Recommandations barrages-voûtes

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Symposium AG du CFBR
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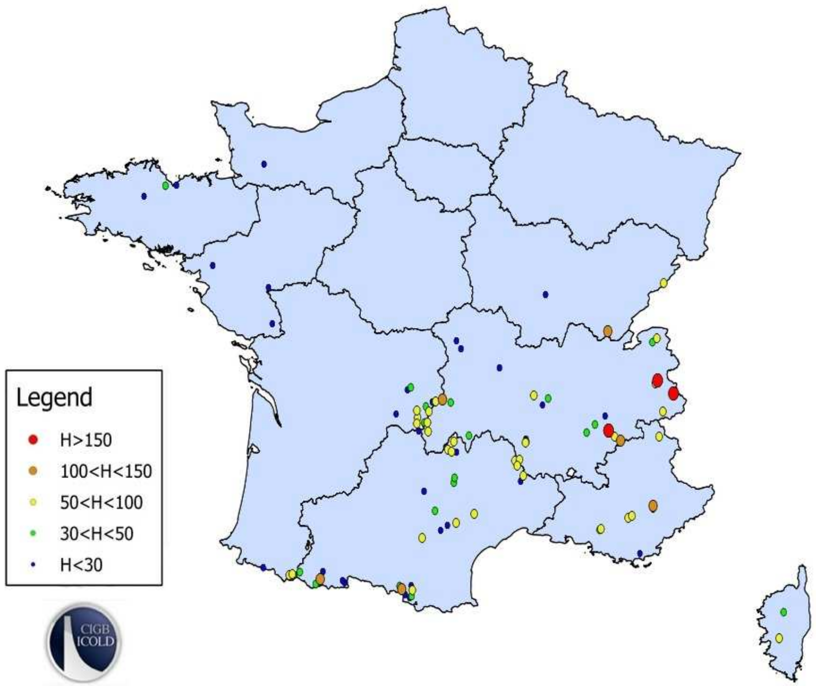
A CFBR (French-COLD) Working Group

- French inventory: 88 arch dams (VA)
- Goal:
  - a state-of-the art for a safety review of arch dam
  - evaluating dam performance from the safety perspective
- Way of thinking: dam accidents and incidents and observed behaviour in order to characterise their specific failure mechanisms.



A CFBR (French-COLD) Working Group: during 4 years

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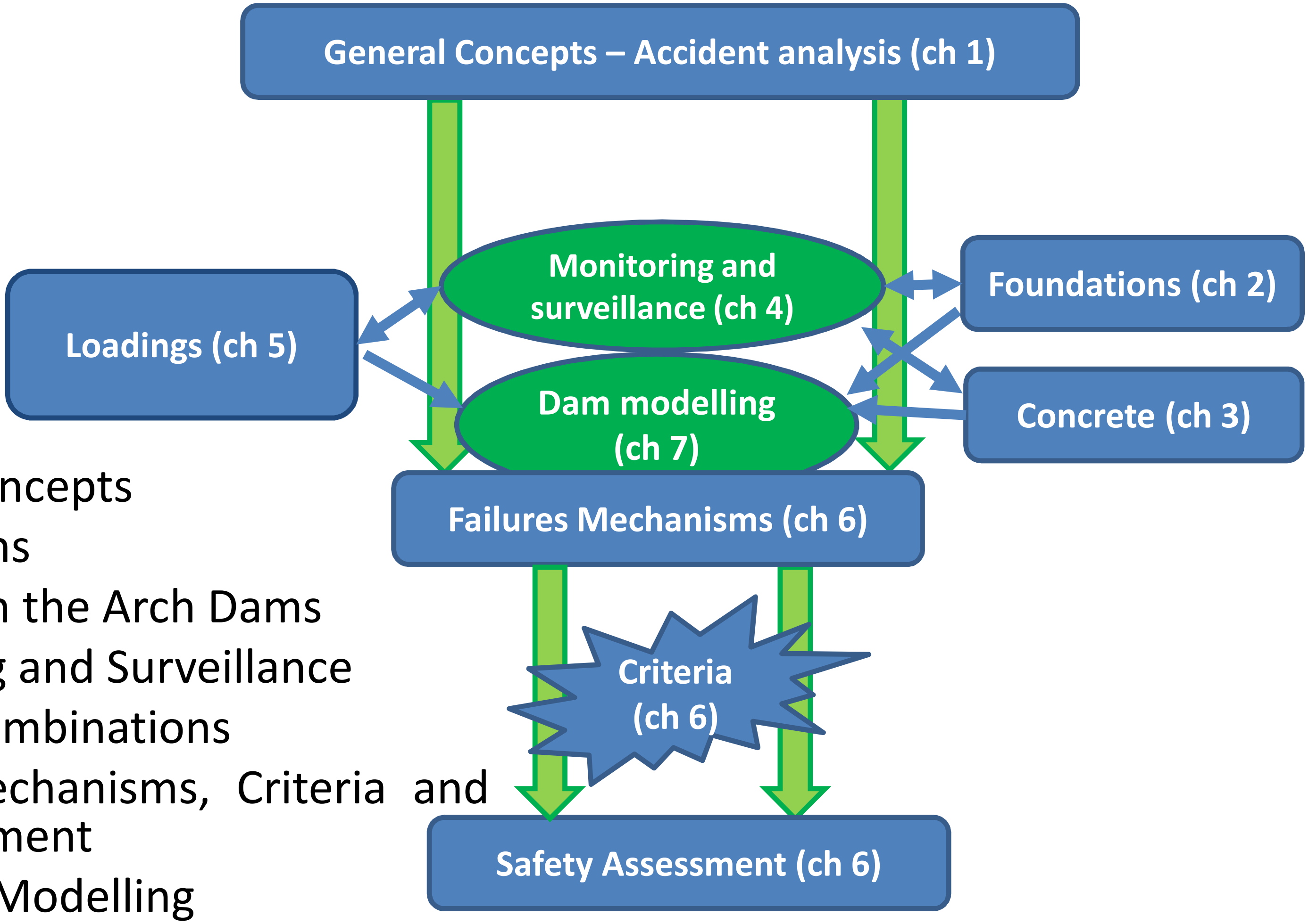
Framework



