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ANALYSES OF EARTHQUAKE RECORDS ON TWO JAPANESE CONCRETE DAMS

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Abstract

Securing of the seismic performance of dams is an extremely important issue. As Japan is one of the most earthquake-prone countries in the world, various kinds of efforts regarding the issue have been carried out. In particular, seismic recordings have been conducted on existing dams in order to empirically compare the characteristics of earthquake input and dam response.

In order to contribute to the further advancement of seismic safety evaluation and the design of dams, the Japan Commission on Large Dams released databases of earthquake recordings in 1978, in 2002 and updated it in 2014.

The study will focus on records on two concrete dams: Tagokura gravity-dam and Kurobe arch-dam with recording devices located in the dam and also in the foundation. For each dam, a minimum set of 5 earthquake records from Magnitude 4 to almost 7 are chosen.

The purpose of the present study is to get as much information as possible on the dam's response by evaluating the first eigenfrequencies. Different methods of analysis (transfer function, frequency domain decomposition, cross-spectrum) will be considered and the variability of the results will be evaluated. The reproducibility of the results with different earthquake records will also be analyzed.

Keywords: seismic monitoring, strong motion records, modal identification, signal processing

1. Introduction

This paper presents a comparison of different methods to identify the first eigenfrequencies of concrete dams from earthquake's records. The knowledge of these eigenfrequencies can then be particularly useful : for comparison with values coming from ambient vibration tests to evaluate if greater solicitations induced by earthquakes might lead to different dam's response, for the calibration of finite-element analyses in order to perform back analyses of the dam, or to get information about the dynamic properties of the concrete.

Analysis of earthquake's record is challenged by two aspects of earthquakes : small duration (a few minutes at most) and high dynamic range. That is why it is less convenient to perform analysis on earthquake records than on longer repetitive records from vibration or shaker test.

As Japan is one of the most earthquake-prone countries in the world, seismic recordings have been conducted on existing dams [1], and among them, more than 150 are concrete dams. The aim of this study is to find the best method to evaluate the first eigenfrequencies for a gravity (Tagokura) or an arch dam (Kurobe) with the best reproducibility over several earthquake's records.

Geometry of the dams and record device

Two dams were selected for this study, a 186 m high arch dam with a 492 m long crest, Kurobe dam and a 145 m high gravity dam with a 462 m long crest, Tagokura dam. Strong motion seismographs (SMAC) are installed at the crest and at the foot of each dam. Some of the sensors are triaxial (A=upstream-downstream, B=bank-to-bank, U=vertical) while others record only in the upstream-downstream direction.

Fig. 1- Kurobe arch dam (left) and Tagokura gravity dam (right) sensor's location

For both dams, triaxial sensors at the crest (T1 or crest1, "T" for "top") and at the toe (F1, "F" for "foundation") are available (see Fig. 1). In Tagokura's case, the sensors are vertically aligned whereas in Kurobe's there is a base sensor and multiple sensors placed along the crest (T1, T2, T3 & T4).

2. Presentation of the earthquakes

The publication of the records compilation "Records on Dams and Foundation No.3" [1] provided a large set of data concerning seismic activity on dams. Analyses on a large set of data aim at challenging the reproducibility of the results over different earthquakes.

The most intense earthquakes records, six for Kurobe dam and five for Tagokura dam, are chosen. Earthquake's characteristics are presented Table 1.

Table 1 - Presentation of the earthquakes, Tagokura & Kurobe

Dam	Earthquake	Date	Epicentral Distance	Magnitude	Water level (m)	PGA (g)	Max crest acceleration (g)	Duration (s)
Tagokura dam	1	10/23/2004	37km	6.8	507.1	0.10	0.46	431 s
	2	10/23/2004	34km	5.3	507.2	0.07	0.71	99 s
	3	10/27/2004	23km	6.1	507.2	0.12	0.61	168 s
	4	10/23/2004	32km	6.5	507.2	0.08	0.51	401 s
	5	12/22/2007	9km	4.4	495.5	0.03	0.32	85 s
Kurobe dam	1	03/25/2007	114km (off Noto peninsula)	6.9	1381.7	0.02	0.17	75.21 s
	2	10/05/2011	3km (hida mountain region)	5.2	1430.4	0.13	0.97	119 s
	3	10/06/2011	1km (Hida mountain region)	4.7	1431.4	0.11	0.46	232 s
	4	10/05/2011	4km (Hida mountain region)	5.4	1430.4	0.07	0.38	77 s
	5	03/11/2011	3km (Hida mountain region)	4.1	1394.4	0.06	0.26	50 s
	6	03/11/2011	2km (Hida mountain region)	2.9	1394.1	0.02	0.10	44 s

For Kurobe dam, water level during the earthquake was either 1430 m or 1390 m; analyses will be mainly performed with earthquakes 2,3,4 that occurred for a coseismic water level (1430 m). The influence of the water level on the results will be analyzed in § 5. For Tagokura dam, the earthquakes chosen occurred for a similar water level (±5 m).

