Workshop UPC: Tunnelling through Saline and Swelling Ground

# Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground


Thomas Marcher, 20.01.2011

## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Motivation

subject of the presentation:

- to identify effects of time-dependent deformations due to swelling based on design and construction experiences of large infrastructure projects:

- Bosruck Road Tunnel, Austria:
  5.5 km long base tunnel - anhydrite swelling
  NATM with stiff lining concept

- Pfänder Road Tunnel, Austria:
  6.6 km road tunnel – argillaceous clay shale swelling
  TBM with segmental / CIP lining concept

- Niagara Tunnel, Canada
  10.4 km water diversion tunnel in clay shales
  swelling design for lifetime of structure

## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Introduction

■ **Terminology**

- time-dependent deformation described as

  "rock squeeze" and "swelling"

  – however, processes are often interrelated,

  – individual effects of each are difficult to distinguish.

- presentation focuses on "swelling of rock"

  time dependent volume increase due to a physico- (and/or) chemical reaction of the rock with water.

- swelling mechanisms distinguished in:

  – swelling of argillaceous clay shales / marls

  – swelling of anhydritic rock formations.



## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Introduction

■ **Significance of Swelling for tunnel construction**

- success of design and construction of a tunnel related to:

  – the knowledge of geological environment,

  – rock mass parameters, overburden thickness,

  – in-situ stress field, tunnel size and shape, etc.

- long-term deformation often governs the final lining design.

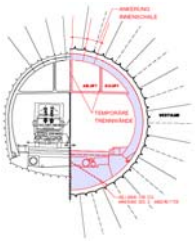
- geotechnical baseline reports often propose unrealistic high swelling pressures:

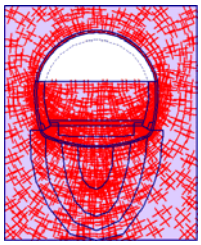
  – due to simply false test results

  – misunderstandings of swelling processes

  overestimations are easily decisive as "go/no-go criteria"

  can be a significant factor for the economic efficiency





## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Introduction

- **Significance of Swelling for tunnel construction**

- **Swelling is not only affected by ground conditions**

  such as rock mass properties, in-situ stress field, supply of water

- **Swelling is also strongly influenced by**
  - the method of excavation (NATM versus TBM),
  - the construction stages
    (full face, fast ring closure, heading stages, etc.),
  - tunnel geometry
    (flat invert versus circular profile and support elements).

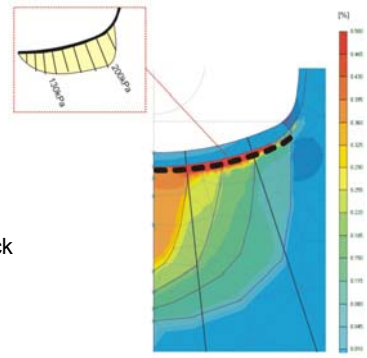


## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Introduction

- **Design Relevant Swelling Pressure**

- swelling pressure in lab tests versus in-situ swelling pressure
  - geomechanical characterization is difficult
  - test and evaluation methods are challenging



- design relevant swelling pressure depends on:

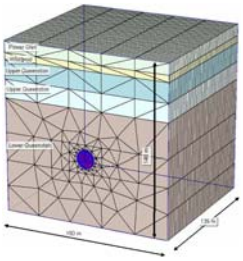
  quality of samples:
  - avoid drying process
  - avoiding volume changes

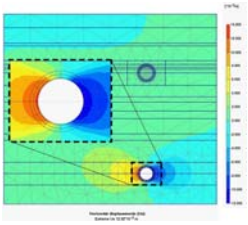
  scaling effect lab / in-situ
  stiffness relation tunnel lining / surrounding rock
  effective water conditions

## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Introduction

- **Applicability of Calculation Methods**





- Numereous calculation methods:
  - time-independent models
  - rheological models
  - coupled (two-phase) models
- highly sophisticated constitutive laws to account for swelling phenomenon
- weak point:
  - identification of key parameters for such swelling laws “scaling effect” does not allow to use test results directly
- alternatives:
  - use of a empirical load” or “volume change” approaches



## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### A9 Bosruck 2nd road tunnel, Austria

- **Content**

- History of Tunneling at Bosruck
- Railway Tunnel
- Motorway Tunnel 1st tube
- Dangers & Rehabilitation
- Design of Motorway 2nd tube
- Excavation works - Status

## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### A9 Bosruck 2nd road tunnel, Austria

■ **Introduction**

- Construction works of 2nd tube of Bosruck road tunnel started in December 2009
- Road tunnel on the A9 Pyhrn motorway
- 4th tube under the Bosruck massiv with a more than 100-year history of tunneling



## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### A9 Bosruck 2nd road tunnel, Austria

■ **History**

- First discussions of a tunnel under the Bosruck tunnel in 1848
- Project failed due to an alternative route passing St. Valentin („Kronprinz Rudolf Bahn – Gesellschaft“)
- Trieste developed beeing a economic centre due to the loss of Venice (1866)
- 1873 economic crisis → no more interest in Pyhrn-tunnel project

## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### A9 Bosruck 2nd road tunnel, Austria

- **History**

  - Due to national interest to improve the importance of Trieste a governmental plan for the construction of the Pyhrn-tunnel was pushed
  - The Bosruck tunnel Project has been estimated to be rather cheap
  - Cost estimate 1901: 12 Mio. Kronen

North Portal – worker's housing



## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### A9 Bosruck 2nd road tunnel, Austria

- **History**

  Construction of the 4766 m long single track railway tunnel started 1901

  - Many violent inrushes of up to 1100 l/s of water into the tunnel

  - KuK supervision and contractors representatives

## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### A9 Bosruck 2nd road tunnel, Austria

- **History**

  - 2300 workers from the Austro-Hungarian monarchy lived together in small villages

  - Flooding of site facilities in the North portal area



## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### A9 Bosruck 2nd road tunnel, Austria

- **History**

  - A methane explosion cost 14 miners their lives. 2 workers died during rescue assistance.


  - Tunneling through November 1905
  - Tunnel has been completed in 1906

## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### A9 Bosruck 2nd road tunnel, Austria

- **History**

  - Total costs: 20.7 Mio Kronen
  - Cost overrun of 80 %
  - Nevertheless, project supported Trieste being most important central european port till 1914
  - 1977 Pyhrn railway lining has been electrified

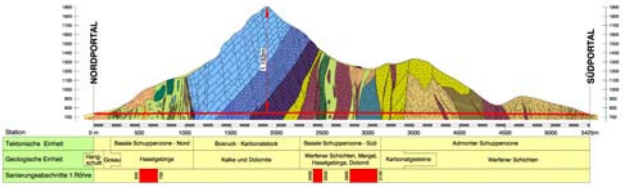



## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### A9 Bosruck 2nd road tunnel, Austria

- **Geology**

  - Eastern part ot the central alps
  - carbonate stock consists of massive and bedded limestone and dolomites
  - basal shale zones (Haselgebirge) consisting of slate, dolomite-anhydrite, marl and limestone
  - to the south lies the Admonter zone consisting mostly of sandstone, claystones, siltstones and quartzite



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### A9 Bosruck 2nd road tunnel, Austria

- **Overview – road tunnel Bosruck**

  - 1978 start of pilot tunnel South
  - 1979 start of pilot tunnel North
  - 1982 1st tube break through
  - 1983 start of traffic 1st tube

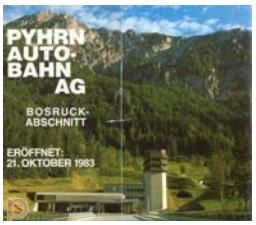



## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### A9 Bosruck 2nd road tunnel, Austria

- **1st tube road tunnel (construction 1980 – 1983)**

  - Positive properties experienced during tunneling through Haselgebirge-formation
  - Only light support has been installed
  - Only small deformations recognized during excavation
  - About a month after first top heading pass first spalling occurred to the structure
  - Proved impossible to stop the creep movement that has started
  - Inner lining (CIP) installed 1983
  - Since 1994 repair works necessary



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### A9 Bosruck 2nd road tunnel, Austria

- **Continuous rehabilitation works**

- 1994 start of intensive measurements
- 1994 systematic additional anchoring
- 1996 / 1998 replacement of the roof in block 425 and 424 (TM 600)
- 1998 – 2000 installing additional monitoring equipment (sliding micrometer, extensometer) TM 600
- 2001 installation of a “safety gear” against “spalling anchors”
- 2002 replacement of the roof in block 426 (TM 600)
- Continuous road rehabilitation
- Rehabilitation of the ventilation & dewatering tunnel

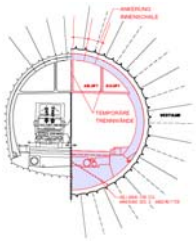


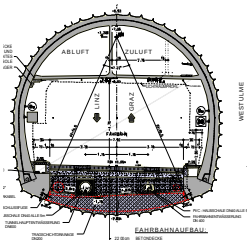
## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### A9 Bosruck 2nd road tunnel, Austria

- **Feasibility study**

- Guaranteeing serviceability
- Guaranteeing ultimate limit state
- Guaranteeing traffic safety
- Reduction of rehabilitation works





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### A9 Bosruck 2nd road tunnel, Austria

- **Results of feasibility study**

  - Original concept listed construction 2nd tube in 2021
  - Feasibility study: 2nd tube to be ready in 2015
    rehabilitation of 1st tube 2016
  - Road rehabilitation (asphalt instead of concrete)
  - Rehabilitation drainage system
  - Stress controller to avoid damage to roofs due to movements



