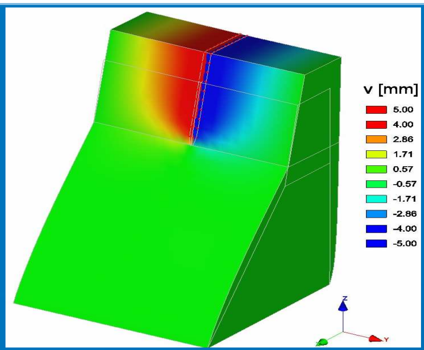

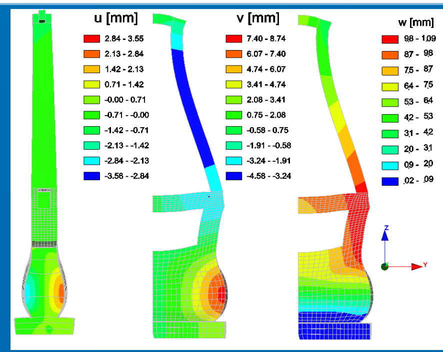

Contact elements, creep and anisotropy for the numerical modelling of concrete structures affected by internal swelling reactions

SSCS – 2012

(Numerical Modeling)

Aix-en-Provence

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STUCKY

IFSTTAR

Outline

- Context and objectives of the study
- Presentation of Software background and developments
- Application to a simple dam structure
  - Effect of stresses on the anisotropy of expansion
  - Compression release due to sawing of dam
  - Effects of basic creep on dam mechanical behaviour
- Conclusions and perspectives

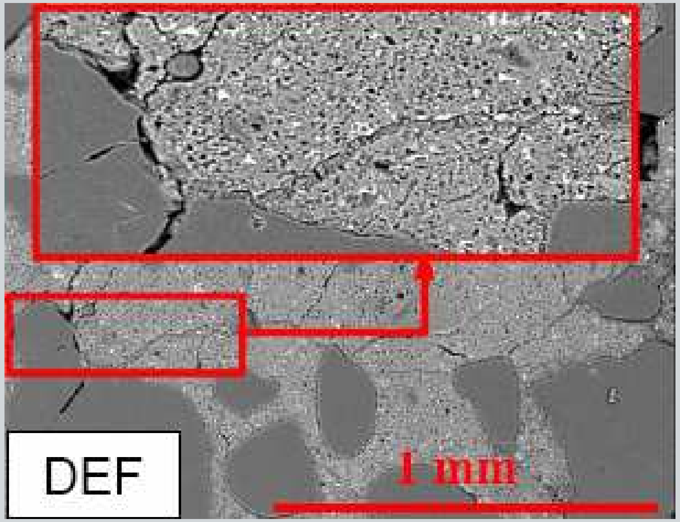
Internal Swelling Reactions

➢ **D**elayed **E**ttringite **F**ormation (**DEF**)

(1978 on precast elements, 1996 for mass concrete)

- Internal reaction: no external (sulphates) reactants
- After heating beyond ~ 65° C
- Late ettringite formation

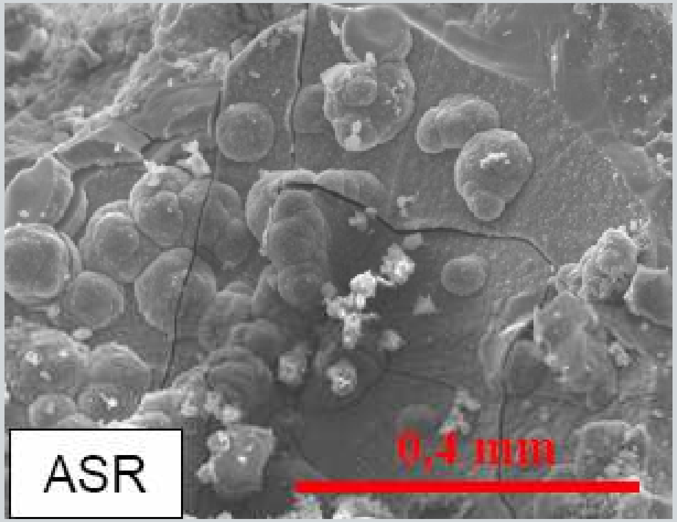
→ Crystallization pressure



➢ **A**lkali-**S**ilica **R**eaction **(ASR)**

(1975 on dams, 1984 on bridges in France)

- Internal reaction
- On aggregate containing reactive silica
- Formation of expansive gels from dissolution of the aggregate silica in presence of alkalis and calcium



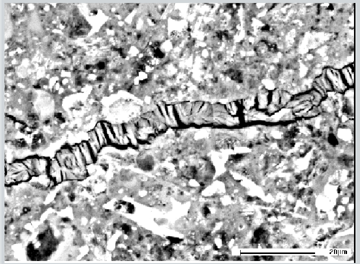
ASR and DEF (sometimes combined) = most of **I**nternal **S**welling **R**eactions (**ISR**)

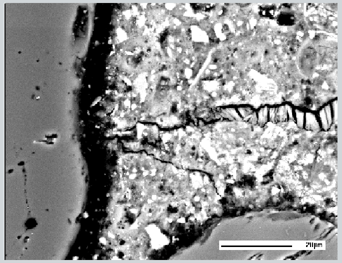
Context and objectives of the study

- A significant number of existing concrete structures are deteriorated by chemo-mechanical processes known as internal swelling reactions (ISR): (DEF and/or ASR).

  Consequences: cracking and expansion of the material which lead to degradation of structures behaviour.

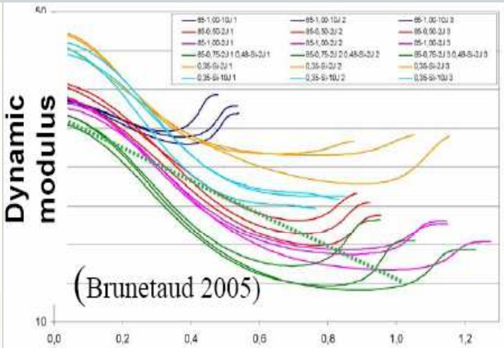
Local effects





Formation of compressed Ettringite in the cracks and propagation to the interface paste / aggregates

Cracking



Stiffness and strength decrease

Effects at the structure scale

Accelerated damage (cracks-induced transfers of aggressive agents)

Large deformations impairing serviceability

Risks on structural integrity

- The development of ISR is influenced by the state of stress in the affected structures (anisotropy of expansion).
- The Ifsttar has developed the RGIB modulus in the CESAR-LCPC FE-code allowing to re-assess ISR affected structures and to predict their mechanical state.

Context and objectives of the study

❖ A novel procedure for modelling displacement discontinuities in ISR-affected concrete structures has been developed, mainly to take into account two types of phenomena where opening of the discontinuity is of relevant concern for the structure management.

