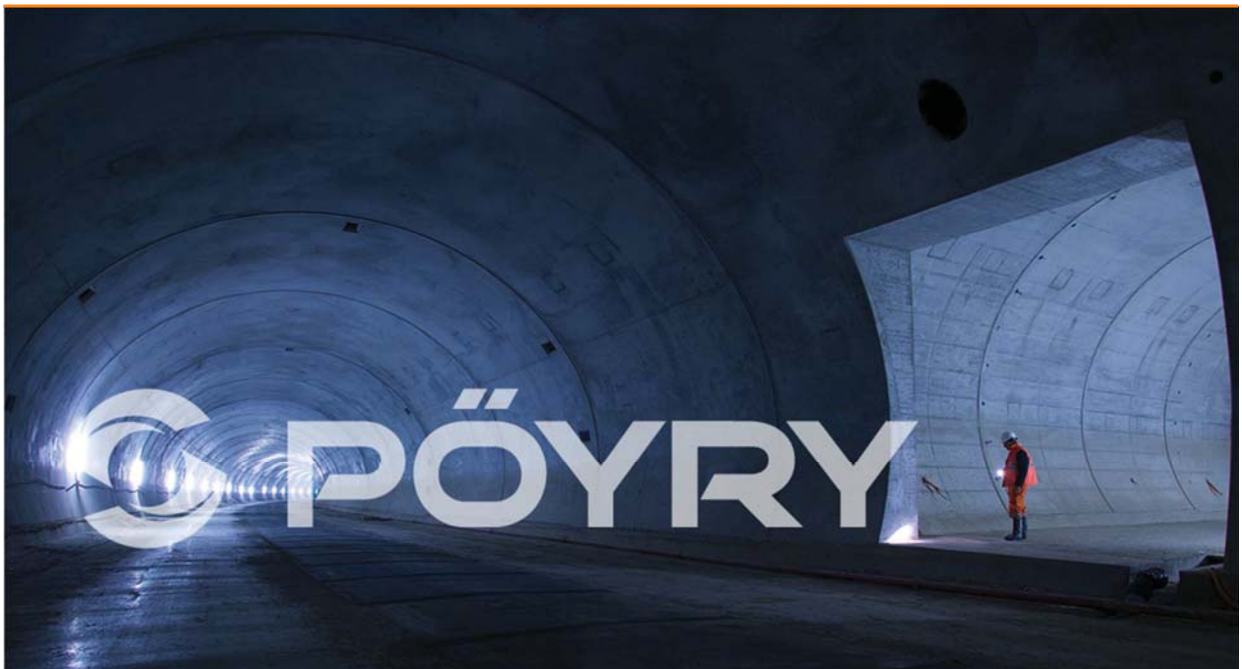


Issues related to the design of a deep geological repository in Opalinus Clay: A parameter study for tunnel stability with conventional design models

