Practical Implication of Brittle Failure on Hard Rock Tunnelling Construction

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Practical Implication of Brittle Failure on Hard Rock Tunnelling Construction

Acknowledgements
Collaborators: Cai, Diederichs, Hajib dolmajid, Martin, McCreath, …
Contractors: MATTRANS, TAT, Herrenknecht AG, …
Mining companies: Vale INCO, Goldcorp, Rio Tinto, …
Science Council: NSERC
and many more …
Experiences from major mining and tunnelling operations
Lessons learned ...

- under stress ... rock is less forgiving
- must learn from costly mistakes

and learn to design smart!
Objective

Review lessons learned
- Interpret observed rock failure processes
- Explain factors affecting constructability
  - to identify opportunities for improvements
    - support design
    - rock excavation techniques
    - ground control measures
  - to reduce construction problems
    - minimize gap between designer and contractor
Primary rock mechanics challenge when tunnelling in massive to moderately jointed rock

Anticipating the actual rock behaviour

• “Brittle” or spalling failure
  – spalling often dominates over shear failure

• Geo-engineering for constructability
  – fractured rock is often difficult to control

Brittle = Spalling
... not just strain-weakening in shear
Site characterization

Geological Model!

Rock Mass Model!

Rock Behaviour Model?
## Modes of tunnel instability

**Focus on massive to moderately jointed rock**

<table>
<thead>
<tr>
<th>Low In-Situ Stress</th>
<th>Massive ($RMR &gt; 75$)</th>
<th>Moderately Fractured ($50 &gt; RMR &lt; 75$)</th>
<th>Highly Fractured ($RMR &lt; 50$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>($\sigma_1/\sigma_c &lt; 0.15$)</td>
<td>Linear elastic response.</td>
<td>Falling or sliding of blocks and wedges.</td>
<td>Unravelling of blocks from the excavation surface.</td>
</tr>
<tr>
<td>Intermediate In-Situ Stress</td>
<td>Brittle failure adjacent to excavation boundary.</td>
<td>Localized brittle failure of intact rock and movement of blocks.</td>
<td>Localized brittle failure of intact rock and unravelling along discontinuities.</td>
</tr>
<tr>
<td>Failure Zone</td>
<td>Brittle failure around the excavation</td>
<td>Brittle failure of intact rock around the excavation and movement of blocks.</td>
<td>Squeezing and swelling rocks. Elastic/plastic continuum.</td>
</tr>
</tbody>
</table>

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<th>High In-Situ Stress</th>
<th>($\sigma_1/\sigma_c &gt; 0.4$)</th>
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<tbody>
<tr>
<td>$\sigma_{max}/\sigma_c &gt; 1.15$</td>
<td>$\sigma_{max}/\sigma_c &lt; 0.4$</td>
</tr>
</tbody>
</table>
1st Challenge - anticipate failure mode

- Observe
- Interpret
- Understand

→ Spalling behaviour must be anticipated in almost rocks!
2nd Challenge - anticipate the extent

- Observe
- **Interpret**
  - Stress field
  - Depth of Failure
- Understand
- Extrapolate
Appropriate failure criteria to model near-wall behaviour ...

Spalling leads to near-excavation strength reduction

(Kaiser et al. 2000)
Field – rock mass strength

From field observations: microseismicity to visual observations
Intact rock too! Revisited data courtesy Hoek (1961)

Failure criteria to model intact rock is actually …

*s-shaped*

with full or “apparent” cohesion mobilization only at high confinement.

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WHY? - Griffith crack simulation

Influence of heterogeneity on propagating path of wing crack in an unconfined sample (simulated with RFPA 2D)
Why?
Heterogeneity causes tensile stresses

\[ \sigma_3 = 2.5 \text{ MPa} \]

PFC Samples: Local tension due to heterogeneity

Yield
Initiation

Courtesy Diederichs 2000
Internal tension causes spalling

Crack propagation

\( \sigma^3 < 0 \)

Propagation → Spalling

Griffith, Hoek, and many others
% tensile stresses $\rightarrow$ spalling limit

Stress ratio = 10 to 20

Area in Tension: 10%  1%  0.1%

Courtesy Diederichs 2000
Appropriate failure criteria to model near-wall behaviour ...

Spalling leads to near-excavation strength reduction

(Kaiser et al. 2000)
Where?