3. Methods of analysis

Modal identification can be achieved through various methods: most of them rely on frequency-domain analysis combined with peak-picking. Translation from the temporal to the frequency domain can be done using a Discrete Fourier Transform (DFT) or Spectrum Response Output (SRO). This last one is almost similar to a DFT but it introduces an amount of frequency-dependent smoothing (coming from the damping used in the computation of SROs). SRO-based methods are presented § 4.

Four methods, among the most commonly used are examined here: cross-spectra (CS), frequency domain decomposition (FDD), transfer functions (TF) and mean transfer functions (TFm). CS and FDD make use of all the sensors whereas TF makes use only of a crest and a base sensor. Records have been translated in the frequency-domain using DFT (SROs are also used in § 4) and are considered at a given frequency f (below the Nyquist frequency, which is 50 Hz in the records of the JCOLD [1]).

Table 2 : Frequency-domain methods

Method	Mathematical Expression	Comment
Frequency Domain Decomposition (FDD) [sum over all the available sensors]	$FDD(f) = \sum_{k=1}^{n} \lvert sensor_k(f) \rvert^2$	- Unnormalized ordinate - slight variations from earthquakes to earthquakes
Cross-Spectrum (CS)	$CSa(f) = \lvert Crest1(f) * Crest1(f) \rvert$ $CSb(f) = \lvert Crest1(f) * Crest2(f) \rvert$ $CSc(f) = \lvert Crest1(f) * Crest3(f) \rvert$	- Significant variations from earthquakes to earthquakes - Unnormalized ordinate
Transfer Function (TF) {phase is not analyzed here}	$TF(f) = \lvert Crest(f)/Base(f) \rvert$	- normalized ordinate
Mean Transfer Function (TFm) {over 1 record, moving windows of $[0,t_0]$ length, shifted by τ}	$TFm(f) = \frac{1}{N}\sum_{i=0}^{N-1} TF_{[i\tau, t_0+i\tau]}(f)$	- normalized ordinate - Good reproducibility over the earthquakes

3.1. Frequency Domain Decomposition

Frequency Domain Decomposition (FDD) is a method that can be used when the input is close from a white nois. In the case of earthquake's records, FDD can show where amplification roughly occurs in the spectrum (due to the dam's response). Its definition (see Table 2) is an estimation of the dam's kinetic energy.

Fig. 2 shows the FDD for earthquakes 2,3&4 for Kurobe and 1,2&3 for Tagokura; the FDD is normalized with respect to its maximum value. Considering the two upper graphs, most of Tagokura's response energy is in the [1Hz, 20Hz] region whereas most of Kurobe's is in [1Hz, 10Hz]. A smoothening window of 0.45 Hz wide was used to plot these graphs.

Looking at the 0-10 Hz content for the FDD of Kurobe dam (see bottom graph, Fig. 2), peaks are observed around 2.3Hz and 3.3Hz. Considering the rather good repeatability of the method on multiple earthquakes, FDD provides a general idea of the arch dam's eigenfrequencies. However, considering Tagokura's results, FDD does not provide consistent results considering several earthquakes, which highlights the limits of this method.

