Tunnel Support Design

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Tunneling Short Course
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Agenda

1.0 Introduction
2.0 Tunnel Support Design Principles
3.0 Input for Design
4.0 Tunnel Support Systems
5.0 Hard Rock Tunnel Support Design Example
6.0 Soft Ground Tunnel Support Design
7.0 Summary
1.0 Introduction

Design Flowchart sample:
(THE Tunnel project)
Rock Support Interaction:

- Optimize support installation - acceptable displacement.

Ground vs Support Reaction Curves

Ground Reaction Curves based on Overburden Depth
3.0 Geologic Input for Rock Tunnel Design

• Rock Mass Classifications:
  – Rock Mass Rating (RMR) System (Bieniawski, 1989)
  – Modified RMR (Laubscher and Page, 1990)
  – NGI’s (Q) System (Barton et al., 1974, 2015)

• Rock Mass Discontinuity Orientation and Properties

• Rock Hardness, Strength and Abrasiveness for Excavation
Initial Ground Support

- Rock Bolts / Dowels
  - Type
  - Length
  - Pattern
  - Anchorage

- Shotcrete
  - Thickness
  - Type, Dry vs Wet

- Lattice Girders
Rock Mass Classification – Q system

**Support categories**

1. Unsupported or spot bolting
2. Spot bolting, SB
3. Systematic bolting, fibre reinforced sprayed concrete, 5-6 cm, B + Sfr
4. Fibre reinforced sprayed concrete and bolting, 6-9 cm, Sfr (E500) + B
5. Fibre reinforced sprayed concrete and bolting, 9-12 cm, Sfr (E700) + B
6. Fibre reinforced sprayed concrete and bolting, 12-15 cm + reinforced ribs of sprayed concrete and bolting, Sfr (E1000) + RRS I + B
7. Fibre reinforced sprayed concrete >15 cm + reinforced ribs of sprayed concrete and bolting, Sfr (E1000) + RRS II + B
8. Cast concrete lining, CCA or Sfr (E1000) + RRS III + B
9. Special evaluation

Bolts spacing is mainly based on Ø20 mm

E = Energy absorption in fibre reinforced sprayed concrete

ESR = Excavation Support Ratio

Areas with dashed lines have no empirical data

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**ROCK MASS QUALITY AND ROCK SUPPORT**

<table>
<thead>
<tr>
<th>ROCK MASS QUALITY</th>
<th>ESR</th>
<th>Span or height in m</th>
<th>Bolt length in m for ESR = 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exceptionally poor</td>
<td>20</td>
<td>0.001</td>
<td>1</td>
</tr>
<tr>
<td>Extremely poor</td>
<td>11</td>
<td>0.004</td>
<td>2</td>
</tr>
<tr>
<td>Very poor</td>
<td>7</td>
<td>0.008</td>
<td>3</td>
</tr>
<tr>
<td>Poor</td>
<td>6</td>
<td>0.01</td>
<td>4</td>
</tr>
<tr>
<td>Fair</td>
<td>5</td>
<td>0.015</td>
<td>5</td>
</tr>
<tr>
<td>Good</td>
<td>3.5</td>
<td>0.02</td>
<td>6</td>
</tr>
<tr>
<td>Very good</td>
<td>2.5</td>
<td>0.025</td>
<td>7</td>
</tr>
<tr>
<td>Extremely good</td>
<td>1.5</td>
<td>0.03</td>
<td>8</td>
</tr>
<tr>
<td>Excellent</td>
<td>1.25</td>
<td>0.04</td>
<td>9</td>
</tr>
</tbody>
</table>

**Rock mass quality**

\[ Q = \frac{R Q D}{J_n} \times \frac{J_s}{J_a} \times \frac{J_v}{SRF} \]

