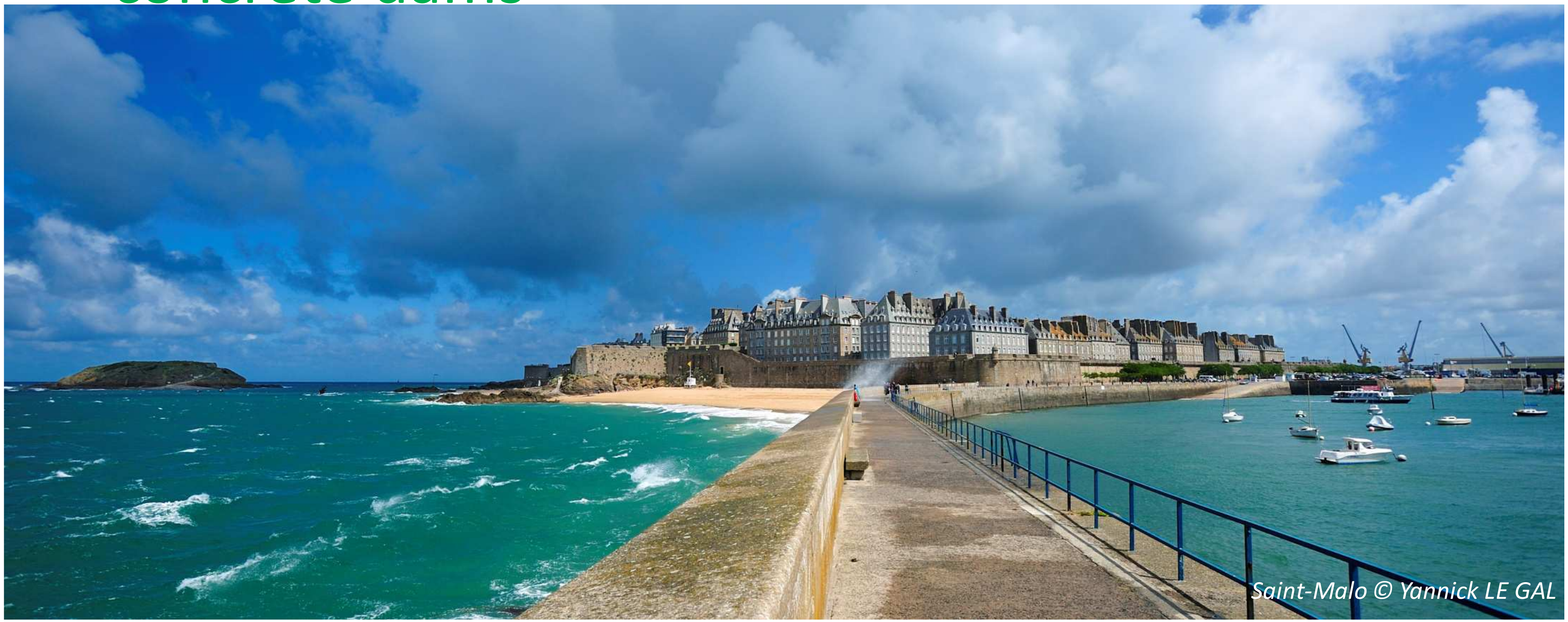
International Symposium
Qualification of dynamic analyses of dams and their equipments
and of probabilistic assessment seismic hazard in Europe
31th August – 2nd September 2016 – Saint-Malo

Emmanuel Robbe – Bruno Pallu

Session :

Dynamic behavior of concrete dams : data processing from the JCOLD database records on concrete dams


Saint-Malo © Yannick LE GAL

SUMMARY

INTRODUCTION

- **JCOLD provided acceleration records on dams and foundation, including a lot of concrete dams (more than 150)**

- **As conventional monitoring of concrete dams provides essential informations about static behavior, acceleration records, correctly processed, might also prove to be very useful to better understand behavior under earthquakes**

- **From accelerations records, data processing is essential and results are strongly dependent of the method used : an evaluation of several methods is then proposed**

- **Correctly analysed, these datas will be used to assess our calculation method**

PRESENTATION OF THE JCOLD DATABASE

- **« Acceleration records on dams and foundation n°3» in 2014 by the Japan Commission On Large Dams**
  - Earthquake records on rock foundation – 1978
  - Acceleration records on dams and foundation n°2 – 2002

- **Including records from :**
  - 1995 Southern Hyogo prefecture earthquake (M7.3)
  - 2000 Western Tottori Prefecture Earthquake (M7.3)
  - 2004 Mid Niigata Prefecture Earthquake (M6.8)
  - 2008 Iwate-Miyagi Nairiku Earthquake (M7.2)
  - 2011 off the Pacific coast of Tohoku Earthquake (M9.0)

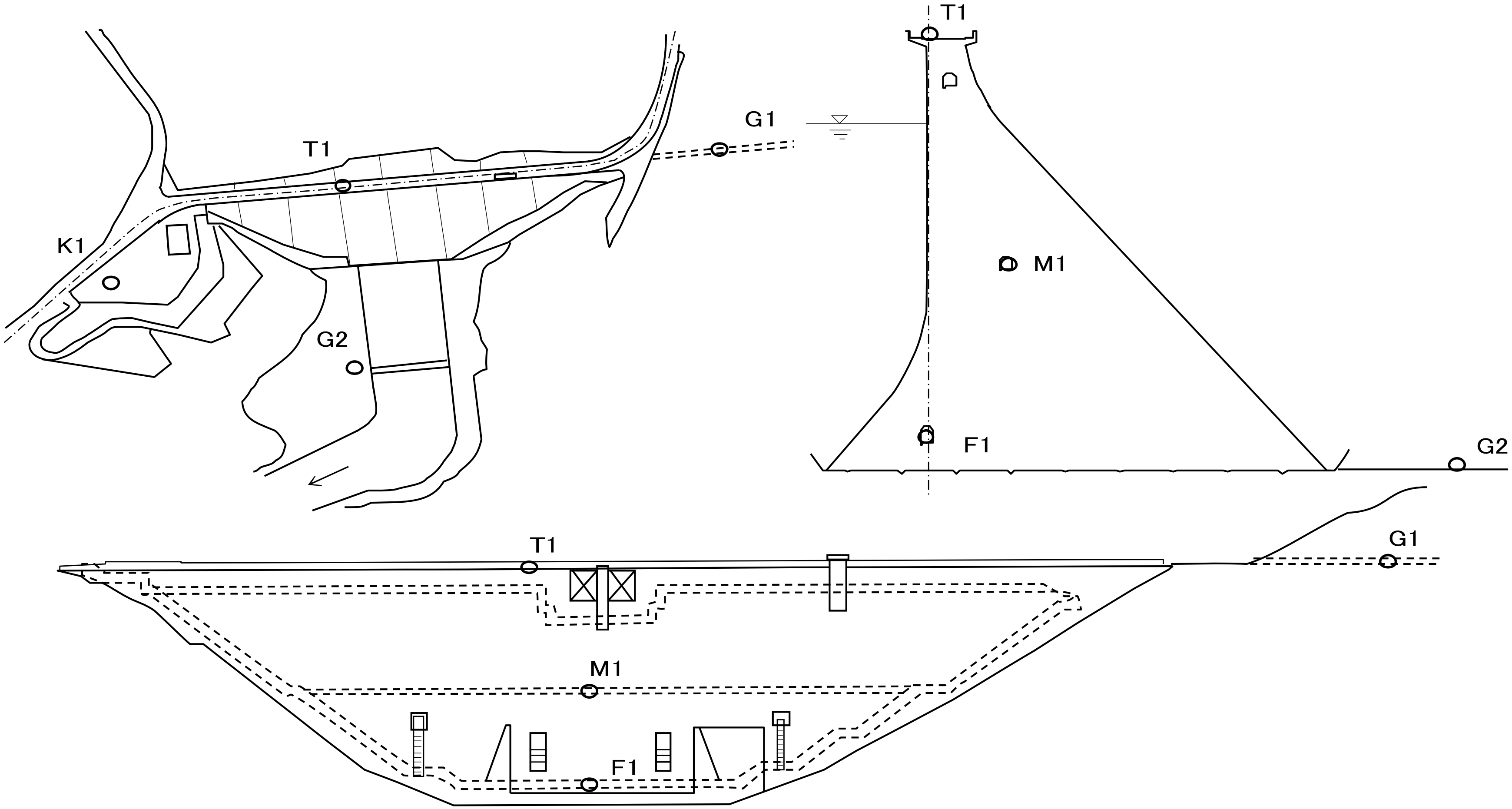
PRESENTATION OF THE JCOLD DATABASE

Dam Type	Symbol	Number of Dams[1)]	Number of Records	Number of Componet of Records
Concrete Gravity	G	135	223	1681
Concrete Arch	A	22	59	573
Rockfill	R	59	163	1888
Earthfill	E	18	99	899
Combined	GF	11	18	207
Concrete Facing	FC	3	15	89
Asphalt Facing	FA	3	15	249
Hollow Gravity	HG	5	5	33
Buttress	B	1	5	30
Total		257	602	5649

1) Number of dams which collected earthquake records

Source : T. SASAKI

PRESENTATION OF THE JCOLD DATABASE



T : Crest,　M : Dam Body,　F : Dam Foundation (Dam Bottom),　G : Ground

Source : T. SASAKI

PRESENTATION OF THE JCOLD DATABASE

Dam number	Name of dam	Type of dam	Height of dam (m)	Location symbol of seismograph	Symbol of direction	Symbol of positive (+) direction	Azimuth of axis (degree) (Positive (+) direction)	Elevation of seismograph (EL.m)	Peak acceleration (cm/s^2)	Name of digital accelerograms file	Coseismic water level (EL.m)	Origin date and time (Japan standard time)	Magnitude (M)	Depth (km)	Epicentral distance (km)	Geographical region name of epicenter (Name of earthquake)	Organization
70501	KUROBE	A	186	G1	A	DS	N4E	1320	-16.5	70501-20070325-094157-G1-A.csv	1381.7	2007/03/25 09:41:57.91	6.9	10.70	114	OFF NOTO PENINSULA	Kansai Electric Power Co., Inc
				G2	A	DS	N4E	1380	-22.8	70501-20070325-094157-G2-A.csv						(The Noto Hanto Earthquake in 2007)	
					B	R	N94E		-18.3	70501-20070325-094157-G2-B.csv							
					U	UP			20.4	70501-20070325-094157-G2-U.csv							
				G3	A	DS	N4E	1395	-26.0	70501-20070325-094157-G3-A.csv							
				Sd1	A	DS	N4E	1375	-69.8	70501-20070325-094157-Sd1-A.csv							
				T3	A	DS	N4E	1440	-54.2	70501-20070325-094157-T3-A.csv							
				T2	A	DS	N4E	1440	-108.0	70501-20070325-094157-T2-A.csv							
				T1	A	DS	N4E	1440	-165.3	70501-20070325-094157-T1-A.csv							
					B	R	N94E		-53.4	70501-20070325-094157-T1-B.csv							
					U	UP			75.4	70501-20070325-094157-T1-U.csv							
				T4	A	DS	N4E	1440	40.8	70501-20070325-094157-T4-A.csv							
				G1	A	DS	N4E	1320	45.5	70501-20110311-145442-G1-A.csv	1394.4	2011/03/11 14:54:42.18	4.1	0.00	3	HIDA MOUNTAINS REGION	
				G2	A	DS	N4E	1380	57.9	70501-20110311-145442-G2-A.csv							
					B	R	N94E		-80.4	70501-20110311-145442-G2-B.csv							
					U	UP			-30.5	70501-20110311-145442-G2-U.csv							
				G3	A	DS	N4E	1395	80.5	70501-20110311-145442-G3-A.csv							
				Sd1	A	DS	N4E	1375	-61.4	70501-20110311-145442-Sd1-A.csv							
				T3	A	DS	N4E	1440	-188.2	70501-20110311-145442-T3-A.csv							
				T2	A	DS	N4E	1440	-260.6	70501-20110311-145442-T2-A.csv							
				T1	A	DS	N4E	1440	176.1	70501-20110311-145442-T1-A.csv							
					B	R	N94E		-77.3	70501-20110311-145442-T1-B.csv							
					U	UP			-135.2	70501-20110311-145442-T1-U.csv							
				T4	A	DS	N4E	1440	65.8	70501-20110311-145442-T4-A.csv							
				F1	A	DS	N4E	1278	30.4	70501-20110311-145442-F1-A.csv							
					B	R	N94E		-27.3	70501-20110311-145442-F1-B.csv							
					U	UP			-20.1	70501-20110311-145442-F1-U.csv							

