2nd "Dams and Seismic" EWG Workshop
Qualification of dynamic analyses of dams and their equipment
and of probabilistic assessment seismic hazard in Europe
Lessons learned from the recent earthquakes in Italy
6th February – 7th February 2017 – Roma

Session 4 : Seismic analysis of embankment dams

Qualification of the simplified JCOLD-CFBR method assessing the seismic behavior of dams founded on rocks

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Introduction

Outputs of exchanges between JCOLD-CFBR

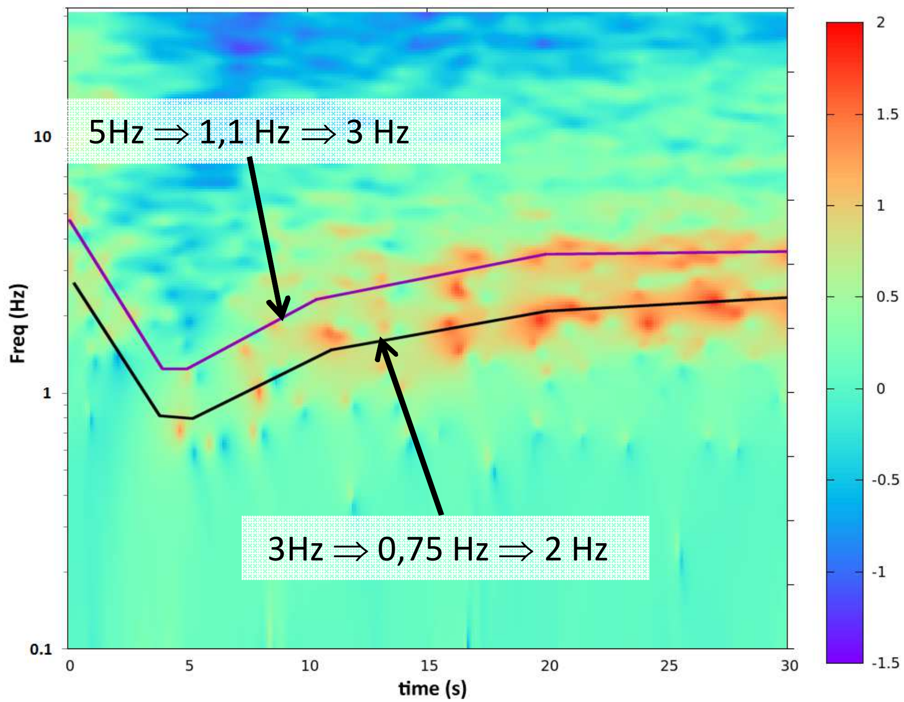
- Thanks to JCOLD, predicted behavior of 2 rockfill dams in Japan could be compared with the predicted behavior by sophisticated or simplified analyses:
  - Aratozawa dam under PGA=1g !
  - Takami dam under PGA=0,05g
- Main conclusions were :
  1. Sophisticated analysis did not converge: large displacements and pore pressure generation were predicted although limited permanent displacements were observed and the dam was safe!!!
  2. usual simplified dynamic methods don't predict pore pressure increase and its impact on dynamic behavior.
  3. Without good fitting, simplified methods can over-estimate instabilities, sliding and permanent displacements. Most of them do not predict the settlement (risk of overtopping)

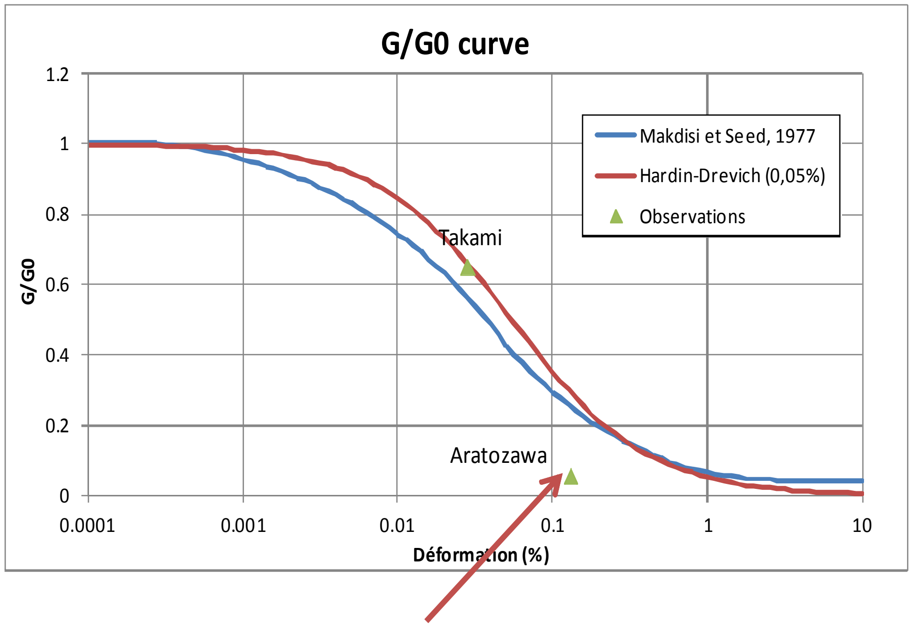
Introduction

Outputs of exchanges between JCOLD-CFBR

- Example of ARATOZAWA dam

Evolution of transfer function ==>> Evolution of shear modulus





Drop of rigidity bigger than predicted

Introduction

Outputs of exchanges between JCOLD-CFBR

- Example of ARATOZAWA dam

Pore pressure increase just after the earthquake (From Ohmachi and Tahara paper, 2011)

Drop of rigidity remains after the earthquake

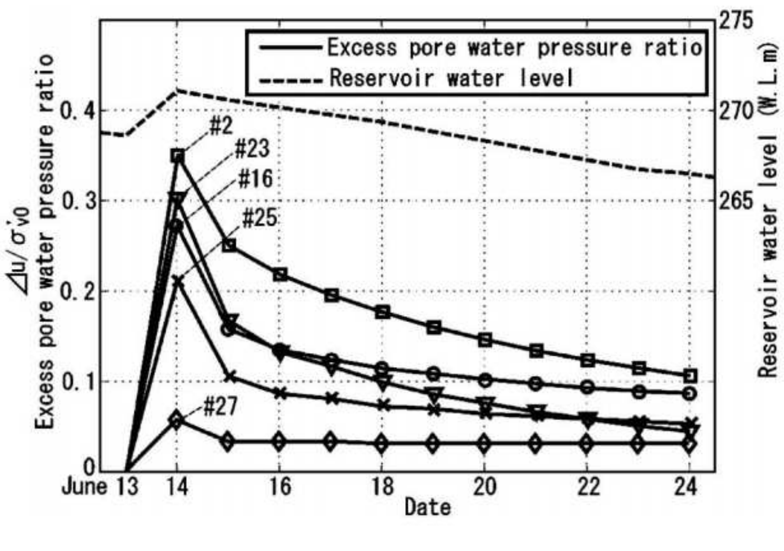
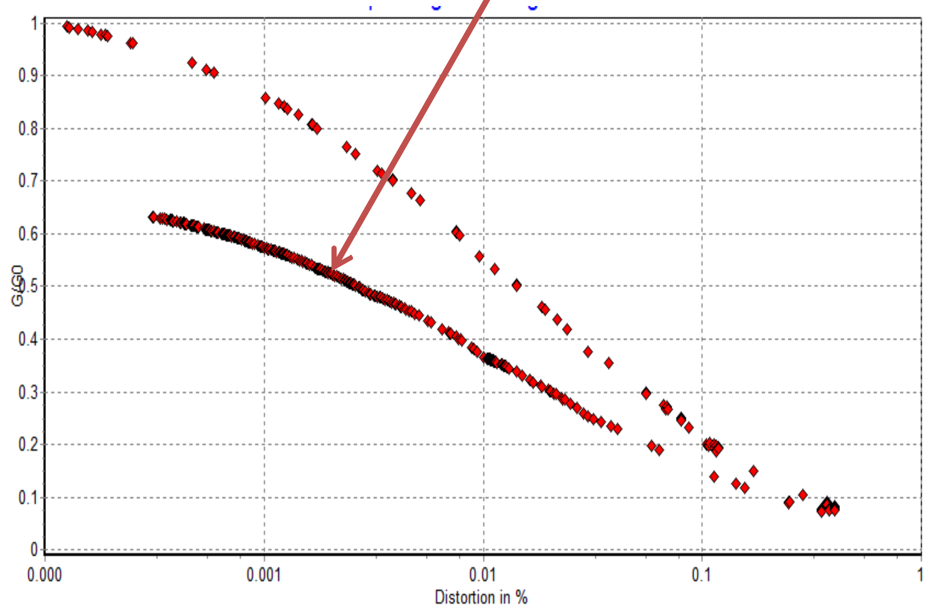


Fig. 17. Change in excess pore water pressure ratios in the core



➔ Drop in rigidity is partially explained by pore pressure increase

Introduction

Outputs of exchanges between JCOLD-CFBR

- Example of ARATOZAWA dam

Observation : Permanent Dx=5cm, Shoulder Dz= 20 cm Core Dz=40 cm
Prediction of simplified methods : large sliding (~meter) and underestimation of settlement (1 to 10 cm)

Introduction

Outputs of exchanges between JCOLD-CFBR

- A new simplified dynamic method has to be developed.
- Main objectives of the new method should be :
  - ➢ The method must be simple, fast and reliable.
  - ➢ It should take into account the pore pressure increase and its impact on dynamic behavior of the dam.
  - ➢ It should give a prediction of the settlement under strong motion.