1) the modelling of the major isolated cracks opening that result from interactions between pathology and mechanical behaviour of the structure,

2) the possibility of stress release (e.g. by sawing of dams), which covers:

- Creation of cutting lines in the structure, with potential release of excessive compressive stresses.
- Reclosing of the cut as a result of subsequent swelling, thus decrease of the potential efficiency of this technique.

❖ A modification of RGIB within CESAR-LCPC Finite Element program has been implemented for modelling the creep of structures, especially those subject to significant long term loads, such as dams or large pre-stressed concrete structures.

RGIB module

- The mechanical calculation is carried out by using the concept of chemically-induced prescribed strain (ε_χ) resulting from the expansion of the ettringite (DEF) and/or silica gel (ASR) inside the porous media (Li *et al.* 2004, Baghdadi *et al*. 2008).

$$\varepsilon_\chi = \varepsilon_\infty . \xi(t)$$

with

$$\xi(t) = \frac{m(t)}{m_\infty}$$

ε_χ : *Chemical strain*

ε_∞ : *Swelling potential*

$\xi(t)$: *Advancement of swelling reaction*

$m(t)$: *Quantity of gel formed at time* (t)

m_∞ : *Total quantity of gel formed at* $t \longrightarrow \infty$

Chemical expansion

Kinetics

$$\varepsilon_\chi(t) = \varepsilon_\infty \frac{1 - \exp\left(\frac{t}{\tau_c}\right)}{1 + \exp\left(\frac{t}{\tau_c} + \frac{\tau_l}{\tau_c}\right)} \left(1 + \frac{\delta}{\varphi + t}\right)$$

Function shape Advancement law

Corrective term for non-constant asymptote

$$\varepsilon_\infty = \alpha \int_0^{t_m} \phi(t)\, dt \qquad \phi(t) = \begin{cases} 0 & \text{if } T(t) \le T_0 \\ e^{\left(-\frac{E}{R}\left(\frac{1}{T(t) - T_0}\right)\right)} & \text{else} \end{cases}$$

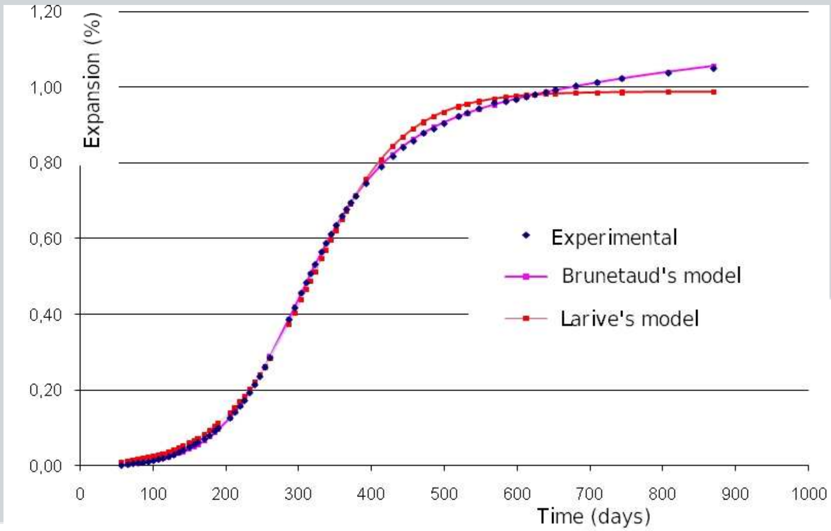
- The advancement of swelling reaction is depending on temperature and saturation degree.

- The adopted chemo-mechanical model is developed in order to predict the mechanical effects of a chemical expansion

$$\sigma = E(\varepsilon - \varepsilon_\chi(t))$$

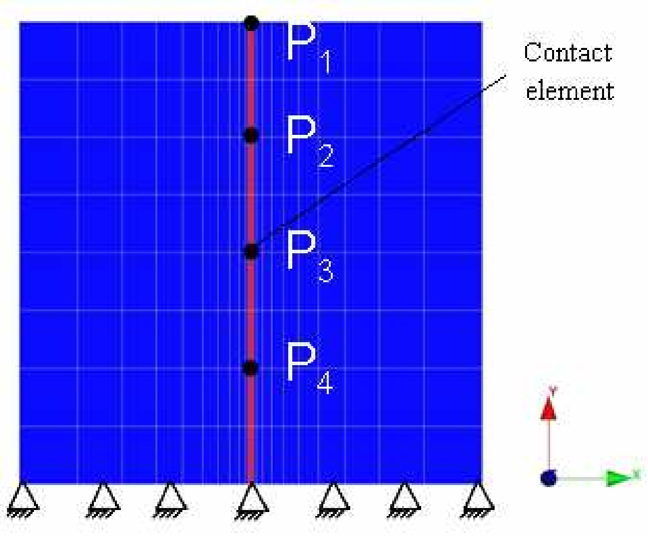
- Effect of stress on the anisotropy of expansion (Baghdadi, 2008)

$$\varepsilon_\chi^{under\ stress} = \varepsilon_{\chi vol}^{free}\, \delta(\sigma_M)\underline{b}$$



TCNL module

➢ The module “TCNL” is based on the method of penalization which was developed in CESAR for contact description using contact elements.



Contact elements have to ensure the continuity of normal and tangential displacements in the interface

They have a weak thickness (not null)

The interface elements have mechanical properties identical to the rest of the structure