- **Example from the database**
  - Name and type of dam
  - Height of the dam
  - Location of seismograph, axis and positive directions
  - Waterlevel during the earthquakes
  - Information about the earthquake (M, depth, epicentral distance, name..)
  - Digital accelerograms file

- **Allow massive data processing with Python software**

SUMMARY

1. INTRODUCTION

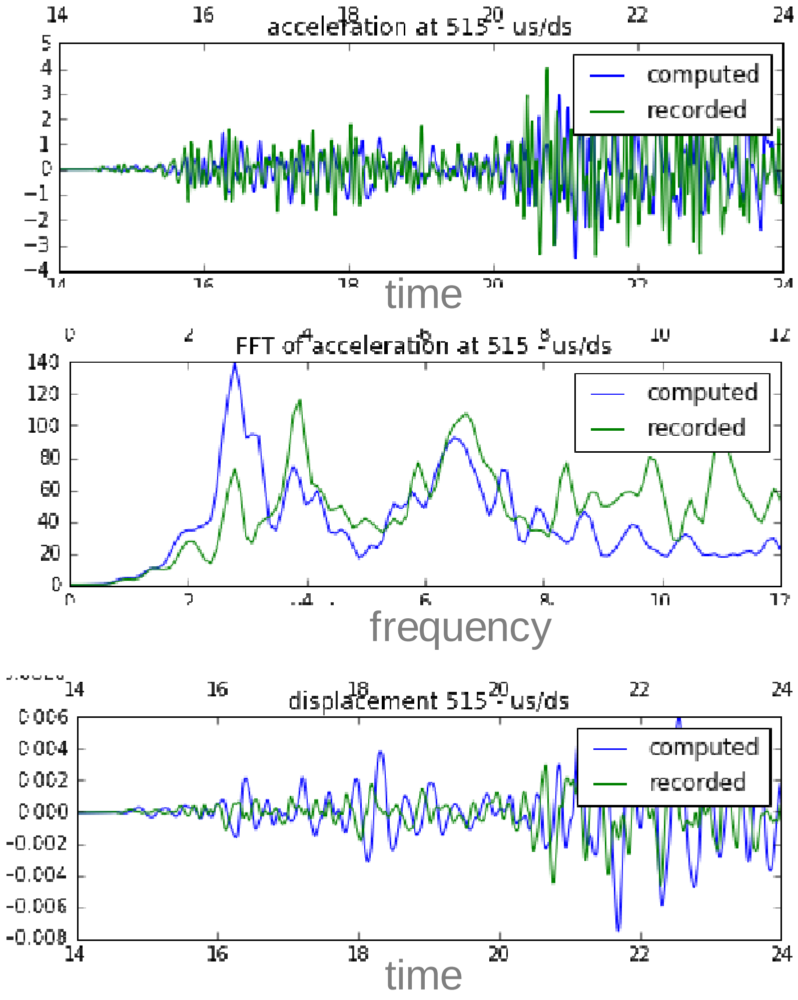
2. PRESENTATION OF THE JCOLD ACCELERATION DATA OF DAMS

3. **DATA PROCESSING FOR CONCRETE DAMS FROM EARTHQUAKES RECORDS**
   METHODS OF ANALYSIS FOR MODAL IDENTIFICATION
   APPLICATION ON TAGOKURA AND KUROBE DAMS

4. SPECIFIC DYNAMIC BEHAVIOR OF CONCRETE DAMS
   ANALYSIS OF KASHO GRAVITY DAM RECORDS
   ANALYSIS OF ASAHI ARCH DAM RECORDS

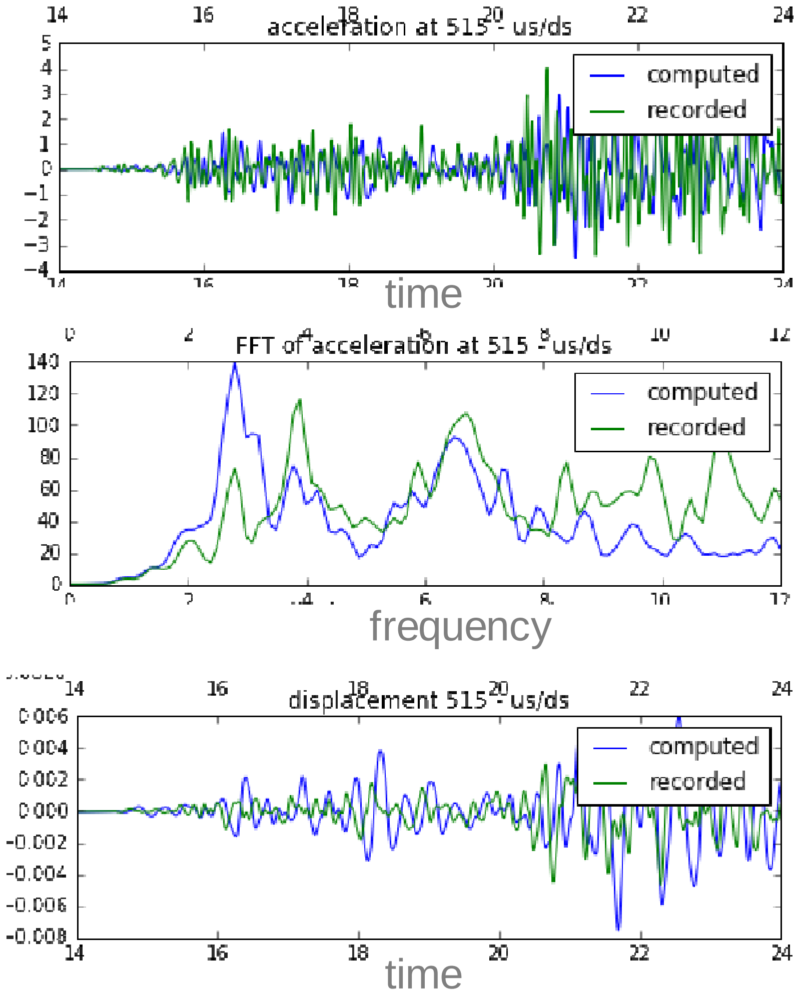
5. A(NOTHER) SIMPLIFIED FORMULA FOR GRAVITY DAM

DATA PROCESSING FOR CONCRETE DAMS FROM EARTHQUAKES RECORDS



- **Quick reminder of some basic operations**
- **Input:**
  - Acceleration vs time
- **Output**
  - Peak acceleration
  - Fourier spectrum = FFT[acc(t)]
  - Response spectrum (peak response of single DOF oscillator of varying natural frequency
  - Velocity, Displacement, Energy…

DATA PROCESSING FOR CONCRETE DAMS FROM EARTHQUAKES RECORDS



- **Quick reminder of some hidden operations**
  - Filtering..
  - Smoothering..
  - Windowing..

- **To make the results more clear..**

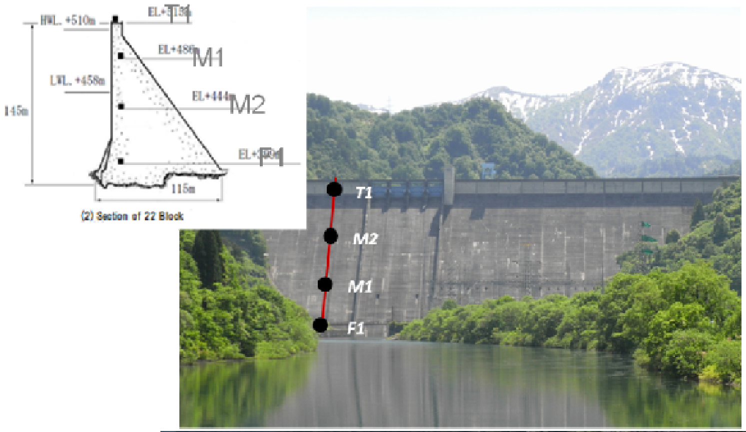
MODAL IDENTIFICATION FOR CONCRETE DAMS FROM EARTHQUAKES RECORDS

- **Evaluate the 1st natural frequencies of the dam**
  - Useful to conduct FE back analyses (calibration of FE model)
  - To compare with natural frequencies guessed from other methods (ambiant vibration tests, simplified formula..)
  - Useful for further data processing (damping evaluation..)

- **methods available are initialy design for conventional structures and long records (20-30 min)**

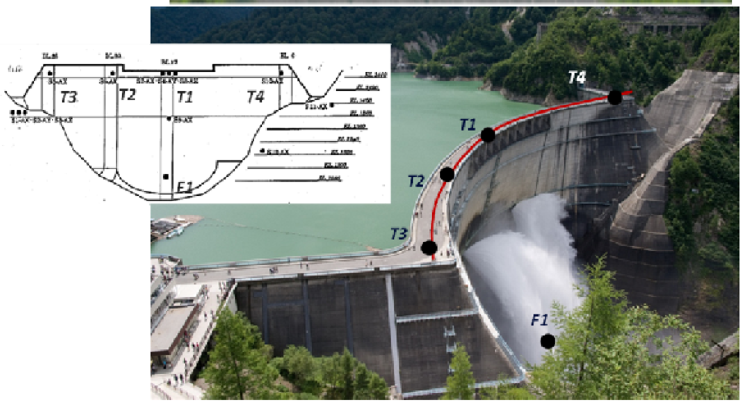
DATA PROCESSING : MODAL IDENTIFICATION

- **Application onTagokura gravity dam and Kurobe arch dam with several earthquakes records**



Tagokura Dam

T1
&
F1



Kurobe dam

T2
&
F1

Sensors actually used

DATA PROCESSING : MODAL IDENTIFICATION

Application onTagokura gravity dam and Kurobe arch dam with several earthquakes records

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

DATA PROCESSING : MODAL IDENTIFICATION

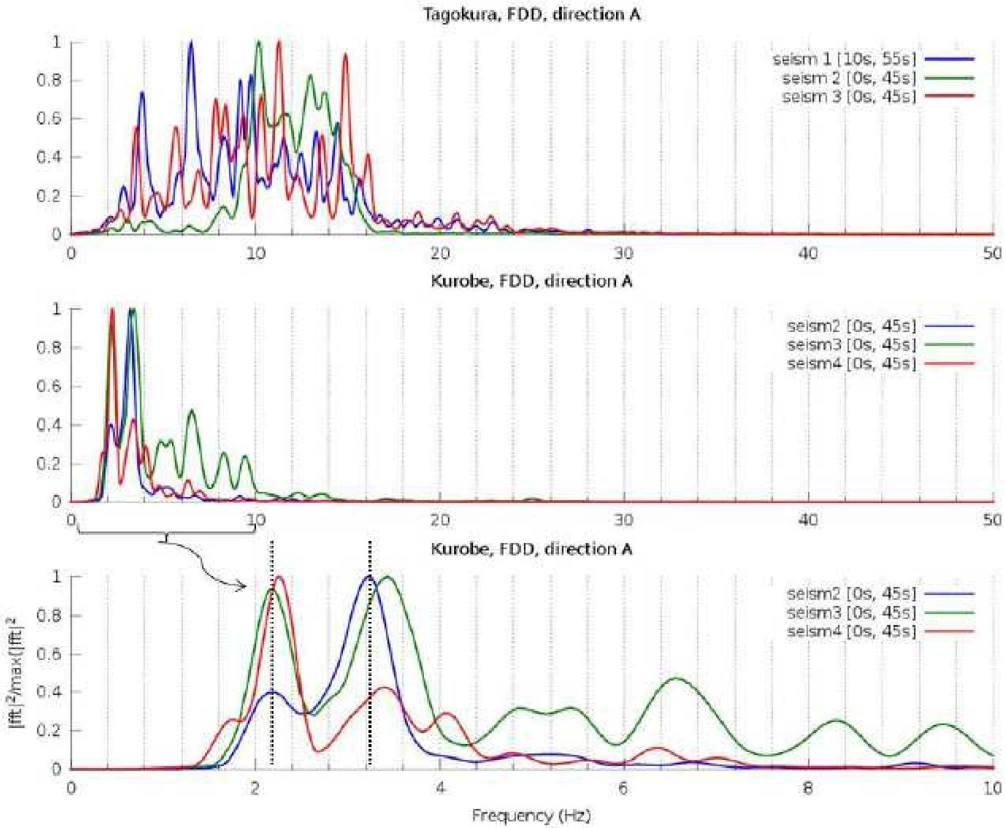
- **Rely on frequency-domain analyses with peak-picking**
- **Translation from temporal to frequency domain with Discrete Fourier transform (DFT) or spectrum response output (SRO)**

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

DATA PROCESSING : MODAL IDENTIFICATION
FREQUENCY DOMAIN DECOMPOSITION (FDD)

$$FDD(f) = \sum_{k=1}^{n} |sensor_k(f)|^2$$

- **Estimation of the dam's kinetic energy**
- **For Kurobe, FDD method shows peak around 2.3 and 3.3 Hz**
- **More difficult to reach any conclusion in Tagokura's case.**



