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

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EDF-Hydro-Engineering Center

CONCRETE DAMS

DYNAMIC ANALYSIS, EXPERIMENTAL AND IN-SITU RESULTS, CALIBRATION AND VALIDATION

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FRAMEWORK

- **On the combined effects of numeric tools and field mesurements improvements, significative progresses have been done in the next 10 years in dynamic dam analysis :**
  - Clarifying some aspects
  - Convergency on some points
- **Different ways of in-situ validation/ calibration are available**
- **Aim of this presentation**
  - To make an overview of the available methods regarding scientific dificulties (some presentation will describe more in detail some of them)
  - To discuss the main obtained results / conclusion drawns
  - To point out further development and collaboration needs

TOPICS OF INTEREST

- **Scientific aspects :**
  - Dam – reservoir interactions
  - Dam – foundation interaction
  - Damping / radiative damping
  - Material properties

- **Calibration / validation :**
  - Benchmark workshops
  - Data from in situ measurements
    - Forced vibration
    - Ambiant vibration
    - Performance based testing
    - Blasting
    - Earthquake measurements
  - Laboratory experiments / Shaking table

LESSONS FROM BENCHMARKS

- **ICOLD Benchmark workshops :**
  - 1992 Bergamo Italy 2A : Seismic analysis of Talvachia dam
  - 1996 Madrid Spain 4A1 : Earthquake response of an arch dam including the non-linear effects of contraction joints opening
  - 2009 Paris 10 C : Stability of a dam abutment including seismic loading
  - 2013 Graz 12 A : Fluid-structure interaction. Arch-dam reservoir at seismic loading (11 papers)
  - 2015 Lausanne 13 A : Arch dam. Seismic safety evaluation of a concrete dam based on guidelines (10 papers)
- **ICOLD Bulletins 94 and 155**
- **USSD workshop on Monticello dam (2016)**
- **CFBR-JCOLD collaboration**

LESSONS FROM BENCHMARK

- **ICOLD benchmark**
  - Blind modelling with results comparison
  - No ‘exact’ solution
  - Collection of results / comparison and discussion
  - Reference solutions available for further computer software tests
- **Monticello benchmark**
  - Blind comparison with in-situ measurements
- **JCOLD-CFBR**
  - Comparison with records during earthquake
  - To progress in the best modelling solutions
  - Perspectives to improve simplified methods

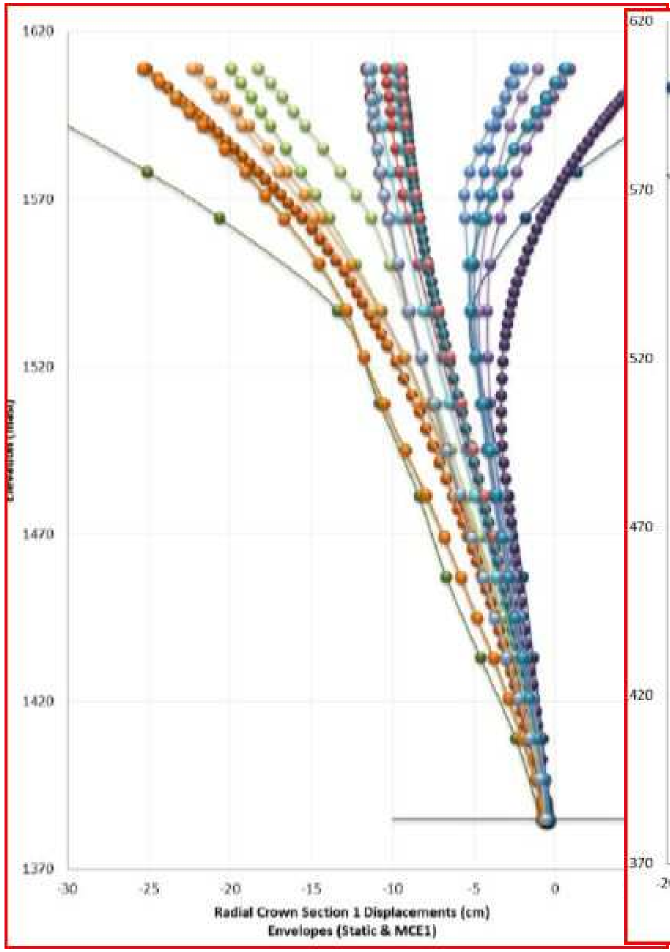
2013 GRAZ ICOLD SYMPOSIUM

- **11 teams / 8 countries**
- **Transient linear elastic modelling : arch dam/ foundation / reservoir model**
- **Intend : to compare the different techniques and the amount of déviation**
- **Despite provided data (mesh, material properties, input), linear analysis, significant differences are observed in the results due to additionnal assumptions : application of the construction sequence, dynamic properties increasing, foundation properties, seismic loading properties, resolution method**
- **Descrepencies on stresses are the most important (up to 2-3 ratio)**

