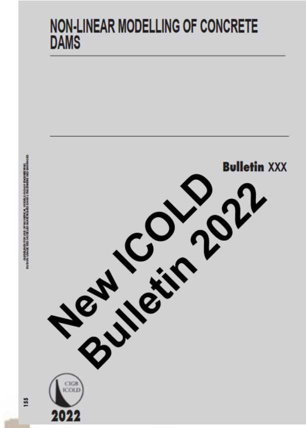
New ICOLD Bulletin Prepared by Technical Committee A
COMPUTATIONAL ASPECTS OF ANALYSIS AND DESIGN OF DAMS (2020-23)

Non-Linear Modelling of Concrete Dams

A new ICOLD bulletin under completion

M. Hassanzadeh, R. Gunn and A. Frigerio



The ICOLD Bulletin on Non-Linear Modelling of Concrete Dams (NLMCD)

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The principal scopes of the bulletin

- Procedures to take into account the non-linear behaviour of
  - constituent materials (material non-linearity),
  - joints (existing naturally occurring and/or pre/post-formed),
  - cracks (interface non-linearity) and
  - supporting structures and foundations.

  caused by mechanical, physical and chemical processes such as external loads, restraints and degradation processes.
- Procedures and tools to solve non-linear static, and non-linear dynamic analyses
- Specify minimum requirements for selection of softwares
- Guidelines for selection of material parameter values for non-linear analysis
- The bulletin disregards geometric nonlinearity

Content of the bulletin

Main chapters and examples of subchapters

Chap. 2 Why and when NLMCD is needed

Chap. 3 Types of structural nonlinearities

Boundary nonlinearities; Material nonlinearities

Chap. 4 Solution methods

Non-linear static and dynamic analysis; incremental iterative solution

Chap. 5 Finite element codes for non-linear modelling

Finite element codes used in past benchmarks; pre-processing & modelling strategy; analysis and post-processing

Chap. 6 Selection of material parameter values for practical NLMCD

Material parameters derived from dam surveillance and monitoring; Material parameters derived from laboratory tests; Material parameters for structural interfaces.

Chap. 7 NLMCD examples and case histories

1) BW 14 cracking of a concrete arch dam due to seasonal temperature variation.

2) Remedial design of cracked dam monoliths subjected to large post-tensioning, flood and earthquake forces.

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5)….

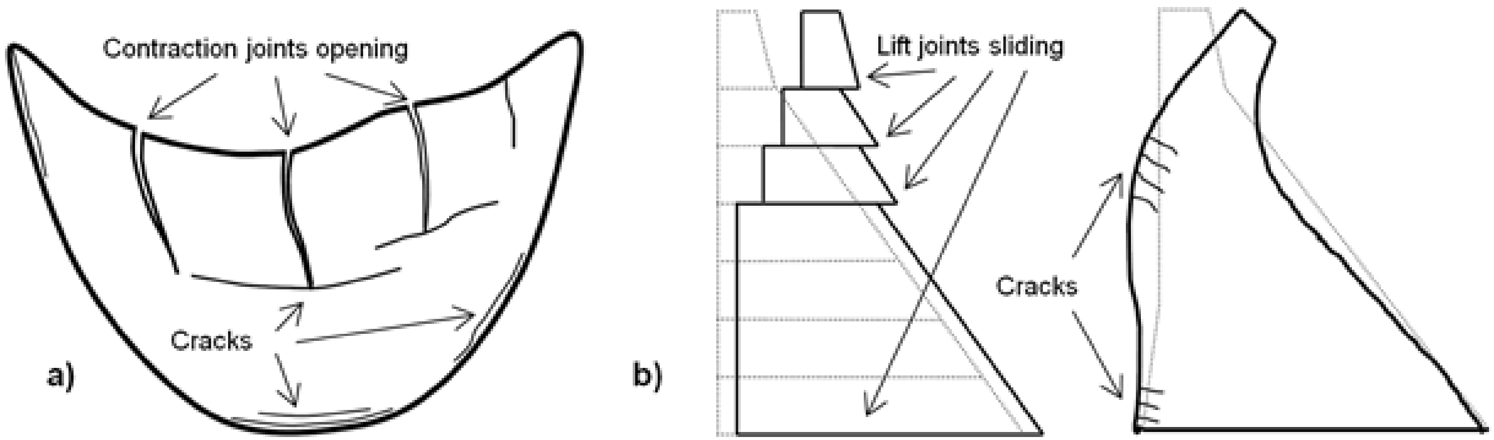
Chap. 8 Conclusions

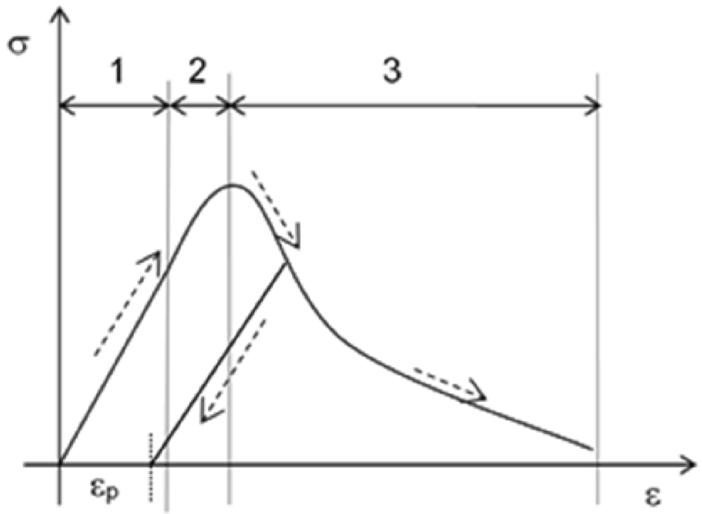
Nonlinear behaviour

$$f = k(u) \cdot u$$

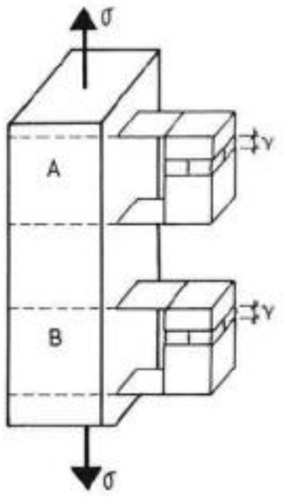
$$M \cdot \ddot{u} + C(u) \cdot \dot{u} + K(u) \cdot u = F(t)$$

Physical/mechanical properties of the material/structure depends on the displacement/strains.

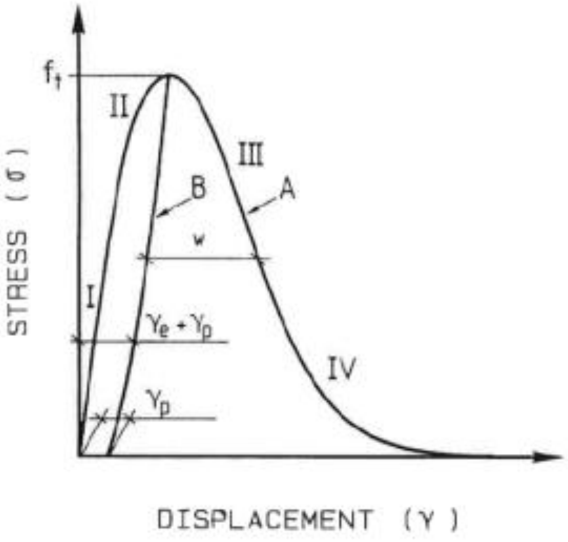




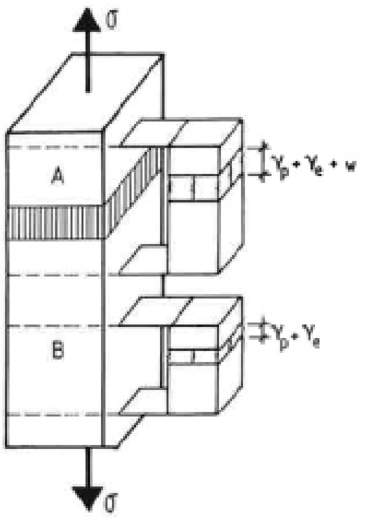
Structural non-linear behaviour caused by material non-linearity in tension



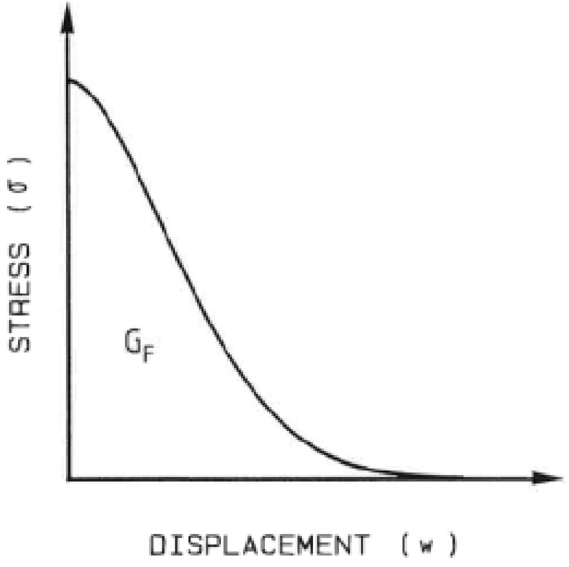
Tensile test setup



Test results



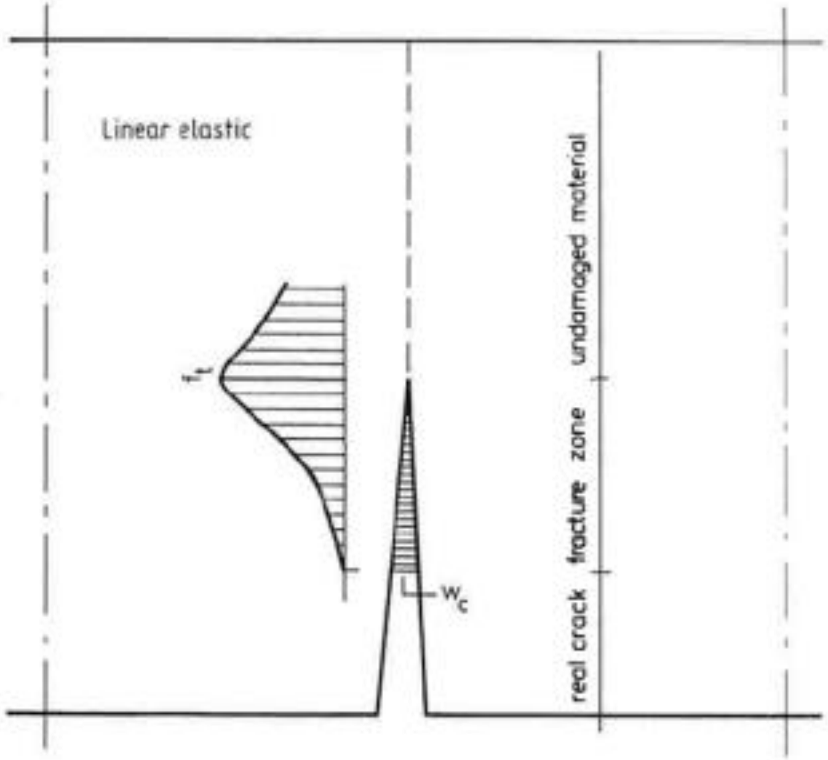
Additional displacement due to formation of fracture zone

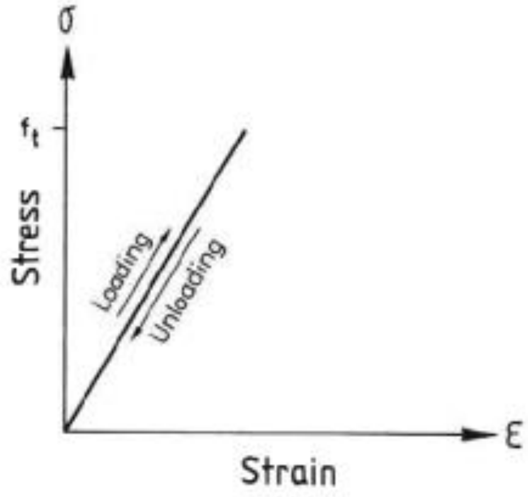


Stress displacement curve of fracture zone

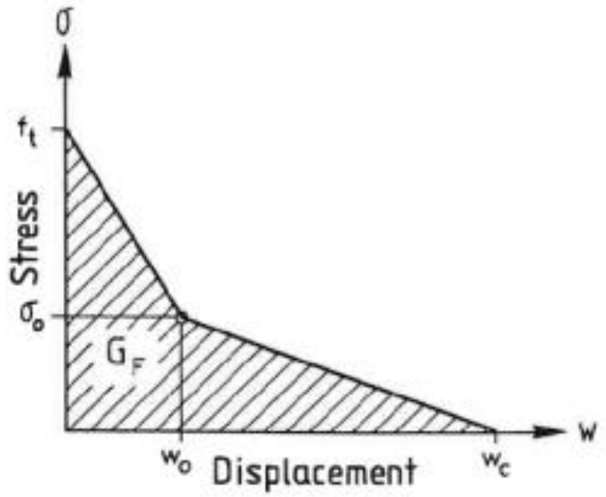
Non-linear material behaviour in a displacement controlled tensile test.

Structural non-linear behaviour caused by material non-linearity





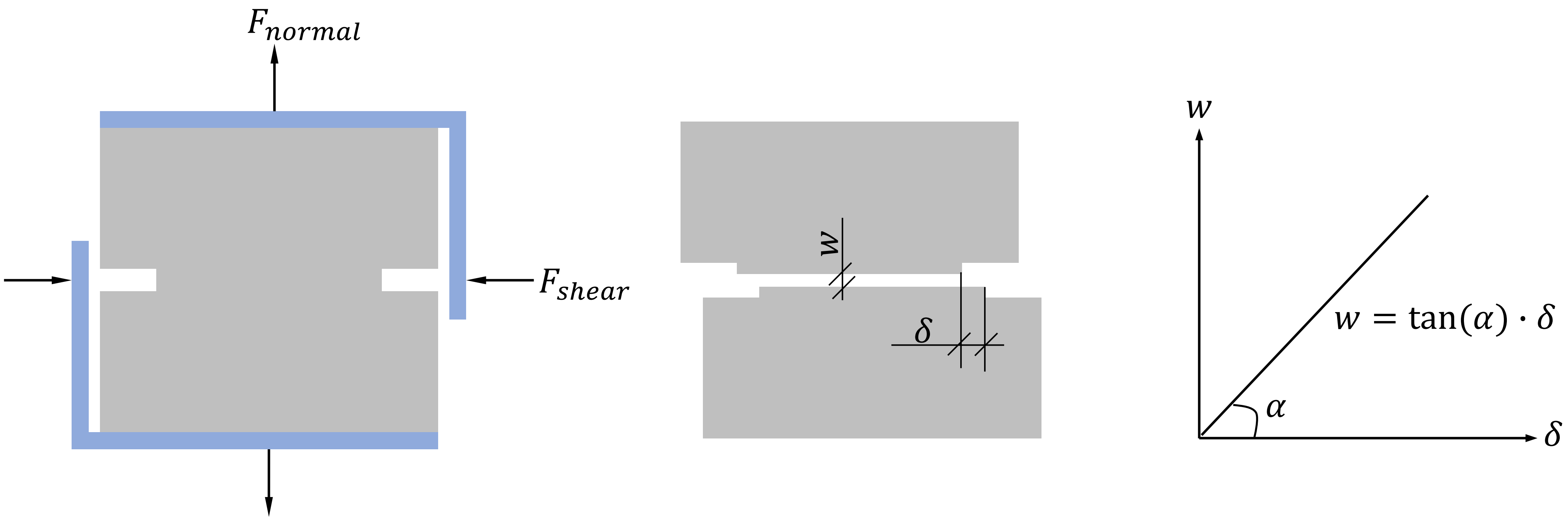
Properties of the linear elastic section



Properties of the fracture zone

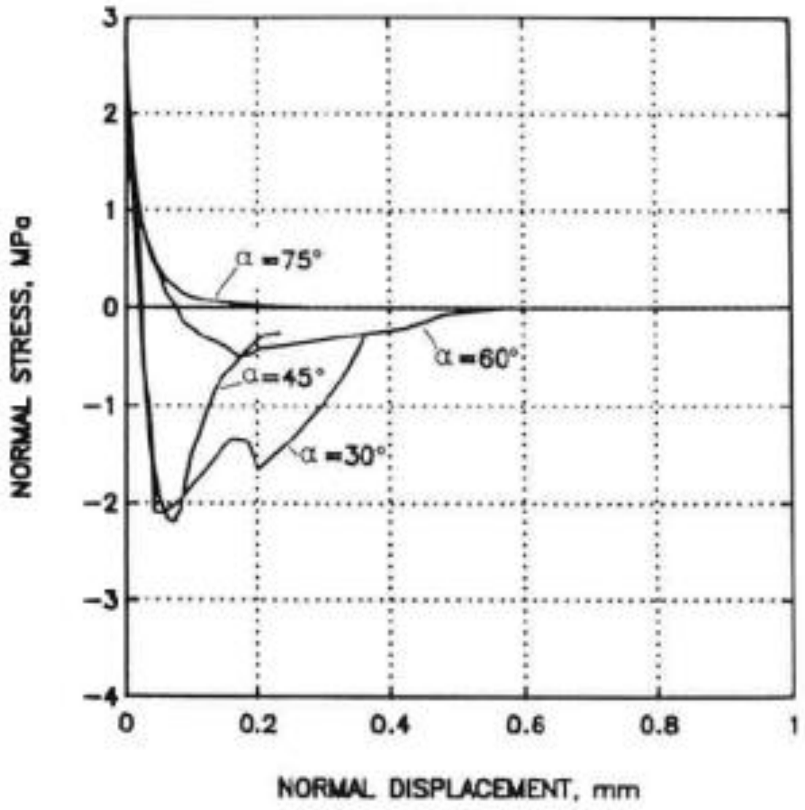
Non-linear material behaviour in a displacement controlled tensile test.

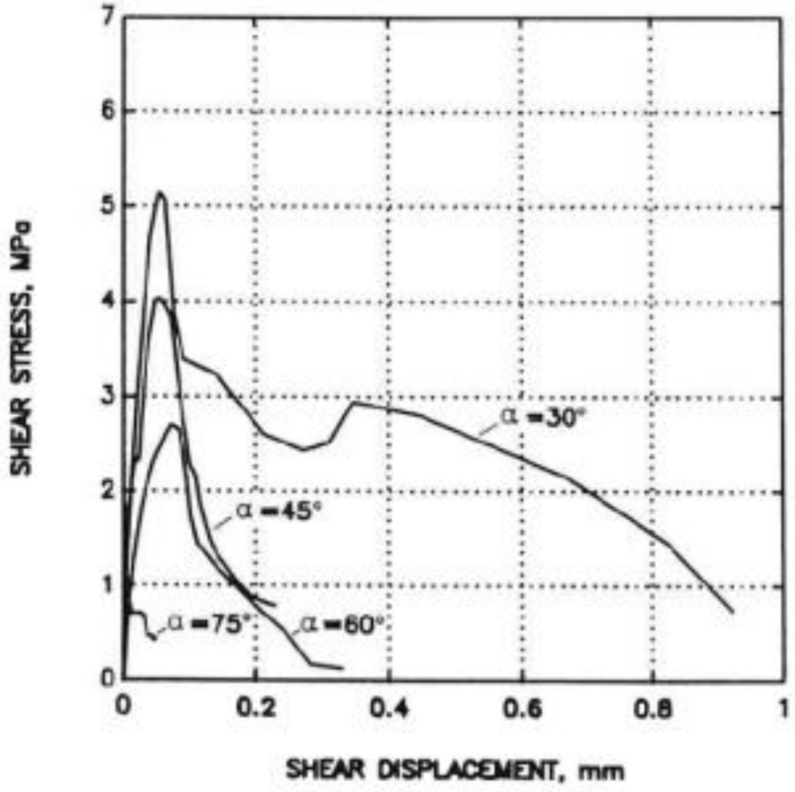
Structural non-linear behaviour caused by material non-linearity

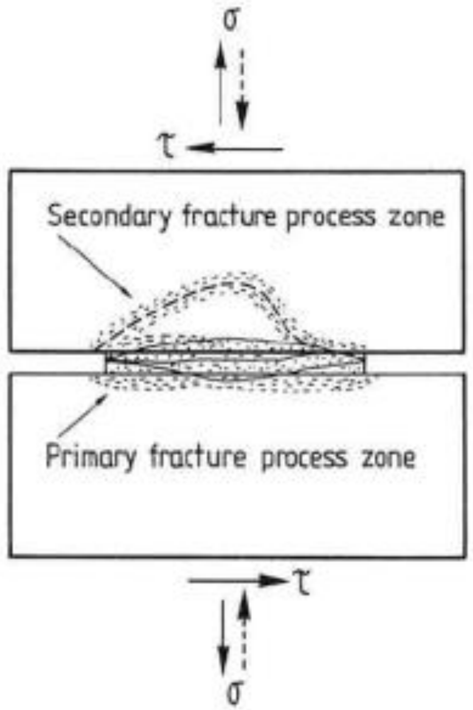


Non-linear material behaviour in a displacement controlled tensile an shear test.

Structural non-linear behaviour caused by material non-linearity







Non-linear material behaviour in a displacement controlled tensile an shear test.

Chap. 3 Types of structural nonlinearities

Boundary and Material non-linearities

The bulletin deals with

Boundary non-linearities

- Vertical contraction joints between cantilever blocks (monoliths)
- Concrete horizontal lift (construction) joints
- Nonlinearity at the dam-foundation interface

Material non-linearities

- Concrete in tension
- Concrete in compression
- Rock foundation

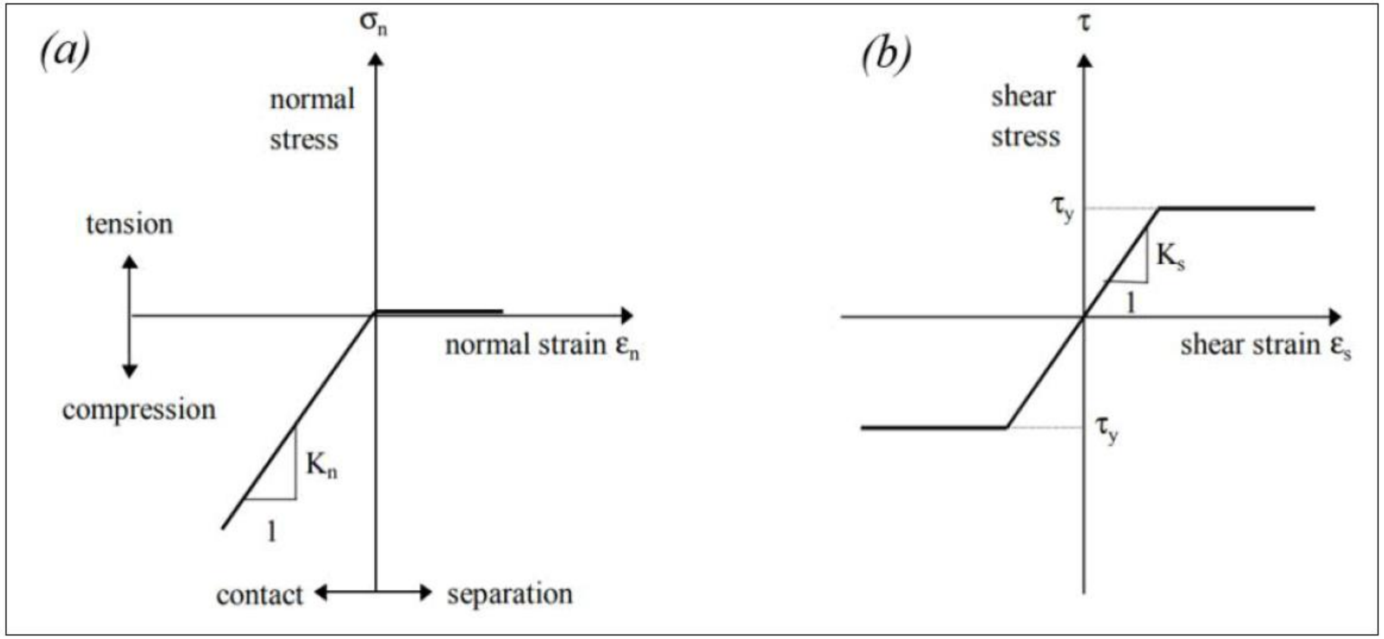
Boundary non-linearities

Deals with modelling of the transition zone between to parts of a structure, between two elements of a structure or between two different structures.

- The transition zone is subjected to sliding as well as separation (opening and closing).
- The transition zone appears in the following structural parts:
  - Vertical contraction joints between cantilever blocks (monoliths)
  - Concrete horizontal lift (construction) joints
  - The interface between the concrete dam and its foundation

Constitutive model for a typical joint element

- It is an elastic-perfectly plastic model, with no tensile strength in the direction normal to the joint element.
- When the joint is separated, neither shear stresses nor normal stresses are transmitted across the joint.
- K_n and K_s are constant when $\tau < \tau_y$.
- Sliding occur when $\tau = \tau_y$ and $K_s = 0$.



Constitutive model for vertical contraction joints

- The spacing of vertical contractions joints is controlled by temperature requirements and construction constraints but are usually around 15 m apart.
- The contraction joints are usually grouted before the first filling of the reservoir.
- Some contraction joints may include shear keys to provide additional sliding resistance by engaging adjacent monoliths.

Constitutive model for the vertical contraction joints

q = normal stress transmitted across the contraction joint

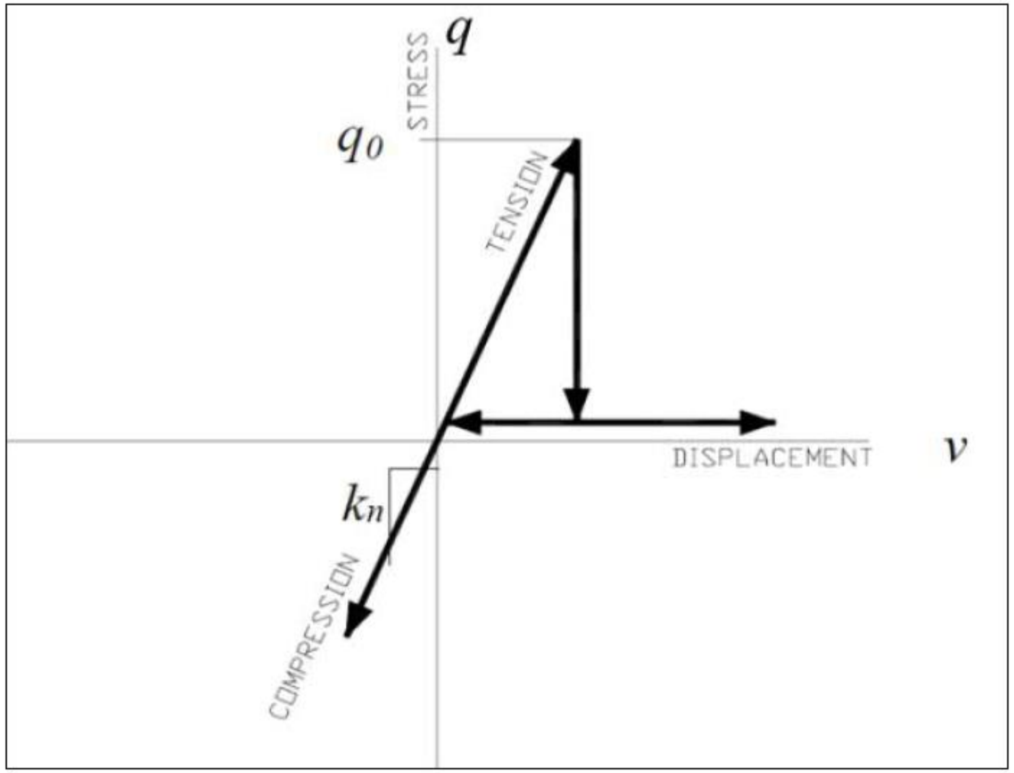
v = relative displacements between both sides of the contraction joint.

k_n = normal stiffness

q_0 = tensile strength

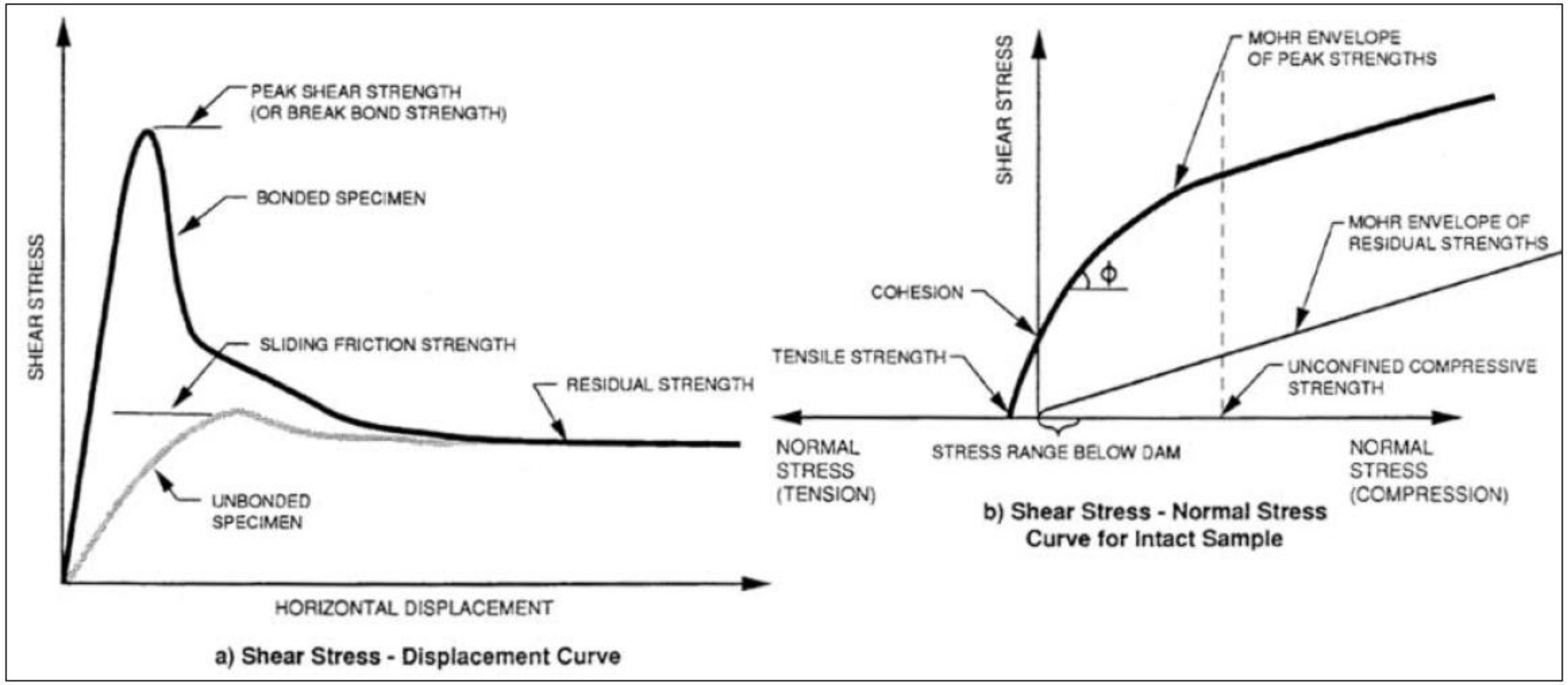
The tensile strength is set to zero to represent an ungrouted contraction joint.

