Tunnelling Contracts – Risk Management

In 1872, armed with the development of new drilling machines and explosives, Swiss engineer Louis Favre undertook to construct, what was once thought of as impossible: the 15 km St. Gotthard tunnel through solid rock to link Zurich with Milan.

Competition for the contract was high and Favre agreed to a fixed price of £1,898,845 to complete the works, a figure that allowed for no contingencies whatsoever.

Favre also agreed to complete the works in 8 years, for which he put up a £320,000 bond. The contract allowed for a bonus of £200/day for finishing ahead of schedule and a similar penalty for every day late, forfeiting the entire bond if not completed within a year of the scheduled completion date.
Tunnelling Contracts – Risk Management

For 7 years Favre, continually threatened by the deadline, worked his men without thought for their health or lives. Pressured to the point of desperation, he would spend days on end in the choking atmosphere of the tunnel. Broken physically as well as financially, Favre succumbed in the tunnel to a heart attack, struggling up to his last breath to advance the work.

By the time the tunnel was completed (approximately 2 years late), Favre’s firm had exceeded the contract price by £590,000 in addition to having forfeited the bond of £300,000. The cost in lives was 310 men, with 877 seriously invalided.

Tunnelling Contracts – Construction Delivery

Design-Bid-Build (design/tender)

Is a project delivery method in which the Owner’s engineer carries out the design, which is then put out to bid. In this arrangement, the design team is impartial and looks out for the interests of the Owner.

Design-Build

Incorporates the contractors’ means and methods into the design stage, contracted for with a single entity known as the design-builder. This system is used to minimize the project risk for an owner and to reduce the delivery schedule by overlapping the design phase and construction phase of a project. Where the design-builder is the contractor, the design professionals are typically retained directly by the contractor.

Build Operate Transfer (BOT)

Allows the builder concession to operate and derive revenue over the concession period before transferring it back to the government authority.
Tunnelling Contracts - Construction Delivery

Public-Private Partnerships (P3s)

Describes a venture which is funded and operated through a partnership of government and one or more private sector companies. Typically, a private sector consortium is contracted to develop, build, maintain and operate the asset for a given period. The public sector usually retains ownership of the facility.

Government takes on a role of actively controlling some of the risks with involvement of statutory authorities who eventually take operational control.

Early tunnels were financed by individuals/private investors. As countries became industrialized, projects were paid for by taxation. However, governments found taxation to be inadequate for the huge infrastructure needs and project financing became a mix of private investment and public financing.

Geotechnical Reporting

Geological Data Report

- compilation of all of the results of the site investigation process;
- generally restricted to factual information and does not include very much interpretation;
- contractor is left to assess the factual information and draw conclusions on the probable groundwater and rock mass behaviour; tasks that may be very difficult to accommodate during the bidding process.

Geotechnical Baseline Report

- interpretative report in which all the factual data collected during the site investigation stages are analysed in terms of potential groundwater and rock mass behaviour and other issues that could cause problems during construction;
- interpretations form a behavioural baseline which can be used in setting contractual limits.
- contractor cannot make claims for ground behaviour which falls at or above the baseline while the owner has to accept responsibility for problems resulting from rock mass behaviour which is worse than that predicted in the baseline report.
**Geotechnical Baseline Reports**

Geotechnical Baseline Reports (GBRs) are charged with portraying a realistic interpretation of the subsurface conditions that are anticipated in the proposed construction. They should include not only the mean conditions of ground behaviour and groundwater conditions anticipated, but the report should also address the range of variances that is expected.

- Aims to establish a contractual understanding of the subsurface site conditions.
- Risks associated with conditions consistent with or less adverse than the baseline are allocated to the contractor and those significantly more adverse than the baseline are accepted by the owner.

Thus, the purpose of the GBR is to establish a realistic, common basis for evaluating any contractor claims for differing site conditions that develop during construction. The GBR is the basis for equitable contractual risk sharing and risk allocation between the project owner and their selected contractor.