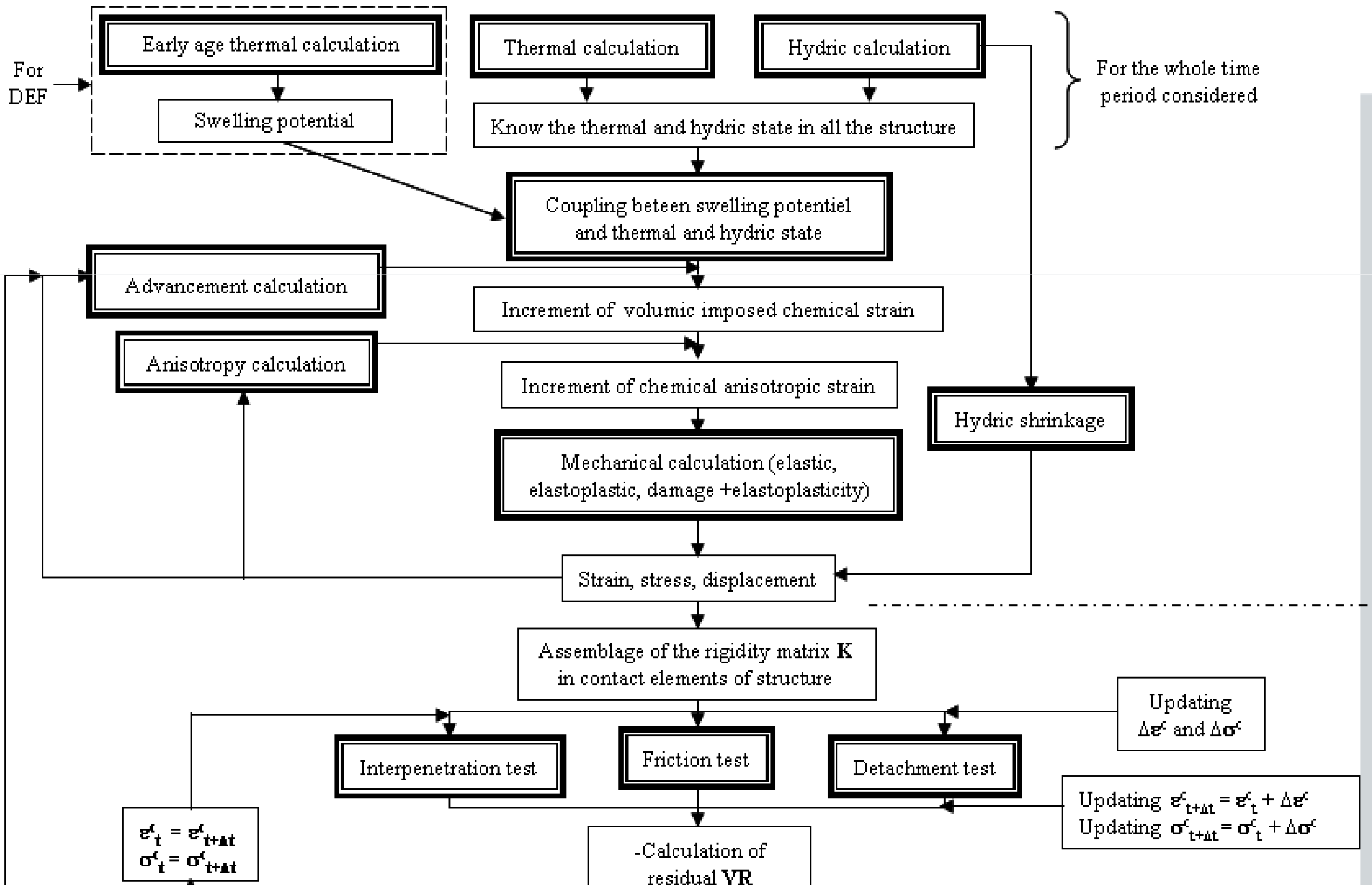
⇒ The same rigidity matrix

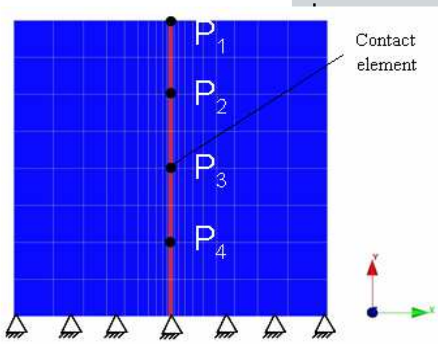
➢ The principle of resolution consists in proceeding to a progressive loading in order to follow the evolution of the effective surface of contact.

➢ For each iteration step, we proceed to three tests:

- a test of non-interpenetration
- a test on the normal stress
- a test of friction

RGIB module





General procedure for a single-solid mesh

Contact

Integration of basic creep in RGIB-Module

➢The basic creep model derives from Granger (1995) and usual shape of creep kinetics in French and European design codes (NF EN 1992-2).

Coupling with saturation degree

$$\underline{\underline{\varepsilon_{fp}}} = E \cdot d\underline{\underline{\varepsilon}}_e \cdot J(t, E, T, h) + E \cdot \underline{\underline{\varepsilon}}_e \cdot \left(\frac{\partial J}{\partial t} \cdot dt + \frac{\partial J}{\partial h}\, dh + \frac{\partial J}{\partial T} \cdot dT + \frac{\partial J}{\partial E} \cdot dE \right) - d\underline{\underline{\varepsilon}}_e$$

Thermal creep

Coupling with ISR

$$J = \frac{1}{E} + h \cdot \frac{T - 25}{45} \cdot \frac{k_{fp}}{E\sqrt{fc}} \cdot \frac{\sqrt{t - t_0}}{b + \sqrt{t - t_0}}$$

Instantaneous + delayed compliance

saturation

Thermal amplification

Elasticity

Effect of concrete mix-design

Kinetics-after AFREM-EN1992-2 model (asymptotic)

t *= time (days)*

t_0 *= loading time (days)*

T *= absolute temperature (Kelvin)*

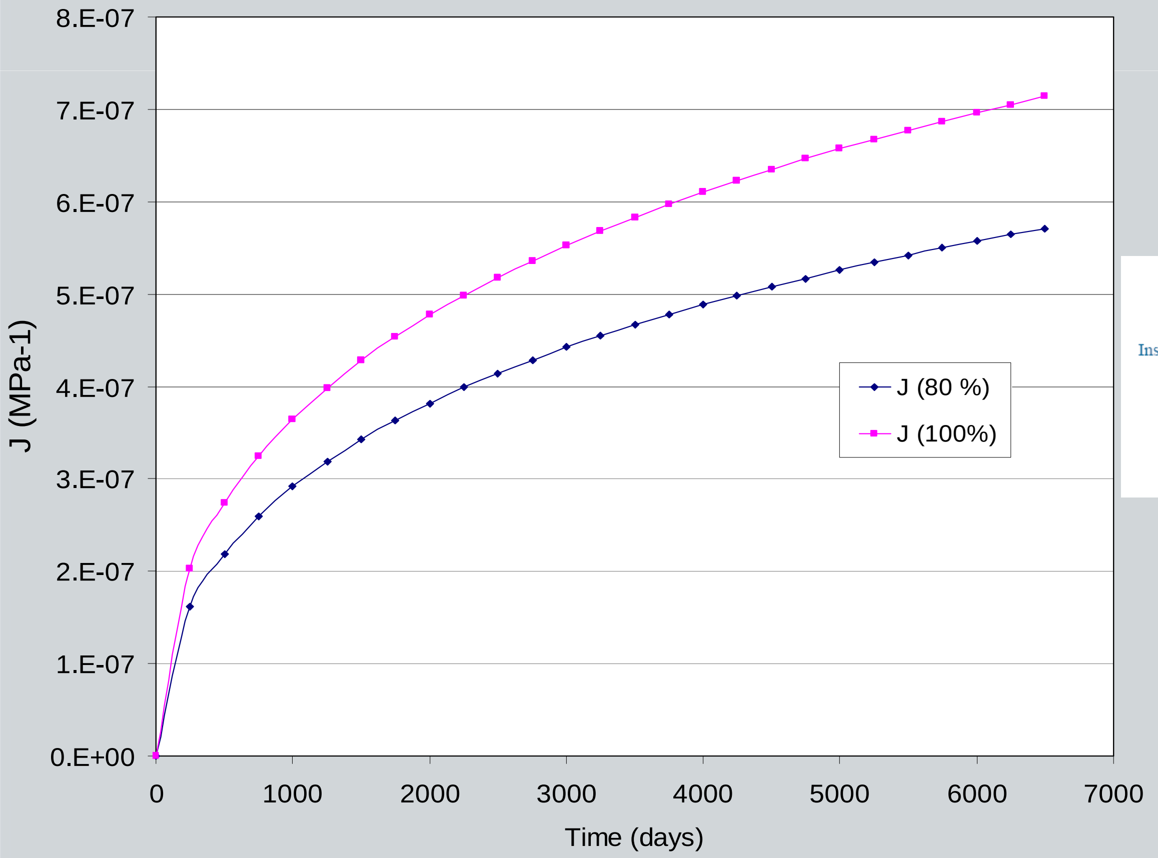
E *= Young's modulus (GPa) which decreases due to ASR / DEF development*

