Ingeokring Autumn Symposium: “Salt of the Earth”

The threat of anhydritic formations to civil infrastructures

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Historic center of Staufen

Staufen

Maximum heave rate 11mm/month

Sass & Burbaum, 2010

Known expansive anhydritic formations in Central Europe

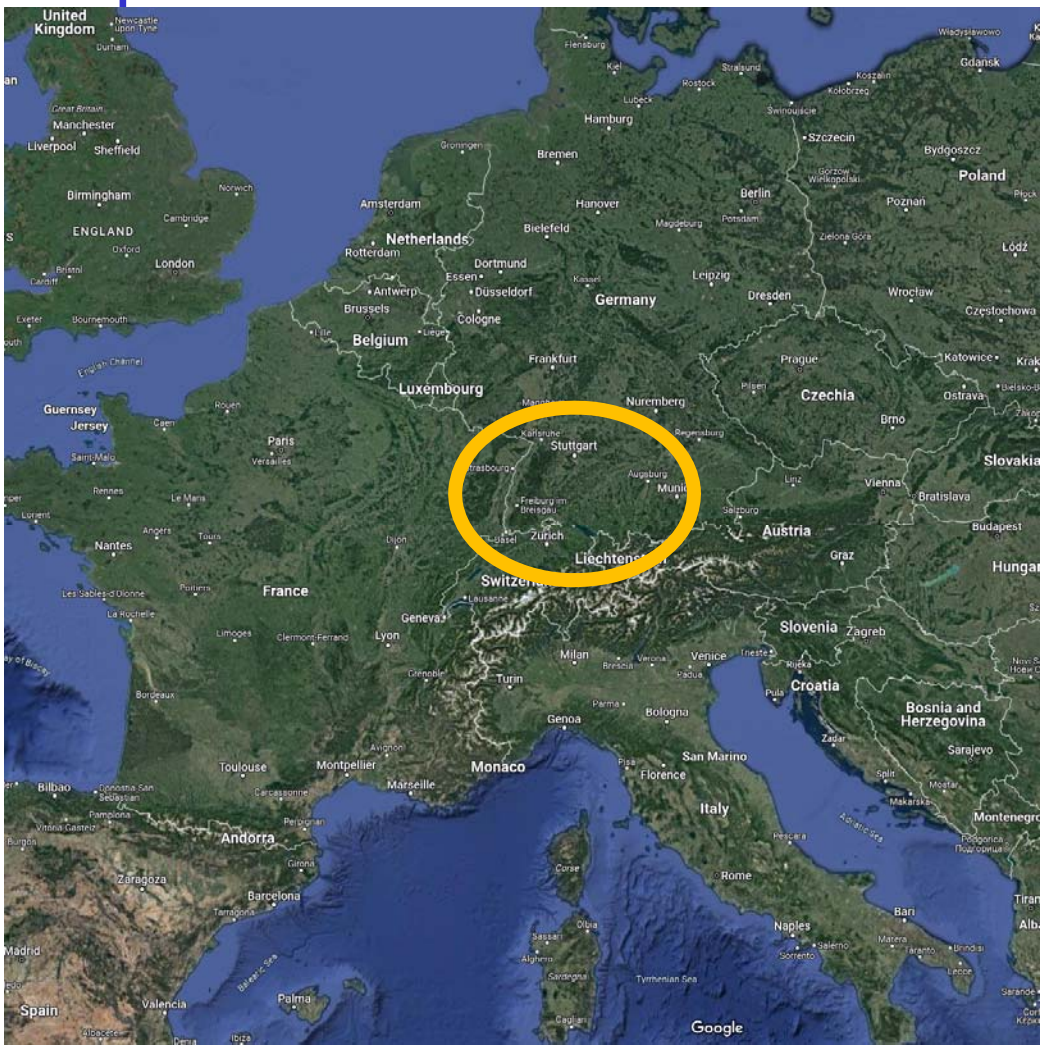
Sulphated rock formations of Tertiary age:
Keuper and "anhydritgruppe"

Baden-Württemberg (South of Germany)

Wagenburg

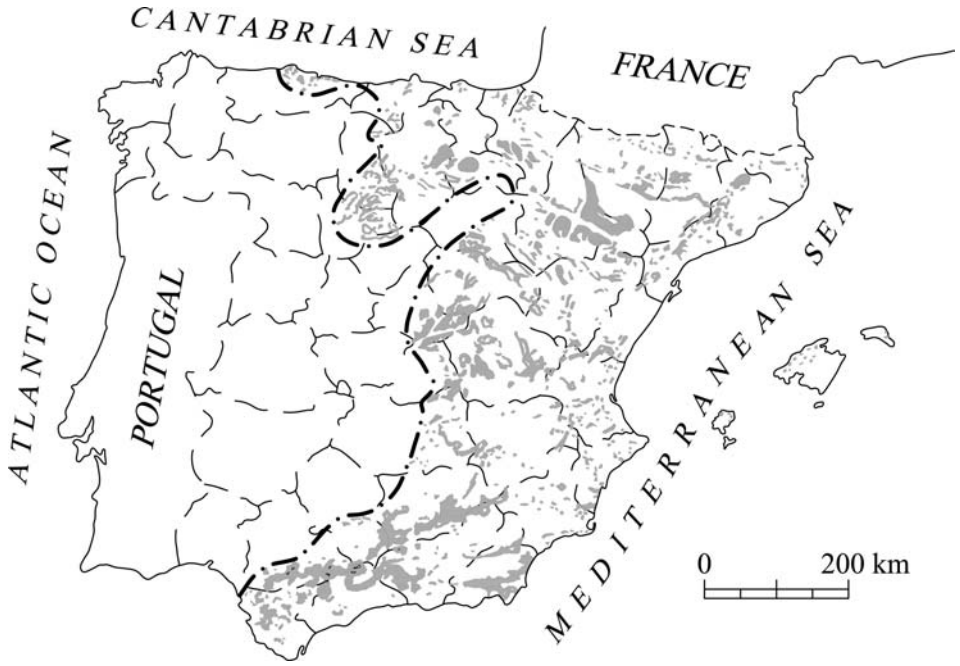
Jura Mountains (North of Switzerland)

Chienberg
Belchen



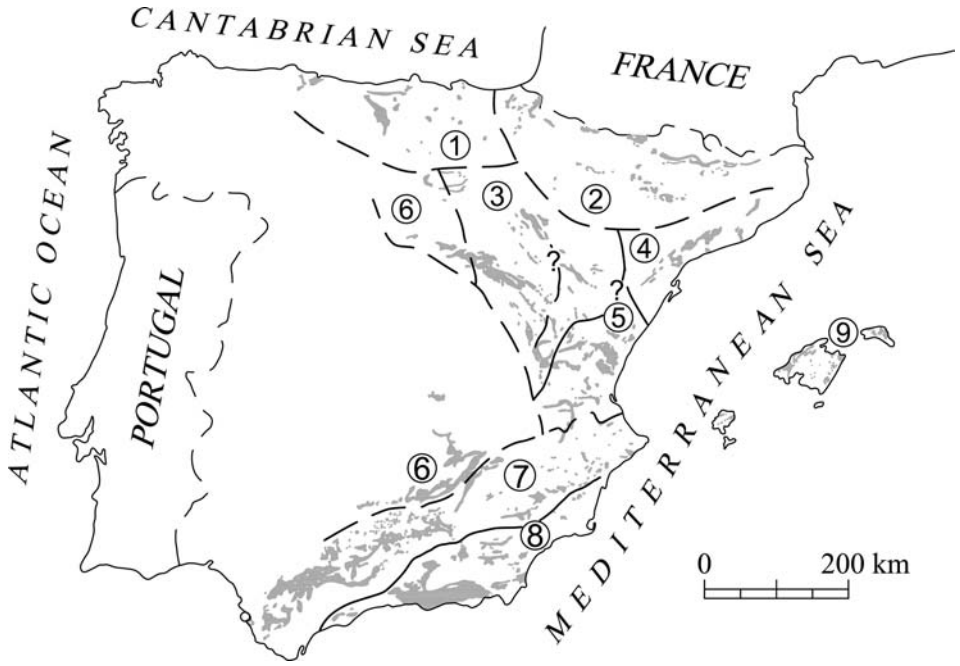
Presence of sulphated formations in Spain

Gypsum outcrops



Riba et al, 1962

Triassic outcrops



IGME, 1962

- *Tertiary formations (Eocene)*
- *Triassic formations (Keuper)*


Sulphated claystones of
Eocene age. Lilla tunnel.
East of Spain (Tarragona)


Sulphated claystones of
Cretaceous age. Albertia tunnel.
North of Spain (Álava)

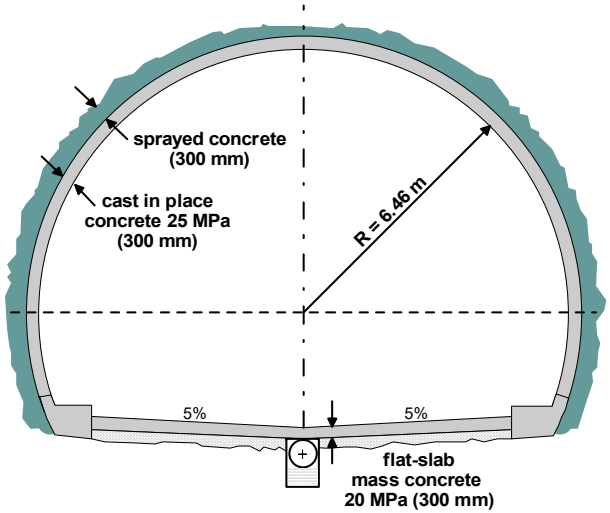
Contents of the presentation

1. Some experiences in anhydritic rocks
2. Swelling mechanism
3. Modelling swelling behaviour. Application to real cases
4. Lessons learned from practice

