Tunneling in swelling rocks - a challenge in design and execution

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Gotthard Base Tunnel: longest railway tunnel in the world: 57 km
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Risks caused by geological and hydrogeological conditions

Instable crown/unstable tunnel face

Groundwater penetration
Risks caused by geological and hydrogeological conditions

Unstable crown together with groundwater leading to partial collapse of the overburden

Example: Adlertunnel (1995)
Risks caused by geology

Swelling rocks
Physical or chemical reaction leading to an increase in volume which can cause damages on the tunnel structure

![Rock sample](image1.jpg)

*after increase of volume*

![Damage during construction](image2.jpg)

*Damage during construction caused by swelling rocks*
2 types of swelling

Clay stone
Addition of water molecules in the clay minerals leads to increase of volume

Anhydrite stone
Chemical process:
Anhydrite + water changes to gypsum
\[ \text{CaSO}_4 + 2\text{H}_2\text{O} \rightarrow \text{CaSO}_4 \cdot 2\text{H}_2\text{O} \]

Risks
Swelling rock
Project examples
Design
Current project
High pressures measured in the laboratory
Pressures which can be expected by confined expansion:
(depending on the geological and hydrogeological conditions)

› Clay stone
   → max. 2 - 3 MPa

› Anhydrite stone
   → in laboratory 7-8 MPa
   → in situ 3 - 4 MPa
   (measured so far, higher pressure possible)

\[
\varepsilon = k \cdot (1 - \log \sigma / \log \sigma_0)
\]

law of swelling
strain $\varepsilon [%]$
Consequences of swelling
In a tunnel in swelling rock, the following can be observed:

*Hazard scenario heave of invert*

- unprotected, open invert
- with water entering, the swelling process was activated
- heave of the invert by 1.50 m within 3 months

Example: Chienberg tunnel
Consequences of swelling

By confining swelling:

*High pressure load on shotcrete and concrete tunnel lining*

Different locations of swelling are possible:

› invert (vertical pressure)
› side (horizontal pressure)

*Heave of the entire tunnel if the pressure is higher than the overburden or the top is soft rock*
Additional risk in Anhydrite
Aggressive groundwater (for concrete) due to sulfate rock

\[ \text{H}_2\text{SO}_4 \]

Highly affected if sulfate content of more than 3’000 mg/l → deterioration of concrete (Ettringite/Thaumasite)
Examples of tunnel projects in swelling rocks

1. Adler tunnel

Switzerland/ Railway tunnel
Excavation ø with TBM: 12.53 m
Length of tunnel: 5’300 m
Invert Segment

Lining (arch) consisting of precast segments, water proofing PVC membrane and inner lining cast in place
Geology

North portal

South portal

830 m
Cut and cover section

4'260 m
Tunnel

210 m
Cut and cover section

Swelling rock

Gypsum keuper (Anhydrite)

Opalinus-clay

Lias

Marl
Damage observed

› Heave of the entire tunnel in a section of 30 meters, maximum heave of the entire tunnel: up to 7 mm a year

\[
\delta \text{heave}
\]

\[
\begin{align*}
\text{time} & : \text{Oct.98} \quad \text{Oct.00} \quad \text{Oct.02} \quad \text{Oct.04} \quad \text{Oct.06} \quad \text{Oct.08} \quad \text{Oct.10} \\
\delta \text{heave} & : 0 \quad 10 \quad 20 \quad 30 \quad 40 \quad 50 \quad 60 \quad 70 \quad 80 \quad 90
\end{align*}
\]
Measures taken to stop the heave on a 30 m long tunnel section

› niches made of concrete on both sides of the tunnel for stiffening
› Upward micro piles
› Side anchors

δ heave

<table>
<thead>
<tr>
<th>Surface</th>
<th>35 m overburden</th>
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<td>0</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>40</td>
<td>50</td>
<td>60</td>
<td>70</td>
<td>80</td>
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\[ p \text{ [MPa]} \]
2. Chienberg tunnel

Switzerland/Highway tunnel
Excavation diameter: 11.90 m
Length of tunnel: 1’400 m
Construction: 2000-2006

Shotcrete technique
Inner lining cast in place
Geology

Geological formations:

- Gypsum keuper (Anhydrite)
- Upper Coloured Marls
- Opalinus-Clay

1443 m
Damage observed

Uplift of the whole tunnel tube in two sections during time of construction

› heave of tunnel maximum 12.5 cm in 2,5 years
› heave of the surface maximum 4.5 cm
**Damage observed**

Uplift of the whole tunnel tube in two sections during time of construction

› heave of tunnel maximum 12.5 cm in 2,5 years
› heave of the surface maximum 4.5 cm
**Observations**

Uplift of the whole site including the tunnel; proved by measurements 15 m beside the tunnel.
**Uplift-mechanism**

Maximum heave:
- Tunnel: 3-4 mm/Mt
- Surface: 1-2 mm/Mt

Quaternary

Uplift of surface (max. 4.5 cm)

Gypsum keuper (weathered)

Uplift of tunnel section (max. ~12.5 cm)

Intensity 3÷4 mm/month

Gypsum keuper / Anhydrite (hard)

Risks
- Swelling rock

Project examples
- Chienberg tunnel

Design

Current project

Chienberg tunnel

25-30 m Overburden
Measures against uplift

Execution before bringing into service

"Full Resistance"

New "modular deformable concept"
Modular deformable system

2 components
- deformable elements
- mobile anchors
Deformable Elements
Below Tunnel Arch

