Practical Considerations for Tunnels Used in Mining Applications

Marco D. Boscardin, Ph.D., DGE, PE
Boscardin Consulting Engineers, Inc.

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Options for Mining Ore

• Surface Extraction
  – Open Pit Mining

• Underground Extraction
  – Room-and-Pillar Mining
  – Cave Mining
  – Block Caving
  – Cut and Fill

• Combined Surface/Underground Facilities
Uses of Tunnels in Mining

- Access to Ore Body
- Haul Routes - Ventilation
- Room and Pillar Mines
- Access to Caving Draw Points
- Access for Drilling for Caving Operations
- House Processing Equipment
  – Conveyors, Crushers, Ore Bins
- Water Drainage and Control
Figure 6.3-8 Underground mining terminology
Figure 6.3-9 Schematic block cave
Information Affecting Mine Tunnel Design and Performance

- Depth of Cover
- Tunnel Size (Min 7 ft, typ. 20+ ft)
- Type of Rock - State of Stress
- Discontinuities (Joints, Faults, Shears)
- Alteration
- Ground Water
- Purpose of Tunnel (Choice of Safety Factor)
Depth of Cover

• Deeper Tunnel Better Arching of Loads Around Tunnel

• Larger the Depth to Diameter Ratio – Better Arching of Loads Around Tunnel

• Deeper Tunnel Usually Results in Smaller But More Widely Spread Surface Subsidence, if it does occur
Zone of Influence of Tunnel
Larger Size of Tunnel

- More Likely to be Affected by Discontinuities
- More Likely to Intercept Water Bearing Seams
- Larger Zone of Influence at Ground Surface
- Larger Support System Loads
Type of Rock

- Rock Strength, Stiffness
  - Soft vs Hard (<6,000 psi, >20,000 psi)
  - Mechanized vs Blasting Excavation
- State of Stress ($K_o$ vs High Lateral Stress)
  - Rock Bursting Hazard
- Discontinuities
- Faults and Shears
- Alteration, Weathering
Roadheader
Drill Jumbo for Blasting
Hydrogeology

- Water Pressures
- Permeability
  - Flow Rate, Initial vs. Long-Term
- Discontinuities
- Faults and Shears
- Potential to Generate Acid
Geologic Information Needed for Tunnel Design

• Rock Mass Characteristics
  – Rock Mass Rating RMR (Bieniawski, 1989)
  – Modified RMR (Laubscher and Page, 1990)
  – Q-System (Barton et al., 1974)
  – GSI (Hoek and Marinos, 2000)

• Orientation and Properties of Discontinuities

• Excavatability – hardness, abrasion, strength
Stability & Factor of Safety

- Limit Equilibrium Approach
  - Highly Dependent on Discontinuity Properties
  - Not as Much on Typical Rock Mass Properties

- Main Access, Haul Routes, Shops - 1.5+

- Temporary Access – 1.3

- Room and Pillar During Retreat – 1.1
Adverse Jointing
Rock Mass Classification Input

- Rock Strength
- RQD
- Fractures
  - Frequency, Orientation, Characteristics
- Weathering
- Water
- Damage Factor
- Structure Orientation, Size and Importance
Table 3: Geological strength index for blocky jointed rock masses.

<table>
<thead>
<tr>
<th>STRUCTURE</th>
<th>surface Conditions</th>
<th>Decreasing Surface Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intact or Massive</td>
<td>Very Good, Very rough, High water table</td>
<td>N/A</td>
</tr>
<tr>
<td>Blocky</td>
<td>Good, Rough, Water table, Medium water table with compacted surfaces</td>
<td>N/A</td>
</tr>
<tr>
<td>Very Blocky</td>
<td>Fair, Poor, Water table, High water table with weak interlocking</td>
<td>30</td>
</tr>
<tr>
<td>Blocky/Disintegrated/Scary</td>
<td>Poor, Water table, High water table with weak interlocking</td>
<td>20</td>
</tr>
<tr>
<td>Laminated/Shredded</td>
<td>N/A, N/A</td>
<td>10</td>
</tr>
</tbody>
</table>