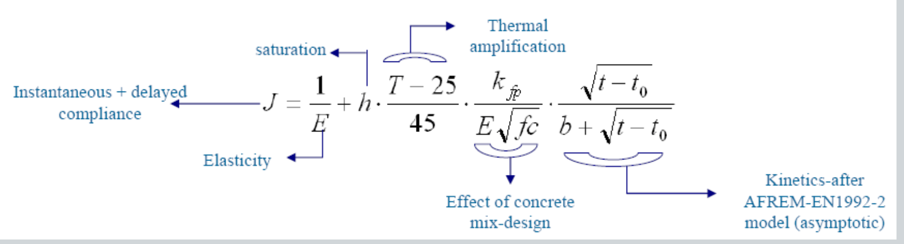
f_c *= compressive strength (MPa)*

The term ***b*** *(square root of days) and k_{fp} coefficient shall be calibrated.*

Integration of basic creep in RGIB-Module

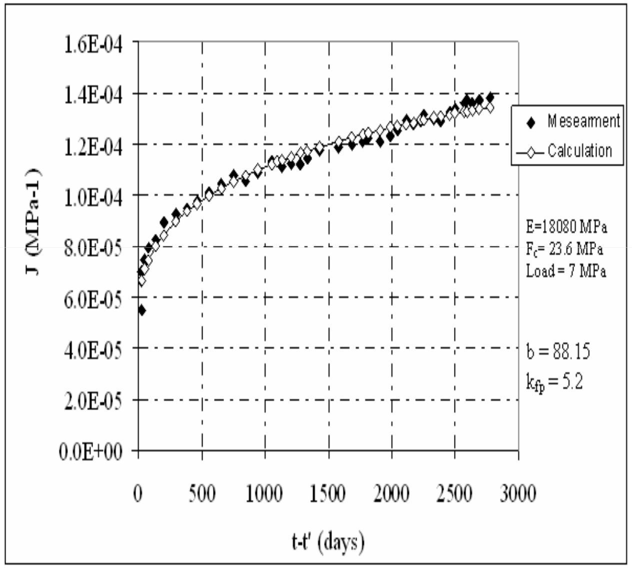
Effect of relative humidity on the evolution of creep function J



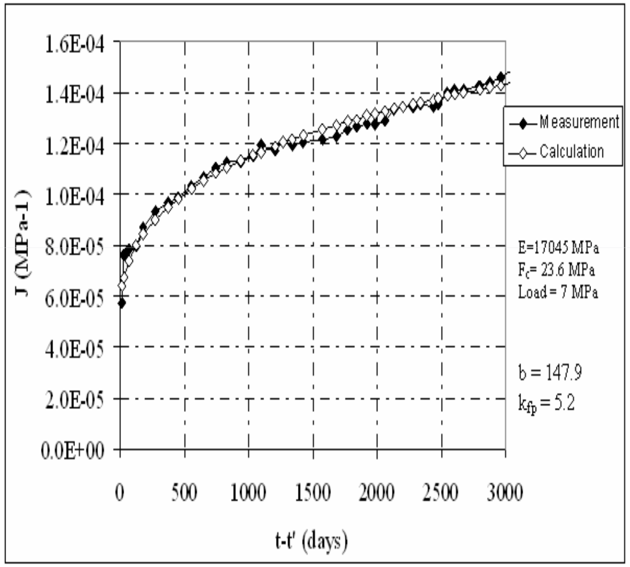


Integration of basic creep in RGIB-Module

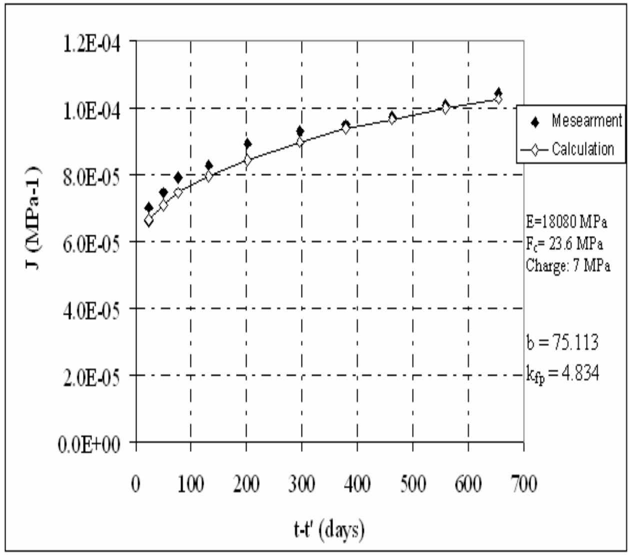
Calibration of parameters K_{fp} and b on long and short term data bases



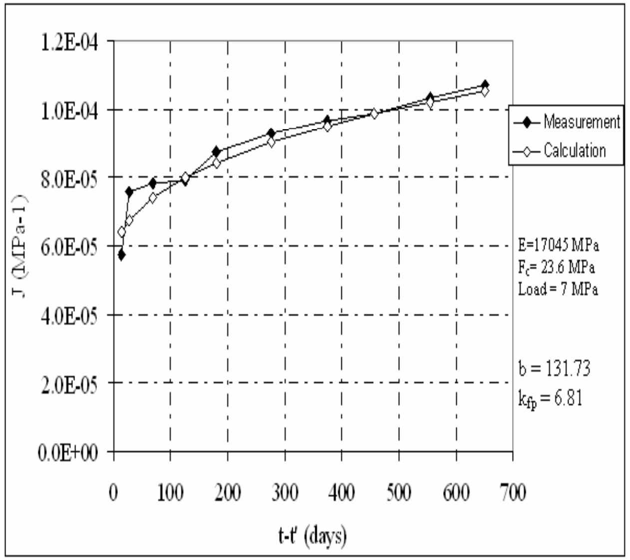
Sample 1: long term kinetics



Sample 2: long term kinetics



Sample 1: short term kinetics



Sample 2: short term kinetics

- ➢ For both cases (short and long term), the curves of function J calculated and measured are almost superimposed.
- ➢ The model gives a good description of the long-term and short-term kinetics of the basic creep of Luzzone dam (Bengougam, 2002).
- ➢ Estimated parameters using 2-years monitoring are reasonably close to the ones fitted with the 10-years data.
- ➢ The results show a robust calibration of the model.