1. General concepts
2. Foundations
3. Concrete in the Arch Dams
4. Monitoring and Surveillance
5. Loading Combinations
6. Failure Mechanisms, Criteria and Safety Assessment
7. Arch Dam Modelling

+ Technical Appendices including an Appendix on Foreign Practices

General concepts

- Design and construction evolution (Appendix 1) of arch dams with accident review (Appendix 6)

Only 2 arch dam breaking : Malpasset (France) et Meihua (China)

- Mechanical aspects and induced behaviors
- Different "limit" states : notion of "adaptation process" (hyperstaticity) :
  - the adaptation states reflecting normal behaviour of the structure that are considered acceptable under usual load combinations
  - the adaptation states that may lead to the gradual emergence of local disorders, without calling into question the overall behaviour of the dam.
  - beyond, the appearance of disorders that can lead to rupture

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The evaluation of the acceptability limits of these adaptations are the main problem of evaluation of the safety of the structures

Geology / Geomechanics

- Importance of the geological and hydrogeological model
- Highlight an output kinematics
- Differentiate scales in the structure of the rock

The geological study must be done by a geologist competent in the field of dams

- Different types of modules (1st load, reversible, dynamic, irreversible) : their determination depends on the evaluation method
- Needed dialogue between the geomechanical engineer and the civil engineer to determine the choice between peak or residual resistance
- No guided values of shear parameters, rather how to get them

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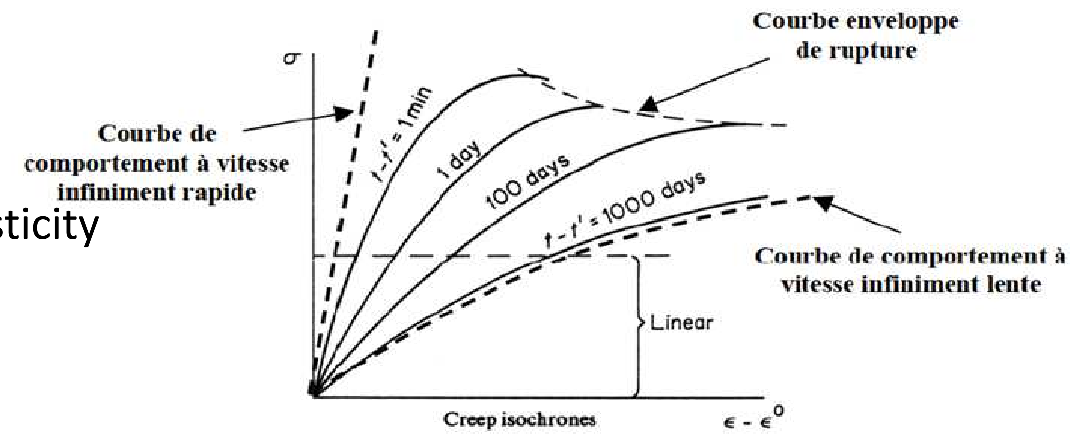
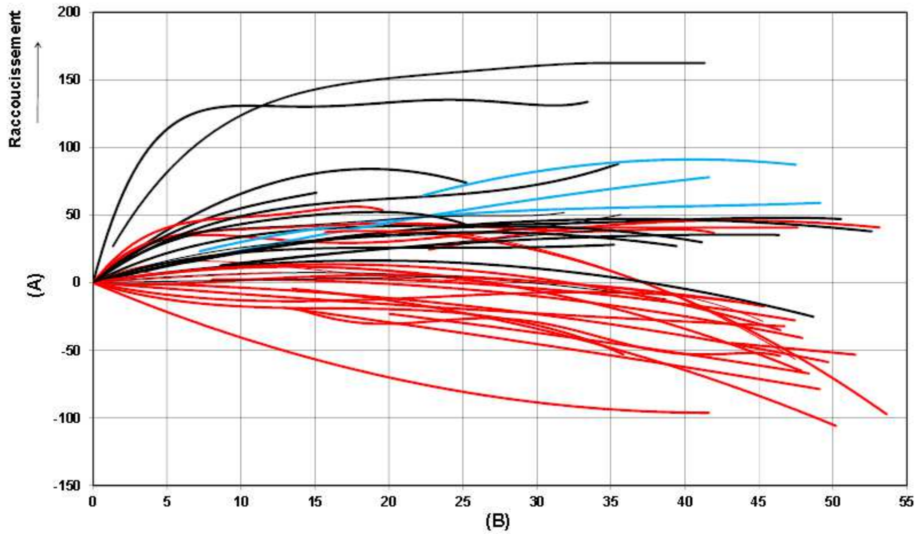
Concrete in the arch dams