Shear keys may also be needed if the joints are expected to open a significant amount and/or significant shear is expected to be transferred between monoliths. If shear keys are to be included, the constitutive model of the contraction joint needs to account for the tangential stiffness (k_s).



Constitutive models for lift joints – shear strength

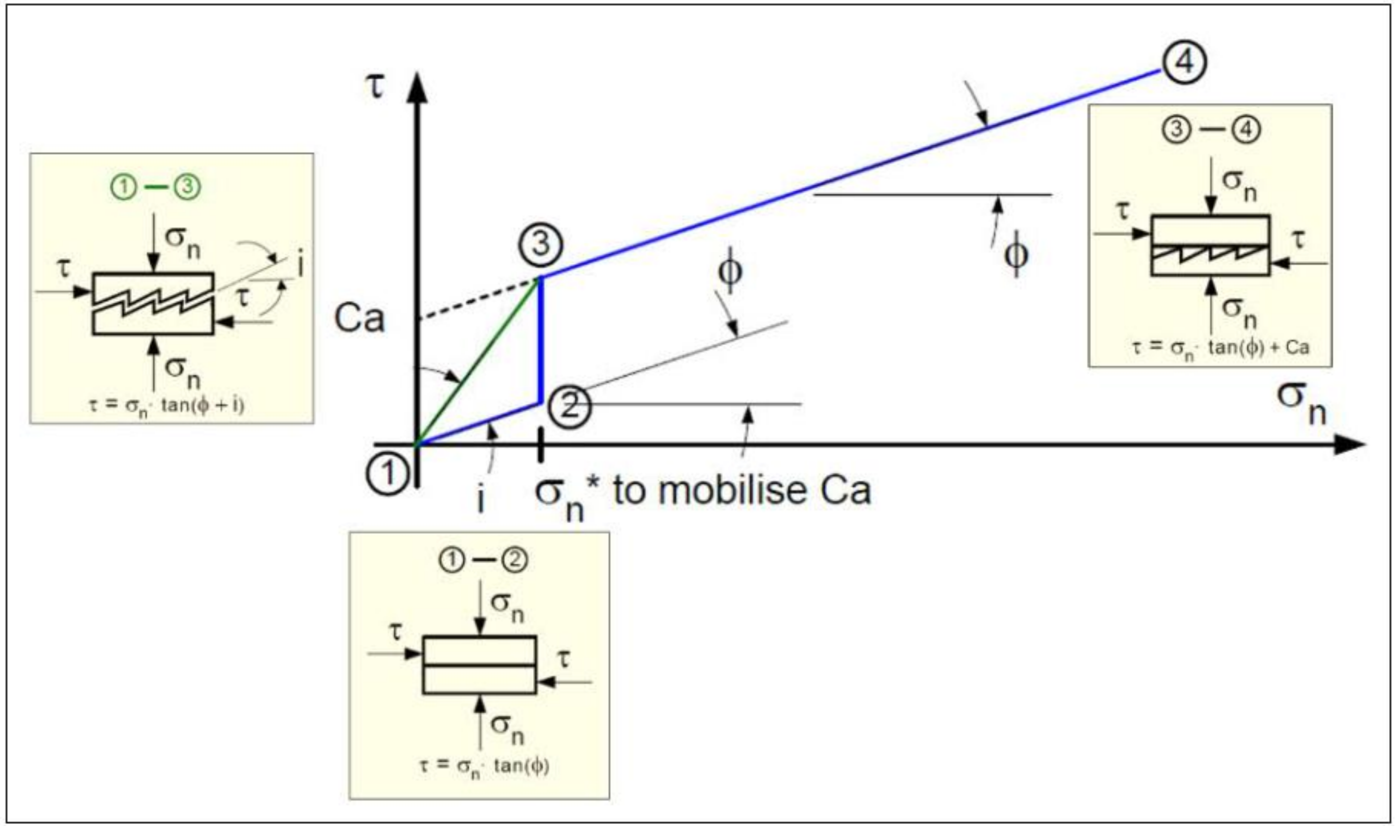
- The peak shear strength is the peak strength on a bonded sample.
- The sliding friction strength is the peak strength on an unbonded sample.
- The residual strength is reached following large displacements.



The shear stress vs. displacement and shear stress vs. normal stress curves for bonded and unbonded lift joints.

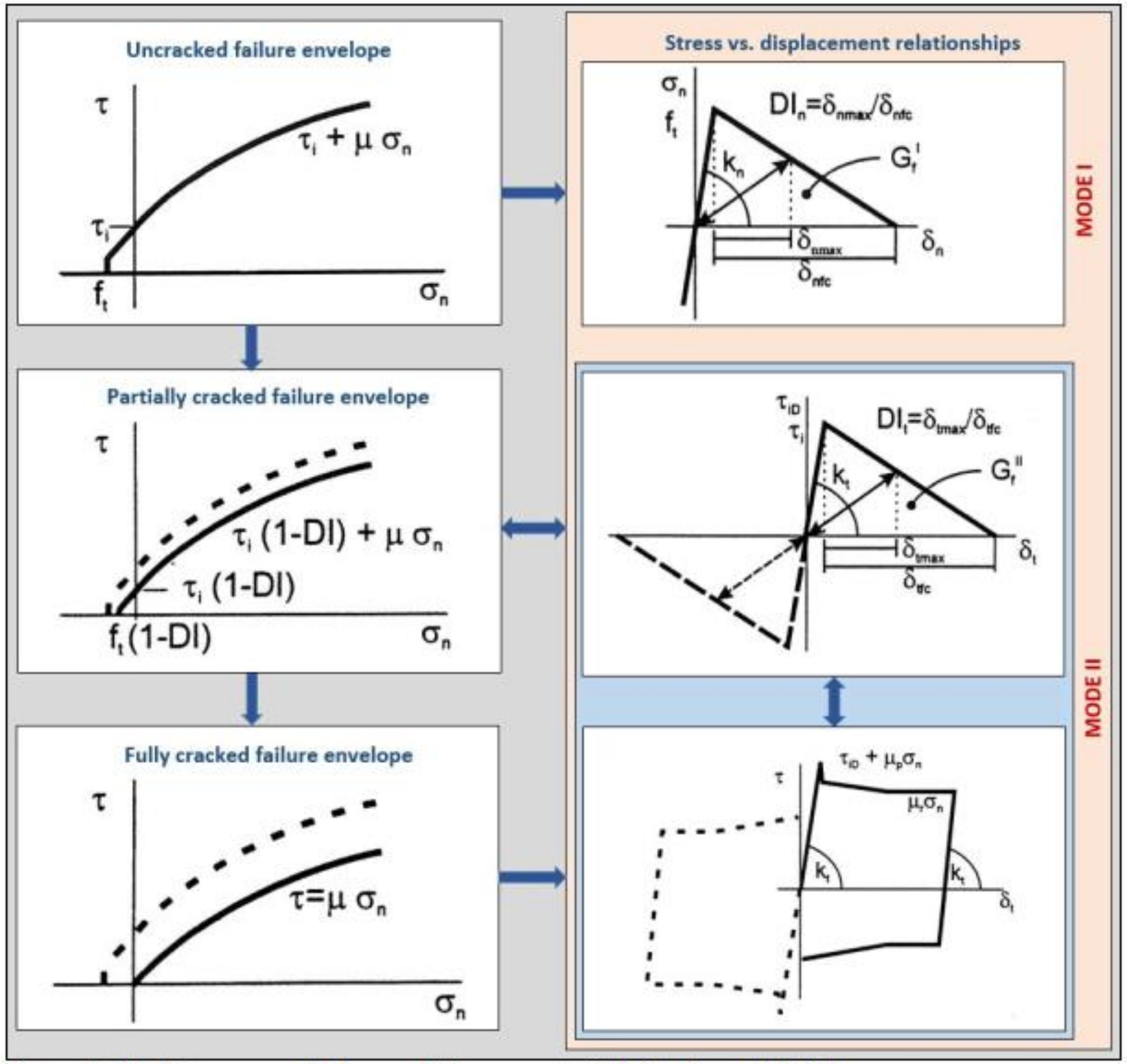
Constitutive models for lift joints – bi-/trilinear models

- 1-Ca-4 bonded and unbonded concrete lift joints with initial cohesion.
- 1-3-4 bilinear relationship for lift joints without initial cohesion, no cohesion $\sigma_n < \sigma_n^*$.
- 1-2-3-4 trilinear relationship for lift joints without initial cohesion, no cohesion $\sigma_n < \sigma_n^*$.



Constitutive models for lift joints – multi-stage model

- **Uncracked stage:** defined by the tensile strength f_t, the cohesion τ_i, and the friction coefficient, μ.
- **Partially cracked stage** (either due to tension or shear): the behaviour follows a classical G_F^I and G_F^{II} fracture energy-based model; the damage index is computed from the damage index DI_n, for tension or DI_τ, for shear; and the normal and shear joint stiffnesses, $K_n$and K_τ respectively, decrease with increasing damage.
- **Fully cracked stage:** the tensile strength is zero, and the shear strength is a function of the normal stress and the shear displacement.



Nonlinearity at the dam-foundation interface

The interaction between the dam and the bedrock is governed by

- the dam structure’s design and size, and the mechanical properties of its constituent materials
- the bedrock’s mechanical properties, existing fracture planes and the water pressure in the bedrock’s cracks, and
- the mechanical and geometrical properties of the transition zone between the dam structure and the bedrock.

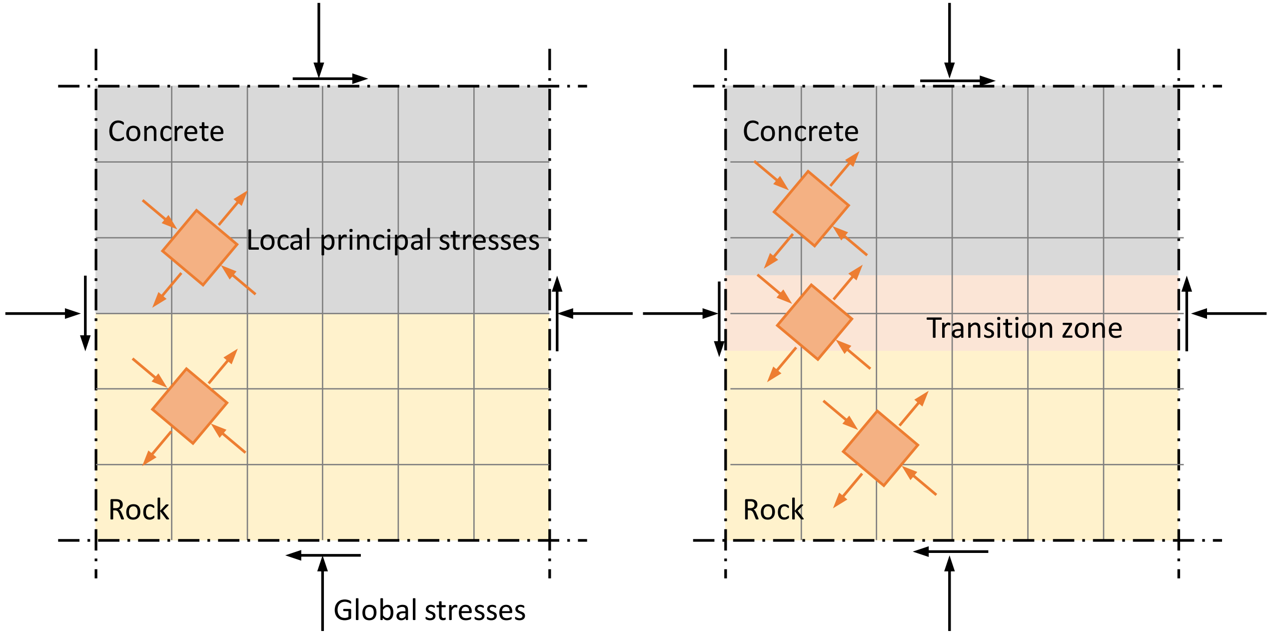
Nonlinearity at the dam-foundation interface

Mechanically, the interaction between the dam structure and the bedrock can be considered as follows:

a. There is no transition zone between the dam structure and the bedrock, that is, there is a rigid connection between the dam and the bedrock.

b. There is a transition zone in between the dam structure and the bedrock, with its own set of mechanical properties.

- Mode I
- Mode II and mixed mode I and II



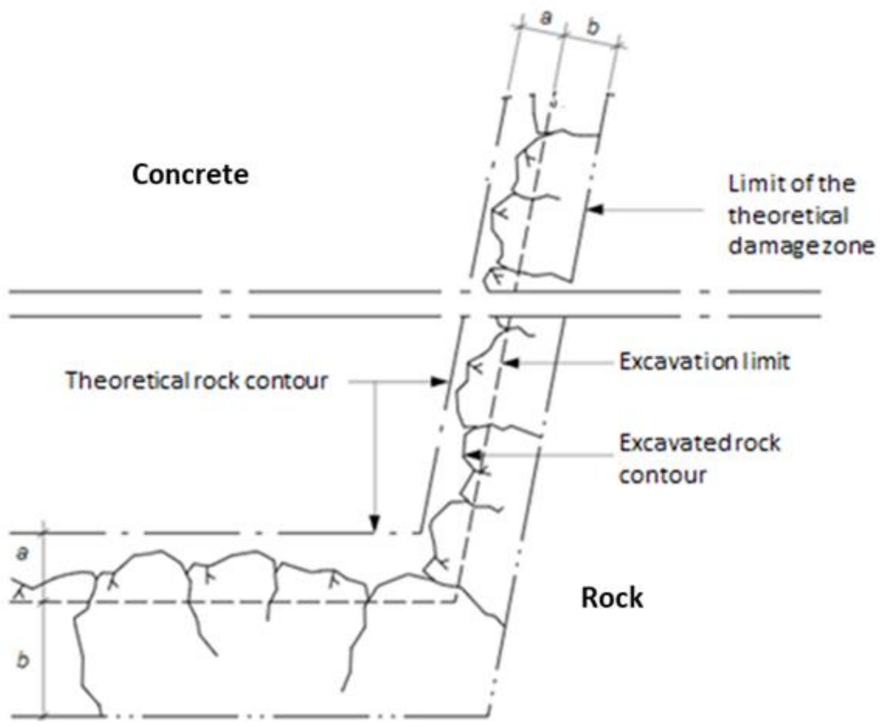
Nonlinearity at the dam-foundation interface

Configuration of the transition zone

Rock excavation class	Excavated rock contour Measure (a)		Theoretical damage zone Measure (b)	
	Wall A	Bottom B	Wall A	Bottom B
1	0.1	0.3	0.2	0.5
2	0.3	0.4	0.3	0.7
3	0.6	0.7	0.5	1.1
4	0.8	1.0	1.1	1.7
5	-[1)]	-[1)]	-[1)]	-[1)]

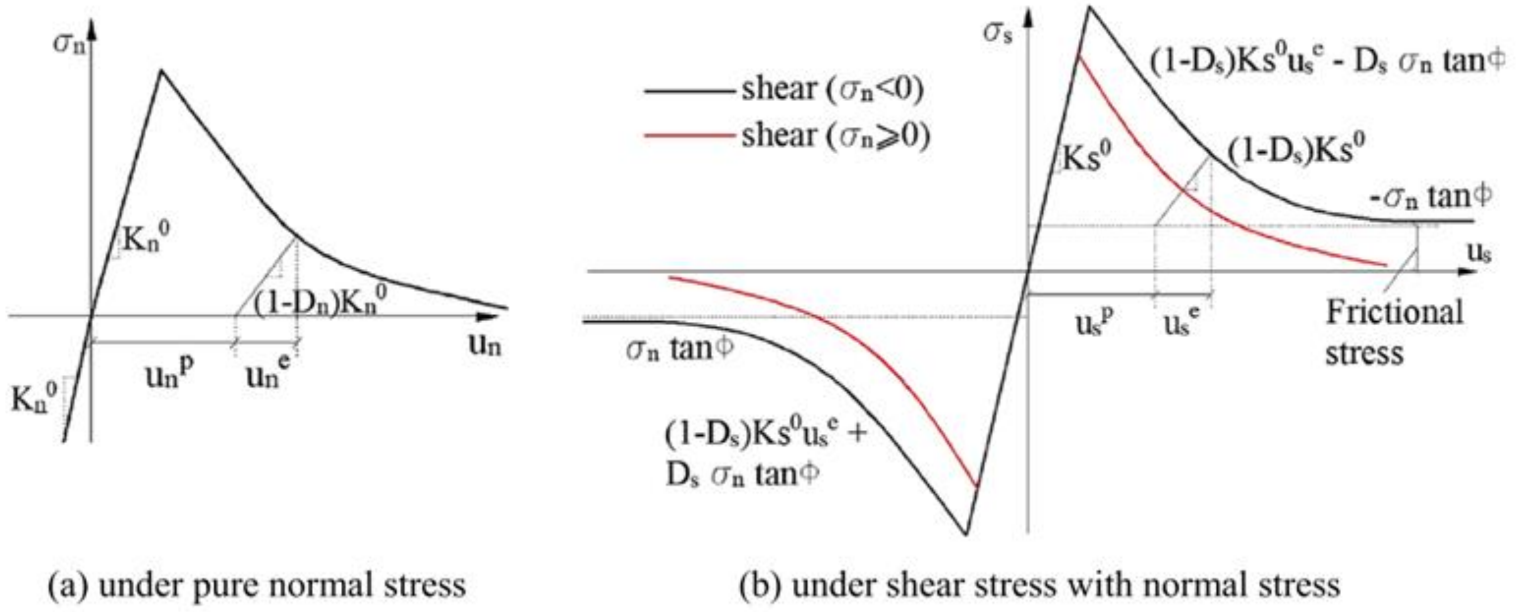
Note: Rock excavation class is indicated by a number (1-5) in combination with a letter (A or B) for the part to which the requirement applies. For only the specified number, the specified rock excavation class applies to both slope / wall and bottom.

1) Excavated rock contour should be outside the theoretical rock contour.



Nonlinearity at the dam-foundation interface

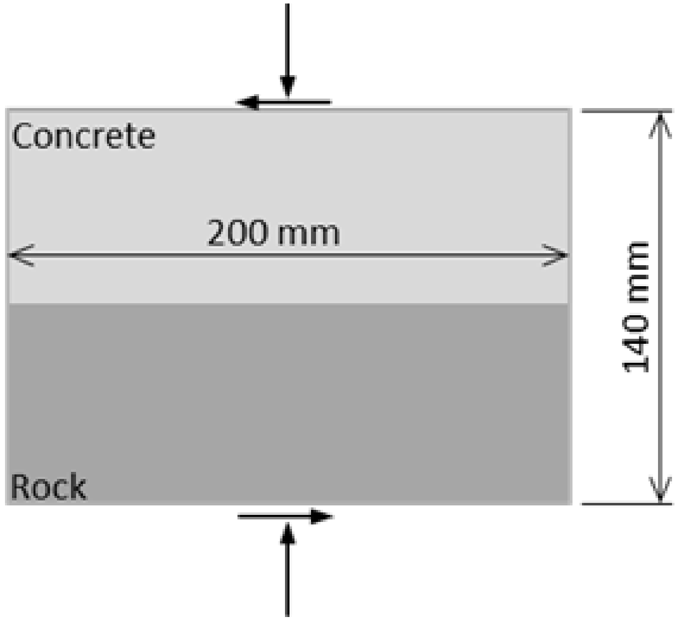
Constitutive model for the transition zone – a damage-plasticity model



Nie et. al. (2022)

Nonlinearity at the dam-foundation interface

An experimental example

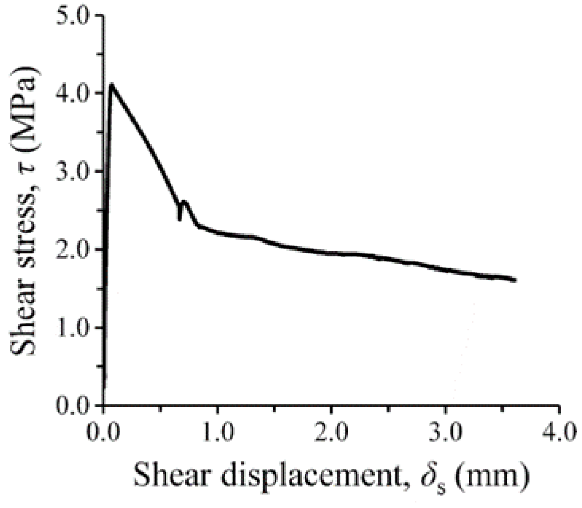


Loading condition and geometry of the specimen 200 mm x 200 mm x 140 mm, Krounis et.al. (2016).

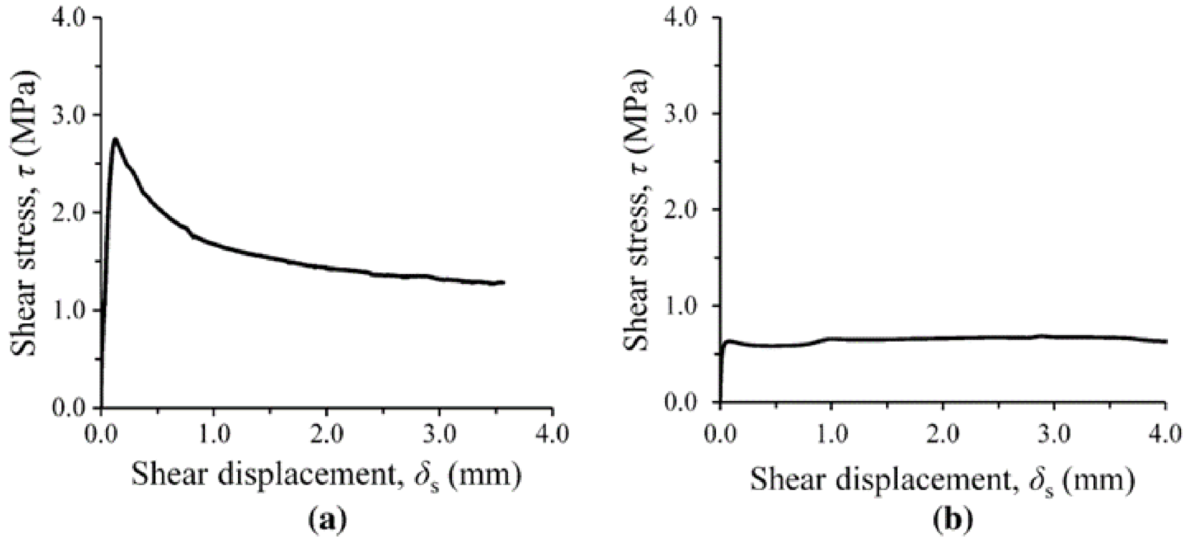
Concrete was cast on Rough or smooth rock surfaces, Krounis et.al. (2016).

Nonlinearity at the dam-foundation interface

An experimental example



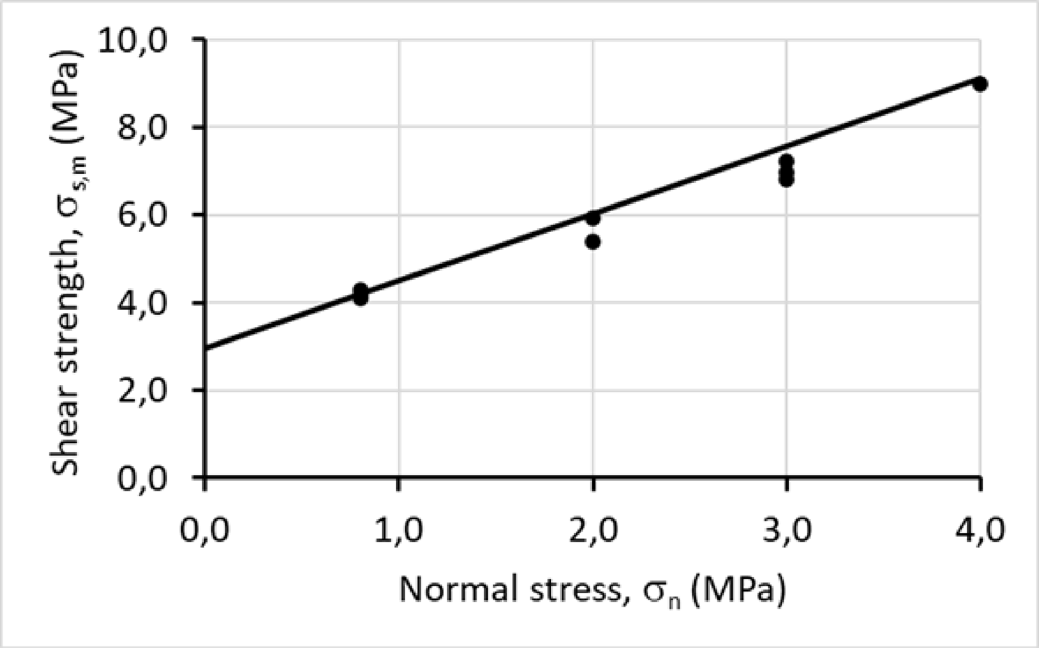
Typical shear stress– displacement curves for bonded samples with rough rock surfaces, at 0.8 MPa normal stress, Krounis et.al. (2016).



Typical shear stress– displacement curves for unbonded samples with (a) rough and (b) smooth rock surfaces, at 0.8 MPa normal stress, Krounis et.al. (2016).

Nonlinearity at the dam-foundation interface

An experimental example



Shear vs normal strength - Best-fit straight line on the results of experiments, c = 3.0 MPa and $\emptyset_i$ = 54.4°, Krounis et.al. (2016).

Material nonlinearity – concrete in tension

Models and material relationships are based on Eurocode and model code

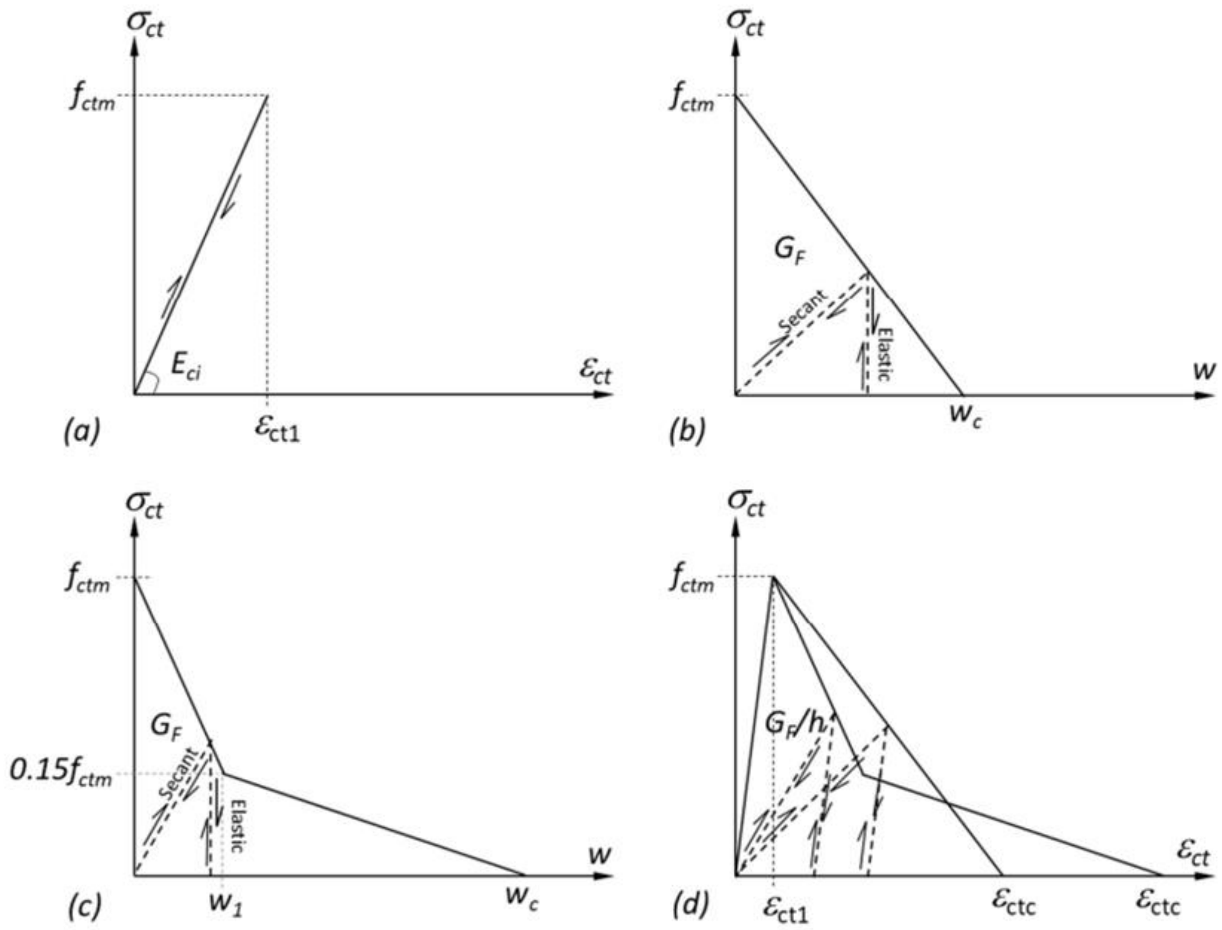
Undamaged material

$$\sigma_{ct} = E_{ci}\varepsilon_{ct} \qquad \varepsilon_{ct} \leq \varepsilon_{ctl}$$

Damaged material – linear $\sigma_{ct} - w$ curve

$$\sigma_{ct} = \left(1 - \frac{w}{w_c}\right) f_{ctm} \qquad \varepsilon_{ct} > \varepsilon_{ctl}\ ,\ w \leq w_c$$

$$w_c = 2\frac{G_F}{f_{ctm}}$$



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Damaged material – linear $\sigma_{ct} - w$ curve

$$\sigma_{ct} = \left(1 - \frac{w}{w_c}\right) f_{ctm} \qquad \varepsilon_{ct} > \varepsilon_{ctl}\ , w \leq w_c$$

$$w_c = 2\frac{G_F}{f_{ctm}}$$

$$f_{ctm} = 0.3 \cdot (f_{cm} - 8)^{2/3}$$

$$E_{ci} = E_{c0} \cdot \left(\frac{f_{cm}}{10}\right)^{1/3}$$

$$G_F = 73 \cdot (f_{cm})^{0.18}$$

f_{cm}= mean compressive strength MPa

Material nonlinearity – concrete in tension – strain rate effects

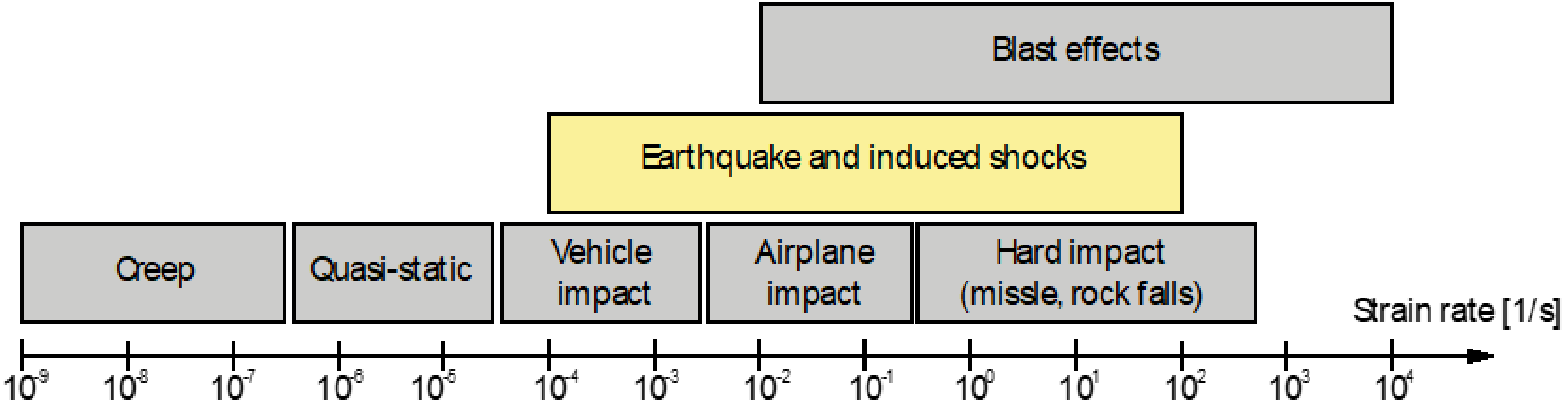
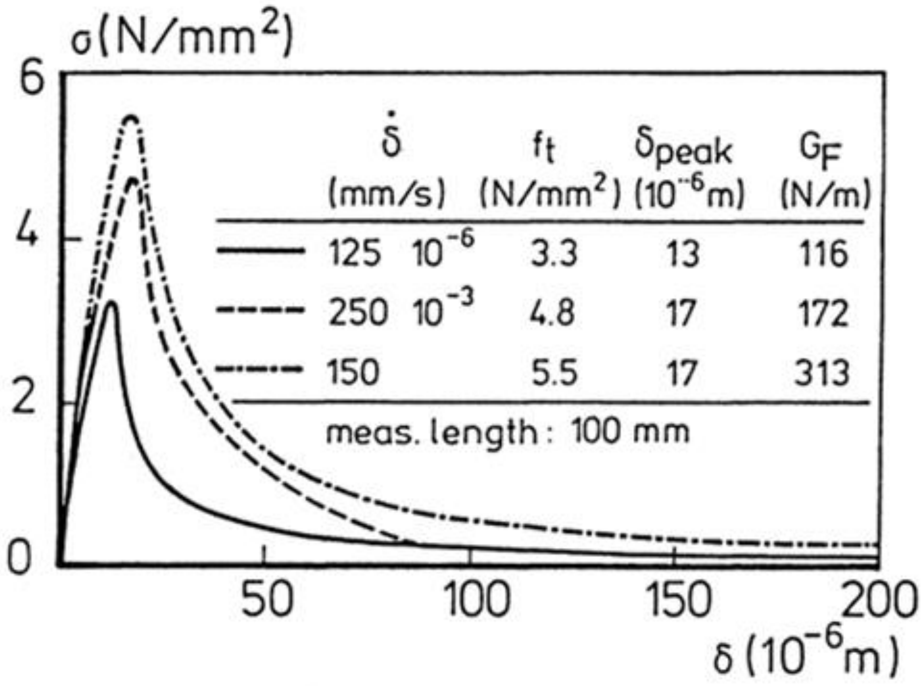


Illustration of the strain rates corresponding to the different loading effects

Material nonlinearity – concrete in tension – strain rate effects



The influence of the deformation rate on uniaxial stress-deformation curve.