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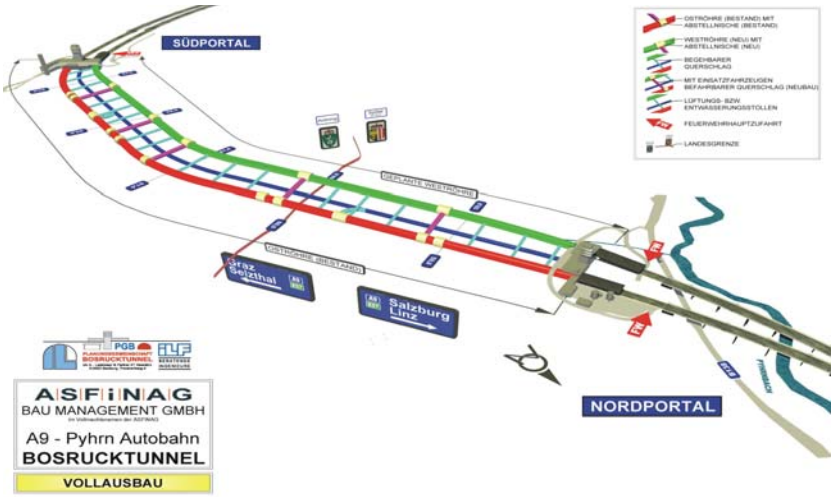
### A9 Bosruck 2nd road tunnel, Austria

- **Design and Rehabilitation Contract**



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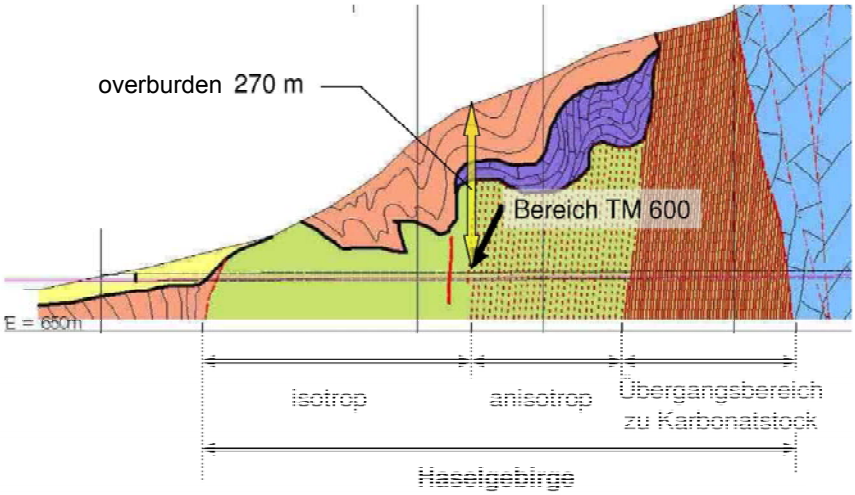
### A9 Bosruck 2nd road tunnel, Austria

- **Geology: Haselgebirge-formation**



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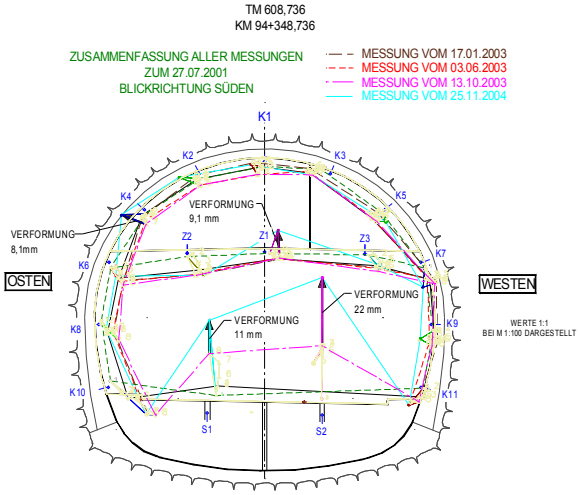
### A9 Bosruck 2nd road tunnel, Austria

- **Monitoring Data from 2001 - ongoing**

- Continuous interpretation
- Deformation rate of max. 6 mm / year !!
- Danger of loss of stability



## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### A9 Bosruck 2nd road tunnel, Austria

■ **Visualization of monitoring data**

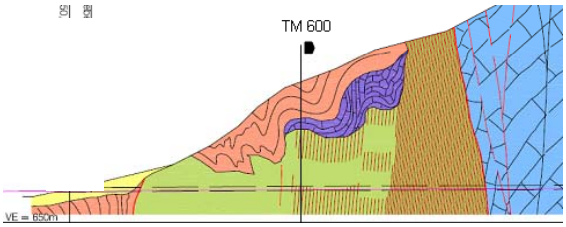



## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### A9 Bosruck 2nd road tunnel, Austria

■ **Potential causes**

- Rock formation:
  - Haselgebirge formation and Anhydrite are highly sensitive to water
  - Haselgebirge formation starts softening
  - Anhydrite is subject to swelling
  - Due to swelling/squeezing processes high rock loads develop
- Construction deficiencies:
  - Inadequate drainage system
  - Existing damage to lining and drainage system
  - Continuous watering of rock



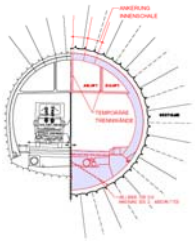
## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

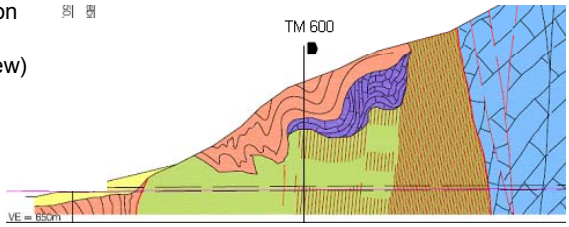
### A9 Bosruck 2nd road tunnel, Austria

■ **Design methodology for Haselgebirge-formation**

- damages occurred in the 1st tube & conclusions regarding the swelling/squeezing behaviour exploited for the design and construction of the second tube
- To cope with expected ground behaviour a circular cross section is applied → "resistance principle"
- 2-step approach for the design:

1. Back calculation 1st tube section
2. Design calculation 2nd tube (new)





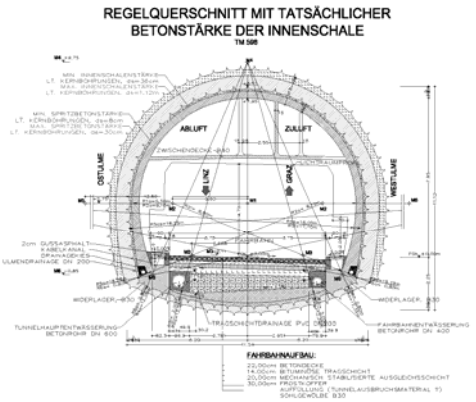



## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### A9 Bosruck 2nd road tunnel, Austria

■ **Back calculation TM 600**

- Geometry 1st tube (representative section)
  - Excavation area 120 m²
  - Shotcrete lining 8 – 30 cm (chosen 18 cm)
  - CIP final lining 36 – 112 cm (chosen 74 cm)

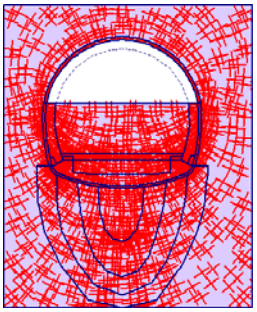


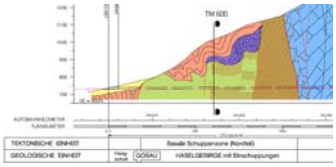
## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

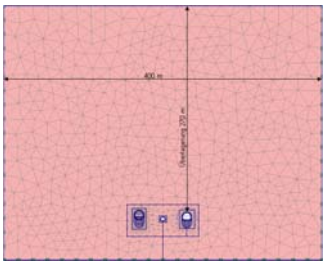
### A9 Bosruck 2nd road tunnel, Austria

■ **Back calculation TM 600**

- FE-model at station TM 600





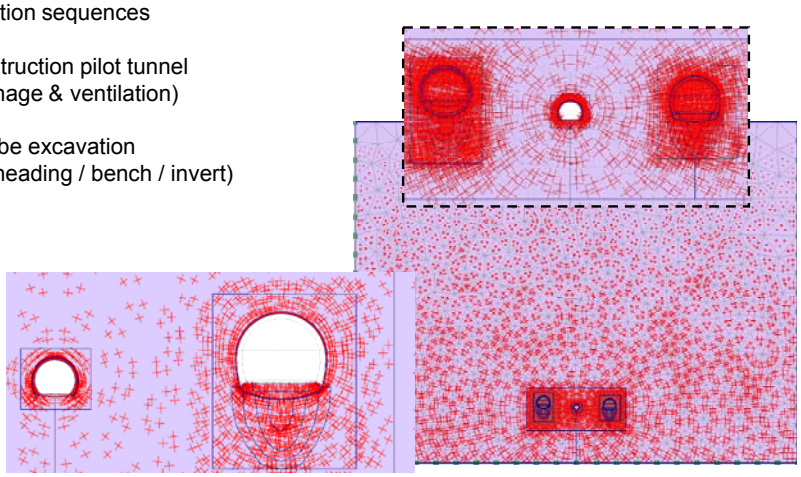


## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### A9 Bosruck 2nd road tunnel, Austria

■ **Back calculation TM 600**

- Construction sequences
  - Construction pilot tunnel (drainage & ventilation)
  - 1st tube excavation (top heading / bench / invert)

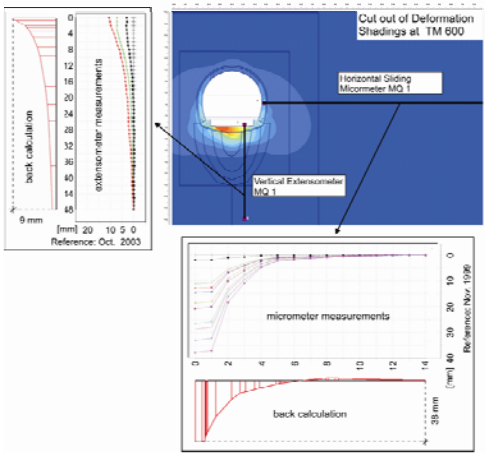


## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### A9 Bosruck 2nd road tunnel, Austria

- **Results of back calculation**

  - Extensometer and sliding micrometer measurements compared to results of back calculation