DATA PROCESSING : MODAL IDENTIFICATION
CROSS SPECTRUM

$$CSa(f) = |Crest1(f) * Crest1(f)|$$

$$CSb(f) = |Crest1(f) * Crest2(f)|$$

$$CSc(f) = |Crest1(f) * Crest3(f)|$$

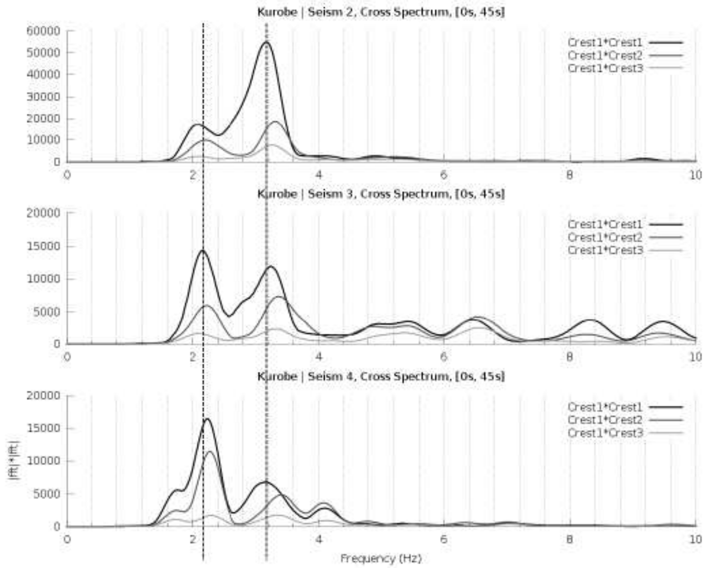
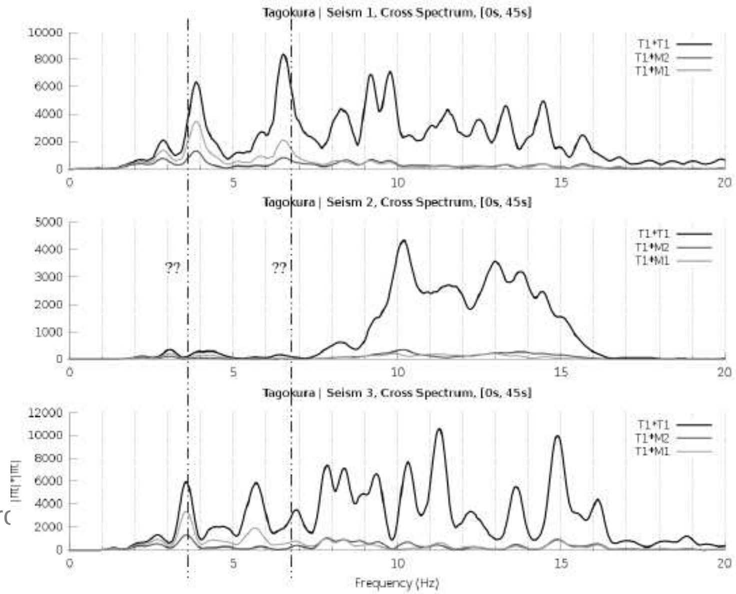


Fig. 3 – Kurobe, Cross-Spectrum, earthquakes 1,5 & 6

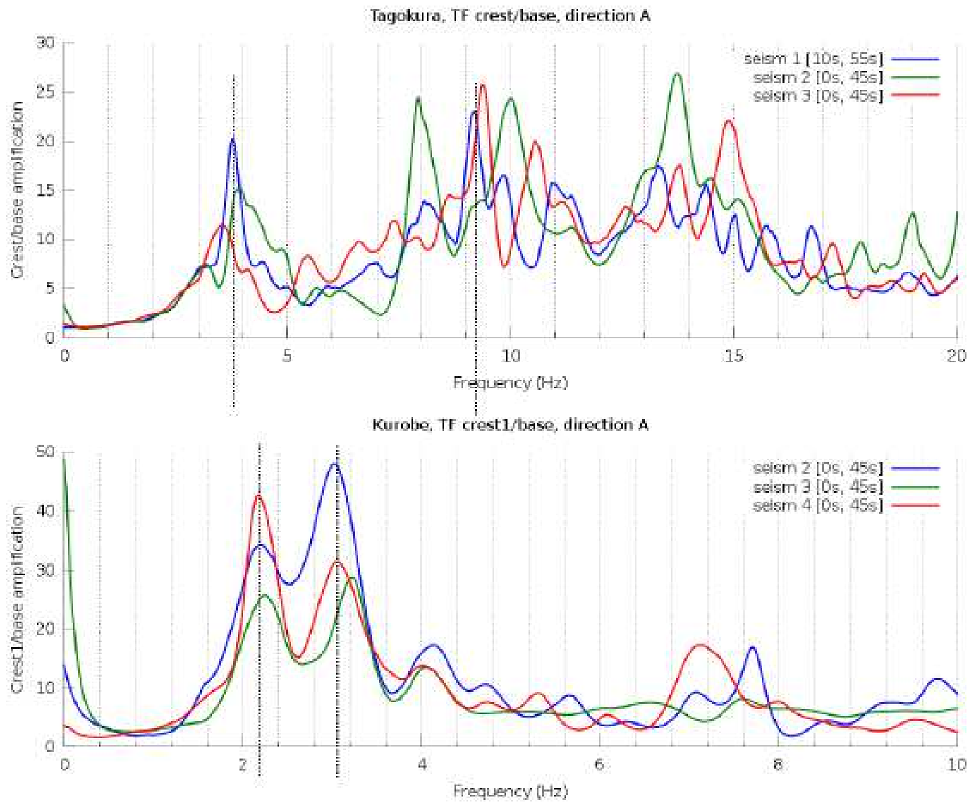
- **Dependent of the input frequency content**
- **For Kurobe, CS method shows peak around 2.2 and 3.2 Hz**
- **More difficult to reach any conclusion in Tagokura's case : first peak around 3.8 Hz for earthquake n°1 and 3 but nothing for earthquake n°2..**



DATA PROCESSING : MODAL IDENTIFICATION
TRANSFER FUNCTION

$$TF(f) = |Crest(f)/Base(f)|$$

- **Characteristics of each dam**
- **No big variations between earthquakes**
- **Results from different earthquake can be compared since the TF is normalized**



DATA PROCESSING : MODAL IDENTIFICATION
MEAN TRANSFER FUNCTION

$$TFm(f) = \frac{1}{N}\sum_{i=0}^{N-1} TF_{[i\tau, t_0+i\tau]}(f)$$

- **Averaging TFs calculated on 'sliding windows' :**
  - TF[0] computed over [0s:15s]
  - TF[1] computed over [1s:16s]
  - …
- **If the standart deviation does not vary to much**

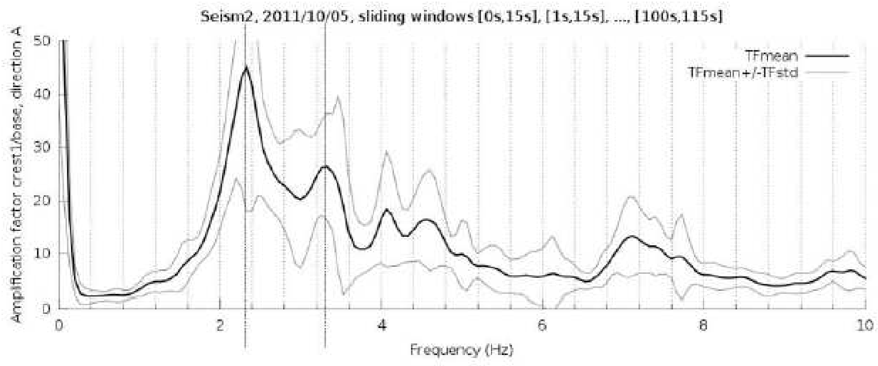


Fig. 6- Mean Transfer Function and standard deviation, Kurobe dam, Seism 2

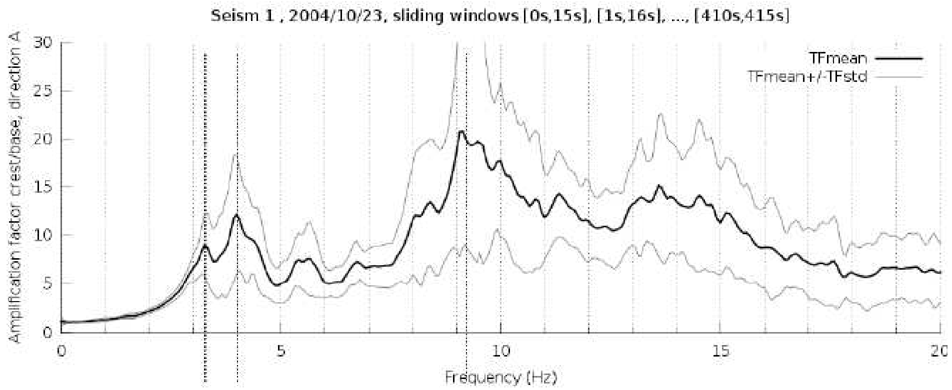


Fig. 7 - Mean Transfer Function and standard deviation, Tagokura dam, seism 1

DATA PROCESSING：MODAL IDENTIFICATION
MEAN TRANSFER FUNCTION

$$TFm(f) = \frac{1}{N}\sum_{i=0}^{N-1} TF_{[i\tau, t_0+i\tau]}(f)$$

- **Averaging TFs calculated on 'sliding windows' :**
  - TF[0] computed over [0s:15s]
  - TF[1] computed over [1s:16s]
  - …

- **If the standart deviation does not vary to much**

- **For Kurobe (high water leve) : 2.3 and 3.3 Hz**

- **For Tagokura : 3.3 and 3.9 Hz**

- **Use of smoothening function 0.06 Hz**

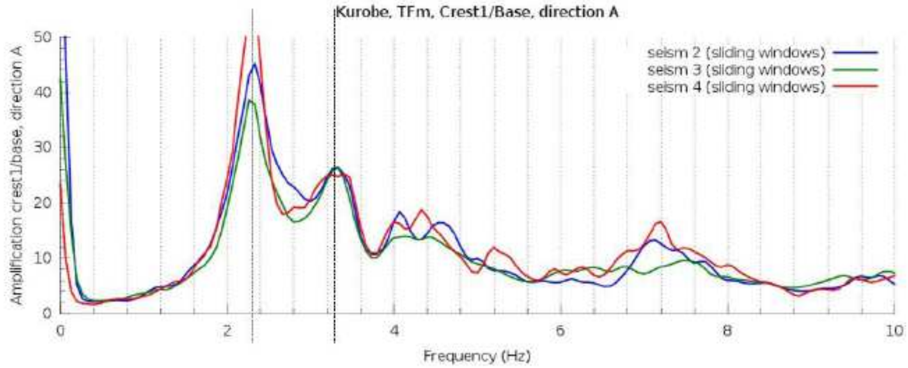
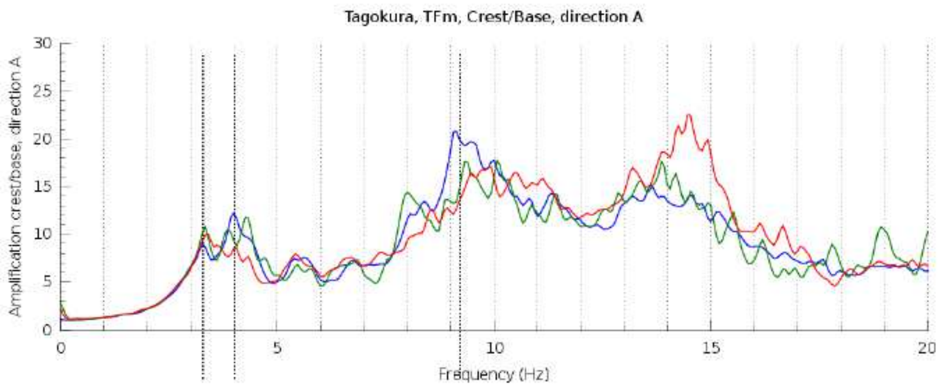


Fig. 8 – Kurobe dam mean Transfer Functions earthquakes 2,3,4 (high water level)