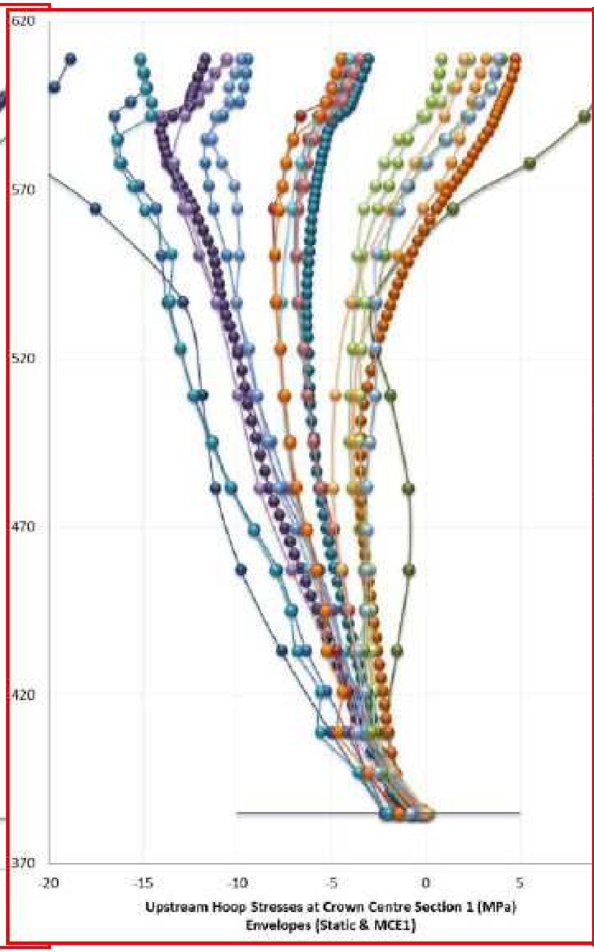
2015 LAUSANNE ICOLD SYMPOSIUM

- Luzzone modelling in accordance with swiss guidelines
- 10 simulations
- Foundation : massless
- Reservoir : westergaard / acoustic (compressible / uncompressible)
- Good agreement for eigen frequencies
- Rather good aggreement on displacements and stresses, Westergaard approach remaining globally conservative
- Graz and Lausanne workshop represent a large amont of work and data which provides usefull references for seismic modelling

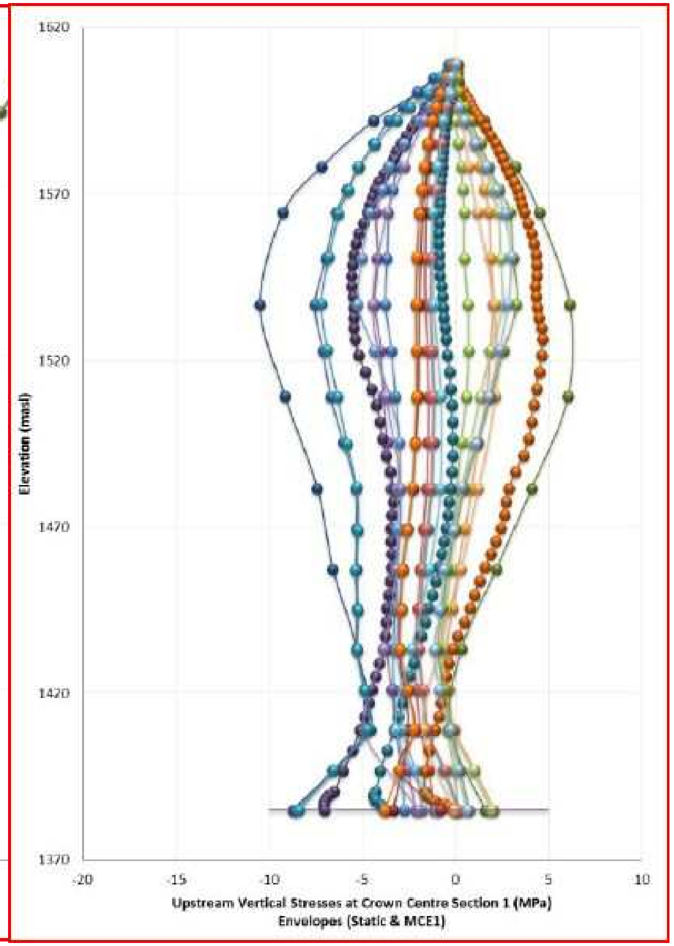
ICOLD 2015 BENCHMARK WORKSHOP LAUSANNE



Horizontal displacements
Central cantilever
Dyn min / Stat / Dyn max



Arch stresses
Central cantilever / Upstream
Dyn min / Stat / Dyn max



Vert stresses
Central cantilever / Upstream
Dyn min / Stat / Dyn max

DAM-RESERVOIR INTERACTION

- **Wave propagation in fluid**
- **Several formulations**
  - Lagrangian : displacements équation (solid approach)
  - Eulerian : U / P / U-P / U-P Phi… formulations
- **Rôle of water compressibility**
- **Wave absorption at reservoir-foundation interface**

$$\frac{\partial p}{\partial z} = q\,\frac{\partial p}{\partial t} \quad \text{with } q = \frac{1}{Cw} \times \frac{1-\alpha}{1+\alpha}$$

α : absorption coefficient at reservoir bottom

Large influence of α when a vertical component is included

EFFECTS OF WATER COMPRESSIBILITY (B. WEBER 1994)

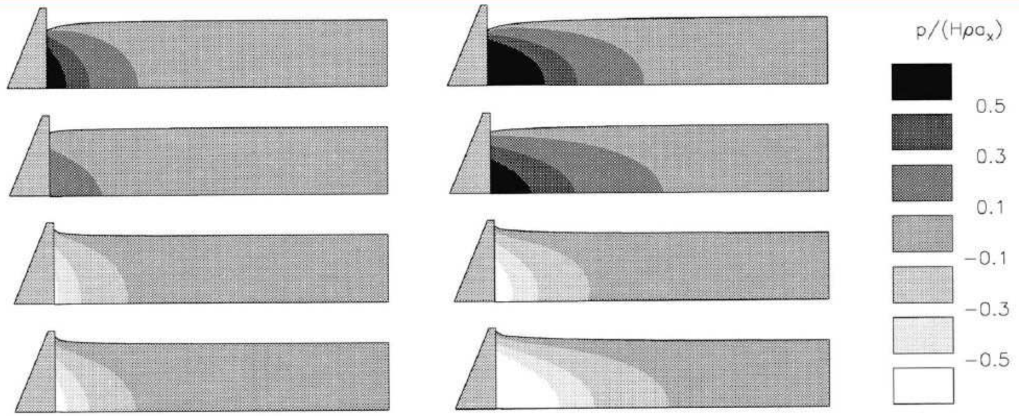


Figure 1.2: Pressure distribution in reservoir, $f = 0.8 f_w$. Left: incompressible fluid. Right: compressible fluid.