February 14th , 2014

Dr. Philippe Nater

PRESENTATION OUTLINE

Aim of the parameter study

Typical cross sections

Lining considerations

Modeling approaches

Results

Conclusions

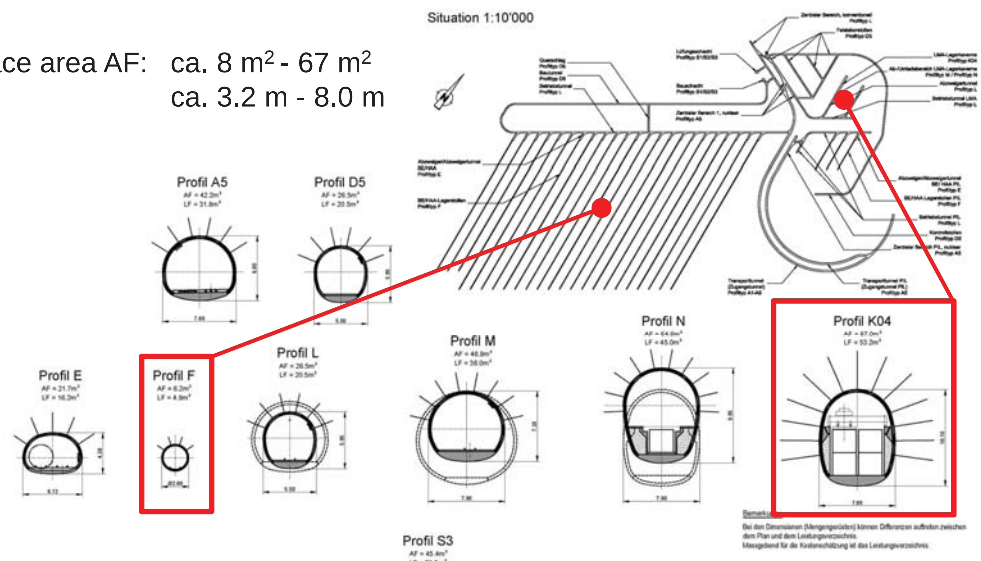
AIM OF THE PARAMETER STUDY

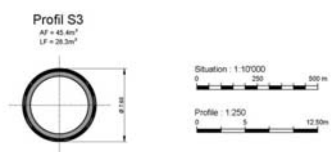
- Assess the engineering feasibility of an underground deep repository
  - In terms of tunnel stability during construction and operation
- How to assess tunnel stability
  - Design the openings according to applicable codes (e.g. SIA 118/198, 197 – 199, 260 - 267)
  - Take advantage of experience: Mont Terri Rock Laboratory (CH), Grenchenberg Tunnel (CH), Schacht Konrad (DE), Meuse-Haut-Marne Rock Laboratory (Fr), etc.
- How to design the underground openings
  - Risk assessment and hazard situations → Identify the main (geotechnical) risks
  - Experience → Find solutions from underground works under comparable conditions
  - Selection of reliable (robust) engineering concepts → Don't drive the system to the limit
  - Geotechnical design calculations! → Evaluate suitability of the selected concepts

Comment: Design is not done only by so called 'design calculations'. It includes proposing robust rock support and lining concepts (e.g. following the concept of support classes), using appropriate construction methods, taking advantage of experience from executed tunneling projects and finally including close observation and supervision during construction (e.g. observation in URL on site).

TYPICAL CROSS SECTIONS

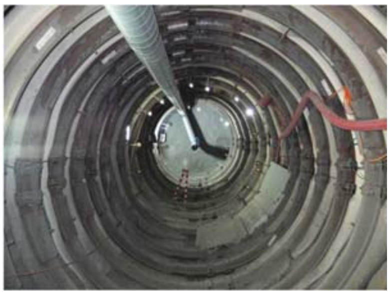
Excavation face area AF: ca. 8 m^2 - 67 m^2
Span width: ca. 3.2 m - 8.0 m





Requirements:
- Reliable stability and serviceability during construction and operation
- Limit host rock disturbance for long term safety

LINING CONSIDERATIONS



FE-Experiment, Mont Terri Rock Laboratory
2 “Intermediate Seal”

- Support
  - Circumferential and as close as suitable to the face
    - Maintain rock mass strength by confinement (EDZ)
    - Avoid open voids in the near field (EDZ)
  - Yielding support ability (flexible liner)
    - Avoid extensive failure in the support by limiting the axial stress

→ 1 Standard support: Sprayed concrete + wire mesh reinforcement + yielding elements
→ 2 “Intermediate Seal”: Steel ribs (TH profiles) + wire mesh + yielding sections
→ 3 Additional support: Combination of 1 and 2
→ 4 Rock bolting: As required

Road header device

- Excavation
  - Road header with short shield
    - Industrial and efficient advance and liner placement
    - Fast liner placement
    - High profile accuracy / limit contour line deviation

→ Allow the support to operate effectively

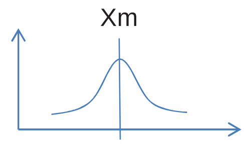
MODELING APPROACHES: GEOMECHANICAL PARAMETERS

- 1 Geomechanical parameters
  - Laboratory scale + experience + interpretation
  - Design levels (Codes)
- 2 Rock mass models
  - Tunnel scale / rock mass scale → conceptualization
  - 6 standard situations describing possible rock-mass conditions
- 3 In-situ stress models
  - 3 standard situations describing probable in-situ stress conditions
- → Geomechanical parameter set
  - Combination of
    - 1 Geomechanical parameters
    - 2 Rock mass models
    - 3 In-situ stress model

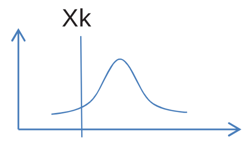
→ To be used as input for further geomechanical considerations

MODELING APPROACHES: GEOMECHANICAL PARAMETERS

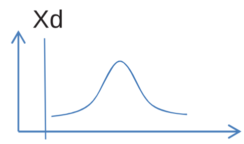
Sketch of design levels based on a normal distribution