2
Description of the new calculation method

Description of the new calculation method

Principle of the new proposed method

- The method is based on « classic » modal projection of the dynamic equation of the dam.
- The new feature is hydro-mechanical coupling with pore pressure increase.
- The result is a temporal evolution of different data : acceleration at crest, liquefaction ratio, shear modulus, damping, settlement, etc…

Description of the new method

▪ Principle of the new proposed method

- At each temporal step, are updated:
  - pore pressure increase : Byrne method (1991)
  - shear modulus decrease
  - and then fundamental frequencies change

- Permanent displacements are calculated:
  - compressibility settlement (decrease of void ratio)
  - slipping of instable masses

Description of the new method

Main equations

- Fundamental period / frequencies : $T_i = 1/f_i = A_i\,(G/\rho)^{0,5}/\,H$
- Acceleration at crest (or in sliding mass) : $A_c = A_{bot} + \Sigma\, FP_i \times OSC(T_i, \xi)$

  with $OSC(T_i, \xi)$ = simple oscillator response to the input accelerogram
- Volume strain decrease per 1/2 cycle : $\Delta\varepsilon_v = C1.\gamma.\exp(-C2.\,\varepsilon_v/\gamma)$,

  (Byrne 1991)
- Pore pressure increase : $\Delta u = M.\Delta\varepsilon_v$
- Shear modulus update : $G = G[\gamma]\;.\;(1 - \Delta u / \sigma'_0)$

In red : input parameter by user, discussed later

Description of the new method

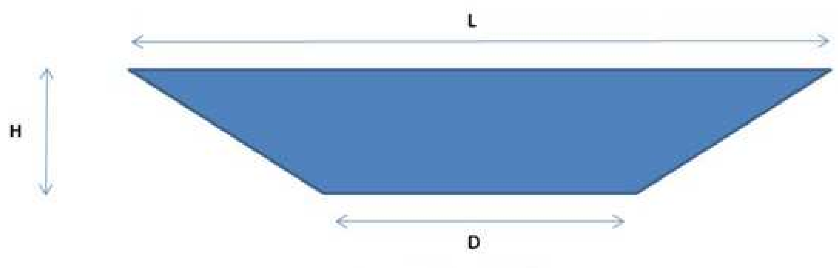
Modes characterization

- Period factors A_i: $T_i = 1/f_i = A_i\,(G/\rho)^{0,5}/ H$
- Participation factors FP_i : $A_c = A_{bot} + \Sigma\, FP_i \times OSC(T_i, \xi)$

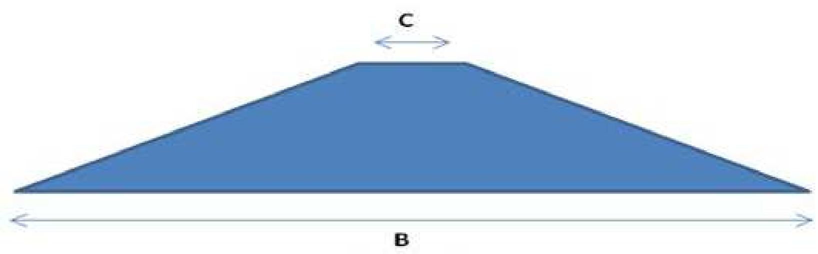
➢ A_i and FP_i depend on the geometry of the dam.

➢ The most important parameter : A_1 the right first fundamental frequency

➢ Very important: A_i and FP_i are computed with 3D FE modal analysis : validation tests show a high impact of 3D on these parameters.



Longitudinal Section



Transversal Section

Description of the new method

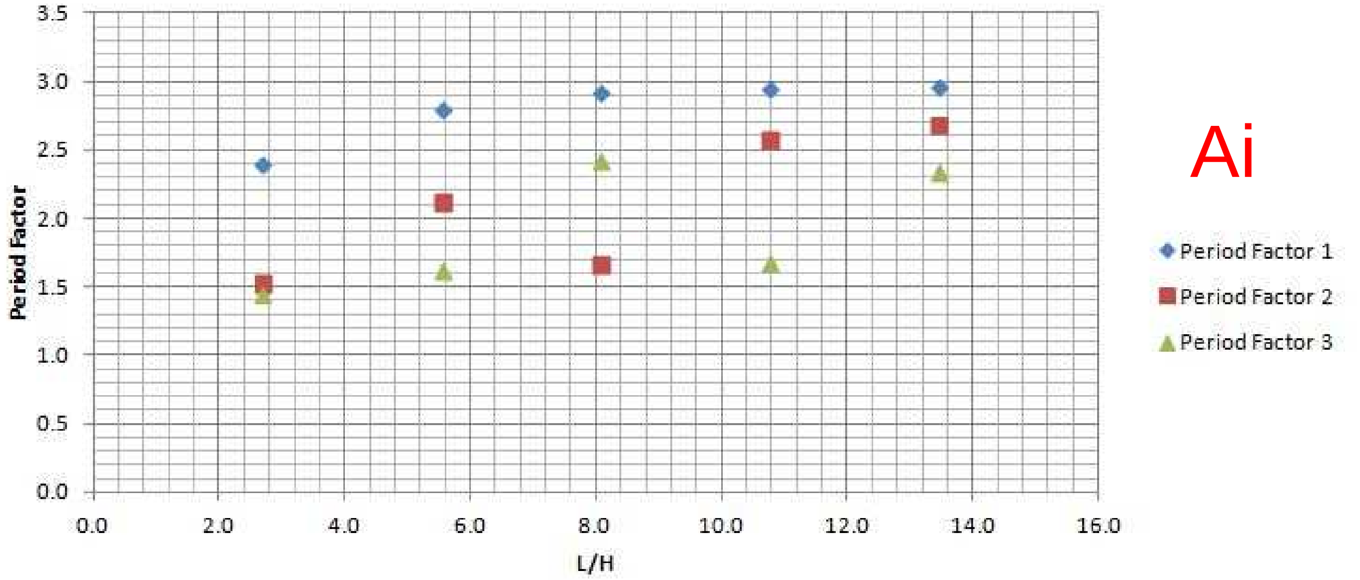
Modes characterization

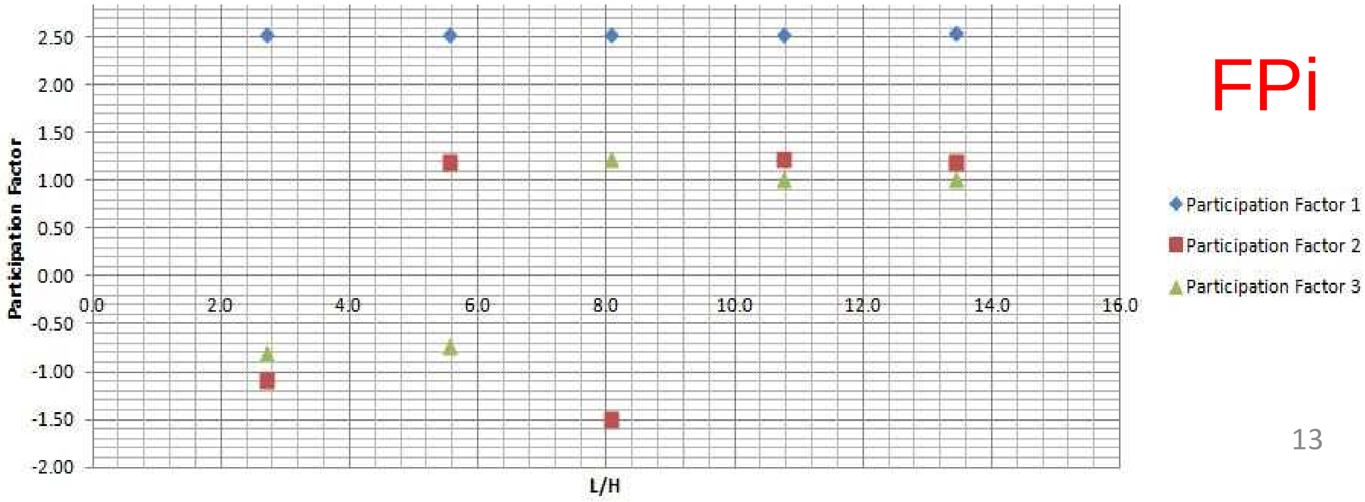
Example of variation

For comparison : M&S gives

$A_1 = 2,63$
$A_2 = 1,14$
$A_3 = 0,72$

$FP_1 = 1,6$
$FP_2 = 1,06$
$FP_3 = 0,86$





Description of the new method

Byrne parameters

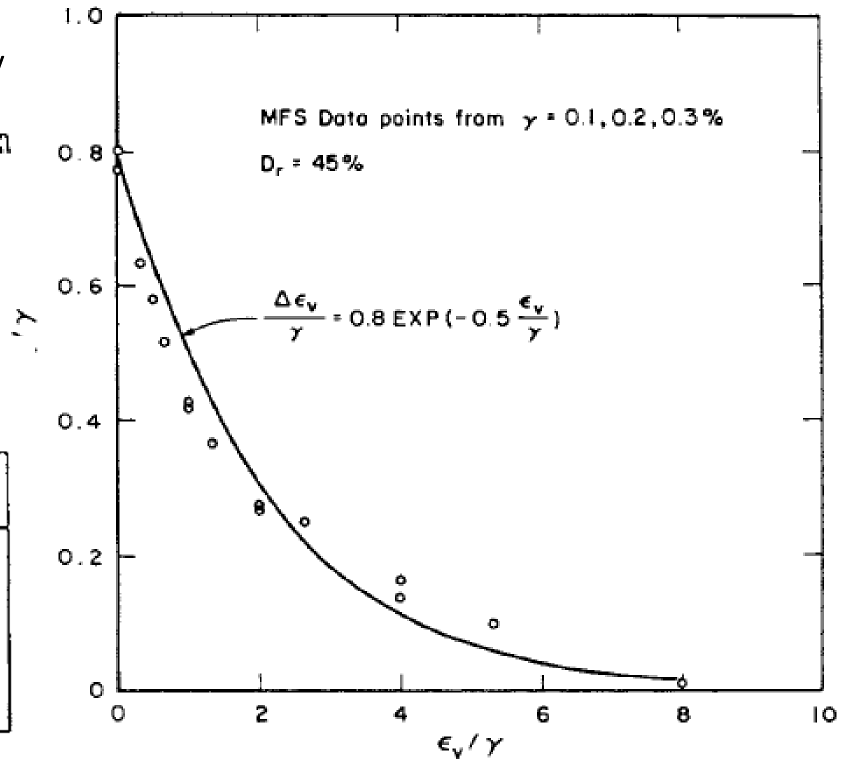
- Cyclic volumetric strain increase : $\Delta\varepsilon_v$ = C1.γ.exp(-C2. ε_v/γ), (Byrne 1991)
- Pore pressure increase : Δu = M.$\Delta\varepsilon_v$