**Costing Stages**

- **Scoping study** (± 30 to 50% accuracy)
  - Consider past experience and similar facilities.
  - Estimate an excavation cost and support cost.
- **Pre-feasibility study** (± 20 to 25% accuracy)
  - General layout is needed.
  - Ground conditions evaluated.
  - Excavation technique outlined (consider overbreak).
  - Total support (bolts, liners etc) considered.
- **Feasibility study** (± 10 to 20% accuracy)
  - Detailed design needed.
  - Excavation sequence detailed including ventilation, temporary and permanent support.
  - Prepare QA systems.
  - Critical path schedule.
  - Personnel requirement and costs.
  - Consumables and services provisions (temporary pumping).
  - Project safety.
Uncertainty in Ground Characterization

- **JORC**
  - Inferred
  - Indicated
  - Measured
  - Increasing level of geological knowledge and confidence therein

- **Investigation**
  - Geotechnical Model
  - Assumed
  - Substantiated
  - Measured

- **Monitoring**
  - Behaviour Model
  - Hypothesized
  - Simulated
  - Observed

Project Deliverables

You are requested to assist in the preparation of a Geotechnical Baseline Report (GBR) and pre-feasibility design, providing the following components:

1. To review the Geotechnical Data Report and advise with respect to the designation of geotechnical domains, providing both Mohr-Coulomb and Hoek-Brown rock mass properties for each of the geotechnical domains defined.

2. To advise the Design Team in assessing the potential for squeezing ground and provide guidance with the preliminary design of tunnel support where severe squeezing is expected.

3. To advise the Design Team in assessing the potential for spalling and rock bursting, and to provide guidance with the preliminary design of tunnel support where severe brittle failure is expected.
Site Investigation: Boreholes

Site Investigation: Simply Drilling Boreholes?
Site Investigation: Simply Drilling Boreholes?

Laboratory Testing of Rock/Soil Behaviour

Granite  | Limestone  | Shale
Data should be measured and recorded in systematic ways using standardized procedures. Much time and effort can be wasted by collecting data which may be irrelevant or inadequate. The nature of the data will also become more specialized as measurements transition from surface boreholes to construction.

The quality of the data is critical to the reliability of the interpretation...

... POOR QUALITY OR INACCURATE DATA CAN BE MISLEADING AND IS WORSE THAN NO DATA.
### Borehole Imaging and Characterisation

<table>
<thead>
<tr>
<th>Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acoustic Televiewer</td>
<td>Provides a continuous record of borehole wall (3-D virtual core); provides high accuracy and confidence in data; can be used in highly fractured rock.</td>
<td>Requires a stable borehole; requires water or mud in borehole to operate.</td>
</tr>
<tr>
<td>Optical Televiewer</td>
<td>Provides a continuous record of borehole wall (3-D virtual core); provides high accuracy and confidence in data; can be used in highly fractured rock.</td>
<td>Requires a stable borehole; requires air or clear water to operate.</td>
</tr>
</tbody>
</table>

Eberhardt & Stead (2011)

Televiewers are chosen for:
- Defining dip, dip-direction and aperture of fractures, bedding and contacts
- Obtaining critical information from areas with missing core or low core recovery (low RQD)
- Detailing fracture and fault zones regarding depth, size, frequency and attitude
- Depicting the in-situ stress field orientation

Willenberg et al. (2008)
Limitations of Borehole Drilling

Spacing & Persistence

spacing

persistence

rock

bridge

increasing persistence
Surface Mapping

Surface Mapping - Limitations
Rock Mass Classification: RMR

The Rock Mass Rating (RMR) system was developed in 1973 in South Africa by Prof. Z.T. Bieniawski. The advantage of his system was that only a few basic parameters relating to the geometry and mechanical conditions of the rock mass were required.

Rating adjustments are included to account for the adverse nature discontinuity angles may have with respect to the excavation or slope direction.

Bieniawski (1989)

Rock Mass Classification: Q-System

The Q-system of rock mass classification was developed in 1974 in Norway by Prof. N. Barton. The system was proposed on the basis of an analysis of 212 tunnel case histories from Scandinavia.

The motivation of presenting the Q-value in this form is to provide some method of interpretation for the 3 constituent quotients.
Rock Mass Classification: Q-System

The first quotient is related to the rock mass geometry. Since RQD generally increases with decreasing number of discontinuity sets, the numerator and denominator of the quotient mutually reinforce one another.

The second quotient relates to "inter-block shear strength" with high values representing better 'mechanical quality' of the rock mass.

The third quotient is an 'environment factor' incorporating water pressures and flows, the presence of shear zones, squeezing and swelling rock and the in situ stress state. The quotient increases with decreasing water pressure and favourable in situ stress ratios.