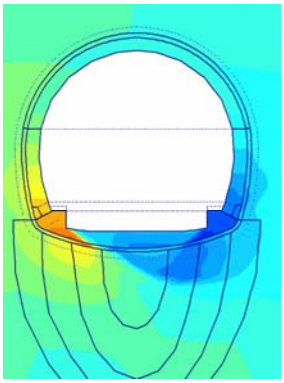



## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### A9 Bosruck 2nd road tunnel, Austria

- **Results of back calculation**

  - simulation of calculated deformations:

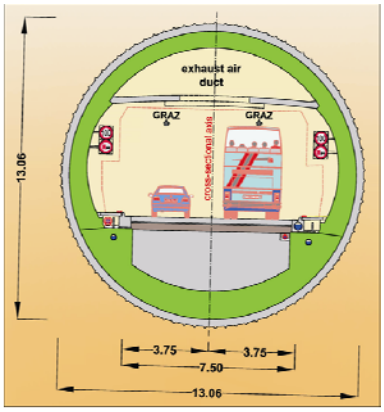


## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### A9 Bosruck 2nd road tunnel, Austria

■ **Design of 2nd tube**

- Typical cross section Haselgebirge-formation
  - circular profile
  - excavation area 130 m²
  - Shotcrete lining 30 cm with yielding elements
  - CIP final lining with 60 – 70 cm thickness
  - invert arch with a min. thickness of 130 cm






## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### A9 Bosruck 2nd road tunnel, Austria

■ **Status of Construction**

- by end of 2010 excavation from the North advanced through the entire Haselgebirge formation.
- excavation from South mainly been performed in silt stone, sand stone and clay stone (Werfen beds).
- According to current time schedule: excavation works finished by end of January 2012

## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### A9 Bosruck 2nd road tunnel, Austria

■ **Experience from Design & Construction**

- critical section designed with
  - a circular shape
  - providing an excavation sequence with a rapid ring closure
- stiff lining concept (i.e. resistant invert arch) has been chosen:
  - dimensions are based on the back-analyses results of the 1st tube.

- uncertainties due to limited knowledge about the swelling / squeezing mechanisms
  - eliminated as much as possible based on experiences gained so far in tunnelling in the Bosruck Massiv during the last 100 years.



## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Pfänder Tunnel 2nd road tunnel, Austria

■ **Content**

- Project overview
- Back calculation 1st tube
- Results of back analysis
- Design aspects 2nd tube
- Conclusions

## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Pfänder Tunnel 2nd road tunnel, Austria

■ **Project overview**

- First Tube:
  under operation since 1980
  L = 6.718 m
- Second tube:
  under construction since 10/2007
  L = 6.586 m




## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

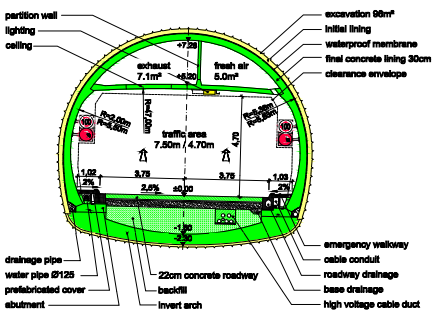
### Pfänder Tunnel 2nd road tunnel, Austria

■ **Project overview**

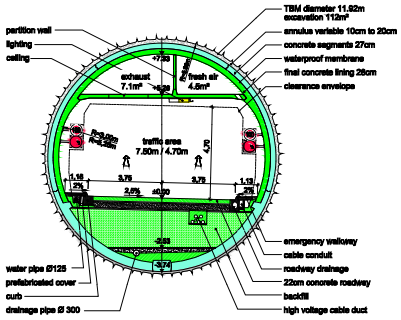
- Drill and Blast (NATM)
- Shield TBM

Double Shell Linings

Shotcrete / Cast concrete




Segmental lining / cast concrete

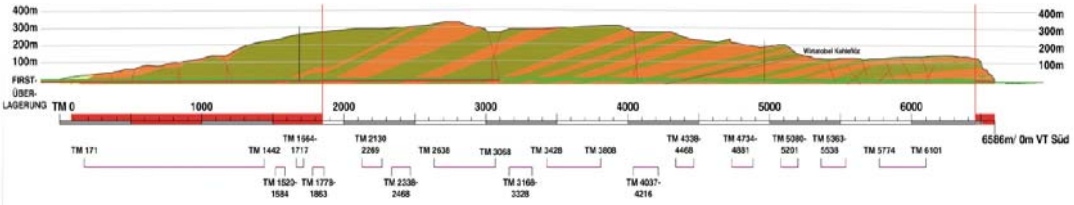


## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Pfänder Tunnel 2nd road tunnel, Austria

■ **Project overview**

- Geology: Molasse




Conglomerate, Sandstone, marly Sandstone

Claystone, marly Clay

max. overburden: 350 m

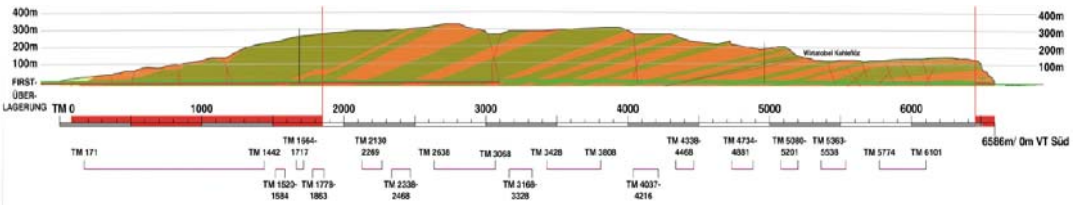


## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Pfänder Tunnel 2nd road tunnel, Austria

■ **Project overview**

- Laboratory investigations for first tube




- max. content of montmorillonite: 7 %
- max. free swelling pressure: 3.5 MN/m²
- max. free swelling heave: 17,8 %

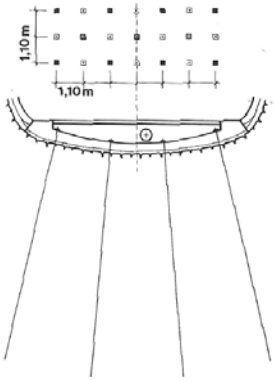
## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Pfänder Tunnel 2nd road tunnel, Austria

- **Back analysis 1st tube**

  - Moderately stiff resistance

    - Invert design:
      400 mm reinforced invert
    - Criterium for anchorage:
      heave exceeding
      5mm / month
    - Durable anchorage:
      52 % typ I = 0,13 MN/m²




ANCHORING OF INVERT
STATION 5290 – 6658

TYPES FOR ANCHORING
SN I $p_A$ = 0,13 MN/m²
SN II $p_A$ = 0,23 MN/m²
SN III $p_A$ = 0.45 MN/m²

NET-LOADBEARING
CAPACITY = 0,64 MN
L = 10,0 m (12,5 m)



## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

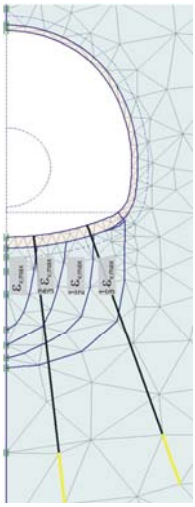
### Pfänder Tunnel 2nd road tunnel, Austria

- **Back analysis 1st tube**

  - Simulation of swelling behavior:

    volumetric strains applied to swelling zone

    - Swelling zone defined based on monitoring results of the 1st tube
    - Swelling strain applied in two stages with variable distribution



## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Pfänder Tunnel 2nd road tunnel, Austria

■ **Back analysis 1st tube**

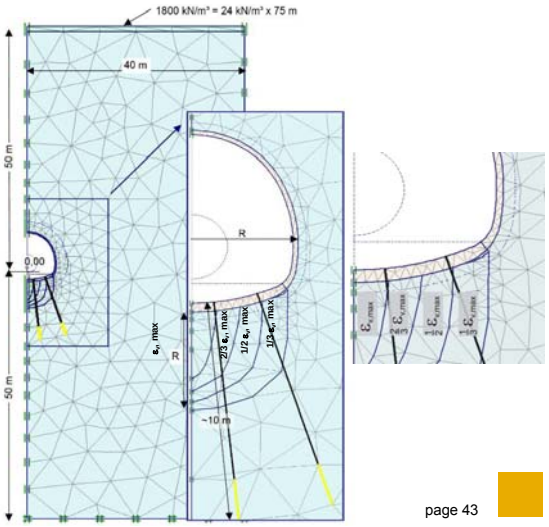
- Simulation of swelling behavior

  Assumptions:

  – Depth of swelling zone: ½ tunnel diameter

  – Max. strain: at center of tunnel

  – Strain distribution: decreasing towards sidewall






## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Pfänder Tunnel 2nd road tunnel, Austria

■ **Back analysis 1st tube**

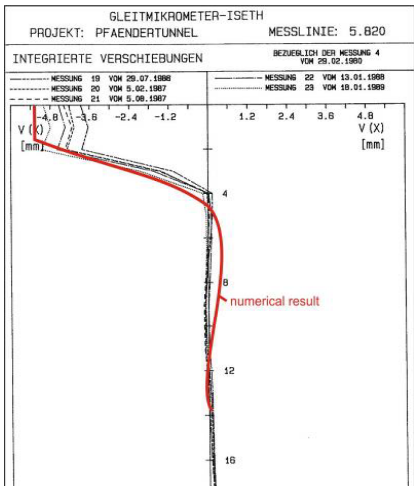
- Comparison of analyses / measurements

  – Result of back analysis:

    50 % swelling after invert construction
    50 % swelling after anchoring

  – Max. swelling strain:

    0,22 % after invert construction
    0,27 % after anchoring

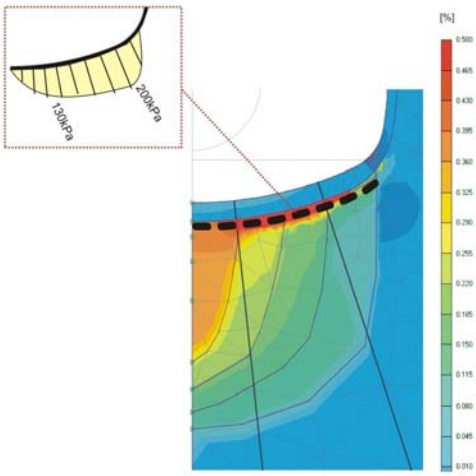


## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Pfänder Tunnel 2nd road tunnel, Austria