$$M = K_m P_a \left(\frac{\sigma'_v}{P_a}\right)^m$$

➢ Byrne correlations for sand :

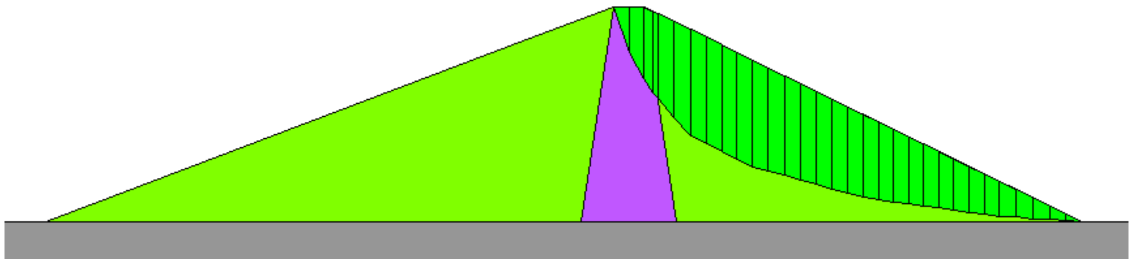
Table 2. C_1 and C_2 from SPT N Values

$(N_1)_{60}$	$(\varepsilon_v^p)_{15}/\gamma$	C_1	C_2
5	5	1	0.4
10	2.5	0.5	0.8
20	1.0	0.2	2.0
30	0.6	0.12	3.33
40	0.3	0.06	6.66



Description of the new method

Mass Equilibrium



Classic approach : pseudo-static calculation gives the critical acceleration k_y
However implementation of important phenomena have to be taken in account:

- Decrease of strength from peak to residual value
- Decrease of effective strength with pore pressure increase

In our tests we took :

- Undrained « equivalent » strength for post-liquefied materials
- Linear decreasing strength between peak (slipping = 0) and residual (at slipping = U_c). U_c is the critical slipping displacement, in general some multiple of D50.

Description of the new method

Sliding displacements

How to calculate the acceleration of the slipping mass ?

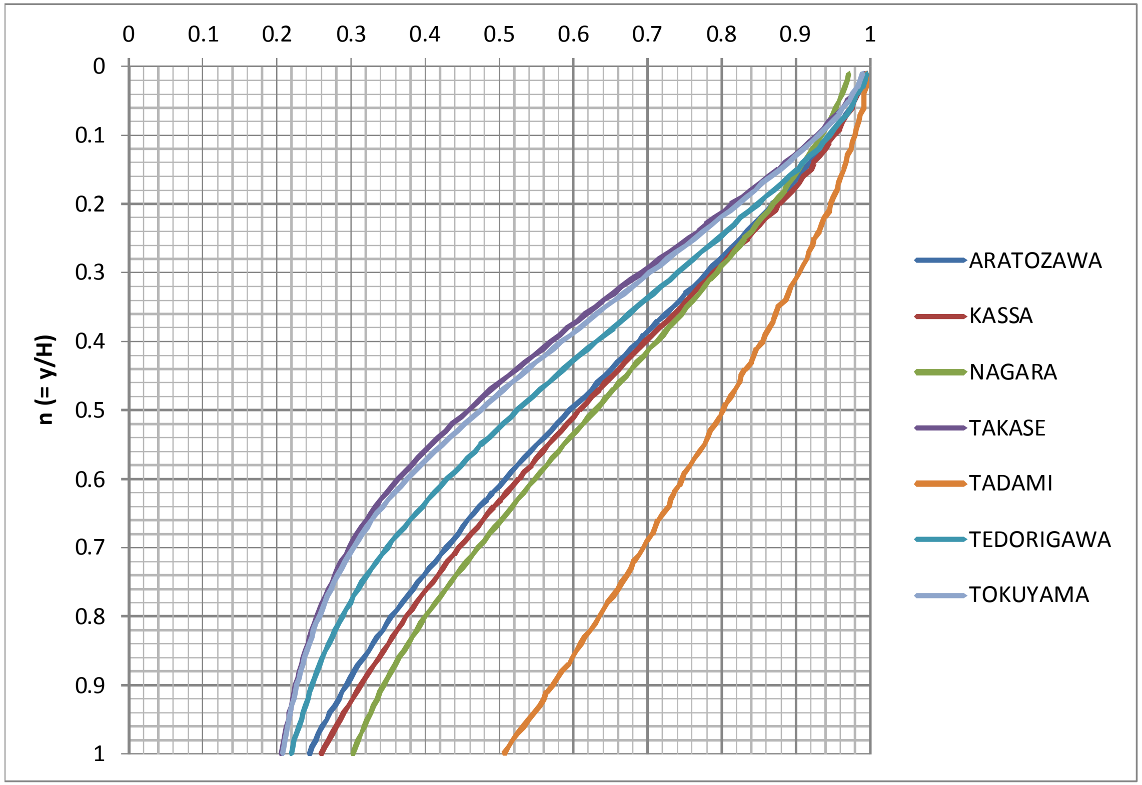
⇒ It is the same principle used for the acceleration at crest BUT : we must replace the participation factor by the ones corresponding to the slipping mass.

$A_c = A_{bot} + \Sigma$ **FP$_i$** $\times$ OSC(T_i, ξ)

By 3D modal analysis we calculate the ratio between :

- P.F. At crest
- P.F. of a circle at depth y.

PF circle / PF at crest for first mode



3
Acceleration records processing

Acceleration records processing

- **The JCOLD database**

- Source : “Acceleration records on dams and foundation n°3” by the JCOLD.
- Recorded accelerograms of numerous Japanese dams.
- Acceleration measured at several locations on the dam.

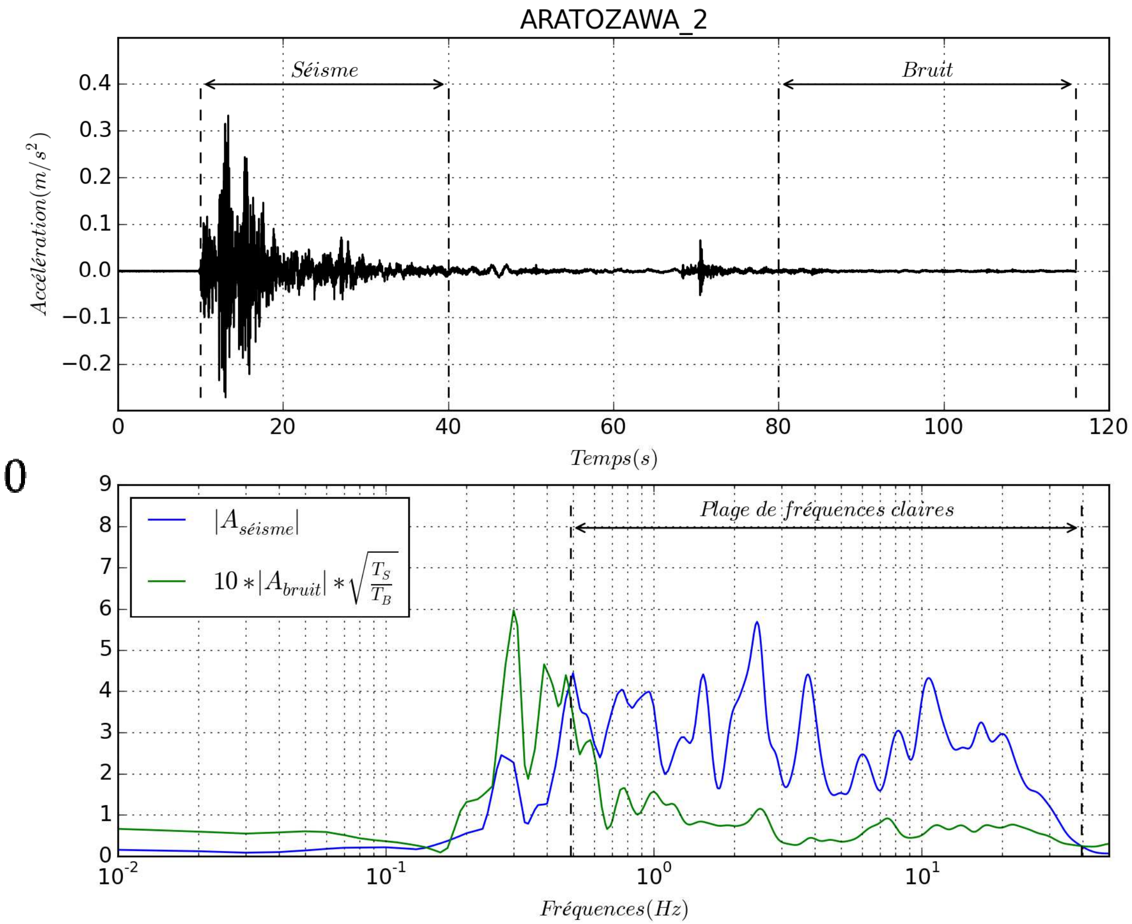
A unique opportunity to have a better understanding of the dam’s behavior under earthquakes.