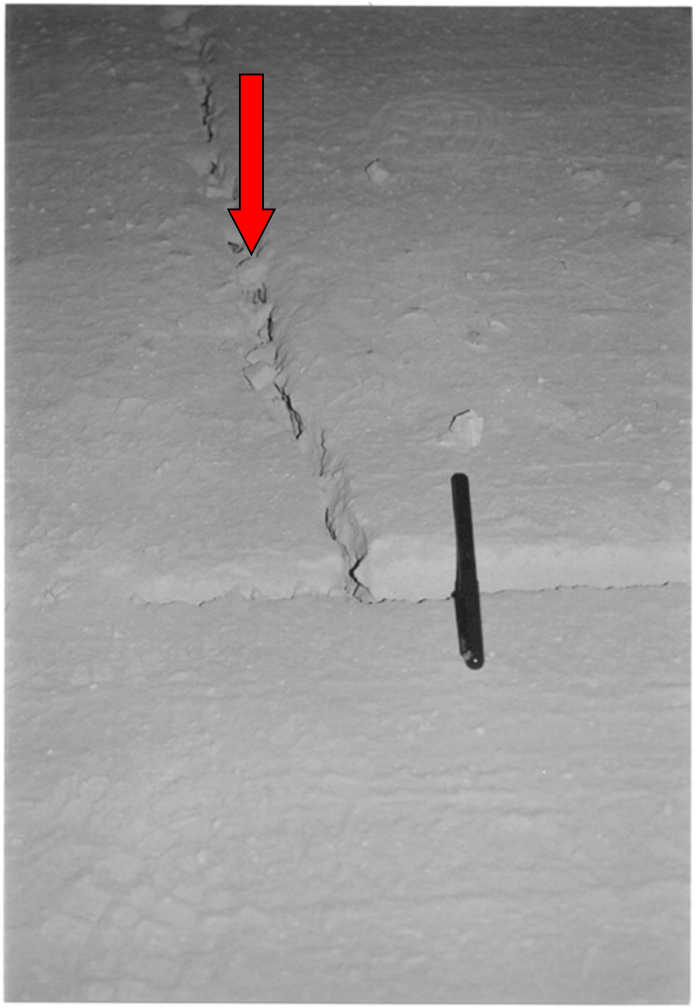
Lilla tunnel. North portal

Floor slab of Lilla tunnel

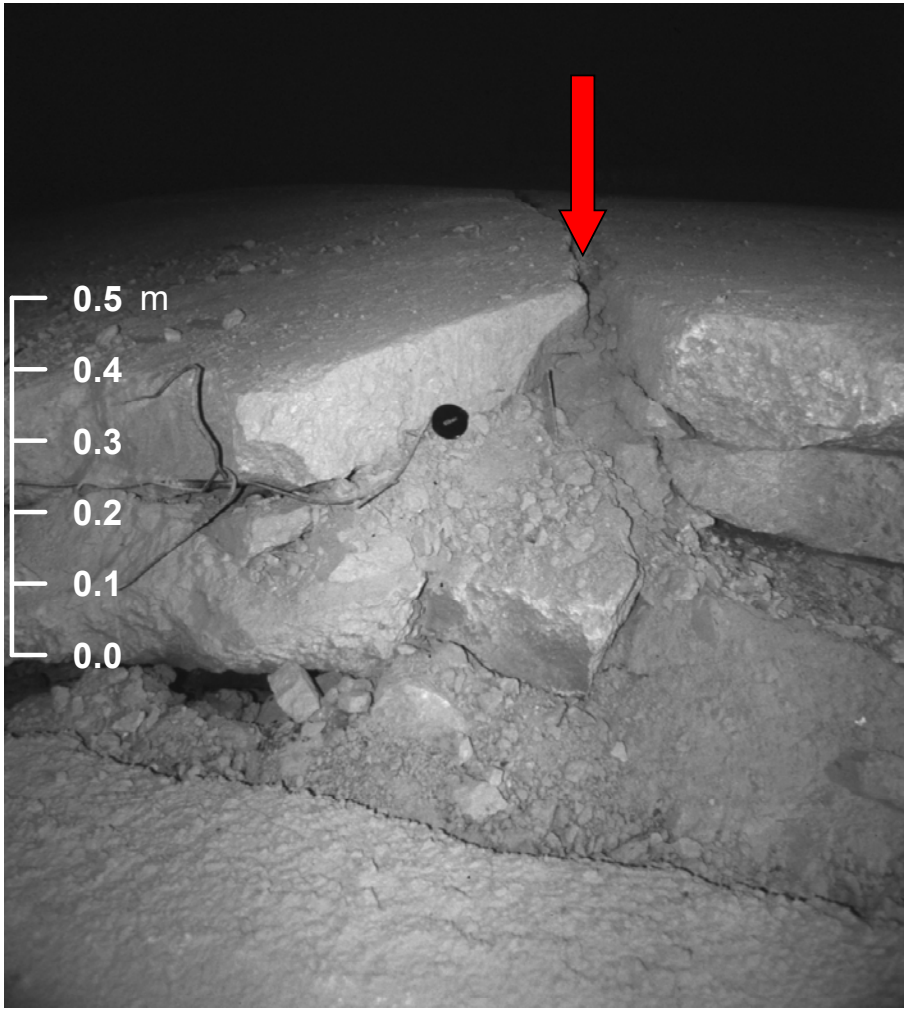
(a few months after the end of construction)