The deformation in the figure varies between the slow rates of quasi-static loading and the slow rates of hard impact loading. The stain rate range in the figure covers more than 60 % of the rate range of the earthquake and induced shocks.

Material non-linearity – concrete in tension – strain rate effects

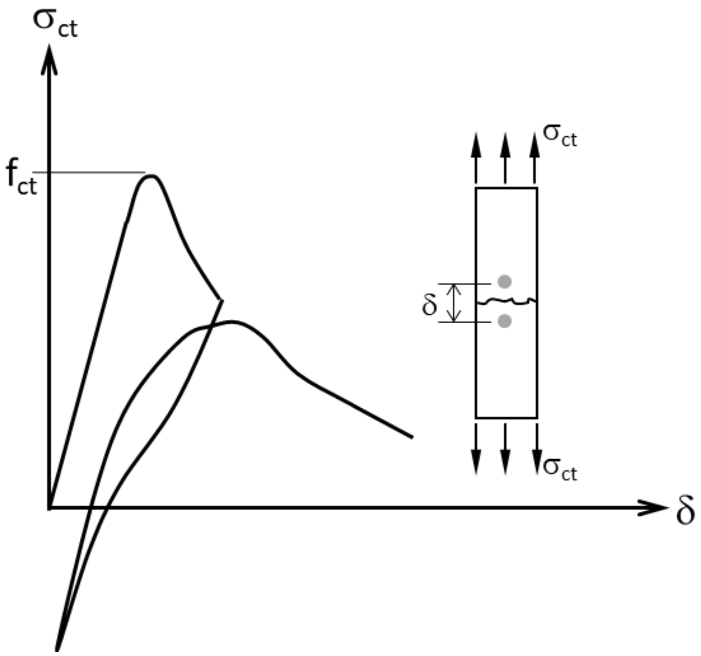
$$l_{ch} = \frac{E_{ci} G_F}{f_{ctm}^2}$$

Characteristic length (l_{ch}, m) is a measure of the material's brittleness. The higher the l_{ch} the less is the brittleness.
The test results show that the l_{ch} is negligibly affected by the strain rate.

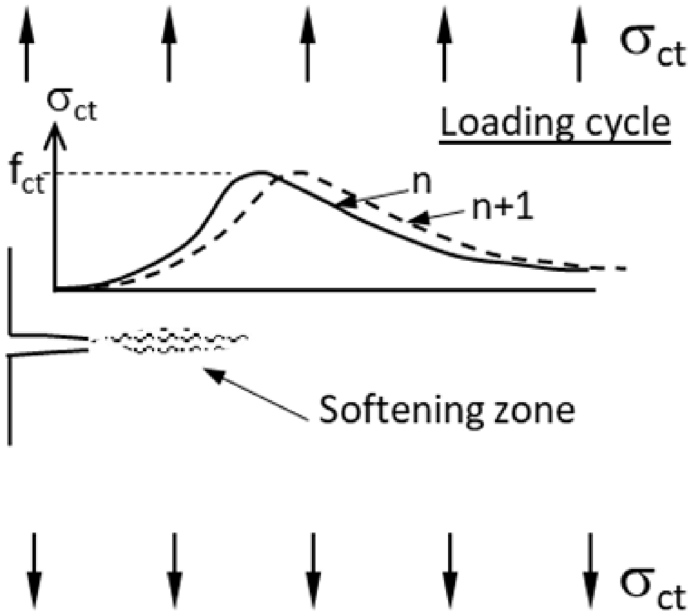
In some codes and references tensile strength and modulus of elasticity are given as functions of strain rates. For a given l_{ch}, which is assumed not to be affected by the strain rate, the G_F and w_c can be calculated. In this way the complete stress-deformation relationship of the material, as a function of the strain rate, can be determined and be used for a non-linear analysis.

The non-linear behaviour of concrete in the cases of creep, low-cycle fatigue and some degradation processes have been treated in a similar way in the bulletin.

Material non-linearity – concrete in tension unloading and reloading

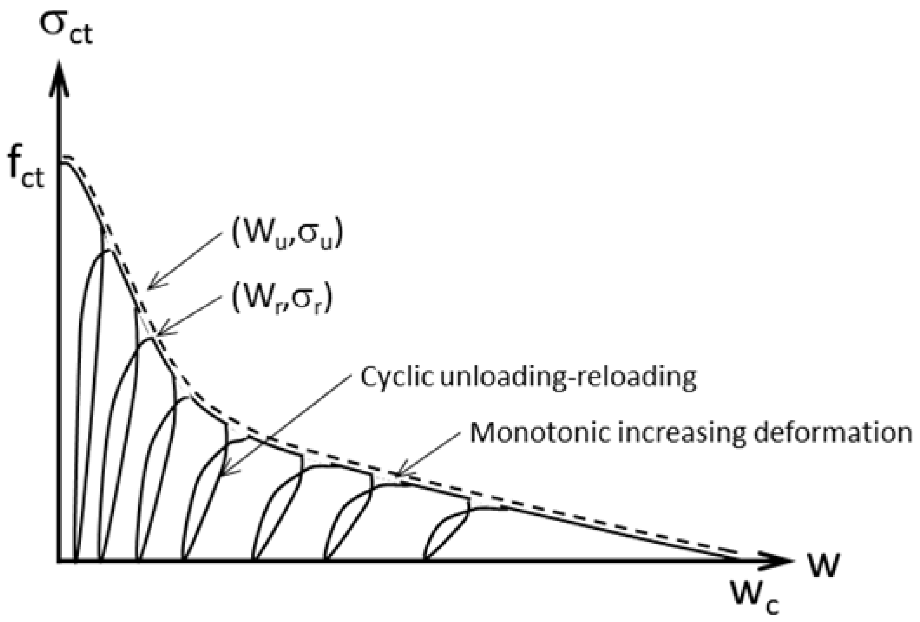


Post peak tensile behaviour of concrete including unloading and reloading, Hordijk (1992).

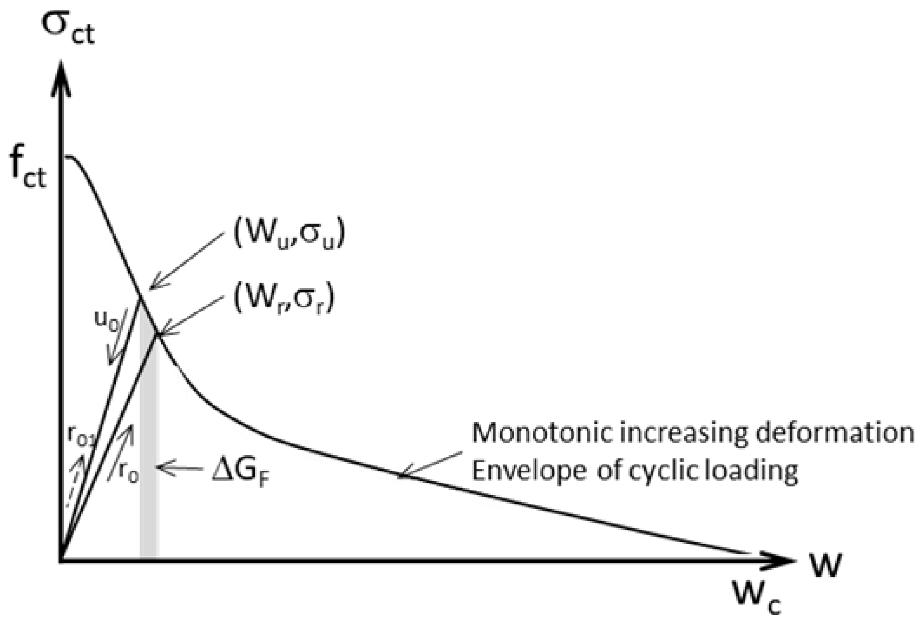


Assumed stress distribution near a crack; before and after a loading cycle, Hordijk (1992).

Material non-linearity – concrete in tension unloading and reloading



Stress-deformation relation of the fracture zone subjected to the monotonic increasing deformation, Hordijk (1992).



Secant unloading and reloading, the simplest model.

Constitutive laws for rock foundations

- The rock mass behaviour is strongly related to the joint spacing and the number of joints.
- For each unique rock mass there exists a specific volume of the rock mass where the behaviour becomes stationary, this volume is usually referred to as the Representative Elementary Volume (REV).
- The behaviour of the rock mass is related to the scale or size of the structure founded on the rock.
- The foundation area against the rock foundation for most dams is usually larger than the REV and an idealization of the rock mass into a continuous material are usually acceptable.

Constitutive laws for rock foundations

$$\boldsymbol{\varepsilon} = \boldsymbol{D} \cdot \boldsymbol{\sigma}$$

Isotropic linear-elastic model

where

$$\boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \varepsilon_{xy} \\ \varepsilon_{yz} \\ \varepsilon_{zx} \end{bmatrix}, \quad \boldsymbol{D} = \frac{1}{E_\mathrm{m}} \begin{bmatrix} 1 & -\nu_\mathrm{m} & -\nu_\mathrm{m} & 0 & 0 & 0 \\ -\nu_\mathrm{m} & 1 & -\nu_\mathrm{m} & 0 & 0 & 0 \\ -\nu_\mathrm{m} & -\nu_\mathrm{m} & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2(1+\nu_\mathrm{m}) & 0 & 0 \\ 0 & 0 & 0 & 0 & 2(1+\nu_\mathrm{m}) & 0 \\ 0 & 0 & 0 & 0 & 0 & 2(1+\nu_\mathrm{m}) \end{bmatrix} \text{ and } \quad \boldsymbol{\sigma} = \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{zx} \end{bmatrix}$$

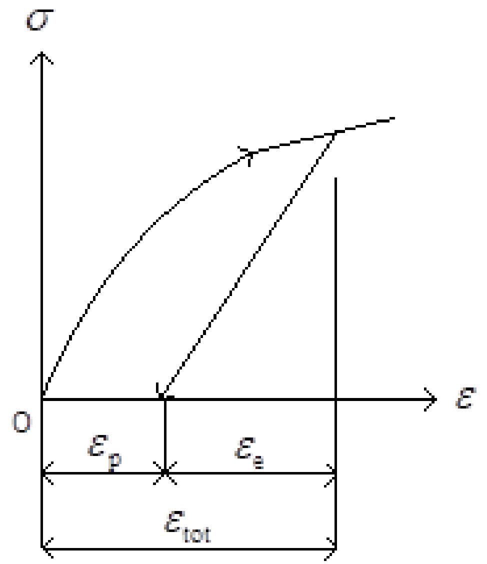
E_m is the Young's modulus for an isotropic rock mass and ν_m is the Poisson's ratio of the rock mass.

Constitutive laws for rock foundations

Nonlinear behaviour – Elasto-plastic model

$$d\varepsilon_{ij}^{\text{tot}} = (D^e)^{-1} d\sigma_{ij} + (D^p)^{-1} d\sigma_{ij}$$

- Yield criterion $f(\sigma_{ij}, \kappa) = 0$
- Flow rule $q(\sigma_{ij}, \kappa) = 0$
- Hardening rule $H = -\frac{\partial f}{\partial \kappa} \cdot \frac{\partial \kappa}{\partial \lambda}$



$\kappa = Hardening\ parameter$

$\lambda = Plastic\ multiplier$

$H > 0\ Hardening$

$H = 0\ Perfectly\ plastic$

$H < 0\ Softening$

Constitutive laws for rock foundations

Mohr-Coulomb failure criterion

$$f = \frac{\sigma_1' - \sigma_3'}{2} - \frac{\sigma_1' + \sigma_3'}{2} \sin \phi_{\mathrm{m}} - c_{\mathrm{m}} \cdot \cos \phi_{\mathrm{m}} = 0$$

$$q = \frac{\sigma_1' - \sigma_3'}{2} - \frac{\sigma_1' + \sigma_3'}{2} \sin \psi_{\mathrm{m}}$$

Non-associated flow potential

σ_1' and σ_3' = major and minor effective principal stress
ϕ_{m} = friction angle of the rock mass
c_{m} = cohesion
ψ_{m} = dilatation angle of the rock mass

Chap. 4 Solution methods

In a non-linear static condition, the load and the displacement are not proportionally related. Therefore, it is not possible to solve the system of equations:

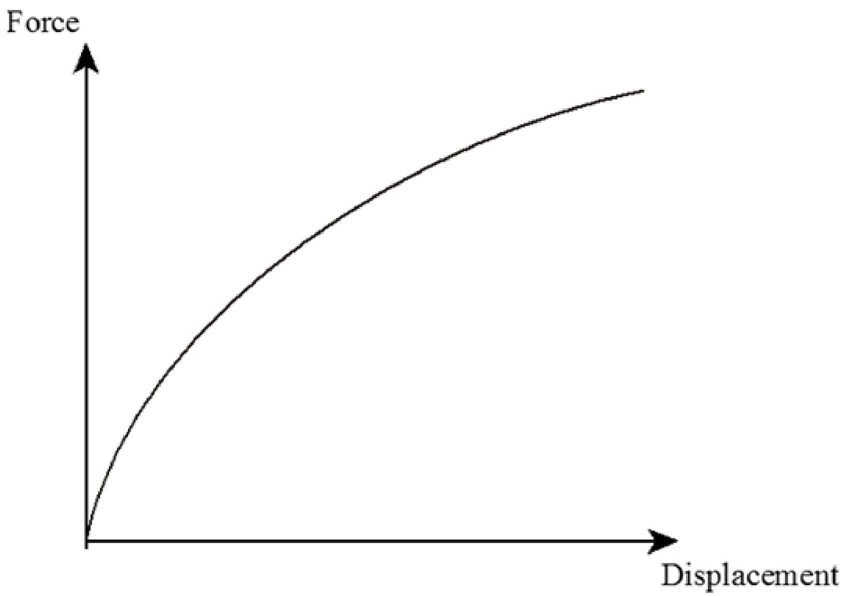
$$F = K_t \cdot u$$

K_t = tangent stiffness matrix

F= force vector

u= nodal displacement vector

by inversing the stiffness matrix. The stiffness matrix depends on the displacement. One needs, therefore, to use an iterative solution method.



In the dynamic and transient conditions other causes of non-linearity are also added to the above-mentioned condition, for instance damping in the case of dynamic loading and alteration of the mechanical and physical properties of the material due to the sustained loading and degradation.

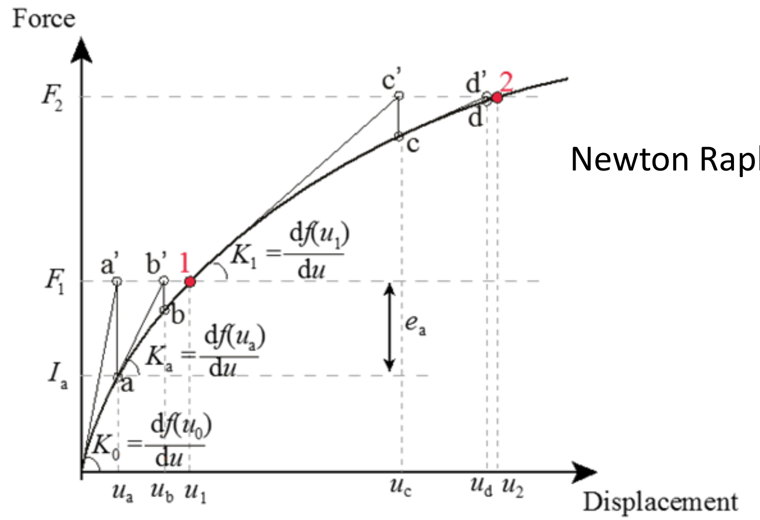
Chap. 4 Solution methods

The bulletin discusses solutions methods for non-linear

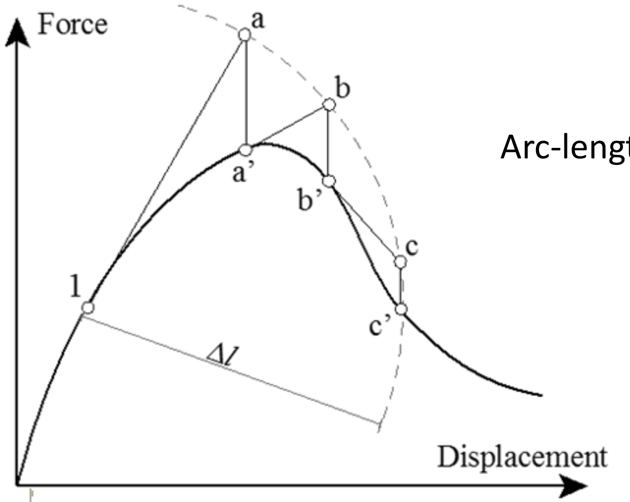
- static,
- quasi-static and
- dynamic.

conditions. Iterative methods such as Newtown Raphson, modified Newton Raphson and Arc-length have been discussed.

Solution methods for quasi-static and dynamic problem are also discussed.



Newton Raphson's method



Arc-length method

NEW

New ICOLD Bulletin Prepared by Technical Committee A
COMPUTATIONAL ASPECTS OF ANALYSIS AND DESIGN OF DAMS (2020-23)

Non-Linear Modelling of Concrete Dams

Chapter 5 - FE-SOFTWARE AND CAPABILITIES FOR THE NON-LINEAR MODELLING OF CONCRETE DAMS

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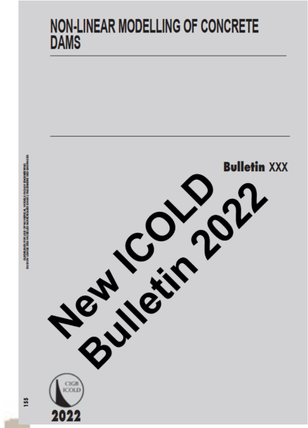
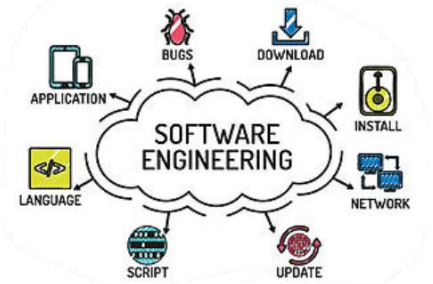


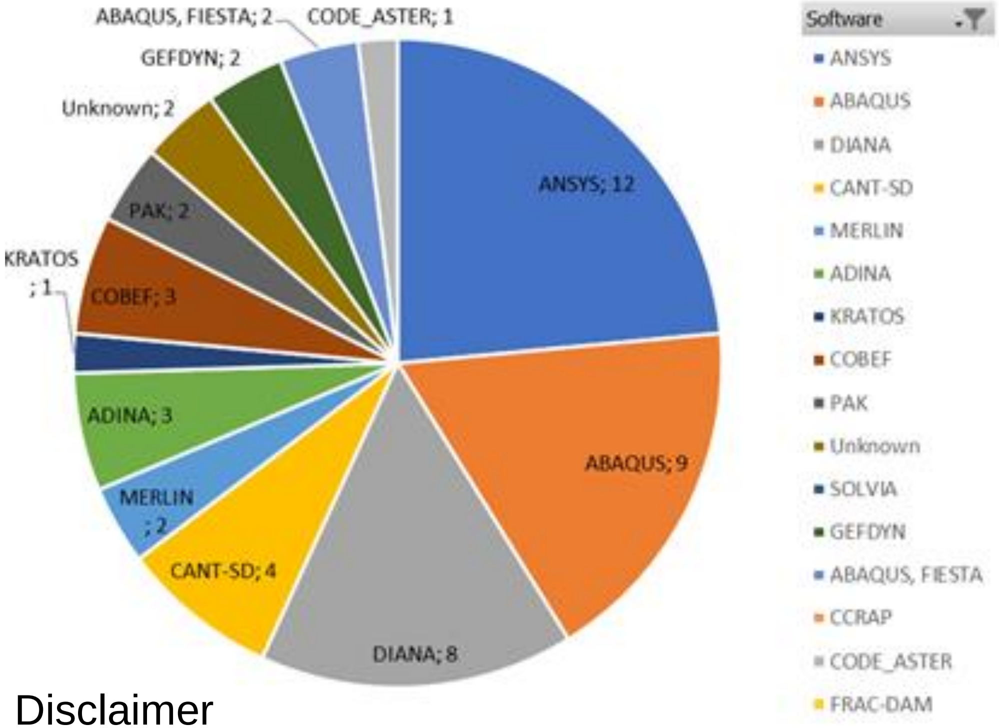
CONTENTS

- ❑ The main objective is to present an **overview of finite element codes or software packages that are frequently used for the non-linear modelling of concrete dams**. In doing so, some of the **minimum software requirements** needed to perform the non-linear modelling of concrete dams and their inherent limitations are exposed.
- ❑ The contents are based largely on data collected and collated from **past ICOLD TCA benchmarks performed over 30 years** that treat directly or indirectly NLMCD.

Note: By indirectly, it is meant that the focus of the benchmark was not necessarily the nonlinear modelling of concrete dams, but rather some other phenomenon such as extreme temperature loading or concrete swelling.

FINITE ELEMENT CODES USED IN PAST BENCHMARKS





Software	NLFEM Arch	Arch-Gravity	Buttress	RCC	Total NLFEM
ANSYS	12		2		14
ABAQUS	9		2	3	14
DIANA	8		2	3	13
CANT-SD	4			1	5
MERLIN	2		2		4
ADINA	3				3
KRATOS	1	1		1	3
COBEF	3				3
PAK	2				2
Unknown	2				2
SOLVIA			2		2
GEFDYN	2				2
ABAQUS, FIESTA	2				2
CCRAP			2		2
CODE_ASTER	1			1	2
FRAC-DAM			2		2
Total	**51**	**1**	**14**	**9**	**75**

Disclaimer

The contents of this chapter are not aimed at favouring or otherwise any specific FEM code or software package or any particular software company. Reference is however made to some codes to highlight a point of technical interest related to the objectives of this chapter of the bulletin.

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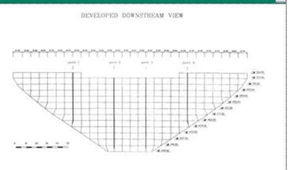
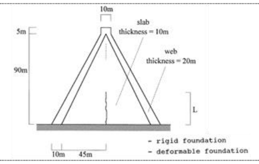
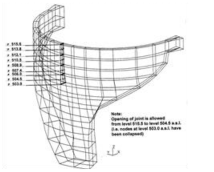
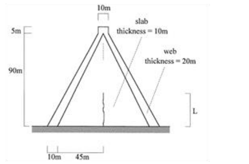
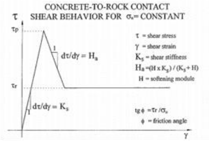
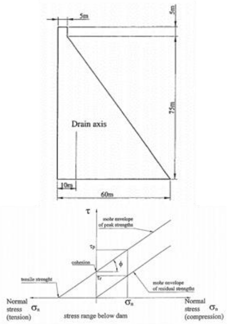
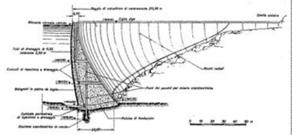
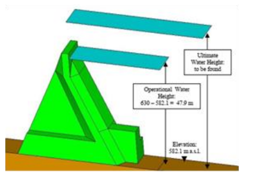
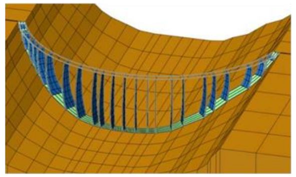
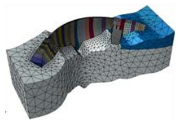
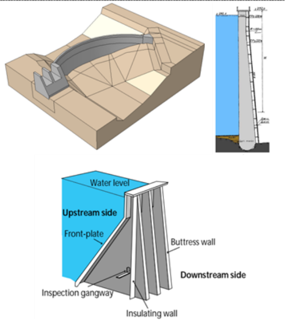
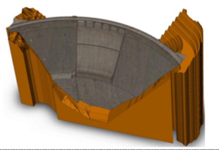
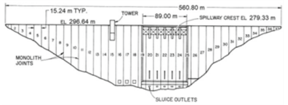
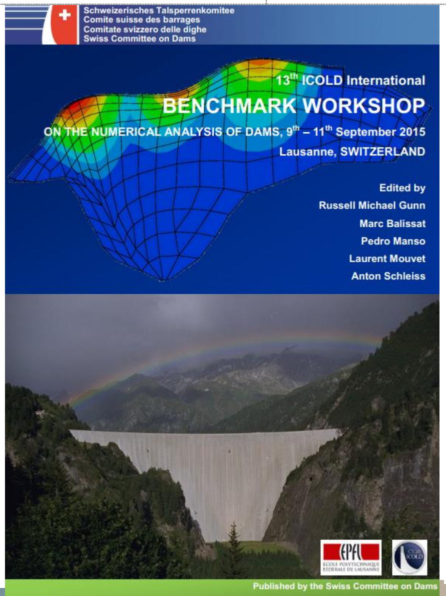
Non-Linear Modelling of Concrete Dams

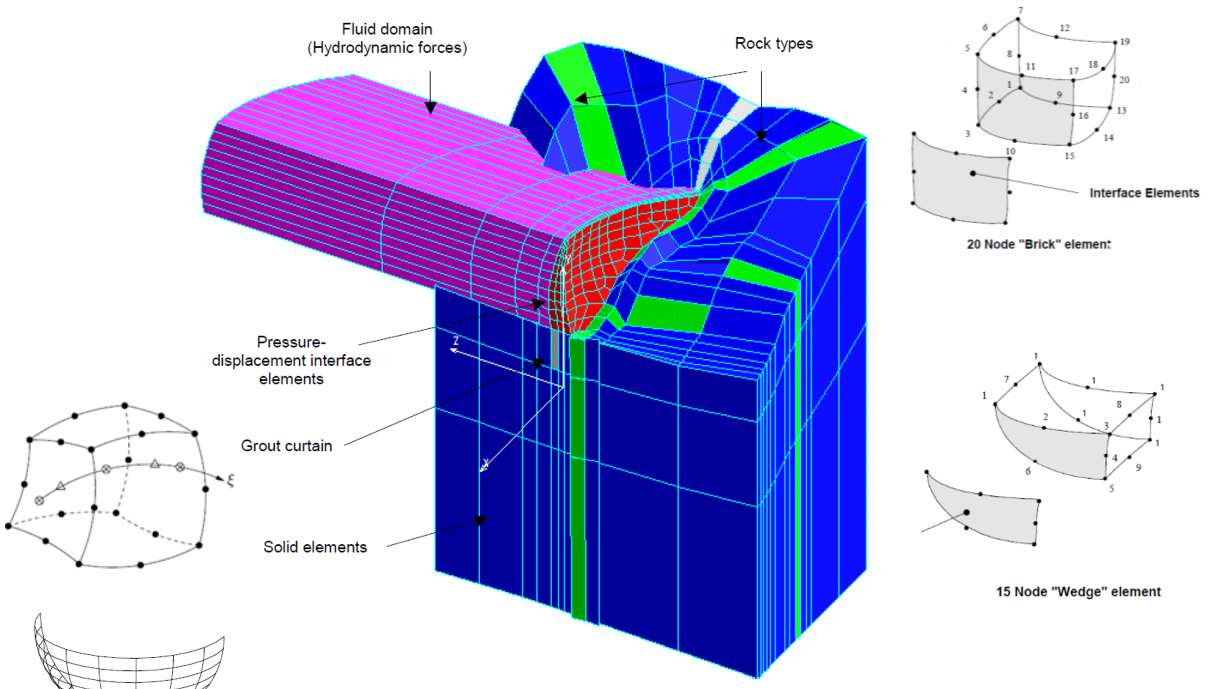
FINITE ELEMENT CODES USED IN PAST BENCHMARKS