- More details than in the recommendations of gravity dams :
  - Characterization of the material
  - Tests / recognitions
  - Behaviour of concrete, irreversible processes (swelling, shrinkage, creep)
  - Mechanical properties
    - zoom on thermal properties
    - zoom on the modulus of elasticity
      - Evaluation method
      - E_s calibrated on monitoring
    - dynamic properties
      - From Ministery guidelines
      - guided values in the text and in appedices



Monitoring and Surveillance

- Particularities of the behavior of the arch dam
  - Specific monitoring and surveillance
- Behaviour
  - Irreversible behaviour
    - shrinkage, swelling, creep, displacements of supports, change of thermal or operating conditions, stresses never known, etc.



Deformations of the crest arc as a function of time and type of the arch dam *(EDF 2003)*

Monitoring and Surveillance

- Supervision and monitoring advice according to the mechanisms identified :
  - Unfavorable factors
  - Characteristic process
  - Surveillance and auscultation possible
- Mechanisms identified (in connection with Chapter 6) :
  - Rock wedge instability
  - Sensitivity to cracking, sliding along the supports
  - Opening upstream toe
  - Swelling of concrete
- Statistical analysis of auscultation data :
  - Standard and more specific analysis methods (see Appendix 4)
  - Historical reenactment

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Loadings

- Distinctive characteristic of arch dams: thermal loads
- But two types of arch dams: vulnerable or not to thermals effects

Load combinations for all dams + Load combinations for vulnerable dam to thermal effects

Vulnerable dam to thermal effects : arch dam in wide valley (L/H>3), arch dam supported by thrust block(s), very thin arch dam

↓

Vulnerability : demonstrated by a numerical model (comparison with and without thermal load) or monitoring analysis

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- Important to focus on situations related to a realistic failure scenario

Loadings

For all arch dams – Situations to be checked

Combination name	Hydrostatic load	Thermal Load
Normal operating situations		
Normal operating situation	**Mean water level**	None
Seasonal operating situation	Water level during the season Water level during the season	**« Winter »** **« Summer »**
Rare Situations		
Rare Flood Situation	**Rare Flood**	None
Rare Seismic Situation (for gated dams)	**OBE**	None
Extreme Situations		
Extreme Flood Situation	**Extreme Flood**	None
Extreme Seismic Situation	**SEE**	None

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Loadings

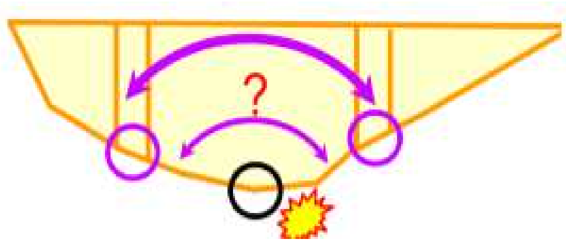
Vulnerable dam to thermal effects – New situations to be checked

Combination name	Hydrostatic load	Thermal Load
Normal operating situations		
Ten-year Seasonal Operating Situation	Water level during the season Water level during the season	**« Ten-year Winter »** **«Ten-year Summer »**
Rare Situations		
Rare Seasonal Situation	**Mean water level** **Mean water level**	**« Winter »** **« Summer »**
Rare Flood Situation with Seasonal Thermal Loading	**Rare flood without marked seasonality of flood distribution**	**« Winter » and « Summer »**
	Rare flood with marked seasonality : Seasonal Flood during the concerned period **Maximum Seasonal Flood**	**Thermal Loading (« Winter » or « Summer ») the most damaging** Thermal loading during the concerned period
Extreme Situations		
Extreme situation with a combination of a flood and a thermal load	Flood to be defined	Thermal load to be defined
Extreme situation with a combination of a seismic load and a thermal load	Seismic load to be defined	Thermal load to be defined

