Complex Design Situations require complex model assumptions

Presentation 28th August 2015 Lausanne
12.11.1973
The consequence?

We always try to do our best.

The times They are A changin.
Challenging Conditions – Fault Zones
# Lateral Dislocations 12km

<table>
<thead>
<tr>
<th>Fault Zone</th>
<th>Position</th>
<th>Overburden</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis</td>
<td>-</td>
<td>732</td>
<td>-</td>
</tr>
</tbody>
</table>

**Longitudinal Section**

**Plan View**
3D Analysis of fault zones

Motivation

+ Distinction of three situations
  + **Design Phase:** According to ÖGG Guideline “Geotechnical design of Underground structures with Conventional Excavation”
  + Assessment of system behaviour in the excavation area
  + **Construction Phase:** Change of support measures
  + Backanalysis based on measurements and experience for the time being
  + Sensitivity analysis
  + **Final phase of project:** Comparison of design assumptions with experience gained during the construction phase
  + Most of the time neglected
3D Analysis of fault zones

**Why 3D and not 2.5D (axisymmetric) or 2D**

- Faults are likely not oriented parallel to a coordinate system.

- 2D analysis (Plane Strain) only when fault is striking parallel to the tunnel axis.

- 2.5D (Axisymmetric model) only when fault is striking perpendicular to tunnel axis and not inclined.

- Sometimes we can neglect slight deviations from this particular situations.
Design situation

Aspects to consider

+ Orientation and hydrological/mechanical properties of the fault zone

+ Structural elements (shotcrete, rock bolts, Damping Elements like LSC etc.)

+ Groundwater / in rocks at which depth ?

+ Constitutive material laws to deploy ?
Material Behaviour – Nonlinearity

Structural Elements

+ **Shotcrete**
  
  + Aging Concrete  
    (Loaded while strength develops - Hydration)
  
  + Creep effects  
    (Linear Creep, Nonlinear creep)
  
  + Shrinkage  
    (Autogenous Shrinkage, Drying Shrinkage)
  
  + Temperature effects  
    (Hydration)
  
  + Microcracking  
    (Shotcrete is loaded beyond the SLS limit of 0.4*f_cm)

+ **Pragmatic Solution**
  Pack all nonlinear effects into a generic Linear Young’s Modulus [between 3 and 5 GPa]
Material Behaviour – Nonlinearity

Structural Elements

+ Shotcrete
  + A more realistic approach - Non linear elastic

[Diagram of Maxwell chain model for aging concrete]

+ Restriction
  Same behaviour in tensile region
Material Behaviour – Nonlinearity

Structural Elements

+ Rock Bolts
  + Modelling of individual bolts
    (Bolts, Interface between bolts and grout / rock)

  + Bolts - steel
    v. Mises criterion $f_{yd}$

  + Interface bolt + grout / rock
    Ultimate shear stress and outer diameter, Stiffness of Interface

+ Pragmatic Solution
  Increase of cohesion (MC-failure criterion - Confining pressure is increased by bolts)
Material Behaviour – Nonlinearity

**Structural Elements**

- Damping Elements (Lining Stress Controllers)
  - Modelling of individual Elements (Hinged Beams with Nonlinear Stress/Strain relation)
Material Behaviour – Nonlinearity

**Rock**

+ **Constitutive law**
  + MC for unfaulted regions is sufficient
  + More sophisticated Material Model for fault zone (Kataclastic Material behaves rather like soil than rock)
  + HSS – Model accounts for
    + Stress dependent Stiffness
    + Nonlinear Stress/Strain relation from the very beginning of loading (nonlinear elastic)
    + Different Stiffness for Primary Loading and Unloading /Reloading
    + Small Strain Stiffness
    + Cap to account for plastic straining in primary compression
  + Ultimate State is defined by Mohr-Coulomb Criterium
Material Behaviour – Nonlinearity

Rock

+ Constitutive law for fault zone
  + HSS-Parameters derived from laboratory tests
Groundwater

Drained vs. Undrained Conditions

To recall: drained is not same as “dry” – it means no excess pore water pressure

Effective Stress Analysis – 2-Phase media strong or weakly coupled

Governing Equations:

\[

v_i = -k_{ij} \left( -\frac{p}{\gamma} + z \right)_{,i} \\
\left( \sigma'_{ij} + S \cdot p \cdot \delta_{ij} \right)_{,j} + f_i = 0 \\
S \cdot \varepsilon_{kk} + v^F_{k,k} - c \cdot p = 0
\]

Darcy’s law (Flow)
Equilibrium (Deformation)
Continuity Equation
Hydraulic Conditions

“Porewater pressure” in rocks

+ Theory - Porous material
  + Effective Stress Concept after Terzaghi
    \[ \sigma'_{ij} = \sigma_{ij} - p \cdot \delta_{ij} \]
    Better: Conventional Effective Stress
  + From Observations (isotropic) and according to M. Biot
    \[ \sigma'_{ij} = \sigma_{ij} - \alpha \cdot p \cdot \delta_{ij} \]
    K … Macroskopic Bulk Modulus
    Ks … Solid Material
  + Different approaches:
    \[ \alpha \ldots \text{according to Innerhofer} - \text{Wetting factor (judgement)} \]
    \[ \alpha = 1 - \frac{K}{K_s} \]
    \[ \alpha \ldots \text{rarely implemented in commercial code (simulation } \gamma F) \]
Finite Element Model

Assembly

Seepage Elements:
Inflow

Shell Elements:
With Contact

Deformation Elements:
e.g. LSC

Unfaulted Zone:
MC-Model
$\alpha = 0.5$

Fault Zone:
HSS-Model
$\alpha = 1.0$

Rock Bolts:
Detailed - problematic
Deformations

Excerpt of Results
Excerpt of Results

Pore Pressure
Excerpt of Results

Axial Force in LSC
Excerpt of Results

Typical Stress Path (Crown)
Conclusion

+ There are ways to model complex situations

+ It is impossible to account for all effects

+ There are always Drawbacks (e.g. simulating α, Rock, Bolts etc.)

+ Huge models are very time consuming in terms of modelling efforts, calculation time, data handling and post processing
Reliability of Results

Conclusion

Bear in Mind

+ We are not able to simulate the reality, we are always analyzing a model
+ Accounting for all Elements of Construction does not mean the solution is closer to reality (Simplicity)
+ An Analysis should help to better understand the mode of action (Results are often qualitatively)
+ Software cannot replace engineering judgement and a computer program cannot take any responsibility
Any Questions?

Thank you for your Attention

+ Credits (Pictures, Diagrams etc.)
  + Doctoral Thesis Bernd Moritz
  + Doctoral Thesis Nedim Radončić
  + Master Thesis Markus Sitzwohl
  + ÖBB Austrian Federal Railway