- Design levels
  - Xm Prediction level
    - Most probable → geomechanical parameter set including variability assessment



  - Xk Serviceability design on “characteristic” level
    - Defined by the code (e.g. SIA 267-4.2.3), taking into account the variability of parameters
    - →Cautious interpretation of the prediction level
    - Creates a unfavorable design scenario (with a small likelihood)
    - → The structure needs to remain in service (serviceability)



  - Xd Ultimate limit state
    - Defined by the code (e.g. SIA 267-5.3.2) to take into account unexpected properties and phenomena
    - →Derived from characteristical level Xk, partial safety factors
    - Creates a design scenario which is beyond experience
    - →The structure needs to remain stable (ultimate limit)

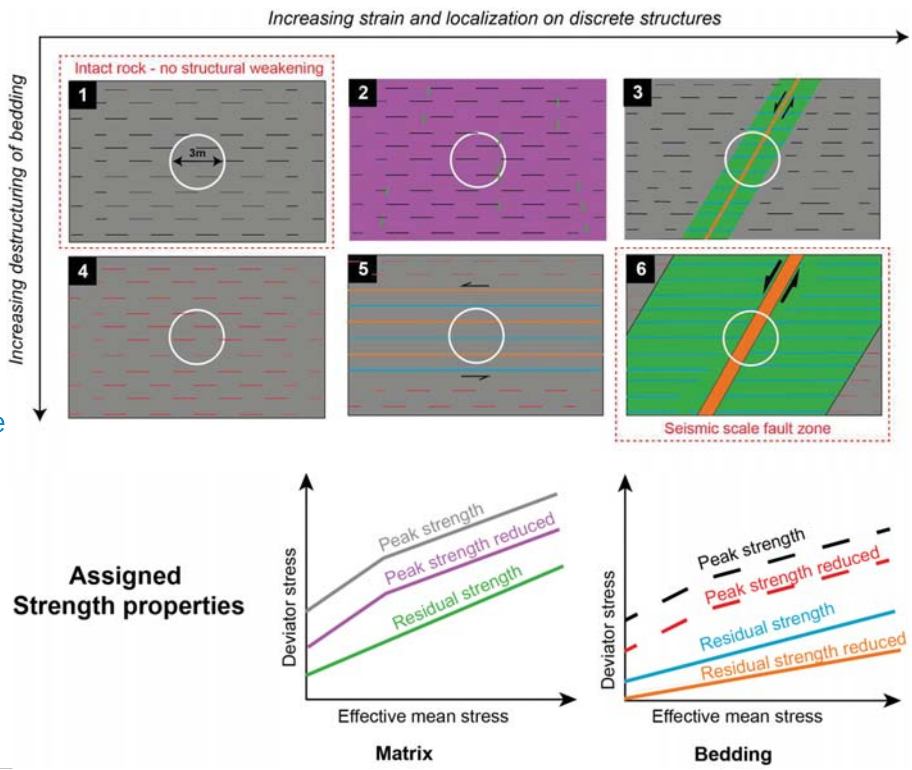
MODELING APPROACHES: ROCK MASS MODELS

- Conceptualization of the rock mass →geomechanical parameter set

- Following rock mass models presented:

1 Intact rock mass (target and reference material)

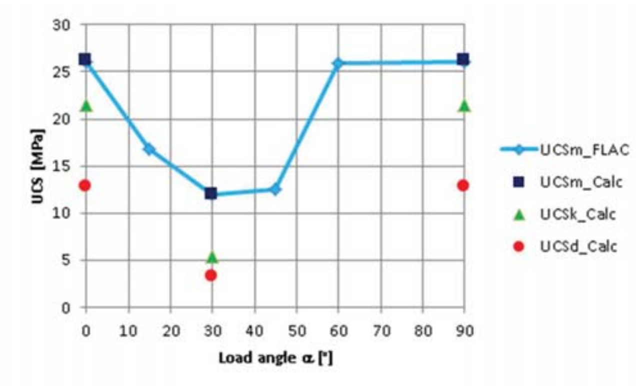
4 Partly damaged bedding



MODELING APPROACHES: STRENGTH ANISOTROPY

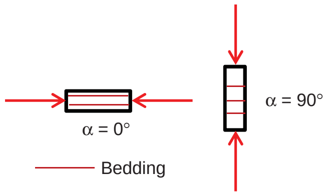
- Laboratory scale - experimental observations
  - Uniaxial compressive strength UCS
  - Dependency of UCS to the load direction

  (is observed in case the fabric/bedding is well represented within a sample)



UCS vs. load angle - computed in FLAC 3d based on Rock mass model 1.