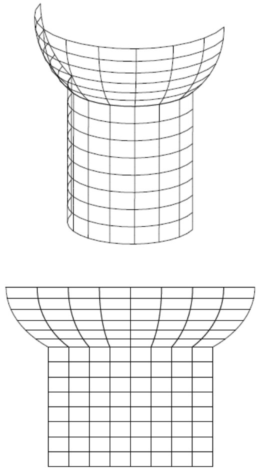
N°	Year	Theme	Title	Material Parameters	Picture
3	1994	A1	Non-linear analysis of joint behaviour under thermal and hydrostatic loads for an arch dam	Young's elastic modulus (concrete)........ E_c = 3.60 exp10 Nm-2 Young's elastic modulus (rock)........... E_r = 1.20 exp10 Nm-2 Poisson ratio coefficient (concrete)....... ν_c = 0.20 Poisson ratio coefficient (rock)........... ν_r = 0.16 Thermal dilatation coeff. (concrete)...... α = 0.7 exp-5 °C-1 Specific weight (concrete) .... γ_c = 24000 Nm-3 Specific weight (water) .... γ_w = 10000 Nm-3 friction factor on joint faces .... f = 0.75	
3	1994	A2	Evaluation of critical uniform temperature decrease for a cracked buttress dam	2.1 -Concrete: - Young's elastic modulus E_c = 3.0 exp10 Nm-2 - Poisson ratio coefficient ν = 0.16 - Thermal dilatation coefficient α = 1.0 exp-5 °C-1 - Toughness K_c = 2.3 exp6 Nm-3/2 2.2 -Rock (deformable foundation): - Young's elastic modulus E_r = 1.0 exp10 Nm-2 - Poisson ratio coefficient ν = 0.2 different crack lengths L: 0.5 m ; 2. m ; 10. m ; 20. m ; 40. m	
4	1996	A1	Earthquake analysis of an arch dam including the nonlinear effects of contraction joints opening	• Young's elastic modulus 3.0 E 10 N/m² • Poisson modulus 0.2 • Concrete density 2450 kg/m³ • Water density 1000 kg/m³ • Hysteretic damping factor 0.04 * * The equivalent viscous damping ratio β is equal to 2% for every value of frequency. The dynamic behaviour of the joint should be reproduced considering a friction factor between faced surfaces equal to 0.75. The joint is considered closed before the application of any load. The foundation rock is assumed to be rigid.	
4	1996	A2	Evaluation of stress intensity factor along a crack tip in a buttress dam under thermal gradient	PARAMETER / SYMBOL / VALUE / UNITS: Mass density / ρ / 2.5E+03 / kg/m³ Specific heat / c / 1.E+03 / Nm/kg °C Conductivity / k / 3.E+05 / N/day °C Young's elastic modulus / E / 3.E+10 / N/m² Poisson ratio / ν / 0.16 / - Thermal expansion coefficient / α / 1.E-05 / °C-1	
5	1999	A2	Evaluation of failure flood level for a gravity dam with interface crack (rock/concrete) and varying uplift pressure.	Material parameters / Rock / Concrete: Density [kg/m³] / 2,700 / 2,400 Uniaxial compressive strength σc [MPa] / 40.0 / 24.0 Uniaxial tensile ultimate strength σt [MPa] / 2.6 / 1.3 Ultimate tensile strain εu / 0.63×10-4 / 0.54×10-4 Fracture strain εf / 6.00×10-4 / 5.00×10-4 Softening law for tensile strength / Linear / Linear Young's modulus E [MPa] / 41,000 / 24,000 Poisson ratio ν / 0.10 / 0.15 Specific mode I fracture energy G_f^I [N/m] / 200 / 150 The rock-concrete interface is pervious and is characterised by (see figg. 3a, b): Material parameters / Mean values: Shear stiffness Ks [MPa/mm] / 20 Peak cohesion [MPa] / 0.7 Residual cohesion [MPa] / 0.0 Tensile strength [Mpa] / 0.0 Friction angle [deg.] / 30 Dilatancy angle [deg.] / 10 Softening module H [MPa/mm] / -0.7 CONCRETE-TO-ROCK CONTACT SHEAR BEHAVIOR FOR σn = CONSTANT 	
6	2001	A	Evaluation of AAR effects	/ Young Modulus E / Poisson Ratio ν / density ρ Dam / 20000 MPa / 0.2 / 2450 Kgm/mc Foundation / 28000 MPa / 0.2 / 0.	
8	2005	A	Evaluation of alkali-aggregate reaction effects on the behaviour of an Italian hollow gravity dam	c) Physical-mechanical parameters of materials: *Concrete* • elastic modulus: 18000 MPa • mass density: 2400 Kg/m³ • Poisson coefficient: 0.2 • compressive strength: 32 Mpa • tensile strength: 1.5 MPa *Rock foundation* • elastic modulus: 10000 MPa • Poisson coefficient: 0.1 • compressive strength: 32 Mpa • tensile strength: 0.15 MPa d) Physical-mechanical parameters of the dam-foundation interface • friction angle: 37 degrees • cohesion: 0.1 MPa e) AAR calibration datum: • total drift vertical displacement at the top of the main block: 30 mm	
8	2005	B	Temperature field simulation and crack analysis of a RCC arch dam	Variable / Symbol / Unit / RCC 2-graded-aggregate / RCC 3-graded-aggregate / CVC / Rock: Density / ρ / kg/m³ / 2475 / 2481 / 2400 / 2400 Poisson's ratio / μ / / 0.167 / 0.167 / 0.167 / 0.21 Expansion coefficient / α / 10-6/°C / 5.22 / 5.37 / 5.37 / 2 The elastic modulus of concretes increases with the development of concrete age. The elastic modulus of the three types of concrete Vs time is shown in Table C below. Table C: Elastic modulus of concrete Vs time Concrete \ Day / 7 / 28 / 30 RCC (2-graded-aggregate) / 2.4 / 3.53 / 3.92 RCC (3-graded-aggregate) / 1.84 / 3.49 / 3.77 CVC / 3.0 / 3.85 /	 Variable / Symbol / Unit / RCC 2-graded-aggregate / RCC 3-graded-aggregate / CVC / Rock: Density / ρ / kg/m³ / 2475 / 2481 / 2400 / 2700 Specific heat / C / kJ/kg/°C / 0.967 / 0.892 / 0.921 / 0.921 Thermal diffusivity / a / m²/d / 0.078 / 0.092 / 0.10 / 0.11 Coefficient of heat conductivity / k / kJ/m/d/°C / 190.58 / 194.14 / 185.06 / 185.06
11	2011	A	A model for concrete swelling for the Kariba dam	Property / Material Unit / Foundation rock / Dam concrete: Modulus of elasticity / GPa / 10.0 / 22.0 Poisson's ratio / / / 0.2 / 0.20 Unit weight / kN/m³ / *Not considered* / 2350 Swelling properties / / *Not considered* / **To be determined** N° / A1 / A2 / A3 / A4 / A5 Institution / RSE / Principia / EDF-CIH / Stucky / TU Delft 1st author / Meghella / Rodriguez / Moles / Menouillard / Esposito Software / CANT-SD / Abaqus/St / ASTER / CESAR / DIANA Model / Charlwood / Saouma / Grimal / Coussy-Larive / Larive/Saouma Kinetics / no / yes / yes / yes / yes/yes Stress effect / yes / yes (delay) / yes (creep) / no / yes (delay) N° / A6 / A7 / A8 / A9 Institution / TNO DIANA / VNIIG / HATCH / TEF-COB 1st author / Schreppers / Kostilev / Curtis / Mériot Software / DIANA / ANSYS / ANSYS / COBEF Model / Larive / cst / Larive / Growth3D / SCAS Kinetics / yes / no / yes / no / no Stress effect / anisotropy / yes / yes (+ creep) / yes	
11	2011	D	Concrete swelling in two Spanish dams	Model by Ulm et al. Model by Saouma and Perotti (kinetic & stress dependent) 	
13	2015	A	Seismic safety evaluation of a concrete dam based on guidelines	Mass Rock Properties / Unit / Value: Static Modulus of Elasticity, E_s / GPa / 18.6 Dynamic Modulus of Elasticity, $E_d = 1.25 \cdot E_s$ / GPa / 23.3 Poisson's Ratio, ν / - / 0.20 Mass Concrete Properties / Unit / Value Old Concrete / Value New Concrete: Density, ρ / t/m³ / 2.5 / 2.4 Static Modulus of Elasticity, E_s / GPa / 20 / 18 Dynamic Modulus of Elasticity, $E_d = 1.25 \cdot E_s$ / GPa / 25 / 22.5 Poisson's Ratio, ν / - / 0.18 / 0.18 Thermal expansion, α / 1/°C / 10^{-5} / 10^{-5} Static Compressive Strength, f_c / MPa / 38 / 32 Dynamic Compressive Strength, $f_{cd} = 1.5 f_c$ / MPa / 57 / 48 Static Tensile Strength, f_t / MPa / 3 / 2.3 Dynamic Tensile Strength, $f_{td} = 1.5 f_t \le 4\,MPa$ / MPa / 4 / 3.5	
14	2017	A	Cracking of a concrete arch dam due to seasonal temperature variations	Description / Parameter / Units / Concrete / Rebar / Rock / Water: Mass density / ρ / kg/m³ / 2300 / 7800 / 2700 / Young's Modulus (secant) / E_s / MPa / 33000 / 200000 / 40000 / Poisson's ratio / ν / - / 0.2 / 0.3 / 0.15 / Tensile strength (Brazilian) / f_t / MPa / 2.9 / / / Compressive strength (cylinder) / f_c / MPa / 38 / / / Coefficient of dilatation / α_c / °C-1 exp-5 / 1 / 1 / 1 / Specific heat capacity / c / Nm/kg °C / 900 / 450 / 850 / Thermal conductivity / W / W/(mK) / 2 / 39 / 3 / Convection heat coefficient concrete/rock to ...) / C / W/(m²K) / 13 / / 1000 / 500 Fracture energy / G_f / N/m / 237.5 / / / Ultimate tensile strain / ε_u / - / / 0.15 / / Yield stress / / MPa / / 360 / / Concrete type / d_a [mm] / f_t [N/mm²] / E [N/mm²] / G_F [N/m] / $l_{ch} = \frac{EG_F}{f_t^2}$ [mm] / w_{max} [mm] / K_{Ic} [MN/m^{3/2}]: Arch dam A / 80 / 2.4 / 36 000 / 230 / 1 440 / 0.25 / 2.9 Arch dam B / 120 / 2.3 / 27 000 / 310 / 1 580 / 0.30 / 2.9 Arch dam C / 120 / 2.0 / 29 000 / 270 / 1 960 / 0.37 / 2.8 Structural concrete / 32 / 3.4 / 36 000 / 140 / 440 / 0.16 / 2.2 d_a = maximum aggregate size	
14	2017	B	Static and seismic analysis of an RCC arch-gravity dam.	Material / Density / Static deformation modulus (GPa) / Dynamic deformation modulus (GPa) / Poisson's ratio / p-wave velocity (m/s) / c (kPa) / ϕ (°) / Tensile strength (MPa): Concrete / 2400 / 20 / 30 / 0.2 / - / - / - / - Bedrock / 2800 (1) / 25 / 30 / 0.25 / - / - / - / - Water / 1000 / - / - / 0.5 / 1414 (1) / - / - / - Dam / foundation interface (2) / - / - / - / - / - / 0 / 45 / 0 (1) To be used for the advanced dynamic interaction models (2) To be used for models with a non-linear dam / foundation interface	
15	2019	A	Seismic Analysis of Pine Flat Concrete Dam.	Parameter / Unit / Concrete / Rock / Water: Elastic modulus / GPa / 22.41 / 22.41 / – Density / kg/m³ / 2483 / 2483 / 1000 Poisson's ratio / – / 0.2 / 0.2 / – Compressive strength / MPa / 28.0 / – / – Tensile strength / MPa / 2.0 / – / – Fracture energy / Nm/m² / 250 / – / – Compressive strain at peak load / – / 0.0025 / – / – Tensile strain at peak load / – / 0.00012ᵃ / – / – Shear wave velocity / m/s / – / 1939 / – Compressive wave velocity / m/s / – / 3167 / 1439	

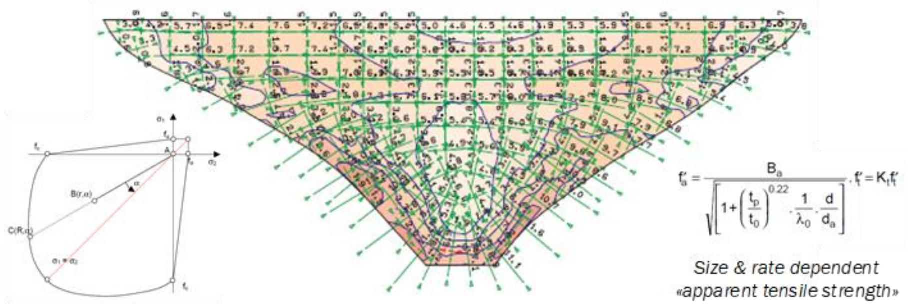


PRE-PROCESSING & MODELLING STRATEGY

- **Geometry** based on as-built drawings, considering: construction change orders & phases, laser scanning coupled with material testing, etc. geometric entities, file format standards, near & far-field zoning, etc.
- **Material properties** with fractile values based on analysis type (linear, non-linear), calibration of numerical model (back-analyses) based on laboratory test results and monitoring data (sensitivity studies).
- **FE model dimensions & size**: Consideration dam-foundation-reservoir interaction and structural features such as joints, rebar, mesh refinement & objectivity, surveillance equipment, etc.
- **Post-processing**: Developed view, selective principal stress plotting, strength zoning, decision-making tools, etc.

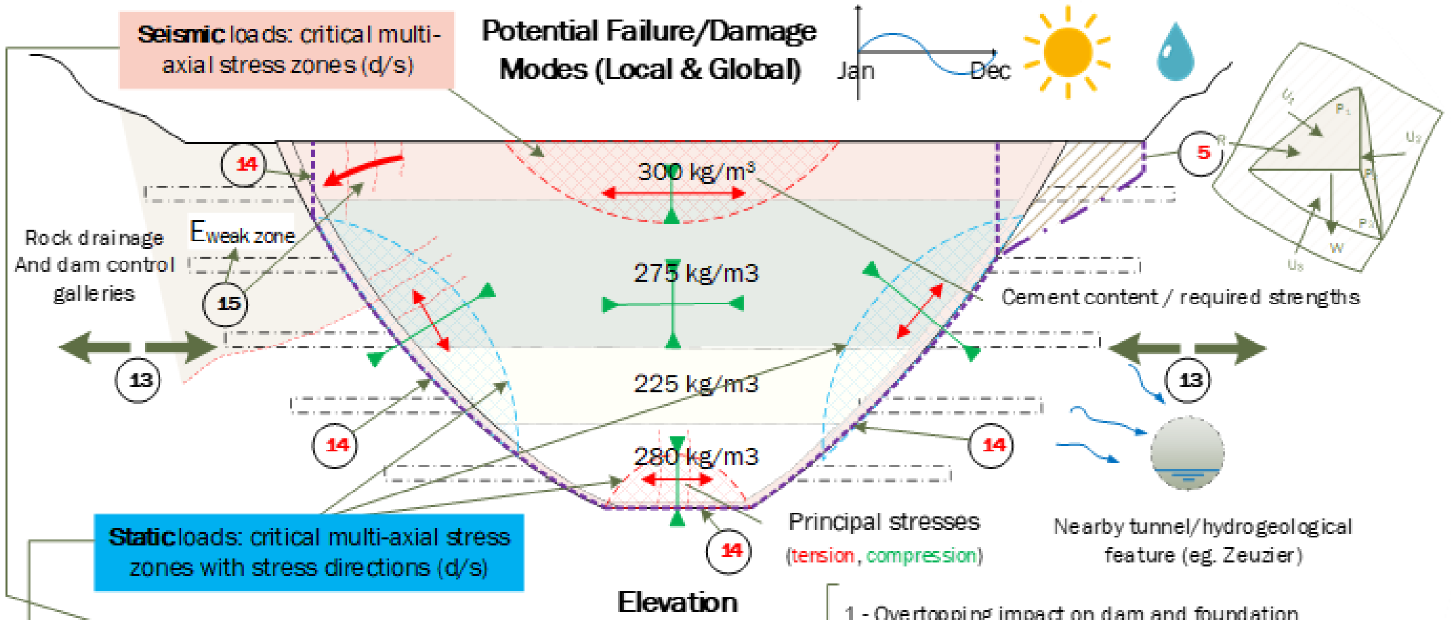


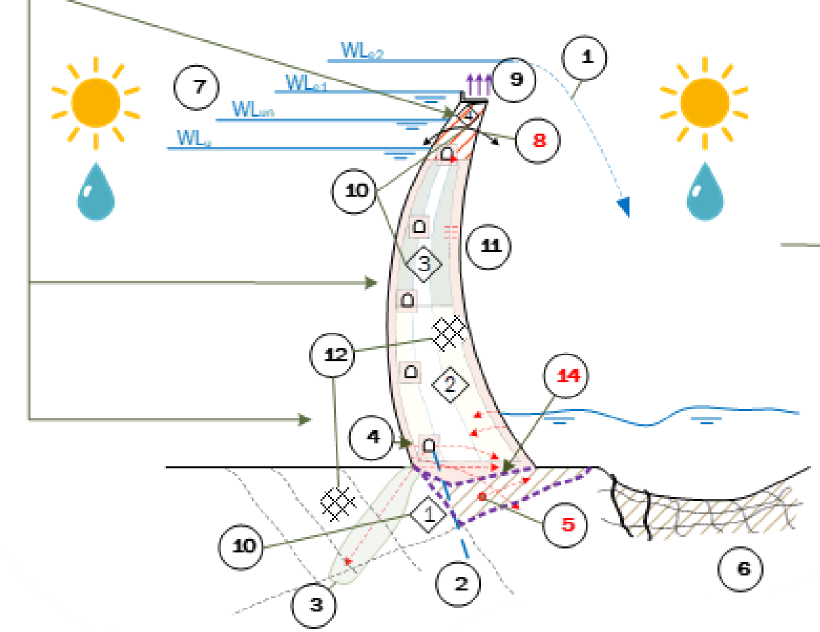




Arch Dam: Typical Biaxial Principal stress orientations & Required Concrete Strength Zoning

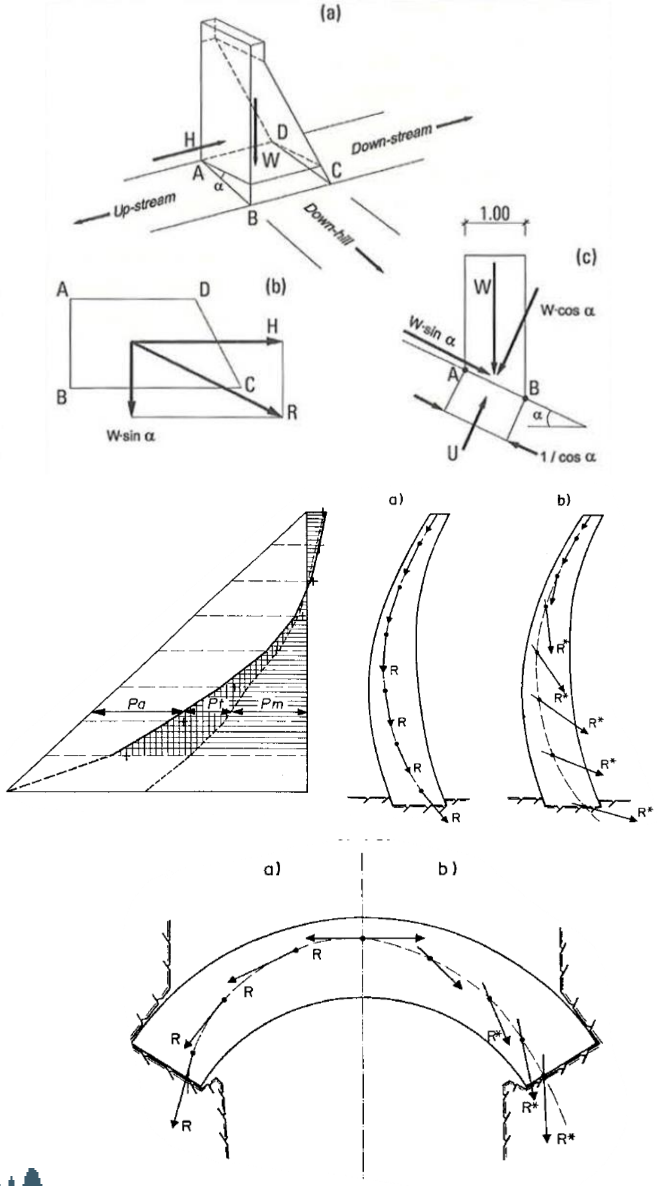
POTENTIAL MODES OF FAILURE & DAMAGE





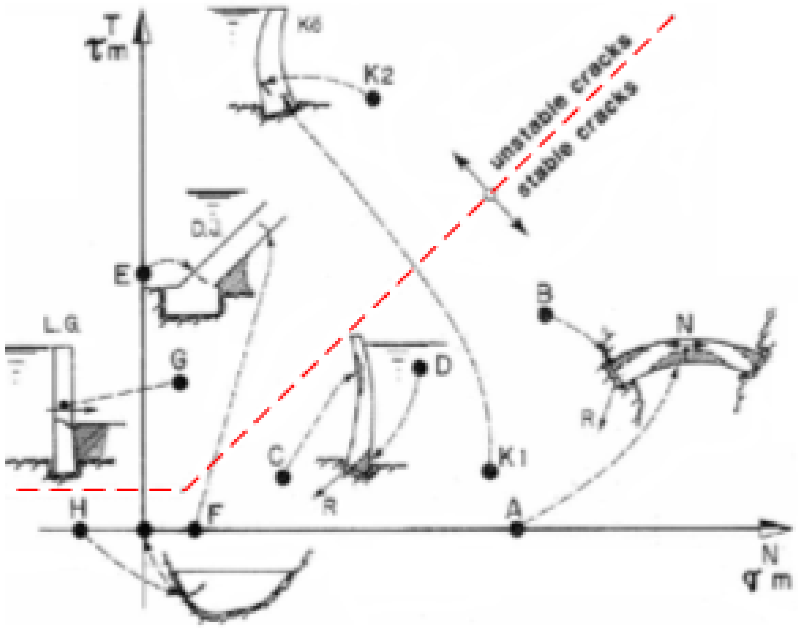
1 - Overtopping impact on dam and foundation
2 - Increased uplift pressures due to clogging
3 - Grout curtain: problem of erosion
4 - Mode I (tension) horizontal & Mode II (shear) oblique cracking
5 - Foundation wedge/multi-plane sliding (e.g. Malpasset)
6 - Rock scouring from Overtopping & outlets
7 - Water line danger levels: Failure/damage
8 - Earthquake rocking/sliding of detached blocks
9 - AAR swelling
10 - Phased construction (initial strain problems)
11 - Thermal cracking: heat of hydration, seasonal temperatures variations
12 - Creep/relaxation/Shrinkage/AAR
13 - Valley movement due to underground structures and/or hydrogeological conditions (eg. Zeuzier)
14 - Sliding at concrete/rock interface (eg. Meihua)
15 - Weak foundation zones (eg. Shahid Rajaee)

(red text = global instability, black text = local instability)



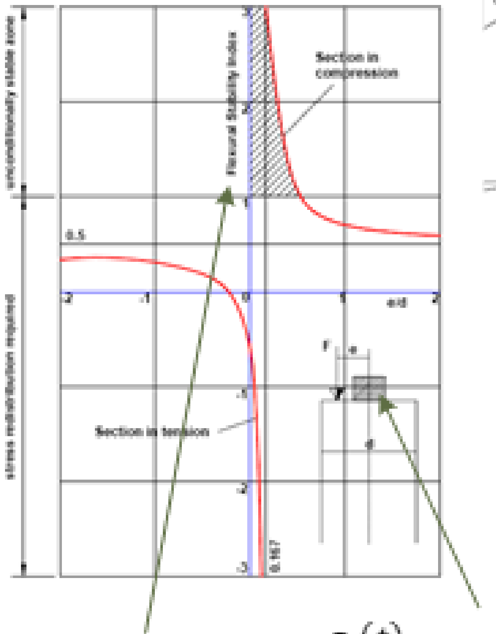
POTENTIAL MODES OF FAILURE & DAMAGE

KNOWING YOUR CRACKS…

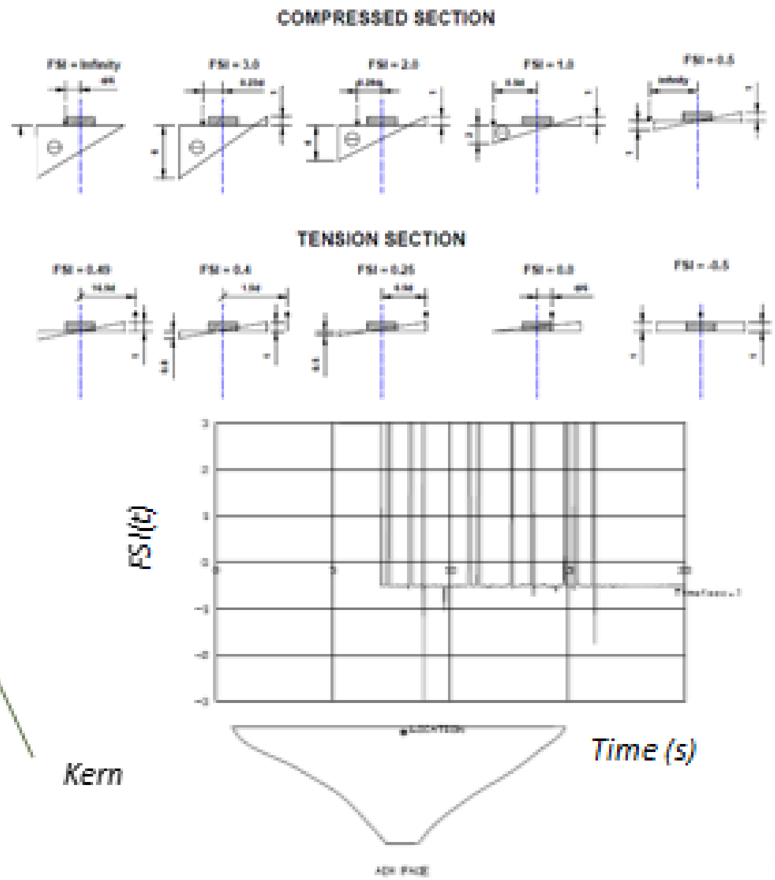


Combined normal and shear forces

Cross-section



$$FSI(t) = \frac{\sigma_f(t)}{2\sigma_t(t)}$$

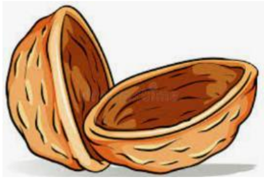


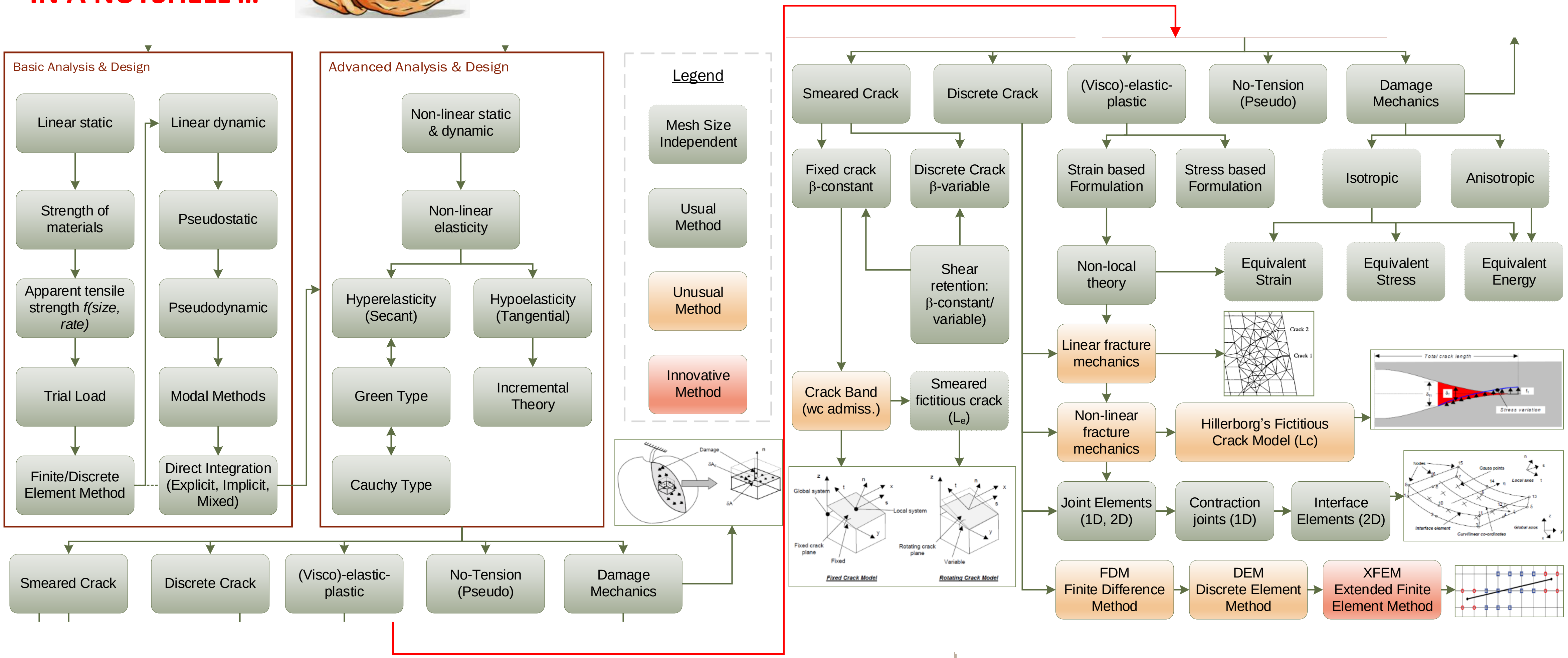
Flexural Stability Index (normal force) – Applicable for Linear Analysis

Legend
Le Gage (LG), Kölnbrein (Kö), Daniel Johnson (DJ), Others (OT)
A, F, H = Air-face large normal force & zero shear force, K, E, G = Large shear forces compared to normal forces, B, C, D = inactive arch part.

$\sigma_f(t)$ = stress on the opposite dam face (compression or tension) acting in the same direction as σ_t.
$\sigma_t(t)$ = tensile stress (greater than the tensile stress limit, eg. f_t).
The FSI indicates whether or not the resultant force remains within the section.