Expansive Phenomena in Flat Slab floor



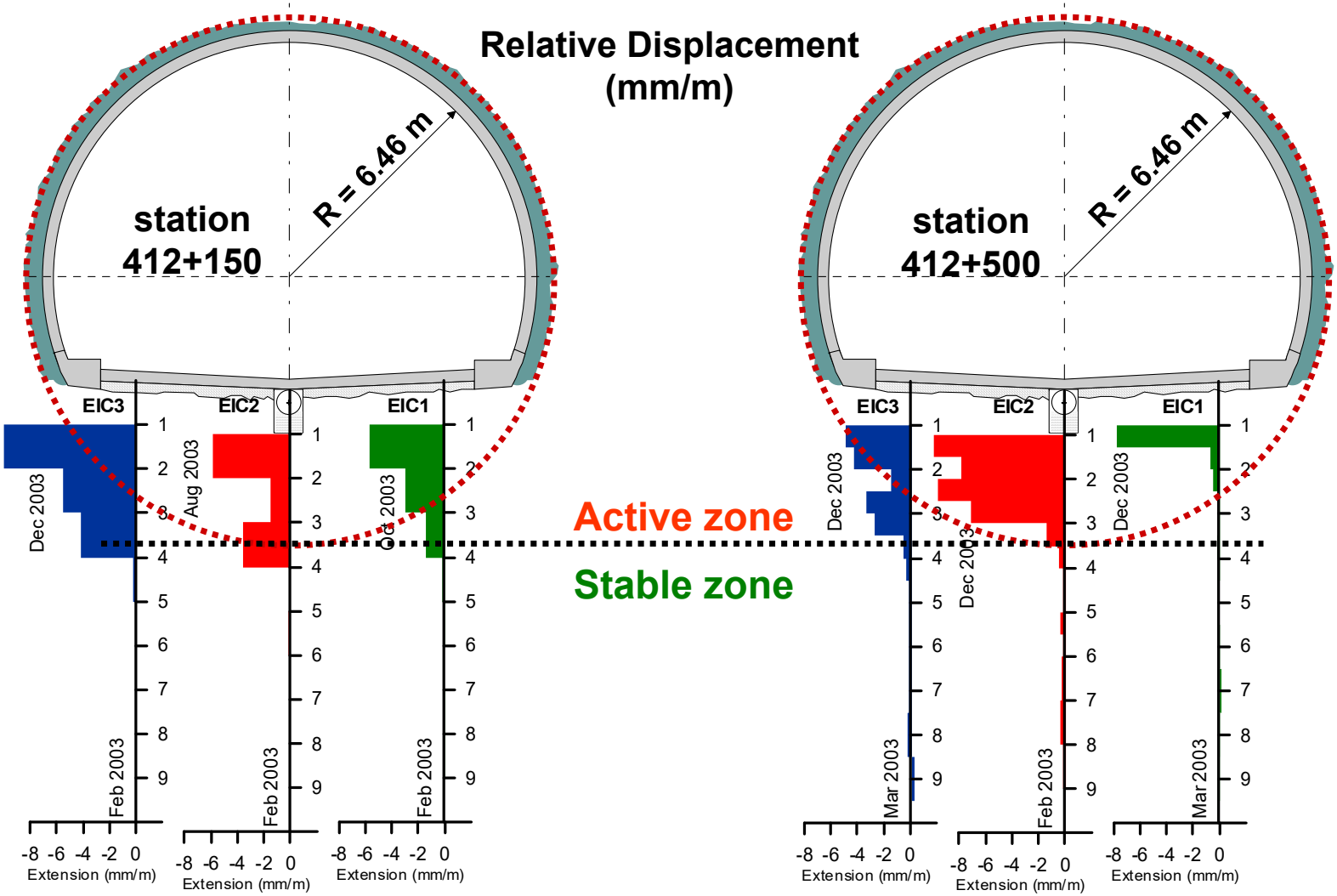
March 2003



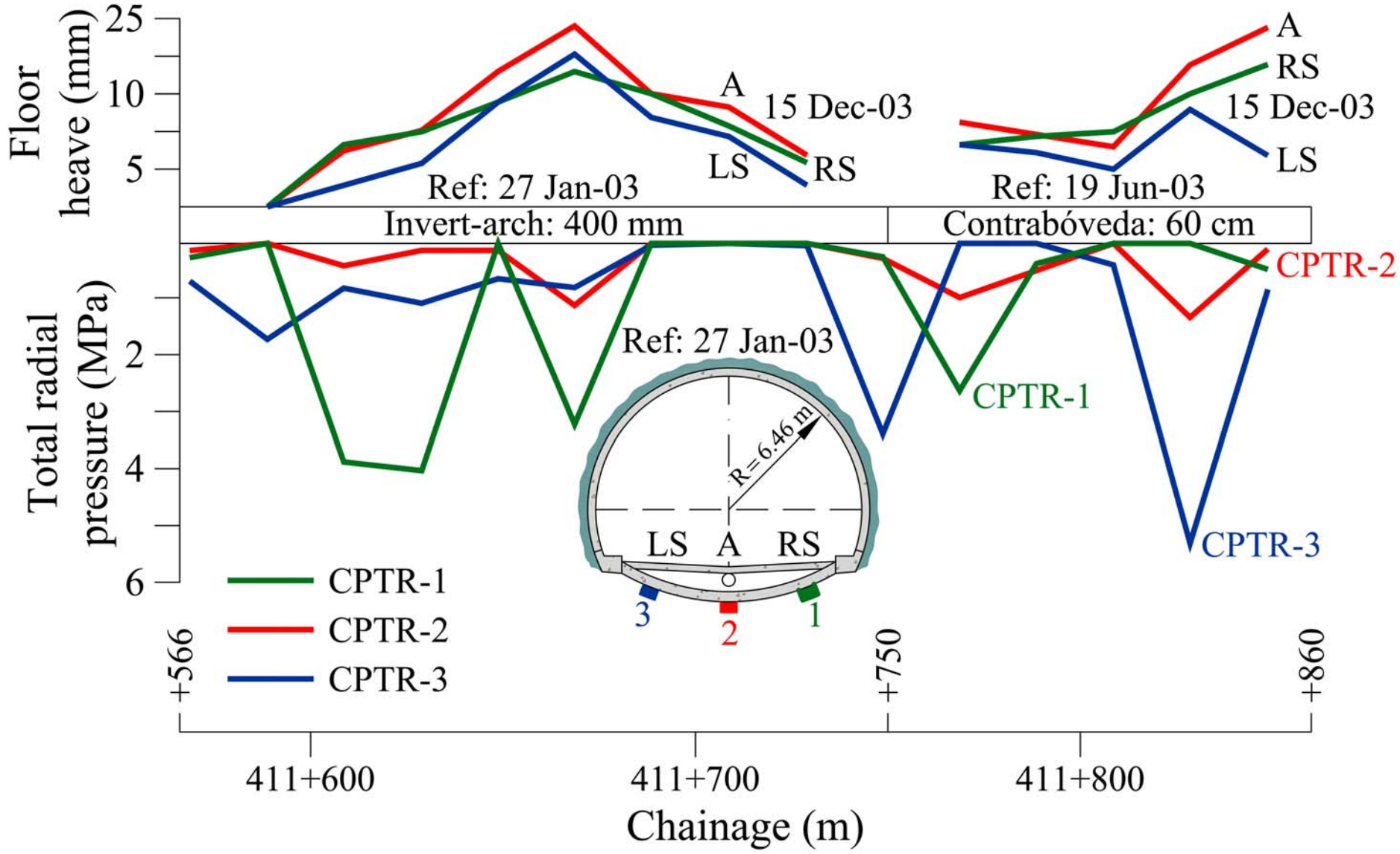
September 2003

Sliding Micrometer's records

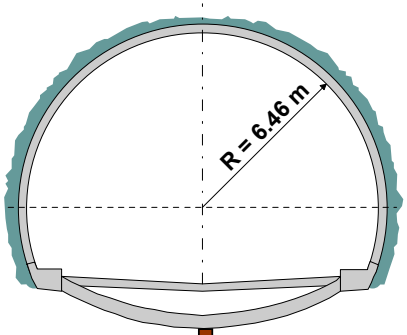
February 2003 – December 2003



Heave and total radial pressure. Curved invert. January 2003 – December 2003



Field observations

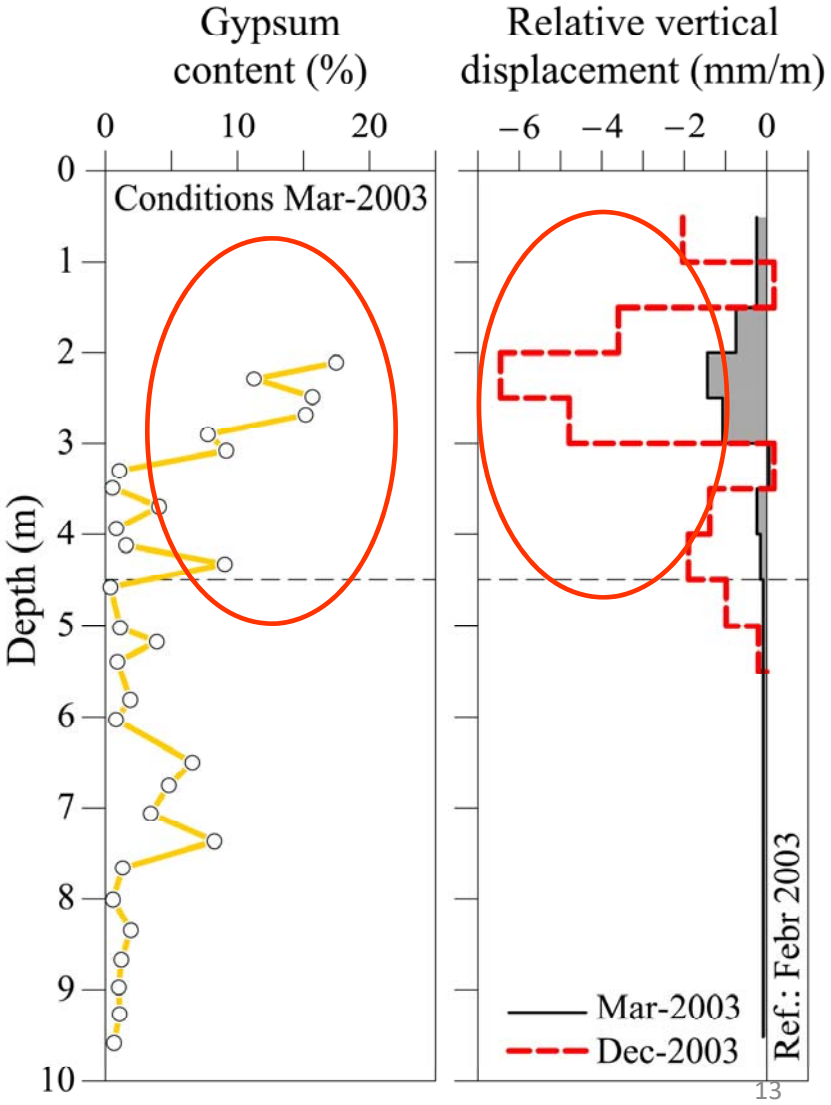


Active zone

Stable zone

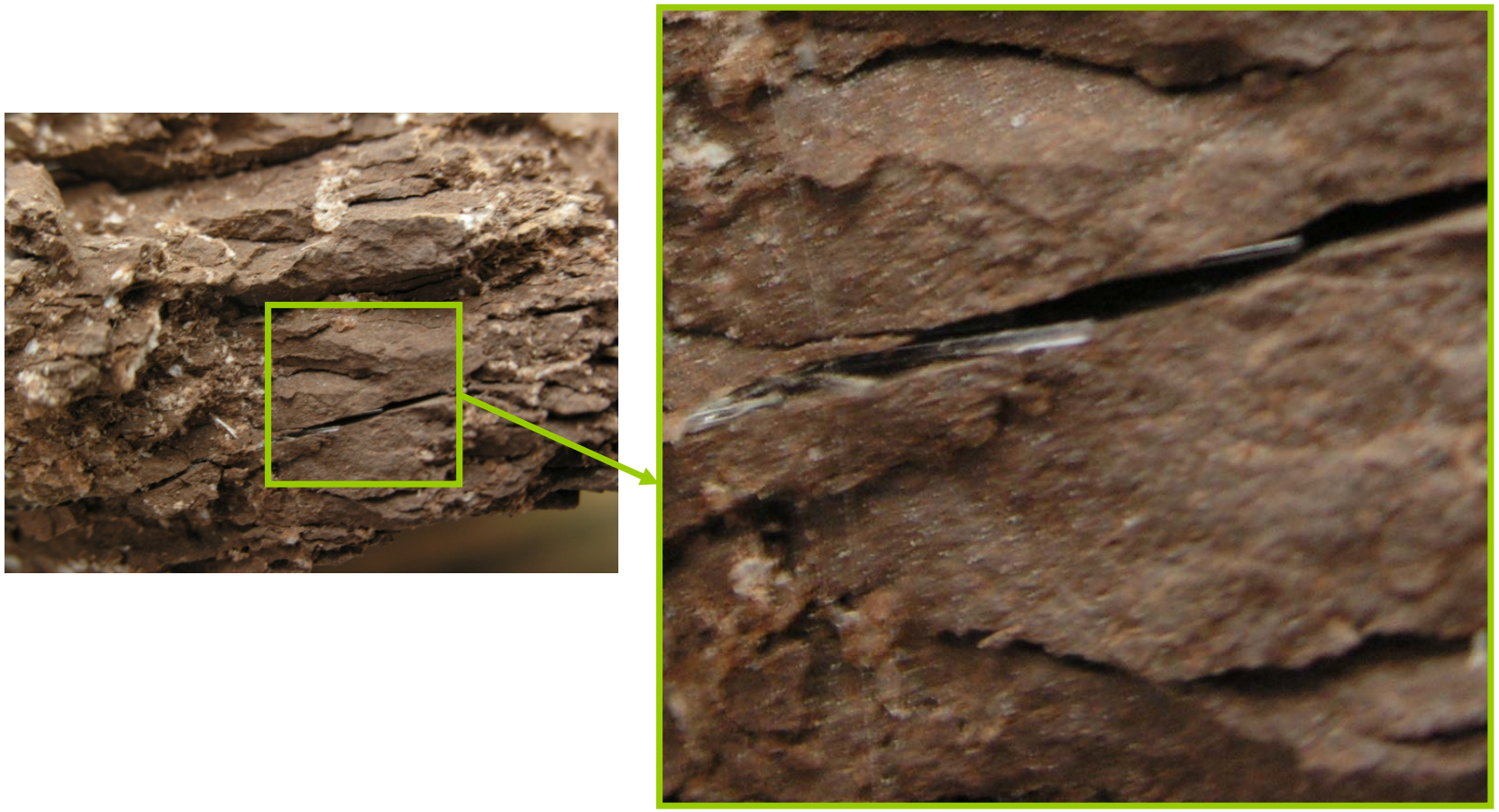
Gypsum needles filling slikensided surfaces

Aggregations of gypsum crystals growing in a discontinuity



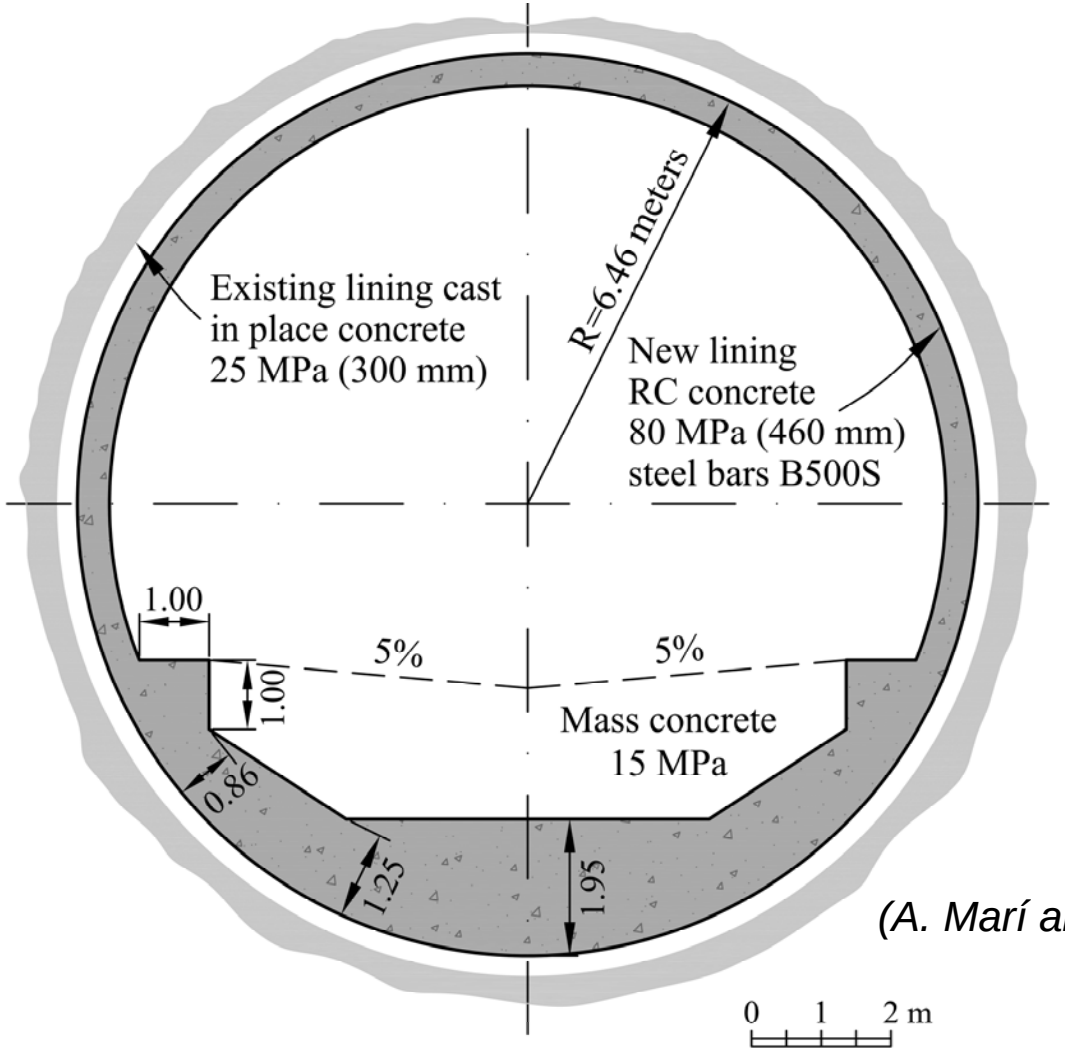

Aggregations of gypsum crystals
growing in a discontinuity

Growth of gypsum crystals in fissures



Reinforcement added to existing support

JULY 2004 – AUGUST 2005



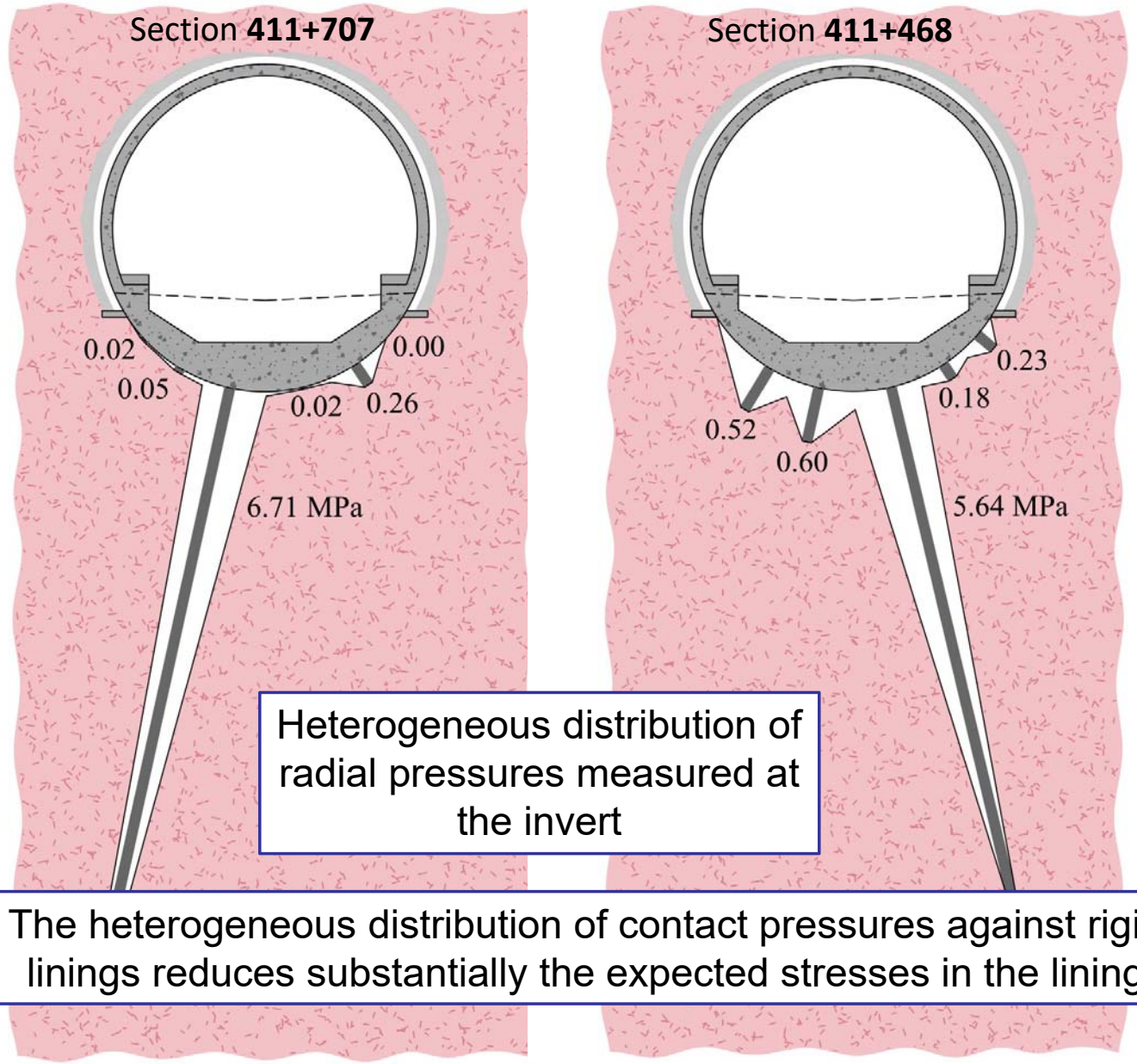
New excavated circular section

Resisting support

(A. Marí and G. Pérez, 2003)