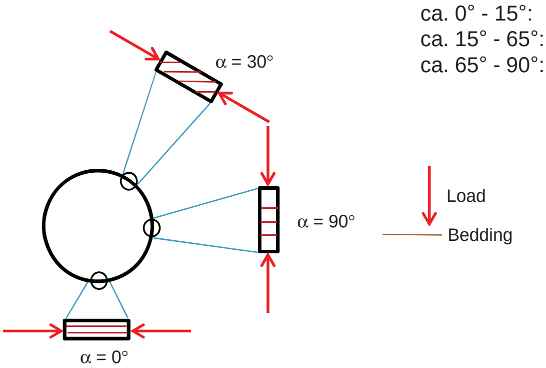
Failure mechanisms:
ca. 0° - 15°: Buckling
ca. 15° - 65°: Shear failure along bedding
ca. 65° - 90°: Shear failure across matrix



MODELING APPROACHES: STRENGTH ANISOTROPY

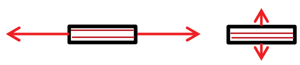
- Tunnel scale / rock mass scale - analytical considerations
  - Laboratory sample at the extrados => UCS – test
  - Tangential stress σ_t at the extrados (Kirsch, 1898)
  - Comparison: UCS vs. tangential stress σ_t (Salencon, 1969)

Failure mechanisms:
ca. 0° - 15°: Buckling – tensile failure of bedding → Roof/Invert
ca. 15° - 65°: Shear failure along bedding
ca. 65° - 90°: Shear failure across matrix– tensile failure of matrix → Springline



Virtual laboratory sample at the tunnel extrados.

Strong axis: Tensile strength parallel to fabric
Weak axis: Tensile strength perpend. to fabric



Tensile strength: Left strong axis, right weak axis.

MODELING APPROACHES: TOOLS

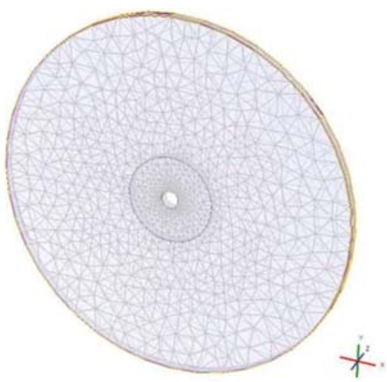
- Closed form solutions, e.g. Salencon (1969), Ground Reaction Curves (e.g. Corbetta et al., 1991)
  - Order of magnitude
  - Identification of significant phenomena
  - Benchmarks
  - Loads for structural analysis => liner design
- VisualFEA
  - Structural analysis of the lining – main design calculation approach in tunnel engineering
- FLAC 2d – numerical code for continuum analysis (drained / undrained)
  - Investigation of the systems behavior
  - Stability and Serviceability assessment
    - Extend of displacements / convergence strain
    - Excavation damaged zone (EDZ)
  - Stability assessment of the rock-mass
  - Stability assessment of the lining (structural design)
- FLAC 3d – numerical code for continuum analysis (undrained)
  - Investigation of the systems behavior
  - Tunnel face behavior

RESULTS: CLOSED FORM SOLUTIONS

- Stress vs. strength comparison: Salencon (1969)
  - Anisotropic in-situ stress
  - Isotropic strength
  - Circular openings
  - No softening, no strength anisotropy

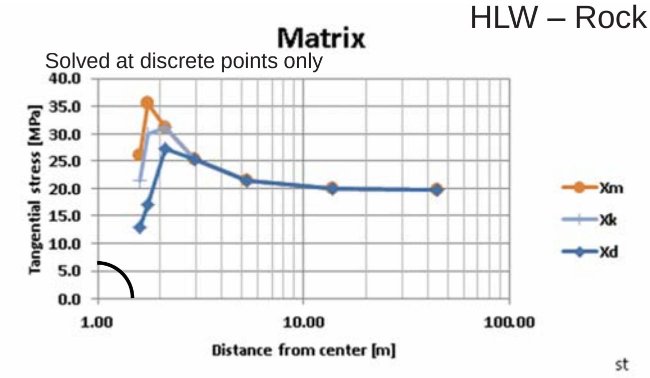
  - Evaluation of tangential stress vs. Mohr-Coulomb strength
    - Peak strength – no softening
    - UCS at excavation surface
  - Overburden: 400 m – 800 m
  - Parameter set: Xm / Xk / Xd
  - Rock-mass model: 1 – intact rock
  - Opening
    - HLW → A = 8 m^2, D = 3.2 m
    - L/ILW, K04 → A = 67 m^2, D = 9.2 m