IN A NUTSHELL …





ANALYSIS

- **Plasticity** (isotropic, orthotropic, visco-plastIc)
- **Smeared cracking** (multi-directional fixed crack, total strain based, Maekawa-Fukuura Model for Concrete, Kotsovos Concrete Model and others.)
- **Viscoelasticity/creep** (power law, Maxwell chain, Kelvin chain. etc.)
- **Creep and Shrinkage** (transient creep at elevated temperatures, uniaxial shrinkage/discrete function (maturity dependent) and Model Code inputs such as CEB-FIP MC 1990, ACI 209R-92, Korean KCI 2007, Dutch NEN 6720/A4, etc.)
- **Interface Behaviour** (such as linear and nonlinear elasticity, discrete cracking, crack dilatancy, bond-slip, friction, combined cracking-shearing-crushing, the Janssen nonlinear relation between bending moment and rotation for line interfaces to shell elements, and general user-supplied models). In addition, many of these models can be coupled with other material laws.
- **Reinforcement** (embedded, bond-slip and many subset constitutive models)
    - Model Code Libraries
    - Concrete (CEB-FIP Model Code 1990, fib Model Code for Concrete Structures 2010, Eurocode 2 EN 1992-1-1, American Concrete Institute (ACI) 209R-92, Am. Assoc. of State Highway and Transportation Officials (AASHTO), Japan Concrete Institute (JCI), Japan Society of Civil Engineers (JSCE), Korea Concrete Institute (KCI) 2007, NEN 6720/A4, JCSS Probabilistic Model Code)
    - Rebar and prestress cables (Eurocode 3 EN 1993-1-1, NEN 6770)
- **User-supplied models** (Elasticity and Viscoelasticity, Nonlinear Elasticity, Plasticity and Cracking, Shrinkage, Bond-slip, etc.)

For example, the **DYNA-3D** software package has **14 types of contact surfaces**, of which the most frequently used:

- **Tied (Type 2):** method used to attach two parts of a finite element model together with differing mesh refinement.
- **Sliding with separation and friction (Type 3):** is a penalty formulation and allows two parts to be either initially separate or in contact; large relative motions are permitted, and Coulomb friction is included but cohesion is not. Surfaces may open or close in a completely arbitrary manner and the choice of master or slave surface is not important.
- **Shell edge tied to shell surface (Type 7)**. is the same as type 2, but only for shell elements.
- **Tied with failure (Type 9):** is a penalty method that ties the surfaces together until a prescribed failure criterion, based on normal and/or shear failure stress, is reached. Thereafter, the surface functions as a Type 3.
- **Shear key contact surface**: This is an in-house contact method developed in DYNA-3D by the Lawrence Livermore National Laboratory (LLNL). The geometry of the shear keys is defined as a sine wave of given amplitude (depth of the shear key) and length (upstream to downstream spacing of the shear keys). The contact can open and close. Sliding along the contact is governed by the opening of the joint and the geometry of the shear keys. The joint slides freely once the height of the shear key is exceeded by the joint opening.


I ♥
CONVINCING
ARGUMENTS

POST-PROCESSING

- The **evaluation and interpretation of results** obtained following the nonlinear analysis of concrete dams depends greatly on the post-processing facilities available within the FE code and the modelling strategy applied in the pre-processing phases of the studies.
- For NLMCD it is recommended to ***consider three-dimensional*** modelling as a standard practice for gravity as well as arch dams. Deviation from this recommendation may result in the use of higher factors of safety.
- ***Displacements*** *are perhaps best represented as vector plots with a component breakdown in the upstream-downstream, tangential and radial directions. These vectors can be overlaid onto contour plots that should be consistently scaled for the range of loading with the same increments.*
- ***Principal stress vectors*** *that overlay stress contours are also practical for evaluation and interpretation purposes.*
- **Potential failure identification**: rocking-sliding blocks, tension, compression, shear and mixed modes.
- *Plotting vectors on* ***developed views*** *that project the curved dam faces to a reference cylinder, with a suitably selected in radius that englobes the crest section, that is in turn "opened-up flat“.*
- **Damage** may be portrayed as a scalar or vector and readily plotted with time. As such "damage disks" can be plotted.
- Cracking and crack propagation can be visualised as lines and/or surfaces.
- **History plots or "videos"** are also a vital and in some cases the only way to understand the phenomena. In this sense, magnified plot histories for seismic and time-dependent effects such as AAR provide the key information needed to pinpoint the source of load and reaction.

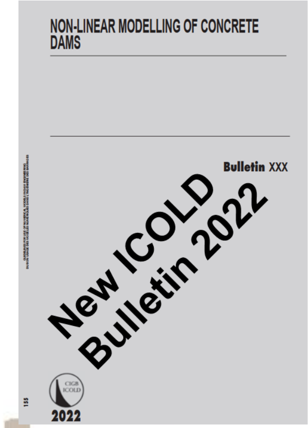

ALMOST THERE...
END OF
TERM

New ICOLD Bulletin Prepared by Technical Committee A
COMPUTATIONAL ASPECTS OF ANALYSIS AND DESIGN OF DAMS (2020-23)

Non-Linear Modelling of Concrete Dams

Chapter 6 - SELECTION OF MATERIAL PARAMETER VALUES FOR THE PRACTICAL NON-LINEAR MODELLING OF CONCRETE DAMS

Russell Michael GUNN
Swiss Federal Office of Energy (SFOE)



CONTENTS

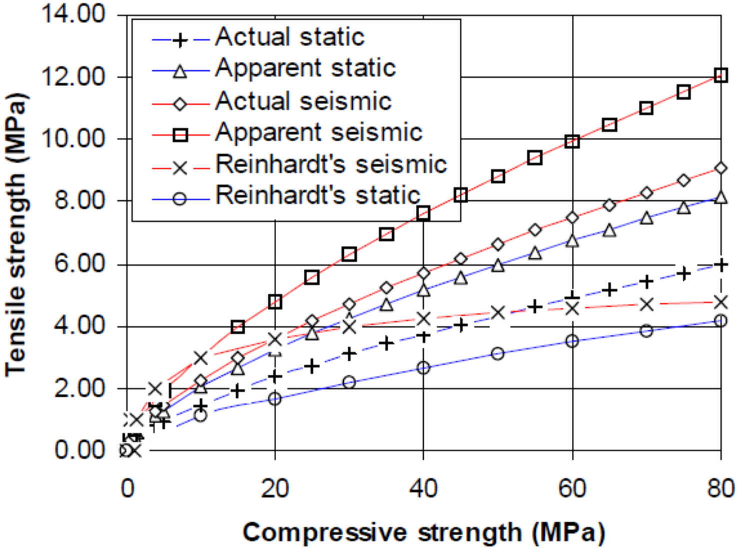
INTRODUCTION

IT'S NOT WHAT WE DO, IT'S HOW WE DO IT …

- This chapter presents an approach that can be adopted for the **selection of material parameters for the practical nonlinear modelling of concrete dams** as well as sample material parameter values collated from the literature and past ICOLD benchmarks (TCA).
- The focus is given to **mass concrete and structural interfaces** and reference to some reservoir and foundation material properties such as different rock types are provided.
- **Great importance** is given herein to **field data** and selecting or ascertaining material properties from ***laboratory*** samples extracted from the structure. Due to economic reasons, more often than not recourse is made to data found in the literature rather than laboratory test results on the actual structure under review. Moreover, only standard short-term tests are performed. This might be a false economy especially when performing NLMCD.
- Distinction is made between ***reversible*** (linear) and ***irreversible*** (nonlinear) movements noting that we are only addressing ***material nonlinearity*** for small displacements.

TRANSITION BETWEEN LINEAR AND NON-LINEAR ANALYSES

TRYING TO RUN BEFORE YOU CAN WALK …



$$f'_a = \frac{B_a}{\sqrt{\left[1+\left(\frac{t_p}{t_0}\right)^{0.22}\cdot\frac{1}{\lambda_0}\cdot\frac{d}{d_a}\right]}}\cdot f'_t = K_t f'_t$$

B_a = experimental parameter (from lab tests)

t_p = time to peak load in the field

t_0 = time to peak load in laboratory tests.

λ_0 = experimental parameter determined fron size dependent laboratory tests.

d = section thickness.

d_a = maximum aggregate size.

f'_t = direct tensile strength given by :

$\alpha_0 + \alpha_1 . f'_c \approx 0.32 . f'^{2/3}_c$.

$\alpha_0 = 0$ when $0 \leq f'_c \leq 15$ MPa

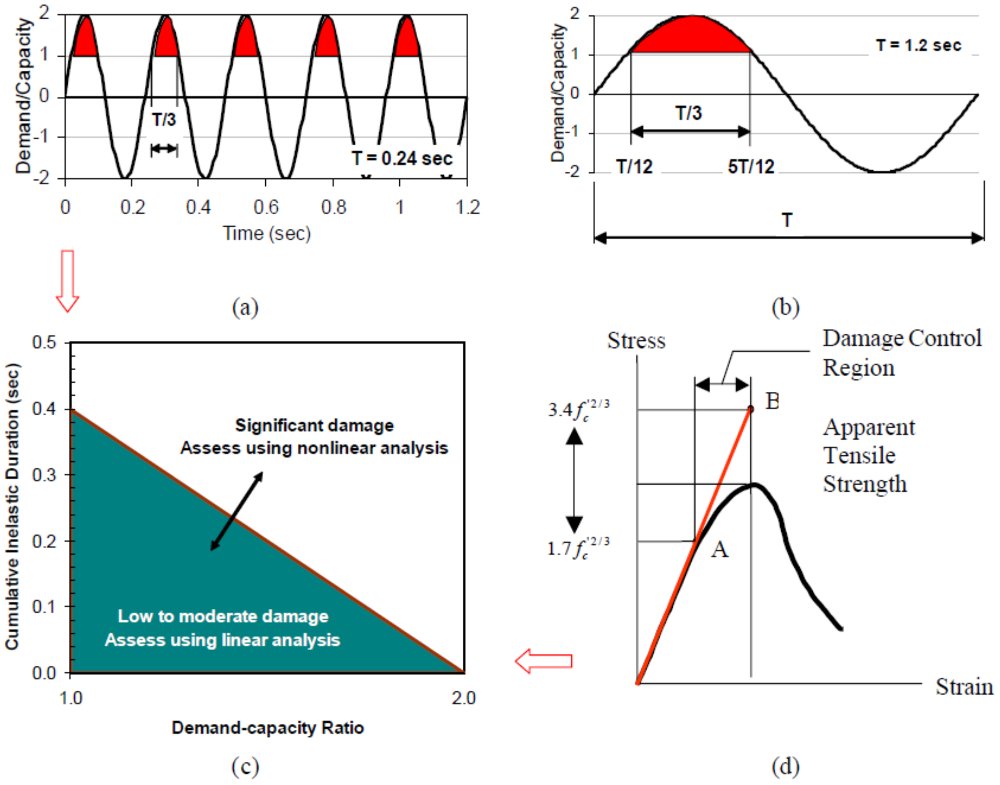
and 1 when $15 \leq f'_c \leq 50$ MPa.

$\alpha_1 = 0.1333$ when $0 \leq f'_c \leq 15$ MPa

and 0.0667 when $15 \leq f'_c \leq 50$ MPa.

Actual and Apparent Tensile strengths taking into account size and rate effects

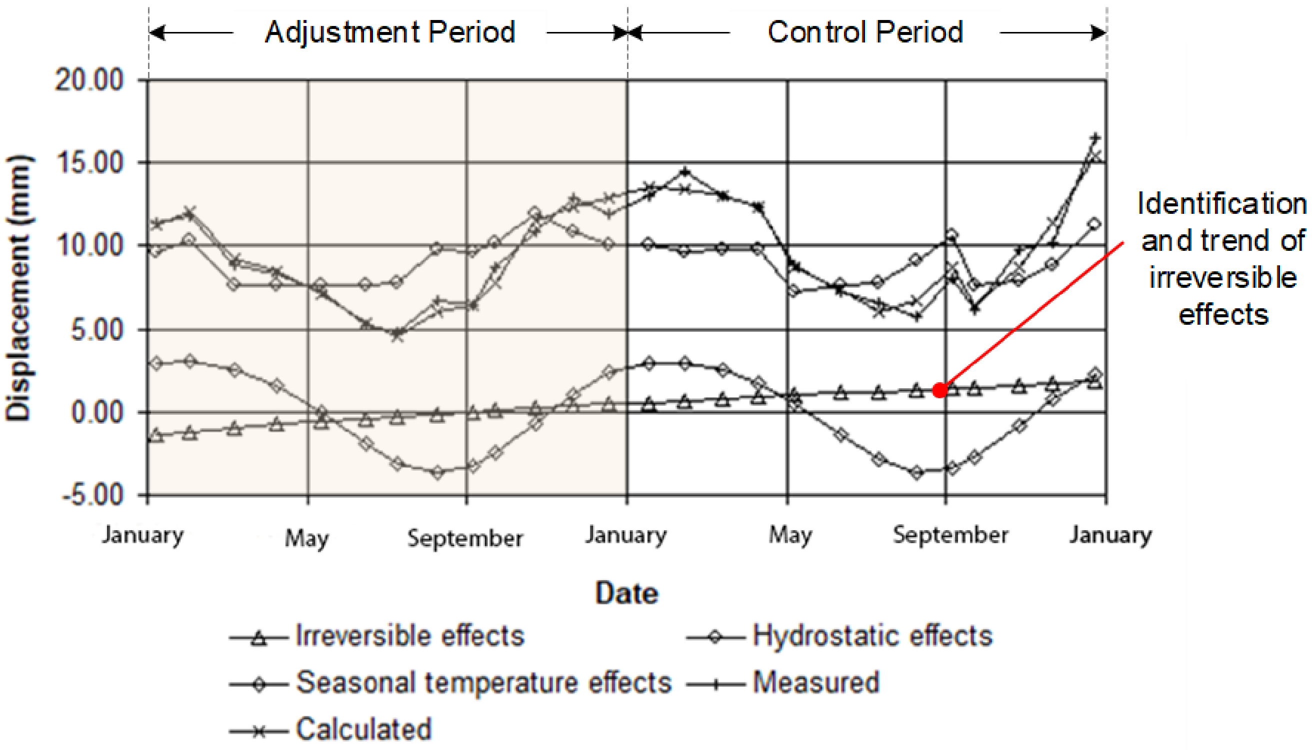
Demand-capacity Ratio



MATERIAL PARAMETERS DERIVED FROM DAM SURVEILLANCE AND MONITORING

PROTOTYPE MATERIAL CALIBRATION … with field investigations .. to be sure!

Three methods may be used to analyse measured data and assist in the selection of material parameters for the NLMCD: (a) ***deterministic*** such as the finite element method; (b) ***statistical***, based solely on the analysis of measurement data and (c) ***hybrid*** methods that incorporate methods (a) and (b).



$$f_i(t,w,s) = f_1(t) + f_2(w) + f_3(s)$$

$$f_1(t) = C_0 + C_1 e^{-t} + C_2 e^{t}$$

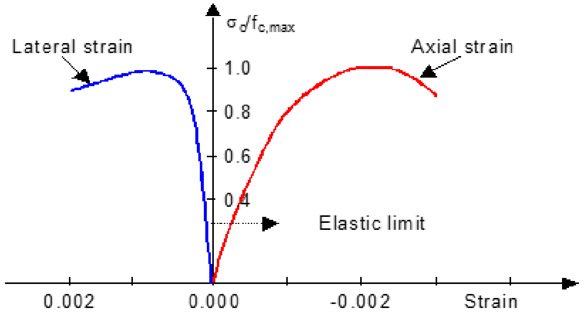
$$f_2(w) = C_3 w + C_4 w^2 + C_5 w^3 + C_5 w^4$$

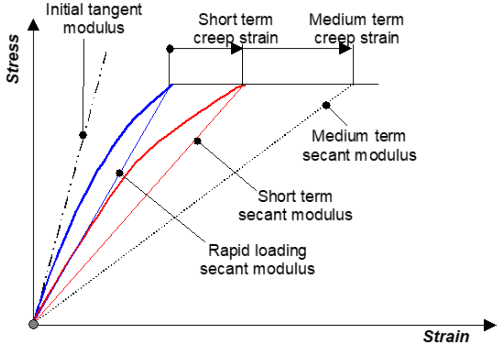
$$f_3(s) = C_7 \cos(s) + C_8 \sin(s) + C_9 \sin^2(s) + C_{10} \sin(s)\cos(s)$$

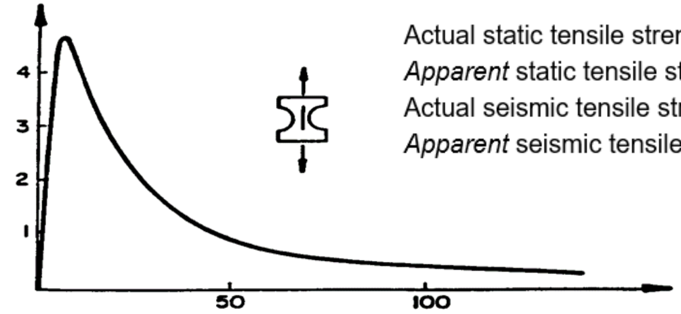
C_i (i = 0 to 10) = unknown coefficients; *s* = seasonal temperatures; *w* = reservoir elevation and *t* = time.

MATERIAL PARAMETERS DERIVED FROM LABORATORY TESTS

MATERIAL PARAMETERS WITH A NICE TWIST …





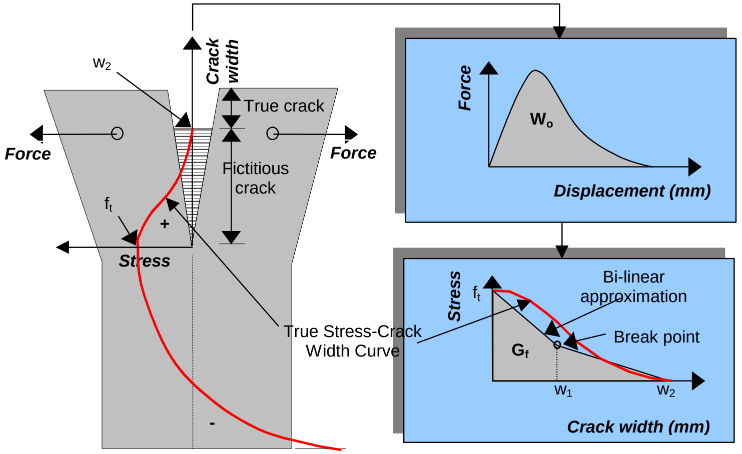


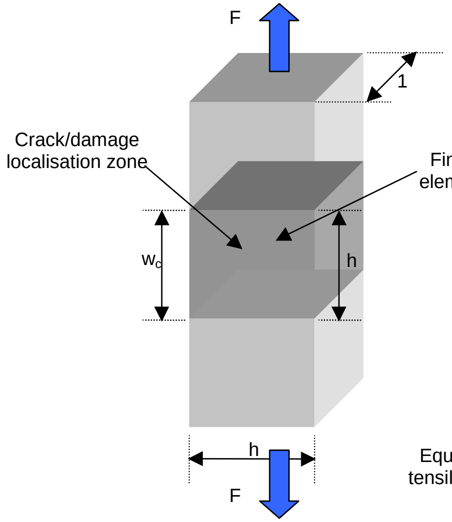
Actual static tensile strength: $f_t = 0.32\ f_c^{2/3}$ (MPa)
Apparent static tensile strength: $f_t = 0.44\ f_c^{2/3}$ (MPa)
Actual seismic tensile strength: $f_t = 0.49\ f_c^{2/3}$ (MPa)
Apparent seismic tensile strength: $f_t = 0.65\ f_c^{2/3}$ (MPa)

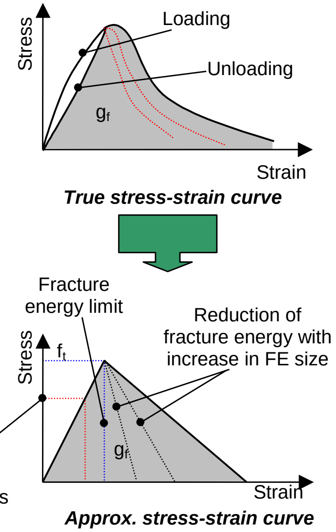
Compressive strength …

Modulus stiffness …

Tensile strength(s) …





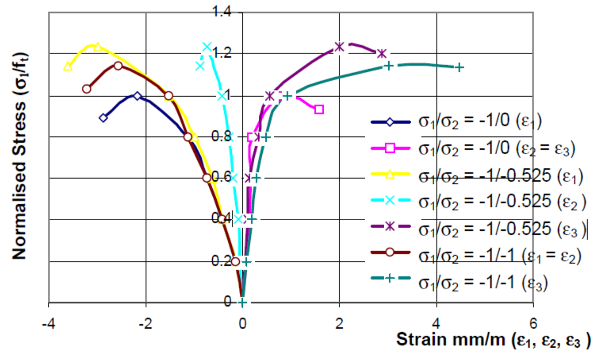


Fracture energy to derive tensile strength with mesh objectivity …

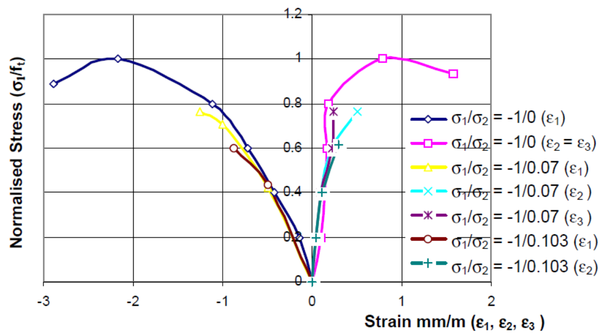
MATERIAL PARAMETERS DERIVED FROM LABORATORY TESTS

Biaxial loading

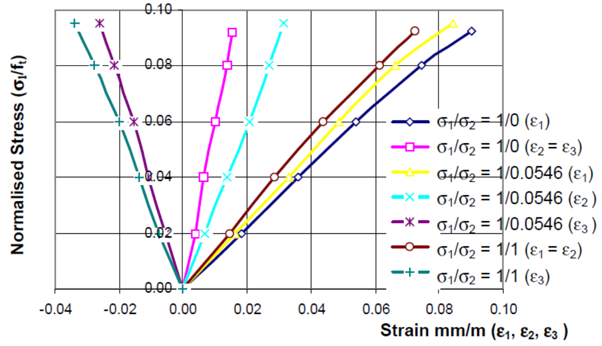
Compression - compression



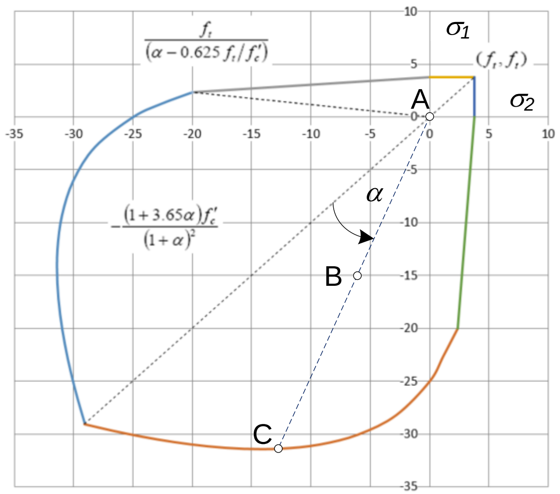
Compression - traction



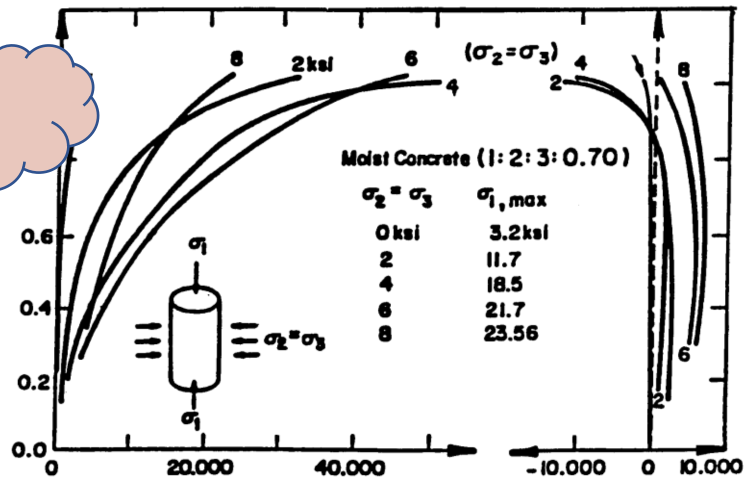
Traction - traction

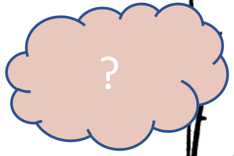


Biaxial envelope



Triaxial loading





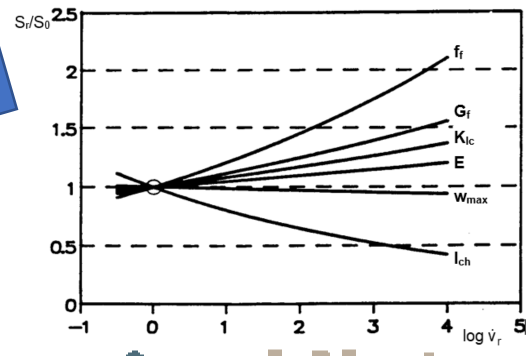
Load Combination	Result.	Sliding[1]		Overturning	Buoyancy	Bearing	Stresses[1]		
	γ_n	γ_{mc}	$\gamma_{m\phi}$	γ_b	F_f [2] >	γ_{mq}	σ_c	$\sigma_{c\text{-}t}$ [3]	σ_t
Construction	e/3	0.0	1.3	1.3	0%	-	2.0	2 à 1.5	1.5
Usual	e/3	0.0	1.5	1.5	0%	1.5	3.0	3 à 2	2.0
Unusual	2e/3	0.0	1.3	1.3	0%	1.3	2.0	2 à 1.5	1.5
Extreme	e	0.0	1.0	1.0	0%	1.0	1.0	1 à 1	1.0

Remarks

f'_c = uniaxial compressive strength at 365 days, cylinder
f'_t = tensile strength (brazilian), cylinder
e = section thickness

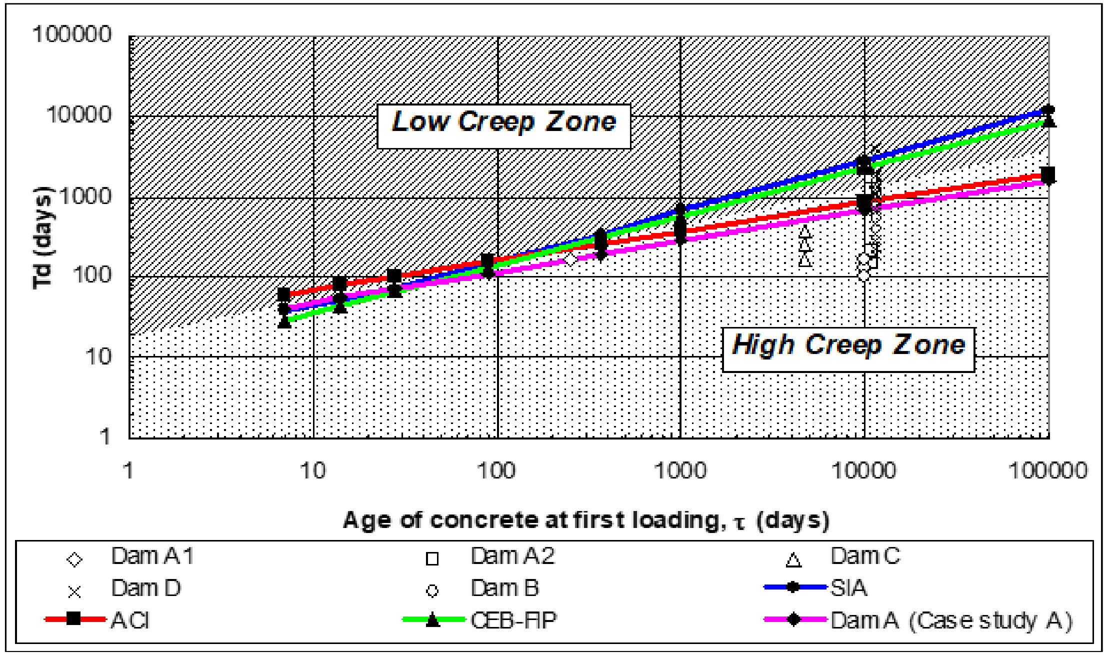
1) State of stress within dam, interfaces and dam-foundation interface
2) $F_f = (N-U) / U$ where
N = Composant of normal force on the section
U = resultant interstitial forces
3) Biaxial strength (*Kupfer et al.*)

Rate effects

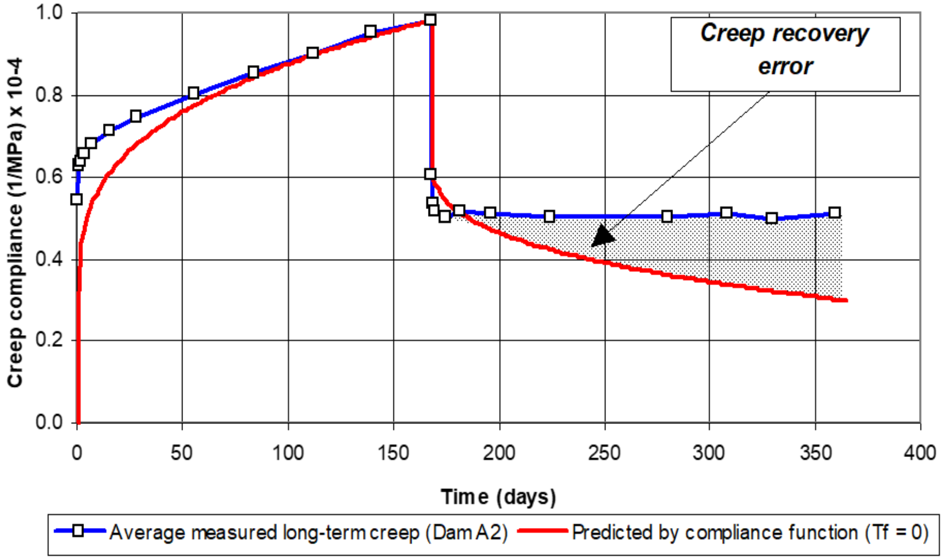


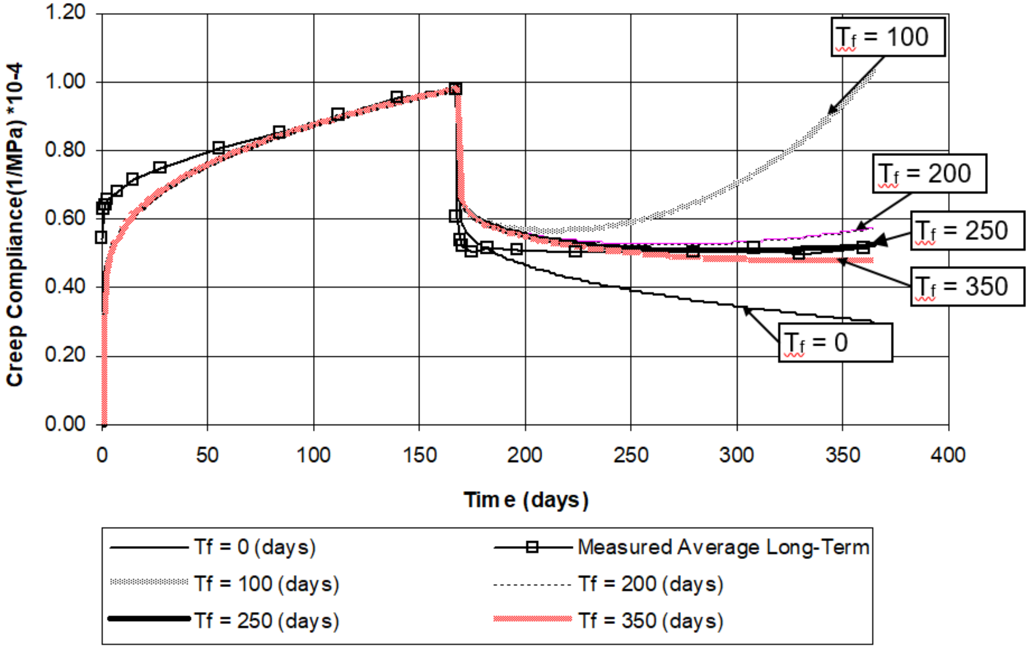
MATERIAL PARAMETERS DERIVED FROM LABORATORY TESTS