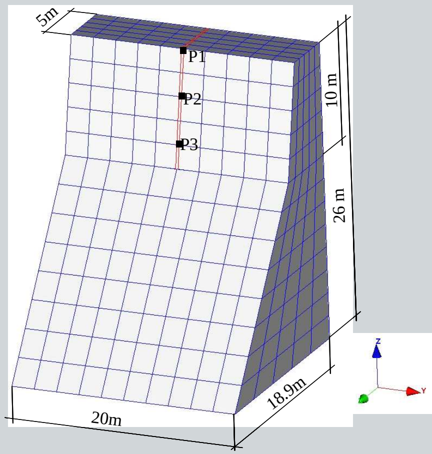
Application to a simple dam structure: Stress release due to sawing of dam

Total of 650 three dimensional elements and 3392 nodes in the entire model are used for finite elements calculations.

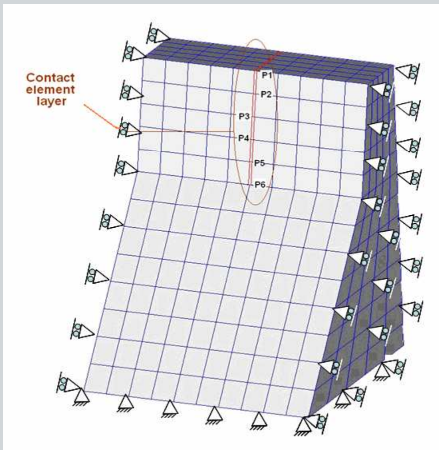
The ambient temperature = 15 ° C and the relative humidity = 100 %

Parameters used for the numerical simulations:

Modelling	E (GPa)	ν	ρ (kg/m^3)	τ_c (months)	τ_L (months)	ε_∞	Duration- analysis (months)	Time steps
Contact elements	30	0.20	2400	60	60	0.0015	480	1 year



Contact elements and boundary conditions in the dam

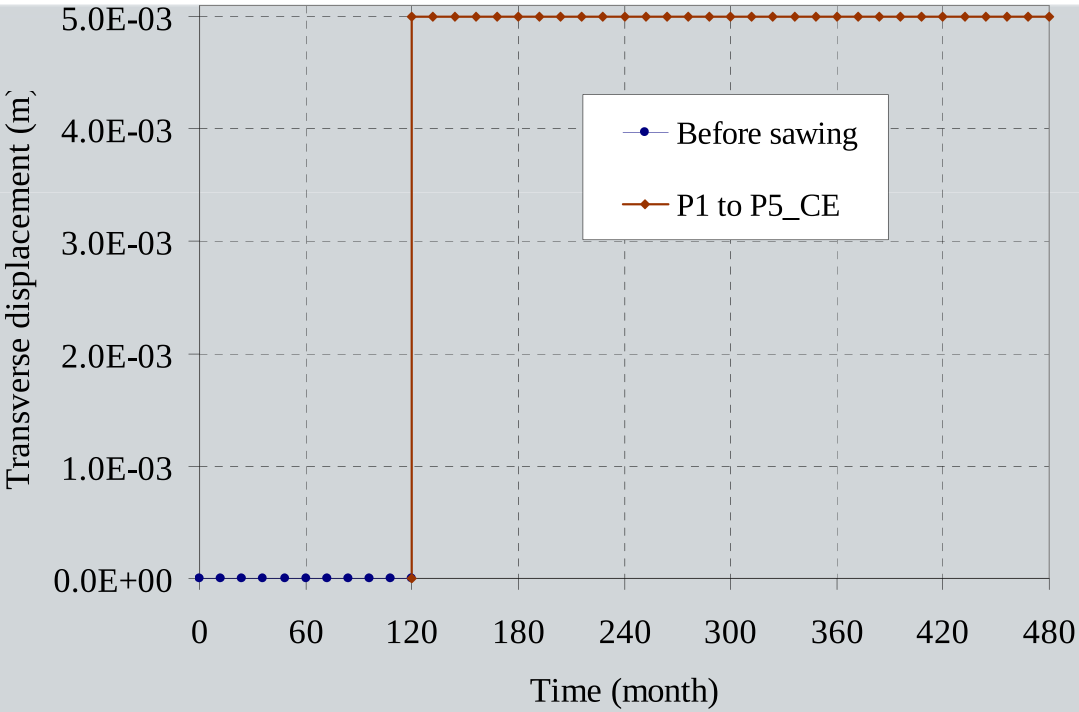


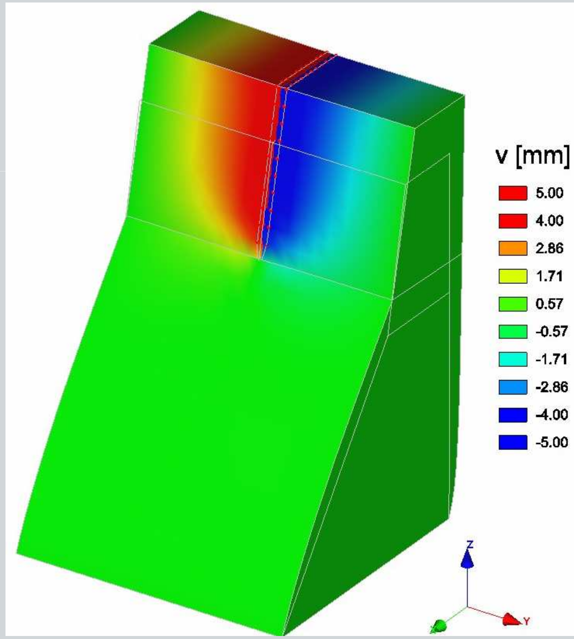
Geometric characteristics of the dam and F.E. mesh

Boundary conditions:

- The transverse displacements were restrained on both sides, while the foundation of the dam was considered as clamped.
- The notch in the dam (thickness = 1 cm) is represented by a contact elements zone (P1 to P6).

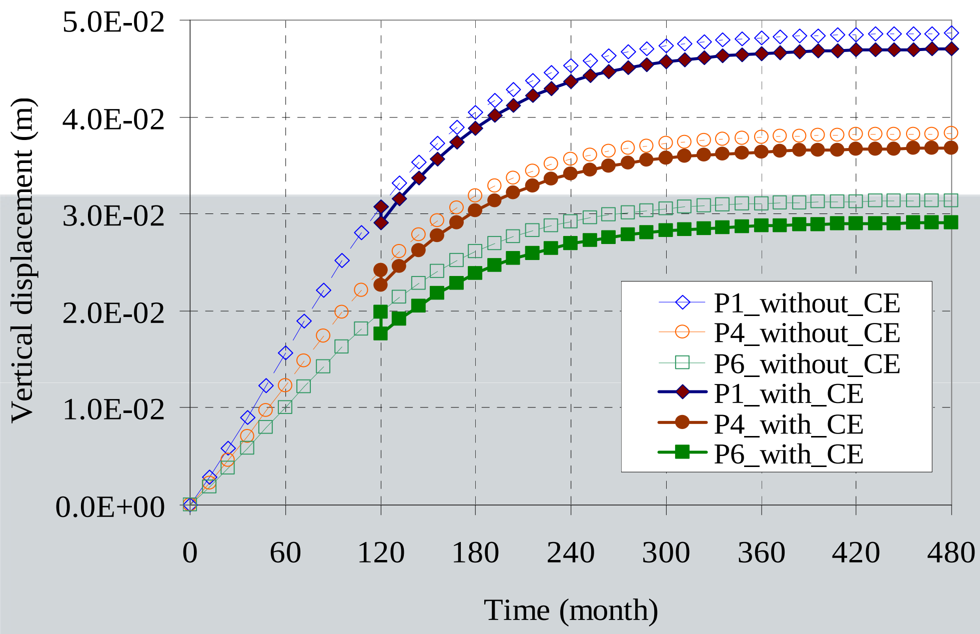
Application to a simple dam structure: Stress release due to sawing of dam