F=0,8 Fw

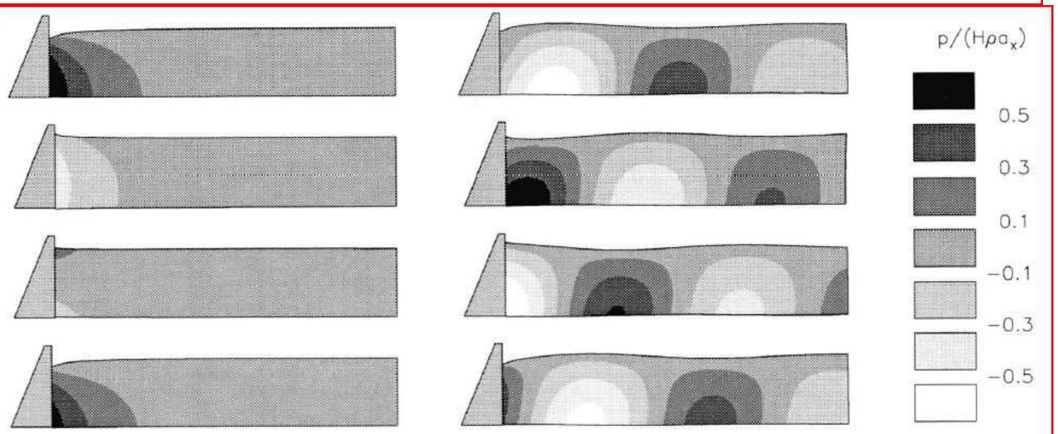


Figure 1.3: Pressure distribution in reservoir, $f = 1.5 f_w$. Left: incompressible fluid. Right: compressible fluid.

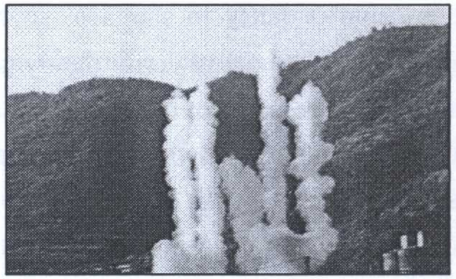
F=1,5 Fw

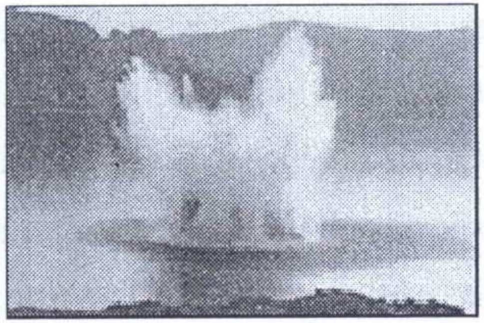
DAM-WATER INTERACTION

- **Effect of water compressibility : significant if**
  - f dam > 0,7 fw (J. Hall) or 0,9 fw (USACE)
  - Fw = C/4H (rectangular channel) C/3,41 H (circular channel)
- **Folsom (USACE 2005) : fundamental frequency easily reproduced with uncompressible model, but water compressibility is necessary for higher frequencies**
- **Hydrodynamic pressure measurements : comparison with simplified formula**
- **Benchmark comparison (Graz 2012, Lausanne)**
- **Balanced effects :**
  - additionnal damping due to reservoir dissipation
  - additionnal energy transmitted to the dam

IN-SITU TESTS / DAM-RESERVOIR INTERACTION

- **Blasting (Chen Houqun 2014) :**
  - Dongjang arch dam : blasting in boreholes in foundation
  - Longyangxia gravity dam : blasting at reservoir bottom
  - Hydrodynamic pressure recording
  - Evaluate the effects of compressibility / acoustic reflection coefficient
  - Promising nevertheless : *'the results indicated that reflection coefficient of the reservoir boundaries actually appears complicated. It is not only frequency dependent but also varies with position at reservoir boundaries. It might be difficult to be measured. Simply defining it as a constant might always be rather arbitrary and questionnable'*





DAM-FOUNDATION INTERACTION

- **Two main approaches**
  - Massless
  - Mass + damping
- **Massless :**
  - Simple, conservative (no radiative damping)
  - Recommanded in first approach (cf. Swiss guidelines)
- **Mass + damping :**
  - Need adapted radiative conditions