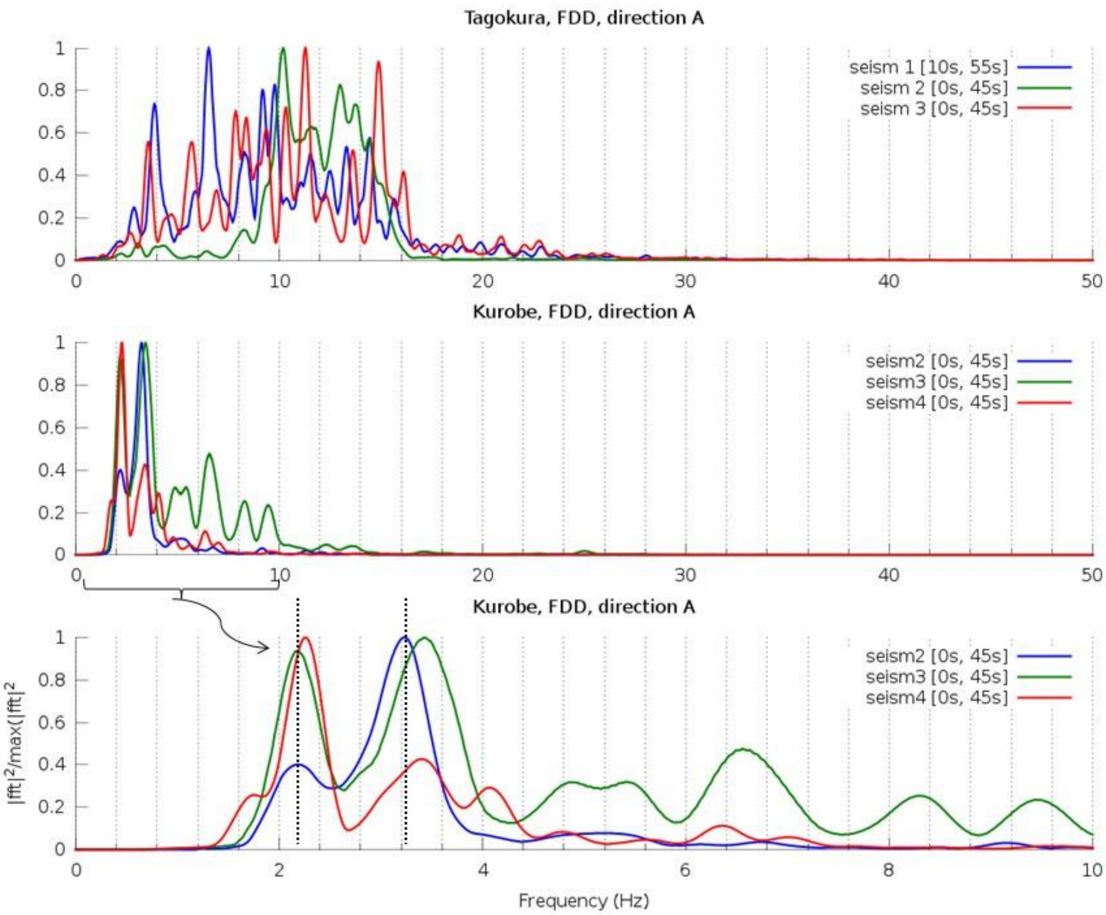

Fig. 2 – Frequency domain decomposition (FDD) for Tagokura dam (top) and Kurobe dam (middle and bottom)

3.2. Cross-spectrum

As presented in Table 2, Cross-spectrum can be used to put forward eigenfrequencies. CS's definition is close to FDD's definition. Therefore, results obtained from cross-spectra are also dependent on the input frequency content.

Cross-spectra for Kurobe dam (earthquakes 2,3&4) and Tagokura dam (earthquakes 1,2&3) are shown Fig. 3 and Fig. 4. They are computed with reference to sensor T1 and for several combinations of sensors (T1*T1, T1*T2 and T1*T3 for Kurobe dam, T1*T1, M2*T1, M1*T1 for Tagokura dam). A wide smoothening window (0.45 Hz wide) is used.

Kurobe dam's cross-spectrum (Fig. 3) shows peaks at ~2.0 Hz and around 3.2 Hz. However, Tagokura dam's CS (Fig. 4) does not show the same peaks for every earthquakes: there might be a peak around 3.8 Hz for earthquakes 1 and 3 but nothing on the 2^{nd} record. Consequently this method does not seem appropriate.