Pressures measured at Lilla tunnel

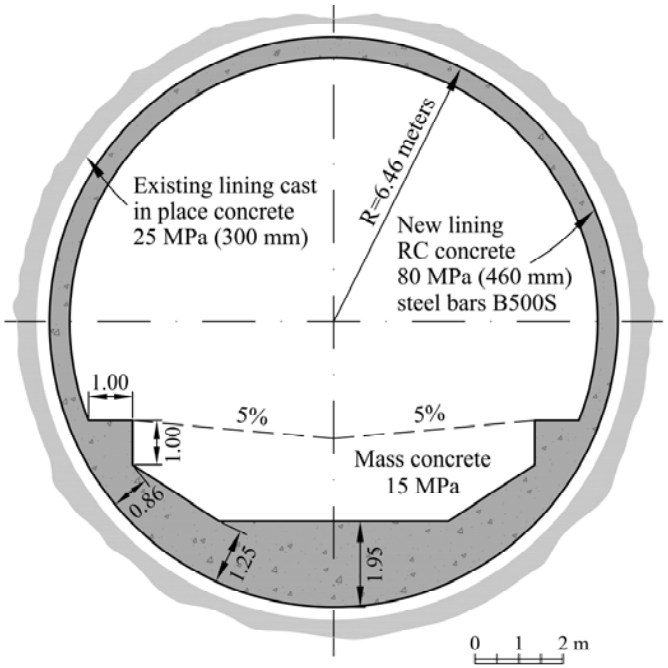
December 2011



Heterogeneous distribution of radial pressures measured at the invert

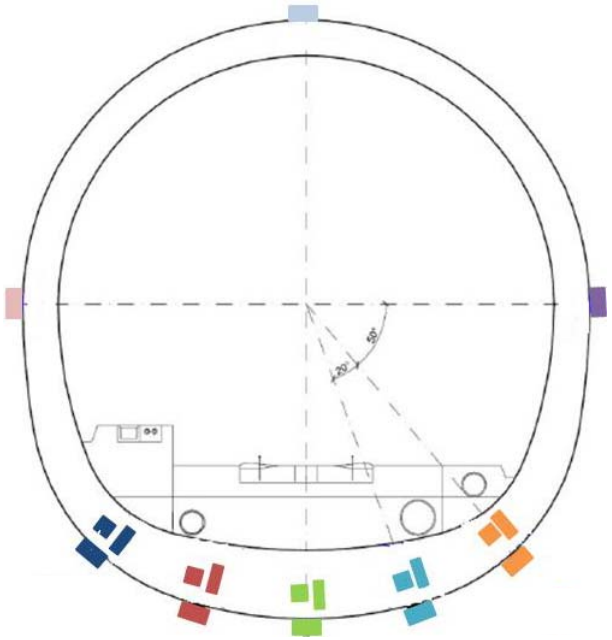
The heterogeneous distribution of contact pressures against rigid linings reduces substantially the expected stresses in the lining

- *The advantage of monitoring when results of general application can be extracted*
- *The design hypotheses of the new lining of Lilla tunnel were very conservative*



Lilla lining, 2003

➢ **Application of an upgraded tunnel lining design**



Albertia tunnel
Anhydritic slates

Albertia lining, 2011

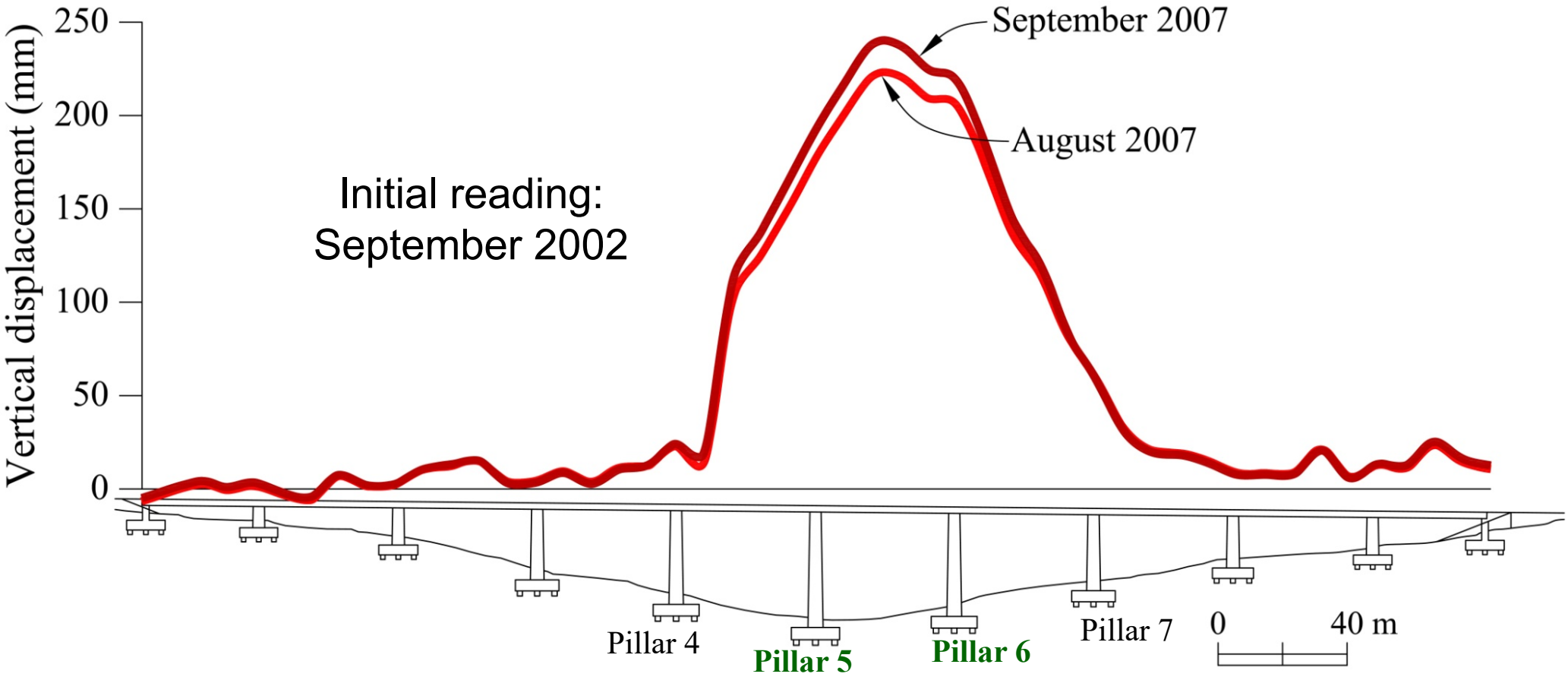
➢ **Development of a novel tunnel design methodology**

Lilla motorway A27 tunnels *Alonso, Ramon & Verda, 2022*

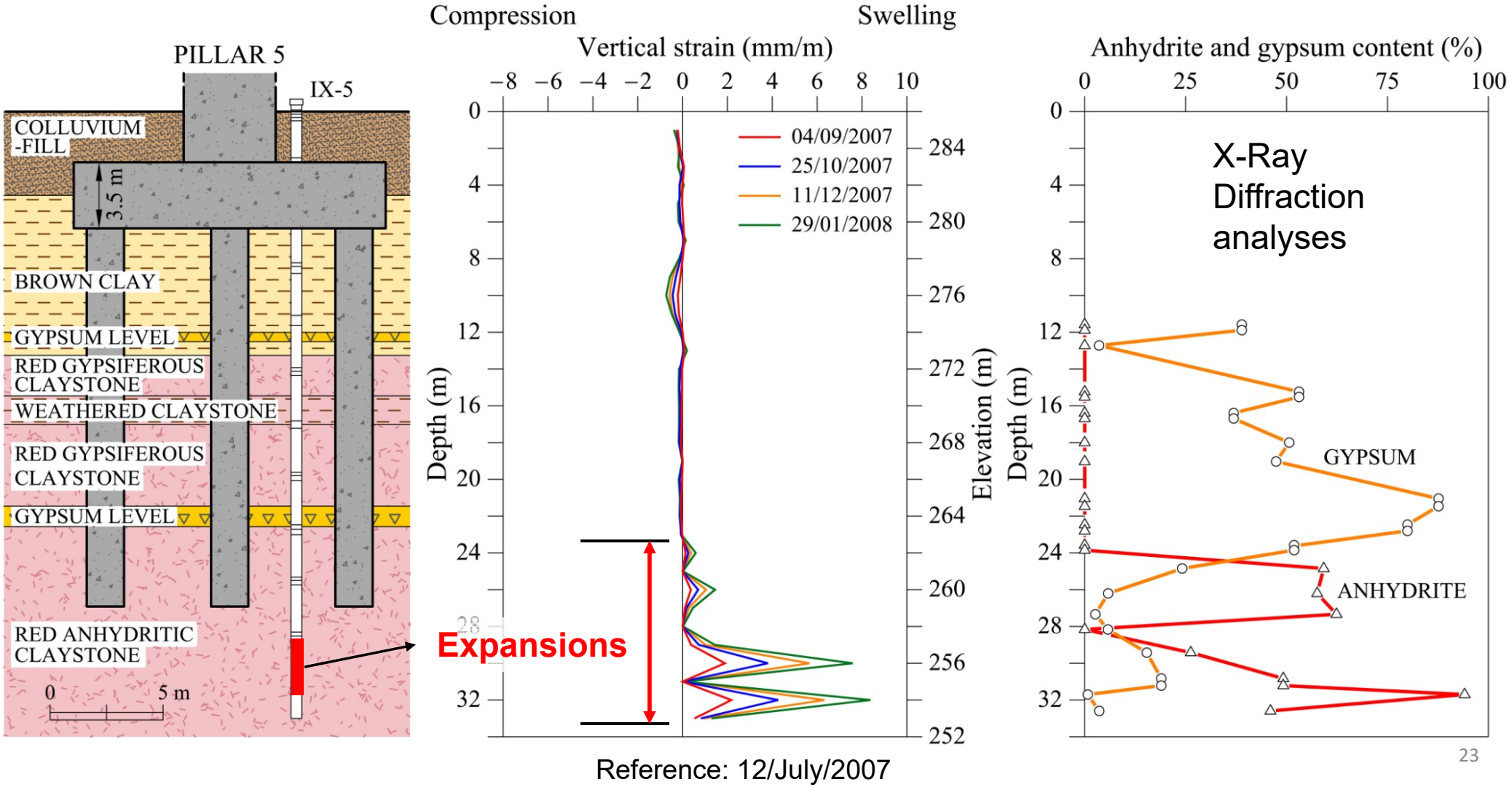
PONT DE CANDÍ
BRIDGE


Pont de Candí bridge
Lilla tunnel
North portal

Heave profiles in August and September 2007



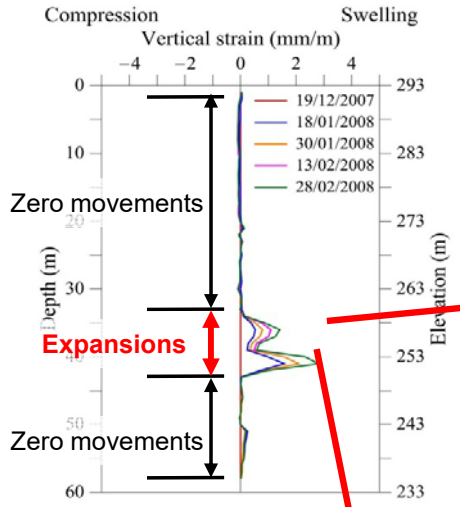
Swelling strains in depth vs anhydrite/gypsum content