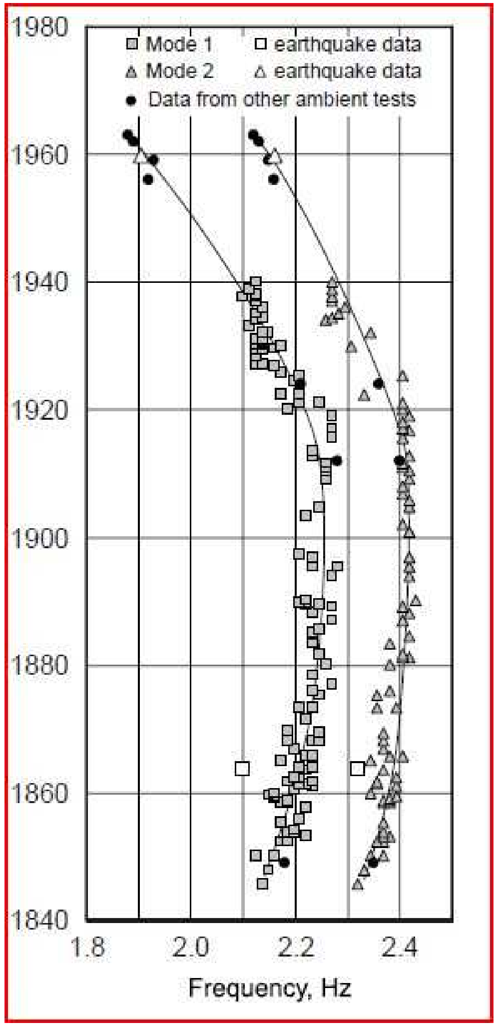
FORCED-AMBIANT VIBRATION TESTS. (1)

- ICOLD 1964 Edimbourg Q 29 R14 : Results of vibration tests and earthquake observations on concrete dams and their consideration. Takahashi Tasadi (R14 Q29). Technical Laboratory of Central Research Institute of Electric Power Industry. Tokyo
- ICOLD 1970 Montréal C4 : Observation and measurement of dynamic behavior of the Kurobe Dam. Masanori Nose. Kansai Electric Power
- ICOLD 1979 New Dehli : Q51
  - The Dynamic behavior or arch dams investigations by means of calculations and measurements (R. Widman) Schlegeis (blasting in reservoir)
  - Experience gained during in situ artificial and natural dynamic excitation of large concrete dams in Italy (ENEL/ISMES)
- 1980 Forced vibration tests and theorical studies on dams (Severn/Jeary/Ellis). Bristol University/Building research departement UK)
- 1982 Vibration test on Emosson arch dam. Deinum and Dungar (Motor Columbus). Severn et al.
- 1984 CALTEC. Forced vibration tests. J. Hall / Z. Duron Santa Anita
- 1985 Lessons from prototype. Dynamic measurements and corresponding analyses. (Ellis/Jeary/Severn) : Emosson / Contra / Zervreila
- 1984-1985 : On-site dynamic investigations / large scale physical model : Inguri / Sayano-Shushenskaya)

FORCED-AMBIANT VIBRATION TESTS (2)

- 1988 Seismic monitoring of dams. A new active surveillance system. ENEL/ISMES. Talvacchia arch dam example.
- 1988 Experimental and finte element studies of the forced vibration response of Morrow Point Dam. Z. Duron, John Hall. CA.
- 1990 Fulls scale dynamic testing and mathematical model validation of dams. Severn/ Taylor/ Brownjohn. Emosson / Contra / Maentwrog dam (driscrepencies with elastic results due to AAR)
- 1991 Measuring hydrodynamic pressure during forced vibration testing of concrete dams. Duron /Hall/ Fink / Straser
- 1992 Dynamic testing of Outardes 3 gravity dams. Paultre / Proulx (Sherbrooke University) Z. Duron / Hydro-Québec
- 1998 Characterising the dynamic behavior of concrete dams Paultre Sherbrooke University / HQ/OFEN/EDF. Outardes 3 and Emosson
- 1998 Ambiant vibration tests at the Mauvoisin dam. EMPA-OFEN Suisse
- 2008 Earthquake response of large arch dams. Observationnal evidence and numerical modelling. Proulx/ Darbre. 10 years of observations (Mauvoisin, Emosson)

EMOSSON DAM. SOME RESULTS (PROULX-DARBRE 2008)



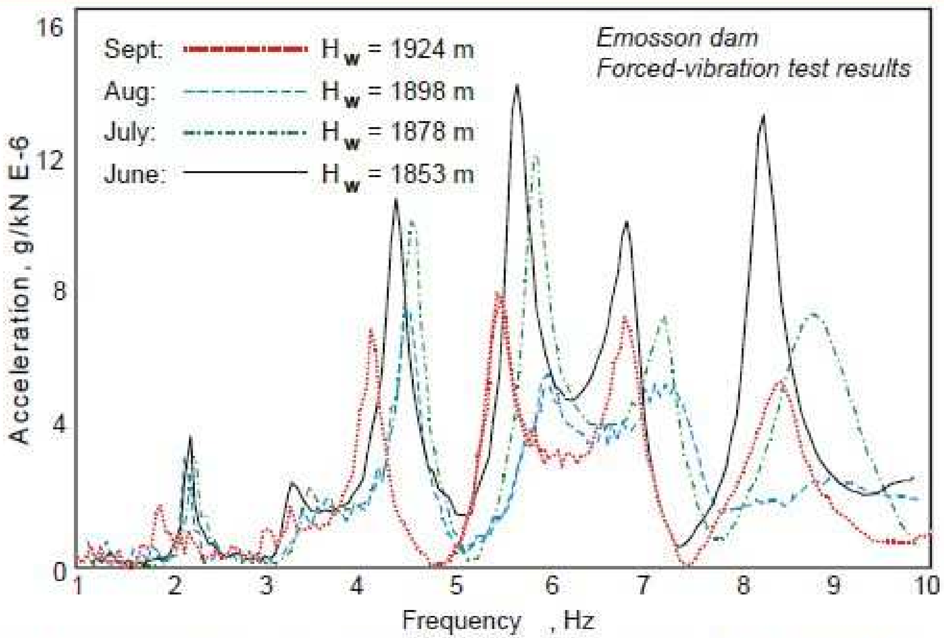


Figure 4: Forced vibration test setup and frequency responses for different water levels (adapted from Proulx *et al*, 2001)

FORCED-AMBIANT VIBRATION TESTS (3)

- 2012 Structural monitoring tests for an aged large arch dam based on ambiant vibration measurements. Okuma et al.Japan. 5 years measurements : effects of thermal and reservoir variations.
- Ambient vibrating measurements at Gouga dam. Getting more information as expected.P. Moyo, L. Hattingh, C. Oosthuizen. ICOLD Seattle 2012.
- Long term integrity monitoring of a concrete arch dam using continuous dynamic measurements and a multiple linear regression model. P. Bukenya et al. ICOLD Johannesburg 2016.
- 2015 Vibration monitoring in large dam. LNEC. Cabril arch dam. Vibration monitoring system and automatic identification of modal parameters anf damping.

