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Challenges with Deep Tunnelling

• Pre-Construction Investigation
• In Situ Stress Determination
• Rock Stability Prediction
• Rockbursting
  • Fracture and Burst Potential
  • Effect of Geo-Structure
  • Rockburst Support
  • TBM and DB Safety
• RQD, Q, RMR, GSI don’t mean much at depth
Challenges with Deep Tunnelling

• RQD, Q, RMR were once invaluable but we need to move on...

• In addition, classification and GSI don’t mean much for hard rock at depth
Site Investigation Access

• Sampling of Rock through Drilling is Practical
  • If depths permit
  • If strata is sub-horizontal
  • If topographic relief is low
  • If access is possible

• Sampling of Rock is often not done at all:
  • If depths are significant
  • If strata is inclined or subvertical and variable
  • If topography is prohibitive
  • If ground above is inaccessible
Tunnel Investigation often stuck on vertical

• Tunnel investigations are often based on sub-vertical holes.
• Provide little information for sub-vertical strata variations
• This limits campaign according to access and cost
• Surface sampling not representative of rock at depth
Fan Drilling, Curved Drilling, Horizontal Drilling

- Many holes can be drilled from one location (where access permits)
- Fan drilling to optimize access
- Geological model construction is essential (folding, faulting, distortion)
- Horizontal drilling from a tunnel niche hundreds of metres ahead to confirm models and detect risks

Typical drilling for mineral exploration.
Directional core drilling in tunnel construction

"Directional drilling techniques are now available to drill from ground level to great depth and then along a horizontal alignment. This method does not require provision of working space at the tunnel level and can be very useful in investigations for deep tunnels."

HK government specs

Continuous rock core:
Fault zones, Fractures, Lithology
Rock mechanical properties

Smooth hole at tunnel axis:
Geophysical Analysis, Water Press/Flow
Stress analysis (frac)

"Directional drilling techniques are now available to drill from ground level to great depth and then along a horizontal alignment. This method does not require provision of working space at the tunnel level and can be very useful in investigations for deep tunnels."

HK government specs

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Getting more out of our boreholes

Acoustic and Optical Televiewers, Improved Logging

D. Garroux Current Queen’s PhD
N. Blacklock Current Queen’s MSc
J. Day Current Queen’s PhD

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Challenges and Innovations in Tunnelling
Surface geology is not tunnel geology
Better 3D visualization is needed...
*and is available!*

- Project geology is often communicated using surface maps.
- Actual geology at the tunnel must be modelled and presented.
- Decisions made based on vertical geology projection are dangerous.
- **NEED** a new approach to the updating of geology actual and for contract purposes during a project.
Geophysics can help with subsurface prediction

- Deep Seismic Refraction can detect the depth of the weathered zone
- Seismic Reflection has been used in gently dipping/folded terrain to confirm strata model
- Seismic Tomography can reveal differences in mechanical properties (and rockburst potential) but $$

Challenges and Innovations in Tunnelling
Geophysics can help with subsurface prediction

• Resistivity surveys can reveal high water zones and can show variations in competence
• Resistivity surveys can differentiate between lithologies
• Resistivity shows where rock fracturing is dominant
• Borehole geophysics can quantify rock properties
In Situ Stress

• Every major tunnelling dispute in my 15 years of consulting (>> $1B in claims and losses) has involved questions of In Situ Stress

• Stress measurement at depth is difficult if K>>1

• Stress measurement at tunnel depth during construction can help confirm

• Local tests have low reliability
• Overcoring Methods
  • Doorstopper
  • USBM Gauges
  • Triaxial strain cell (CSIRO)

• Hydraulic Methods
  • Hydraulic fracturing
  • Hydraulic testing of pre-existing fractures

Suitable for use in deep, water-filled boreholes but unreliable when \( k >> 1 \)
Constrain through Borehole Breakouts and Deformation

A. Leriche  Current Queen’s MSc

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Challenges and Innovations in Tunnelling
Possible to estimate Stress Magnitude Ratio and Orientation from borehole breakout observations

G. Walton Queen’s PhD  2014

Need OTV or ATV data
In Situ Stress

• Good geological considerations are the best tool.

• The horizontal stress ratio is ALMOST NEVER 1:1 for deep rock tunnels in competent rock
  There are a few exceptions

• Don’t ignore stress in a GBR
  • It will ALWAYS end in tears!
Use “Corroborating Evidence” Approach

(ISRM Suggested Method Part 5, Stephansson and Zang, 2012)
In Situ Stress

• Prediction based on regional data, tectonic interpretation

• Modelling can be used to combine tectonics with topography

• Local tests from within tunnel should be specified as soon as target ground is encountered
Consider geological setting

Reverse faulting

Strike-slip

Normal faulting

Normal faults occur when the maximum compressive stress is vertical.

Reverse or thrust faults occur when the minimum compressive stress is vertical.

Strike-slip faults occur when both S1 and S3 are horizontal.

