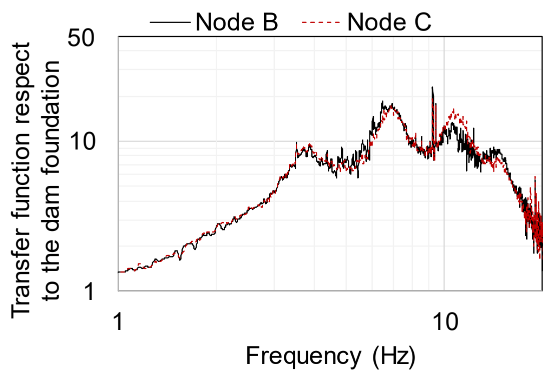


(b) Maximum vertical stress distributiion

Figure 6 : Maximum response of the dam with and without spillway structures, Upstream view.



(a) Spectrum with and without spillway



(b) Wave propagation characteristics in the dam

*Nodes in figures are shown in Figure 6 (a).

Figure 7 : Frequency characteristics of acceleration response with and without spillway structures

5. REALTIME DEFORMATION MONITORING DURING EARTHQUAKES OF DAMS USING GPS SELF-RELATIVE SINGLE POSITIONING

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 and/or the pendulums in concrete dams, while the deformation behavior during the earthquake is unknown. The applicability of GPS positioning for the deformation monitoring of dams has recently been verified (Shimizu et al. 2014, Yamaguchi 2014). It has been widely arranged on the surface of the existing dams for the monitoring of the long-term behavior. 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 (Kashiwayanagi et al. 2017, 2019) 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. The concept of the new method and its practical application for a composited sensor are shown in Figures 8. The experimental verification using the vibrating table clarify its performance as shown in Figure 9.

It is promising monitoring method for the dynamic 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

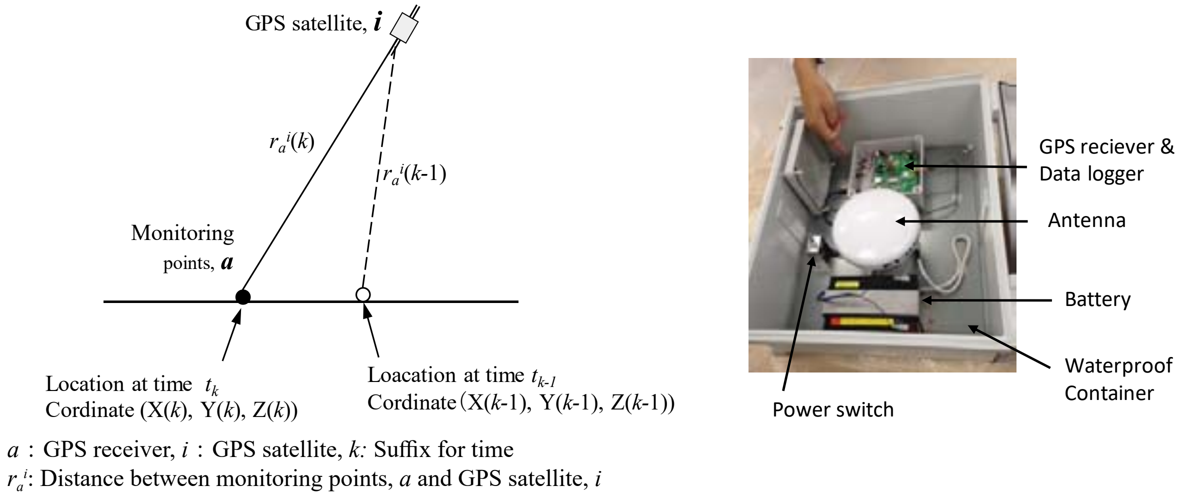
A few considerations on earthquake monitoring of dams are introduced in terms of enhancement of earthquake monitoring and safety assessment of dams. The conclusions extracted are summarized below.

(1) TFM clearly demonstrate that dams under earthquake load behave in a distinctive manner according to material, configuration and foundation condition. While concrete gravity dams behave selectively in upstream-downstream direction as two-dimensional structures due to high stiffness of dam concrete and rock foundation, the behavior of embankment dams is three-dimensional, attributing to dilatancy characteristics and the relatively low stiffness of materials and rock foundation.

(2) The predominant frequency (f_p) of concrete gravity dams vary to intensity of response during the specific earthquake as well as to reservoir water depth acting on its upstream surface. Even after taking such characteristics into consideration, f_ps scatter in a certain range that should be compensated by other unknown factors. Further investigation of the characteristics of dynamic behavior of dams is mandatory in order to diagnose the soundness and assess the safety of existing concrete dams.