From the lithology, structure and surface conditions of the discontinuities, estimate the average value of GSI. Do not try to be too precise. Quoting a range from 30 to 37 is more realistic than stating that GSI = 35. Note that the table does not apply to structurally controlled failures. Where weak planar structural planes are present in an unfavorable orientation with respect to the excavation face, these will dominate the rock mass behaviour. The shear strength of surfaces in rocks that are prone to deformation as a result of changes in moisture content will be reduced if water is present. When working with rocks in the fair to very poor categories, a shift to the right may be made for wet conditions. Water pressure is dealt with by effective stress analysis.
Figure 3: Plot of the ratio of rock mass strength / intact rock strength versus GSI for a range of $m_i$ values.
Design of Tunnels

- Stability
  - Joints and Discontinuities

- Deformation
  - Rock Mass Classification Systems
  - Numerical Modeling
  - Observational Method

- Water
  - Modeling
Stability vs Classification
Tunnel Support

- Ribs and Lagging
- Timber
- Rock Bolts/Dowels
- Shotcrete
- Straps
- Mesh
- Plates
Water Inflow Estimates

- Field Data Indicates that Analytical and Numerical Approaches Tend to Over-Estimate Inflow
- As Much as 5 to 8 Times
- Possibly Due to Limited Permeability Data and Modeling as a Particulate vs. Discontinuous Medium
Figure 4. Relationship between steady state inflow and equivalent permeability
### Case 3: Using Breakdown for sections, faults and permeabilities

Assume 10D+ (50+ m Cover)

<table>
<thead>
<tr>
<th>Section No.</th>
<th>Start, m</th>
<th>End, m</th>
<th>Length, L, m</th>
<th>ke, cm/sec</th>
<th>H, m</th>
<th>( \text{Factor, } F_h )</th>
<th>( \text{qs/H L/min/100 m/m}^2 )</th>
<th>( \text{qs, L/min/100m} )</th>
<th>Qs, L/min</th>
<th>Heading Zone Length, m</th>
<th>( \text{Qh, L/min} )</th>
<th>( \text{Best Estimate of Cumulative, Steady State Flow to End of Section Not Including Heading Flow for that Section, L/min} )</th>
<th>( \text{Best Estimate of Cumulative, Steady State Flow to End of Section Not Including Heading Flow for that Section, L/sec} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>28</td>
<td>28</td>
<td>2.5x10^6</td>
<td>5</td>
<td>1.4</td>
<td>0.4</td>
<td>2</td>
<td>0.6</td>
<td>30</td>
<td>0.8</td>
<td>0.6</td>
<td>0.009</td>
</tr>
<tr>
<td>2</td>
<td>28</td>
<td>46</td>
<td>18</td>
<td>1x10^3</td>
<td>10</td>
<td>3.5</td>
<td>20</td>
<td>200</td>
<td>36.0</td>
<td>18</td>
<td>126.0</td>
<td>36.6</td>
<td>0.6</td>
</tr>
<tr>
<td>3</td>
<td>46</td>
<td>200</td>
<td>154</td>
<td>2.5x10^6</td>
<td>40</td>
<td>1.4</td>
<td>0.4</td>
<td>16</td>
<td>24.6</td>
<td>30</td>
<td>6.7</td>
<td>61.2</td>
<td>1.0</td>
</tr>
<tr>
<td>4</td>
<td>200</td>
<td>500</td>
<td>300</td>
<td>2.5x10^6</td>
<td>80</td>
<td>1.4</td>
<td>0.4</td>
<td>32</td>
<td>96.0</td>
<td>30</td>
<td>13.4</td>
<td>157.2</td>
<td>2.6</td>
</tr>
<tr>
<td>5</td>
<td>500</td>
<td>752</td>
<td>252</td>
<td>2.5x10^6</td>
<td>110</td>
<td>1.4</td>
<td>0.4</td>
<td>44</td>
<td>110.9</td>
<td>30</td>
<td>18.5</td>
<td>268.1</td>
<td>4.5</td>
</tr>
<tr>
<td>6</td>
<td>752</td>
<td>770</td>
<td>18</td>
<td>1x10^3</td>
<td>110</td>
<td>3.5</td>
<td>15</td>
<td>1650</td>
<td>297.0</td>
<td>18</td>
<td>1039.5</td>
<td>565.1</td>
<td>9.4</td>
</tr>
<tr>
<td>7</td>
<td>770</td>
<td>1084</td>
<td>294</td>
<td>2.5x10^6</td>
<td>60</td>
<td>1.4</td>
<td>0.4</td>
<td>24</td>
<td>70.8</td>
<td>30</td>
<td>10.1</td>
<td>635.8</td>
<td>10.6</td>
</tr>
<tr>
<td>8</td>
<td>1084</td>
<td>1082</td>
<td>18</td>
<td>1x10^3</td>
<td>60</td>
<td>3.5</td>
<td>15</td>
<td>900</td>
<td>162.0</td>
<td>18</td>
<td>567.0</td>
<td>797.8</td>
<td>13.3</td>
</tr>
<tr>
<td>9</td>
<td>1082</td>
<td>1200</td>
<td>118</td>
<td>2.5x10^6</td>
<td>50</td>
<td>1.4</td>
<td>0.4</td>
<td>20</td>
<td>23.8</td>
<td>30</td>
<td>8.4</td>
<td>821.2</td>
<td>13.7</td>
</tr>
</tbody>
</table>
Examples of Mines