■ **Result of back analysis**

- max. swelling pressure 200 kPa, sickle-shaped distribution
- max. pressure at abutment





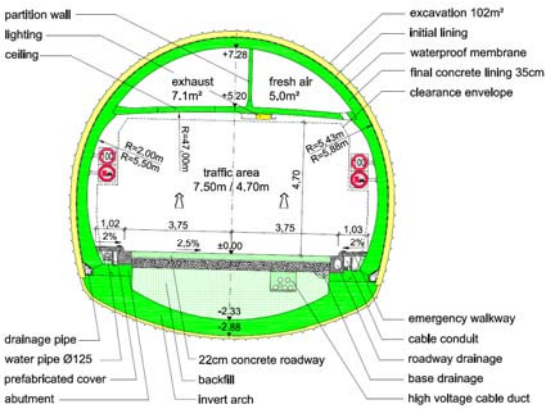

## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Pfänder Tunnel 2nd road tunnel, Austria

■ **Design Aspects 2nd tube**

- Cross Section – Drill and Blast (NATM)
  - Semi Stiff Lining Concept:

    deep invert (optimized)
    invert thickness min. 70 cm
    no anchorage

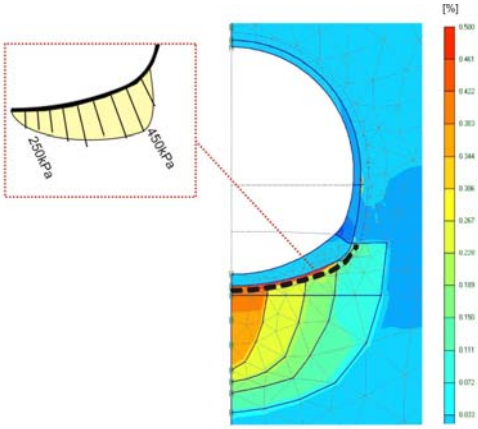


## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Pfänder Tunnel 2nd road tunnel, Austria

■ **Design Aspects 2nd tube**

- Drill and Blast (NATM)
  - Swelling pressure during final stage: 250 to 450 kPa
  - Sickle-shaped distribution
  - Maximum Pressure at abutment



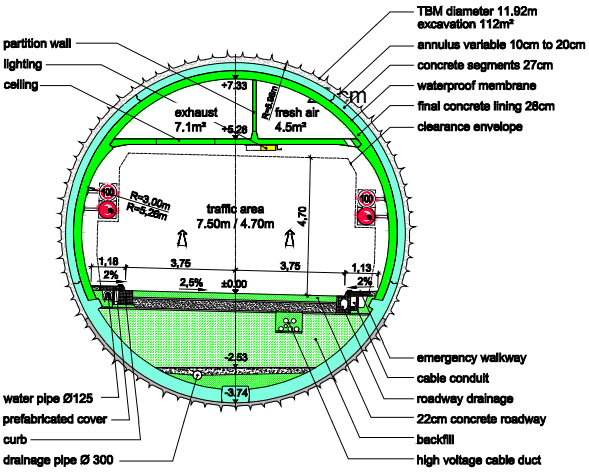



## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Pfänder Tunnel 2nd road tunnel, Austria

■ **Design Aspects 2nd tube**

- Cross Section – Shield TBM
  - Profile lining segments concrete 28 cm
  - Invert lining segment 55 cm

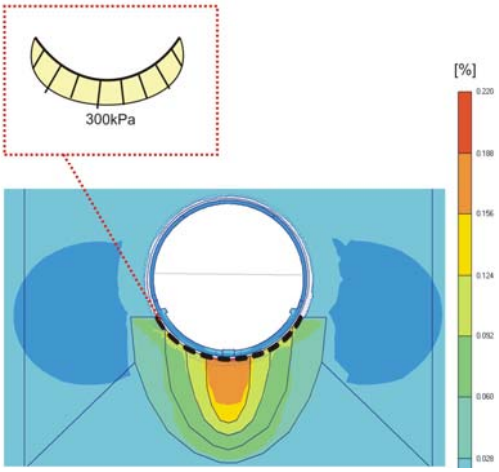


## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Pfänder Tunnel 2nd road tunnel, Austria

■ **Design Aspects 2nd tube**

- Shield TBM
  - Swelling pressure during construction max. 300 kPa
  - Uniform distribution
  - Zero at abutment



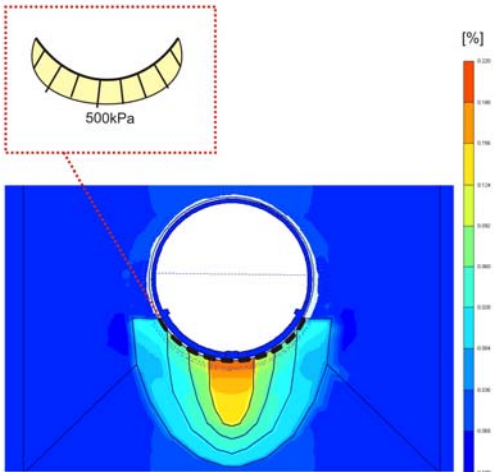



## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Pfänder Tunnel 2nd road tunnel, Austria

■ **Design Aspects 2nd tube**

- Shield TBM
  - Total swelling pressure after installation of final lining max. 500 kPa
  - Uniform distribution
  - Zero at abutment



## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Pfänder Tunnel 2nd road tunnel, Austria

■ **Design Aspects 2nd tube**

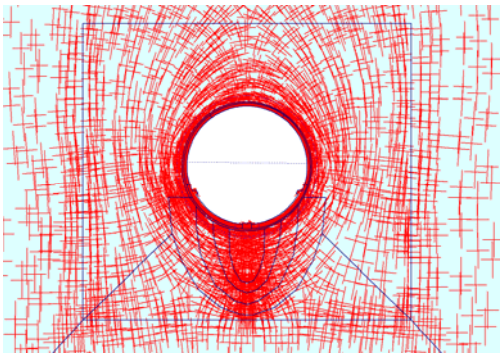
- Shield TBM awarded

  Conclusion:

  – Swelling pressure back calculated from drill and blast = safe side

  – Lining capacity depends on subgrade reaction

  – High swelling pressure requires grouting of pea gravel





## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Pfänder Tunnel 2nd road tunnel, Austria

■ **Status of Construction**

- TBM excavation initiated in September 2008
- in November 2009 TBM breakthrough took place
- sequential excavation works were completed in July 2010
- concreting works are expected to be completed in late 2011
- second tube is scheduled to be opened to traffic by mid-2012 (as is the start of the rehabilitation works for the first tube).

## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Pfänder Tunnel 2nd road tunnel, Austria

■ **Experience from Design & Construction**

- 1st tube of the Pfänder Tunnel:

  - high swelling pressures caused damage to the invert slab
  - required a permanent anchorage of the reinforced invert slab
  - used to optimise the invert design for the 2nd tube.

- stresses acting on the tunnel invert depend greatly on:
  - tunnel geometry (shape, size)
  - support resistance of the invert.

- presumed swelling strain model:
  - able to yield reasonable swelling stresses (max. swelling stress and distribution) if magnitude of swelling strain can be back-calculated from measured data



## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Niagara – Water Diversion Tunnel, Canada

■ **Content**

- Project Overview
- Key Design Aspects
- Chloride Diffusion Analysis
- Rock Swelling Analysis
- Conclusions

## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Niagara – Water Diversion Tunnel, Canada

- **Project Overview**


Fig. 3. Niagara Tunnel Project – Elements and Layout of the Work

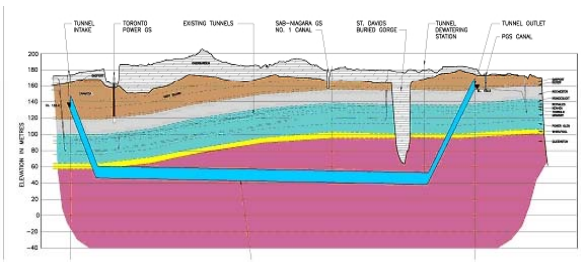



## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Niagara – Water Diversion Tunnel, Canada

- **Project Overview**

- 10.4 km water diversion tunnel
- 14.4 m diameter excavation
- discharge 500 $m^3/s$
- Overburden of approx. 140 m underpassing a glacial gorge filled with sediments



## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Niagara – Water Diversion Tunnel, Canada

- **Project Overview**

# Canada launches world's largest hard-rock TBM

A CEREMONY was held on August 8 to celebrate the official start-up of the largest hard-rock TBM in existence for the Niagara Tunnel Project. The 14.4 m (47.5 ft)-diameter Robbins TBM has now been fully assembled in Queenston, Ontario, Canada and is currently under way.

The completion of the machine comes several weeks ahead of an aggressive 12-month schedule. The TBM was assembled onsite rather than at the Robbins factory in Solon, Ohio. The swift build was hailed by contractor Strabag AG as "unprecedented for a TBM of this size."

As of mid-August, the Robbins TBM was ready to begin its 10.4 km long bore connecting the Sir Adam Beck Generating Complex to an intake shaft above Niagara Falls. The project, launched by owner Ontario Power Generation (OPG), will increase the maximum capacity of the generating complex by 150 MW. The increased power generation is much needed since the current system is close to exceeding its capacity during peak summer months.

The TBM launch ceremony was attended by top executives from Ontario Power Generation, Strabag AG, and The Robbins Company. Dalton McGuinty, the premier of Ontario, gave a speech and started the machine. The ceremony concluded with the turning of the cutterhead.