FORCED/AMBIANT VIBRATION. RESULTS

- **Forced vibration : historical method**
- **Ambiant measurements becoming the reference methods due to the developments in sensor technology and data processing algorithms**
- **Main results :**
  - Modal characteristics identification : frequency / mode shapes / damping (half power-band width, logarithmic decrement methods)
  - FEM comparison and calibration
    - Elastic properties (dam-foundation)
    - Damping
    - Boundary conditions
    - Effets of joints / temperature
    - Dam/foundation interaction
    - Effect of water compressibility

FORCED/AMBIANT VIBRATION. RESULTS AND PERSPECTIVES

- Wind influence on arch (Emosson)
- Temperature influence
- Use for improving simplified formula for modal characteristics

- **Toward long term integrity monitoring ? Damage evolution survey**
  - Roode Elsberg / Kouga dam (South Africa)
  - Hitotsuse dam (Japan)
  - Cabril (Portugal)

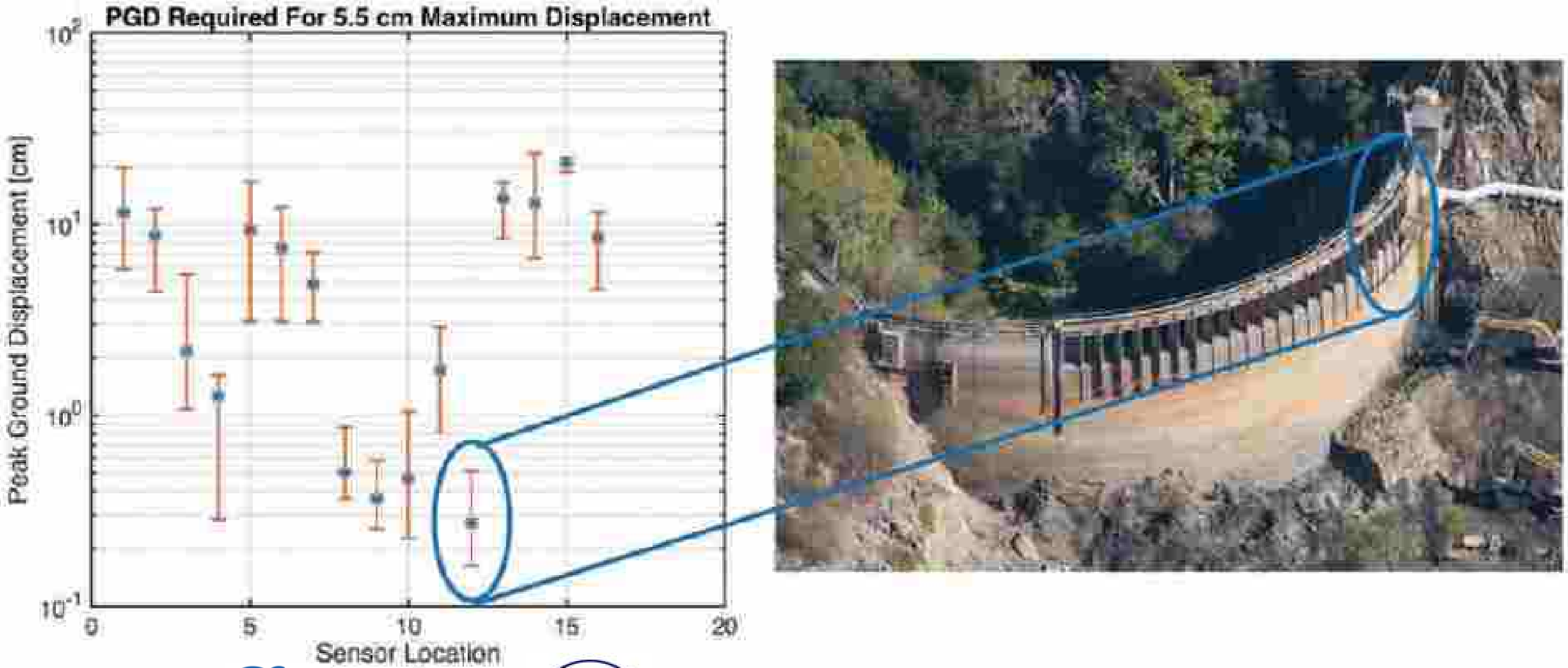
AMBIENT SEISMIC MEASUREMENTS

Saint-Guérin experiment
One year recording of ambiant seismicity
Study of the input spatial variability
EDF/UPA/3SR/ISTERRE collaboration
Eleni Koufoudi presentation

PERFORMANCE BASED TESTING (Z. DURON ET AL)