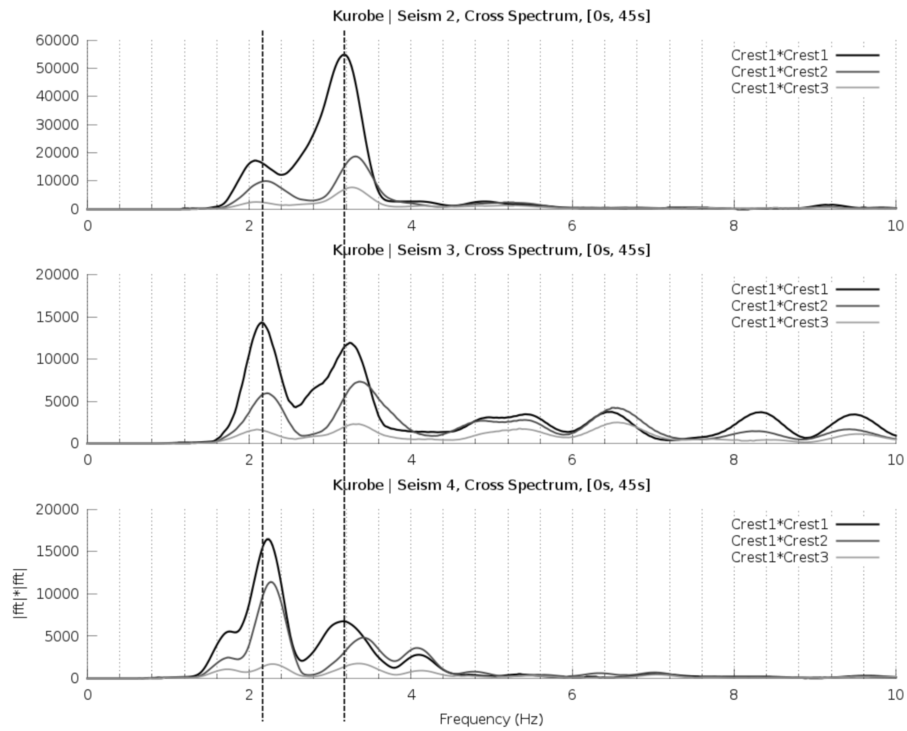

Fig. 3 – Kurobe, Cross-Spectrum, earthquakes 1,5 & 6

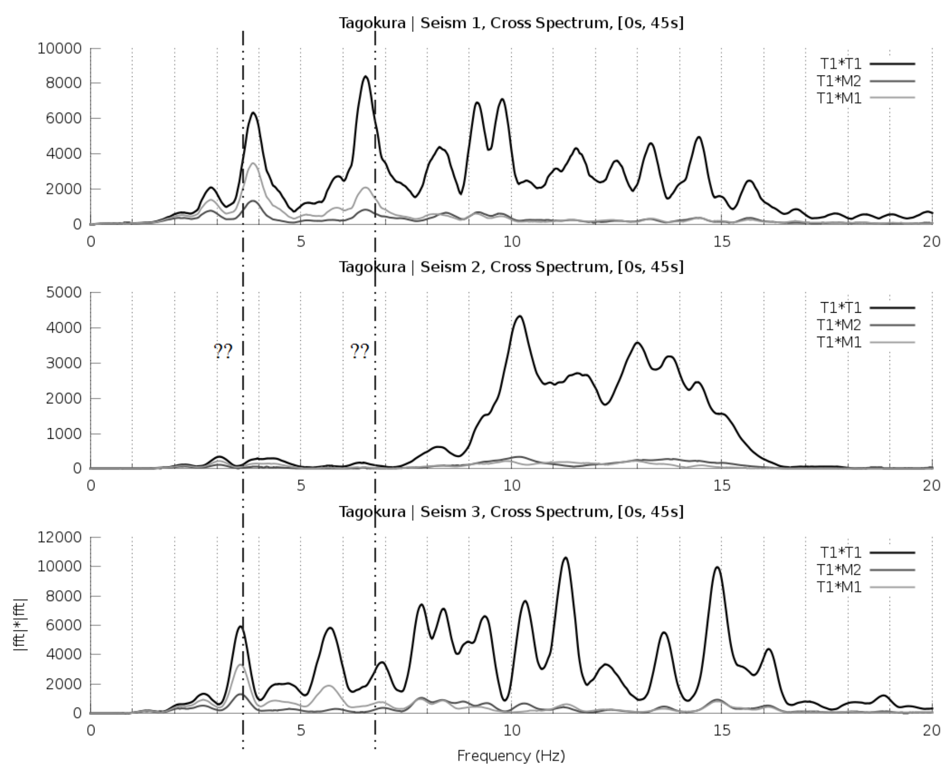

Fig. 4 - Tagokura, Cross-Spectrum, earthquakes 1,2 & 3

3.3. Transfer Functions

Transfer functions (TF) are intrinsic characteristics of each dam. Transfer functions between the crest (T1) and the base (F1). Compare to the previous methods, results are related to the concrete characteristics only, without taking into account for the soil-structure effect. Theoretically, eigenfrequencies should then be higher, considering the flexibility of the foundation is not considered in the analysis. This method is quite powerfull to compare the response of the dam with several earthquakes since the TF is normalized (ordinate corresponds to a gain at a specific frequency).

Results are shown for Tagokura dam and Kurobe dam in Fig. 5. The direction studied is the upstream-downstream direction (direction A). They were plotted using a wide smoothing window (approximately 0.4 Hz wide). The following earthquakes are considered in Fig. 5:

- Tagokura dam: earthquakes 1,2&3 (water level, 507.1-507.2m)
- Kurobe dam: earthquakes 2,3&4 (high water level, ~1430 m)

This example shows that TFs do not significantly vary between earthquakes. The first two eigenfrequencies of Kurobe dam can be identified (2.2 Hz and ~3.0 Hz) as well as the first two eigenfrequencies of Tagokura dam (~3.8 Hz and ~9.0 Hz).