- Old Newgate, CT
- PA Mine
- CA Mine
Old Newgate

• 1705 – 1772  a Mine
• 1772 – 1827  a Prison
• 1830’s & 1850’s  a Mine Again
• 1850’s on Tourists
• 1970 State Owned
Geology

- Triassic Age Sediments with Basalt Flows
- Red-Brown Arkosic Silt Stone and Arkose
- Ore Body is Bleached Zone of Arkose
- Tabular Body, Dips 20E, 6-8 ft opening, 2% Copper
Shaft to Surface – Original Entrance
Water Drainage and Ventilation
Friedensville Mine

- Worked 1860’s to 1983, Most 1953 to 1983
- Brecciaed Limestone and Dolomite
- Room and Pillar – 35 ft Pillars
- 25 ft Benches – Sometimes 4 Benches
- 8+ Levels of Mines
- Pattern Bolting
- 20,000+ gpm Water
Surface to 700 Level
700 Level
CA Mine

- 1860’s to 1963
- Igneous Rock, Rhyolite, Pyrite
- Mixed Surface and Underground Mine
- Fractured Rock with Water = Acid
- Affects Support Systems and Water Management
Mine Map
Shotcrete Supported Portal
Resupported Tunnel
Resupported Tunnel
Effects of Corrosion
Pillar at Intersection of Tunnels
Acid-Related Features
Rock Bolt with Shotcrete
Shotcreted Pillar – Convergence Point
Steel Sets with Lagging
Timber Sets with Lagging
Timber Sets with Lagging
Ribs and Lagging Support
Mesh Support
Caving Area
Caving Area
Drainage Control
Summary

• Tunnels are an Integral Part of a Mining Operation

• Design of Mine Tunnels is Different than of Civil Works Tunnels

• Geology Controls Mine Development

• Water can be a Controlling Factor
Jointing vs. Stability

Figure 6.3-3 Laubscher’s 1981 classification for cavability
Stability vs. Classification

Figure 6.3-4 Laubscher's cavability related to hydraulic radius and MRMR.
Figure 4: Plot of rock mass deformation modulus against GSI for a range of intact rock strength values.
Deformation and Support