Failure mechanisms

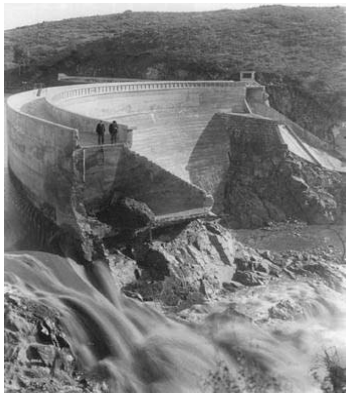
Rock wedge instability

Sliding along the dam/foundation interface



Shear overloading at the base of cantilevers

Excessive stress in concrete



Bedrock erosion by overflow

Erosion internal erosion for specific geological conditions

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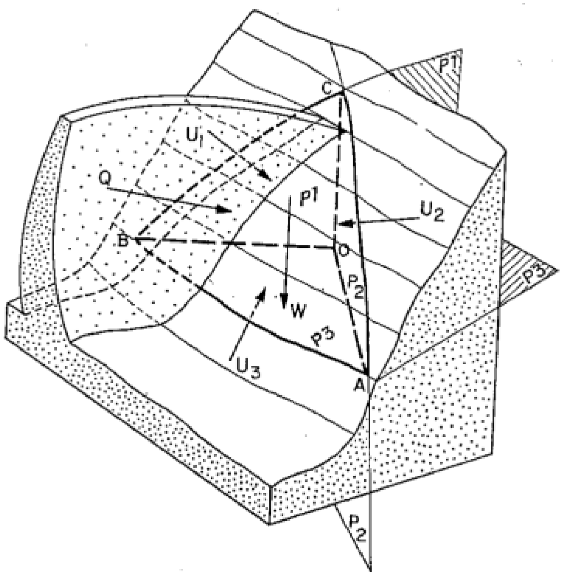
Failure mechanism: Rock Wedge Stability

- Accidents : <u>Malpasset</u>, but also Frayle, Idbar, El Atazar, Montsalvens
- Identify the likely kinematics
- <u>Londe's method</u>, or other more recent methods (discrete element modeling)
- Perform sensitivity analyzes, rather than introducing safety factors on :
  - » uplift pressures
  - » angles of friction
- Retro-analyzes (historical loadings)
- If low safety margins $\rightarrow$ drainage in the rock foundation block.



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Failure mechanism: Sliding along the dam/foundation interface

- Analysis based on:
  - Normal and tangential forces/stresses in the concrete/foundation interface area
  - Shear stress in the concrete/foundation interface area
- Gradual Approach

Linear Elastic Approach → **Non-Linear Approach**

Case of Thurst Block

Approaches

Linear Elastic Approach

- Accepted if a reasonable area of the concrete/foundation area remains in the elastic domain
- Accepted for arch dam in narrow valley (L/H < 2,5)

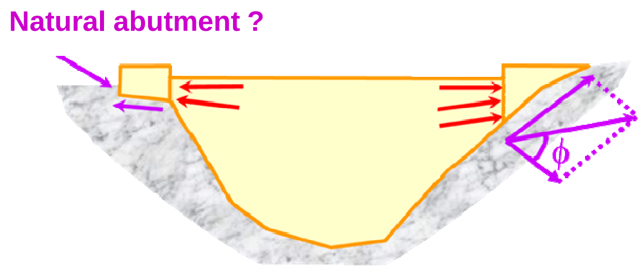
Non-Linear Approach

- Make sure that transfer of thrust on adjacent cantilevers with a new equilibrium state
- Millimetric-irreversible-displacement accepted in normal or rare situation
- Centimetric-irreversible-displacement accepted in extreme situation
- decreasing the shear strength (C and Φ) to search margins of safety,
- [1.5] / [1.2] / [1] for normal/rare/extreme situations

Case of Thurst Block

- Same steps
- But, if the Thrust Block have a significant role on the arch dam stability

To be ckecked as a gravity dam



Failure mechanism: Shear overloading at the base of cantilevers

- No accident, but incidents (possibility of accident ?)
- Similar approach
- Aspects to be checked:
  - Location of the contact opening and the propagation of uplift;
  - Increasing of hydraulic gradients
  - Possible sliding of a rock wedge located immediately downstream;
  - Magnitude of calculated displacements
  - Consequences of stress distribution/reorganisation on other failure kinetics

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Failure mechanism: Excessive stress in concrete

- Accidents : No dam breaking due to an excess of compressive stresses, but…
- The development of cracking (traction) is not directly a mechanism of breaking
- The uncracked area will undergo a greater compression and efforts transmitted are accentuated
- Compression criteria to be checked :

Situation	Linear analysis	Non-linear analysis
Normal	Rc/[3]	Rc/[2]
Rare	Rc/[2]	Rc/[1,5]
Extreme	Rc/[1,1]	Rc/[1,05]

- Make sure that no significant shear stress area in concrete (Mohr-Coulomb criterion).