Reference: 12/July/2007

Core observations in Pont de Candí bridge

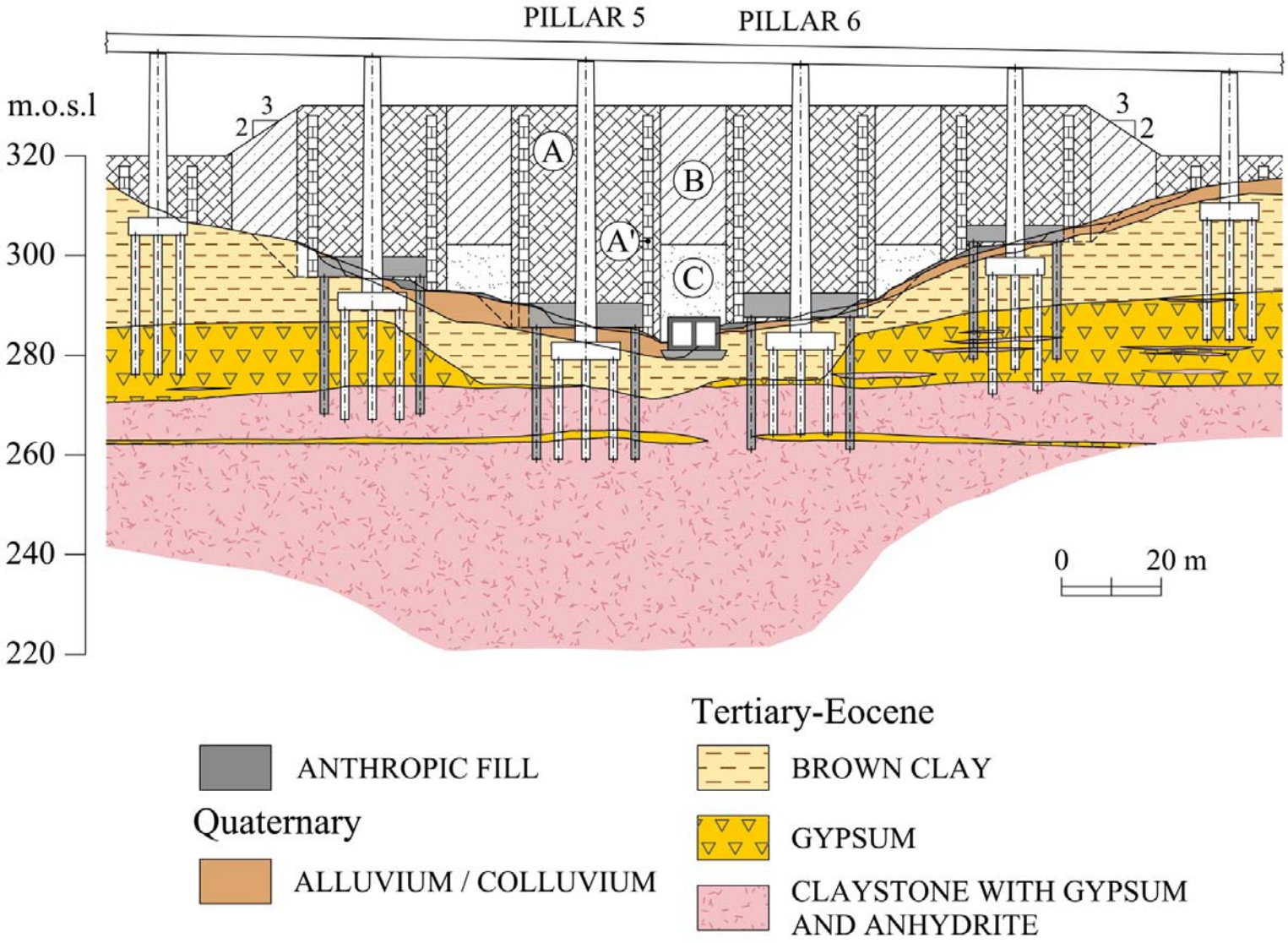
Presence of gypsum crystal growth in some open discontinuities at depths corresponding to the active layer



Laminar gypsum crystal growth “inside” the clay matrix

Gypsum needles crystal growth on open discontinuities

Pont de Candí bridge: Embankment construction



Pont de Candí bridge: Embankment construction

Pont de Candí bridge: Embankment construction

¿How the works alter the natural conditions?
¿Which factors trigger the expansion?

- Stress relief (excavation)
- "Damage" of the rock (opening of fissures, joints, slickenside planes…)
- Access of water to anhydrite (increase of permeability; boreholes, wells)

SWELLING MECHANISMS

The swelling phenomenon induced by precipitation of gypsum crystals

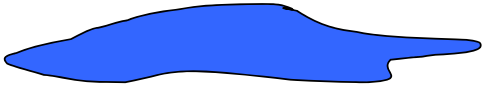
Saturated concentrations in the presence of Gypsum and Anhydrite. Effect of temperature