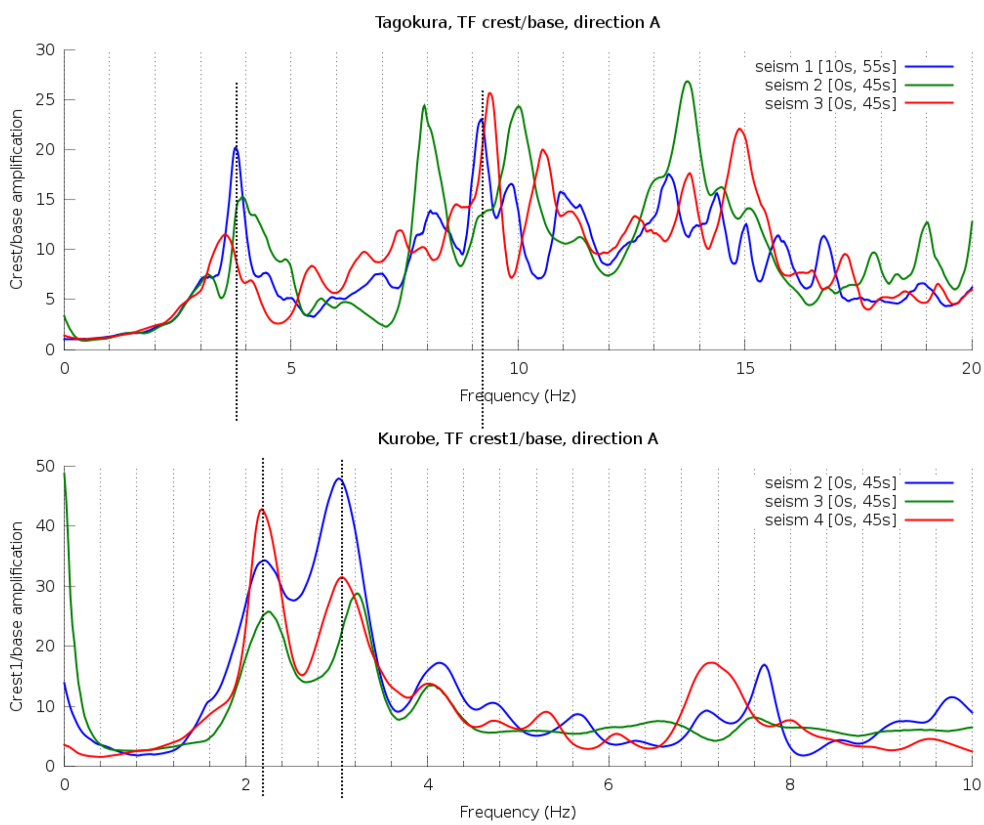

Fig. 5 – Transfer Function, Tagokura dam & Kurobe dam (high water level)

3.4. Mean Transfer Functions

Given the length of the records (ranging from 44 s to 400 s), the frequency resolution available is more than sufficient. In such a situation, a method inspired from Welch's periodogram ("Mean Transfer Functions" in Table 2) is applied, making use of the whole record's length; it results in a tradeoff between frequency resolution and noise reduction.

This method consists in averaging TFs calculated on overlapping windows (or "sliding windows"). The parameters from Table 2 are chosen as t_0=15 s and τ=1 s (therefore TF[0] is computed over *[0s,15s]*, TF[1] is computed over *[1s,16s]*, TF[2] is computed over *[2s,17s]* and so on). Once several TFs are computed, a mean TF and a standard deviation TF are plotted. Examples of this method are shown in Fig. 6 and in Fig. 7.

Within each seism, the reproducibility of the TF over each sliding window is quite satisfying as the standard deviation TF does not vary too much from the mean TF, allowing the identification of the eigenfrequencies (see Fig. 6 and Fig. 7).