    (Circle with equivalent area)

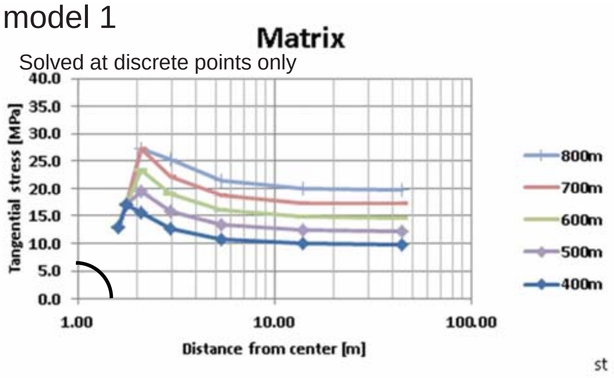


Cylindrical hole in a Mohr-Coulomb medium (RockScience: RS3 verification example)

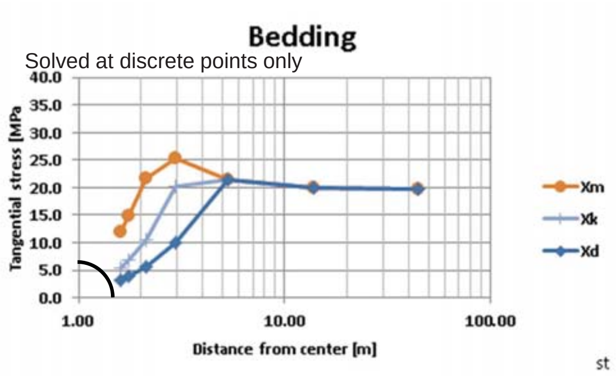
HLW – Rock model 1

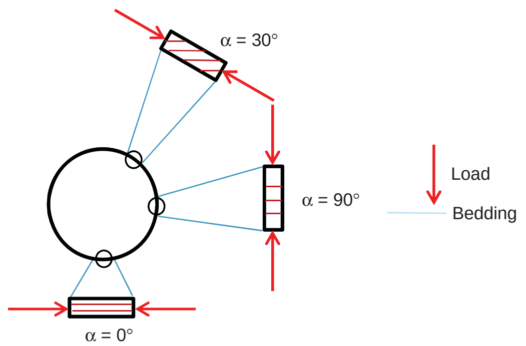


800 m – Influence of the design level



Xd – Influence of the overburden





RESULTS: CLOSED FORM SOLUTIONS

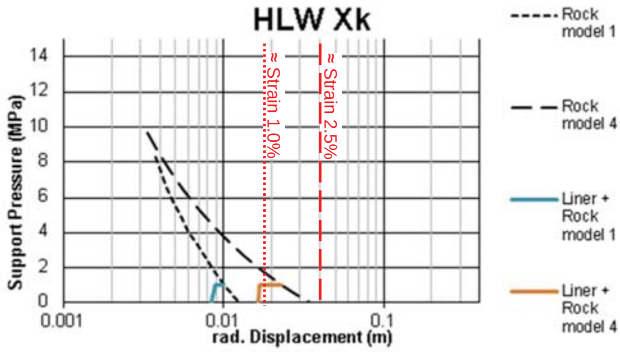
- Ground reaction curve (GRC): Corbetta et al. (1991)
  - Isotropic in-situ stress
  - Isotropic strength
  - Circular openings
  - No softening, no stress anisotropy, no strength anisotropy

  - Radial displacement vs. support pressure
  - Overburden 800 m
  - Parameter set Xk / Xd
  - Rock-mass model: 1-intact rock / 4-partly damaged bedding
  - Opening
    - HLW → A = 8 m^2, D = 3.2 m
    - L/ILW, K04 → A = 67 m^2, D = 9.2 m