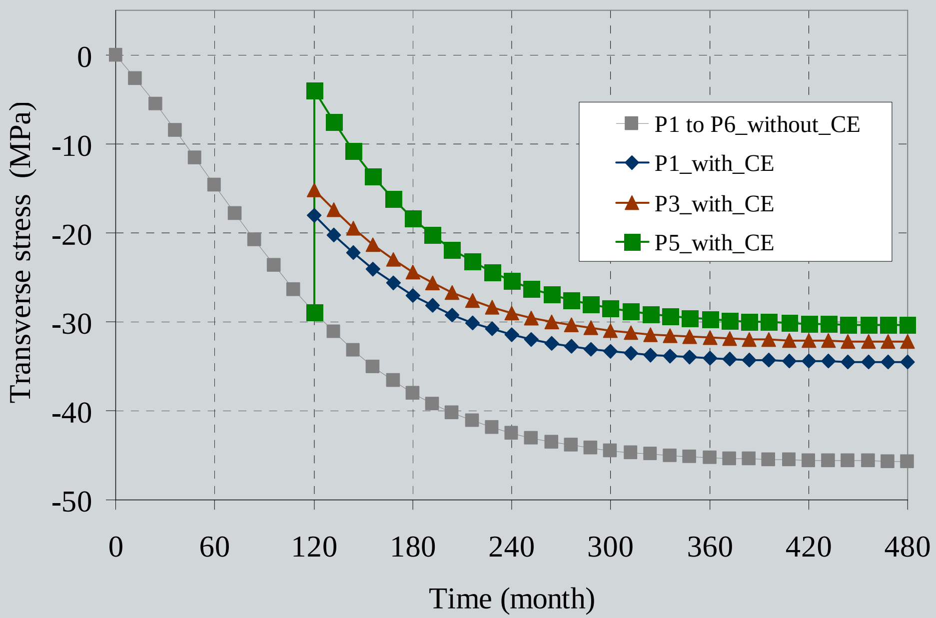


- Transverse displacements are zero for points (P1 to P5) until 10 years.
- After sawing (e = 1 cm), the notch closes instantaneously.
- Displacements on both sides of this notch take exactly the value of the sawing thickness.
- The notch remains open only at point P6 (artefact: connection point between the end of the notch and the solid blocks).

Application to a simple dam structure: Stress release due to sawing of dam



- The vertical displacement increases with time and becomes more important when one approaches the upper surface near the crest for both cases.
- It stabilizes after about 25 years.
- After sawing (10 years), the displacements decrease instantaneously and increase again
- They stay about 5 % lower than the vertical displacements of reference case (without sawing).



- Without sawing, the transverse stress increases with time until its stabilization at a value of $E_c.\varepsilon_\infty^0 = 45\ MPa$
- The stresses decrease instantaneously just after sawing.
- They increase again with time until stabilization at values of 30 to 35 MPa
- The creation of the notch lead to reduce the transverse stress: $\sigma = E.\varepsilon_\infty^0 - E_c.\dfrac{e}{L}$
- The notch at point P6 stays open, which is highlighted by a tensile stress in this zone.

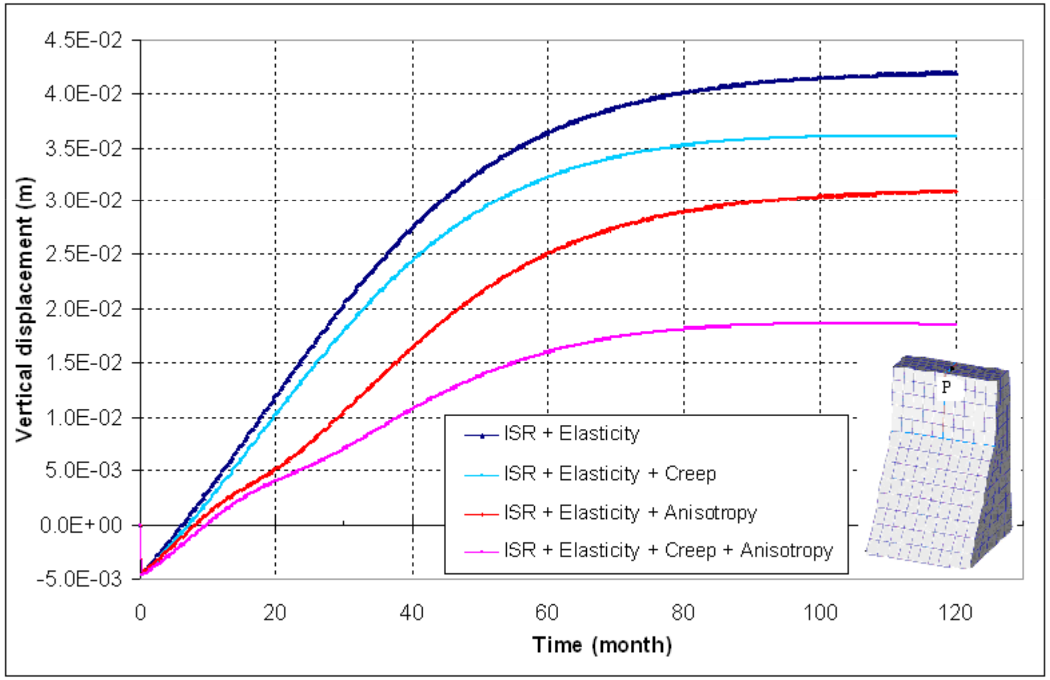
For a correct average estimation of the stress release efficiency the mesh must be refined enough.