*The huge cutterhead of the Robbins Niagara TBM taken with a fisheye lens*

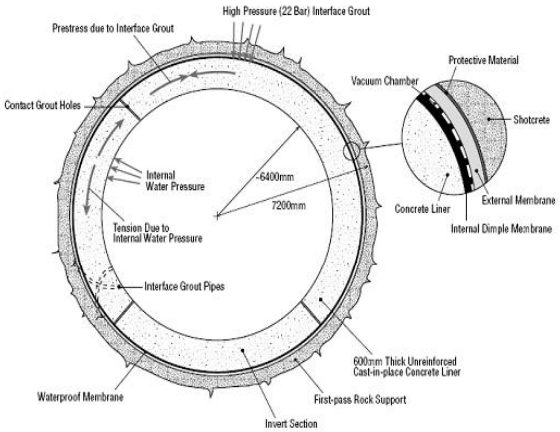


## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Niagara – Water Diversion Tunnel, Canada

- **Key Design Aspects**

  - Tunnel lining concept

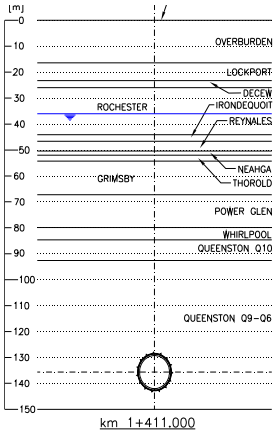


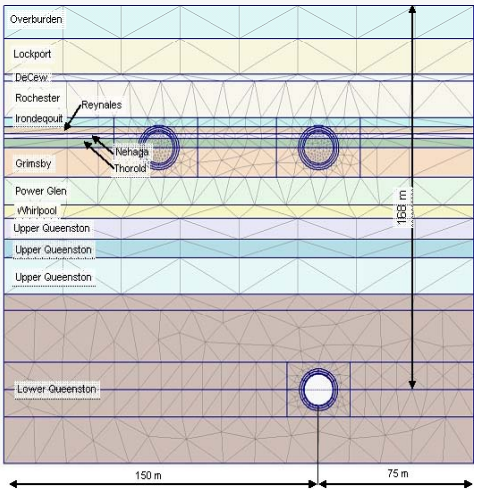
## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Niagara – Water Diversion Tunnel, Canada

■ **Key Design Aspects**

- Geological / geotechnical model



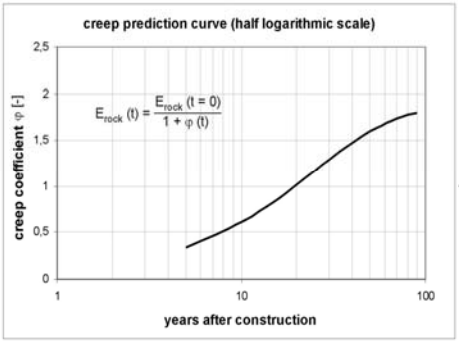


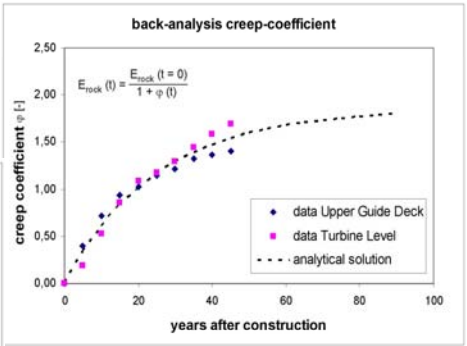

## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Niagara – Water Diversion Tunnel, Canada

■ **Key Design Aspects**

- Creep / squeezing conditions



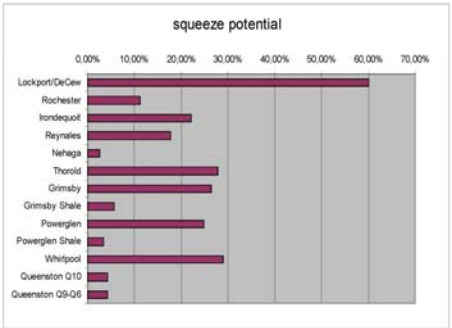



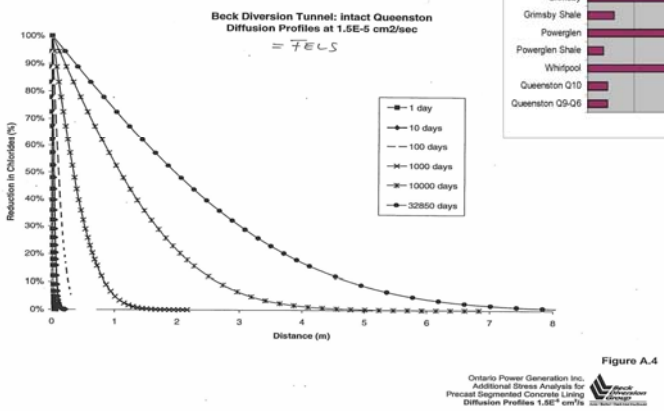
## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Niagara – Water Diversion Tunnel, Canada

■ **Key Design Aspects**

- high content of chloride
- Chloride ions concentration changes
- swelling potential due to reduction of chlorides






## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Niagara – Water Diversion Tunnel, Canada

■ **Chloride Diffusion Analysis**

- Shales with high chloride contents swell if concentration of chloride ions in pore fluid of rock mass is reduced

  ⇨ assumption: initiation of swelling for a 2% reduction

- question:

  How do boundary conditions govern penetration depth of diffusion front into surrounding rock over a period of 90 years?

- scope:

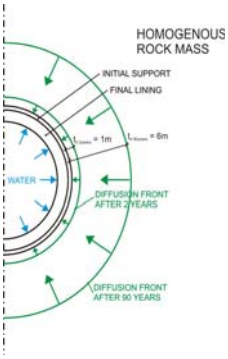
  investigate influence of materials' diffusion coefficients and shotcrete thickness on penetration depth of 2% reduction front

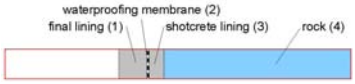
## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Niagara – Water Diversion Tunnel, Canada

■ **Chloride Diffusion Analysis**

- Physical Background
  - Diffusion within pore fluid from zones with higher concentration (in-situ rock mass) to lower concentration (tunnel circumference)
  - 4 layers: final lining, waterproofing membrane, shotcrete and rock, applied at different excavation stages
    ⇨ influence diffusion gradient
    ⇨ consideration of multiple-phase-medium necessary






## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Niagara – Water Diversion Tunnel, Canada

■ **Chloride Diffusion Analysis**

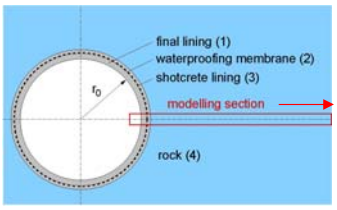
- Numerical Modelling
  - Differential equation for diffusion, expressed for radial symmetry:

$$\frac{\partial C}{\partial t} = -D \cdot \left( \frac{1}{r} \frac{\partial C}{\partial r} + \frac{\partial^2 C}{\partial r^2} \right)$$

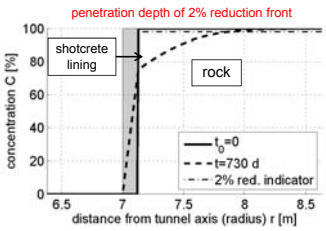
with chloride concentration $C$, time $t$, coefficient of diffusion $D$ and radial coordinate $r$

⇨ Solution with two-dimensional Finite Difference Scheme (MATLAB) Point 2.2

  - Discretisation of the time variable $t_j$ (j=1…m) with increments $\Delta t$ = 0.1 d and spatial variable $r_i$ ($i$=1…n) with increments $\Delta r$ = 1.0 cm
  - Integration with an implicit "forward time, centred space" scheme

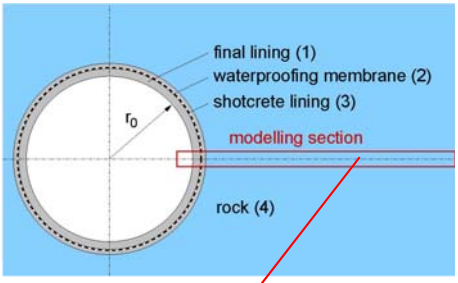



cf. Figure 2

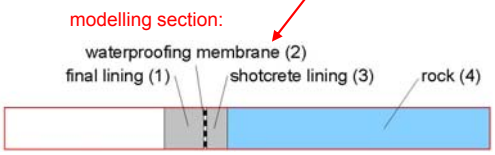


## Chloride Diffusion Analysis

- analysis
  - geometry of the multiphase system




  - modelling section



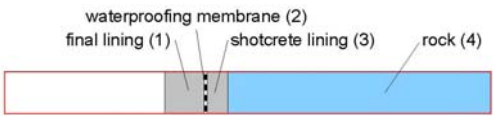





## Chloride Diffusion Analysis

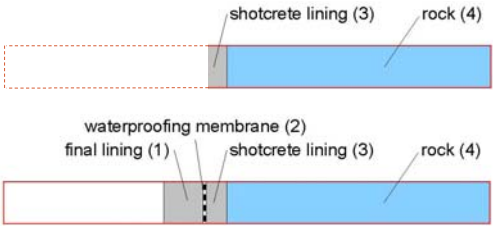
- geometry and material parameters

| | layer thickness | diffusion coefficient |
|---|---|---|
| final lining: | $d_1$ = 0.600 m | $D_1 = 1.5\times10^{-5}$ cm²/s |
| membrane: | $d_2$ = 0.003 m | $D_2 = 1.5\times10^{-8}$ cm²/s |
| shotcrete lining: | $d_3$ = 0.130 m | $D_3 = 1.5\times10^{-6}$ cm²/s |
| rock: | $d_4$ = 14.000 m | $D_4 = 1.5\times10^{-5}$ cm²/s |



## Chloride Diffusion Analysis

- time discretisation
  - calculations from $t_1$ = 0 (start of the tunnel excavation) to $t_{end}$ = 33,580 d (construction time + lifetime of the structure)
  - for the first 2 years (= 730 days) only layers 3 and 4 active
  - after that layers 1 and 2 activated and change in chloride concentration calculated for an additional 90 years