After NGI 2015
# RMR Classification

<table>
<thead>
<tr>
<th>A. CLASSIFICATION PARAMETERS AND THEIR RATINGS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parameter</strong></td>
</tr>
<tr>
<td>Strength of intact rock material</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Dull core Quality (RQD)</td>
</tr>
<tr>
<td>Spacing of discontinuities</td>
</tr>
<tr>
<td>Rating</td>
</tr>
<tr>
<td>Condition of discontinuities (See E)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Rating</td>
</tr>
<tr>
<td>Ground water level</td>
</tr>
<tr>
<td>General conditions</td>
</tr>
<tr>
<td>Rating</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B. RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS (See F)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strike and dip orientations</strong></td>
</tr>
<tr>
<td>Tunnels &amp; mines</td>
</tr>
<tr>
<td>Foundations</td>
</tr>
<tr>
<td>Slopes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>C. ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Class number</strong></td>
</tr>
<tr>
<td><strong>Description</strong></td>
</tr>
<tr>
<td><strong>Average stand-up time</strong></td>
</tr>
<tr>
<td><strong>Cohesion of rock mass (kPa)</strong></td>
</tr>
<tr>
<td><strong>Friction angle of rock mass (deg)</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>D. MEANING OF ROCK CLASSES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Class number</strong></td>
</tr>
<tr>
<td><strong>Discontinuity length (perpendicular)</strong></td>
</tr>
<tr>
<td><strong>Rating</strong></td>
</tr>
<tr>
<td><strong>Separation (aperture)</strong></td>
</tr>
<tr>
<td><strong>Roughness</strong></td>
</tr>
<tr>
<td><strong>Rating</strong></td>
</tr>
<tr>
<td><strong>Weathering</strong></td>
</tr>
<tr>
<td><strong>Rating</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>E. GUIDELINES FOR CLASSIFICATION OF DISCONTINUITY CONDITIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strike perpendicular to tunnel axis</strong></td>
</tr>
<tr>
<td><strong>Drive with dip</strong> (Dip 45 - 90°)</td>
</tr>
<tr>
<td><strong>Drive with dip</strong> (Dip 45 - 90°)</td>
</tr>
<tr>
<td><strong>Drive against dip</strong> (Dip 45 - 90°)</td>
</tr>
<tr>
<td><strong>Strike parallel to tunnel axis</strong></td>
</tr>
</tbody>
</table>

*Some conditions are mutually exclusive. For example, if infilling is present, the roughness of the surface will be overshadowed by the influence of the gouge. In such cases use A 4 directly.

**Modified after Wickham et al (1972).**
Tunnel Support Design

Support Estimate:

• Empirical Approach
• Analytical Approach
  – Kinematic (Block stability)
  – Rock Reinforcement (Bischoff and Smart)
• Numerical Modeling
Empirical Methods

- **Terzaghi’s Rock Load (conceptual)**
  - More conservative
  - Modified by Deere et al., 1970

### Table: Rock Load

<table>
<thead>
<tr>
<th>Rock condition</th>
<th>Rock load, $H_p$</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Hard and intact</td>
<td>0/0</td>
<td>Lining only if spalling or popping</td>
</tr>
<tr>
<td>2. Hard stratified or schistose</td>
<td>0/0.258</td>
<td>Spalling common</td>
</tr>
<tr>
<td>3. Massive moderately jointed</td>
<td>0/0.58</td>
<td>Side pressure if strata inclined, some spalling</td>
</tr>
<tr>
<td>4. Moderately blocky and seamy</td>
<td>0/0.259 / 0.36C</td>
<td>Lining only if spalling or popping</td>
</tr>
<tr>
<td>5. Very blocky, seamy and shattered</td>
<td>0 to 0.6C / 0.35C / 1.1C</td>
<td>Little or no side pressure</td>
</tr>
<tr>
<td>6. Completely crushed</td>
<td>1.1C</td>
<td>Considerable side pressure. If seepage, continuous support</td>
</tr>
<tr>
<td>7. Gravel and sand</td>
<td>0.04C to 0.07C</td>
<td>Dense</td>
</tr>
<tr>
<td>8. Squeezing, moderate depth</td>
<td>1.0C to 1.2C</td>
<td>Dense</td>
</tr>
<tr>
<td>9. Squeezing, great depth</td>
<td>2.1C to 4.6C</td>
<td>Dense</td>
</tr>
<tr>
<td>10. Swelling</td>
<td>up to 75 m (250 ft)</td>
<td>Heavy side pressure, continuous support required</td>
</tr>
</tbody>
</table>

**Notes:**
1. For rock classes 4, 5, 6, 7, when above groundwater level, reduce loads by 50 percent.
2. If $H_p < C$ where $C = \gamma H_t$ - weight - height of tunnel
3. $\gamma$ = density of medium.
Empirical Methods

Graphical – Ubiquitous Joint Method (No. 7 Subway Line Extension)

CASE I

\[ W_I = \gamma \times A = 6,270 \text{ LBS.} \]

CASE II

\[ W_{II} = \gamma \times A = 19,845 \text{ LBS.} \]

CASE III

\[ W_{III} = \gamma \times A = 11,120 \text{ LBS.} \]
Kinematic Approach

Jointed Rock Mass

- DIPS and UNWEDGE software (Rocscience)