Challenges and Innovations in Tunnelling
Horizontal Stresses Due to Gravity and Topography

Stresses Due to Tectonics

Variable Magnitude and Orientation of Stresses
Calibrate Model to Known Point Data and Regional Data

S Gaines Queen’s MSc 2013
Rock Stability Prediction

- Need to consider possible failure modes not just properties
- Indicate in GBR/GRR
- Given site conditions, likelihood of different failure modes can be determined from basic case modelling
Failure Modes

Case 1: Squeezing

Case 2: Stratified Structure

SAME Q!

Case 3: Spalling

Case 4: Metamorphic Structure

Case 5: Raveling

M. VdP Kraan  Queen’s MSc 2014
Supported Results

Case 1
Squeezing

Case 2
Sedimentary Structure

Case 3
Spalling

Case 4
Metamorphic Structure

Case 5
Raveling

SAME Q!
MAJOR CHALLENGES IN DEEP TUNNELS

- Extreme Squeezing
- Structural Overbreak
- Water Inflow and Pressure
- Major Faults
Rockbursts

= Brittle Failure + Rapid Energy Release
A Major Rockburst 8m/s
Main Issue with Deep Tunnelling

• Highly unlikely that standard risk sharing or risk shedding models will be effective in managing geological variability and risk.

• In modern tunnelling and with zero risk culture:

  ROCKBURSTS ARE A PROJECT KILLER

Owners and Contractors Beware:
There is no way to pass the buck on this one!
This is everyone’s problem.
Rockburst damage due to a remotely triggered event

Most common in Mining

CRBH 96

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Challenges and Innovations in Tunnelling
Auto-seismic Event (Strainburst)
Most common in Tunnelling
What is a Rockburst?

An explosive failure of rock which occur when very high stress concentrations are induced around underground openings (Hoek 2006)

A sudden and often violent breaking of a mass of rock from the walls of a tunnel...caused by failure of highly stressed rock and the rapid or instantaneous release of accumulated strain energy. (US Bureau of Mines)

Damage to an excavation that occurs in a sudden or violent manner and is associated with a seismic event (Canadian Rockburst Handbook, 1996)

Loss of continuity of the production process of the mining operation, caused by the rupture and instant projection of the rock mass, associated with a seismic event.” (Codelco (2008)
Mild Bursting Behind Shield
Floor Heave (Bursting after Shield)
Local Bursting
Strong Bursting
Bursting at the Face
Rockburst Components

- Stress Concentration (geometry, geology)
- Brittle Failure (brittle rockmass)
- Energy Capacity (high strength capacity)
- Energy Storage (stress path, geometry)
- Rapid Release (stiff rock or soft surroundings)
- Failure Volume (Instantaneous Yield via Geometry or Structure)
Spalling can lead to Bursting
Simple Models to Predict Overstress (Burst) Hazard

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Simple Modelling can Demonstrate the Nature of the Hazard

Yield (Fracture) Zone

Centreline

A

50 MPa

55 m

B

40 MPa

75 MPa

55 m
Simple Modelling with Geological Section Detail Shows Stiffness Contrasts That Can Increase Stress Concentrations
Brittleness and Burst Potential - Think Geology: Rock types prone to brittle failure

More Brittle

PLUTONIC ROCKS

VOLCANIC ROCKS

More Brittle

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Challenges and Innovations in Tunnelling
Aphanitic

Dacite

Andesite
Porphyry/Breccia

Fine grained
Uniform
Strong
Brittle

Course grained
Heterogenous
Less Strong
Less Brittle

Think Geology
Energy Storage and Release
### Think Geology: Moderately Jointed Rockmass

#### Graphical Representation:
- **GSI > 90**: Spall
- **GSI = 85**: <br>Joint slip
- **GSI = 75**: <br>Joint slip
- **GSI = 65**: Spall
- **GSI = 55**: Spall
- **GSI = 45**: Spall

#### Table: Strength Ratio vs. GSI Interval

<table>
<thead>
<tr>
<th>Strength Ratio</th>
<th>GSI &lt; 55</th>
<th>GSI = 55 to 65</th>
<th>GSI = 65 to 80</th>
<th>GSI &gt; 80</th>
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<tr>
<td>UCS/T &lt; 8</td>
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<td>shear</td>
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<tr>
<td>UCS/T = 9 to 15</td>
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<td>spall/shear</td>
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<tr>
<td>UCS/T = 15 to 20</td>
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<td>shear/spall</td>
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<tr>
<td>UCS/T &gt; 20</td>
<td>shear</td>
<td>shear/spall</td>
<td>spall</td>
<td>spall</td>
</tr>
</tbody>
</table>
Energy Storage and Release
High Storage + “Soft System” = Burst Hazard

- Load
- Deformation

**Yield**

**STIFF SYSTEM UNLOADING**
- System Releases Energy Elastically

**FAILING ROCK**
- Consumes Energy as Function of Failure mode and stiffness

**SOFT SYSTEM UNLOADING**
- Excess Energy Converted to Velocity
Energy Storage – Face Bursting

![Graph showing energy storage and face bursting](image)

- Hoek-Brown Intact Rock UCS=200 mi=23
- Spalling according to Diederichs 2007
- GSI=75 Rockmass Shear
- GSI=65
- GSI=55

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Challenges and Innovations in Tunnelling
Energy storage and Release

• Energy release is controlled by geometry
• Simple modelling can be used to compare profiles

Simpler Geometries are Stiffer – Less Post Failure Closure = Less Energy
Modern discontinuum models are useful for exploring influence of structure at high stress.