... near excavations in low $\sigma_3$ range

$K_o = 0.75$

$K_o = 1$

$K_o = 1.33$

$\sigma_3 = 12\text{MPa}$
Quartzite as an analogue of a rock mass
Probability of yield (100 – 0% failed elements) and deviatoric stress ($\sigma_1 - \sigma_3$) contours

$\text{CoV} = 15\% \text{ to } 45\%$

$x = \text{shear}$

$o = \text{tension}$

Kaiser 2010 Eurock
Spalling limit or $\sigma_1/\sigma_3$ - ratio

![Graph showing stress ratio $\sigma_1/\sigma_3$ vs distance along edge of yield zone [m]. The graph includes lines for mean stress ratio, +1sd, -1sd, and normalized crack length.](image-url)
Yield actually means deep spalling

Spalling not shear yield
Stress issues even at shallow depth

Summary from detailed measurements

Martin 1999
• Tender documents, tend to ...
  – emphasise description of geology, rock and rock mass, and
  – **underemphasise** description of the anticipated rock behaviour ... and spalling is not anticipated (?)

• When getting rock behaviour wrong
  → numerical models and **design** are likely “wrong”
  → and **construction** is often **difficulties**
Implications of behaviour misinterpretation illustrated on case example

• Stand-up time issues $\rightarrow$ delays $\rightarrow$ $$
Implications of getting rock mass rock mass behaviour wrong

For example ...

- reduction in advance rate [m/d]

→ **Raveling** rock behind the open TBM “split” the advance and support cycle
Stress-driven rock mass degradation often dominates the behavior of rock masses in tunnelling projects. The diagram illustrates the GSI (Geological Strength Index) chart, which is a key tool in assessing the strength and stability of rock masses. The chart categorizes rock masses based on their geomechanical properties, including joint or block wall conditions, block size, and joint condition factor (Jc).

- **Massive** rock masses, characterized by a very high, intact, undisturbed rock mass with very wide joint spacing, are denoted by GSI values of 150.
- **Very blocky** rock masses, with wide, well-weathered, and interlocked blocks, are categorized by GSI values between 70 and 90.
- **Blocky/disturbed** rock masses, with poorly interlocked or blocky, destructured, and sheared rock masses, are assigned GSI values between 40 and 60.
- **Disintegrated** rock masses, with a mixture of angular and rounded rock pieces, have GSI values ranging from 2 to 4.
- **Jointed** rock masses, with well-defined joint sets, are categorized by GSI values from 1 to 2.

The chart uses symbols such as (b) and (c) to indicate specific rock mass conditions, with (b) showing a typical jointed condition and (c) illustrating a more disturbed and sheared state. The diagram also includes a stress indicator symbol (σ) to denote the direction and magnitude of applied stress.

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Stand-up

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Bieniawski 1987
Progressive failure process produces “blocky”, unravelling ground with rock mass bulking.
Instabilities of highly stresses tunnel face

- Anticipating behaviour at depth
- Fracture propagation from stress raisers at "corners" (e.g. incl. tunnel face)

Massive rock ... unravels
Anticipate TBM face behaviour

- Observe
- Interpret
- Understand
- Extrapolate
  - to depth
  - Face behaviour ➔ now can also anticipated spalling at tunnel face

Increasing stress or depth
Spalling at tunnel face

- Predictions and observations
Unravelling tunnel face

- What is seen in roof is to be expected at face!
- Unravelling of face before wall!
Rock support of brittle failing ground with rock mass bulking

“blocky” ground = unravelling rockmass broken by stress
Challenge – anticipate rock mass bulking (geometric volume increase).

Field measurements with ELFEN model showing BF = 0 to 10% for different support types.

(a) Courtesy Cai 2006

(b) Simulation with ELFEN

Dilation or Bulking Factor BF [%]

Confinement [MPa]

BF = 0 to 10%

Light support

Strong support

Uni-directional

Courtesy Cai 2006

Reference source not found.
Yield and $\sigma_3$ pattern near tunnel

- Circular tunnel at 2000m and $K_o=0.5$

5% of 1.5m = 75mm

Yield

Bulking
Radial strain (%) control

σ₃ < 2 MPa → BF = 0-10%

→ with dense bolting and retention (shotcrete)

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Lessons learned ...

When dealing with brittle failure in tunnelling ...

→ observe, interpret, and understand
→ adjust design and construction procedures to match ground behaviour

• Stressed ground is less forgiving
  → stress breaks even good ground
  → good ground becomes poor ground
  → massive, brittle rock disintegrates
  → “cohesionless” ground

→ Quantum shift in constructability
Lessons learned ...

When highly stressed brittle rock fails by spalling .. not shear

→ degradation cannot be prevented

→ conventional failure criteria mislead designers → s-shaped

→ spalling process affects both tunnel walls roof and face

→ select excavation and support techniques appropriate for broken rock

→ No ravelling, raining rock and flying arches!
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Thank you!

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