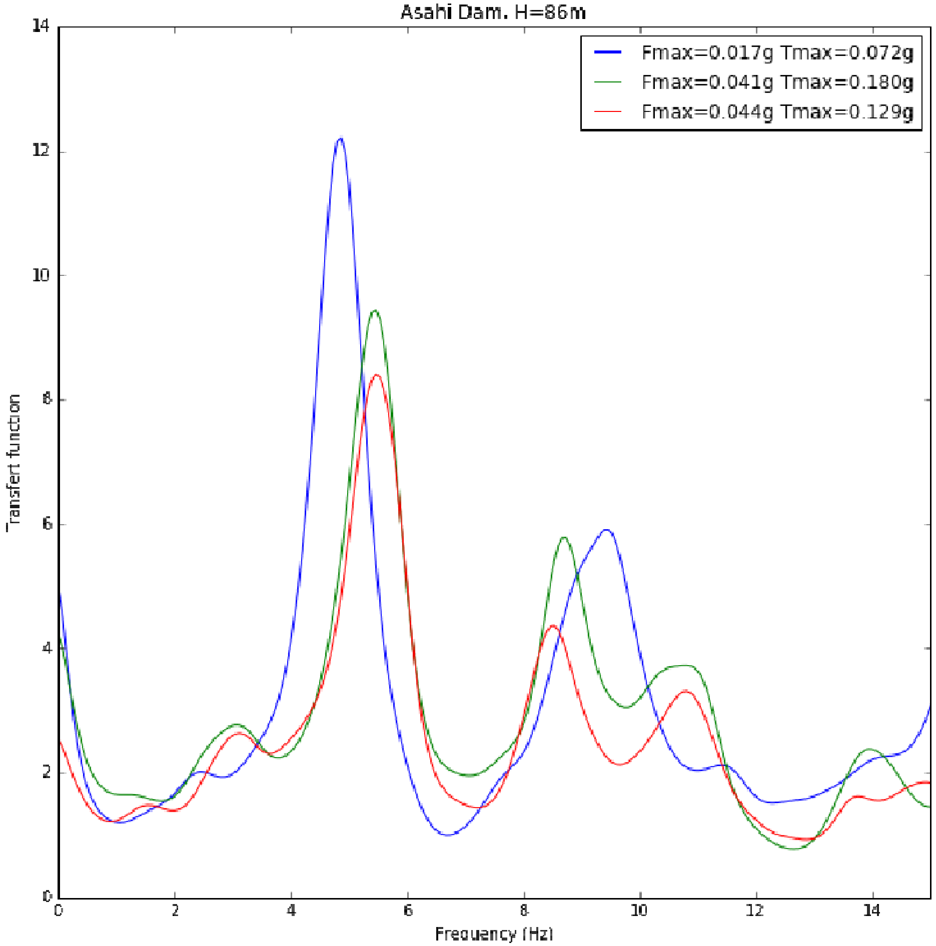
DATA PROCESSING : MODAL IDENTIFICATION
COMPARISON WITH SHAKER AND AMBIANT NOISE TESTS

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
July, 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

- **For comparable water level, eigenfrequencies evaluated by earthquake's record analysis are close from 1996 test**
- **Differences with 1965 and 1969 test might come from thermal effects**

SUMMARY

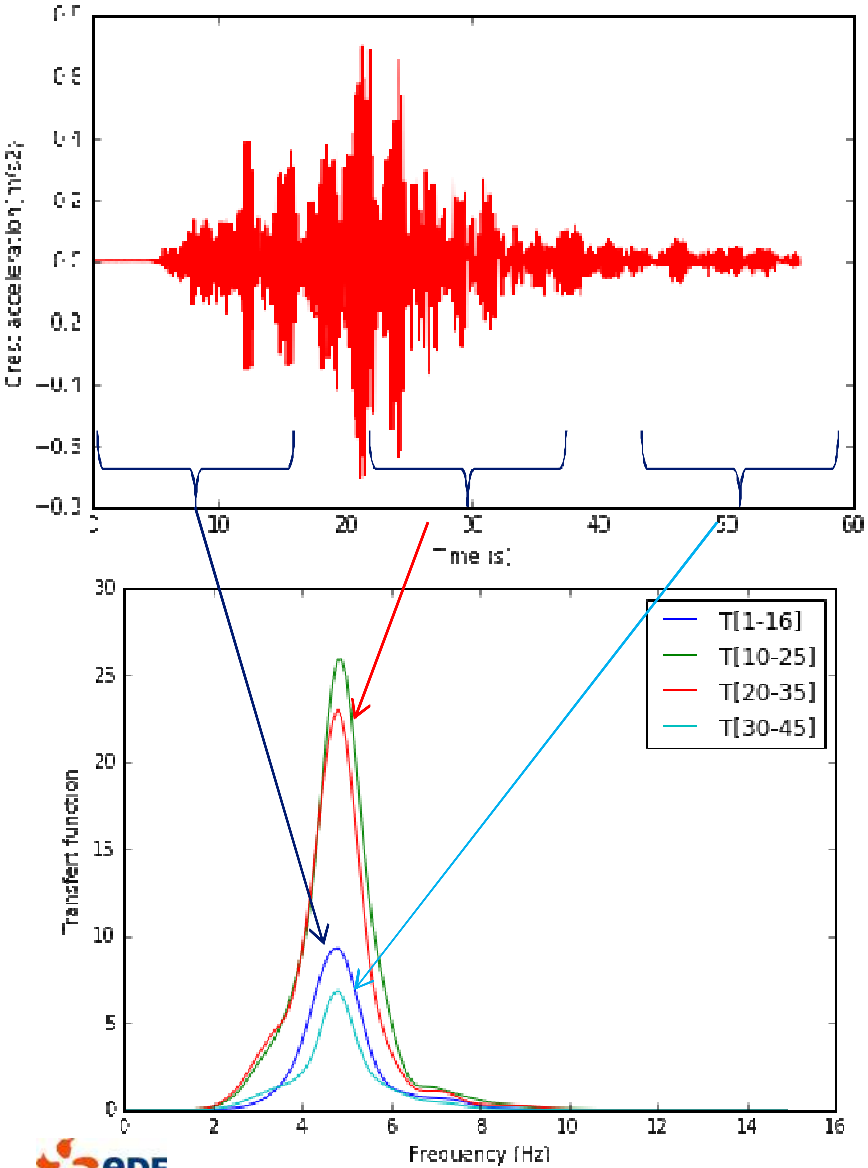
SPECIFIC DYNAMIC BEHAVIOR OF CONCRETE DAM



- **Analysis of ASAHI arch dam records (H=81.5m)**
  - 17 jan 1995 (M7.3)
    PGA 0.017 g –water level : 434.5
  - 5 sept 2004 (M7.1)
    PGA 0.041g – water level : 447.3
  - 5 sept 2004 (M7.4)
    PGA 0.044g – water level : 447.3

- **←Mean Transfert function**
  - 1st natural freq varies :
    4.9 Hz for low water level +winter
    5.5 Hz for higher water level + summer

SPECIFIC DYNAMIC BEHAVIOR OF CONCRETE DAM



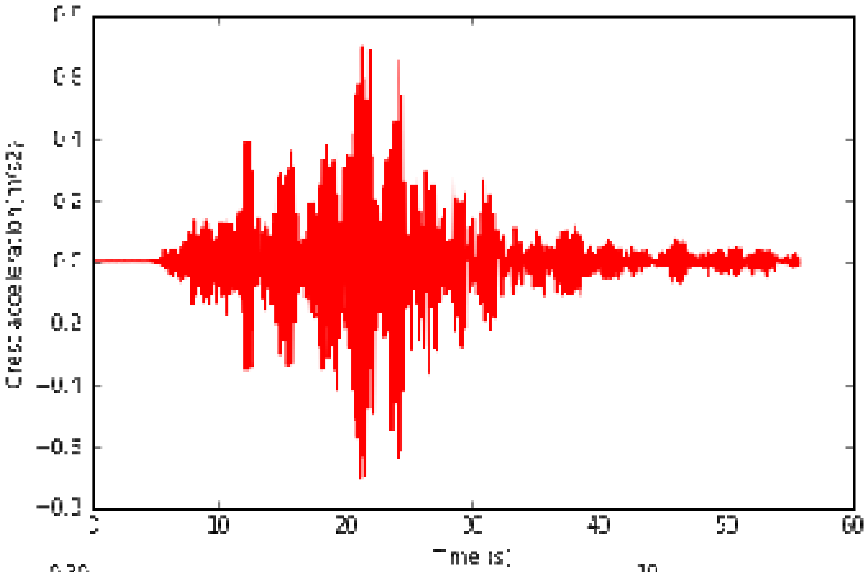
- **Analysis of ASAHI arch dam records (H=81.5m)**
  - 17 jan 1995 (M7.3)

  PGA 0.017 g –water level : 434.5

From crest record :

- bandpass filter [3-7Hz] (around nat. freq)
- FFT(acc[0-15s]), FFT(acc[1-16s]….)
- Evalutation of 1st natural frequency
- Evaluation of damping by halfpower bandwith method

SPECIFIC DYNAMIC BEHAVIOR OF CONCRETE DAM

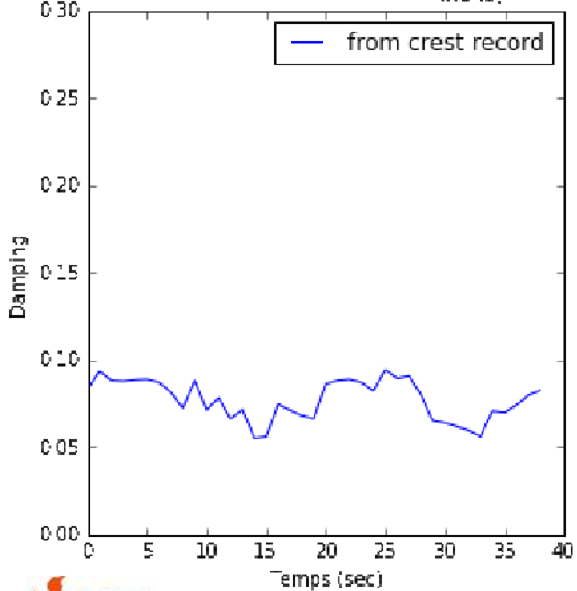


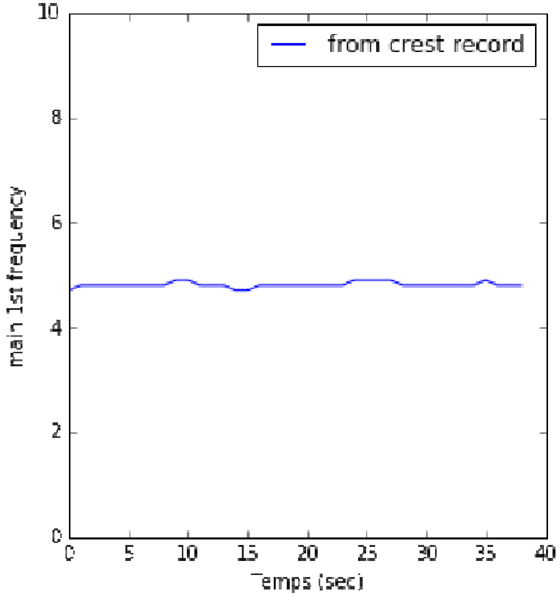
- **Analysis of ASAHI arch dam records (H=81.5m)**
  - 17 jan 1995 (M7.3)