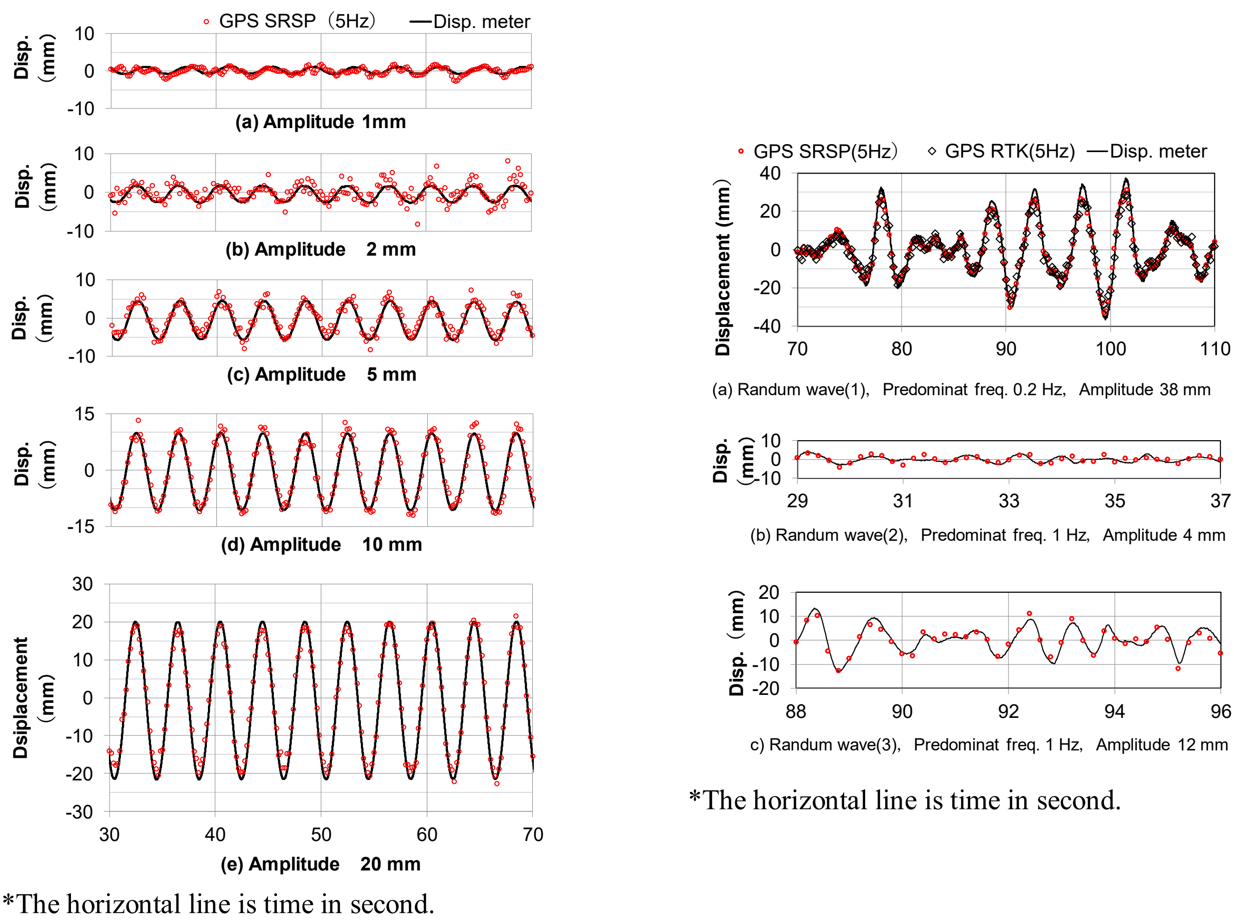
(3) Regarding the earthquake monitoring in dams with spillway being arranged in the middle section, it is an adequate practical method that earthquake monitoring is conducted at dam crest in the adjacent monolith of the spillway. Little disturbance of the spillway behavior during earthquakes is estimated on the earthquake monitoring data at the dam crest by the numerical study.

(4) The new method of GPS self-relative single positioning is a promising monitoring method for the dynamic 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, while the long-term behavior including the residual deformation of dams after the earthquake is evaluated by the conventional GPS relative positioning.



(a) Concept (b) Unified GPS sensor using the method

Figure 8 : GPS self-relative single positioning with carrier phase (Kashiwayanagi et al. 2017)



(a) Sinusoidal waves (Frequency is 0.25 Hz) (b) Randum wave Artificial earthquake)

Figure 9 : Experimental verification (Kashiwayanagi et al. 2017)

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