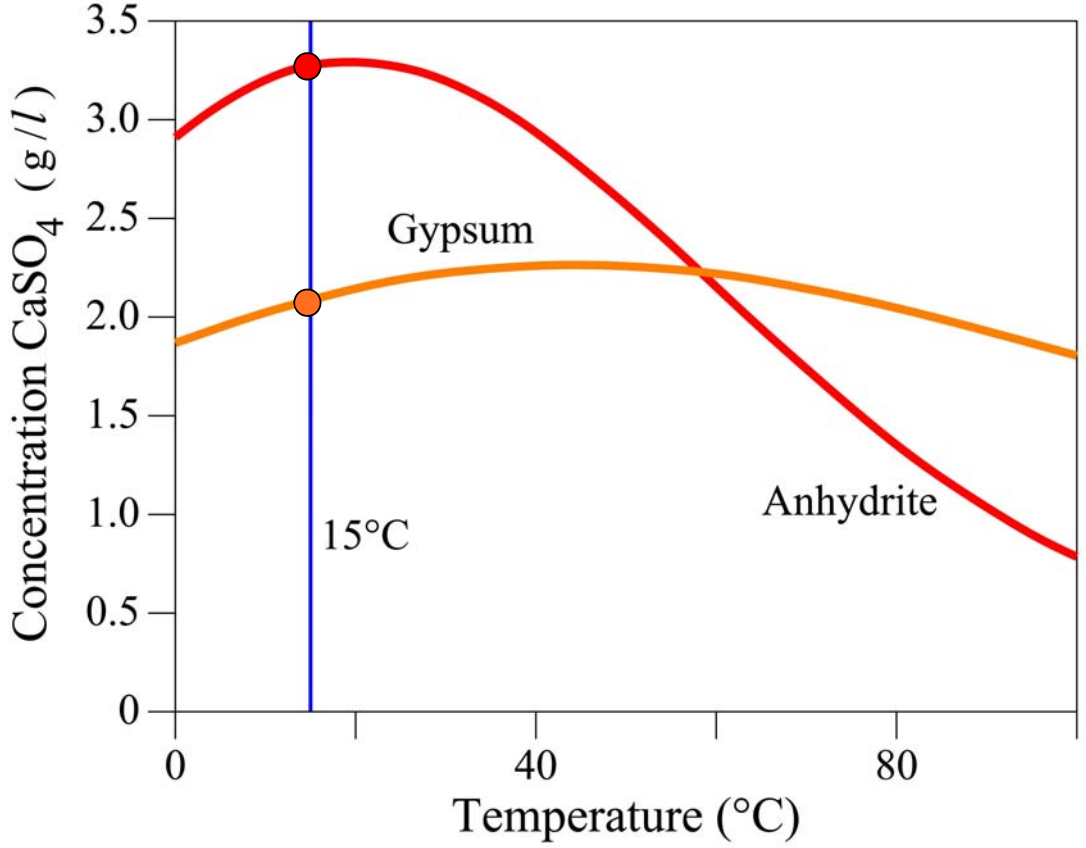
Clay matrix

Gypsum: $CaSO_4 \cdot 2H_2O$

Anhydrite: $CaSO_4$

Water in discontinuities



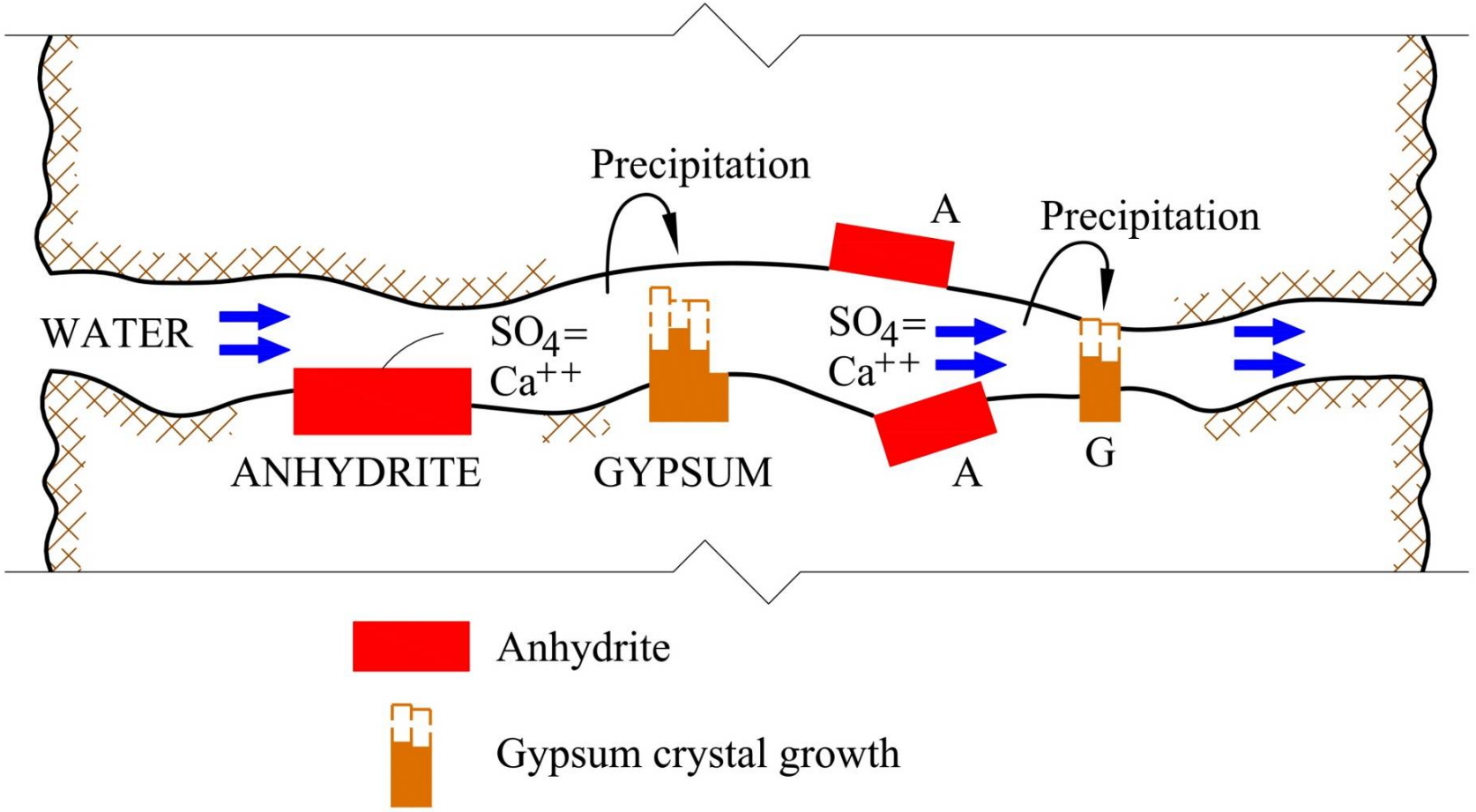


$$c_{sat,gyp}\left(T = 15\ ^{o}\mathrm{C}, p = 0\right) = 2.0\ \mathrm{g/l}$$

$$c_{sat,anh}\left(T = 15\ ^{o}\mathrm{C}, p = 0\right) = 3.2\ \mathrm{g/l}$$

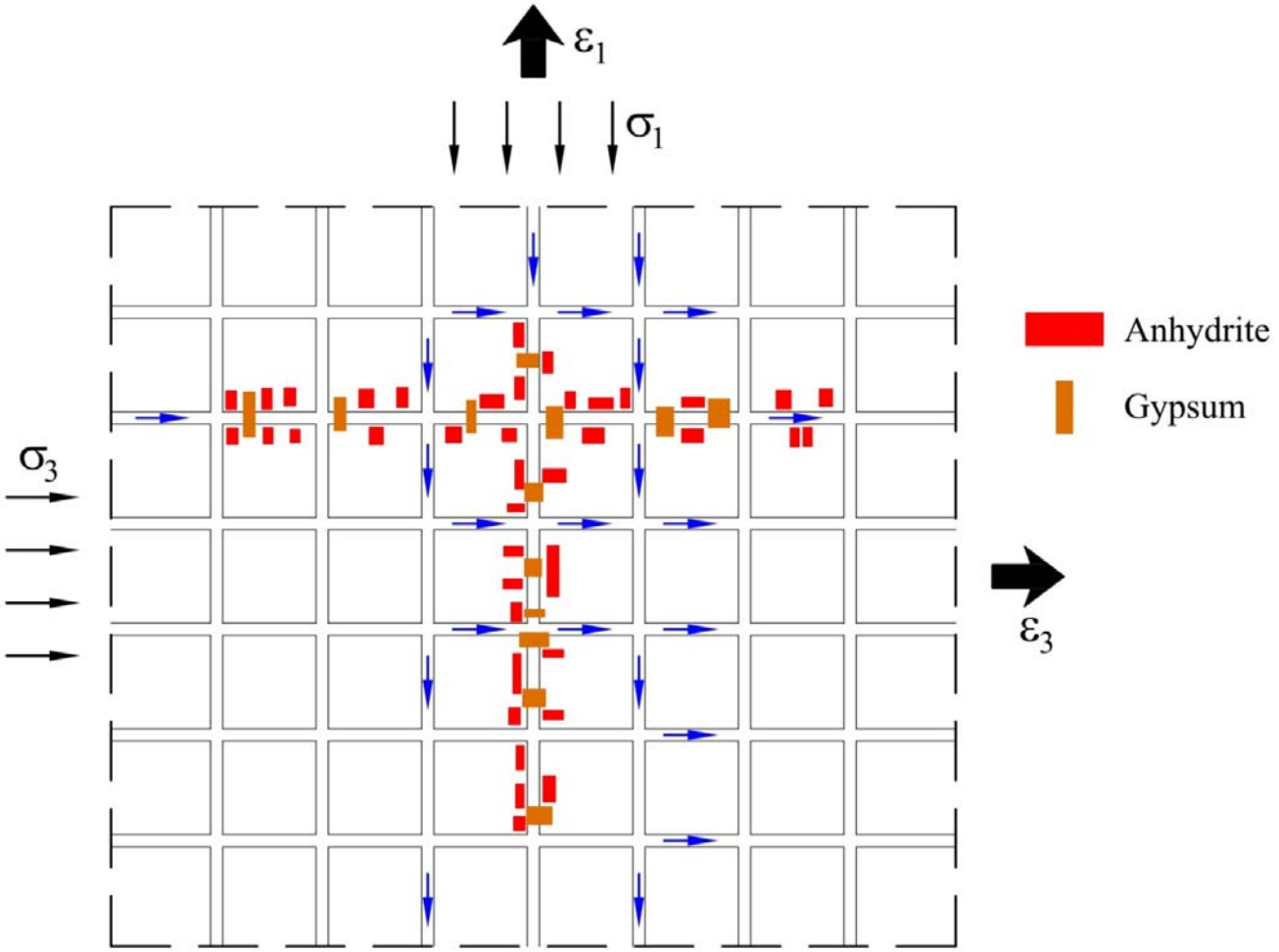
Anhydrite tends to dissolve and gypsum tends to precipitate

Conceptual model. Precipitation of gypsum crystals in discontinuities



FORMULATION OF THE CRYSTALLIZATION OF GYPSUM IN ANHYDRITIC ROCKS

A “representative element” of the anhydritic rock for swelling in two directions



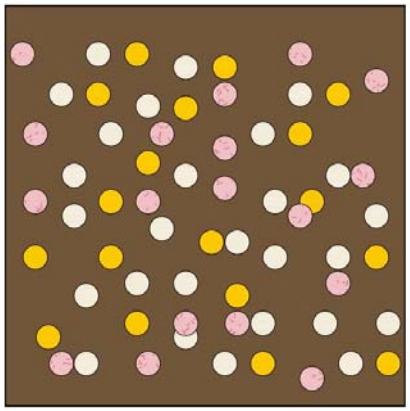
Singular characteristics of the phenomenon

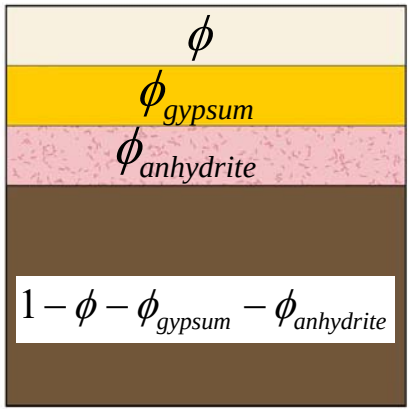
- Three solid species
  - Non soluble minerals (clay …)
  - Anhydrite
  - Gypsum
- Dissolution and precipitation
- Water sinks and sources (local)
- Imposed swelling strains (“external”)
- Solute transport (calcium sulphate)
- Development of fractures

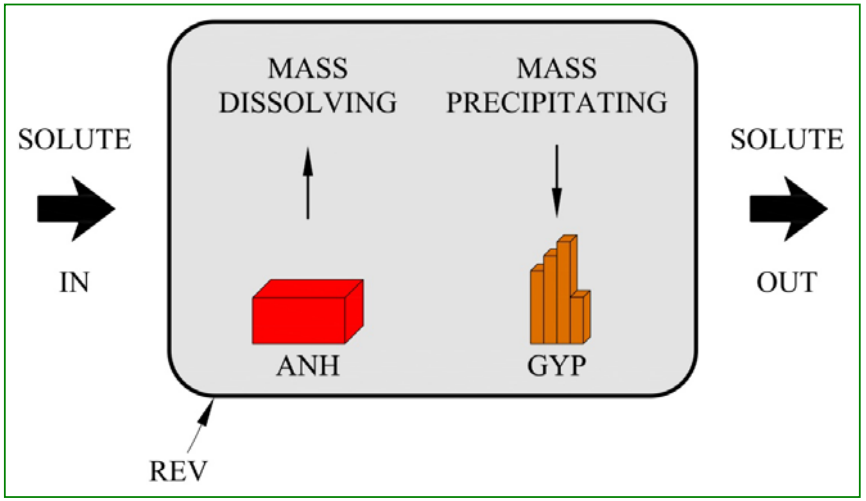
A General Calculation Model (THM)

- Mass balance of solids
- Mass balance of water
- Energy balance
- Equilibrium
- Constitutive equations

Kinetic equation for Dissolution-Precipitation of Gypsum or anhydrite







REV: Representative Element Volume

Concentration of solute in water

$$\frac{dm_{gyp}}{dt} = \sigma_c \kappa \xi \phi_{gyp} \left(\left| \left(\frac{\omega_l^m}{\omega_{sat,gypl}^m(T,p')} \right)^\theta - 1 \right| \right)^\eta ; \qquad \xi = \frac{\omega_l^m - \omega_{sat,gypl}^m}{\left| \omega_l^m - \omega_{sat,gypl}^m \right|}$$

Sign

Specific surface of crystals (m^2/m^3)

Rate constant

Compound kinetic coefficient

Volumetric fraction of gypsum

$$\omega_{0l,sat,gyp}^m \exp\left(\frac{p'\nu_c}{R_g T} \right)$$

(Lasaga, J. of Geophysical Research, 1984)

(Scherer, Cement and Concrete Research, 1999)

Mechanical effects. Strains induced by precipitation of gypsum

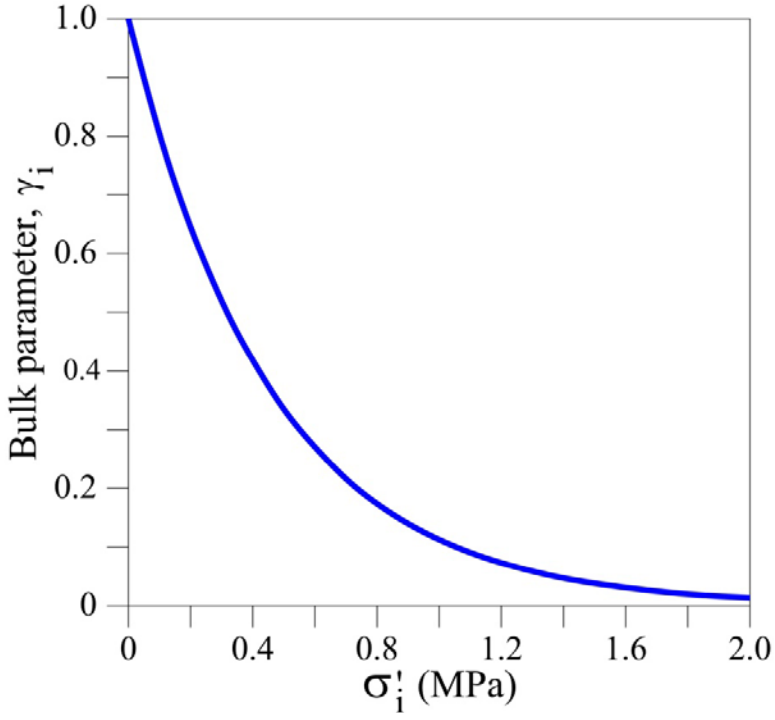
$$\dot{\varepsilon} = f(\dot{V}_{precipitate}, \sigma')$$

$$\frac{d\varepsilon_i}{dt} = \frac{\gamma_i}{\rho_{gyp}} \frac{dm_{gyp}}{dt} \quad , \quad i = 1,\ 2,\ 3$$

γ_i : Coefficient measuring the effect of stresses in the rock mass

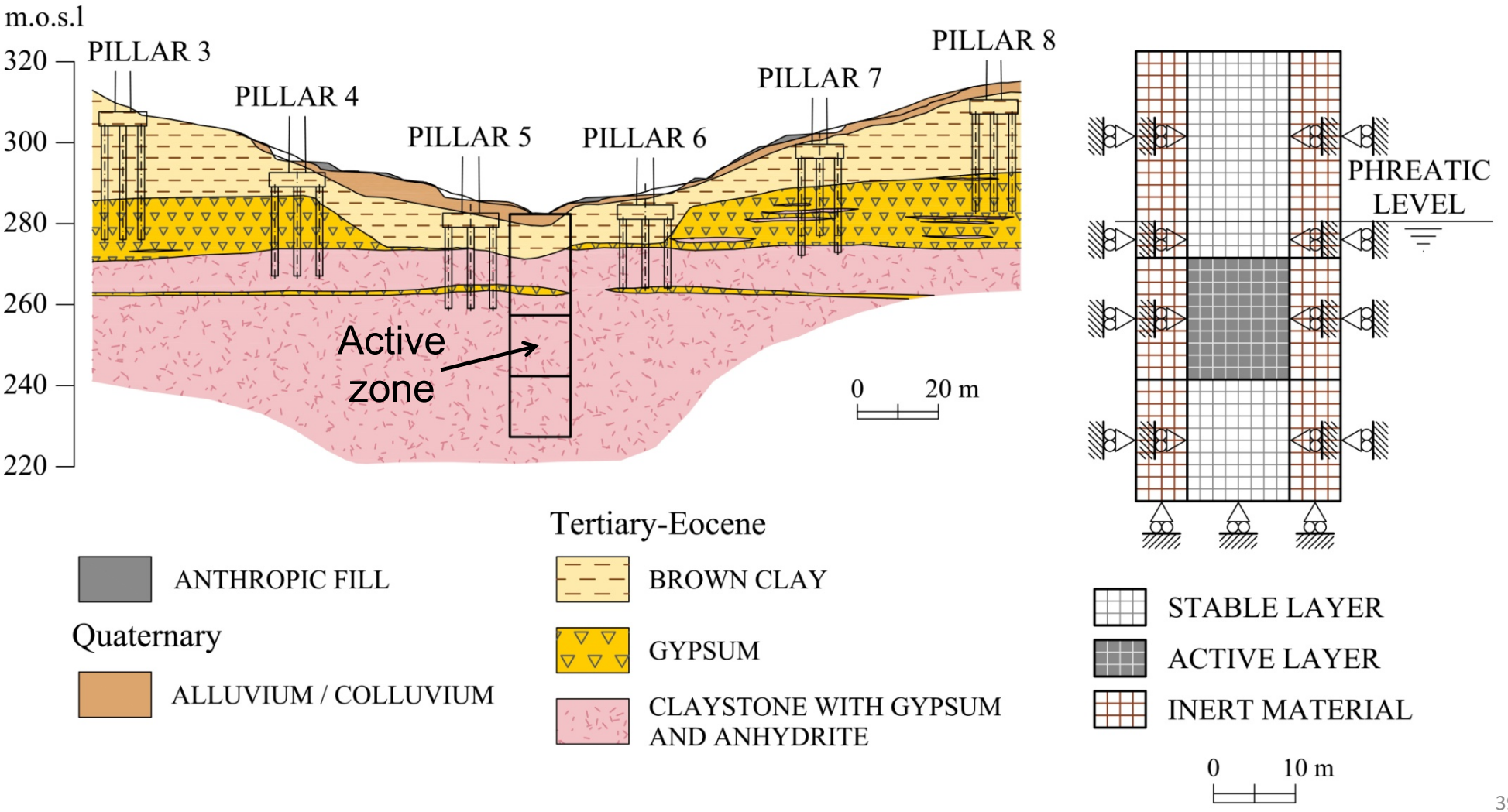
$$\gamma_i = \gamma_{\max} e^{-b\sigma'_i} \qquad \sigma'_i > 0$$