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Failure mechanism: Scour by overtopping

- Accidents :
  - Generally insensitive to overflow (cf. Vajont)
  - Dam abutment breaking due to overflow : Sweetwater and Moyie River (USA)
- Erosion evaluation methods still remain in the field of research. Annex 6 briefly discusses the available methods
- **Three erosion phenomena identified :**
  - Bank erosion in the vicinity of the part of the dam against the bank (bypass)
  - Erosion of the rock on the banks, by scour of rock fragment under the effect of dynamic pressures
  - Erosion of the rock at the bottom of the valley (impact of the waterfall)
- The **hydraulic engineer and the geologist determine the scour**. Then, the **civil engineers checks the mechanical strength of the structure** following the loss of rock volumes

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Failure mechanism: Internal erosion in foundation

- REX : abutment breaking of Lake Lanier dam (USA)
- Structures not very sensitive, due to the good quality of the rock in foundation of, but particular geological conditions are possible :
  - regressive erosion (faults with mylonite, arenic zones ...)
  - sandy and / or clay fills

- Impossible to define a limit gradient beyond which erosion begins

→ Risk assessment by a geologist

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Dam Modelling

- **Modelling approach**
- **Modelling advice on usual loads**
  - Geometric model and mesh
  - Field of initial stress under self-weight
  - Hydrostatic pressure and hydro-mechanical coupling
  - Thermal Load
- **Choice and adjustment of model parameters**
  - Especially by monitoring

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Dam Modelling

- **Constitutive Equations**
  - Modelling and analysis of the dam body (including non-linear approach)
    - ➢ Discrete element approach
    - ➢ Damage elements
  - Modelling and analysis of the foundation
    - ➢ Isotropic / anisotropic
    - ➢ Discontinuous approaches (Londe's Method, discrete elements)
  - Modelling and analysis of the dam / foundation interface
    - – Linear approach
    - – Non-linear appraoch
      - ➢ Mechanical constitutive equations (Mohr-Coulomb…)
      - ➢ decreasing the shear strength (C and Φ) to search margins of safety
    - – Hydro-mechanical coupling

- **Phenomena causing irreversible behavior**

- **Seismic Modelling**

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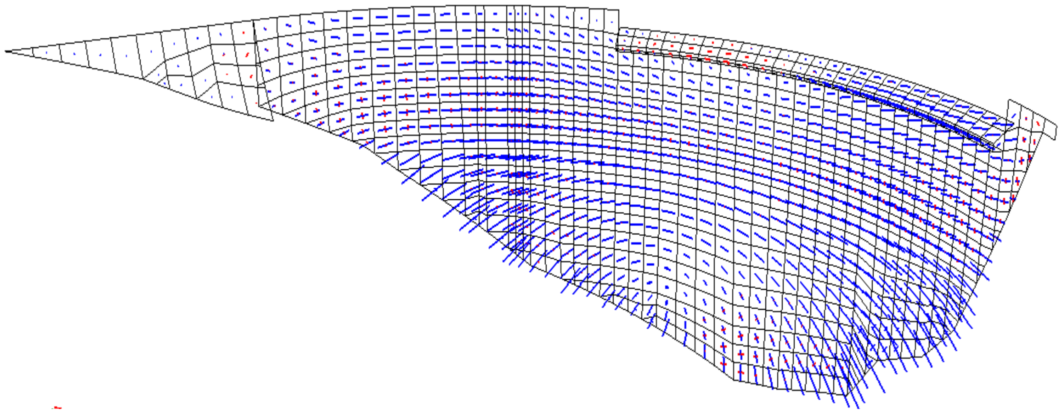
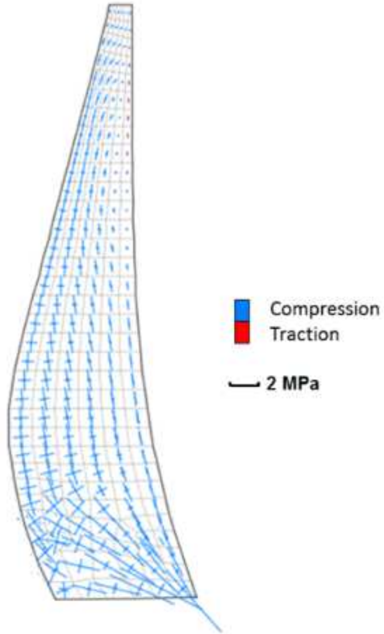
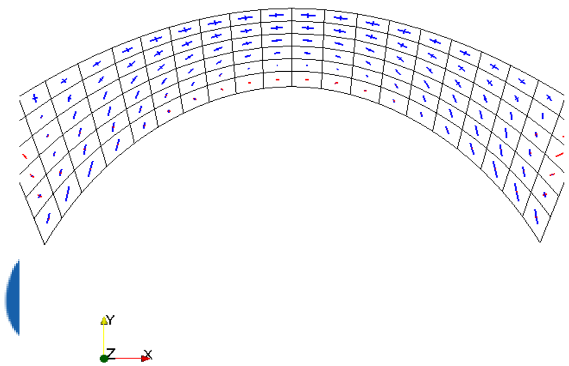
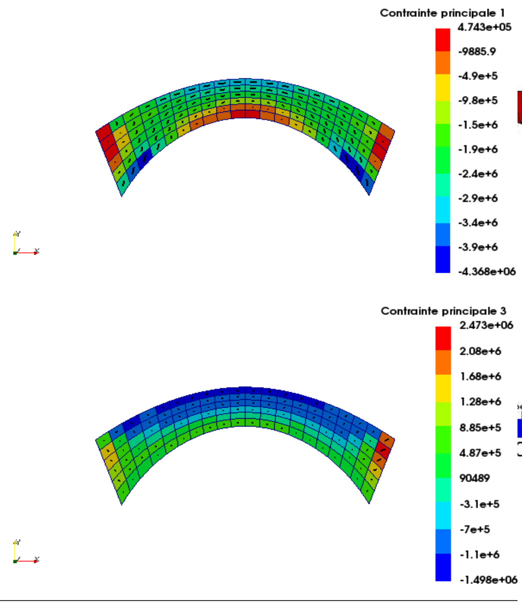
▪ Post-treatments