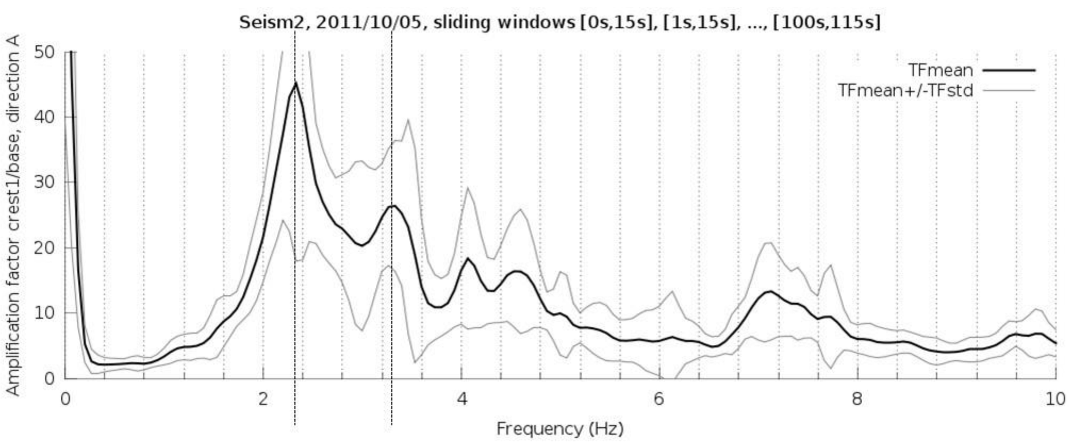

Fig. 6- Mean Transfer Function and standard deviation, Kurobe dam, Seism 2

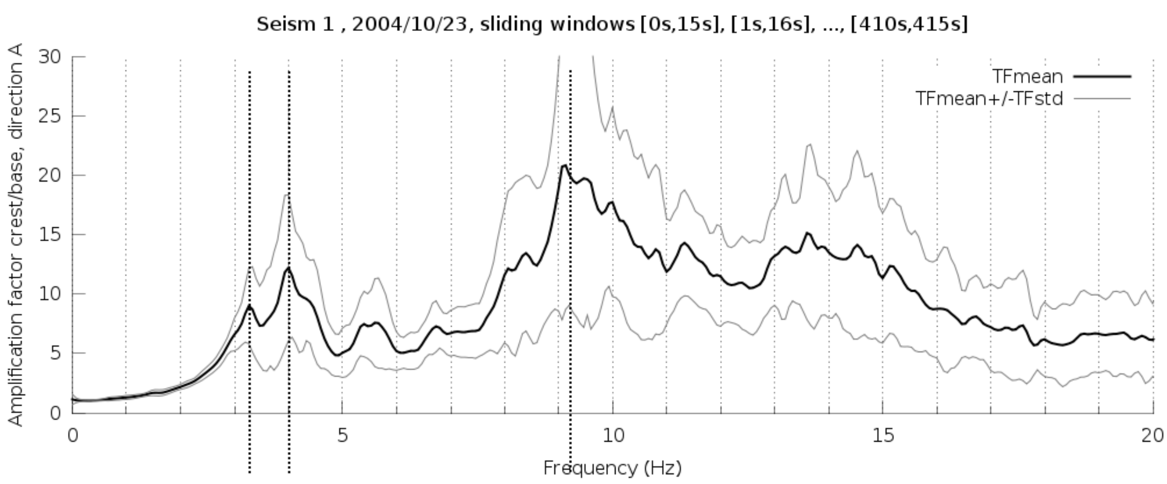

Fig. 7 - Mean Transfer Function and standard deviation, Tagokura dam, seism 1

The method "Mean Transfer Function" is applied to multiple earthquakes as previously. Results are presented Fig. 8 (for Kurobe, high water level) and Fig. 9 (for Tagokura). The first two eigenfrequencies for Kurobe at a high water level are identified at 2.3 Hz and 3.3 Hz; for Tagokura dam, the first eigenfrequencies are identified around 3.3 Hz and 3.9 Hz and 9 HZ.

This method helps achieving a better reproducibility. It must also be noted that in Fig. 8 and Fig. 9, the smoothening function used was narrow (approximately 0.06 Hz wide) which demonstrates that averaging TFs also has a smoothening effect.

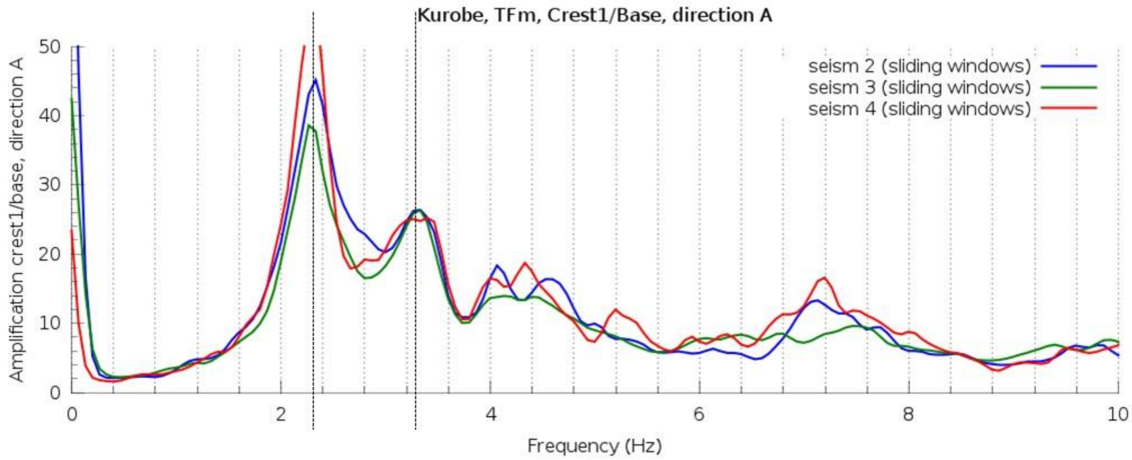

Fig. 8 – Kurobe dam mean Transfer Functions earthquakes 2,3,4 (high water level)

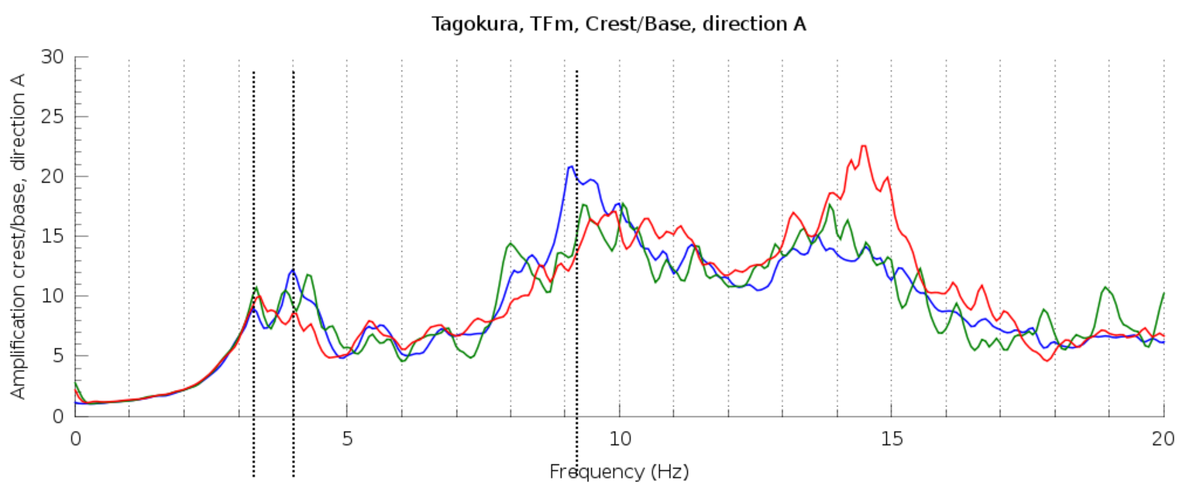

Fig. 9 – Tagokura dam mean Transfer Functions earthquakes 1,2,3

4. Spetrum Response Output

Spectrum Reponse Output (SRO) can be calculated from time-series to a frequency-series in place of the usual DFT. SROs are sometimes used to compute TFs (thus called SROTFs). The TFs shown in Fig. 5 are calculated using SRO to show the difference between SRO and DFT; the result is presented in Fig. 10. Frequency bins are exponentially spaced from 0 Hz to 10 Hz. (0.1×1.0312^i : [0.1Hz, 0.10312Hz, …, 9.73Hz, 10.03Hz]).