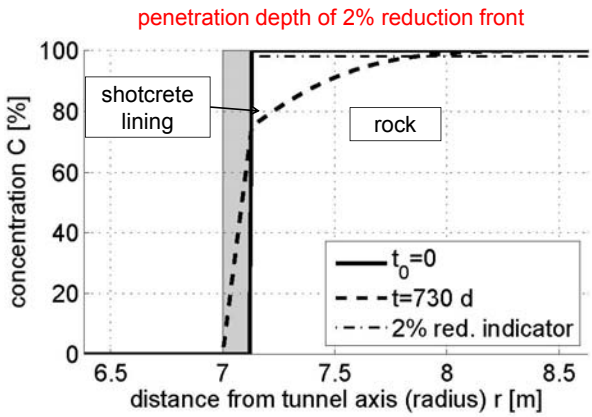







## Chloride Diffusion Analysis

- Evaluation of Results
  - Distribution of chloride concentration after 2 years



## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Niagara – Water Diversion Tunnel, Canada

■ **Chloride Diffusion Analysis**

- Evaluation of Results
  - Distribution of chloride concentration after 90 years

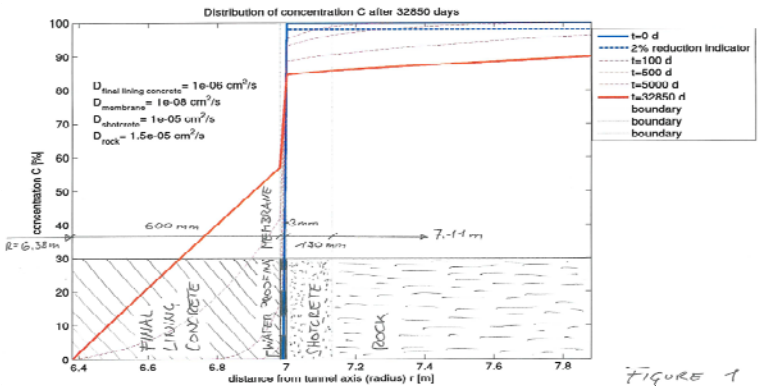



FIGURE 1

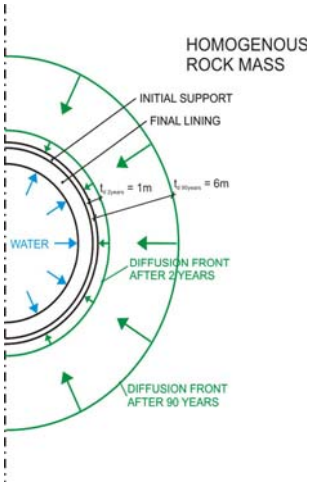


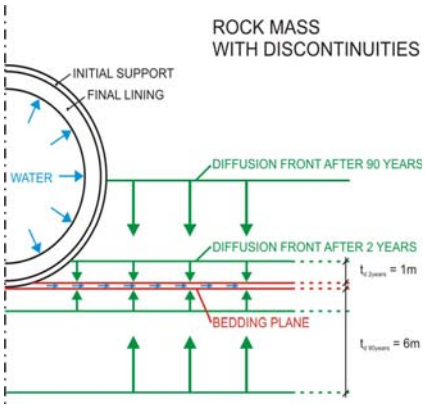
## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Niagara – Water Diversion Tunnel, Canada

■ **Chloride Diffusion Analysis**

- Evaluation of Results



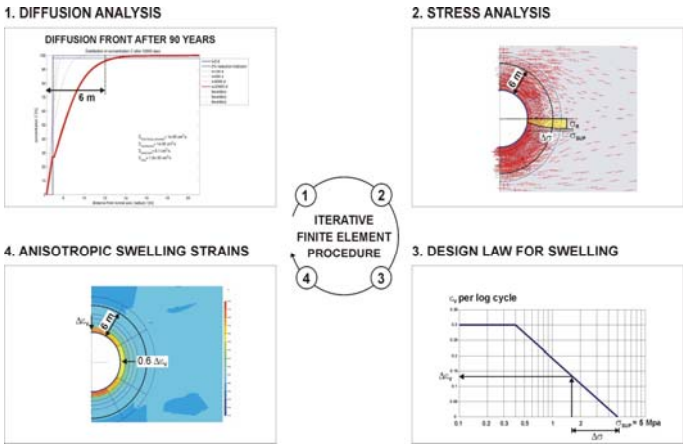



## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Niagara – Water Diversion Tunnel, Canada

■ **Rock Swelling Analysis**

- Calculation procedure of swelling



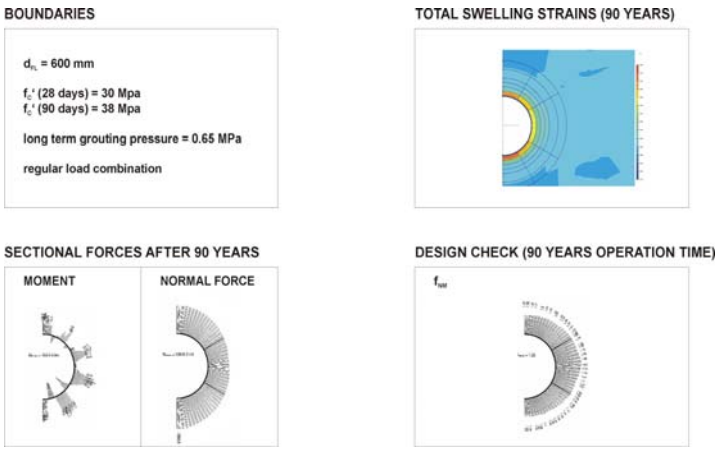



## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Niagara – Water Diversion Tunnel, Canada

■ **Rock Swelling Analysis**

- Calculation Results

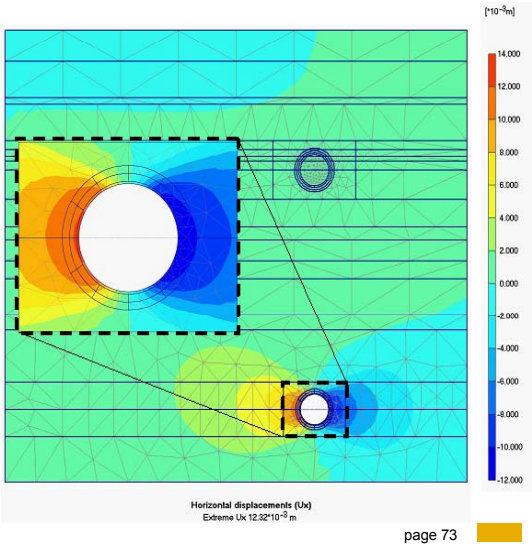


## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Niagara – Water Diversion Tunnel, Canada

- **Rock Swelling Analysis**

  - Calculation Results






## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Niagara – Water Diversion Tunnel, Canada

- **Status of Construction**

  - September 2005 official ground breaking ceremonies
  - TBM excavation initiated in 2006/2007
  - end of 2010 the TBM has reached 9,200 meters:

    - TBM is approximately 68 meters below the surface of the Niagara River and is mining an average of 9.7 meters daily

  - at 9,846 meters TBM will breakthrough into the existing grout tunnel
  - project to be completed in 2013.

## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Niagara – Water Diversion Tunnel, Canada

- **Experience from Design & Construction**

- design swelling pressure may correspond to the final equilibrium state expected in the long term
  -> swelling potential exhausted.
- for long-term, swelling design can be optimised
  -> expected pressure at the end of the intended lifetime
- for the project a reduction of chloride concentration by 2 % is defined as the extent of swell initiation
  -> “diffusion front”
- based on differential equations for diffusion a robust and fast numerical model developed
  -> estimate the potential and order of magnitude of swelling (spatial and timely distribution) for the intended lifetime of the tunnel structure.



## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground

### Conclusions

experiences gained in the projects can be used to make the following statements:

- essential for reducing the swelling is preventing the introduction of water.
  -> avoid any water ingress into the rock formation.
  -> rock surface shall be immediately sealed with shotcrete when using NATM.
  -> in case of TBM drives, it is important to avoid importing water into tunneling works.
- to minimize existing water from ingressing into the surrounding rock
  -> chose favourable cross sections
  -> preventing the formation of water routes (especially in edges)
- selecting preventive construction sequences:

  -> invert ring closure close to the excavation face
  -> by NATM fast ring closure
  -> by TBM shield tunnelling with immediately installed precast segments.

## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground
### Conclusions

- laboratory **swelling tests lead to an overestimation** of swelling pressures and strains:

  -> reason could be sample disturbance (strength, stiffness, stress state, etc.)
  -> scaling factor between the macro behaviour in the rock mass and the meso behaviour in the lab tests

- tunnelling in swelling ground is **not a problem that has been solved** at all.

- **no criteria exist** for the selection of a lining principle.

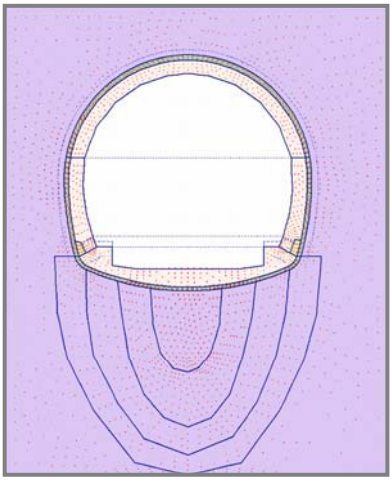
- due to uncertainties in describing swelling behaviour there is a **great need for research**:

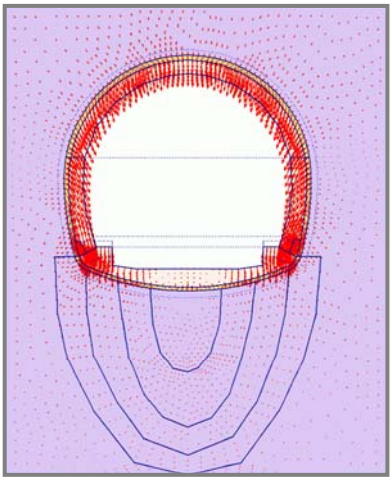
  -> in laboratory testing (taking the long periods of observation into account)
  -> developing more realistic and adequate constitutive swelling laws.