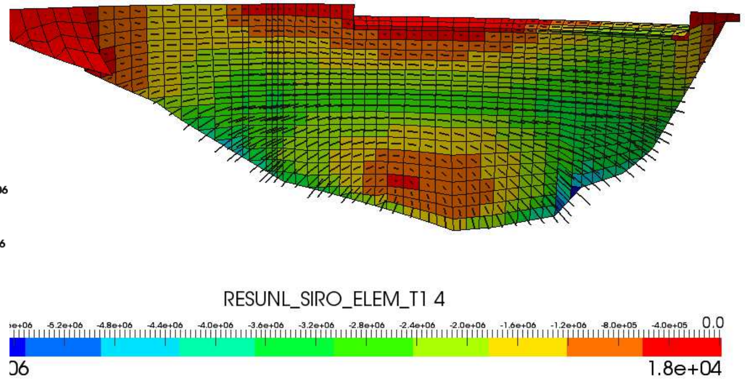
- Projection of main stresses





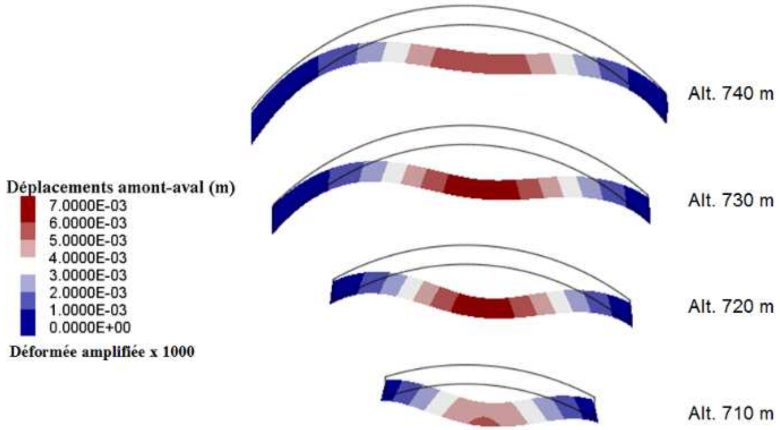


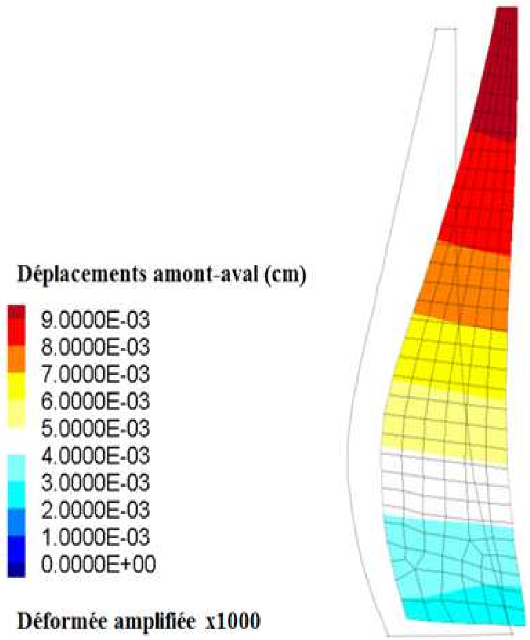




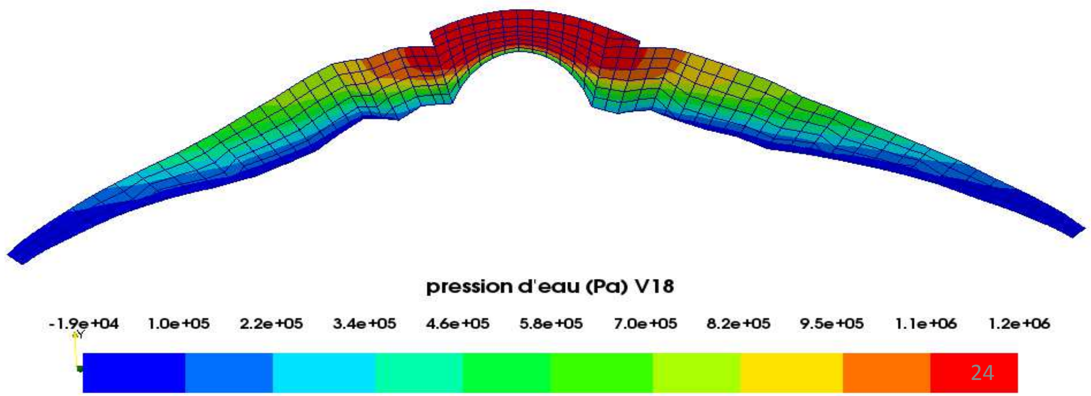
▪ Post- treatments

- Deflection



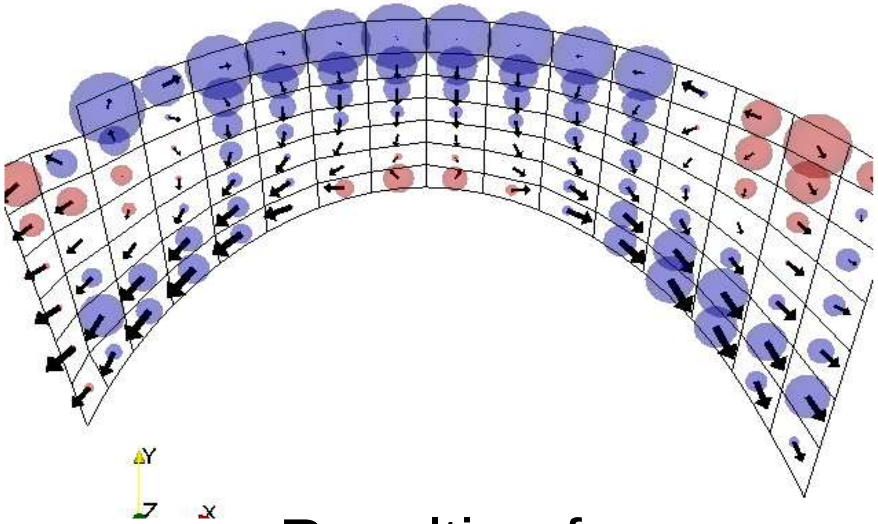


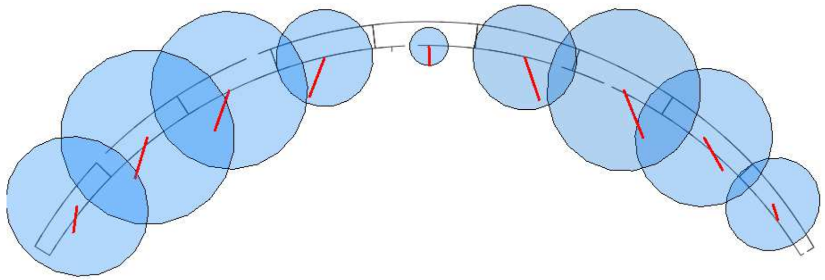
- Uplift at the concrete/rock interface



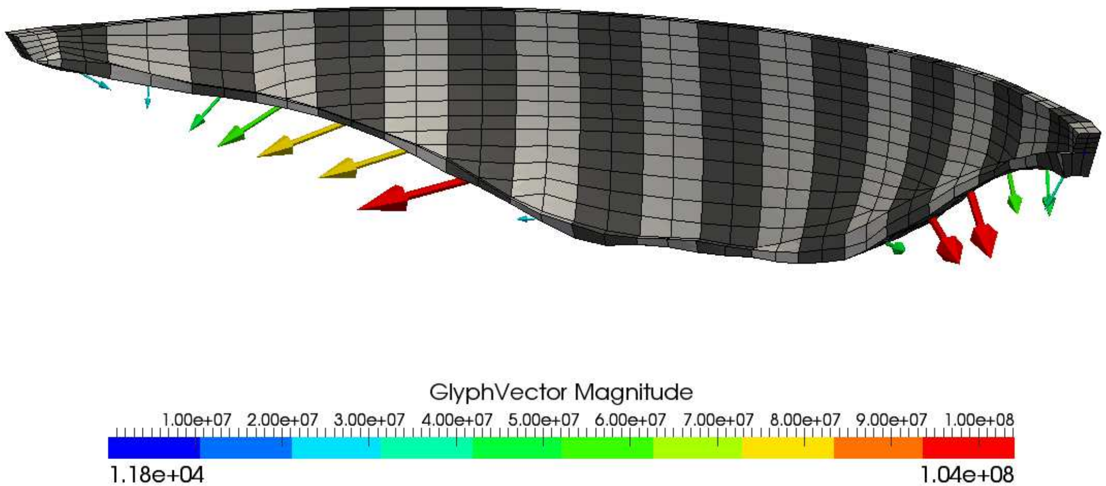
▪ Post- treatments

- Normal and tangent stresses





- Resulting forces on each cantilever



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Appendices

- **Appendix 1: Evolution of justification methods for arch dams**
- **Appendix 2 : Foundations**
  - Characterization of Rock Foundations- Empirical Approaches (H & B, Barton)