    PGA 0.017 g –water level : 434.5

    <u>PCA/PGA = 4.1</u>

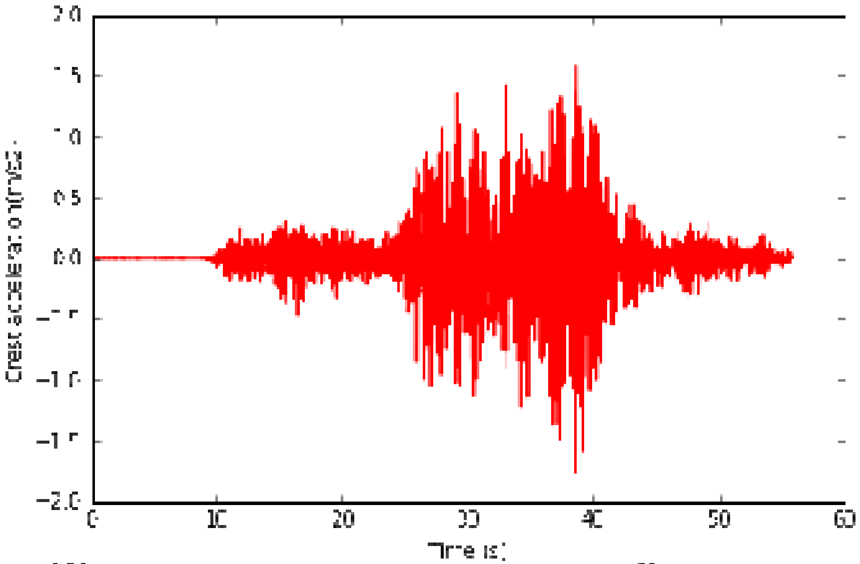
    From crest record :





damping around 7% for eq1

SPECIFIC DYNAMIC BEHAVIOR OF CONCRETE DAM

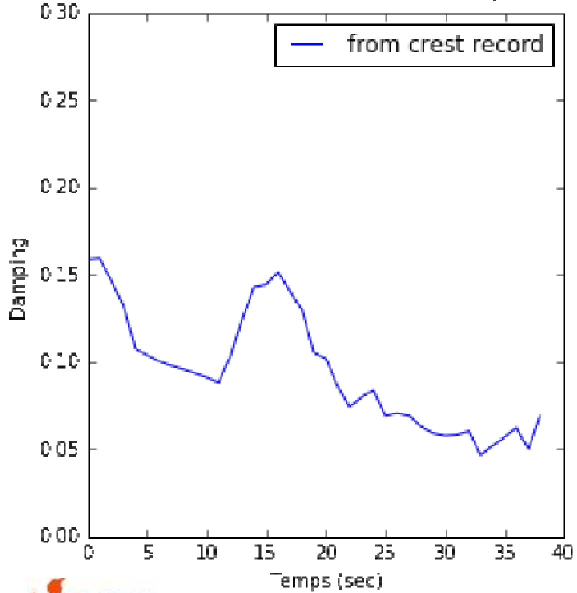


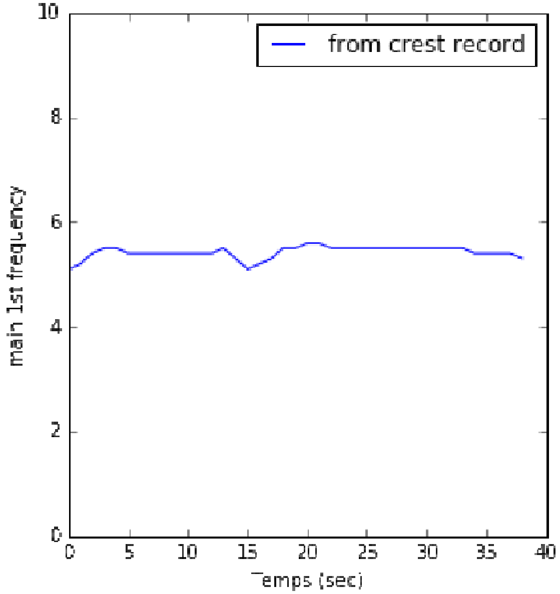
- **Analysis of ASAHI arch dam records (H=81.5m)**
  - 5 sept 2004 (M7.1)

PGA 0.041g – water level : 447.3

PCA/PGA=3.9

From crest record :

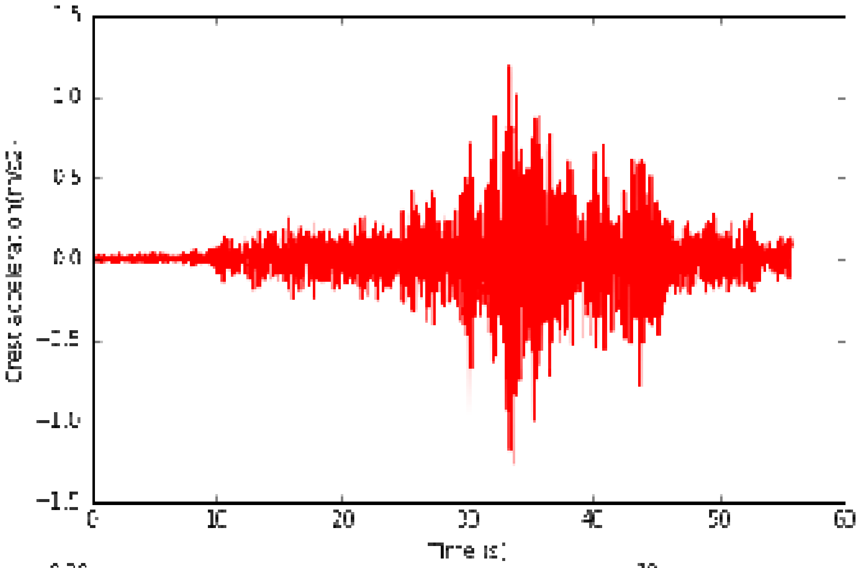




damping around 7% for eq1

damping 10--> 5% for eq2

SPECIFIC DYNAMIC BEHAVIOR OF CONCRETE DAM

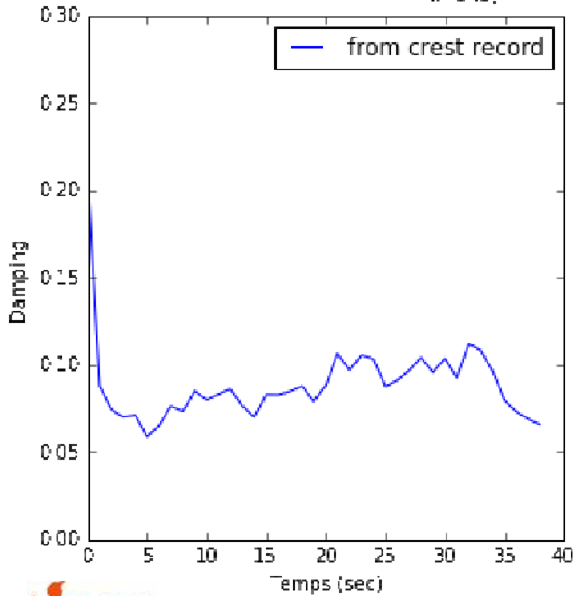


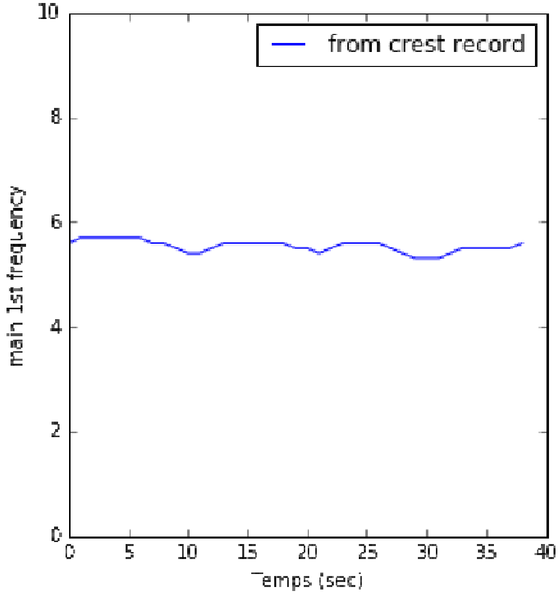
- **Analysis of ASAHI arch dam records (H=81.5m)**
  - 5 sept 2004 (M7.4)

    PGA 0.044g – water level : 447.3

    PCA/PGA=3.3

    From crest record :





damping around 7% for eq1

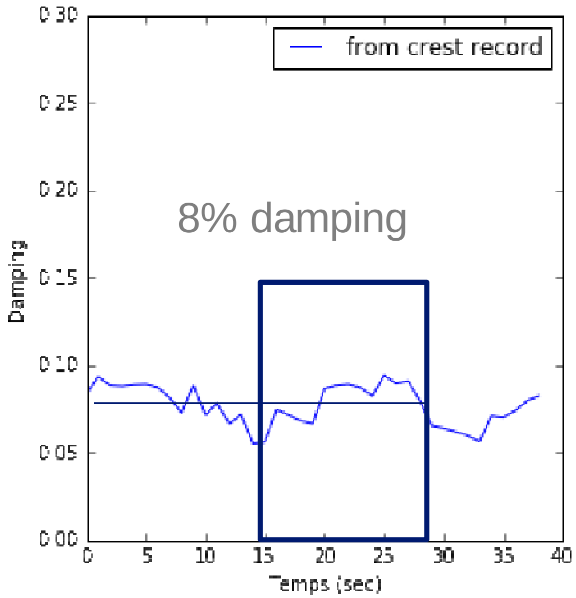
damping 10--> 5% for eq2

damping 7--> 10% for eq3

SPECIFIC DYNAMIC BEHAVIOR OF CONCRETE DAM

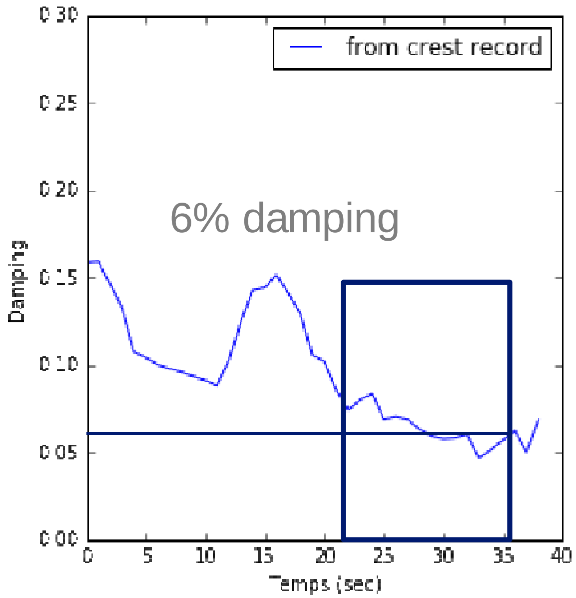
- **Analysis of ASAHI arch dam records (H=81.5m)**