Acceleration records processing

- **Noise interference**

➢ In order to avoid noise interference, we take:

$$\frac{S}{N}(f) = \left|\frac{FFT_S(f)}{FFT_N(f)}\right| * \sqrt{\frac{D_N}{D_S}} > 10$$



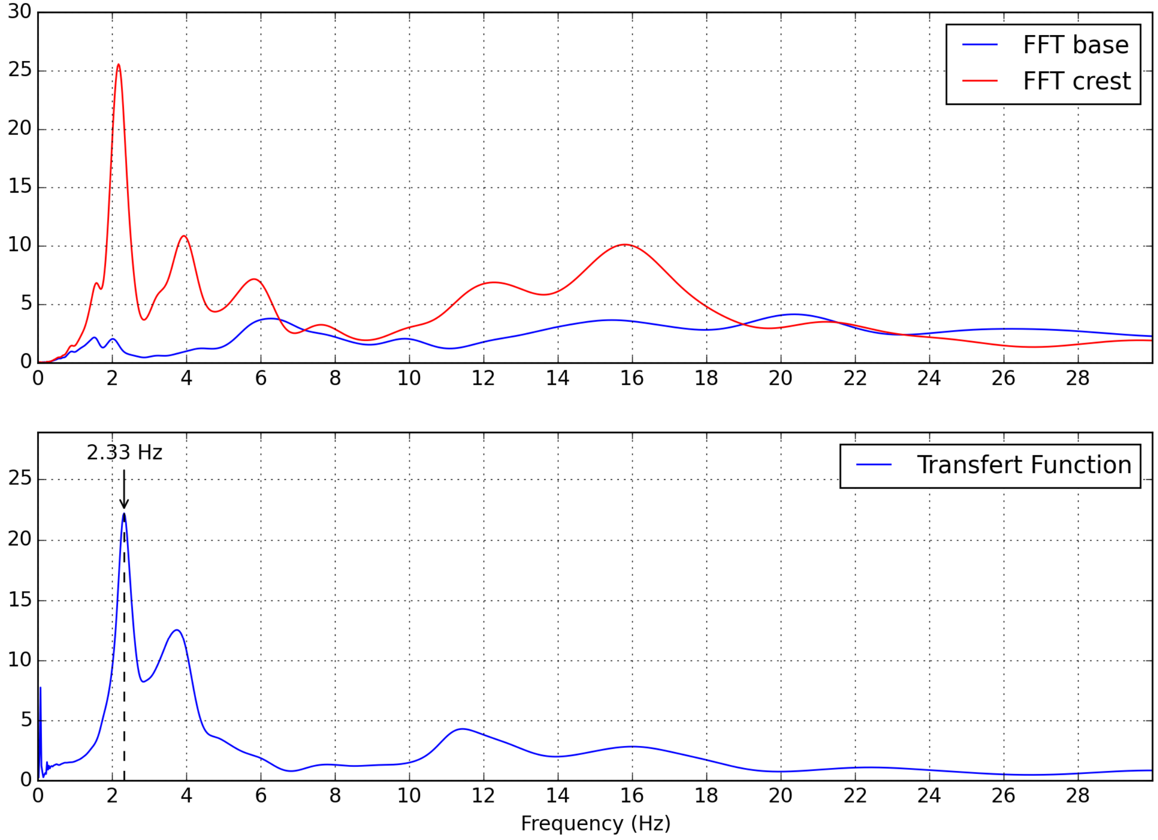
Acceleration records processing

- **Fundamental frequencies and their evolution under strong earthquakes**

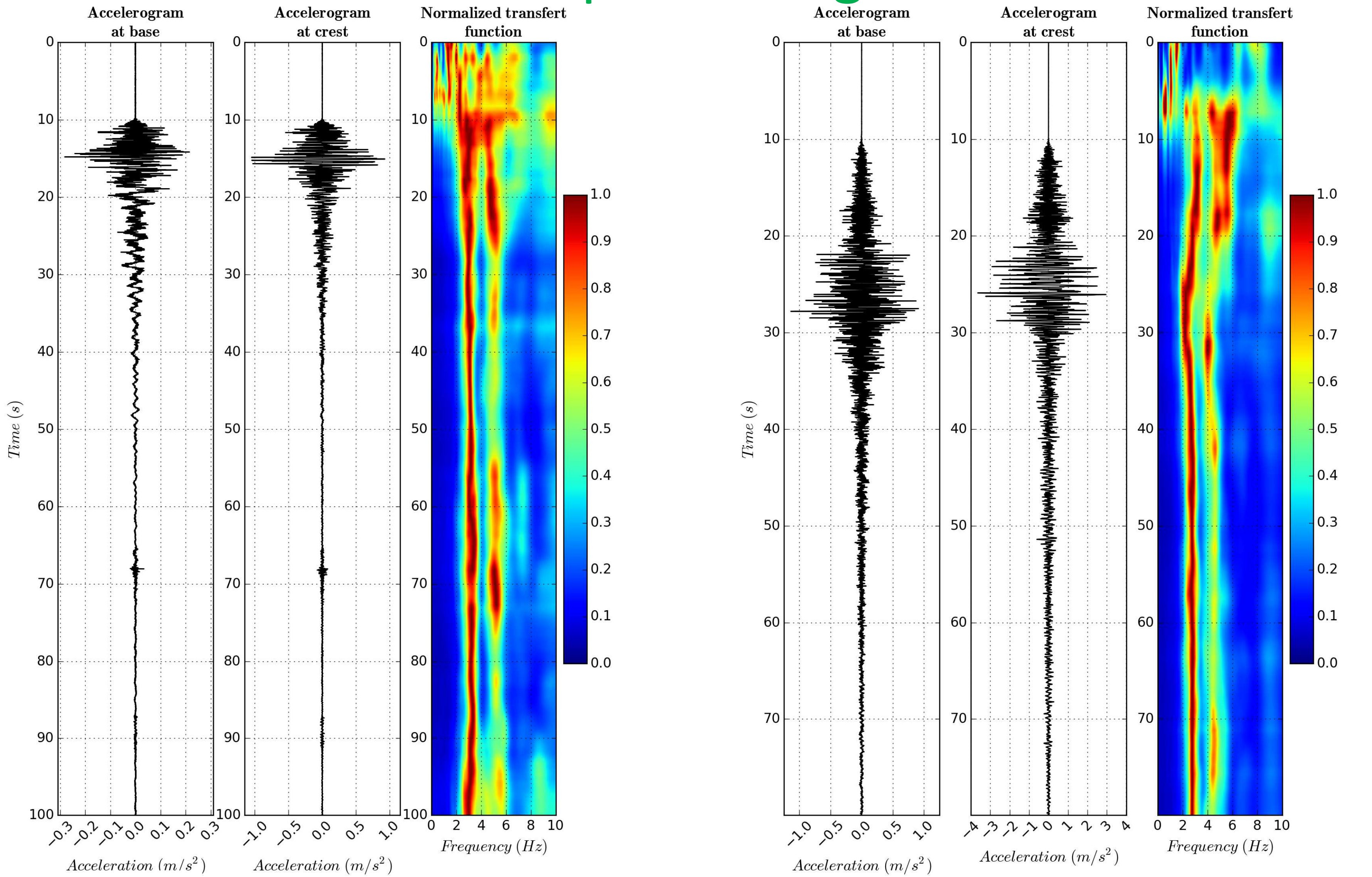
➢ The transfer function between the records at the base and the record at the crest gives the first natural frequencies of the dam.

➢ But under strong earthquakes the fundamental frequencies drop. The calculation over the all record is then inaccurate.

➢ TF on a short time window



Acceleration records processing



4
Validation procedure

Validation procedure

- **Validation data**

- Several Intensity Indices were calculated : peak acceleration, Arias intensity, Significant Duration, Cumulative Average Velocity.
- We choose accelerograms in function of :
  - Availability of data at the bottom and crest of the dam.
  - Significant duration of at least 2 seconds.
- Finally 28 records on 15 different dams are selected.

Validation procedure

- **Criteria of goodness of fit**

ANDERSON (2003) proposed quantitative measure of the goodness-of-fit of synthetic accelerograms. This measure rests on 10 parameters with as score from 0 to 10 :

- C1: Arias Duration
- C2: Energy Duration
- C3: Arias Intensity
- C4: Energy Integral
- C5: Peak Acceleration
- C6: Peak Velocity
- C7: Peak Displacement
- C8: Response Spectra
- C9: Fourier Spectra
- C10: Cross Correlation

Total Score	Verbal value
8-10	Excellent
6-8	Good
4-6	Fair
<4	Poor

KRISTEKOVA (2009) proposed a verbal scale based on total score to qualify the calibration

Validation procedure

- **Choice of initial elastic shear modulus G_0 and damping ξ**

Hypothesis : G_0 is expressed as a multiple of $H^{0.5}$

$$G_0 = K. (H/[1m])^{0.5}$$

The only parameter to fit is K, independant from the height H.