<table>
<thead>
<tr>
<th>Strain (%)</th>
<th>Geotechnical issues</th>
<th>Support types</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Less than 1</td>
<td>Few stability problems and very simple tunnel support design methods can be used. Tunnel support recommendations based upon rock mass classifications provide an adequate basis for design.</td>
<td>Very simple tunnelling conditions, with rockbolts and shotcrete typically used for support.</td>
</tr>
<tr>
<td>B 1 to 2.5</td>
<td>Convergence confinement methods are used to predict the formation of a ‘plastic’ zone in the rock mass surrounding a tunnel and of the interaction between the progressive development of this zone and different types of support.</td>
<td>Minor squeezing problems which are generally dealt with by rockbolts and shotcrete, sometimes with light steel sets or lattice girders are added for additional security.</td>
</tr>
<tr>
<td>C 2.5 to 5</td>
<td>Two-dimensional finite element analysis. Incorporating support elements and excavation sequence, are normally used for this type of problem. Face stability is generally not a major problem.</td>
<td>Severe squeezing problems requiring rapid installation of support and careful control of construction quality. Heavy steel sets embedded in shotcrete are generally required.</td>
</tr>
<tr>
<td>D 5 to 10</td>
<td>The design of the tunnel is dominated by face stability issues and, while two-dimensional finite analyses are generally carried out, some estimates of the effects of forepoling and face reinforcement are required.</td>
<td>Very severe squeezing and face stability problems. Forepoling and face reinforcement with steel sets embedded in shotcrete are usually necessary.</td>
</tr>
<tr>
<td>E More than 10</td>
<td>Severe face instability as well as squeezing of the tunnel make this an extremely difficult three-dimensional problem for which no effective design methods are currently available. Most solutions are based on experience.</td>
<td>Extreme squeezing problems. Forepoling and face reinforcement are usually applied and yielding support may be required in extreme cases.</td>
</tr>
</tbody>
</table>

Figure 7: Approximate relationship between strain and the degree of difficulty associated with tunnelling through squeezing rock. Note that this curve is for tunnels with no support.
Example Con’t.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total, m = 1200</td>
<td></td>
</tr>
<tr>
<td>1. Heading factor, Fh, from Heuer, 2005 Figure 4.</td>
<td></td>
</tr>
<tr>
<td>2. qs/H from Heuer, 2005 Figure 4, Based on 4D Cover Line</td>
<td></td>
</tr>
<tr>
<td>3. Distance from Lower End of Tunnel</td>
<td></td>
</tr>
<tr>
<td>Expected Upper Limit of Cumulative Steady State Flow is Approximately 2 x’s the Best Estimate</td>
<td>821.2</td>
</tr>
<tr>
<td>Best Estimate of Total, L/min =</td>
<td>13.7</td>
</tr>
<tr>
<td>Best Estimate of Total, L/sec =</td>
<td></td>
</tr>
<tr>
<td>UL Total, L/min =</td>
<td>1642.5</td>
</tr>
<tr>
<td>UL Total, L/sec =</td>
<td>27.4</td>
</tr>
<tr>
<td>Best Est. of Max. Temp Flow Total, L/min =</td>
<td>1040</td>
</tr>
<tr>
<td>Best Est. of Max. Temp Flow Total, L/sec =</td>
<td>17</td>
</tr>
<tr>
<td>Expected Upper Limit of Additional Temporary Flow at Heading During Construction</td>
<td></td>
</tr>
<tr>
<td>Best Estimate of Additional Temporary Flow at Heading During Construction</td>
<td></td>
</tr>
<tr>
<td>Expected Upper Limit of Additional Temporary Flow at Heading During Construction, Up to</td>
<td></td>
</tr>
<tr>
<td>UL of Max. Temp Flow Total, L/min =</td>
<td>2080</td>
</tr>
<tr>
<td>UL of max. Temp Flow Total, L/sec =</td>
<td>35</td>
</tr>
</tbody>
</table>