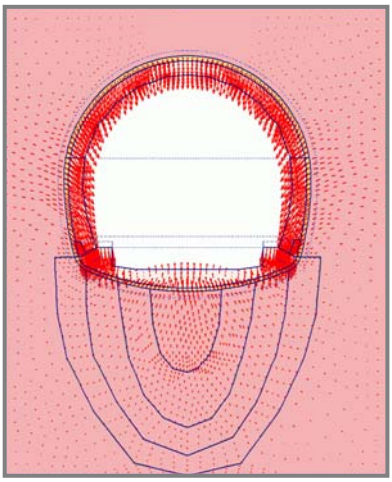


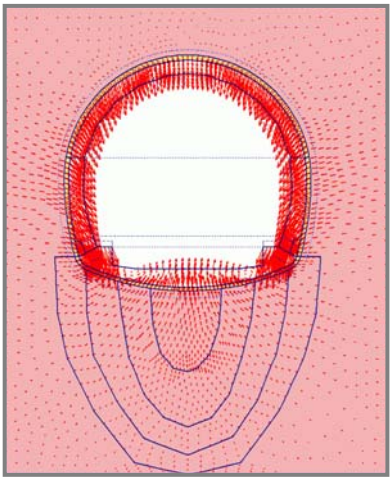
## Tunnel Design and Construction Practice: Technical Solutions in Swelling Ground
## Thank you for your attention!