Initial guess is K = 70 MPa

For damping : $\xi = \xi[\gamma] + \xi_{extra}$

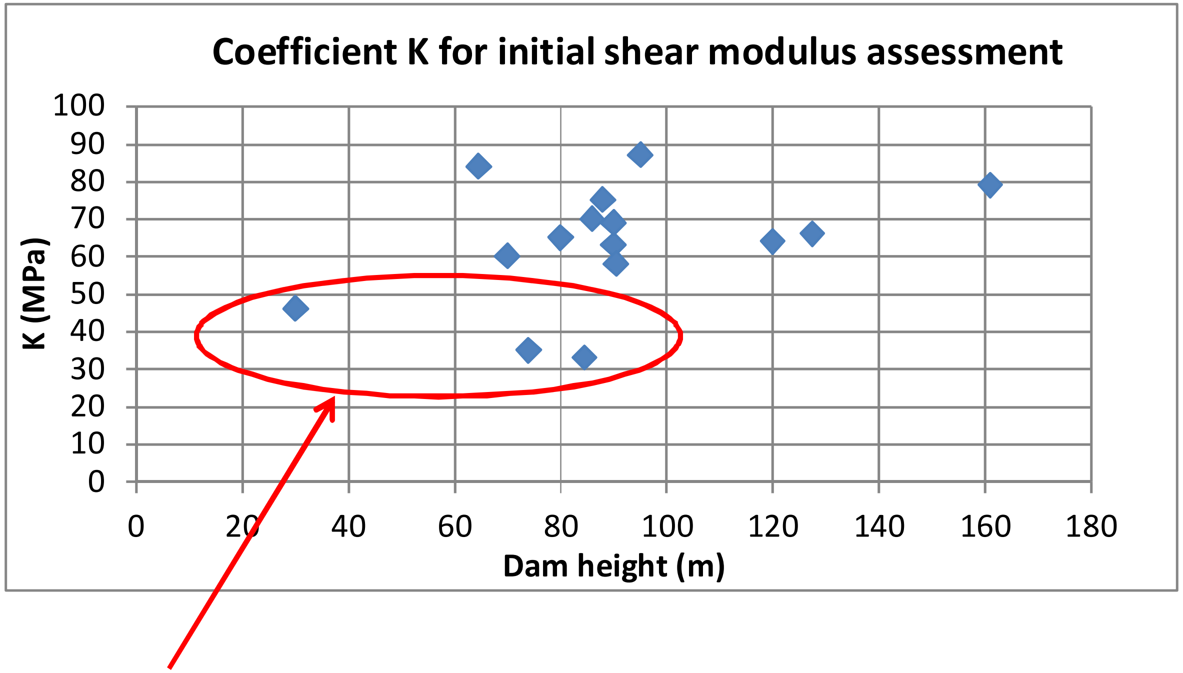
$\xi[\gamma]$ is the plastic damping increase versus deformation from lab test,

ξ_{extra} is an extra damping (radiative) to be calibrated

Validation procedure

- **Choice of initial shear modulus G_0 and damping ξ**

Shear modulus, results after calibration :

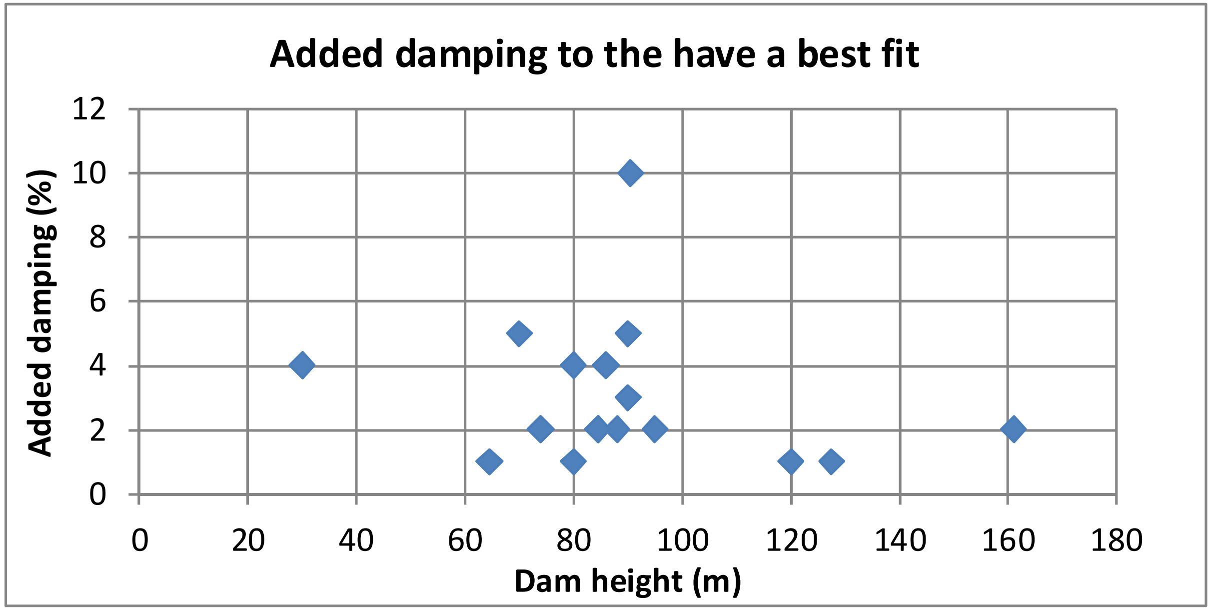


3 extreme cases : low fundamental frequencies and then low shear modulus.
We need more information to give a good explanation : perhaps non rock foundation or special geometry.

Validation procedure

- **Choice of initial shear modulus G_0 and damping ξ**

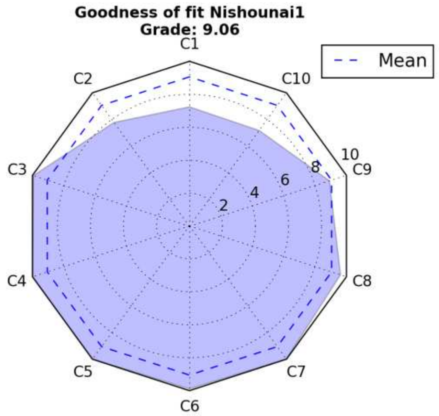
Extra damping, after calibration :

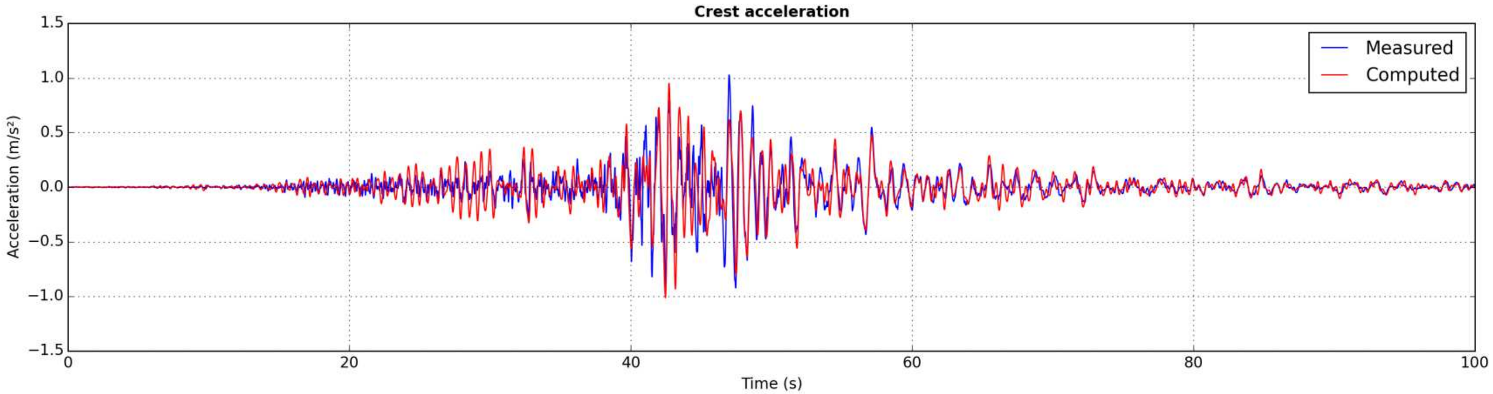


Extra damping around 2% (between 0 and 6 %) except one special case.