CYCLIC CREEP WITH RECOVERY *by relaxation …*



$$J(t,\tau)=\frac{1}{E_0}\left(K_1+K_2\left(1-e^{\left(\frac{t_u-\tau}{T_f}\right)}\right)\right)\left(1+\varphi\left(\tau^{-m}+\alpha\right)(t-\tau)^n\right)$$

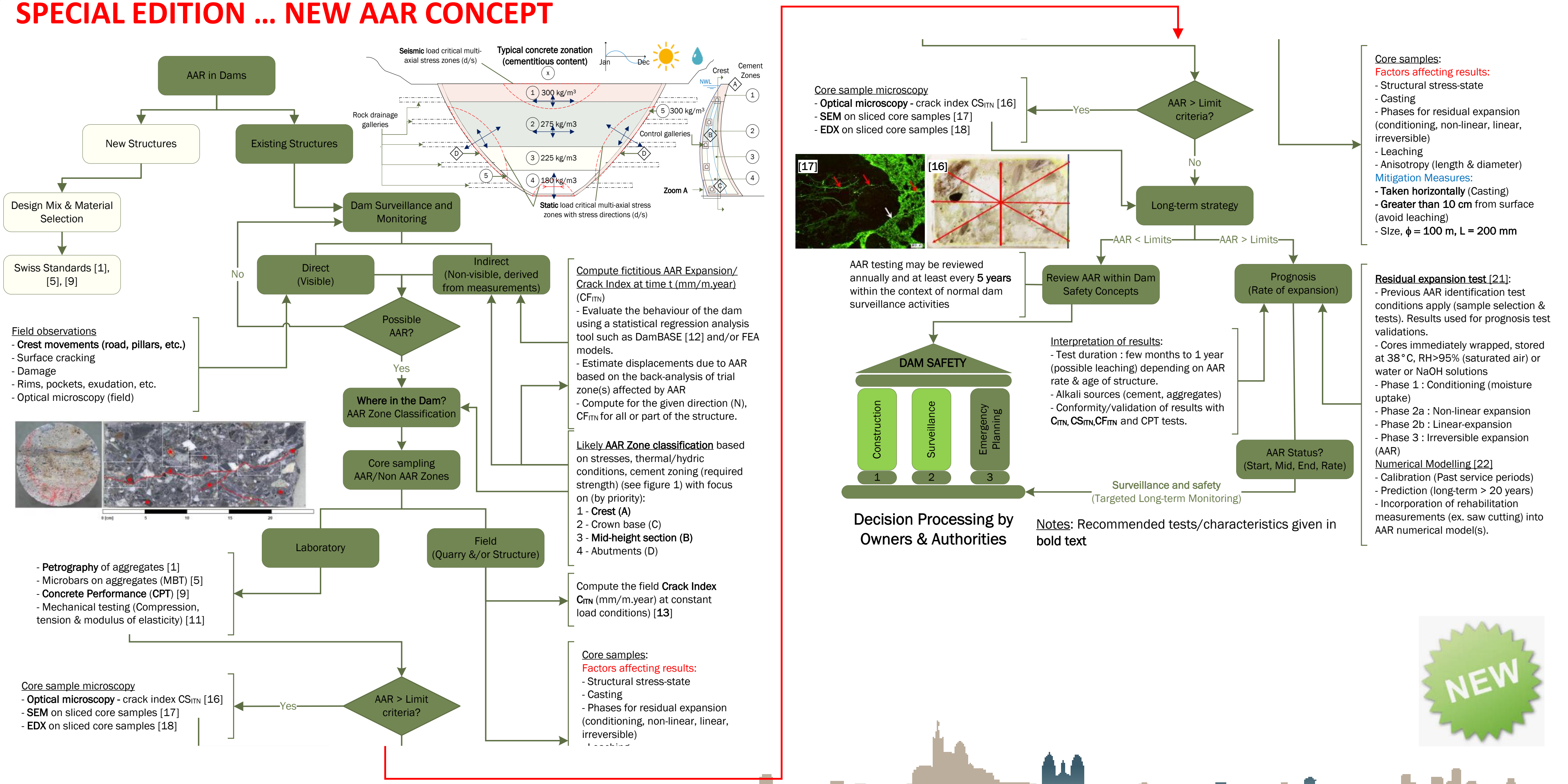




Cyclic long-term creep: Double power (top right) and modified double power laws (bottom right).

SPECIAL EDITION … NEW AAR CONCEPT

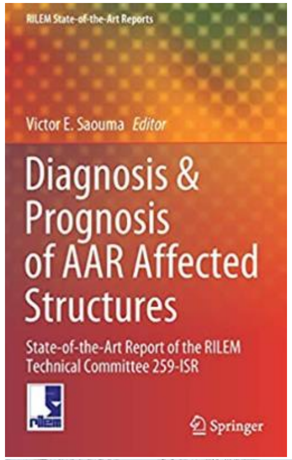
MATERIAL PARAMETERS DERIVED FROM LABORATORY TESTS



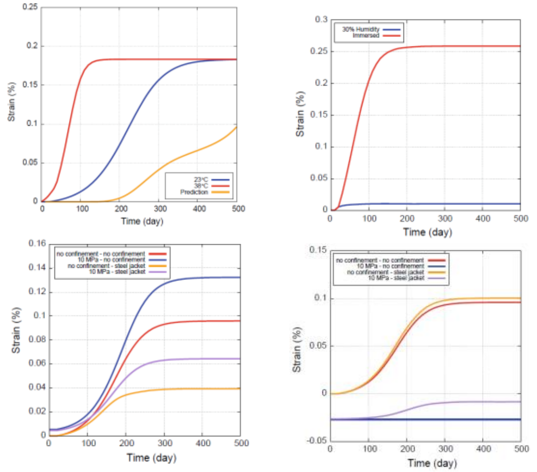
MATERIAL PARAMETERS DERIVED FROM LABORATORY TESTS

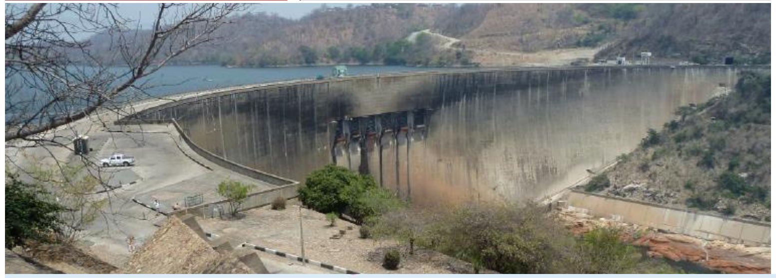
New three-step approach to select AAR material parameters

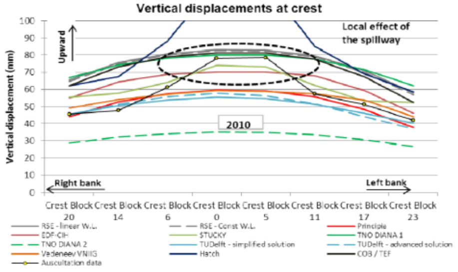
- ***Phase 1*** *- FE code and constitutive model validation* based on core laboratory experiments (**RILEM 2021**);
- ***Phase 2*** *- Existing dam structural or macro level calibration* based on observed field measurements (**BMW11**);
- ***Phase 3*** – Rehabilitated dam structural or macro level calibration based on the results of steps 1 and 2 (**CHJE2021**).

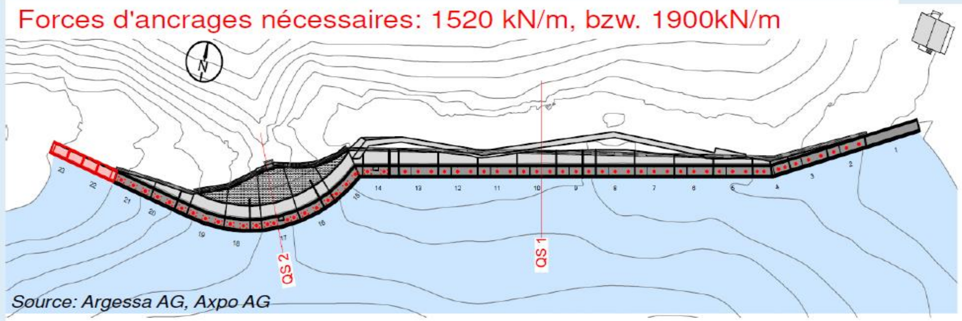


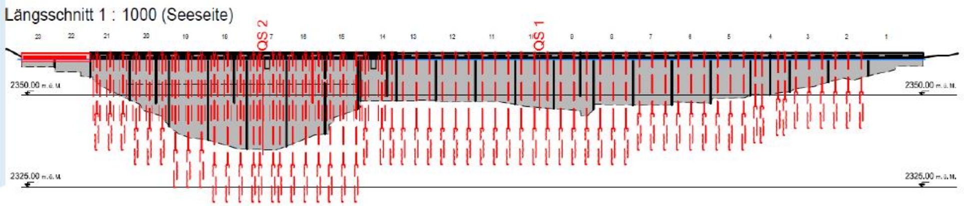
Phase 1 - Finite Element and Constitutive Model Benchmarks based on Laboratory Exp			
Steps	Objective	Cylinder ɸ x h (cm)	Initial conditions
1a	Constitutive Model (mechanical properties)	16 x 32	f_c = 38.4 MPa f_t = 3.5 MPa, E = 37.3 GPa, ε_c = -0.002, G_{ft} = 100 Nm/m2 and G_{fc} = 10 000 Nm/m2
2a	Capturing drying and shrinkage	16 x 32	RH & reactive, non-reactive concretes, RH = 85%, T (t = 0) = 38°C
3a	Capturing creep	13 x 24	Note - creep predominated in the constrained direction
4a	Effect of temperature on AAR free expansion	13 x 24	RH (t =0) = 100%, Cylinder base is free to deform
5a	Effect of relative humidity on AAR free expansion	16 x 32	RH (t =0) = 85%, T = 38°C
6a	Effect of confinement on AAR free expansion	13 x 24	T = 38°C

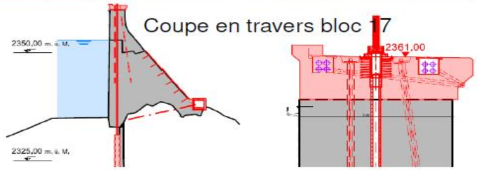






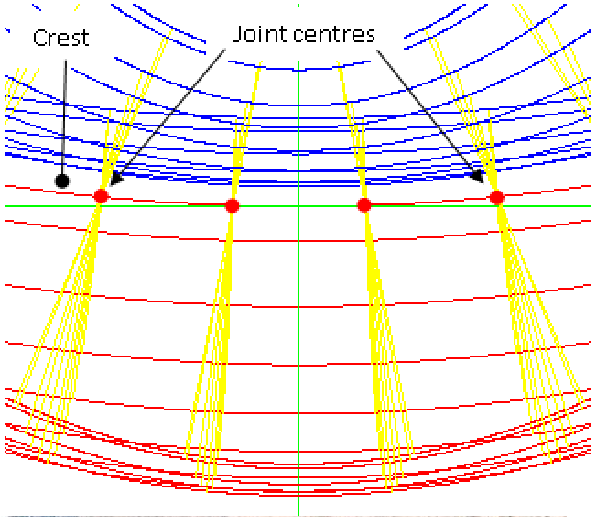


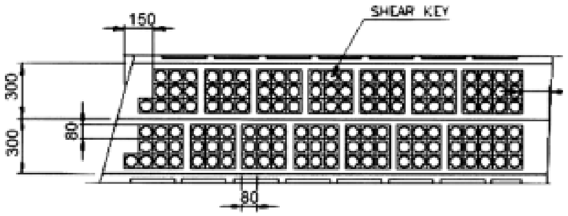


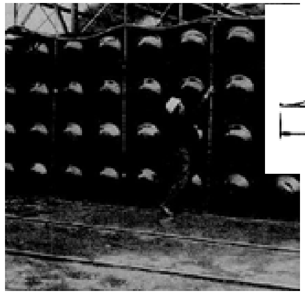


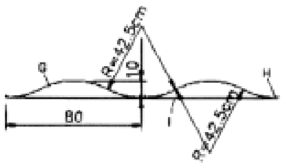
MATERIAL PARAMETERS FOR STRUCTURAL INTERFACES

STRUCTURAL INTERFACES EXPLAINED …..







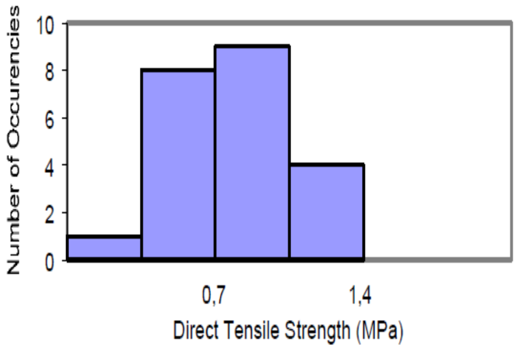


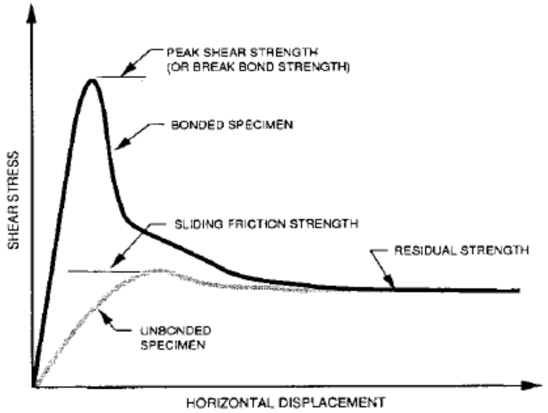
LIFT JOINTS

Tensile strength	Static Conditions		Dynamic Conditions	
	psi	MPa	psi	MPa
Parent concrete (splitting)	1.7 $f'c^{2/3}$	0.32 $f'c^{2/3}$	2.6 $f'c^{2/3}$	0.49 $f'c^{2/3}$
Bonded lift joints (direct)	0.85 $f'c^{2/3}$	0.16 $f'c^{2/3}$	1.3 $f'c^{2/3}$	0.24 $f'c^{2/3}$
Unbonded lift joints	Nil	Nil	Nil	Nil

Shear Strength	Cohesion		Angle of friction
(Peak)	c (psi)	c (MPa)	f (°)
Best fit	304.58	2.10	57
Lower bound	137.79	0.95	57
Sliding friction strength			
Best fit	72.52	0.50	49
Lower bound	0.00	0.00	48

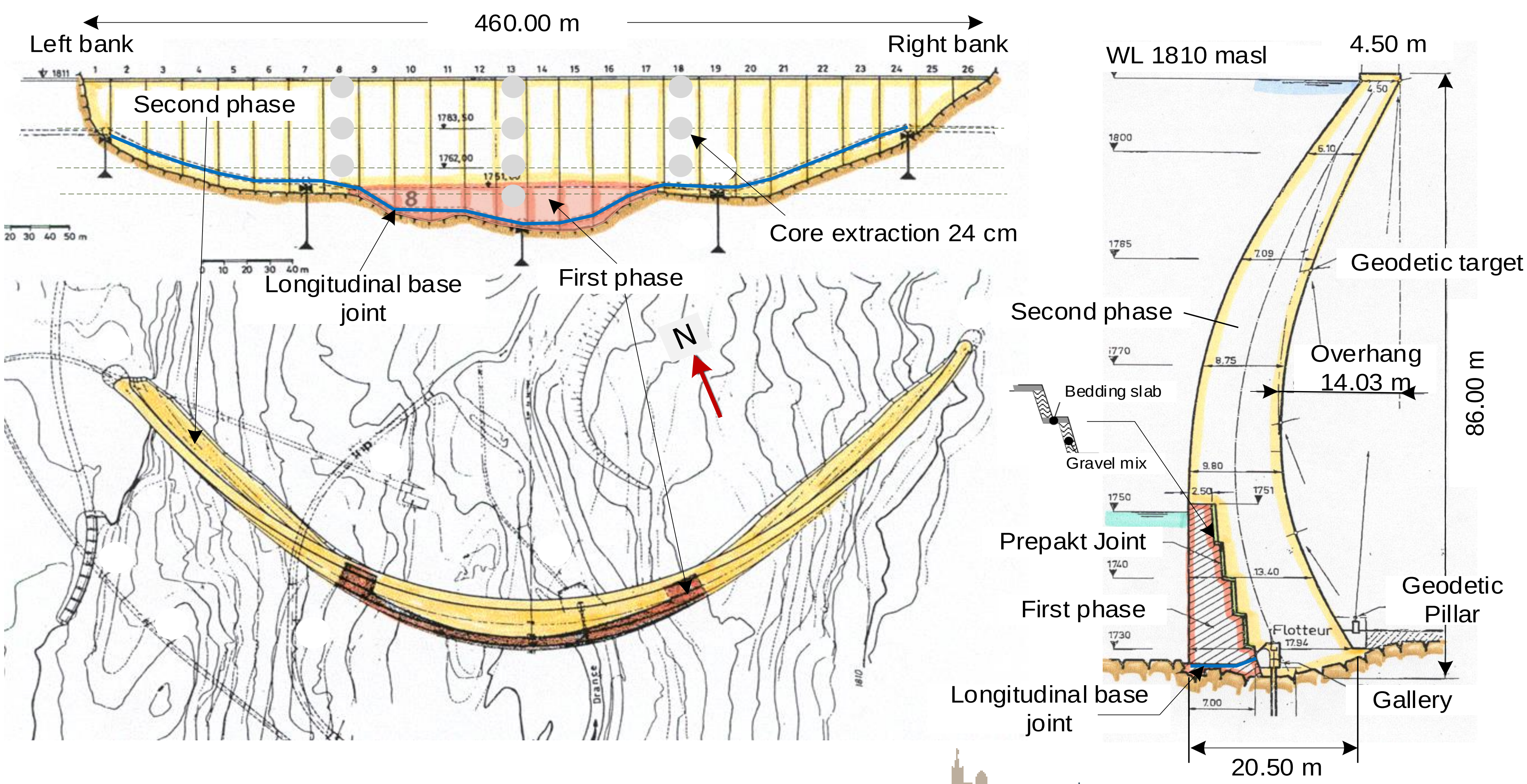
DAM-FOUNDATION INTERFACES





PUTTING IT ALL INTO PRACTICE .....

CASE STUDY



PLACE YOUR ORDERS to learn more …..

CASE STUDY


Last But Not Least

CIGB ICOLD 2022 MARSEILLE

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Thank you for your attention

Merci pour votre attention

12th ICOLD European Club Symposium

Swiss Committee on Dams 2023

75

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Chapter 7

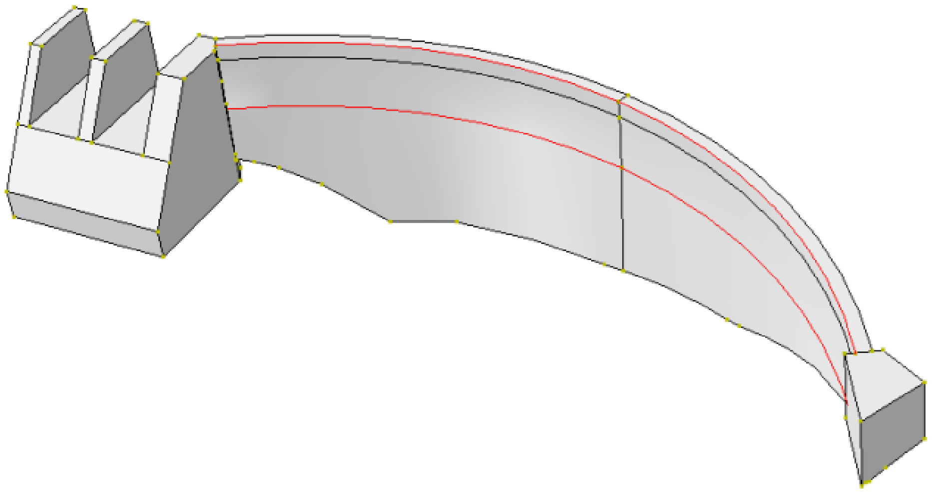
NLMCD EXAMPLES AND CASE HISTORIES

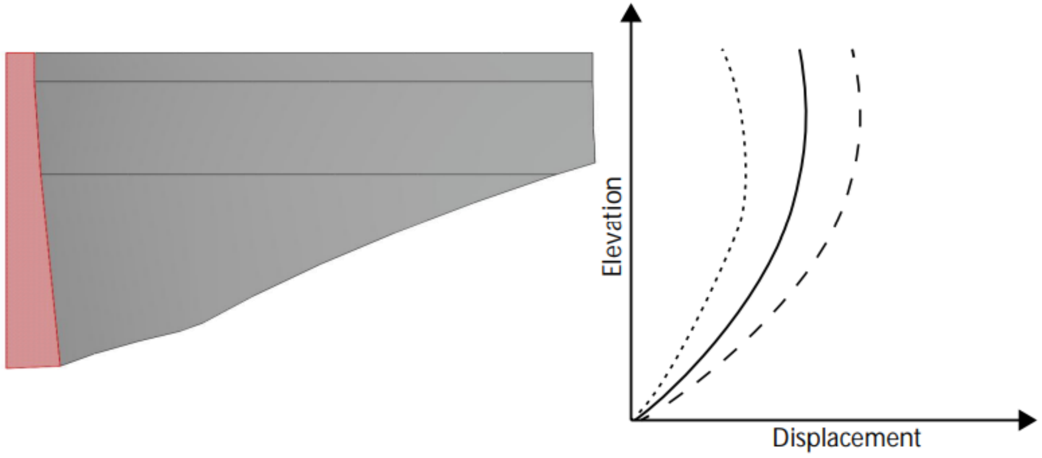
- BW 14 - Cracking of a concrete arch dam due to seasonal temperature variation
- BW 13 - Numerical modelling of the partial demolition of Beauregard dam
- …
- Many examples outline how calibrate numerical models with measured data

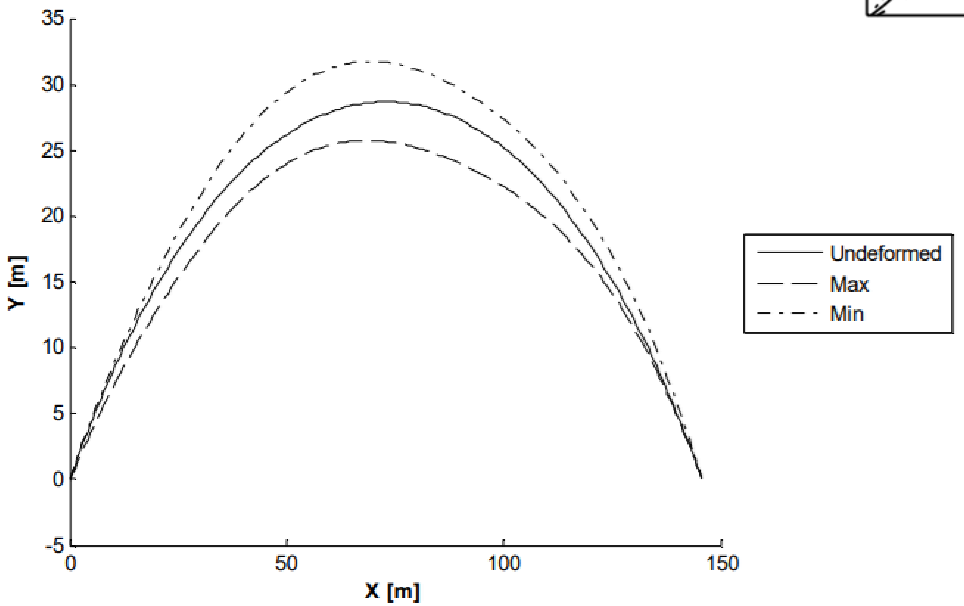
Cracking of a slender, reinforced concrete arch dam due to seasonal temperature variations

Each participant had to predict

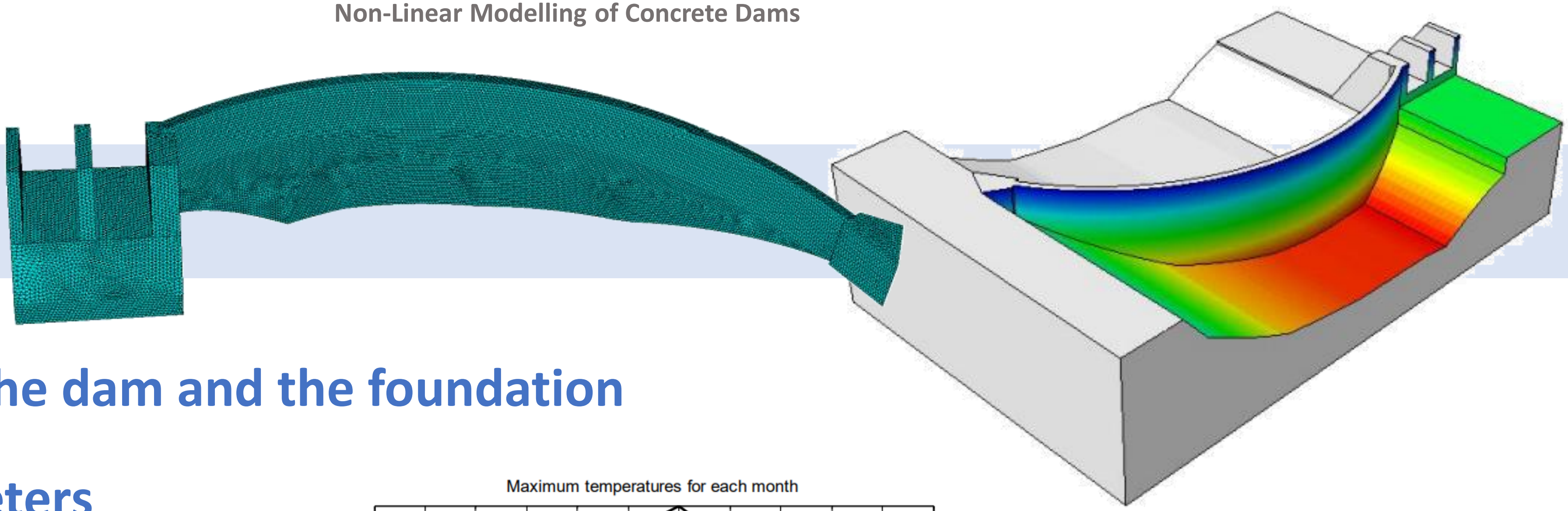
1. The **extent of cracking** on the dam
2. The **displacements** of the dam in **summer and winter conditions**







Provided data



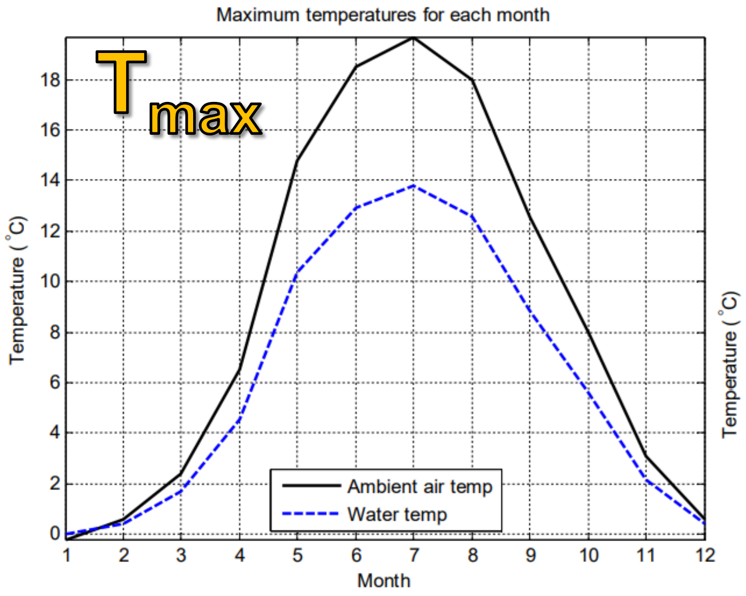
Geometry and mesh of the dam and the foundation

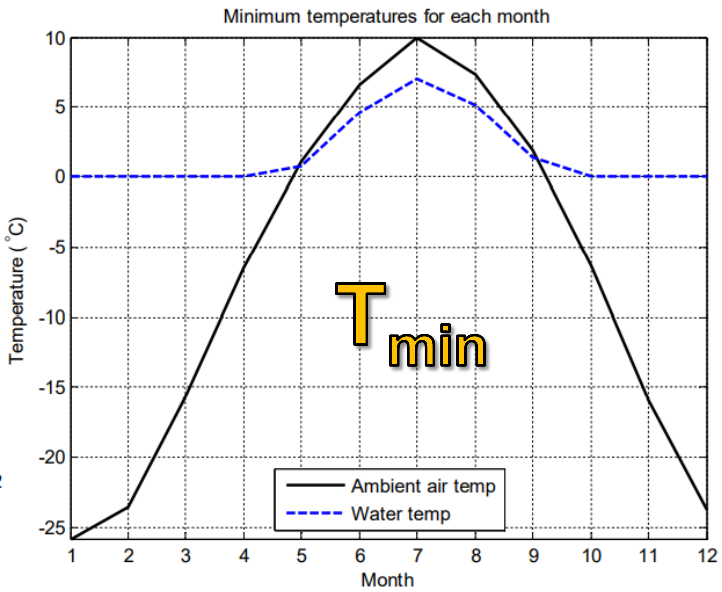
General material parameters

- Density, E-modulus, Poisson's ratio, thermal data, strengths etc.