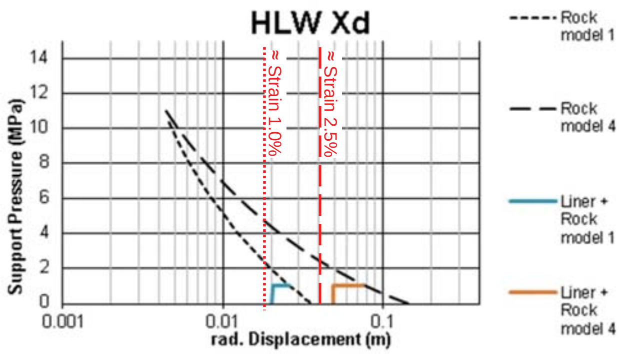
      (Circle with equivalent area)
  - Lining: 0.2 m reinforced shotcrete including yielding elements (corresponding support pressure approx. 1 MPa)

- Plastic part of the GRC
  - Within the graph: Influence of the rock mass model (1 vs. 4)
    - Xk and Xd: approx. x 2.5
  - Comparing the graphs: Influence of the design level (Xk vs. Xd)
    - Rock model 1 and 4: approx. x 2.5

→Variability impact from
Xk / rock model 1
to
Xd / rock model 4
approx. 2.5 x 2.5 > 6



800 m

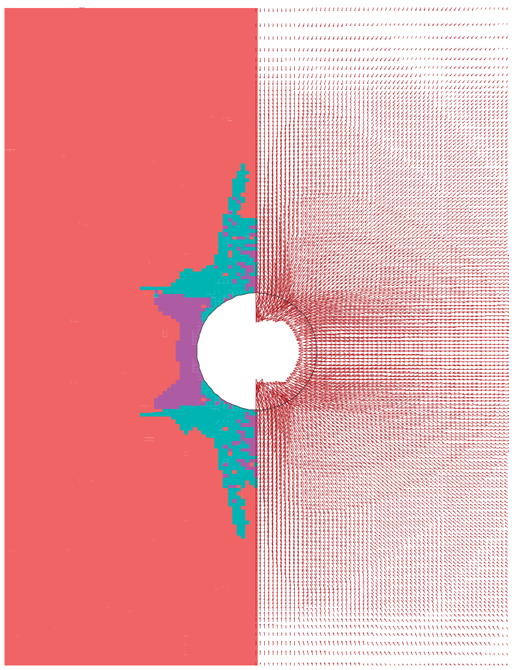


RESULTS: FLAC 2D

- Numerical analysis on a continuum
  - Anisotropic in-situ stress
  - Anisotropic strength
  - Arbitrary openings
  - Softening
  - Hydro-mechanical coupling
  - No stiffness anisotropy

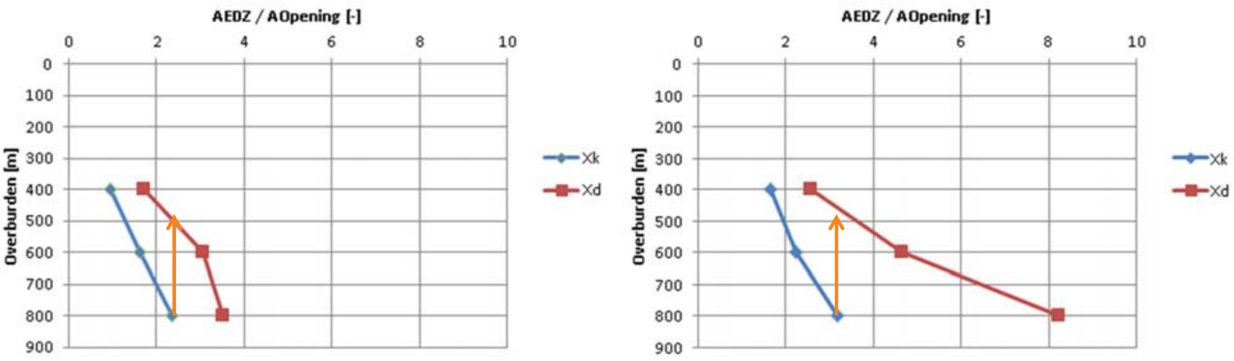
  - Evaluation displacements & EDZ
  - Overburden: 400 m – 800 m
  - Parameter set: Xk / Xd
  - Rock-mass models: 1 & 4
  - Opening HLW