Rock Mass Classification – Examples

- blocky rock
- low stress regime
- minimal but systematic ground support
- RMR = 70 (good rock)
- Q = 15 (good rock)

Courtesy: Golder Associates
Rock Mass Classification – Examples

- blocky rock
- high stress regime
- RMR = 40 (poor to fair rock)
- Q = 0.8 (very poor rock)

\[ Q = \frac{RQD \cdot I_s \cdot I_m}{SRF} \]

Application of Classification Systems

Both of the classification systems described were developed for estimating the support necessary for tunnels excavated for civil engineering schemes. For example, the database for the RMR has involved over 351 case histories throughout its development.

Bieniawski (1989)
Experience-Based Design: Empirical Approaches

... 38 different support categories have been suggested by Barton (1974) based on the relationship between the Q index and the equivalent dimension of the excavation.

Kaiser et al. (2000)
Subjectivity in Empirical Design - Undersampling

It must be remembered though, that such guidelines are drawn from previous experiences (i.e. case histories) and are therefore limited by the range of conditions under which these experiences were generated.

Bieniawski (1989)

Rock Mass Characterization vs. Classification

Classify the rock mass using:

Q
RMR

Describe the joints
- Block Size
- Roughness/Strength
- Tunnelling Factors

DESIGN

Empirical database
Support Requirements

Geological Strength Index

Hoek-Brown Failure Envelope
- m (friction)
- s (Cohesion)

DESIGN

Stability Analysis
Quantified Factor of Safety

Rock Mass Behaviour
Rock Mass Properties - Strength

Remember!! - we’re now talking about rock mass failure, not structurally controlled failures.

Mohr-Coulomb Failure Criterion

The Mohr-Coulomb failure criterion expresses the relationship between the shear stress and the normal stress at failure along a shear surface.

BASIC EQUATIONS

Rock fails at a critical combination of normal and shear stresses:

\[ t_f = c + \sigma_n \tan \phi \]

\[ c = \text{cohesion} \]

\[ \tan \phi = \text{coeff. of friction} \]

\[ t_f = \frac{1}{2} (\sigma_1 - \sigma_3) \sin 2\beta \]

\[ \sigma_n = \frac{1}{2} (\sigma_1 + \sigma_3) + \frac{1}{2} (\sigma_1 - \sigma_3) \cos 2\beta \]

FUNDAMENTAL GEOMETRY

The equation for \( t_f \) and \( \sigma_n \) are the equations of a circle in \((\sigma_f, \tau_f)\) space:

At failure, 
\[ 2\beta = 90 \times \phi \]

\[ \beta = 45 \times \frac{\phi}{2} \]
Problems with Mohr-Coulomb

Although the Mohr-Coulomb failure criterion remains one of the most commonly applied failure criterion, and is especially significant and valid for discontinuities and discontinuous rock masses, several key limitations apply to rock slope stability analyses.

Non-linear failure envelopes.

Scale effects.

Hoek-Brown Failure Criterion

Generalized Hoek-Brown failure criterion: 

$$\sigma'_1 = \sigma'_3 + \sigma_{ci} \left( \frac{m b}{\sigma_{ci} + s} \right)^a$$

Intact rock strength: 

$$m \sim \text{lab-determined bulk modulus}$$

Rock mass strength

$$s \sim \text{Cohesion}$$

$m$ & $s$ are derived from empirical charts that are related to rock mass quality

$m \sim \text{Friction}$
Rock Mass Properties - Strength

Mohr-Coulomb

\[ \tau = c' + \sigma \tan \phi' \]

\[ \sigma'_1 = \frac{2c' \cos \phi' + 1 + \sin \phi'}{1 - \sin \phi'} \sigma'_3 \]

Generalized Hoek-Brown

\[ \sigma'_1 = \sigma_3 + \sigma_3 \left( \frac{m_h}{\sigma_3} + s \right) \]

Hoek-Brown Failure Criterion

\[ a'_1 = a'_3 + \sigma_3 \left( \frac{m_h}{\sigma_3} + s \right) \]

Intact rock strength: \( a'_1 \)

\[ \sigma_1 \]

\[ \sigma_3 \]

Hoek & Brown (1997)
Geological Strength Index (GSI)

The GSI provides a system for estimating the reduction in rock mass strength for different geological conditions.

Values of GSI are related to both the degree of fracturing and the condition of the fracture surfaces.

mainly jointing

mainly faulting

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mainly jointing

mainly faulting

GSI (for those familiar with rock mass classification)

Not a rock mass characteristic!