-Cold Gaz Thruster
-High amplitude and short duration force pulse

$$y(t) = f(t) * h(t) = \int_{\infty}^{\infty} f(\tau)h(t-\tau)d\tau$$

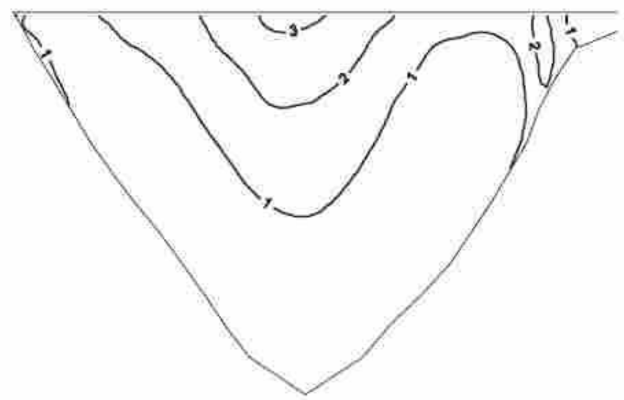


EARTHQUAKE MEASUREMENTS AND OBSERVATIONS

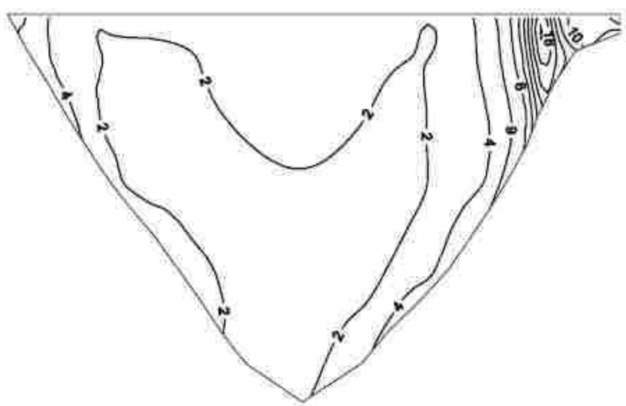
- **JCOLD / CFBR collaboration : application to Kurobe and Tagokura.**
- **In-situ observations :**
  - Cracking
  - Non accessible location (uptream face / dam-foundation contact)
  - Interpretation difficulties (leakages…) / Shapai (cracking…)
- **Use of numerical results in order to refine seismic instrumentation / to focuse on special points**
- **Two recent references :**
  - Back calculation on Pacoima and Shapai dams

SEIMIC OBSERVATION ON MAUVOISIN AND PACOIMA DAM COMPARISON WITH MODELLING RESULTS(CHOPRA)

- **Effect of radiative damping in foundation**
  - Damping with foundation massless model : 6,2 – 6,6 %
  - Damping with mass + radiative conditions in foundation : 2%
  - Damping (half-power bandwidth method) 6,7 – 7 %
- **Effects of spatially vaying input :**
  - explanation of cracking in left abutment thrust block



Spatially-uniform base

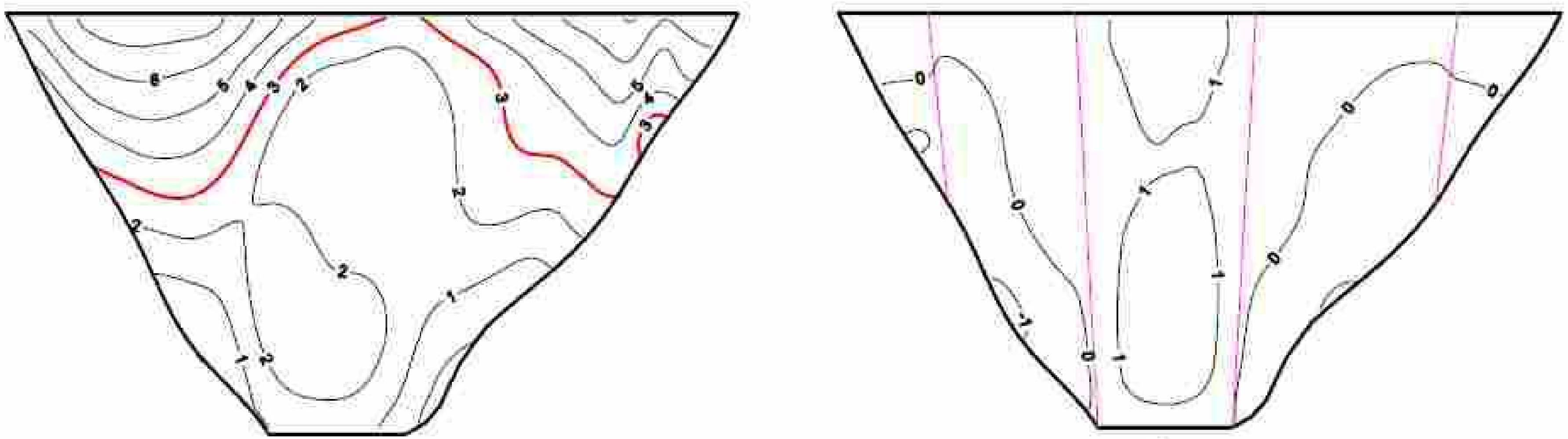


Spatially-varying excitation

SHAPAI : WENCHUAN EARTHQUAKE 2008 (0,4 G)
15 WCEE LISBOA 2012

Two calculations :

- Linear , massless foundation (a) 7 à 9 MPa
- Non-linear (joints opening) + radiative boundaries (b): inf 3 MPa
- No dégradation observed



(a)

(b)

(III) Tensile arch stress on the downstream dam surface

SHAKING TABLES

- **Difficulties in verifying similitude conditions :**
  - Material : strength / density…
  - Loading
- **Two cases with non-linear observations**
  - Sliding of concrete interfaces / pore pressure propagations
  - Dam failure mechanism investigation
- **Main uses :**
  - Not a reduced scale test but means to get experimental data for mechanisms investigation and numerical model calibration on specific aspects
  - Well defined conditions : boundaries, materials, loading

