CRYSTAL GROWTH UNDER BRIDGE FOUNDATIONS

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Motivation

Pont de Candí bridge
High speed railway line Madrid - Barcelona

Pont de Candí bridge
Geological profile

Pont de Candí bridge
Heave profiles in August and September 2007

Initial reading: September 2002
Observations in a long extensometer

In-situ investigations

Reference measurement: 19/December/2007
The active expanding layer

Pont de Candí bridge

IX : Incremental extensometer
SL : Sliding micrometer
: Recorded swelling
Swelling probably occurs
: at deeper locations

Approximate limits of active zone
Swelling strains vs anhydrite/gypsum content

Reference:
12/July/2007
Contours of surface heave


Five months
Evolution of vertical displacements of the cap of extensometers at ground surface, measured by topographic levelling

In-situ investigations

The heave did not stabilize; in some areas it accelerates
Core observations in Pont de Candí bridge

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

Gypsum needles crystal growth on open discontinuities

Laminar gypsum crystal growth “inside” the clay matrix
FORMULATION OF COUPLED HMC PROCESSES
Anhydrite tends to dissolve and gypsum tends to precipitate. Saturated concentrations in the presence of Gypsum and Anhydrite. Effect of temperature.

\[
\begin{align*}
    c_{sat, gyp} (T = 15 \, ^\circ C, p = 0) &= 2.0 \, \text{g/l} \\
    c_{sat, anh} (T = 15 \, ^\circ C, p = 0) &= 3.2 \, \text{g/l}
\end{align*}
\]

Anhydrite tends to dissolve and gypsum tends to precipitate.
Model formulation

Conceptual representation

WATER

ANHYDRITE

SO₄⁻⁻ = Ca²⁺⁺

GYPSUM

SO₄⁻⁻ = Ca²⁺⁺

A

A

G

Precipitation

Precipitation

Anhydrite

Gypsum crystal growth
Coupled THM analysis in porous media

Balance equations

- **MASS BALANCE OF SOLID PHASE**
  \[
  \frac{D_s \phi}{Dt} = \frac{1}{\rho_s \omega_s^s}[ (1 - \phi) \frac{D_s \rho_s \omega_s^s}{Dt} ] + (1 - \phi) \nabla \cdot \frac{du}{dt}
  \]

- **MASS BALANCE OF WATER**
  \[
  \phi \frac{D_s \left( \omega_i^w \rho_i S_i + \omega_g^w \rho_g S_g \right)}{Dt} + \left( \omega_i^w \rho_i S_i + \omega_g^w \rho_g S_g \right) \frac{D_s \phi}{Dt} + \left( \left( \omega_i^w \rho_i S_i + \omega_g^w \rho_g S_g \right) \phi \right) \nabla \cdot \frac{du}{dt} + \nabla \cdot \left( j_i^w + j_g^w \right) = f^w
  \]
  - Mass storage terms
  - Adveective flow induced by solid motion
  - Adveective/diffusive mass flow rates
  - Sources/sinks

- **MASS BALANCE OF AIR**

- **MOMENTUM BALANCE OF THE MEDIUM**
  \[
  \nabla \cdot \sigma + b = 0
  \]

- **INTERNAL ENERGY BALANCE FOR THE MEDIUM**
  \[
  \frac{\partial}{\partial t} \left( E_s \rho_s (1 - \phi) + E_i \rho_i S_i \phi + E_g \rho_g S_g \phi \right) + \nabla \cdot (i_c + j_{Es} + j_Ei + j_{Eg}) = f^Q
  \]
Model formulation

Additional ingredients

- Three solid species
  - Insoluble clay minerals
    - Anhydrite
    - Gypsum
- Dissolution and precipitation
- Water sink and source terms
- Imposed “external” swelling strains
- Solute transport
Mass balance for the solid phase

Mass balance of insoluble solid species
\[
\frac{\partial}{\partial t} \left( \rho_s (1 - \phi - \phi_{anhydrite} - \phi_{gypsum}) \right) + \nabla \cdot \left( \rho_s (1 - \phi - \phi_{anhydrite} - \phi_{gypsum}) \frac{d\mathbf{u}}{dt} \right) = 0
\]

Mass balances of soluble solid species
\[
\frac{\partial}{\partial t} \left( \rho_{gypsum} \phi_{gypsum} \right) + \nabla \cdot \left( \rho_{gypsum} \phi_{gypsum} \frac{d\mathbf{u}}{dt} \right) = \frac{dm_{gypsum}}{dt}
\]
\[
\frac{\partial}{\partial t} \left( \rho_{anhydrite} \phi_{anhydrite} \right) + \nabla \cdot \left( \rho_{anhydrite} \phi_{anhydrite} \frac{d\mathbf{u}}{dt} \right) = \frac{dm_{anhydrite}}{dt}
\]
Mass balance for the solid phases