PGA=0.017g
PGV=0.011m/s
PGD=1.08mm



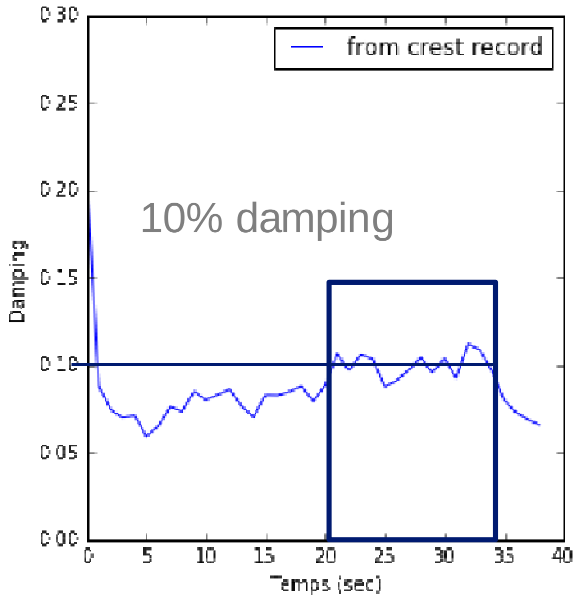
PCA/PGA=4.15

PGA=0.041g
PGV=0.012m/s
PGD=0.65mm



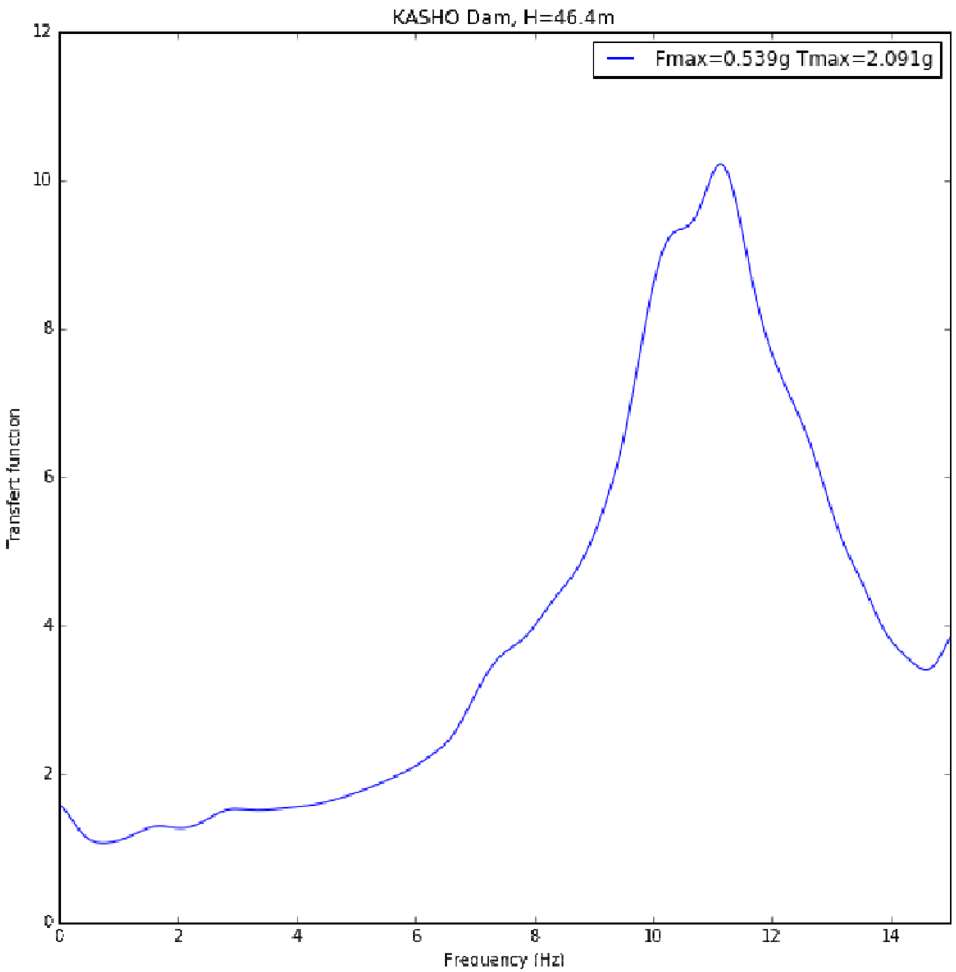
PCA/PGA=3.9

PGA=0.044g
PGV=0.015
PGD=1.02mm



PCA/PGA=3.3

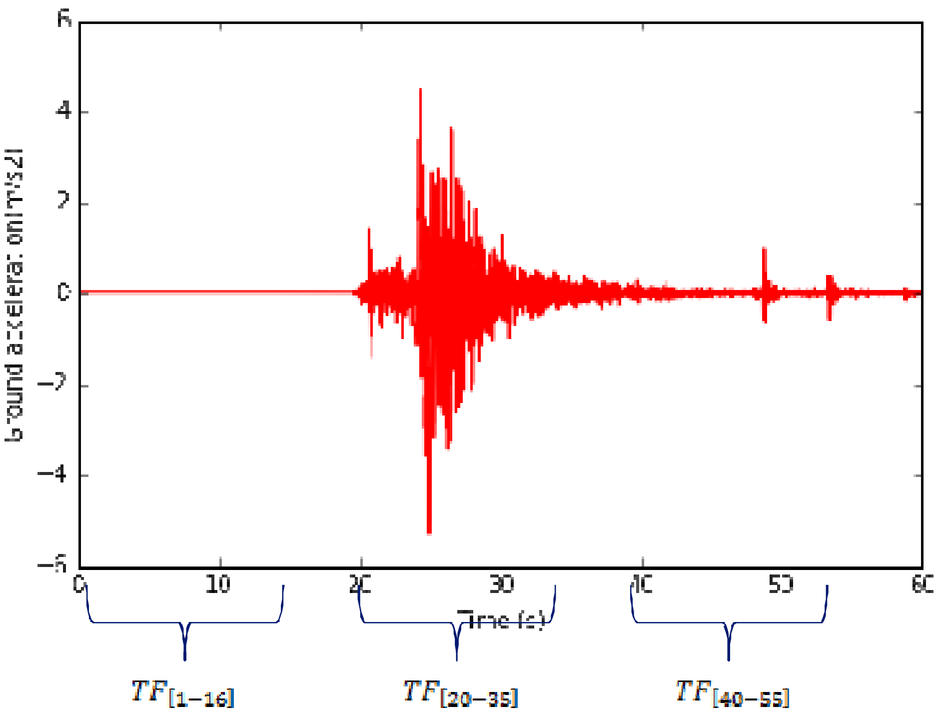
SPECIFIC DYNAMIC BEHAVIOR OF CONCRETE DAM

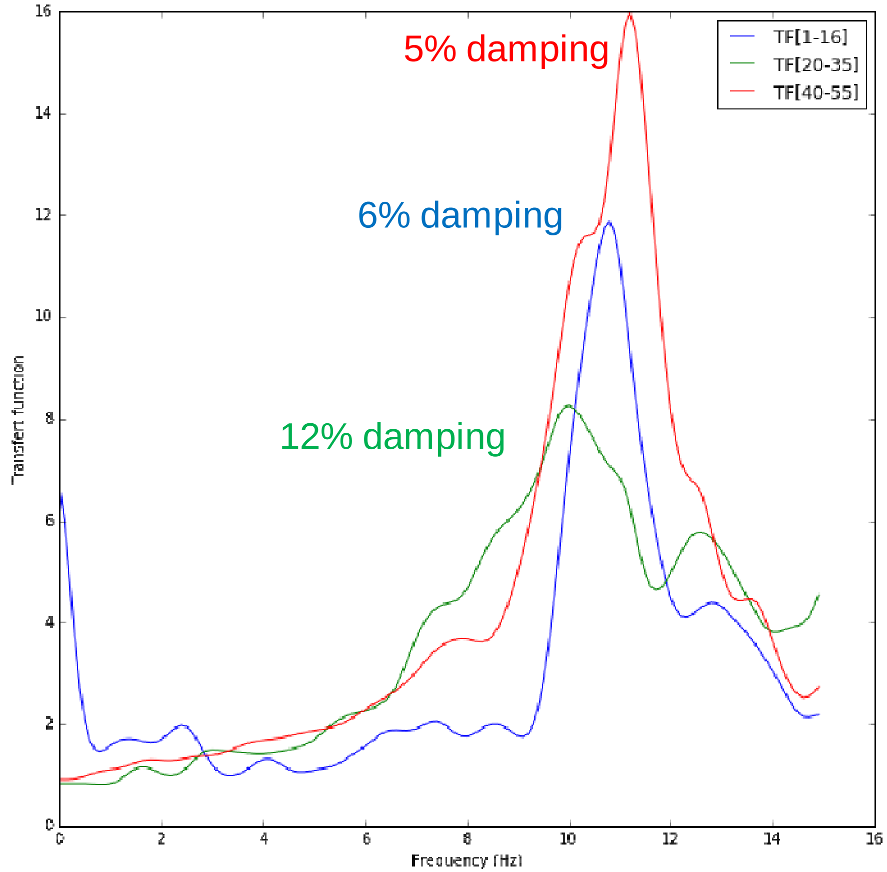


- **Analysis of Kasho dam records (H=46.4m)**
  - 6 oct 2000 (M7.3)
  - PGA 0.54 g recorded at the bottom of the dam
- **←Mean Transfert function**

SPECIFIC DYNAMIC BEHAVIOR OF CONCRETE DAM

- **Analysis of Kasho dam records (H=46.4m)**

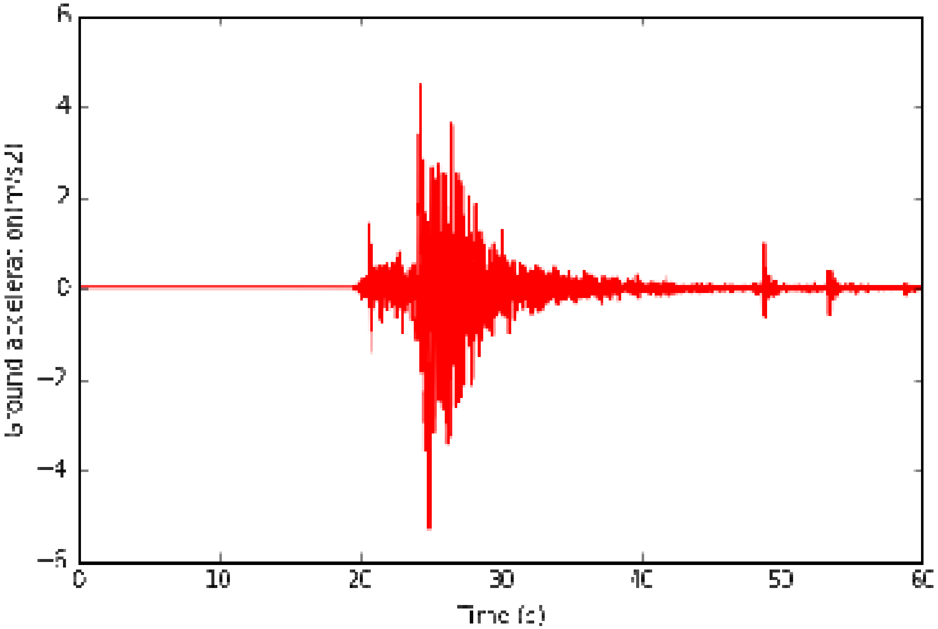




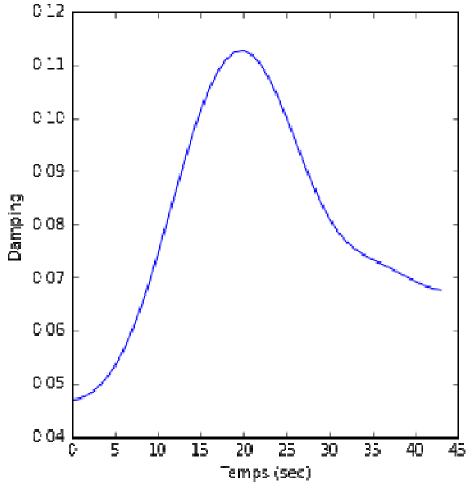
Evaluation of the damping with halfpower bandwith method :

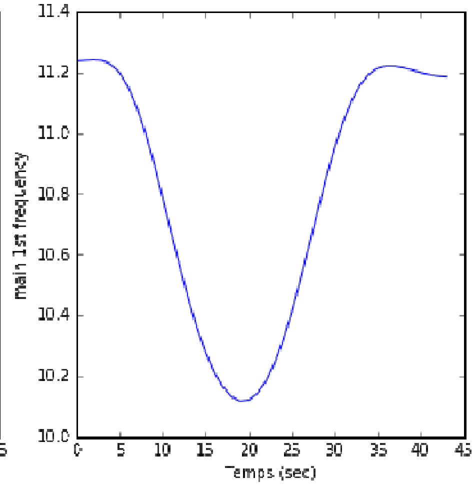
- values vary with data processing (smoothening, hanning window)

SPECIFIC DYNAMIC BEHAVIOR OF CONCRETE DAM



- **Analysis of Kasho dam records (H=46.4m)**
  - Evolution of the damping and 1st frequency





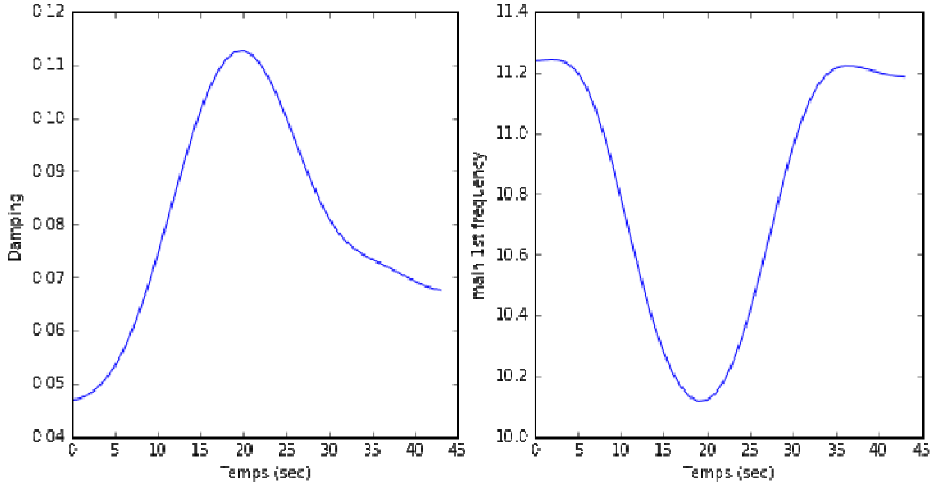
SPECIFIC DYNAMIC BEHAVIOR OF CONCRETE DAM

In this case : during the high intensity content of the earthquake :

- increase of the damping from 5→11 %

- slight decrease of the first frequency (might be due to the opening of the vertical joint opening = reduction of the 3D effect

- **Analysis of Kasho dam records (H=46.4m)**
  - Evolution of the damping and 1st frequency