SHAKING TABLE EXPERIMENT / MODELLING

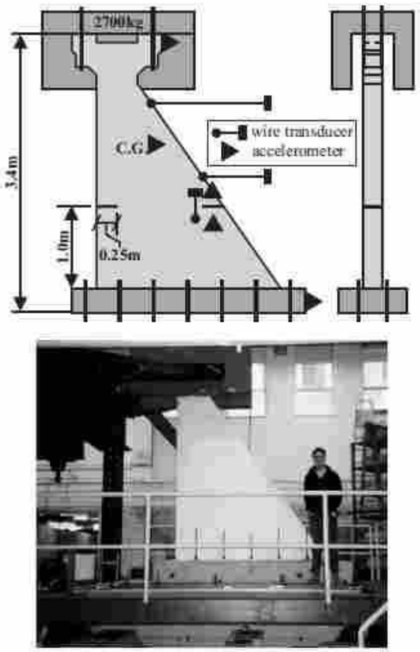
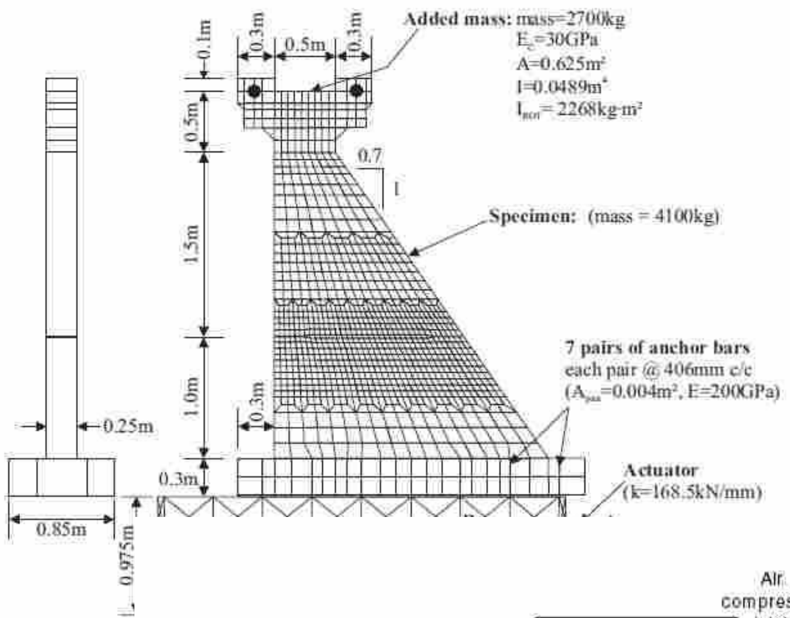


Figure 1: Monolithic dam model and instrumentation setup.



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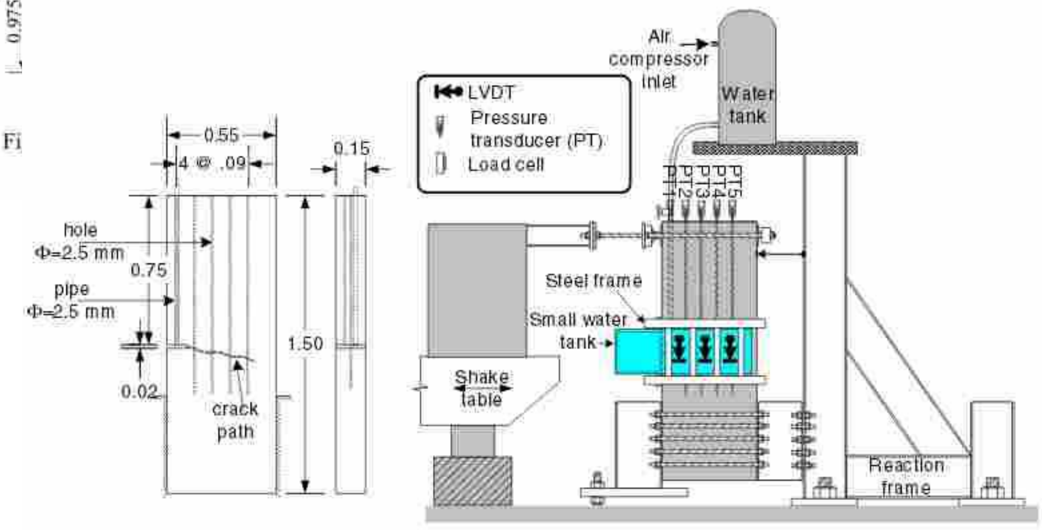
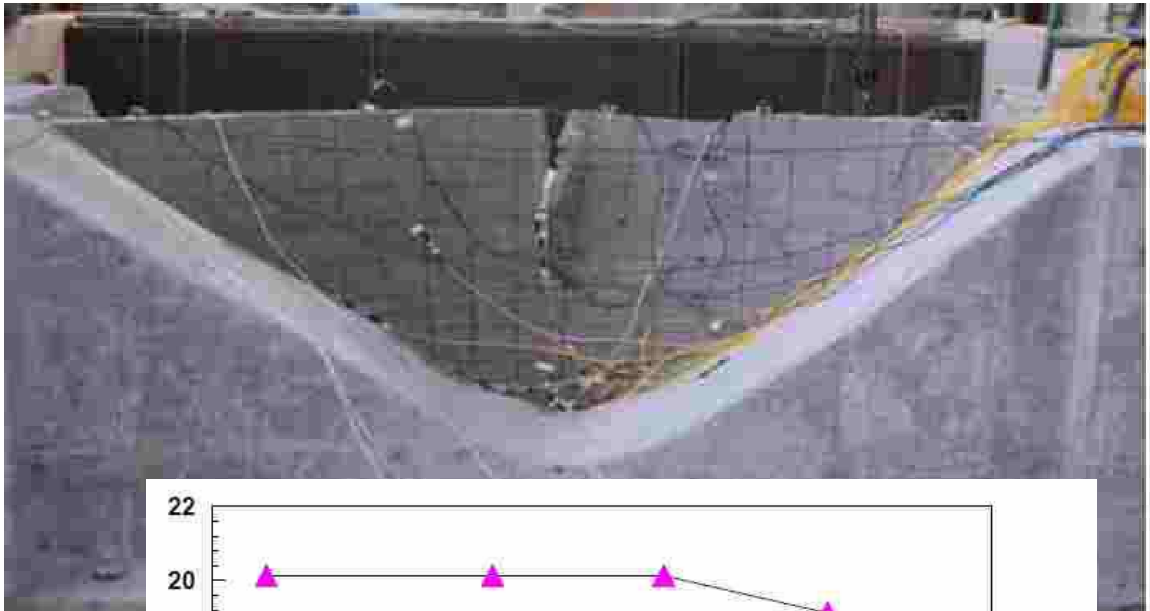