Combined Rock Fracture and Structural Failure

Structural Weakening with Major Wall Buckling
Complexities of Joints combined with filled veins = Burst hazard

Modern desktop tools can simulate this.
Combining Empirical and Numerical Tools to Predict Damage and Energy Release

= Baseline Rockburst Hazard

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Challenges and Innovations in Tunnelling
Impact of Structure

Hazard **Reduction** for Poorer Quality Rockmasses

Hazard **Increase** for Critical Combinations of Structure
Rockburst Support

rock stresses

reinforce

retain

hold

rock loads
Rockburst Support System - TBM

Shield – Pressure Control
  (Maintain to reduce heave – Release if clamped)

Steel Rings, Channels, Lattice – Load Capacity

Mesh – Retain and Integrate
  (Above rings and held by rebar)

Rebar or Super Swellex – Reinforce

Yielding or Deformable Support
  (Many products now available)

Shotcrete – System Integration
  (Also emergency profile control)
Rockburst Support System - Drill and Blast

Shotcrete - Maintain Profile and Integrity

Rapid Remote Support – Swellex or Resin Bolts

Mesh – Retain and Reinforce Shotcrete

Rebar – Reinforce
  must be accompanied by...

Yielding or Deformable Support
  (Many products now available)

Surface Mesh - Protection
Combination Bolt (D-Bolt)
Reinforcement and Displacement Capacity
What is Rockburst Risk?

**ROCKBURST (Hazard)**
(Likelihood of) Damage to an excavation that occurs in a sudden or violent manner, associated with a seismic event.

**ROCKBURST RISK**
A measure of the potential for impact, due to damage associated with a rockburst, to:

1) safety of personnel,
2) continuity of construction/operational objectives or
3) equipment and infrastructure

Auto-Seismic HAZARD may be unavoidable
Rockburst RISK is a management issue
Challenges and Innovations in Tunnelling

"BOWTIE" RISK MANAGEMENT
FOR
LOCAL TUNNEL-INDUCED
ROCKBURST

HAZARD (Likelihood)

Control:
- Reinforce (prevent failure)
- Minimize Energy Storage
- Blast/Advance Control
- Respond to Geology
- Maintain Profile
- Preconditioning

Understanding:
- Probe Drilling
- Video Monitoring
- Seismic Monitoring

IMPACT (Consequence)

Management:
- Control Entry to Face
- Displacement Support
- Energy Absorbing Support
- Robotic Construction
- Worker Protection
- Safety Training

RISKS
- Fatality
- Significant Injury
- Project Shutdown
- Major Delay
- Reduced Advance Rate
- Equipment Damage
- Support Costs

TRIGGERS
- Geology
- Stress
- Structure
- Strength/Stiffness
- Energy
- Geometry
- Profile
- Round Length
- Blasting

Contractor Control

Project Priority
Rockburst Hazard Assessment

Anticipate geological change:

Warnings for Moderately Stress/Strength
- Moving from soft to stiff or vice versa
- Surface parallel structure
- Heterogeneous rockmass (stiff and soft elements)

Warnings for High Stress/Strength
- Any of the above conditions
- Fracture with persistent steep structure
- Massive face in brittle rock
Look ahead Seismic Monitoring

GFZ Potsdam

Challenges and Innovations in Tunnelling
Look Ahead Seismic Monitoring
GFZ and Herrenknecht
ROCKBURST MONITORING

Acquisition unit

Accelerometers installed in small borehole in a geometric note disposition

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Challenges and Innovations in Tunnelling
Rockburst Risk Management

• Managing worker exposure during construction
  • Robotic installation, protective cages, re-entry protocols

• Minimizing failure depth (lower available energy)
  • Proper static support with excess capacity, stiff elements

• Maximizing support and energy absorption
  • Deformable Support

• Minimize energy storage and release
  • Preconditioning, sequencing, round and profile control

• Monitoring
  • Seismic System, event records, observations

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Mitigation – Preconditioning/Destress Blasting (?)

Perimeter Pattern

next blast round

Face Pattern

without pre-conditioning

with pre-conditioning

Stress

Strain
Scaling vs Excavating
Challenge in Tunnelling
Safely installing rockburst support at face
Exposure Control  (Drill and Blast)

Risk Balance

Support Increases Safety After Installation

Support Installation Increases Exposure
Mesh Installation Arm
• Expanding Hybrid Shield (Fingers or McNally System)
• Wide angle bolt support
• Hybrid “McNally System” allows for stiffer finger response when installed
• Hybrid “McNally System” allows for switching to strap mode
CRITICAL ELEMENT:
Rear loading cutters are a must for deep tunnelling
Thank you

Queen’s University, Kingston, Ontario