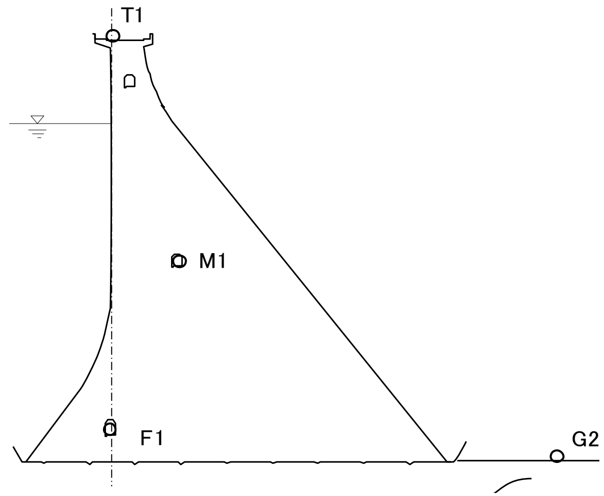
SUMMARY

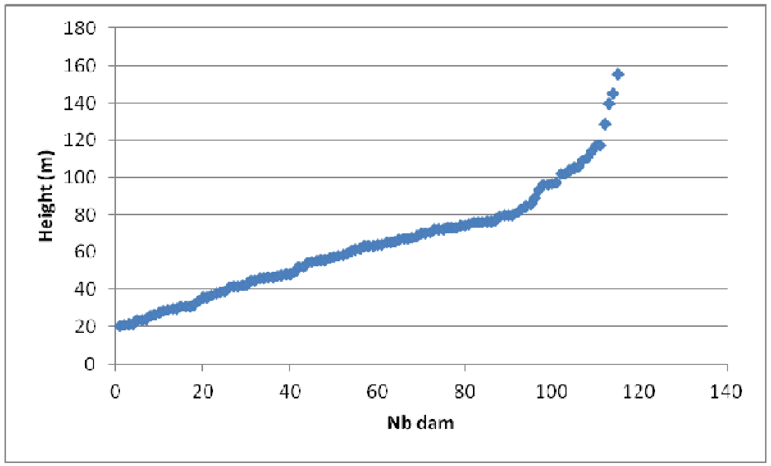
ANALYSES OF GRAVITY DAM RECORDS

- **From the records of 115 gravity dams (/135) with F1 (bottom) and T1 (crest) records available**

- **8 dams with more than 4 records available**
  - (among them : 10 for Tagokura dam, 9 for Kasho dam, 8 for Tase dam)

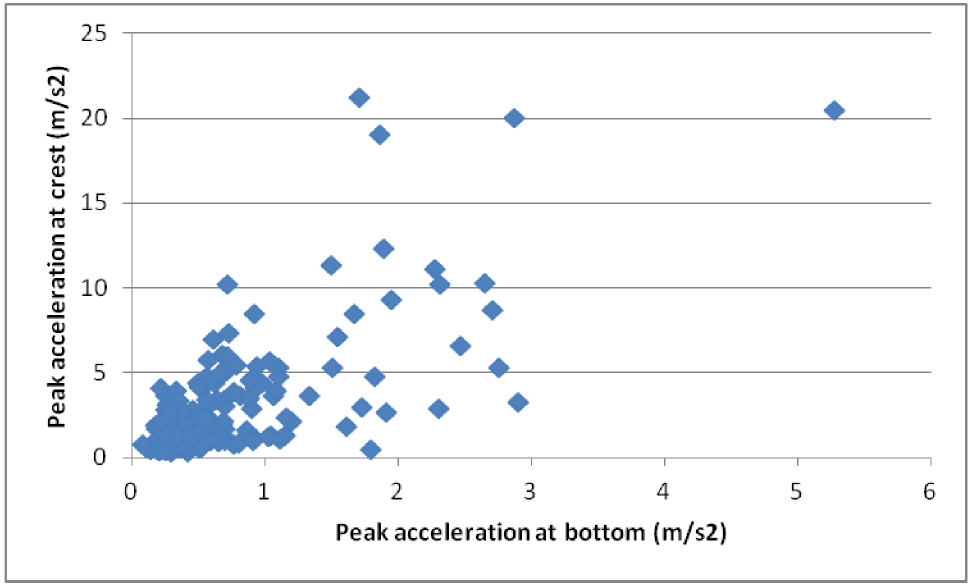
- **Height of dam from 20.3 → 155m with a good representation of each size**





ANALYSES OF GRAVITY DAM RECORDS

- **Peak acceleration at crest vs peak ground accélération**
  - (With 1-15 Hz filter)



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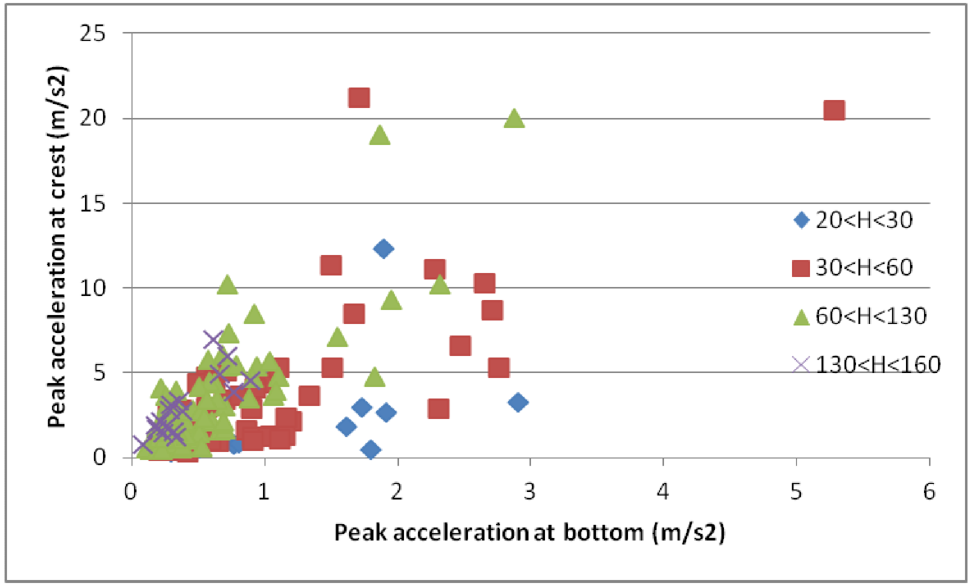

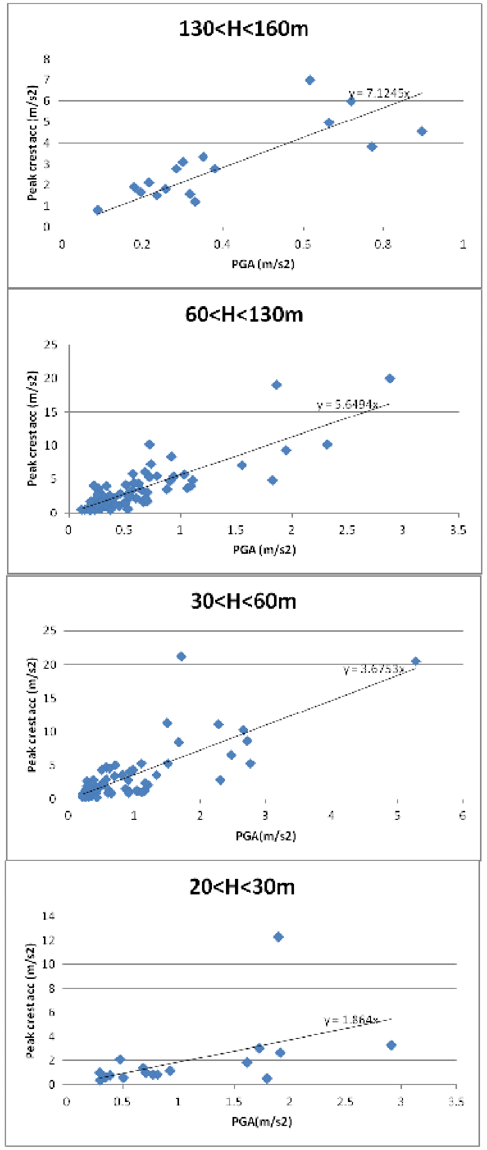

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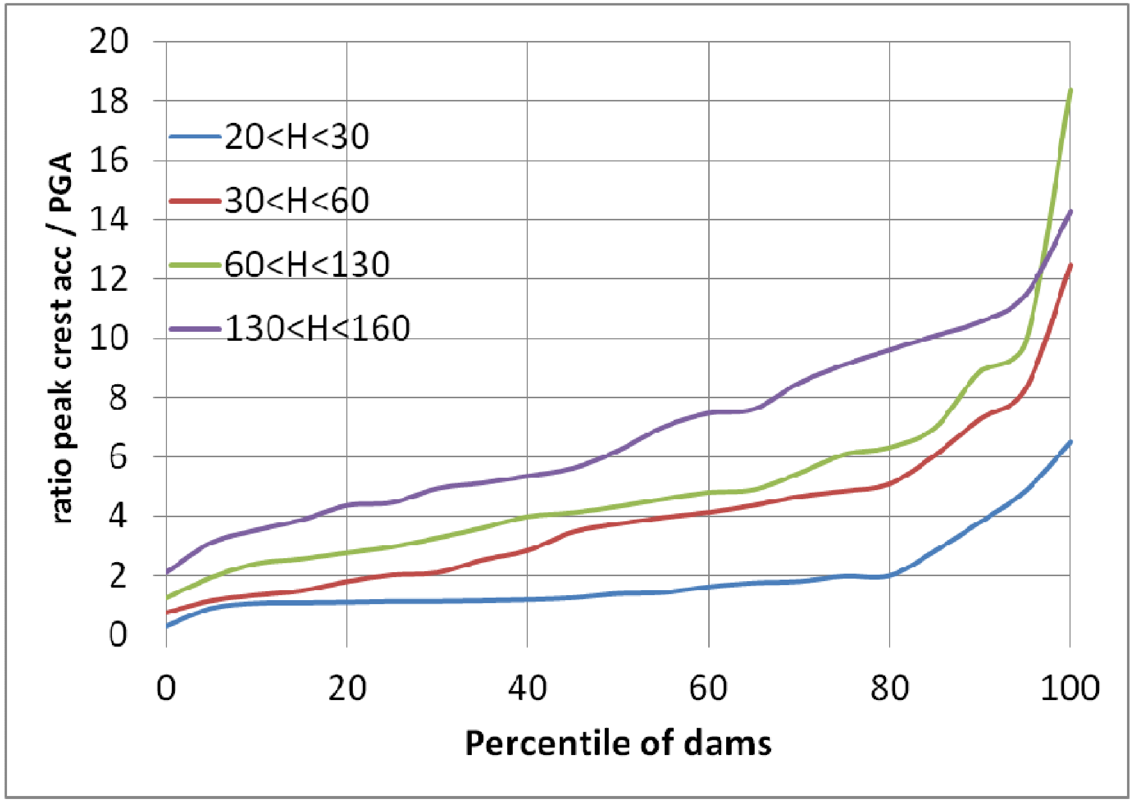
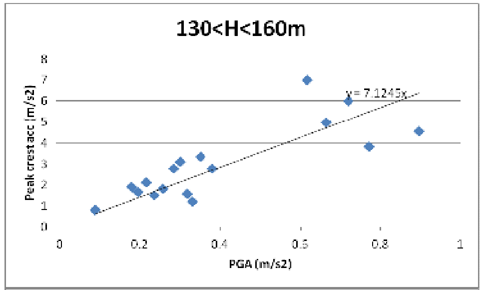
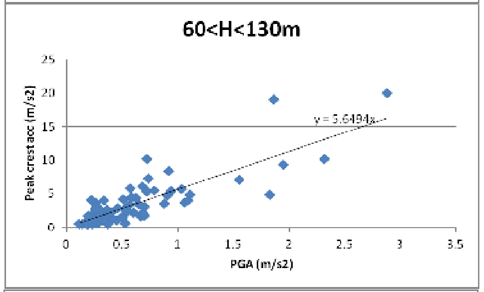
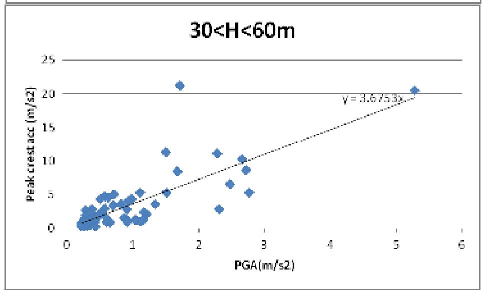
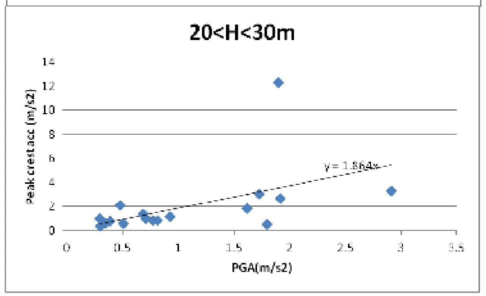