EDZ Displacements

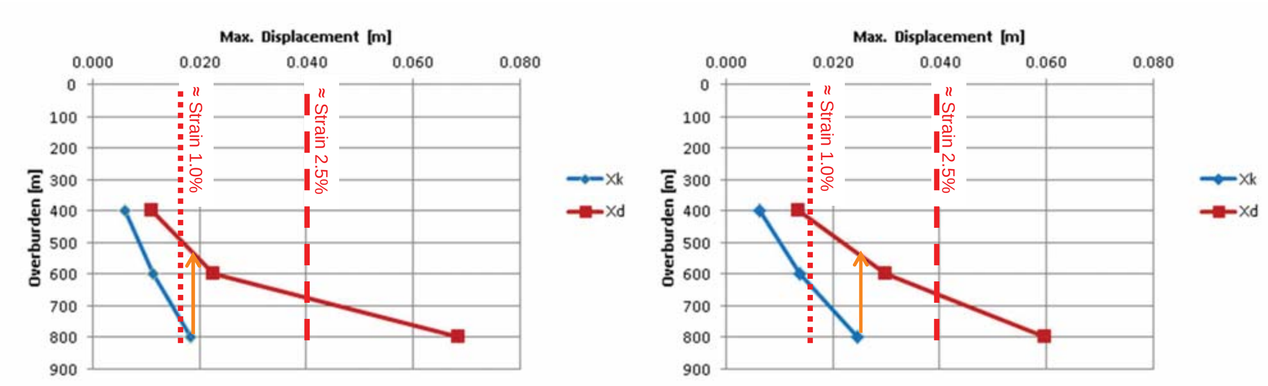


Rock mass model 1: Intact rock

Rock mass model 4: Partially damaged bedding

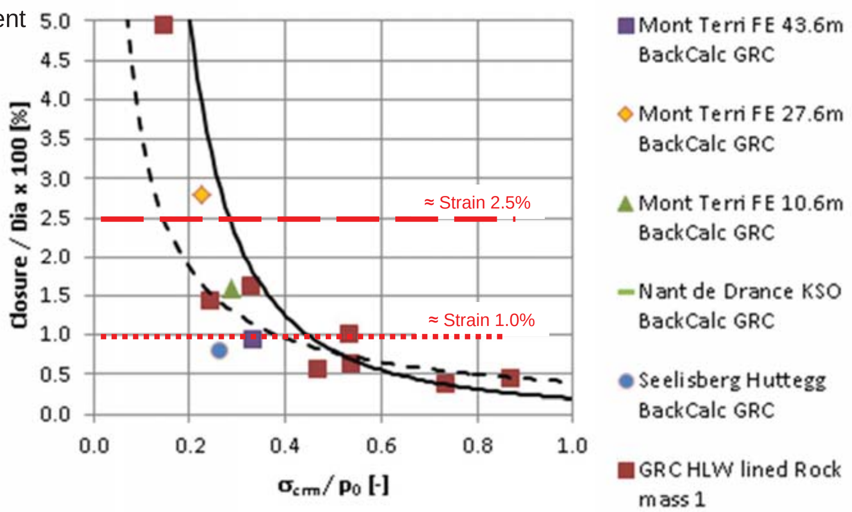


Max. target convergence strain: 1.0 % - 2.5 %



RESULTS: COMPARISON TO EXPERIENCE

- Experience
  - Evaluation of displacement measurements (closure) of recently excavated tunnels
  - Closure (Convergence strain [%]) → Measured
  - Rock mass strength → Back calculated using GRC
- Scope calculations
  - HLW
  - GRC
  - 800 m
  - Xm / Xk / Xd



Above: → severe squeezing problems reported

Beneath: → few support problems reported

Best fit for unlined tunnels (Hoek & Marinos, 2000)

Best fit for back calculations based on convergence measurements on lined tunnels

CONCLUSIONS

- Design considerations include
  - Risk assessment and hazard situations (not presented)
  - Experience
  - Selection of reliable (robust) engineering concepts
  - Geotechnical design calculations

- The presented results indicate that
  under favorable conditions a depth up to 800 m below ground might be feasible

- However, observations at the Mont Terri Rock Laboratory indicate that
  under unfavorable conditions a depth of 800 m below ground is too ambitious
  → a careful approach is essential

- Additional calculations are ongoing to capture the full range of uncertainties

- But anyway: *"The deeper we go, the tougher it gets"*

Work in progress

THANK YOU!

PÖYRY
Engineering balanced sustainability™

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