(a) Specimen (dimensions in m)

(b) Test set up

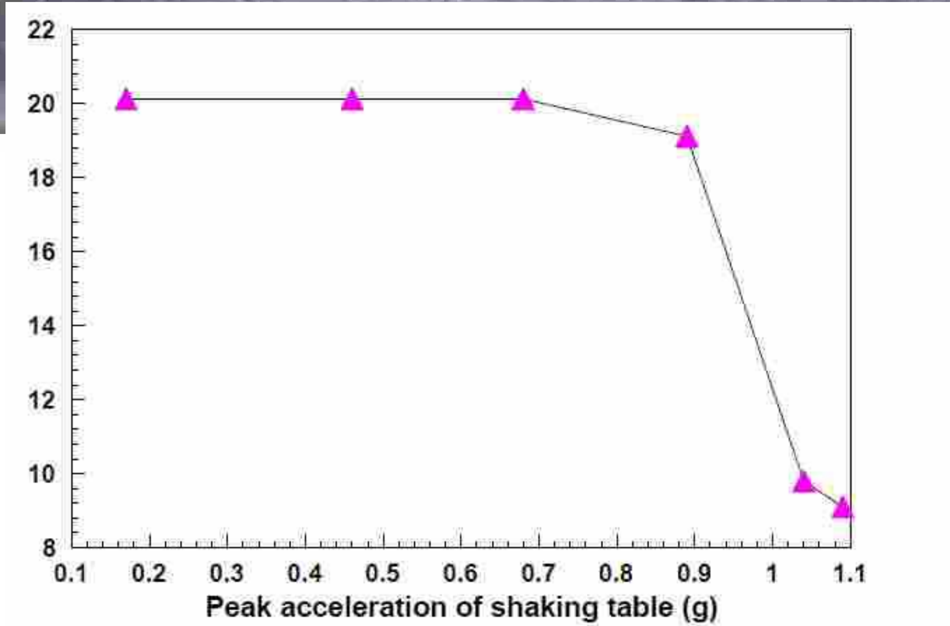
DAM CRACKING SIMULATION

INVESTIGATION OF SEISMIC FAILURE FOR HIGH ARCH DAM WITH MODEL TEST ON SHAKING TABLE (DALIAN UNIVERSITY 2012)



- 1,1 g up/downstream
- Monolithic structure

- Frequency drop with damaging



SYNTHESIS

Methods	+	–	Comments
ICOLD Benchmark	Reference solutions	No comparison with records	Valuable use for software tests
Forced vibration	Load and locationcontrol, Harmonic loading	Special devices	Historical
Ambiant noise	Simple, Rapid, ponctual / permanent	No control loading / loading intensity	Sensor and data processing development
Ambiant seismicity	Significant excitation level	Duration	Multi-support excitation analysis
Performance test	Excitation level Dam response determination	Excitation source constraints	New approach
Earthquake Records	Real loading	Number of events Number of stations	Main importance for improving modeling ralism
Shaking table exp.	Reference solution for modelling on specific topics	Similitude Reservoir loading	Necessity to well define the scope of their use

CONCLUSIONS

- **Modelling calibration /validation is a classical step in static conditions through monitoring results comparison**
- **In dynamic conditions it remains more rare / difficult**
- **Several ways are available in order to move forward model validation and calibration**
- **JCOLD-CFBR collaboration demonstrates the interest to value seismic records and observations**

eDF

Cfbr comité français des barrages et réservoirs

Université de Toulouse

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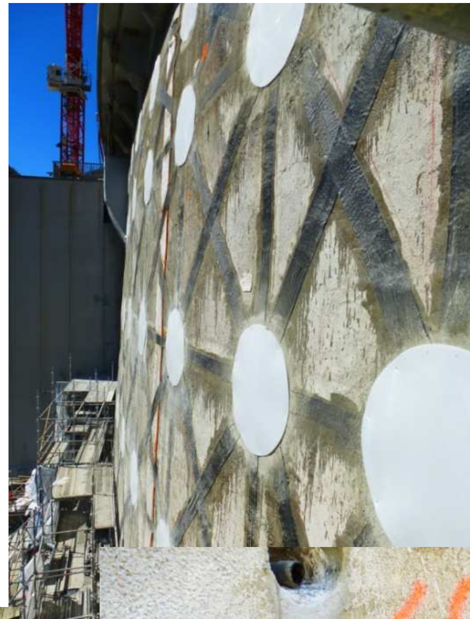
DSC2017

Swelling concrete in dams and hydraulic structures

International Workshop

Chambéry, France, June 13-15 2017

LE CHAMBON DAM




THANK YOU
FOR YOUR
ATTENTION