Stereonet of structural discontinuity planes
(No. 7 Subway Line Extension)

Cavern cross-section – wedge formation and initial support pattern
(No. 7 Subway Line Extension)
Numerical Modeling Example – THE Tunnel 34th Street Station Cavern

Station Cross section (THE Partnership)

Station Longitudinal section (THE Partnership)
Excavation Sequence:

**Stage 1:** Excavation of four TBM tunnels (TBM1, 2, 3, and 4) through the station cavern

Installing initial ground supports behind TBM shield as required.
Excavation Sequence:

Stage 2: Excavation of Top-heading (Side-drift 1, Side-drift 2, and Center-drift 3)

Stage 3: Excavation of Benches and Inverts (4, 5, 6, 7, 8 and 9)

Installing initial ground support after excavation of each blast round including rock bolting and shotcreting.

Full excavation sequence
**Numerical Modeling Example** – THE Tunnel 34th Street Station Cavern

- **Partially release** of stress at the **face** of excavation at each excavation round before installing initial support.

Evaluating stress release considering forces on ground and lining:
- Size of Excavation Face
- Ground Stiffness (Elastic Modulus, Poisson’s ratio)
- Initial Support Stiffness
- Length of Unsupported Excavation Round

(after Hoek)
Stress release for each excavation step before installing initial support in the model:

- TBM1 = 10%, TBM2 = 10%, TBM3 = 10%, TBM4 = 10%
- Side-Drift1 = 30%, Side-Drift2 = 30%
- Center-Drift3 = 40%
- Bench4 = 50%, Bench5 = 50%
- Bench6 = 50%, Bench7 = 50%
- Invert8 = 50%, Invert9 = 50%
- Final Lining = 100% relaxation

At the final stage: Eliminating the initial supports
• Simulate excavation sequence
  – Consider ground strain due to excavation at each Stage (Estimate stress release at each stage)

\[ E_{\text{ground}} = \frac{\text{Stress}}{\text{Strain}} \]

Installing initial support for each stage after simulating the strains in the numerical model

(THE Partnership - ILF)
Numerical Modeling Example – THE Tunnel 34th Street Station Cavern

Top heading / bench / invert excavation at Final Stage
(prior to removing the initial support)

General Station Cavern Excavation combining TBM and SEM Enlargement
Top heading / Bench / Invert

(THE Partnership - ILF)
Numerical Modeling Example – THE Tunnel 34th Street Station Cavern

Total displacement contours with deformation vectors and deformed boundaries

Contours of yielded elements

(THE Partnership - ILF)
After Elimination of Initial Support

Axial Forces

Bending Moments

(THE Partnership - ILF)
Ground Support

- Ground support classes
- Pre-support
- Ground Treatment / Ground improvement
**Ground Support Classes**

**Contract - Typically 2 to 3 initial support classes**

- Hard rock TBM example:

  **Support Class I: Pattern rock dowels**

  **Support Class II: Additional mine-straps and/or shotcrete support**

  **Support Class III: Steel rib support**
Tunnel Support Systems

- **Hard Rock** – Available Tunnel Support Systems
  - Rock bolts
  - Rock Anchors
  - Rock Dowels
  - Mine straps
  - Shotcrete – plain and reinforced (either steel fibers or WWF)
- **Soft Ground** – Available Tunnel Support Systems
  - Soil Nails
  - Rebar / Pipe Spiling
  - Lattice Girders
  - Shotcrete
  - Cast-In-Place
Tunnel Support Systems

• **Open (Gripper) TBM** – Available Tunnel Support Systems
  • Rock bolts / Rock dowels
  • Steel Ribs with channel lagging or minestraps
  • Shotcrete (limited to extremely poor ground)
  • CIP Lining

• **Double shield EPB / Slurry Face** – Available Tunnel Support Systems
  • Segmental lining
  • Annular and Secondary Grouting
Ground Support through Shear Zone

- WWF and minestraps
- Spiling and shotcrete
- Steel mat lagging
Pre-support Systems

Spiling (Fore-poling)  Pre-grouting ahead of face  Double-roof pipe canopy arch
Canopy spiling at Portal
Ground Treatment

Ground freezing

Pre-Grouting
Groundwater Control

Tunneling – infiltration control and waterproofing systems

Pre-excavation grouting of open fracture (South River Tunnel, Atlanta, GA., 2011)
CEMENTITIOUS vs. POLYURETHANE GROUTS