Validation procedure

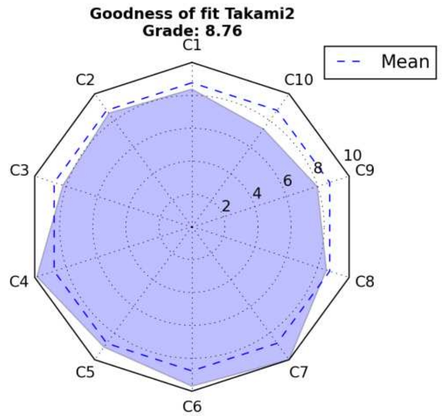
- **Example of calibration - excellent**

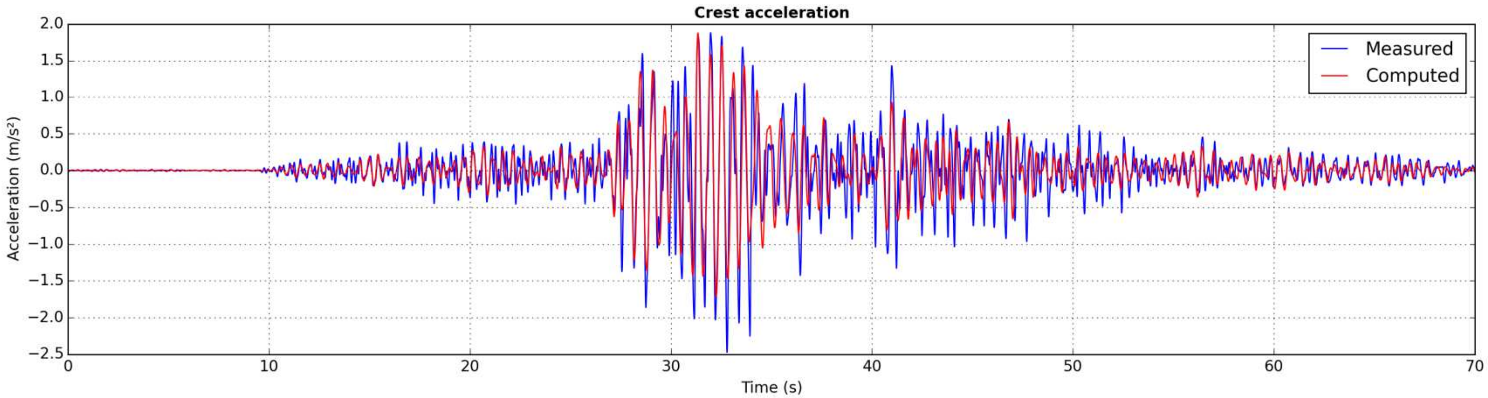




Validation procedure

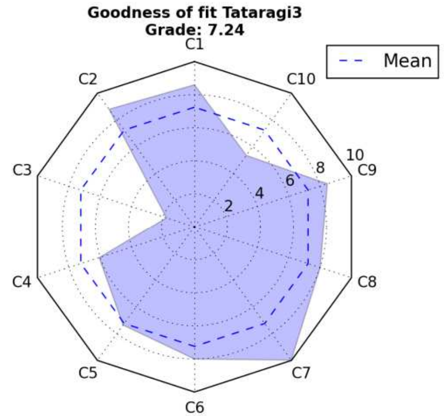
- **Example of calibration - excellent**