Combining the three equations:

\[
\frac{D_s \phi}{Dt} = \left[ \frac{1 - \phi - \phi_{anh} - \phi_{gyp}}{\rho_s} \right] \frac{D_s \rho_s}{Dt} + \frac{\phi_{anh}}{\rho_{anh}} \frac{D_s \rho_{anh}}{Dt} + \frac{\phi_{gyp}}{\rho_{gyp}} \frac{D_s \rho_{gyp}}{Dt} + [1 - \phi] \nabla \cdot \frac{du}{dt} - \frac{1}{\rho_{gyp}} \frac{dm_{gyp}}{dt} - \frac{1}{\rho_{anh}} \frac{dm_{anh}}{dt}
\]

If \( \rho_s, \rho_{gyp}, \rho_{anh} \) = constant

\[
\frac{D_s \phi}{Dt} = \left[ \frac{1 - \phi}{\rho_s} \right] \nabla \cdot \frac{du}{dt} - \frac{1}{\rho_{gyp}} \frac{dm_{gyp}}{dt} - \frac{1}{\rho_{anh}} \frac{dm_{anh}}{dt}
\]

Volumetric strain rate induced by solid displacements

Volumetric ratio of precipitated/dissolved crystals
**Kinetic equation for Dissolution-Precipitation of Gypsum:**

\[
\frac{dm_{gyp}}{dt} = \sigma_c K \xi \phi_{gyp} \left( \frac{\omega_l^m}{\omega_{sat,gypl}^m(T, p)} \right)^\theta \left( 1 - \frac{\omega_l^m}{\omega_{sat,gypl}^m(T, p)} \right)^\eta
\]

\[\xi = \frac{\omega_l^m - \omega_{sat,gypl}^m}{\omega_l^m - \omega_{sat,gypl}^m}\]

*(Lasaga, J. of Geophysical Research, 1984)*

\[
\omega_{0l, sat, gyp} \exp \left( \frac{p'v_c}{R_g T} \right)
\]

*(Scherer, Cement and Concrete Research, 1999)*
Summary of balance equations: solid, water, equilibrium

1. **MASS BALANCE OF SOLID PHASE**

\[
\frac{D_s \phi}{Dt} = \left( (1-\phi) \right) \nabla \cdot \frac{du}{dt} - \frac{1}{\rho_{\text{gyp}}} \frac{dm_{\text{gyp}}}{dt} - \frac{1}{\rho_{\text{anh}}} \frac{dm_{\text{anh}}}{dt}
\]

2. **MASS BALANCE OF WATER**

\[
\phi \left( \frac{D_s \left( \omega^w \rho_l S_l + \omega^w \rho_g S_g \right)}{Dt} \right) + \left( \omega^w \rho_l S_l + \omega^w \rho_g S_g \right) \frac{D_s \phi}{Dt} + \left( \omega^w \rho_l S_l + \omega^w \rho_g S_g \right) \phi \nabla \cdot \frac{du}{dt} + \nabla \cdot \left( j^w_l + j^w_g \right) = f^w
\]

3. **EQUILIBRIUM**

\[
\nabla \cdot \sigma + b = 0
\]

+ imposed strains induced by precipitation
Mechanical effects. Strains induced by precipitation

Deformation rates induced by precipitation

\[ \dot{\varepsilon} = f(\dot{V}_\text{precipitate}, \sigma') \]

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

\[ \gamma_i : \text{ Coefficient measuring the \textbf{“}bulking\textbf{”} effect in the rock mass} \]

\[ \gamma_i = \gamma_{\max} e^{-b \sigma'_i}, \quad \sigma'_i > 0 \]

\[ \gamma_i = \gamma_{\max}, \quad \sigma'_i = 0 \]
Solute mass conservation equation

\[
\frac{\partial}{\partial t} \left( \phi \omega_l^m \rho_l \right) + \nabla \cdot \left( \rho_l \omega_l^m \mathbf{q}_l - \mathbf{D} \nabla \omega_l^m \right) + \nabla \cdot \left( \phi \omega_l^m \rho_l \frac{d\mathbf{u}}{dt} \right) = -\frac{dm_{\text{gyp}}}{dt} - \frac{dm_{\text{anh}}}{dt}
\]

- Rate of change of dissolved mass in the saturated voids
- Advective (Darcy) and diffusive mass flow rates
- Advective mass flow rate induced by the solid motion
- Solution and precipitation rates of gypsum and anhydrite
Summarizing

FULL THMC FORMULATION

• Solid balance equation (Two soluble species + One insoluble)
• Water and air mass balance equations (Sink/source terms from dissolution/precipitation)
• Equilibrium (imposed swelling deformations from precipitated gypsum)
• Solute mass conservation equation (for the calcium sulphate)

FINITE ELEMENT PROGRAM
MODELLING THE SWELLING BEHAVIOUR OF PONT DE CANDÍ BRIDGE
Suggested scenario. Pont de Candí bridge
Modelling the swelling behaviour of Pont de Candí bridge