Loading conditions

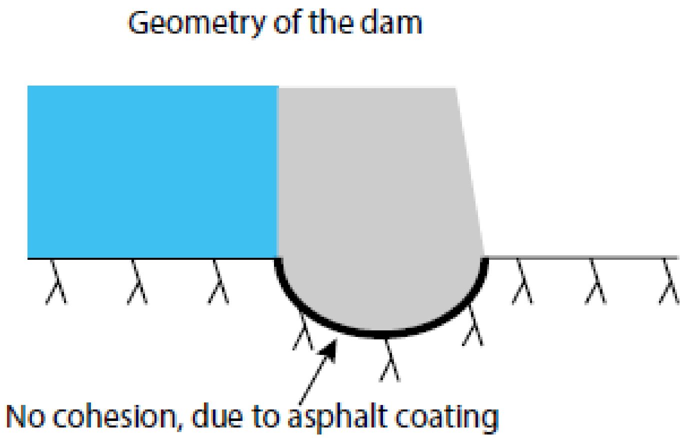
- Gravity
- Hydrostatic water pressure
- Seasonal temperature variations

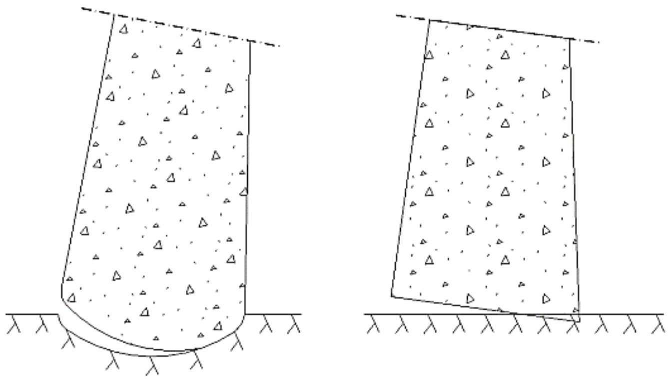




Aspects of the numerical modelling to be freely chosen

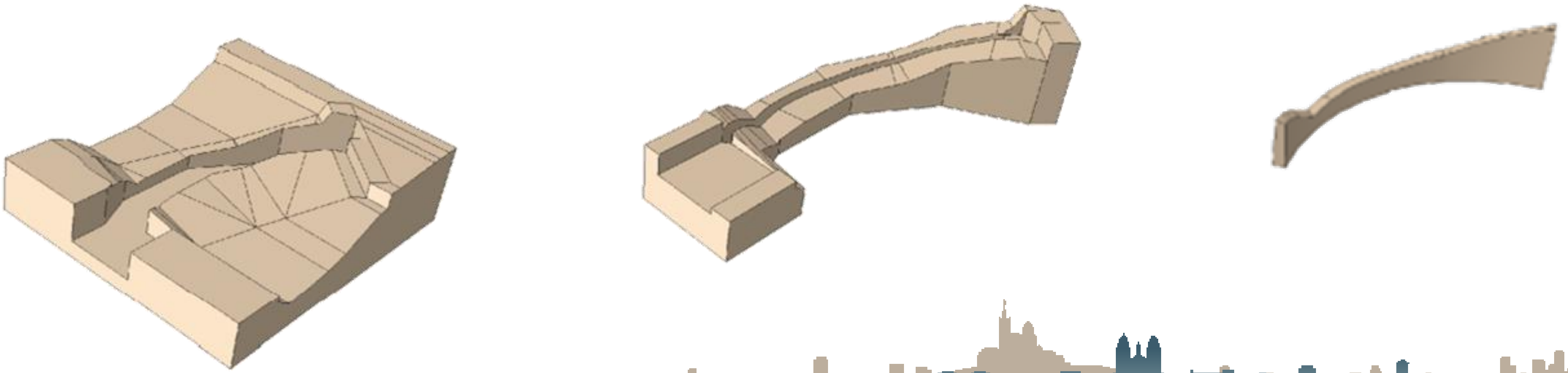
- How to perform the **thermal analysis** (steady state vs transient analysis, convective boundary conditions vs prescribed nodal temperatures etc.)
- How to model the **contact** between the dam and the foundation (fixed contact, contact formulation, interface elements etc.)





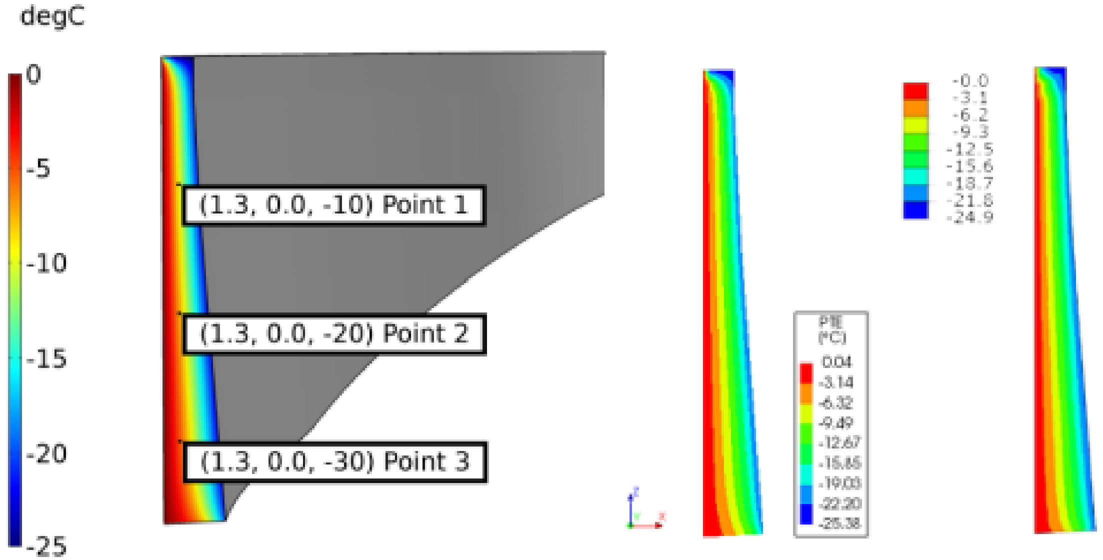
Aspects of the numerical modelling to be freely chosen

- **Fracture energy** and type of **non-linear material model for concrete**
- How to include the **rock mass** and assign **boundary conditions** (size of the rock and where and how to apply the boundary conditions)

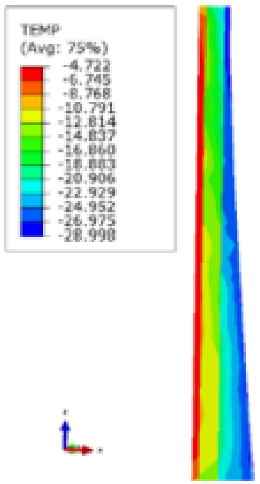


Thermal analyses results

Most participants performed **transient analysis** with **convective boundary conditions** (Robin) instead of prescribed nodal temperatures conditions (Dirichlet) but **all results are in good agreement**

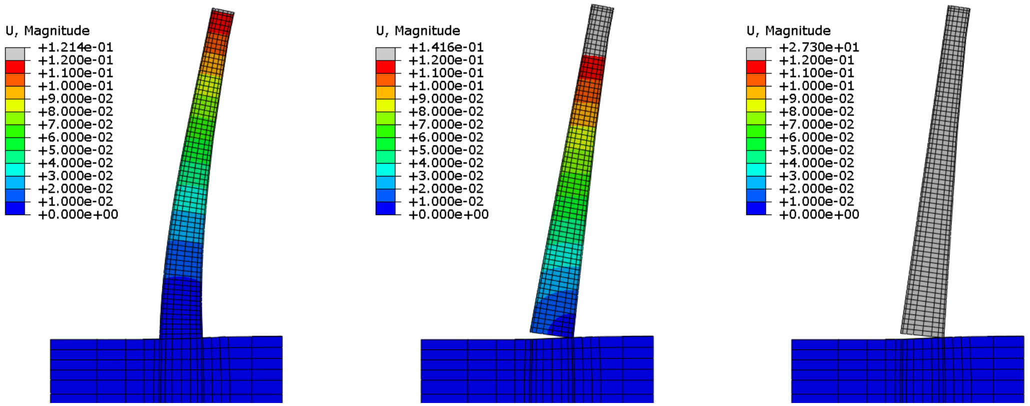


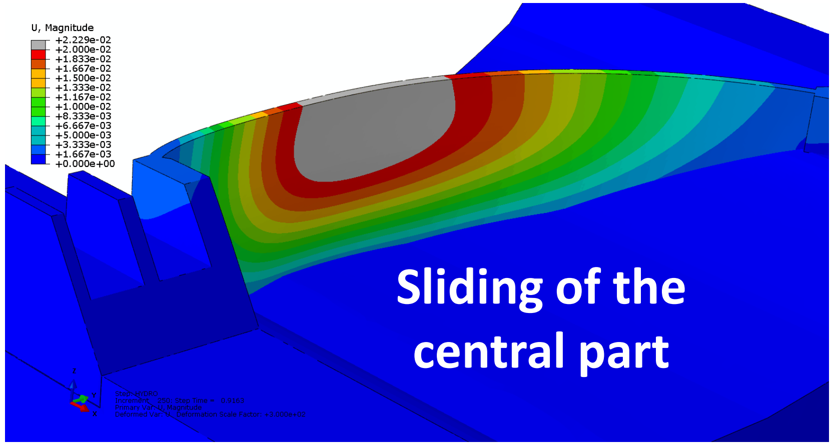
Three examples of transient analyses



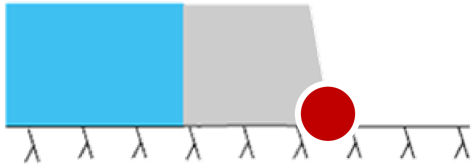
An example of steady state analysis

Influence of contact modelling



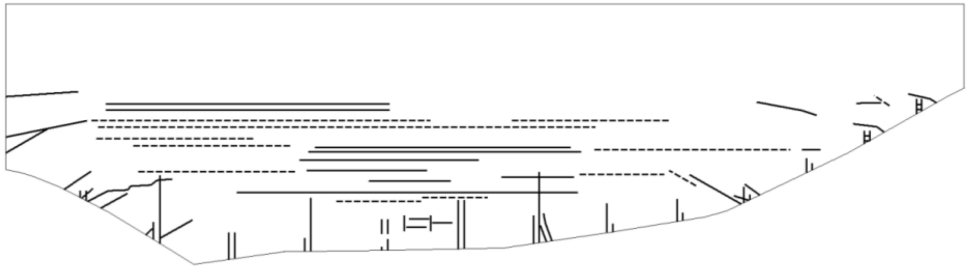


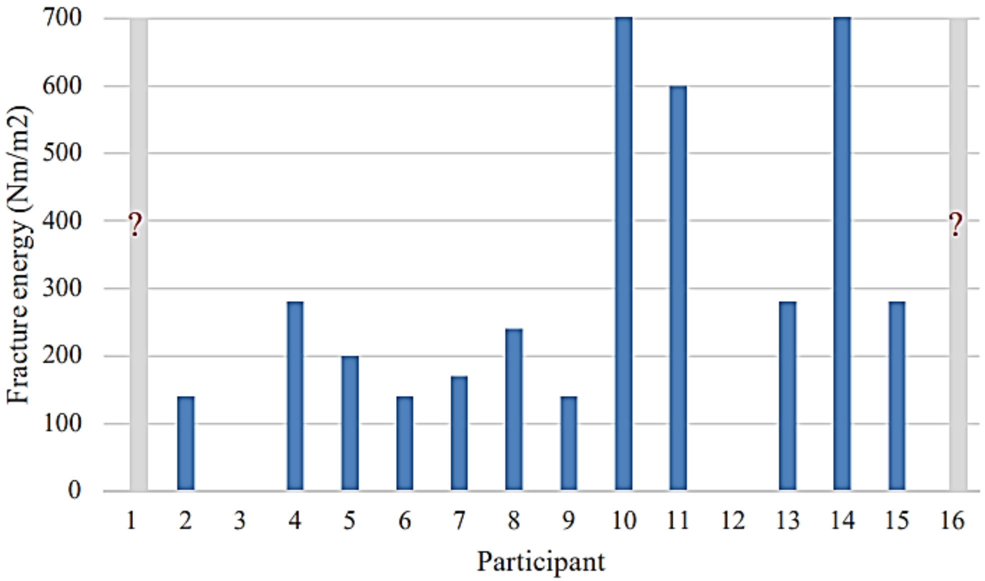
- Different approaches influence the displacements of the dam and the crack pattern
- Numerical issues arise related to the local sliding, especially in the central part of the dam
- A participant constrained the downstream line of the concrete dam only to avoid sliding

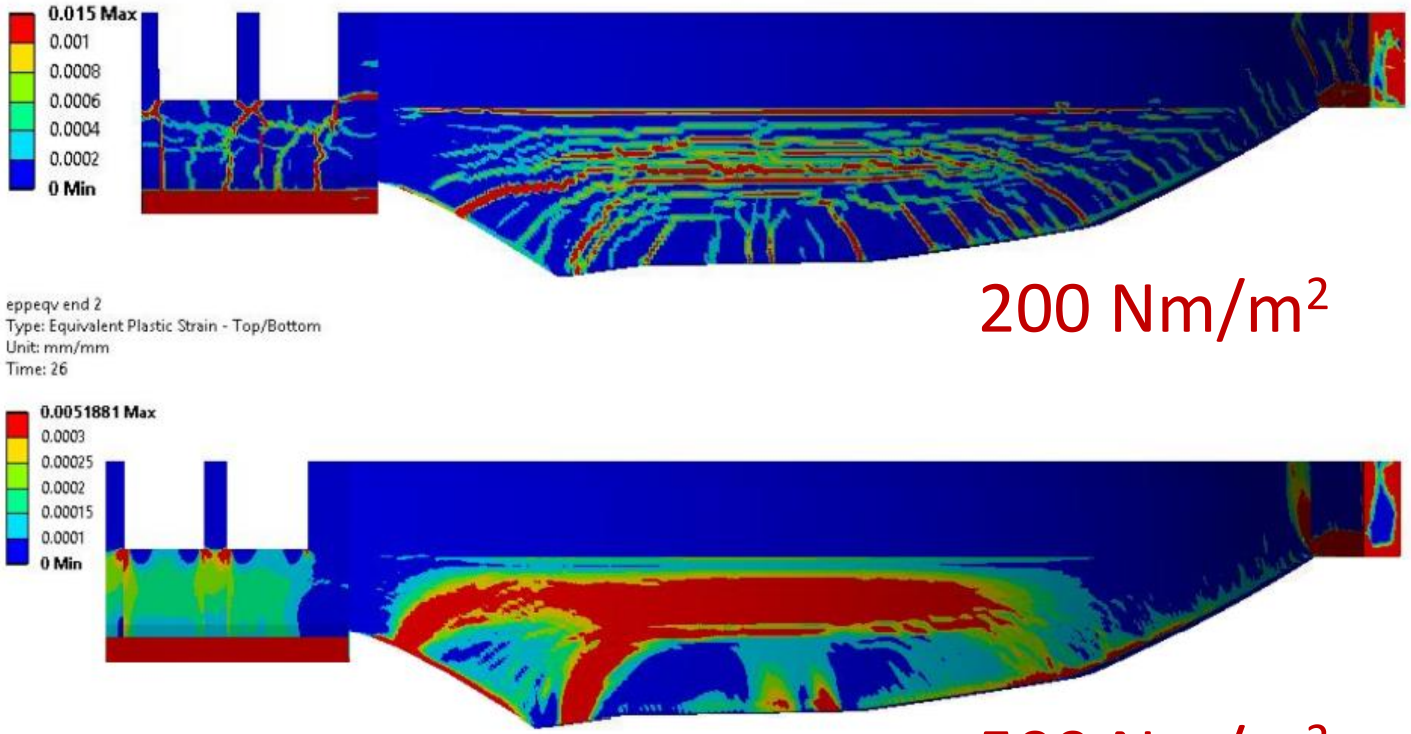


Influence of the fracture energy on the crack pattern

Observed crack pattern



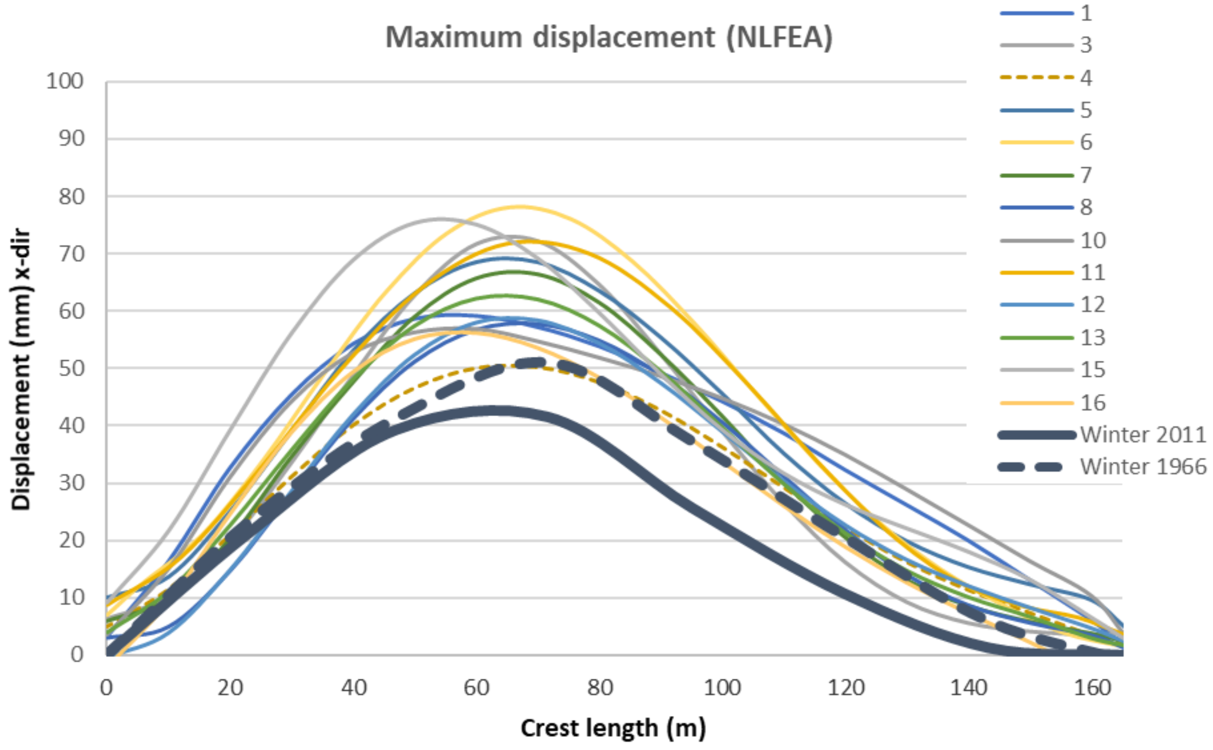




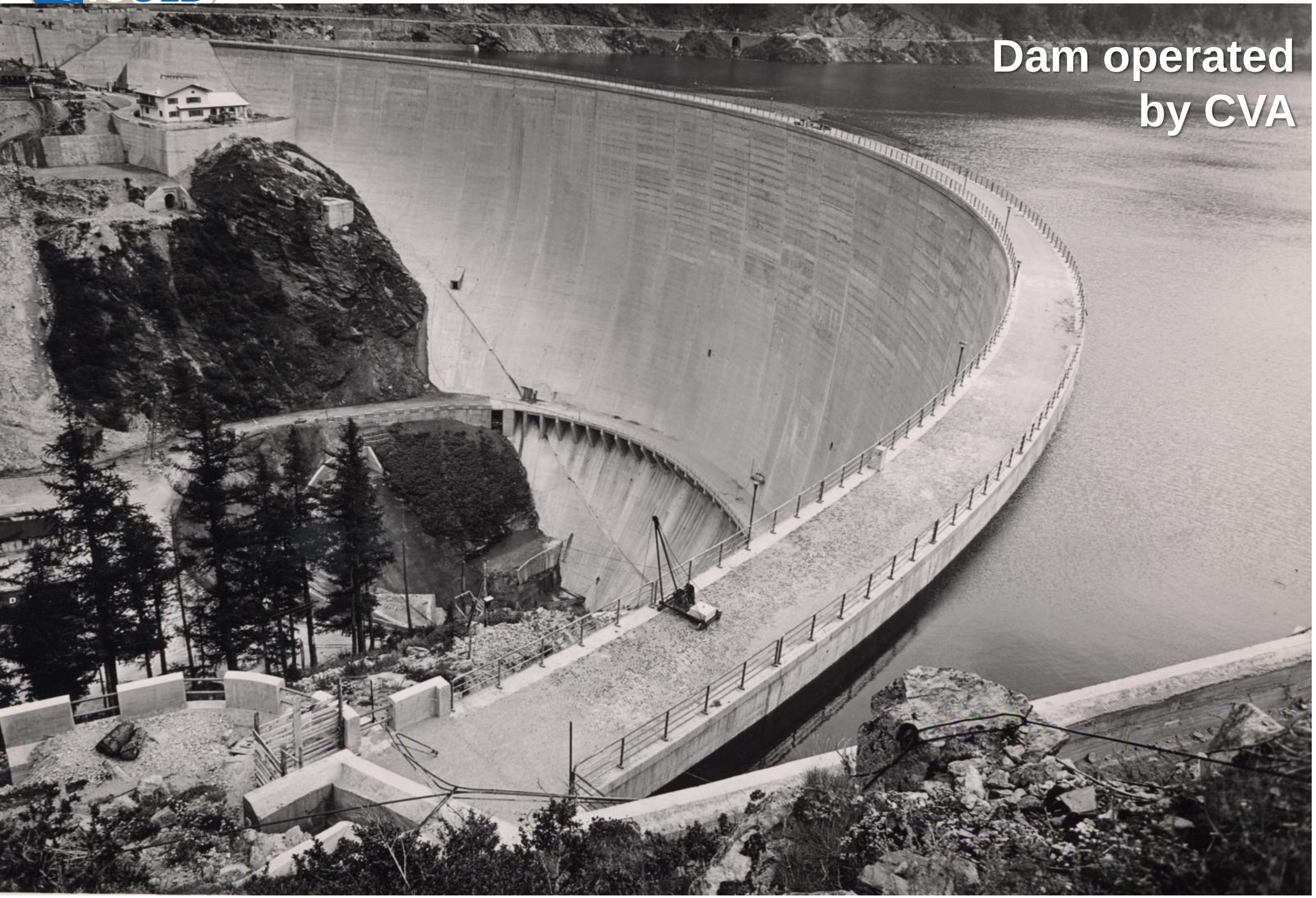
200 Nm/m^2

500 Nm/m^2

- The concrete-rock interaction has large influence on the predicted displacements (large joint opening occurs due to the slenderness of the dam)
  - Cohesive interface models have no influence on the results
  - Tied constraints provide results in bad agreement with the measured one

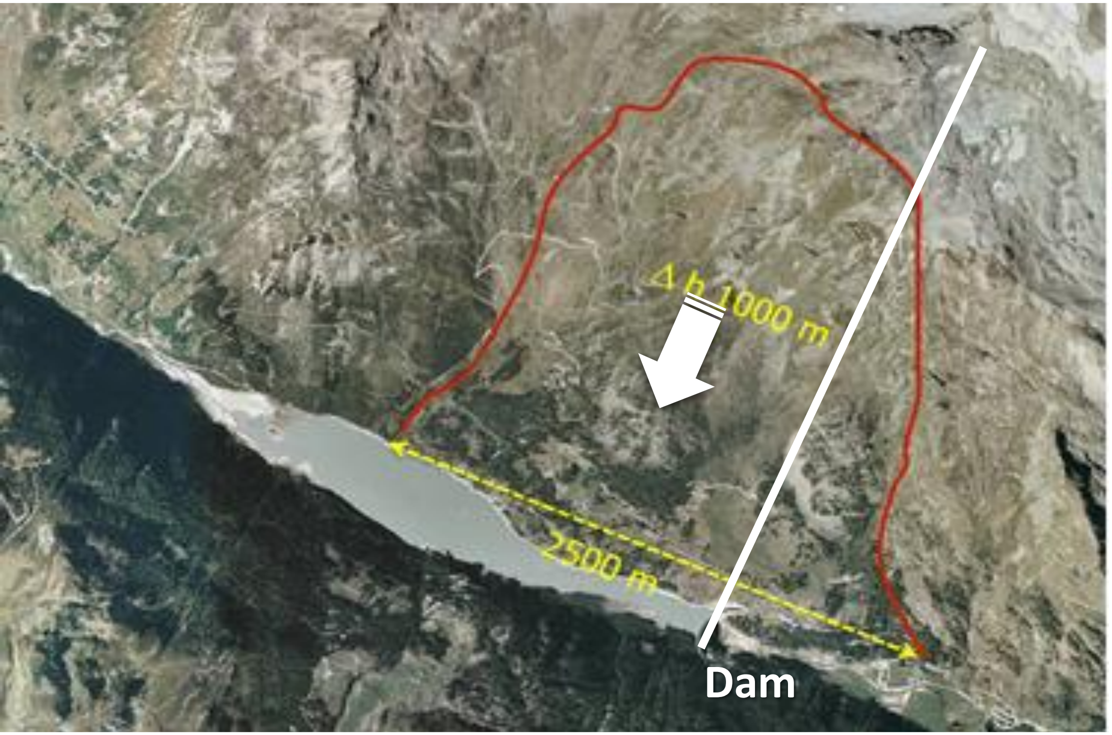


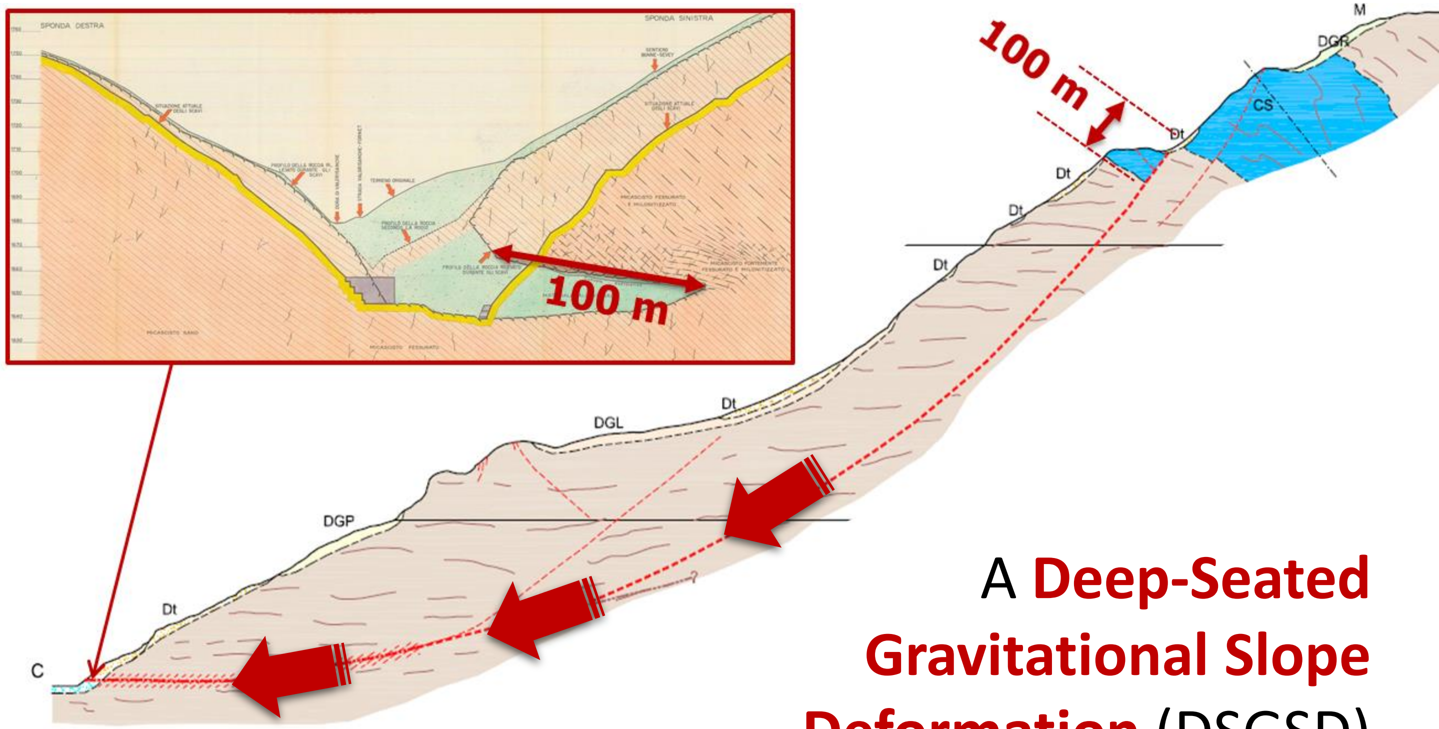
The temperatures provided to the participants were more extreme than those recorded when measuring the dam displacements



Modelling of the nonlinear behaviour of Beauregard dam

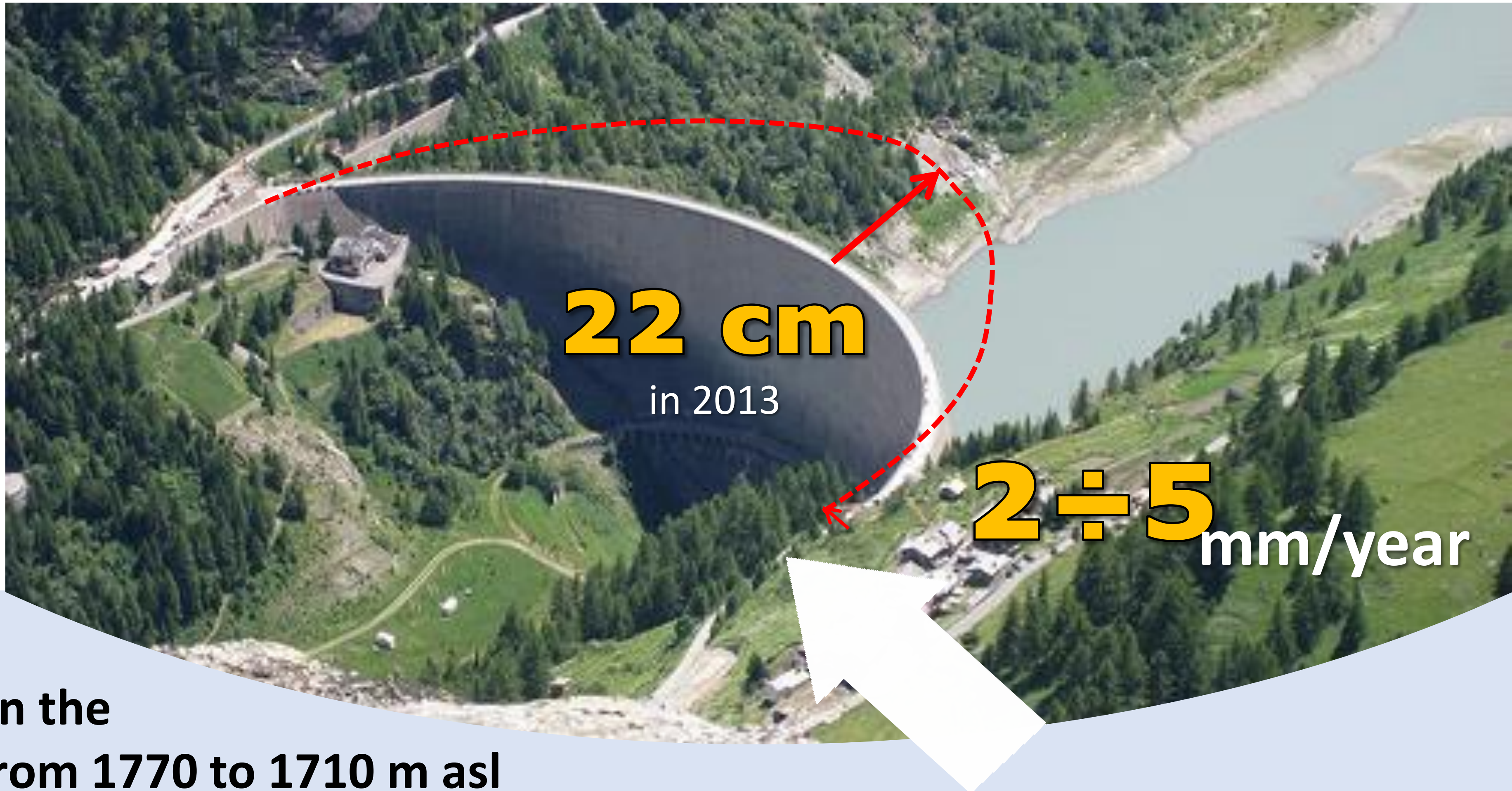
What was going on?