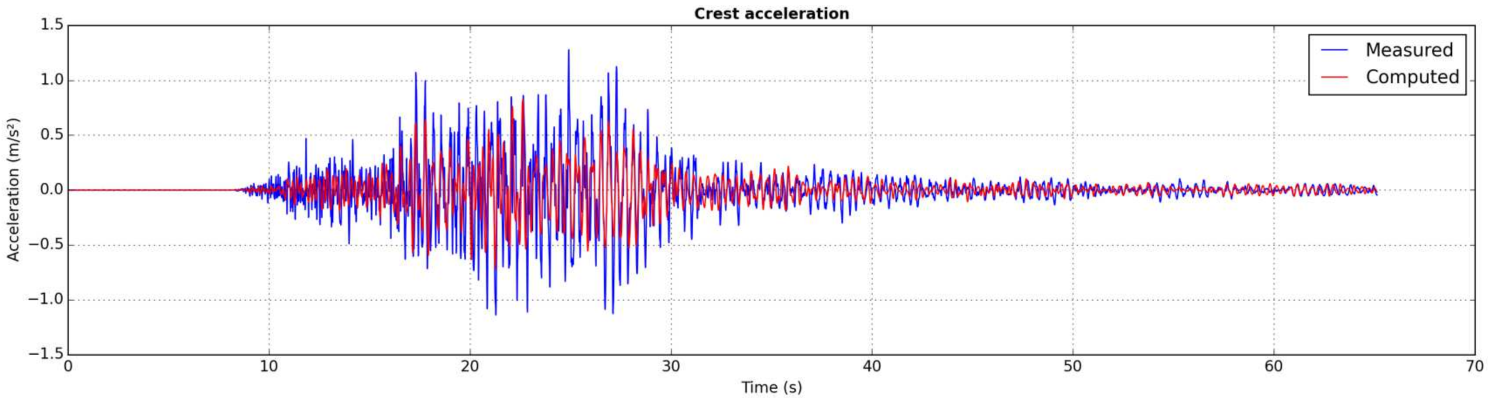




Validation procedure

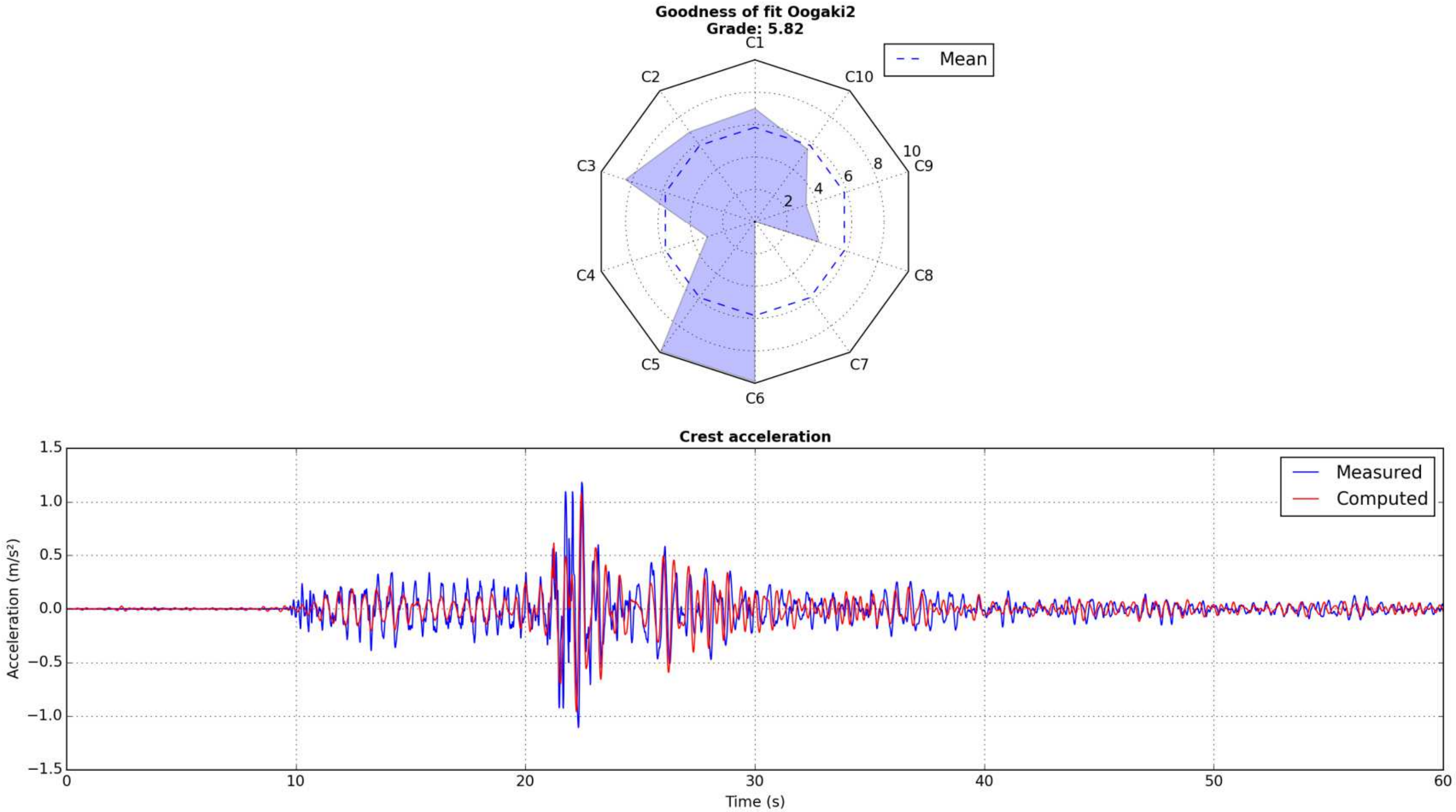
- **Example of calibration - good**





Validation procedure

- **Example of calibration – fair (the worst example)**



Validation procedure

- **Synthesis**

Dam	Re-cord	Goodness-of-fit		Scores detail									
		Score	Verbal appreciation	C1 DIA	C2 DIE	C3 IA	C4 IE	C5 Amax	C6 Vmax	C7 D_{max}	C8 SA	C9 FFT	C10 CC
INAMURA	1	7.3	Good	7.6	7.8	3.2	9.7	7.5	9.5	9.9	7.6	5.5	4.7
IWAYA	1	7.3	Good	5.6	5.6	9.0	9.4	9.9	10.0	9.7	6.5	3.3	4.4
KASSA	1	8.5	Excellent	7.9	8.2	8.4	9.9	9.6	10.0	9.8	9.2	8.1	4.2
	2	7.7	Good	5.0	5.6	6.5	8.6	9.6	10.0	9.7	9.0	7.2	6.3
	3	8.7	Excellent	7.6	8.0	10.0	9.6	9.6	9.9	10.0	9.6	8.1	4.9
MIHO	4	7.8	Good	6.6	7.8	7.4	9.9	9.2	8.5	9.6	7.5	7.5	4.3
SHICHIKA-SHUKU	1	6.9	Good	7.4	7.7	5.5	0.3	9.9	8.3	9.3	8.1	7.9	4.3
	2	8.0	Good	7.1	6.9	9.3	4.7	9.9	8.5	10.0	8.9	8.5	6.1
	3	8.8	Excellent	8.5	7.9	9.8	9.6	9.6	9.8	10.0	9.4	8.0	5.5
TADAMI	1	8.6	Excellent	7.1	8.6	7.8	10.0	8.9	9.9	10.0	8.5	9.0	5.7
	2	8.8	Excellent	6.7	8.7	9.9	10.0	9.2	9.5	9.9	9.2	8.6	6.1
	3	6.9	Good	8.4	3.7	9.8	0.4	9.7	10.0	6.3	7.4	7.2	6.6
TAKAMI	1	7.9	Good	8.2	7.5	3.5	8.3	9.2	9.6	10.0	7.7	8.1	6.5
	2	8.8	Excellent	8.4	8.6	8.2	9.9	9.1	9.7	10.0	8.6	8.0	7.4
NANAKITA	1	8.8	Excellent	8.0	7.4	10.0	10.0	10.0	9.8	10.0	8.4	8.5	6.0
	2	8.7	Excellent	7.5	8.6	10.0	10.0	10.0	9.6	10.0	8.2	7.3	5.5
SHIMOYU	1	8.9	Excellent	7.2	8.5	10.0	9.9	10.0	10.0	10.0	9.1	8.5	6.2
TOKUYAMA	1	8.3	Excellent	5.6	5.9	9.2	10.0	8.4	9.3	10.0	8.2	8.6	7.5
URUSHIZAWA	1	7.6	Good	7.7	9.3	2.6	10.0	5.4	10.0	10.0	7.6	8.3	4.6
	2	8.9	Excellent	8.7	9.1	9.6	9.5	10.0	9.4	10.0	8.8	8.7	5.6
	3	7.8	Good	7.43	7.24	9.09	4.24	9.35	9.07	9.96	8.45	8.11	5.09
NISHOUNAI	1	9.1	Excellent	7.2	7.8	10.0	10.0	10.0	9.9	10.0	9.6	8.9	7.2
OOGAKI	1	8.3	Excellent	6.5	7.9	10.0	9.8	8.5	9.9	9.9	8.1	6.5	6.3
	2	5.8	Fair	7.0	6.9	8.4	3.1	9.9	9.9	0.0	4.2	3.3	5.5
	3	8.3	Excellent	8.3	7.6	8.5	9.1	9.2	10.0	9.5	7.8	6.6	6.5
TATARAGI	3	7.2	Good	8.6	8.8	1.8	6.1	7.4	8.0	10.0	8.0	8.5	5.4
	4	7.3	Good	7.4	7.4	2.4	5.3	9.3	9.8	9.5	8.8	8.6	4.9
YASHIO	3	9.1	Excellent	8.6	8.6	10.0	9.8	10.0	10.0	10.0	9.3	9.5	5.7

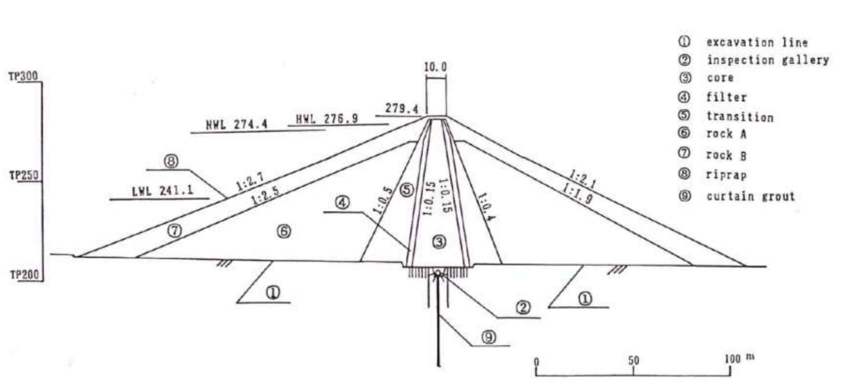
5
Example of application

Example of application

- **Aratozawa dam, earthquake of June 2008**

Paramaters taken :

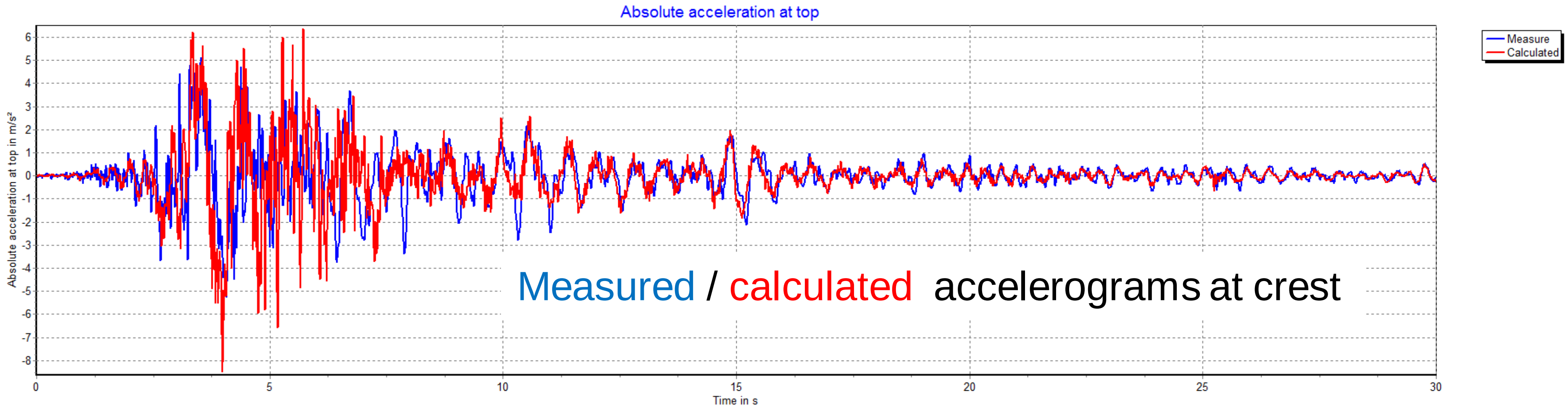
- G_0 = 750MPa (K=90MPa)
- ξ_{extra} = 5%
- A_1 = 2.7, FP_1 = 2.5
- C1 = 0.2, C2 = 2.0, M = 240 MPa

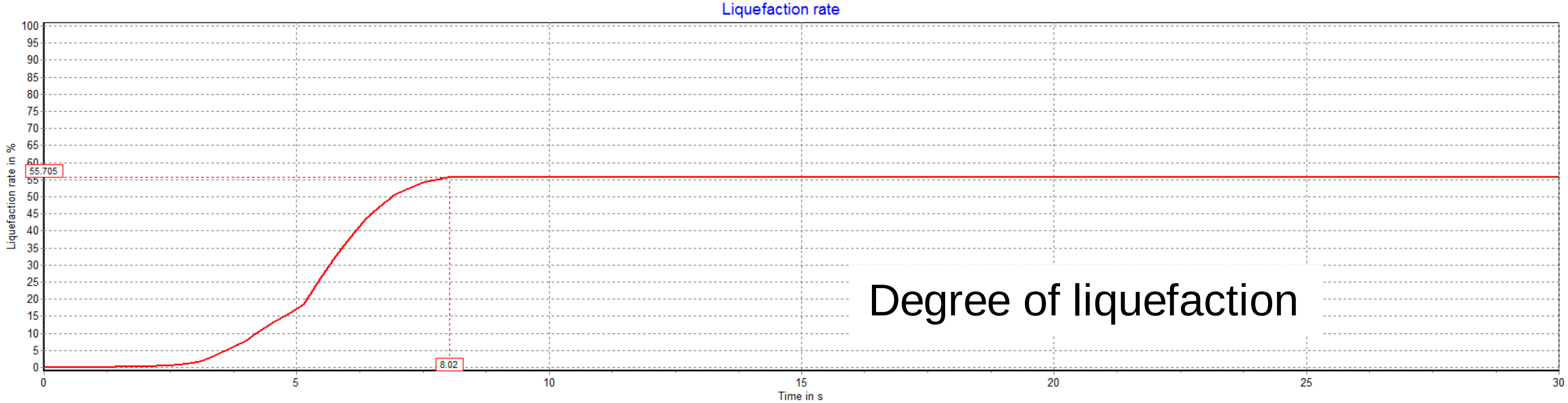


TYPICAL CROSS SECTION

Examples of application

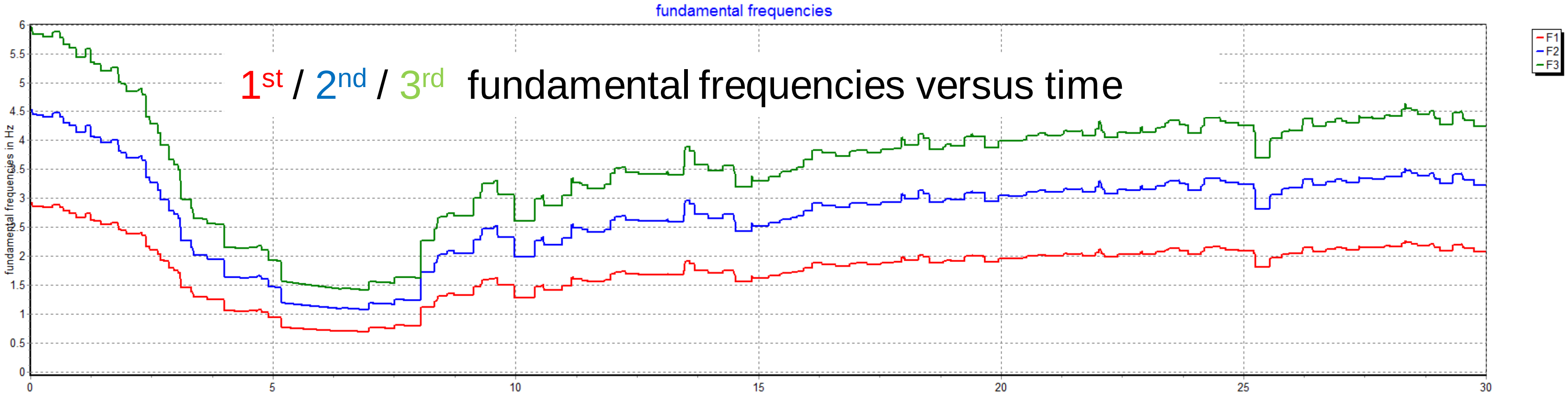
- **Aratozawa dam, earthquake of June 2008**