Pressure due to swelling of Anhydrite, Load: $F_s$

$F_{o}$
Counter-pressure by overburden

Level remains constant → no uplift of tunnel anymore

$F < F_{o}$
max. compression ~35%
constant force

Deformation of deformable elements

Force on tunnel section
Uplift Measurements
Tunnel - Zone 2

Uplift temporarily up to 4 mm/month

Installation of countermeasures

Countermeasures executed

No uplift anymore
Deformable elements today
3. Engelbergtunnel
(Germany/Highway tunnel)
Length of tunnel: 2'530m
Tunnel with 3 traffic lanes and 1 emergency lane
**Damage observed**
Lateral swelling pressure leads to a high pressure load on the tunnel lining.
Damage observed due to swelling:
Cracks in the tunnel lining through which also ground water enters into the tunnel

- cracks in side walls
- cracks, parallel to the tunnel lining
- leakages
Measures that will be taken:
Strengthening of the existing tunnel lining
› new additional lining with a new lining of concrete with a low shrinking concrete
› new suspending ceiling which is able to absorb lateral forces
› execution from 2019 on
Leading design specifications for tunnels in swelling rocks

Selection of system

- Risk of swelling
- Swelling pressure
- Selection of system

- by confining swelling
- by accommodating swelling
Selection of the shape of the tunnel

*circle form shape*

Best shapeform to resist the pressure due to swelling
Structural design
Design of the tunnel lining by applying the method of confining swelling

Approach:
Swelling pressure as external load to the tunnel lining

Establishing (empirical) a max. expected external swelling pressure
For Adler- Chienberg- and Belchen tunnel: q = 4.0 MPa
with load factor: \( \gamma_f = 1,0 \) and
resistance factor for concrete: \( \gamma_m = 1,5 \)

model: with springs spring to simulate the bedding in the rock

Final state q = 4MPa to segment- and inner lining

FEM model
Measures against heave of the entire tunnel

In case the tunnel is located in swelling Anhydrite and the cover (H) is less than 50m, a heave of the entire tunnel is possible.

Design measures:
Changing the tunnel alignment so that in Anhydrite the cover will be always 50m or more.

if not possible: *deformable elements*
→ like Chienbergtunnel
Measures against heave of the tunnel invert

In order to avoid an uncontrolled heave of the invert, a fast ring closure is required e.g. with a TBM and segment lining.
Measures against aggressive ground water
(→ protection of concrete structure)

Special concrete mix design

- High sulfate resistant concrete
- Dense concrete (low W/C-ratio)
- Epoxy coating of the segment surface
- Water sealing membrane

For Example: C55/67

- Chlorid migration coefficient < 3\times 10^{-12}
- Waterproof
- Sulfate resistance
Excavation specifications

**No** water on unprotected rock; because without water *no* swelling

→ **Immediate sealing** of the surface with shotcrete

→ **drainage of the water** in closed piping system

→ drilling for anchors without using water
Current project: Belchen tunnel
an example of a new tunnel in swelling rocks

3rd Belchen tunnel
(Switzerland / Highway tunnel)
Length of tunnel: 3’200 m
Excavation ø of tunnel: 13,56 m
Hard rock shield TBM
Start of construction: 2015
Commissioning: 2021
The existing two Belchen tunnels are in service since 1970.

Significant damages on the tunnel due to the swelling phenomena.

→ Decision for a third Belchen tunnel in order to rehabilitate the two existing tunnels without traffic obstruction (two tunnels always in service).

The existing two tunnels will be rehabilitated after the opening of the 3rd Belchen tunnel.
Geology

Tunnel, length 3'200m
Gypsum keuper (clay, marl, anhydrite) 40% of the length of the tunnel → strong swelling rock
Opalinus-clay 20% of the length of the tunnel → swelling rock
Lime-/marlstone 40% of the length of the tunnel

Transitions with disturbed rock layers
Design

Standard cross section for TBM
Design of the segment - and inner concrete lining
High pressure on the tunnel lining due to swelling solution:

- Segment lining
  - 6+1 segment elements
  - thickness 0.35m, concrete class C55/67
  - reinforcement from 102 to 229 kg/m³
  - additionally: steel fibers: 30 kg/m³

- reinforced inner concrete lining
  - max. thickness in the Anhydrite section at the invert 1.00m and at the top 0.75m
  - concrete C55/67

The standard cross section is designed to resist a swelling pressure of maximum 4 MPa

load factor: \( \gamma_f = 1.0 \)
resistance factor for concrete: \( \gamma_m = 1.5 \)
**Dewatering**

**Hazard scenario:**
Ground water, flows in longitudinal direction of the tunnel entering into swelling rock zones

**Solution:**
14 drainage slots at the invert, located before and after swelling rock zones;
Water is pumped into a longitudinal drainage pipe
→ this measure shall prevent water from flowing into swelling rock.
Concrete mix design

High requirements for the concrete in the tunnel sections in swelling rocks

→ High strength

→ High sulfate resistance
   Special concrete mix design: C55/67 for segment- and inner lining concrete

Specification:
Compressive strength C55/67
f_{ck}[N/mm^2] after 28 days

Executed:
Inner concrete lining (cast in place)
193 samples
average: 75.5 N/mm^2
max. value: 87.0 N/mm^2

Segment lining concrete (precast)
133 samples
average: 89.5 N/mm^2
max. value: 105.0 N/mm^2
Tunneling requirements

- Fast ring closure with load bearing inner concrete lining
- Stringent requirements on the sequencing of the work and the logistic of the contractor

Ring closure in swelling rock (Anhydrite and Opalinus-clay): Within 4 months after excavation the inner concrete lining has to be in place at that location
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Thank you for your attention