$$\gamma_i = \gamma_{\max} \qquad \sigma'_i = 0$$

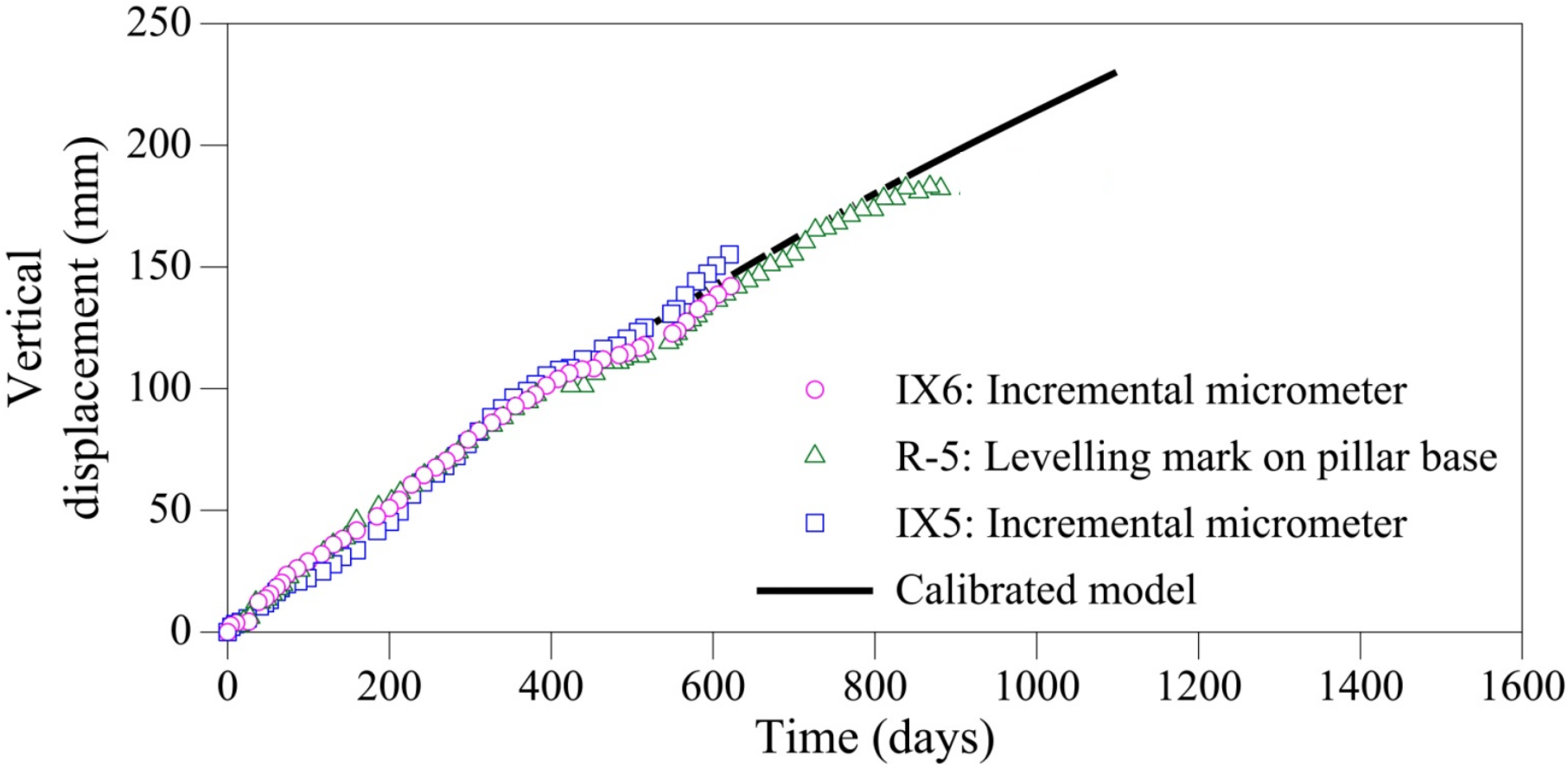


MODELLING SWELLING BEHAVIOUR IN PONT DE CANDÍ BRIDGE

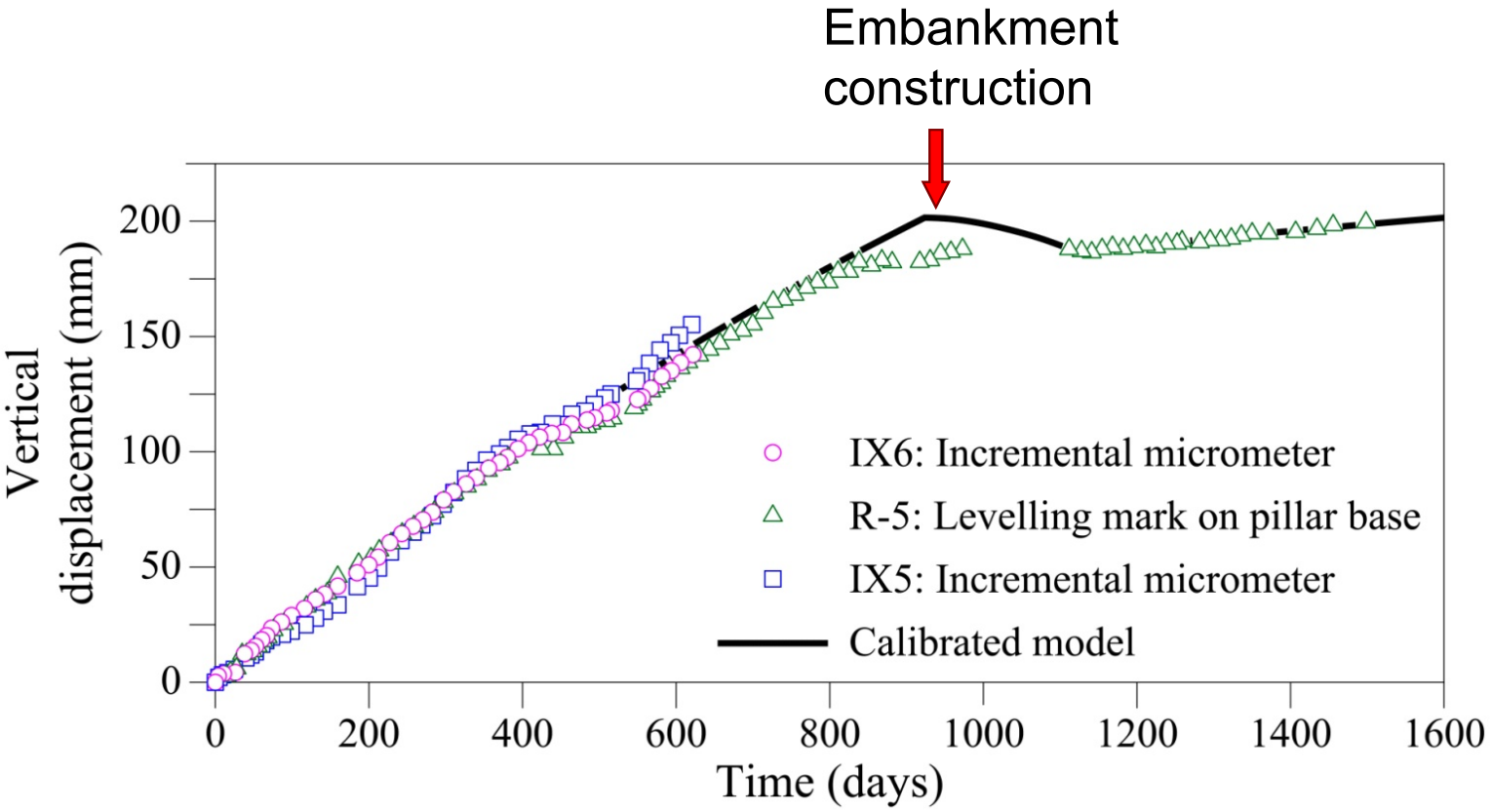
Modelling the swelling behaviour of Pont de Candí bridge



Model calibration



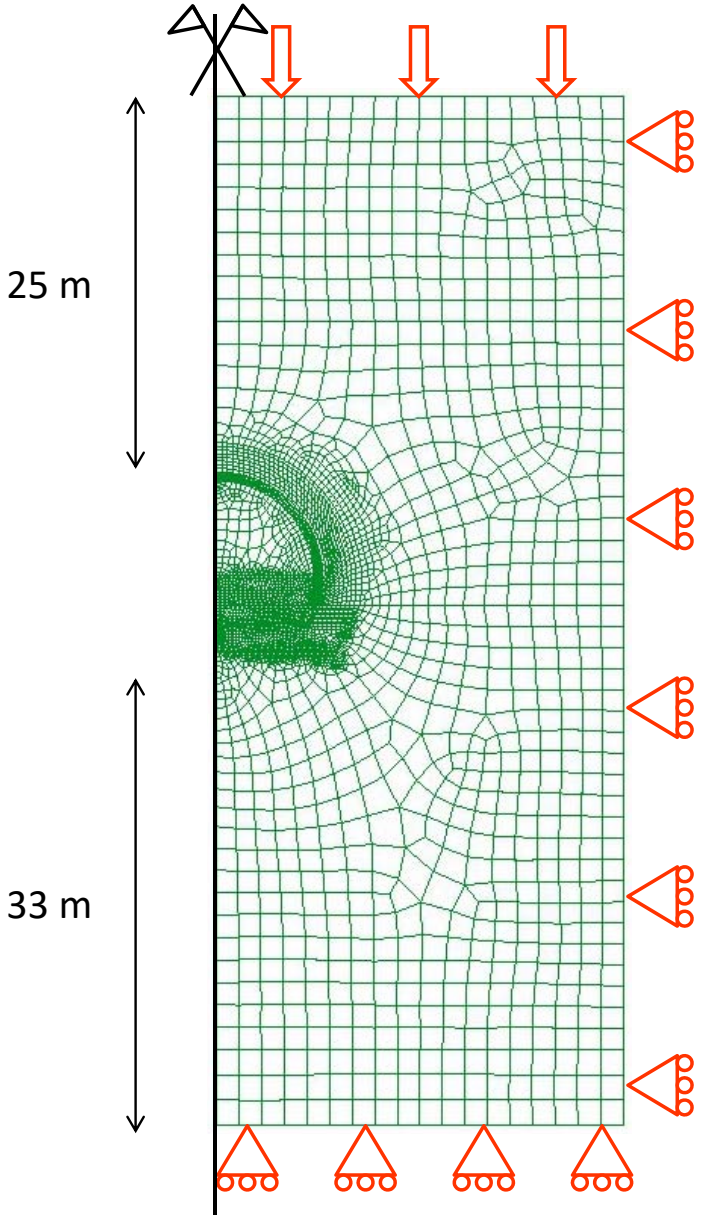
Calculated heave of ground surface



MODELLING THE SWELLING BEHAVIOUR OF LILLA TUNNEL

Simulation of excavation and crystal growth-induced swelling of Lilla tunnel

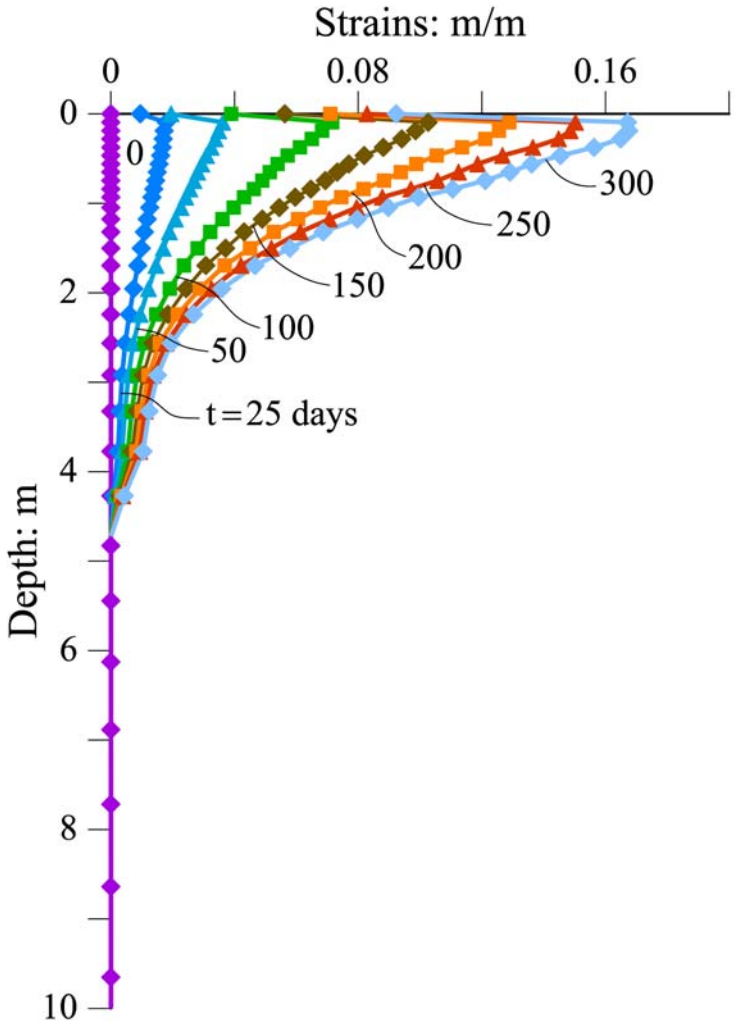
Reference position:
Chainage 411+600
Overburden 77m