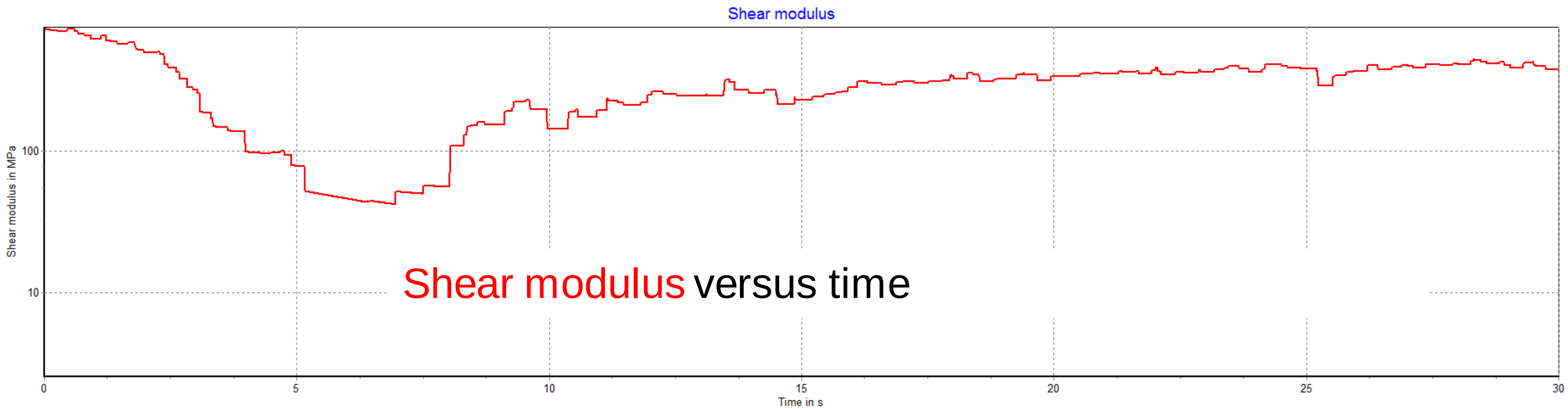




Examples of application

- **Aratozawa dam, earthquake of June 2008**





Examples of application

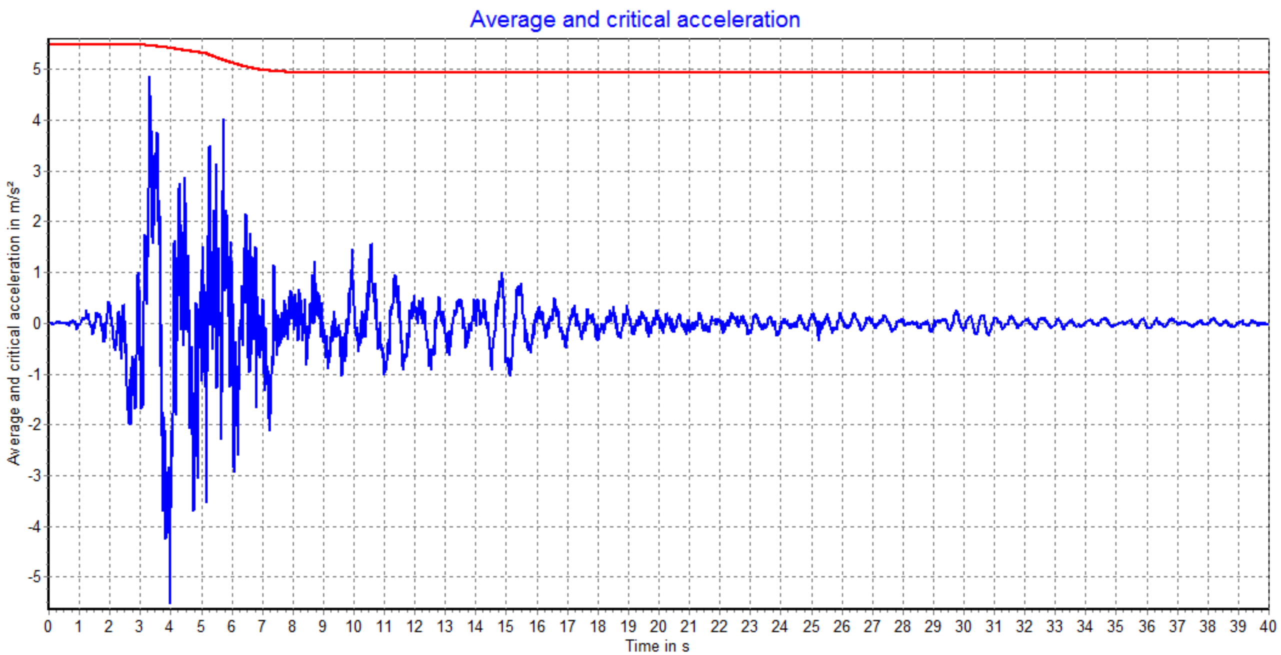
- **Aratozawa dam, earthquake of June 2008**

Critical acceleration with no pore pressure increase :

Peak = 5,5 m/s² , residual = 4,5 m/s² after Uc = 20 cm

If liquefaction of the core :

Peak = 5,0 m/s² , residual = 4,0 m/s² after Uc = 20 cm



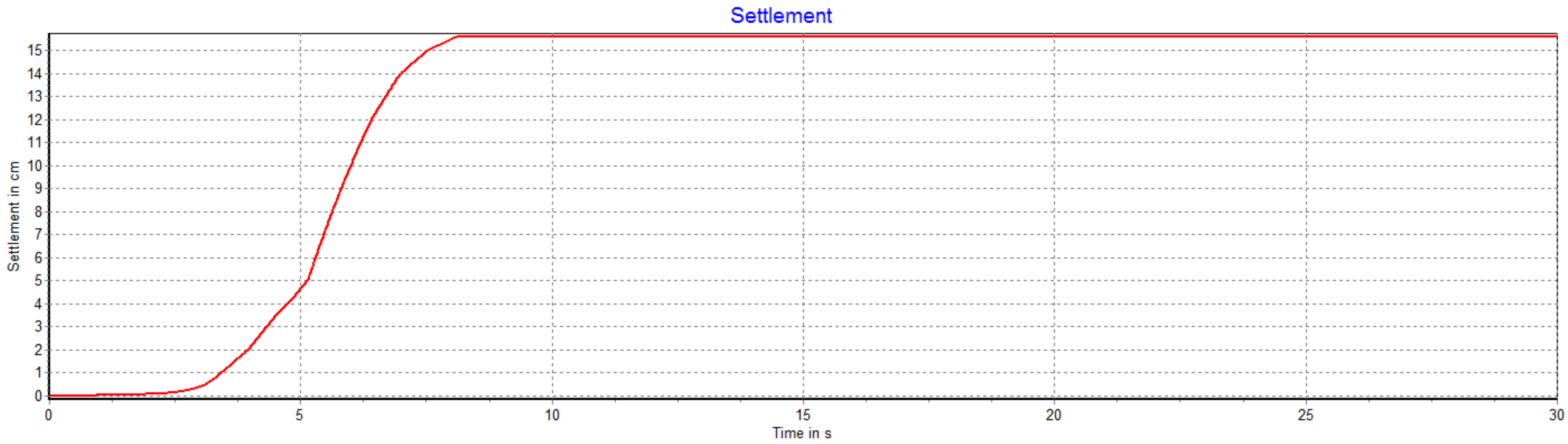
$\Rightarrow$ No slipping !

Examples of application

- **Aratozawa dam, earthquake of June 2008**

Settlement : only explained by volumetric settlement (void ratio decrease).

Maximum calculated = 15.5 cm



Conclusion and prospects

- **Conclusion**

The simplified method presented here brings a new approach to evaluate the dynamic behavior of dams under strong earthquakes.

The main fundamental assumptions of this method are :

- this method is non linear and temporal,
- acceleration (at crest or averaged in a volume) is calculated by modal projection at first modes,
- pore pressure increase and dam rigidity is updated at each time step,
- calculation of volumetric settlement, pore pressure increase and their impact on the behavior of the dam : decrease of rigidity and stability.

Thanks to recorded data given by JCOLD, we can validate and adjust the main parameters of this new method.

Conclusion and prospects

- **Prospects**

  - A guide must be written to describe and help the selection of parameters.
  - For some special case studies, work is still required to explain differences between calculation and measures.
  - The work on permanent displacement is to be continued, in particular : post-liquefaction resistance and the settlement assessment.
  - The impact of soil foundation has to be taken into account.

THANK YOU FOR YOUR ATTENTION