  - Precisions on the rupture criterion (description of the shear of a discontinuity, dilatancy)
- **Appendix 3 : Mechanical characteristics of concrete discontinuities (guided values)**
- **Appendix 4 : Monitoring and surveillance**
  - The main types of cracking
  - Principles of statistical analysis methods of measured quantities
  - Measured displacements to internal deformations
  - Feedback on the pressure fields observed in foundation at the central part of the arch dams
  - Use of monitoring for calibration of models

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Appendices

- **Appendix 5 : Accident Analysis**
  - Main events in the world
  - Extracts from the article by E. Bourdarot at the CFBR 2016 conference
- **Appendix 6 : Overflow rock erosion**
  - Main methods
- **Appendix 7 : Foreign regulations and practices**
  - USA, Australia, Switzerland
  - Comparative tables (loads, criteria)
- **Appendix 8 : R&D axis**

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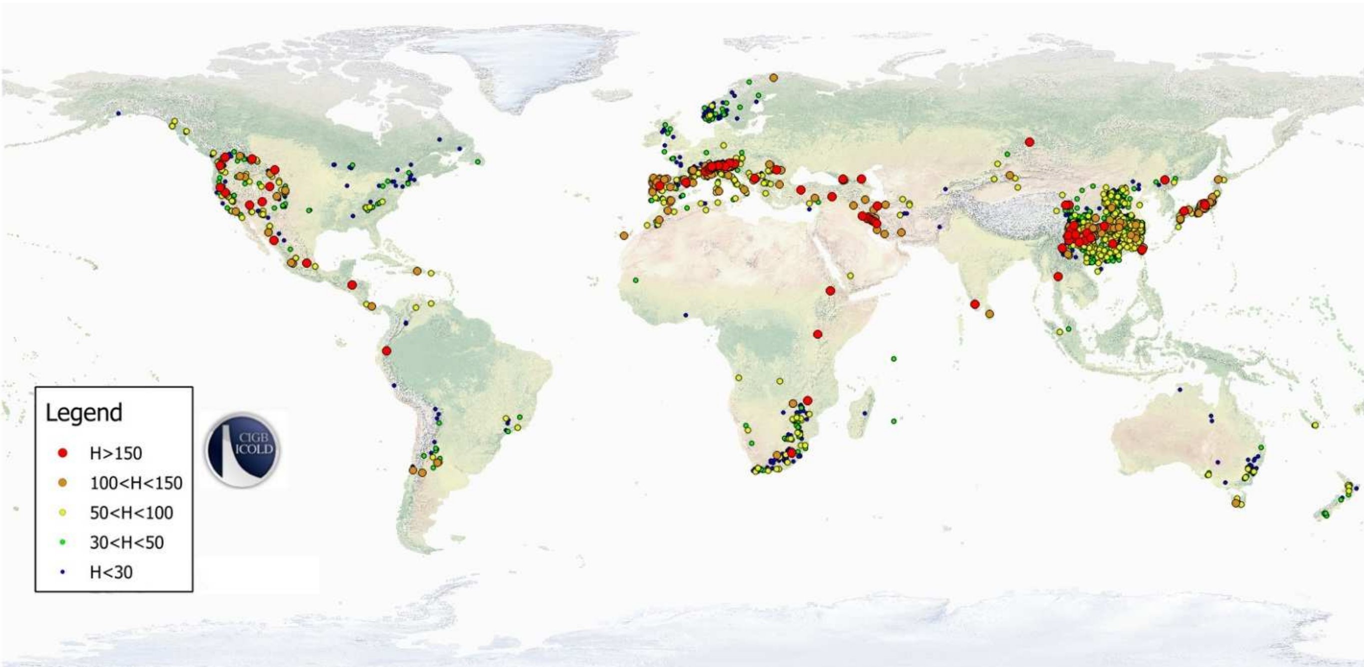
Conclusion

- It was a very short overview of the report
- Article in French for the 2018 ICOLD congress in Vienna but available in English:
  http://barrages-cfbr.eu/IMG/pdf/gtvoute_vienne2018.pdf
- Report available in French on the CFBR website: http://barrages-cfbr.eu
- Report planned to be translated in English



Thanks…

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