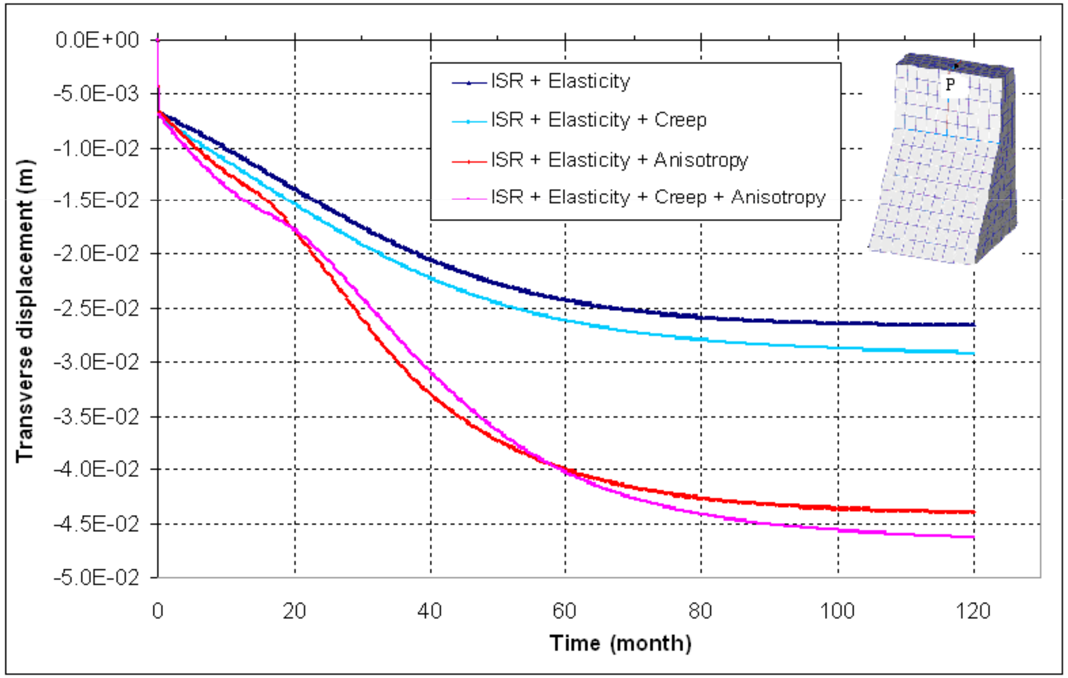
The results highlight that the stress-release by sawing can be effective.

Application to a simple dam structure: Effect of stress on the anisotropy of expansion + creep

Parameters used for the numerical simulations:

f_t (MPa)	E (GPa)	ν	ρ (kg/m^3)	τ_c (months)	τ_L (months)	ε_∞	k_{fp}	b	Duration- analysis (months)	Time steps (days)
3.6	17	0.20	2400	18	18	0.0015	5.2	88	120	6





- ❑ Taking only creep into account leads to 15% lower crest raise after 10 years.
- ❑ Considering anisotropy effects reduces about 26% the vertical displacement because of the influence of stresses caused by the weight of the dam.
- ❑ Crest uplift decreases about 57% when considering both creep and anisotropy effect.
- ❑ A correct analysis of ISR affected structures requires considering all these factors influencing the mechanisms of these pathologies.
- ❑ The results highlight the effect of stress on the anisotropy of expansion
- ❑ They are in perfect agreement with the hypothesis that the state of stress creates a privileged direction of swelling.

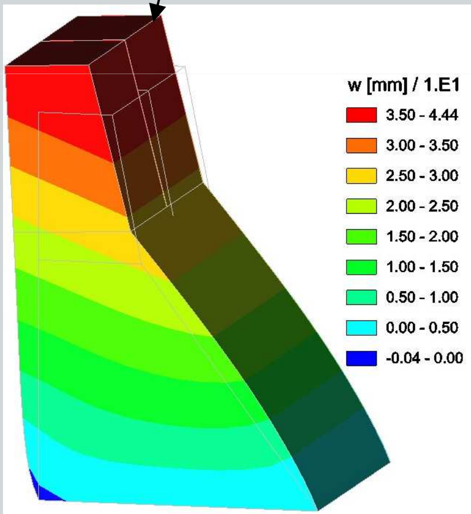
Application to a simple dam structure:
Effect of stress on the anisotropy of expansion + creep