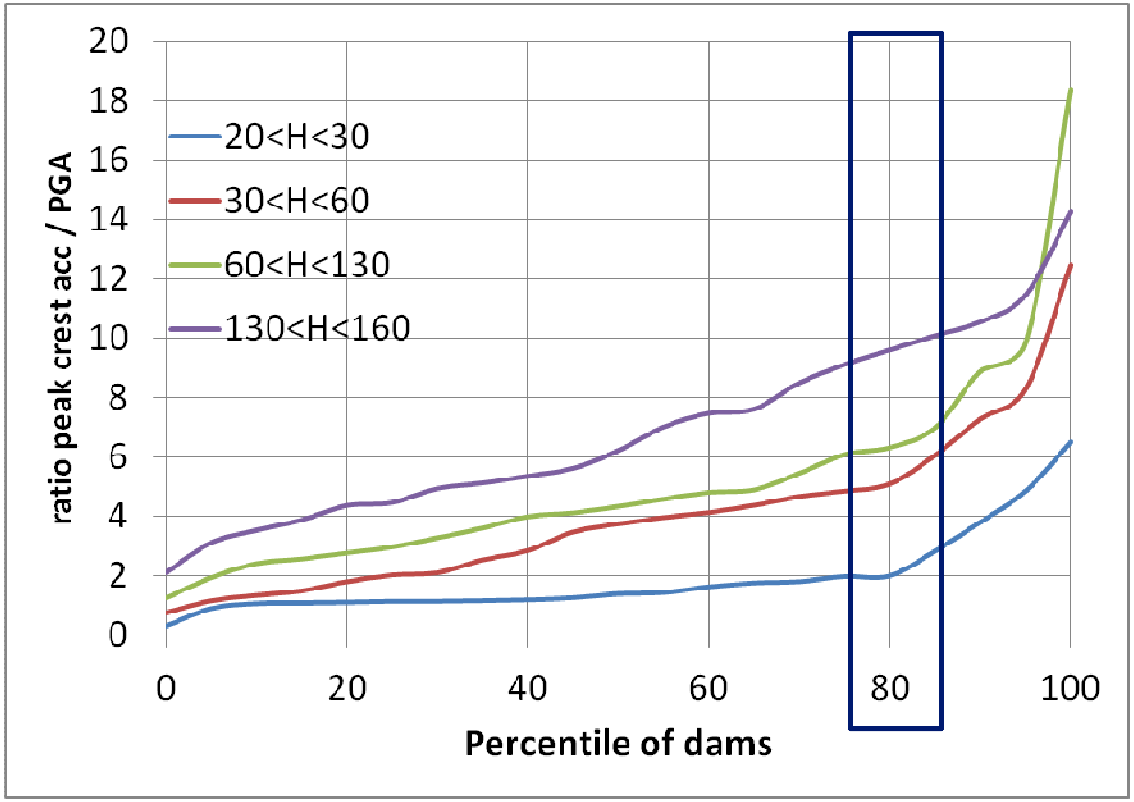






ANALYSES OF GRAVITY DAM RECORDS

- **Peak acceleration at crest vs peak ground accélération**



For 80% of the dams :

20<H<30m : PCA/PGA<2

30<H<60m : PCA/PGA<5

60<H<130m : PCA/PGA<6.3

130<H<160m : PCA/PGA<9.6

Roughly : **PCA = PGA*0.07*H**

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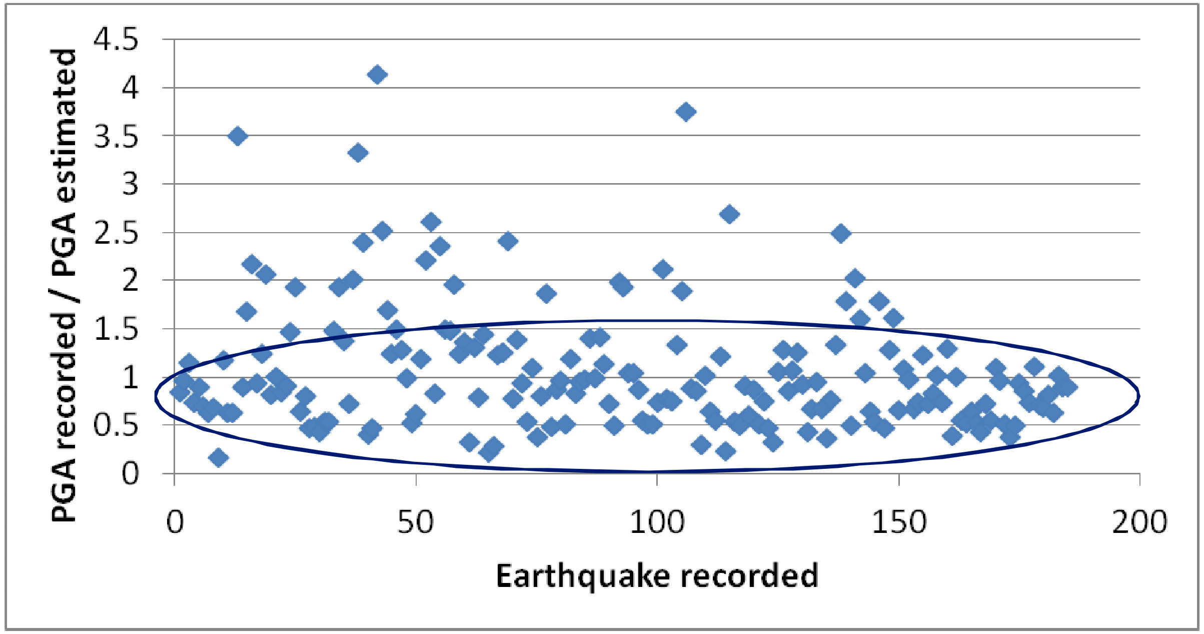

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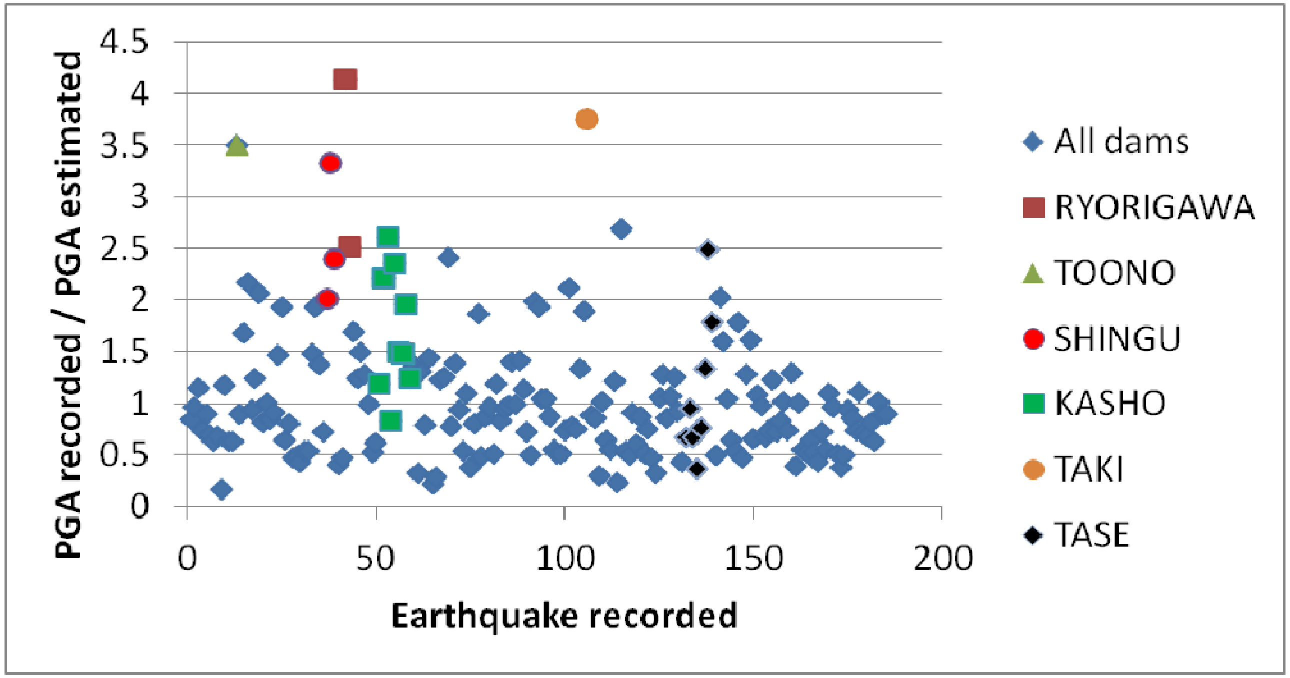


Interesting to look for results well over the average :

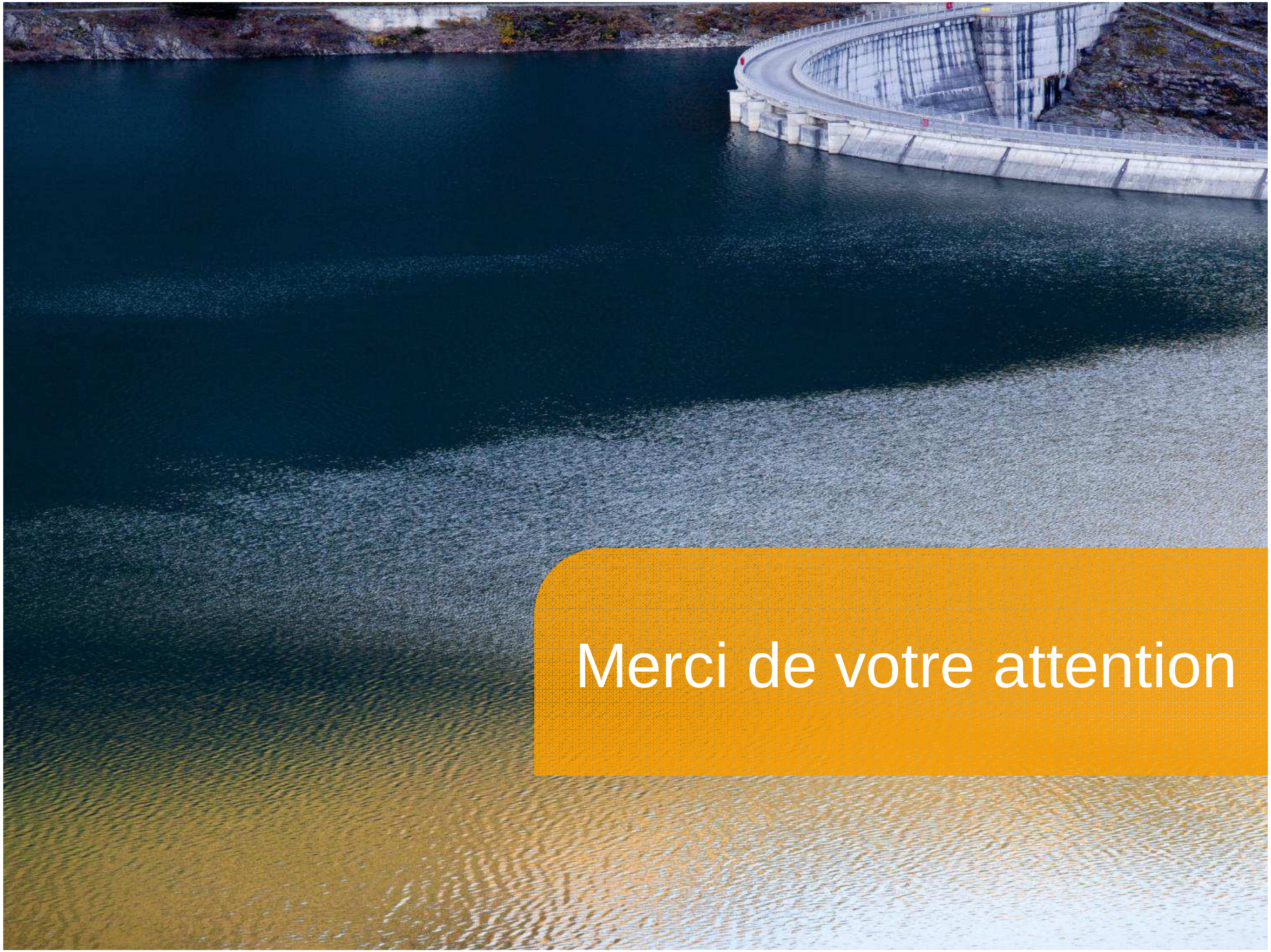
- due to the position of the accelerometer (Kasho dam?)

-due to the dam's characteristics?

- due to the earthquake input? (Tase dam ?)

CONCLUSION

- **Data processing of the JCOLD database should be very useful to :**
  - Better understand dam’s behavior under earthquake
  - Try to quantify characteristics (damping, 1st natural frequency)
  - Calibrate and evaluate FE and simplified analyses
- **Still a lot of analyses to do to understand response’s variation for a dam with several earthquakes**
- **To be continued**


Merci de votre attention