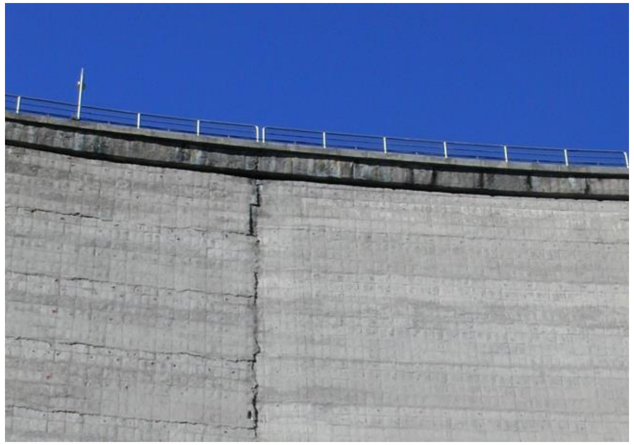
A **Deep-Seated Gravitational Slope Deformation** (DSGSD) strongly affected the dam

Since the first fillings, the dam started deflecting upstream



In 1969 the Italian Dam Authorities lowered down the operational water level from 1770 to 1710 m asl
(limited volume nearly 1/10 of the designed one)

Cracks on the downstream face and sliding of some vertical joints



Why non linear numerical modelling?

Focus on step 1

1

Identify the material parameters of the numerical model to interpret the dam behavior since its first fillings

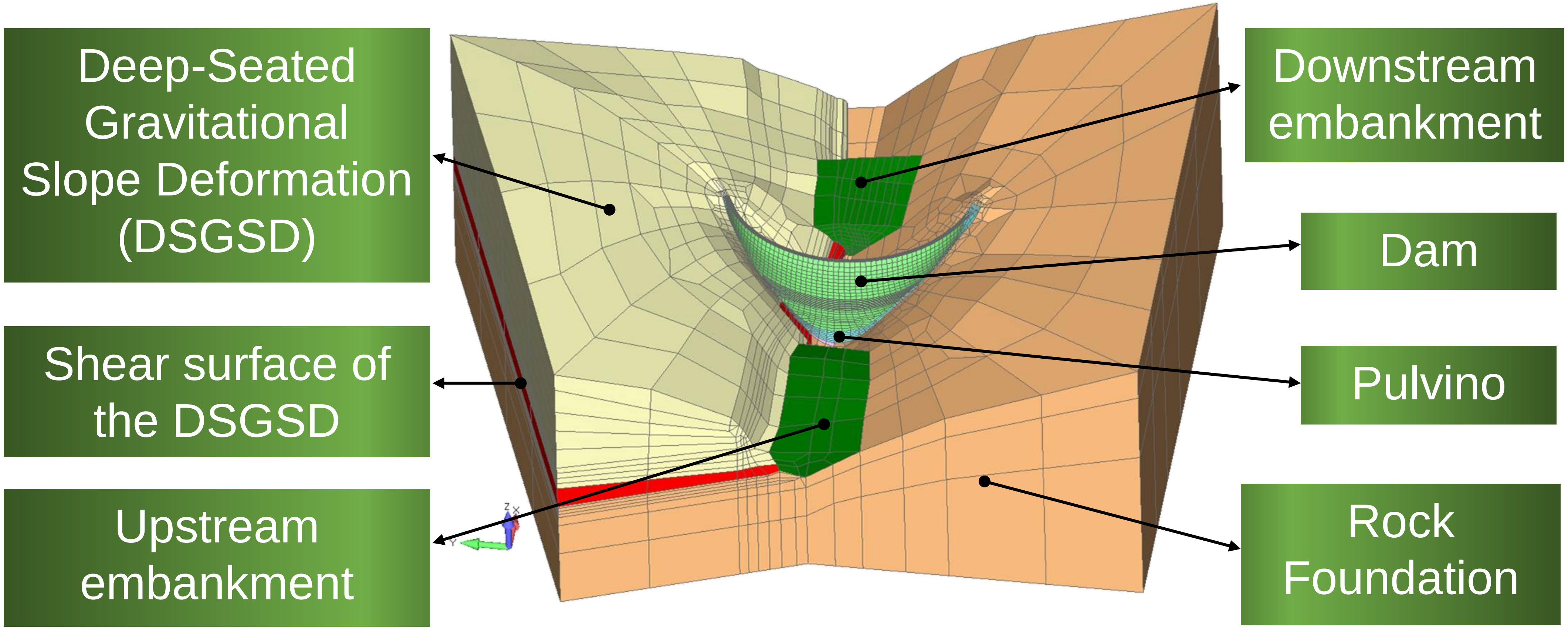
2

Forecast the future dam behavior at short-medium term resorting to the calibrated numerical model

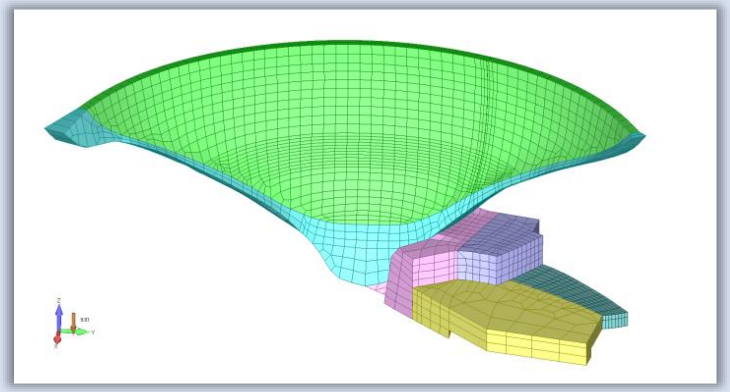
3

Support the designer to assess different rehabilitation solutions to guarantee the safety long-term operation of the dam

The numerical finite element model

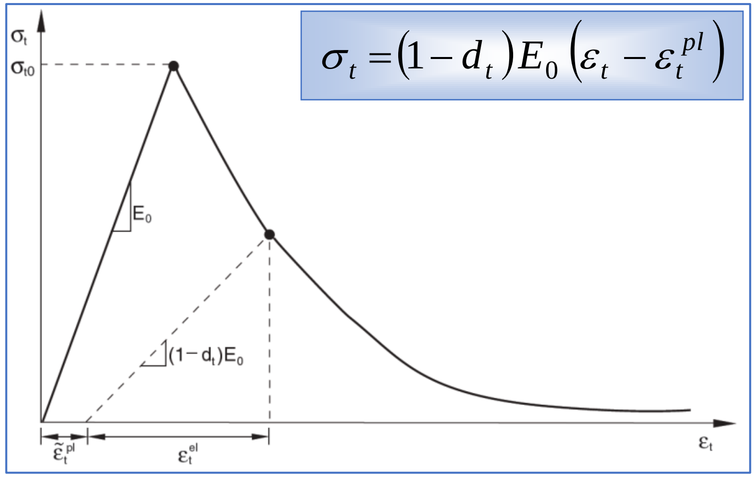


… and 16 contact surfaces

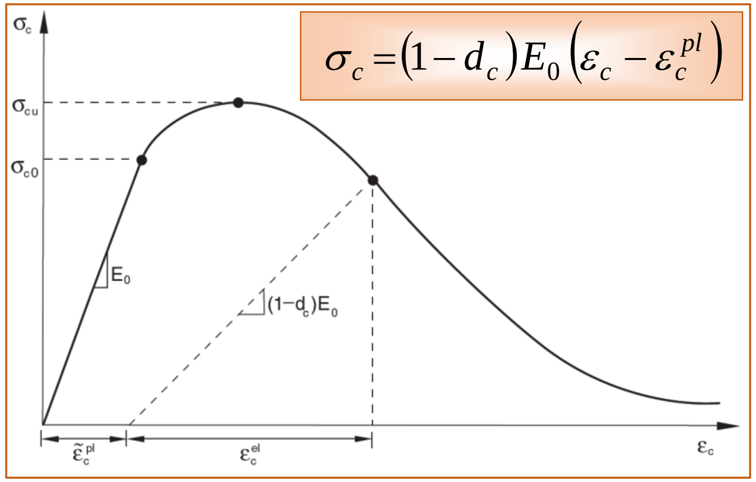


In situ and testing data were used to define the material parameters of the constitutive laws of concrete

Uniaxial loading in tension

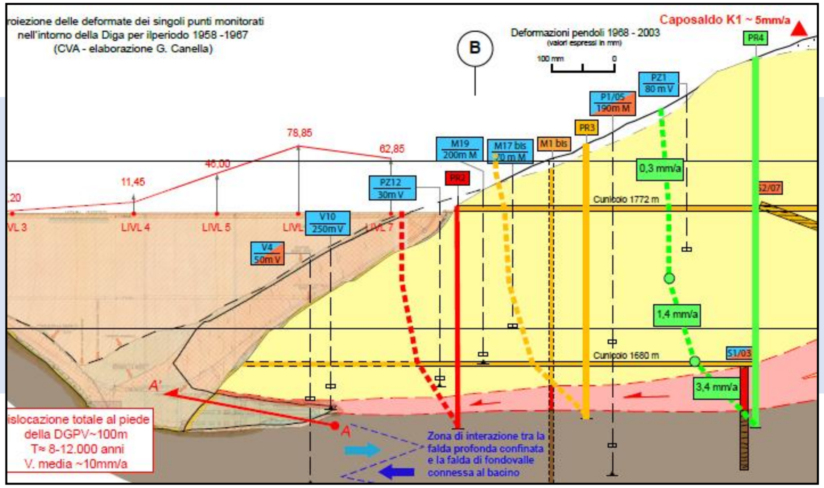


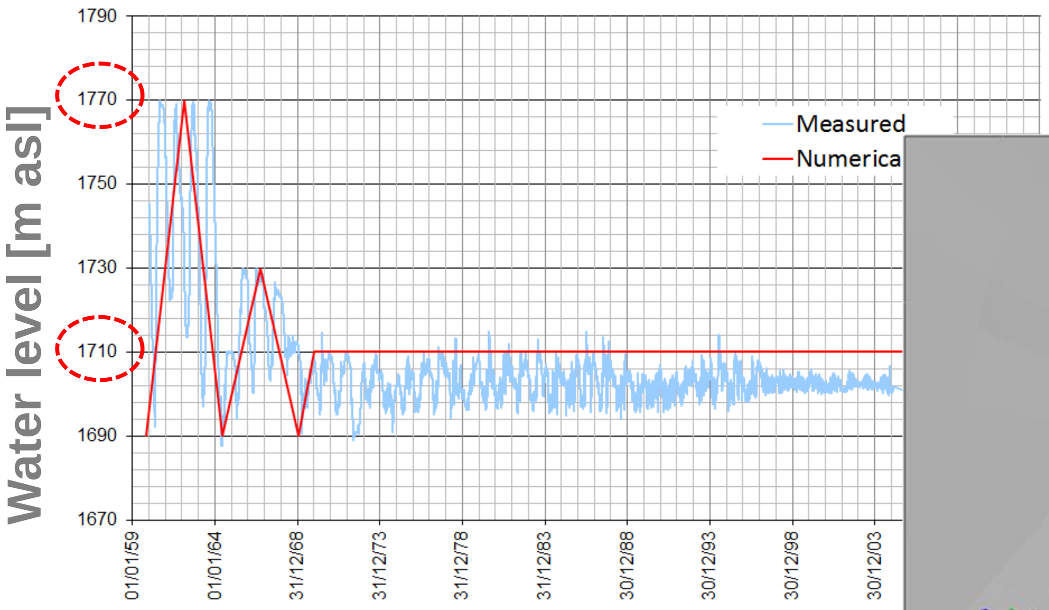
Uniaxial loading in compression

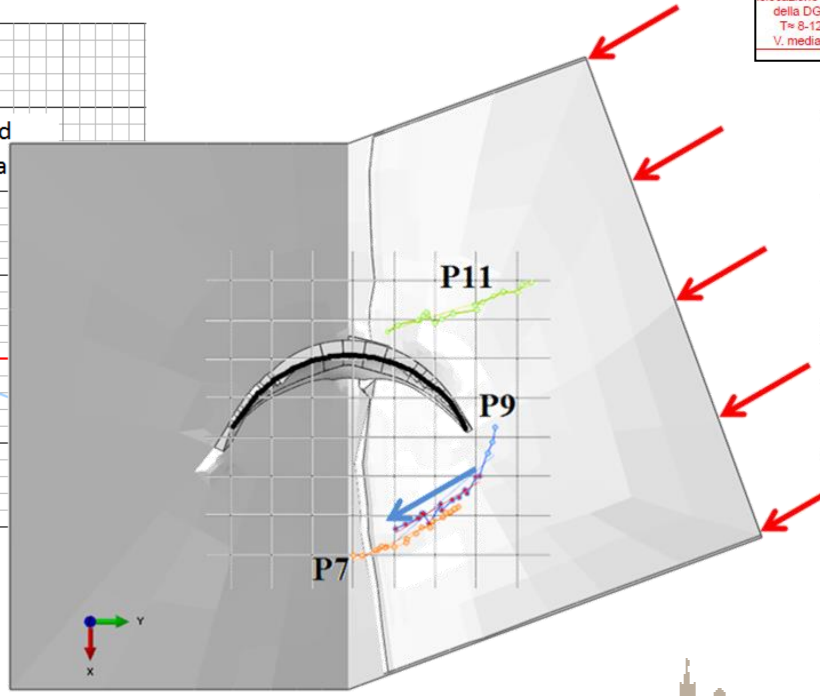


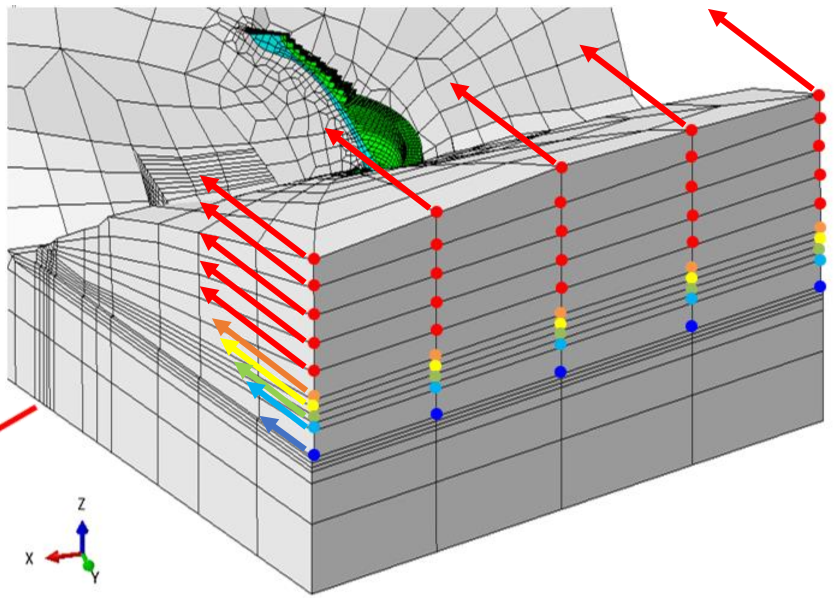
Concrete Damage Plasticity constitutive law for concrete

Data from the monitoring and control systems are important first to set up properly the loading and kinematic conditions of the numerical model

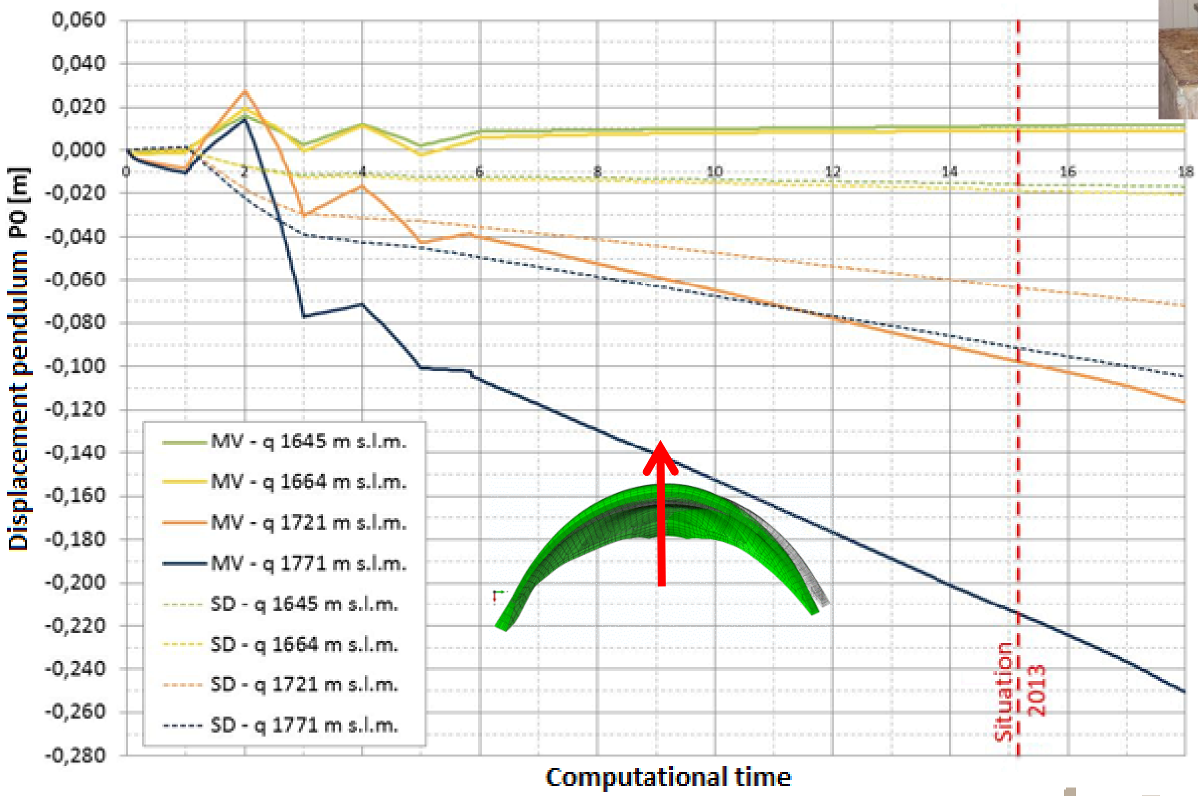


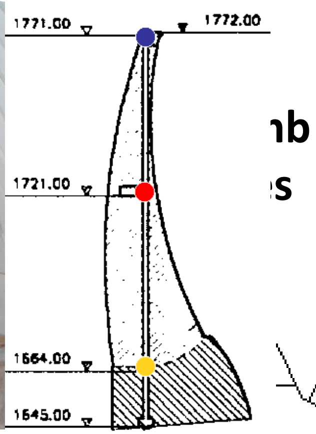


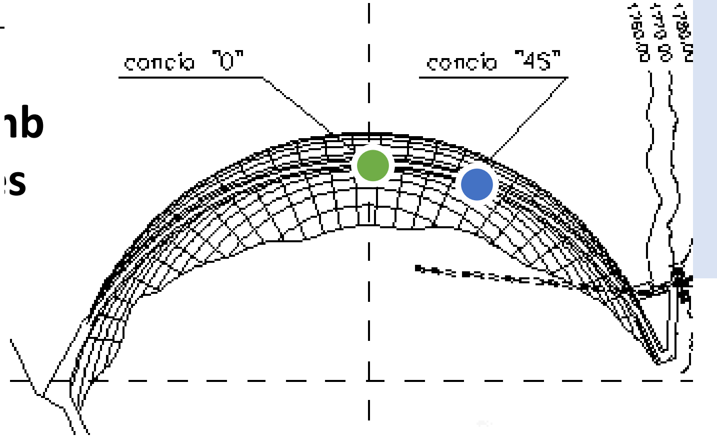


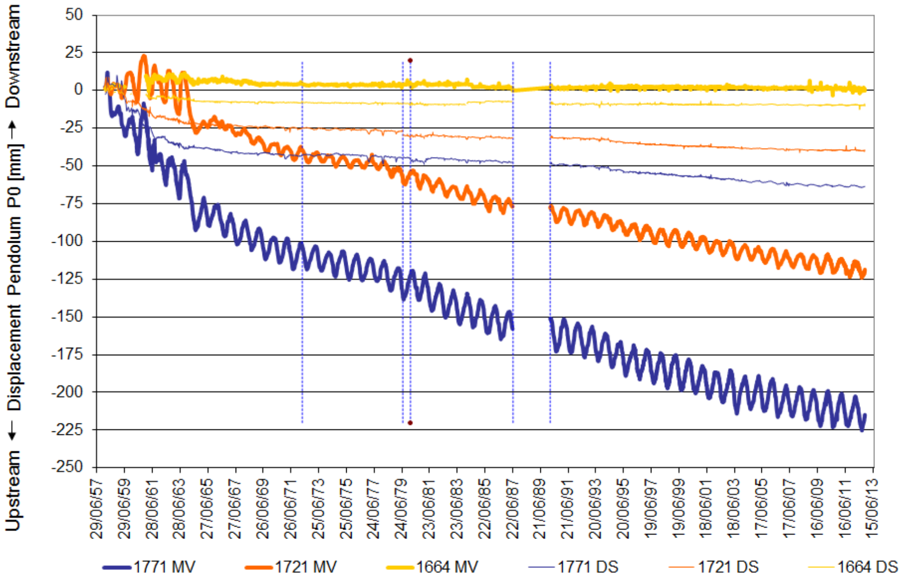


Numerical displacements compared to the measured ones to calibrate the structural response of the numerical model



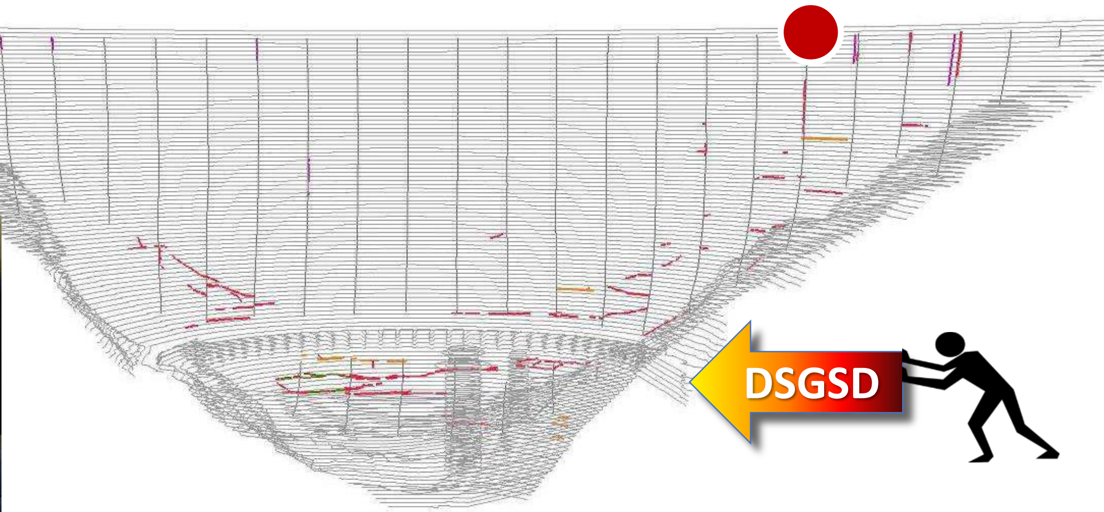


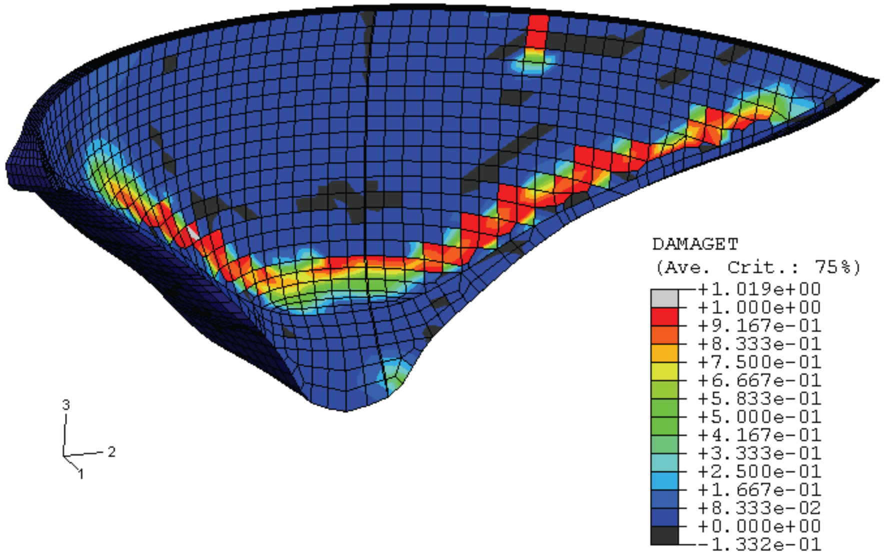


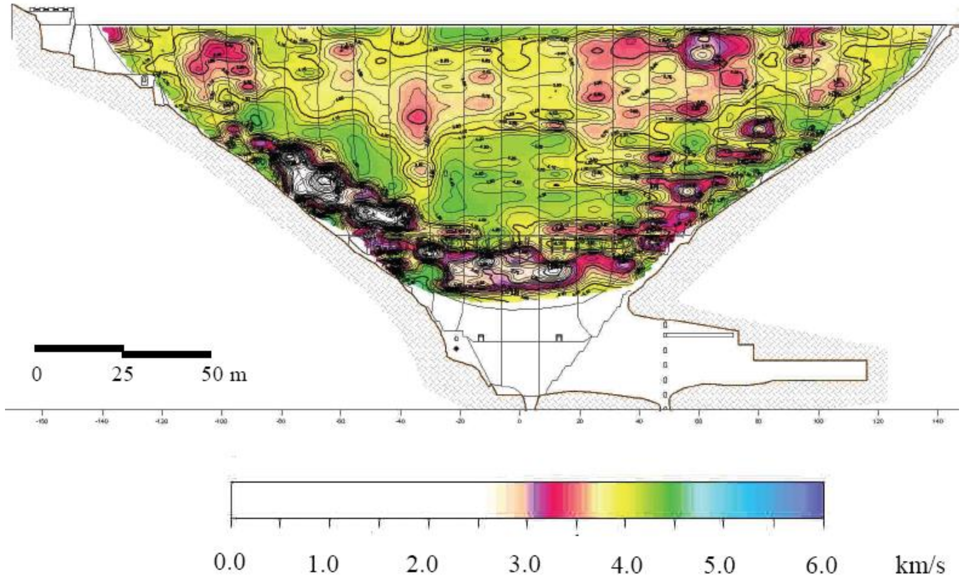


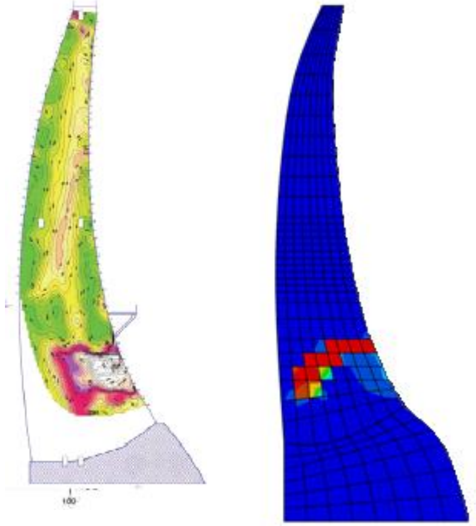
The numerical damage parameter contour was compared with:

1. the cracks detected by visual inspections
2. the P-wave velocity tomography measured on the downstream face and the main vertical section

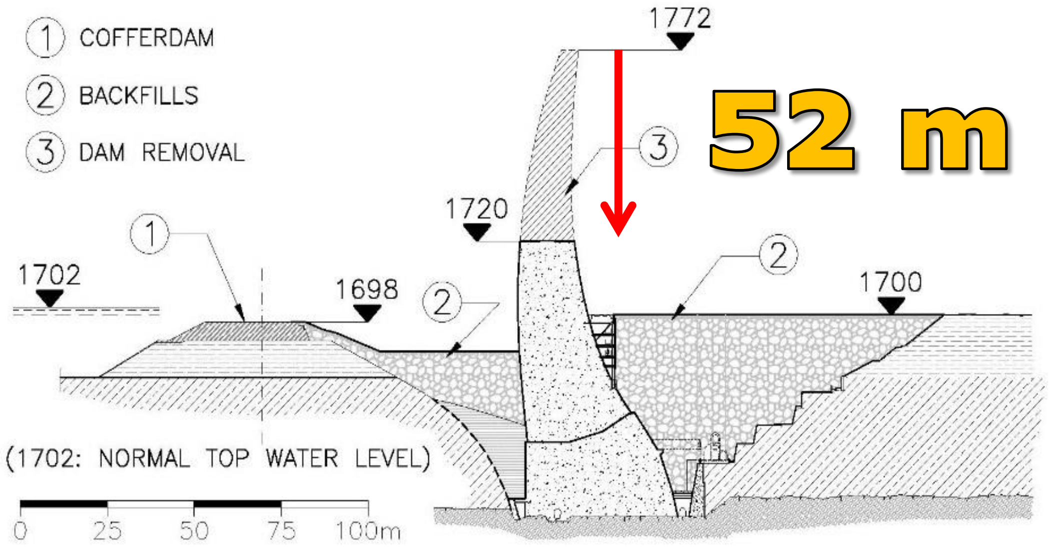








Partial demolition by blasting



ICOLD & CFBR Technical Committee Workshop on Non Linear Modelling of Concrete Dams

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