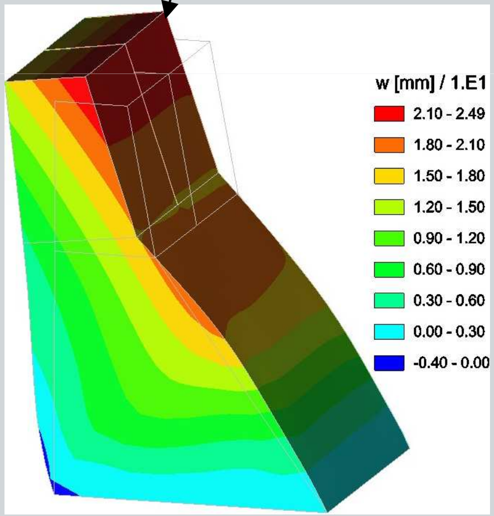
ISR + Elastcity

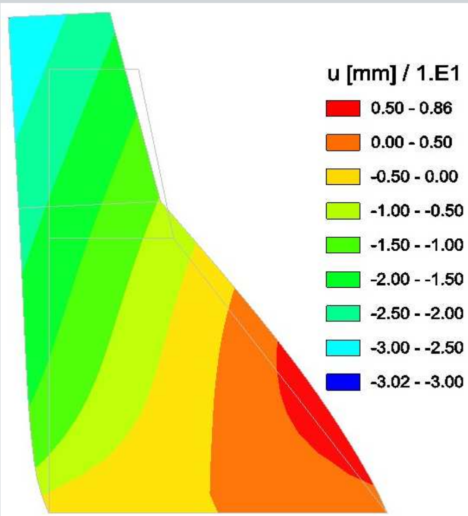
ISR + Elastcity + Creep + Anisotropy

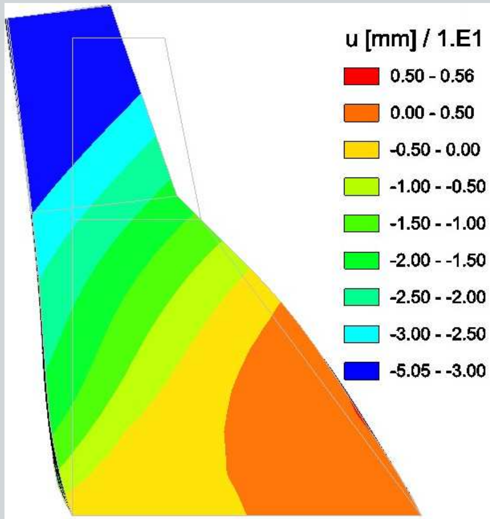
44.5 mm

25 mm



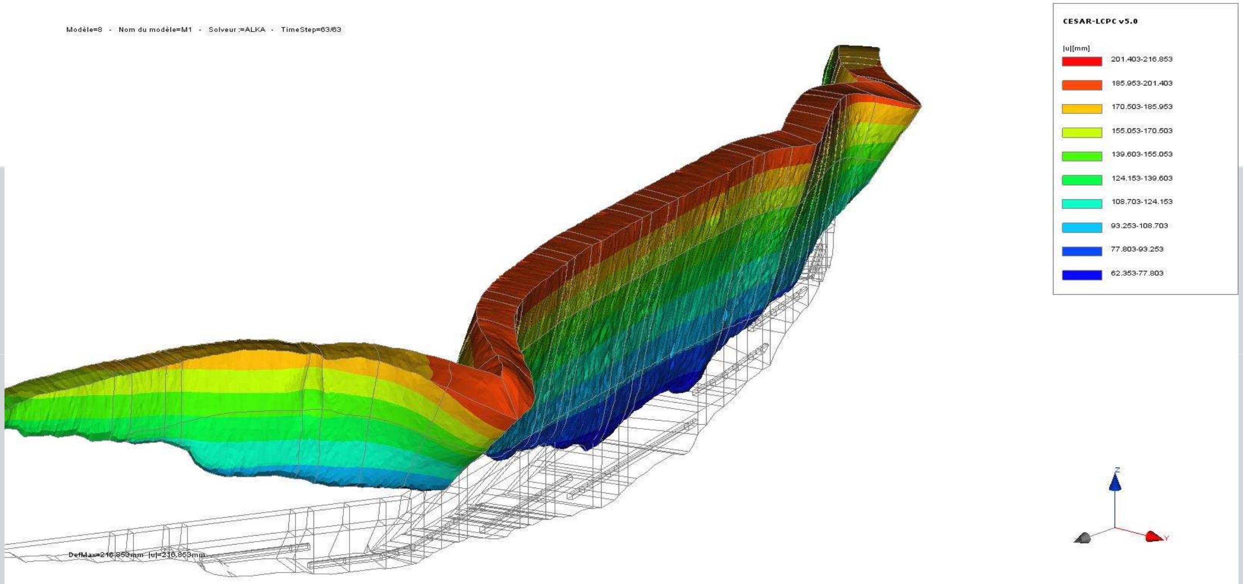




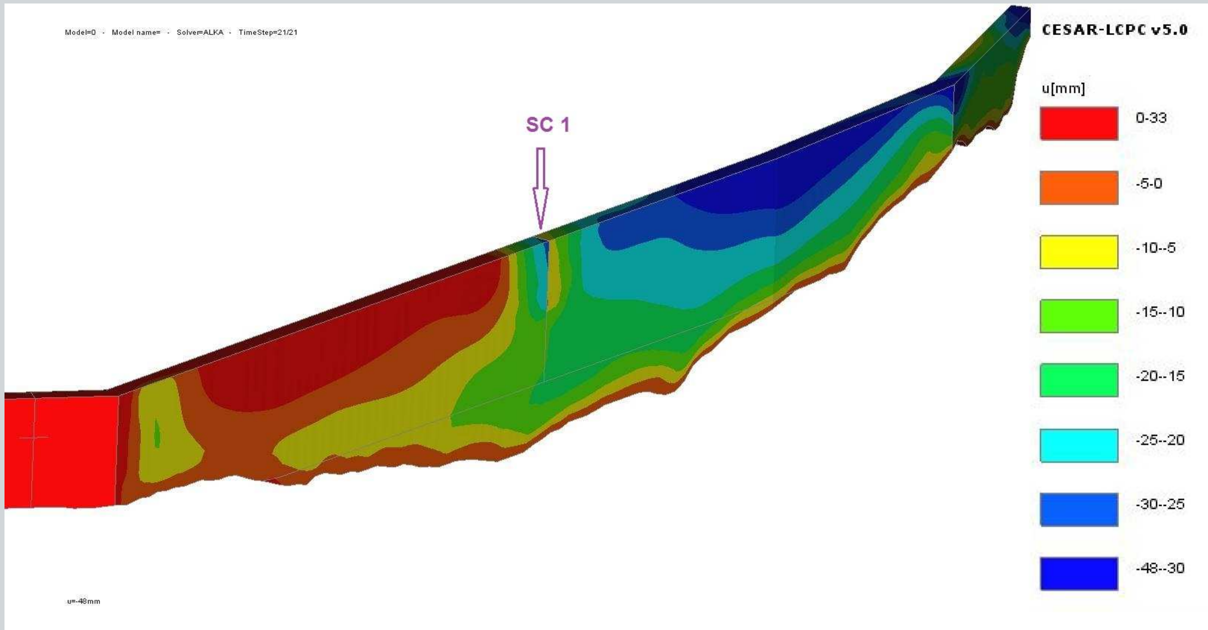


- The vertical displacement at the top of the dam reaches a maximum value of about 44.5 mm without considering the effect of anisotropy and creep.
- this value is reduced to about 25 mm by taking into account these factors.
- In addition to the creep effect, the anisotropy leads to reduce the displacements in the vertical directions.

Application to a real dam structure



Iso-values of displacement after the notch opening



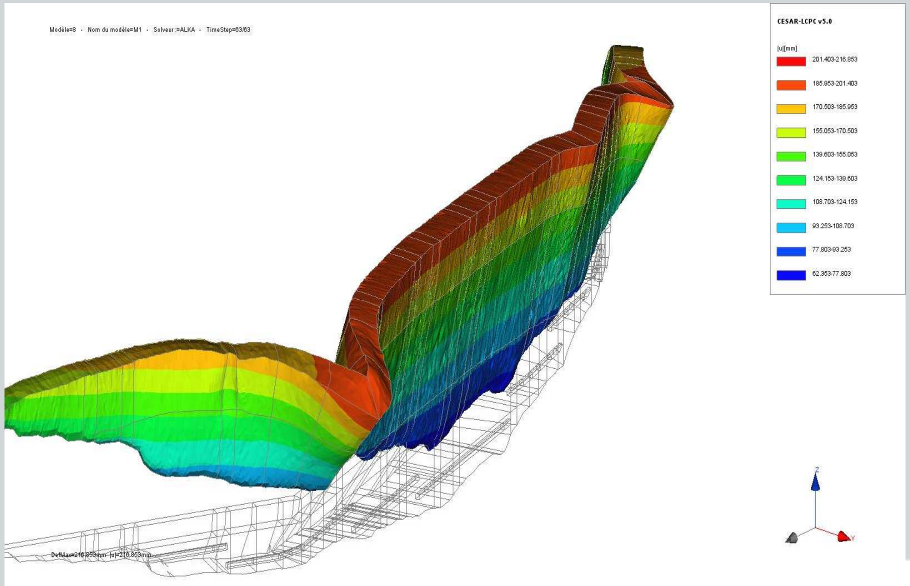
Transverse displacement of the considered dam after 62 years

Conclusions

- The development of new functions of a Finite Element Software has been presented for modelling displacement discontinuities in concrete structures affected by Internal Swelling Reaction (ASR and/or DEF).
- It makes it possible to evaluate the potential efficiency of stress release (e.g. by sawing of dams), it can help the engineer in deciding on the choice of the number of cutting lines and their locations in the structure in order to increase its lifetime.
- This F. E. Software allowed modeling the effect of stresses on the anisotropy of expansion.
- The creep model was integrated in RGIB-module and will improve the physical adequacy of this numerical tool for the reassessment of gravity dams.

→ Experience in progress on real cases (Stucky – Ifsttar partnership)

Thank you for your attention



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