Fig. 10 should be compared to Fig. 5 to see the difference between DFT and SRO. Results are almost similar and the same set of eigenfrequencies can be identified. However the method “Mean Transfer Function” presented §3.4 allows for a better reproducibility of the results than the TF using SRO.

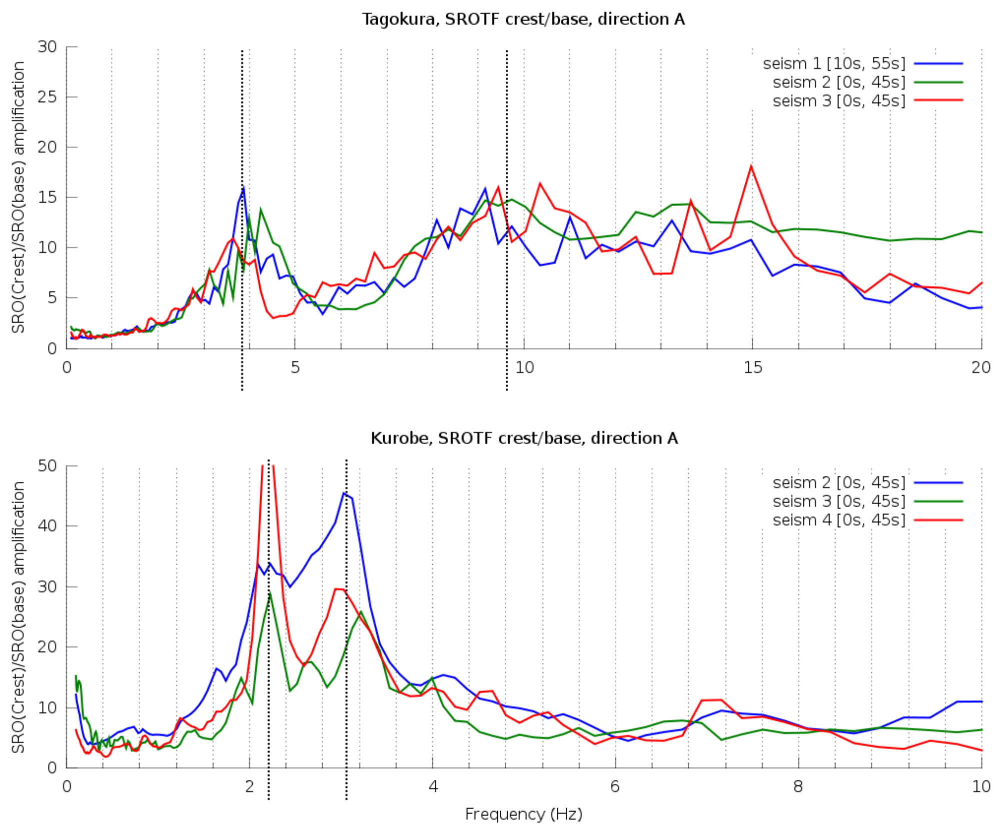

Fig. 10 – Transfer Function, Tagokura dam and Kurobe dam (high water level) using SRO

5. Influence of the water level, Kurobe dam

The “Mean Transfer function” was identified as the most relevant method for eigenfrequencies evaluation using earthquake records. It is therefore used to analyze the earthquakes 1,5,6 at Kurobe dam that occurred for a low water level (1390 m). Results are shown Fig. 11. It has been shown that concrete dam’s eigenfrequencies change with water level and temperature [3], [4] : not only because of the mass added by the increase of the water level but also by the change of the whole structure’s stiffness due to the opening or closing of the vertical joints.

Fig. 11 shows high variability among the low water level earthquakes, caused by the small duration of these earthquakes (see Table 1, mean duration of earthquakes 1,5,6 is 55 s whereas mean duration of earthquakes 2,3,4 is 140 s). Greater durations allow for more windows to be averaged which enhances the efficiency of the TFm method.

In the absence of additional records that occurred for a low water level (around 1390 m) and with the methods presented here it is not possible to conclude to a possible shifting of the eigenfrequencies with changes in the water level.