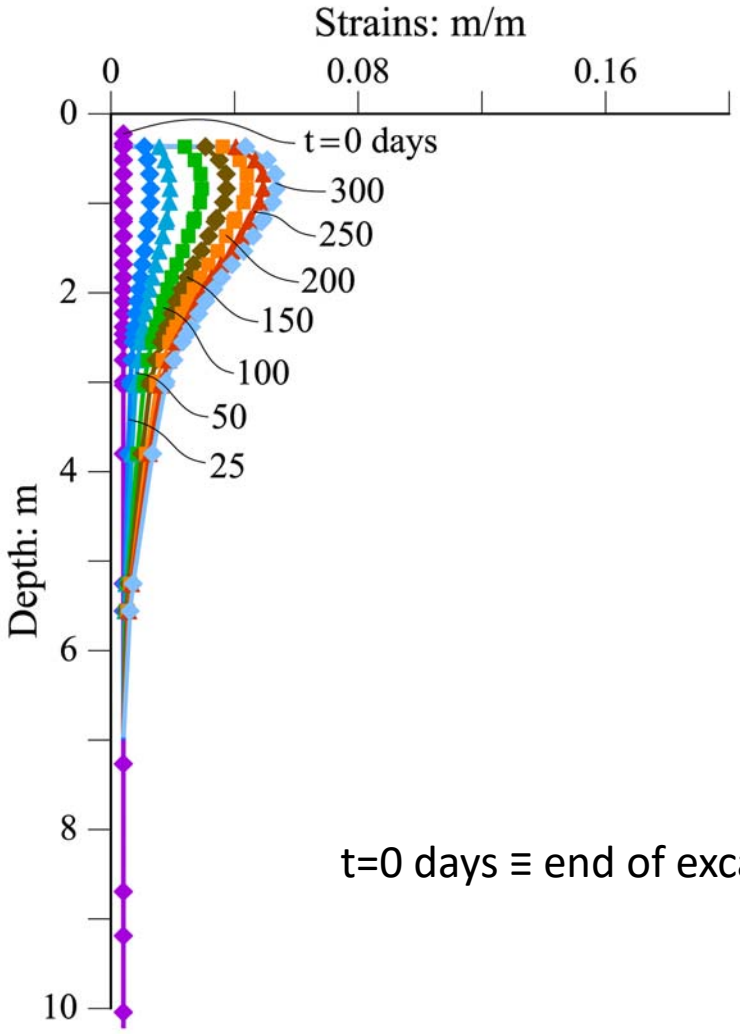
Ramon et al., 2017

Calculated vertical strains after excavation

tunnel axis



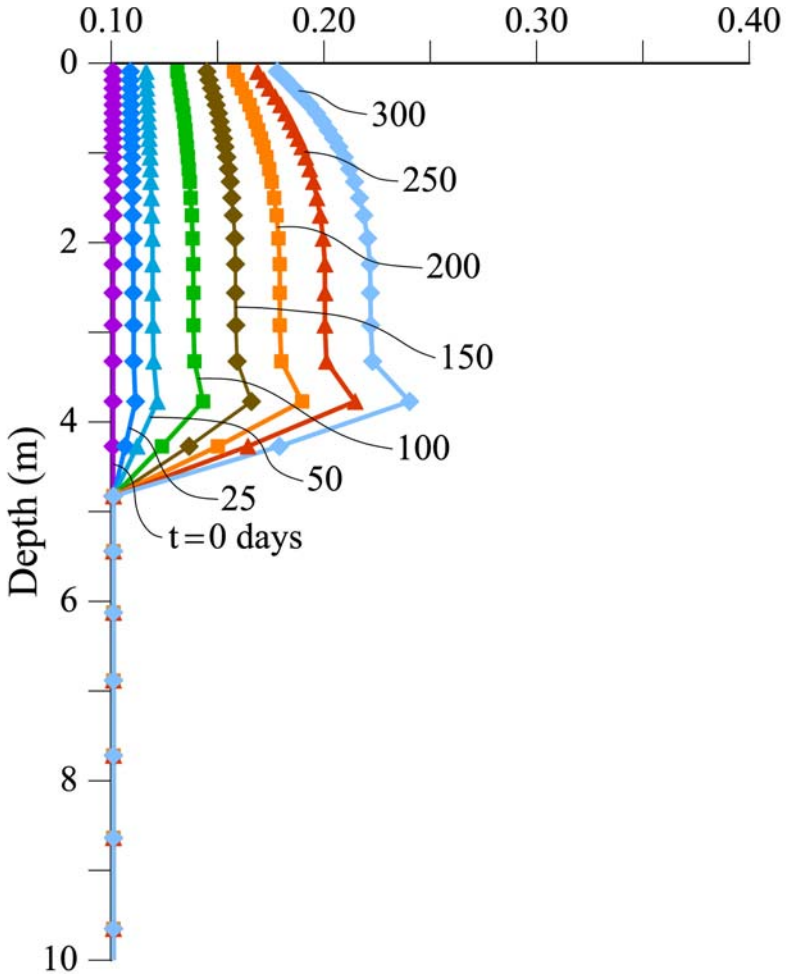
3.5 m from tunnel axis



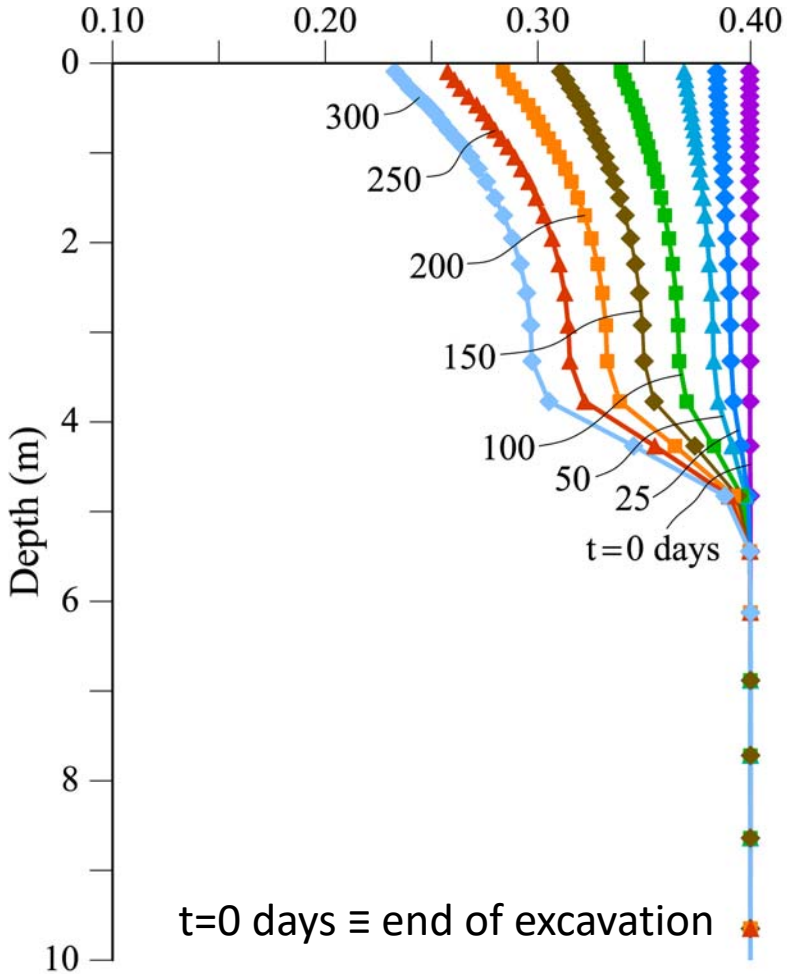
t=0 days ≡ end of excavation

Evolution of calculated mineral content in depth

Gypsum content evolution



Anhydrite content evolution



t=0 days ≡ end of excavation

LESSONS LEARNED FROM PRACTICE

Lessons learned from practice

CASE	ORIGIN/MECHANISMS	REMEDY
Tunnels		
Lilla AVE		
Lilla motorway A-27		
Albertia		
..		

Lessons learned from practice

CASE	ORIGIN/MECHANISMS	REMEDY
Tunnels Lilla AVE Lilla motorway A-27 Albertia ..	▪ Stress relief o Rock degradation o Loss of confinement stress ▪ Flow modification (Tunnel » Drainage) ▪ Rock in contact with “atmosphere”	

Lessons learned from practice

CASE	ORIGIN/MECHANISMS	REMEDY
Tunnels Lilla AVE Lilla motorway A-27 Albertia ..	▪ Stress relief o Rock degradation o Loss of confinement stress ▪ Flow modification (Tunnel » Drainage) ▪ Rock in contact with “atmosphere”	▪ Resist pressure ▪ Circular linings, convex geometries ▪ ¿Impermeabilization? Difficult control

Lessons learned from practice

CASE	ORIGIN/MECHANISMS	REMEDY
Foundations		
Pont de Candí bridge		
Uplift of buildings Corbera Staufen ..		

Lessons learned from practice

CASE	ORIGIN/MECHANISMS	REMEDY
Foundations Pont de Candí bridge Uplift of buildings Corbera Staufen ..	▪ Modification of hydraulic conditions o Boreholes, wells, deep foundations o Deficient drainage ▪ Excavation: stress relief, rock fissuration	

Lessons learned from practice

CASE	ORIGIN/MECHANISMS	REMEDY
Foundations Pont de Candí bridge Uplift of buildings Corbera Staufen ..	▪ Modification of hydraulic conditions o Boreholes, wells, deep foundations o Deficient drainage ▪ Excavation: stress relief, rock fissuration	▪ Apply load (embankment: Pont de Candí) ▪ Resist expansion (micropiles: Corbera) ▪ Sealing of boreholes, wells (Staufen)

Aknowledgements

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- Prof. Luciano Oldecop, U. de San Juan, Argentina
- Profs. Esperança Tauler and Manuel Labrador, Faculty of Geology, Universitat de Barcelona
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  INECO. Engineers: M. Alfonso; A. López P.

  FCC. Engineers: J.M. Gutiérrez M.; M.V. Gil; J. Torres

  IIC: Field investigation, instrumentation and laboratory tests. Engineer: C. Sanz

  Cedex, Collado Villalba; Cepasa: Laboratory tests

Publications

Journal papers

Alonso, E., Ramon-Tarragona, A. & Verda, L. (2022). Designing Tunnel Lining in Anhydritic Claystones. Intensity and Distribution of Swelling Forces. Rock Mech Rock Eng 56, 1467–1487.

Ramon, A.; Alonso, E. (2018). Heave of a building induced by swelling of an anhydritic Triassic claystone. Rock mechanics and rock engineering. 51 - 9, pp. 2881 - 2894.

Ramon, A.; Alonso, E.; Olivella, S. (2017). Hydro-chemo-mechanical modelling of tunnels in sulfated rocks. Géotechnique. 67 - 11, pp. 968 - 982.

Alonso, E.; Sauter, S.; Ramon, A. (2015). Pile groups under deep expansion: a case history. Canadian geotechnical journal. 52 - 8, pp. 1111 - 1121.

Alonso, E.; Ramon, A. (2013). Heave of a railway bridge induced by gypsum crystal growth: field observations. Géotechnique. 63 - 9, pp. 707 - 719.

Alonso, E.; Berdugo, I.; Ramon, A. (2013). Extreme expansive phenomena in anhydritic-gypsiferous claystone: the case of Lilla tunnel. Géotechnique. 63 - 7, pp. 584 – 612

Ramon, A.; Alonso, E. (2013). Heave of a railway bridge: modelling gypsum crystal growth. Géotechnique. 63 - 9, pp. 720 - 732.

Book Chapters

Ramon, A.; Alonso, E. (2023). Les précipitations minérales à grande échelle et leurs effets sur les infrastructures. In: Cristallisation de sels en milieu poreux. pp. 147 - 180. ISTE Editions Ltd, ISBN 978-1-78948-114-3

Alonso, E., Ramon, A. and Berdugo, I. (2011). Túneles en terrenos expansivos. Chapter of the book: Manual de túneles y obras subterráneas. pp: 1097-1154. Universidad Politécnica de Madrid (UPM). ISBN: 978-84-96140-36-3 Legal deposit: M. 16.764-2011.

Thank you very much for your attention!

Hartelijk dank voor uw aandacht!