For RMR 89′ > 23: \[ GSI = \text{RMR} \, 89′ - 5 \]

For RMR 89′ < 23: \[ GSI = 9 \log Q' + 44 \]

\[ Q' = \frac{RQD}{J_w} \times \frac{J_n}{J_a} \]

Note that the Q-system quotient terms "Jw/JSR" are dropped as these, likewise, are not rock mass characteristics!
A simplified procedure to determine the Hoek-Brown rock mass strength parameters:

\[ \sigma_1' = \sigma_3' + \sigma_{ci} \left( m_b \frac{\sigma_3'}{\sigma_{ci}} + s \right)^a \]

First, calculate \( m_b \):  

\[ m_b = m_i \exp \left( \frac{GSI - 100}{28} \right) \]

**Hoek-Brown Simplified Procedure**

<table>
<thead>
<tr>
<th>Rock type</th>
<th>Class</th>
<th>Group</th>
<th>Medium</th>
<th>Fine</th>
<th>Var.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plagioclase</td>
<td>Lithic</td>
<td>Granite</td>
<td>35 - 3</td>
<td>30 - 5</td>
<td>39 - 5</td>
</tr>
<tr>
<td></td>
<td>Dark</td>
<td>Dark</td>
<td>17 - 13</td>
<td>15 - 8</td>
<td>N/A</td>
</tr>
<tr>
<td>Micas</td>
<td>Pyroxene</td>
<td>Pyroxene</td>
<td>20 - 5</td>
<td>25 - 5</td>
<td></td>
</tr>
</tbody>
</table>

**Hoek-Brown Failure Criterion**

For GSI > 25:

\[ s = \exp \left( \frac{GSI - 100}{9} \right) \]

\[ a = 0.5 \]

For GSI < 25:

\[ s = 0 \]

\[ a = 0.65 - \frac{GSI}{200} \]

Intact rock strength: \( \sigma_3' \)

Rock mass strength: \( m_b \) = rock mass adjusted \( \sigma_3' \)

"s" is a rock mass constant based on how fractured the rock mass is (where s = 1 for intact rock).
**GSI Disturbance Factor**

A disturbance factor, "D", may also be applied to the Hoek-Brown parameters to account for the degree to which a rock mass may have been subjected to blast damage and stress relaxation.

- Small-scale blasting in civil engineering slopes results in minimal rock mass damage, particularly if controlled blasting is used, as shown on the left-hand side of the photograph. However, stress relief results in some disturbance.
- Very large open pit mine slopes suffer significant disturbance due to heavy production blasting, and also due to stress relief from overburden removal.
- In some softer rocks, excavation can be carried out by ripping and dosing, and the degree of damage to the slopes is less.

\[
m_s = m_i \exp\left(\frac{GSI - 100}{28 - 14D}\right) \quad s = \exp\left(\frac{GSI - 100}{9 - 3D}\right)
\]

**Hoek-Brown & GSI Systems**

- Geological observations
- Descriptive input
- Quantitative input based on established rock mass indices
- Laboratory testing of intact rock samples
- GSI Characterization
- Hoek-Brown criterion - engineering properties of rock masses
- Parameters required for numerical analysis
- In situ stresses
- Groundwater
- Damage Factor
- Excavation sequence

Hoek et al. (2013)
Where Mohr-Coulomb properties are required (or preferred because we have more experience and an intuitive feel for $c$ and $\phi$), these can be derived by fitting a linear failure envelope across the non-linear H-B envelope:

Note change in $\sigma_{3\text{max}}$ for increased slope height, and corresponding change in fit of linear M-C envelope.
Rock Mass Characterization & Design

Rock Mass Classification
- Block Size
- Roughness/Strength
- Tunnelling Factors

Geological Strength Index
- Hook-Brown Failure Envelope
  - $m$ (friction) $\phi$
  - $s$ (Cohesion) $c$

DESIGN
- Empirical database
- Support Requirements

Applicability of the GSI?

Hoek's GSI Classification
- Intact rock
- Fractured rock
- Foliated rock

Ground response

Q RMR

Stability Analysis
- Quantified Factor of Safety
Empirical & Analytical Design

- Geological data collection
- Laboratory tests and in situ tests
- Rock mass classification and characterisation (Q- and RMR-values, joint properties, in situ stress etc.)
- Selection of excavation alternatives
  - Analytical methods
  - Empirical methods
  - Block failure
  - Stress failure
- Excavation method selection and support design
- Support installation and quality control
- Monitoring of excavation and support behaviour

Lecture References


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<table>
<thead>
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