Hydraulic cross-hole tests

In-situ investigations

PILLAR 5  PILLAR 6

S3  S2  S1

S3

8 meters

S2  S1

4 meters

Observation borehole

Injection borehole

Testing section

Control lines

Pressure sensor

Upper packer

Pressure sensor

Lower packer

Pressure sensor
The active expanding layer had a system of hydraulically connected horizontal discontinuities.
Modelling the swelling behaviour of Pont de Candí bridge
### Anhydrite-gypsum transformation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass fraction of gypsum in water for saturated conditions (kg/kg)</td>
<td>$2.0 \cdot 10^{-3}$</td>
<td>At $T = 15^\circ C$</td>
</tr>
<tr>
<td>Mass fraction of anhydrite in water for saturated conditions (kg/kg)</td>
<td>$3.2 \cdot 10^{-3}$</td>
<td>At $T = 15^\circ C$</td>
</tr>
<tr>
<td>Initial gypsum “porosity” $\phi_{\text{gyp initial}}$</td>
<td>0.20</td>
<td>Approximate field observations</td>
</tr>
<tr>
<td>Initial anhydrite “porosity” $\phi_{\text{anh initial}}$</td>
<td>0.15</td>
<td>Matching swelling records</td>
</tr>
<tr>
<td>Compound kinetic coefficient $(\text{kg/m}^3\cdot\text{s})$</td>
<td>$0.76 \cdot 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>Molecular diffusion coefficient $(\text{m}^2/\text{s})$</td>
<td>$3.9 \cdot 10^{-9}$</td>
<td></td>
</tr>
</tbody>
</table>

Modelling the swelling behaviour of Pont de Candí bridge
### Model parameters

<table>
<thead>
<tr>
<th>Hydraulic</th>
<th>Initial open porosity</th>
<th>$\phi_{\text{initial}}$</th>
<th>0.09</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Intrinsic permeability</td>
<td>$K$</td>
<td>$2 \cdot 10^{-13}$ m$^2$</td>
</tr>
</tbody>
</table>

- Higher than conventional porosity to account for fissures
- Found in cross hole hydraulic tests
### Model parameters

#### Mechanical

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic parameter</td>
<td>1000 MPa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.2</td>
</tr>
<tr>
<td>At rest, earth pressure coefficient, $K_0$</td>
<td>2</td>
</tr>
<tr>
<td>Solid specific unit weight $(\gamma_s/\gamma_w)$</td>
<td>2.63</td>
</tr>
<tr>
<td>Gypsum density</td>
<td>2.3 Mg/m³</td>
</tr>
<tr>
<td>Anhydrite density</td>
<td>2.96 Mg/m³</td>
</tr>
</tbody>
</table>

Estimated for a fissured Tertiary claystone

Laboratory determinations

Modelling the swelling behaviour of Pont de Candí bridge
Calculated strains in active zone
Modelling the swelling behaviour of Pont de Candí bridge

Model calibration

![Graph showing vertical displacement over time with different markers and a calibrated model line.](Image)
Modelling the swelling behaviour of Pont de Candí bridge

Long term performance

![Graph showing the long term performance of Pont de Candí bridge with graphs for vertical displacement and volume fraction over time.]

- **Vertical displacement (m)**
  - Time (days): 0 to 10000
  - Vertical displacement: 0 to 0.4

- **Volume fraction**
  - Time (days): 0 to 10000
  - Volume fraction: 0 to 0.4

- **Graphs**
  - **Gypsum**: Volume fraction increasing over time.
  - **Anhydrite**: Volume fraction decreasing over time.
Sensitivity analysis

Effect of initial anhydrite content

![Graph showing the effect of initial anhydrite content on vertical displacement over time.](image-url)
Sensitivity analysis

Effect of initial gypsum content

Vertical displacement (mm)

Time (days)

φ gypsum = 0.3
0.2
0.1
0
Sensitivity analysis

Effect of vertical stress

Modelling the swelling behaviour of Pont de Candí bridge
REMEDIAL MEASURES
Remedial measures: Pont de Candí bridge

Pont de Candí bridge: Embankment construction
Remedial measures: Pont de Candí bridge

Pont de Candí bridge: Embankment construction
Remedial measures: Pont de Candí bridge

Pont de Candí bridge: Embankment construction
Effect of vertical confining stress on the heaving rate measured in the lower part of pillar P5

Effect of embankment construction on measured heave rate

Remedial measures: Pont de Candí bridge

Effect of vertical confining stress on the heaving rate measured in the lower part of pillar P5
Effect of embankment construction on strains measured at depth

Remedial measures: Pont de Candí bridge

Embankment construction

Measured displacement in the depth interval 25 to 52 m

Measured total displacement (2-52 m deep)

100 days
Model reaction to embankment construction

Remedial measures: Pont de Candí bridge

![Graph showing vertical displacement over time for embankment construction](image-url)
Conclusions

- Gypsum crystal growth in discontinuities is the main mechanism explaining swelling in gypsum and anhydrite rich claystone.

- Necessary conditions to initiate the process are:
  - Significant anhydrite content
  - Water flow
  - Previous damage or fracturing of the rock

- The model developed is capable of reproducing the swelling and heave phenomena observed in Pont de Candí viaduct.
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