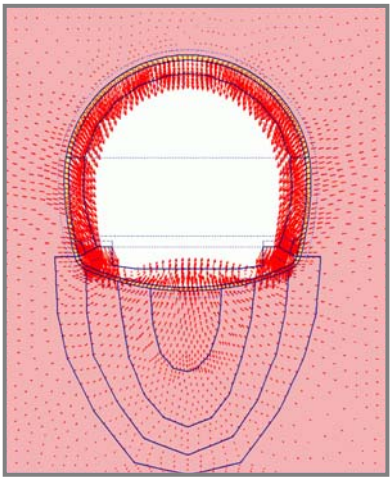
# MOVIE

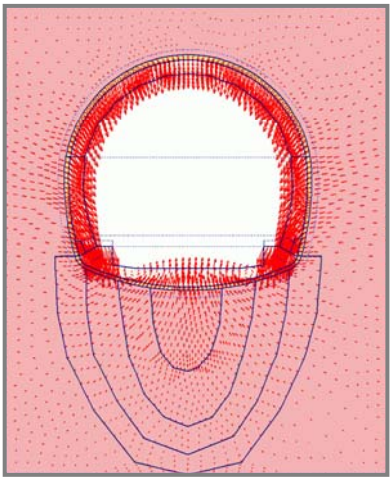


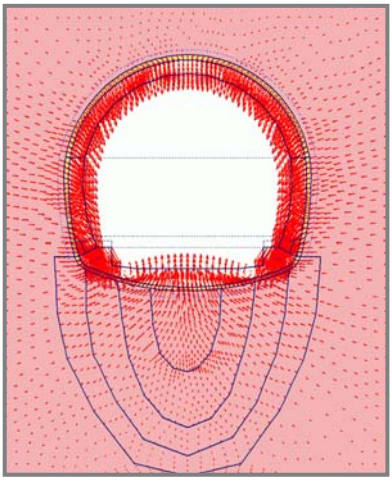


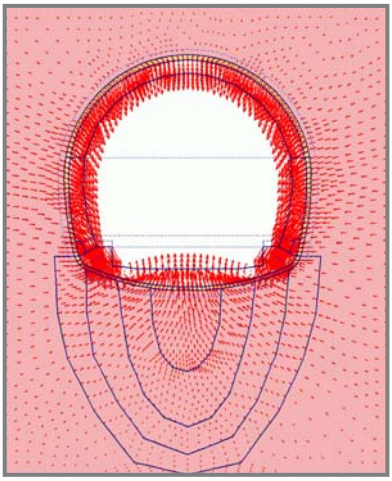


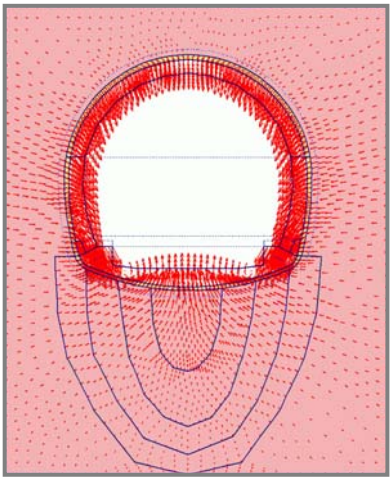


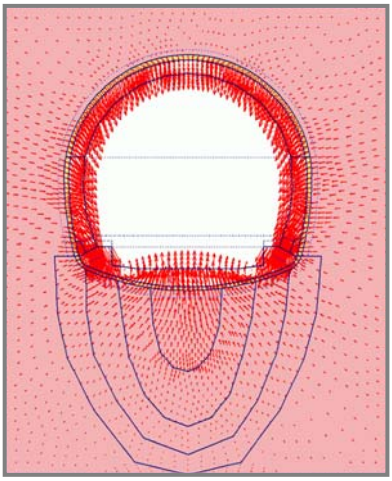


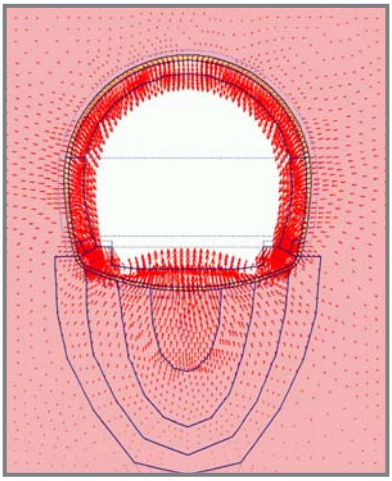


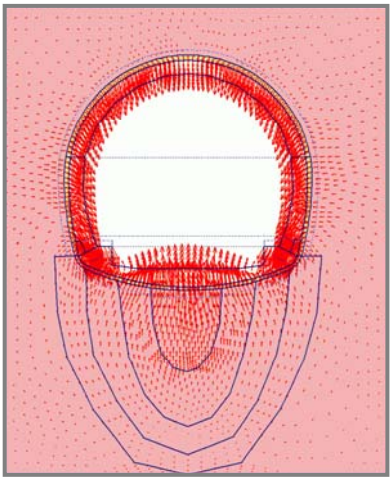


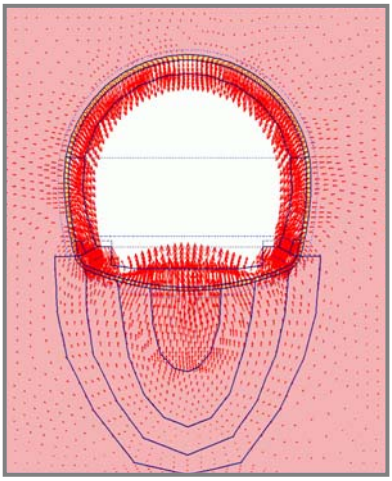


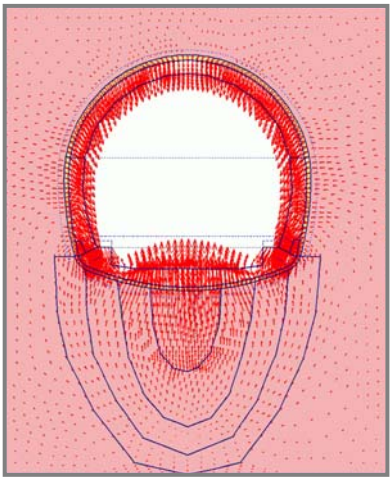


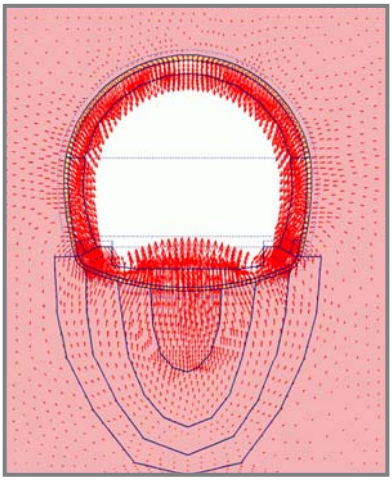


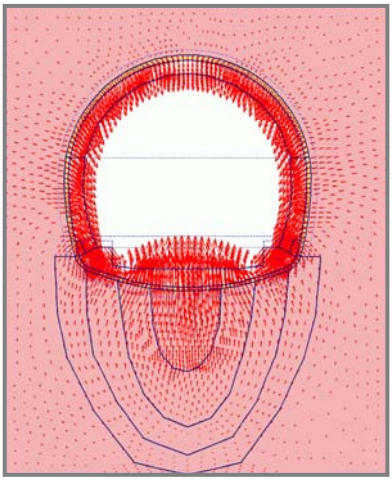


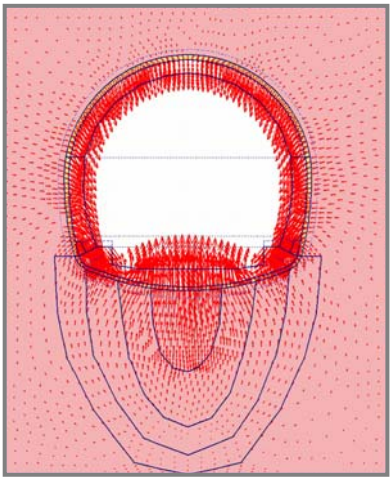


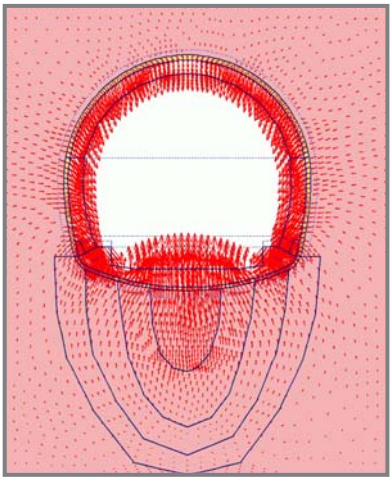


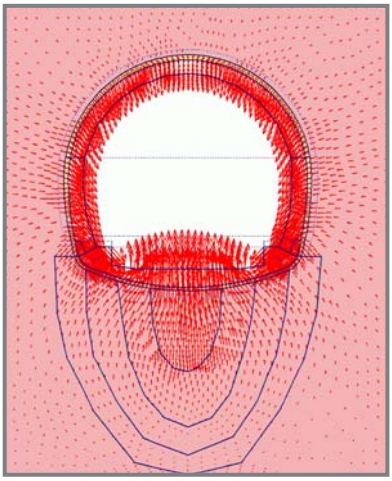


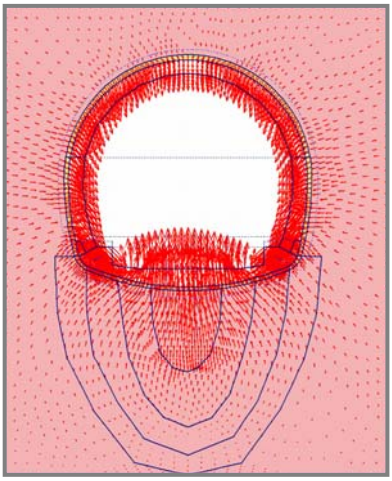


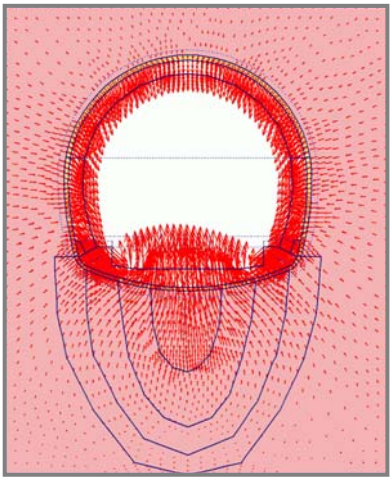


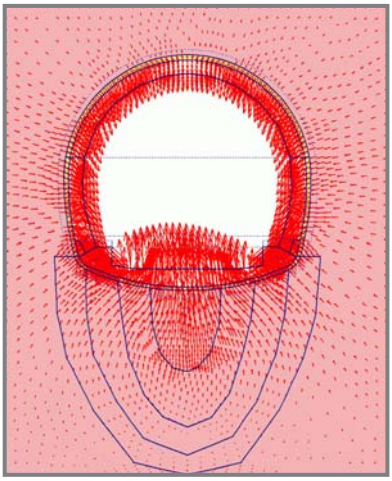


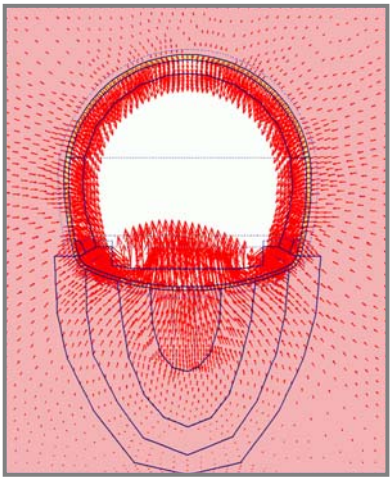


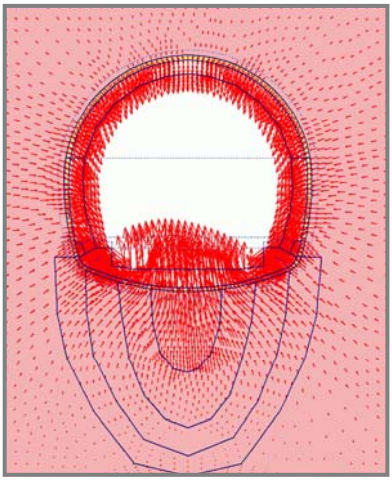


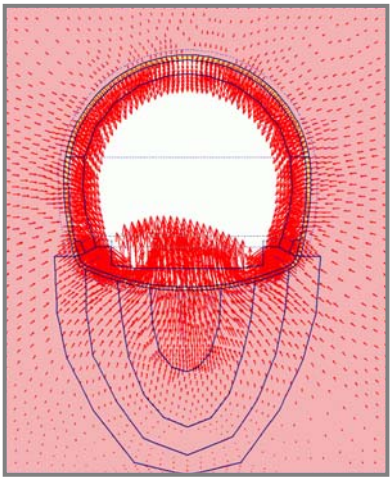


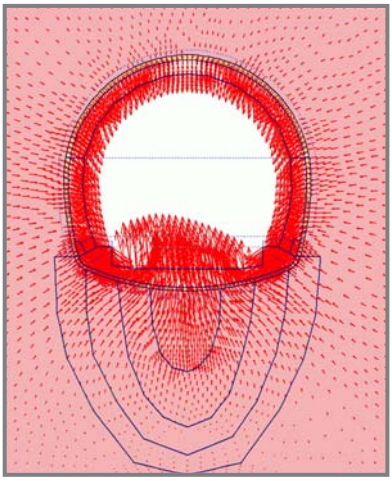


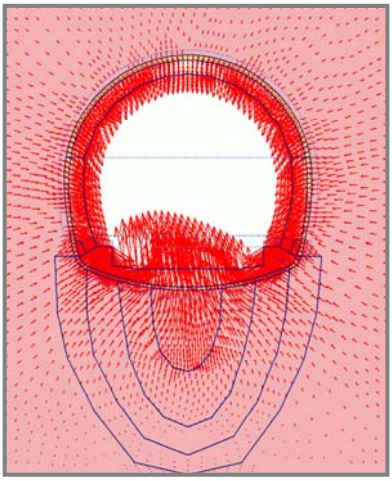


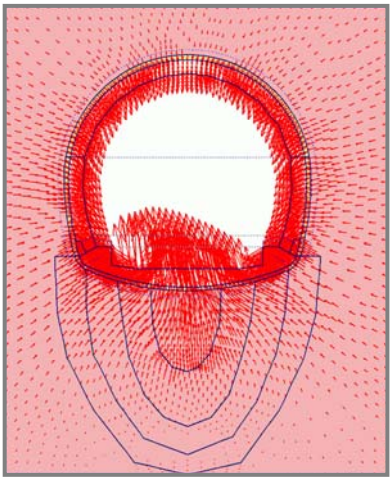


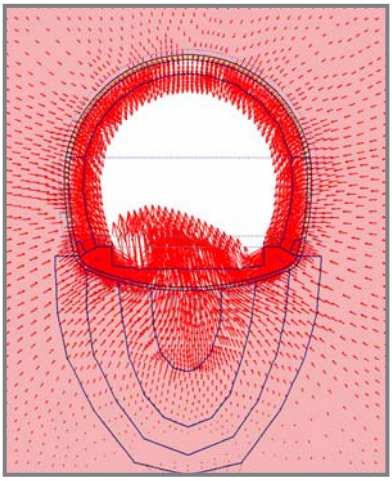


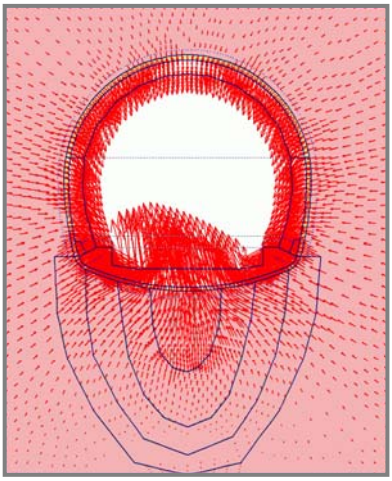


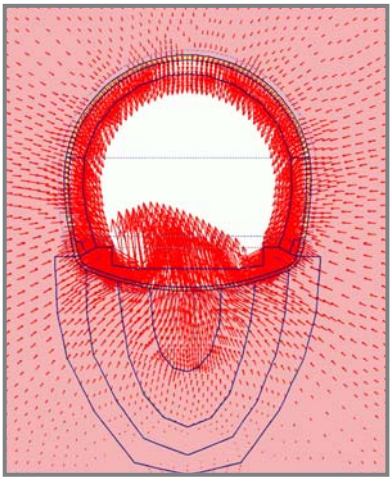


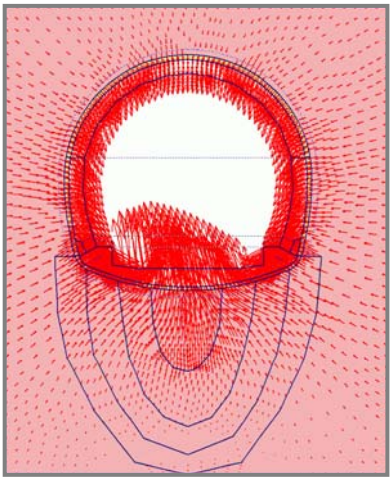


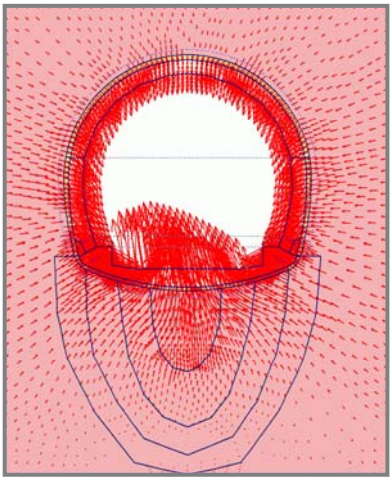


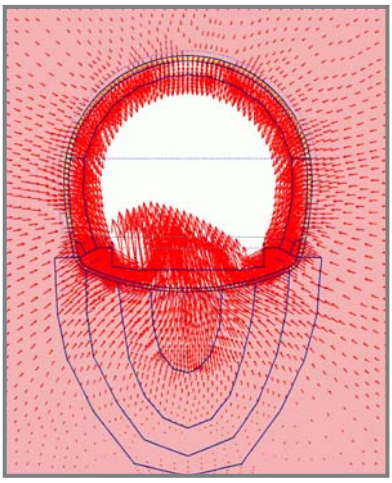












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