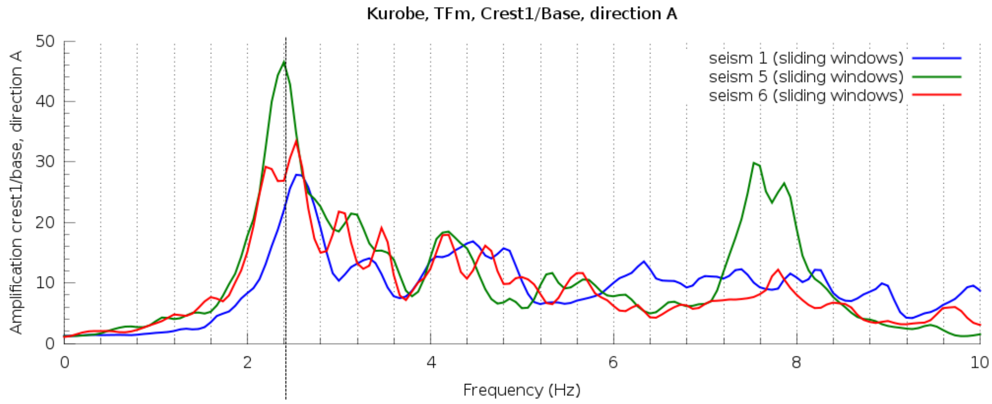

Fig. 11 - Kurobe mean Transfer Functions earthquakes 1,5,6 (low water level)

6. Comparison with forced vibration tests, Kurobe dam

At Kurobe dam, forced vibration tests were conducted at reservoir water level of 1430 m in 1965 and 1448 m in 1969 [2]. In 1996, a second set of measurements at reservoir water level of 1417 m was done using ambient vibration (or microtremors) [2]. Results from both these tests are presented Table 3.

Results from the analysis presented in this paper are included; however mode shapes are not yet evaluated. Eigenfrequencies from earthquakes records are closest to those evaluated from the ambient noise analyses of 1996. Both tests were done at comparable water level (difference is less than 10% of the reservoir's height) and in October (therefore at comparable concrete's temperature).

Differences between the earthquake's record and the shaker tests of 1965 could be explained by the differences in the temperature of the dam's concrete. The reservoir's water level was the same in both cases but shaker tests were conducted in July when concrete has not yet reached its maximal temperature and consequently, eigenfrequencies might be affected by a slight opening of the vertical which reduces the stiffness of the whole dam.

Table 3 : Shaker and ambient noise tests

Date	Water level (m)	Method	Eigenfrequencies		
			1st symmetrical	1st asymmetrical	2nd symmetrical
July, 15th 1965	1430 m	Shaker test	2.0 Hz	2.4 Hz	3.6 Hz
Ju1y, 1st 1969	1448 m	Shaker test	1.8 Hz	2.1 Hz	3.2 Hz
October, 28th 1996	1417 m	Ambient noise	2.3-2.5 Hz		3.7 Hz
October, 5th 2011	1430 m	Earthquake's record analysis (high water level)	2.3 Hz (mode shape unevaluated)		3.3 Hz

7. Conclusions

The goal of this paper was to identify and evaluate several existing methods that could be used to extract eigenfrequencies from seismic records. They are applied to two different dams: Tagokura dam (145 m high gravity dam) and Kurobe dam (186 m high arch dam). The reproducibility of these methods' result is assessed by using different strong-motion seismic record from JCOLD [1].

With output-only methods such as cross-spectra (CS) or frequency domain decomposition (FDD), it possible to estimate value of the first eigenfrequency for Kurobe arch dam. However for the gravity dam Tagokura, CS and FDD are not able to give precise information on the first eigenfrequencies.

The benefit of using Transfer Functions, which is an input-output method, over output-only methods such as cross-spectra or FDD allow for reasonable reproducibility for different earthquakes. When dealing with transfer functions, some techniques such as smoothening in the frequency domain or averaging TFs computed from sliding windows (as inspired by Welch's periodogram) prove to be useful. They allow the identification of eigenfrequencies even though only one record is available. However the method does not offer enough precision to evaluate the effect of water level on Kurobe arch dam's eigenfrequencies.

A comparison with eigenfrequencies evaluated from low-amplitude vibrations records at Kurobe dam (ambient vibration and shaker tests in 1965, 1969 and 1996) shows rather good agreement when the water level and thermal conditions are the same but slight differences when thermal conditions are different even with the same water level.

8. Acknowledgements

This paper is based on the data recorded on Japanese dams and made available through [1]. The authors thank the JCOLD and dams' owners (J-POWER and KEPCO) which delivered the data as well as crucial information on the dams' geometry and the sensor layout in order to analyze it. The initiative of sharing this data is of great importance for countries that have not as much experience as Japan in this field in order to improve dam's safety.

9. References

[1] JCOLD (2014): Acceleration Records on Dams and Foundations No.3, *the Japan Commission on Large dams*

[2] JCOLD (2011): Static and Dynamic behaviour of Kurobe Dam – Record of measurements and observations on a High Arch Dam (1960-2007), Kansai Electric Power Co., Inc

[3] S.B.M Oliveira (2015): Vibrations monitoring in large dams, – *second international dam world conference*

[4] S.W. Alves, J.F. Hall (2006), System identification of a concrete arch dam and calibration of its finite element model, *Earthquake engineering and structural dynamics*