CEMENTITIOUS:
• Dry, open joints
• Long-term strength

POLYURETHANE:
• Wet conditions or relatively narrow fissures
• Time dependent properties
• Flow behavior (unreacted & reacting)
Tunnel Grouting

Pre-exavation Combined Cement + Water-reactive Polyurethane Grout:

Steps

1. Polyurethane (TACSS – single component pre-polymerized polyurethane) reaches permeable rock mass – forms barrier upon reacting with water

2. Subsequent Cement grout able to begin filling crack and curing with dilution from leaky crack.
5.0 Example - Pillar Stability Evaluation

• Phase 2D - Pre-support considered
• Staged Excavation

Results
• **No** significant yielding & deformations at 60% gripper pressure
• **Localized spalling** of Starter Tunnel shotcrete lining at 30% gripper
• No impact on Global Stability
Pillar Stability Evaluation
Pillar Stabilization Measures
Starter Tunnel Rock Reinforcement

Cradle for TBM launch

Brow and gripper wall support
Starter Tunnel Rock Reinforcement

1. Install gripper wall channels to provide proper radius gripper walls.

2. Apply gripper wall shotcrete.

3. Install gripper wall wire mesh at 38' intervals.
In Blocky ground

- Prevent rock mass raveling and loosening between bolts
- Typical failure modes:
  - Adhesive
  - Direct Shear
  - Flexural
  - Punching Shear

Applied Load Model - Shotcrete Support
(after Barrett and McCreath, 1993)
Failure modes (blocky ground):

- **Adhesive failure**

Adhesive failure model

(after Barrett and McCreath, 1993)
Failure modes (blocky ground):

- **Direct Shear Failure**

**Failure mode** (after Barrett and McCreath, 1993)

**Direct Shear failure model**

(after Barrett and McCreath, 1993)
Failure modes (blocky ground):

- **Flexural failure**

Failure mode (after Barrett and McCreath, 1993)

Flexural failure model

(after Barrett and McCreath, 1993)
Failure modes (blocky ground):

- **Punching Shear failure**

Failure mode (after Barrett and McCreath, 1993)

Punching Shear failure model
(after Barrett and McCreath, 1993)
**Good bond** between rock and shotcrete

- Direct Shear Failure unlikely
- Adhesion Failure > 4m spacing
Poor bond between rock and shotcrete
- Direct Shear Failure unlikely
- Adhesion Failure > 2.25 m spacing

Shotcrete Stability Chart
Thickness = 75 mm, Age = 28 Days

Model Parameters:
- Unit Weight of Rock = 27 kN/m³
- Width of Face Plate = 200 mm

Adhesive Properties:
- Adhesive Bond Strength = 0.5 MPa
- Adhesive Bond Length = 30 mm

Region of Shotcrete Failure

(after Barrett and McCreath, 1993)
**Soft-ground Tunneling**

- Continuous support of face and periphery (invert)
- Timely groundwater control

Horizontal vacuum system (after Taiwan HS Rail, 2001-2003)
Soft-ground Tunneling

- 3D tunnel convergence monitoring – vertical and transverse
- Reference THSR:
  - 40-ft diam SEM tunnel
Soft-ground Tunneling

• Continuous tunnel convergence monitoring - longitudinal

Reference THSR: 40-ft diam SEM tunnel
Face bolting and Ring Cut in Sandy Ground

SECTOR EXCAVATION
SEQUENCE of EXCAVATION and FACE SUPPORT

- Excavation Sector
- Shotcrete Lining
- Face Bolt with Load Distribution Plate
- Face Support Core
- Back Fill Material
- Temp. Shotcrete Invert
1. Face Bolting

2. Partial Excavation
Running Ground

- Periodic sealing (accelerator)
- Contact Grouting of Arch
Protection of Adjacent Structures

- Identify reinforcement/underpinning needs
- Instrumentation & Monitoring Program
- Control Ground movement/Subsidence
- Rigid Water-tight Excavation Support under construction as well as permanent conditions
1. Initial screening
2. Develop settlement profile
3. Evaluate settlement profile per project criteria (max surface settlement, impact to structures, etc.)
4. Identify sensitive structures within influence zone - more comprehensive analysis
5. Mitigation measures – construction restrictions
Protection of Existing Structures – Potential Impacts

1. TransPak (Shipping depot - single-story warehouse bldg.) – settlement shallow (35-ft) cover
2. Bayshore Freeway (Route 101) – adjacent highway slight embankment shallow (30-ft) cover
3. Lower Silver Creek – shallow cover settlement cracking of liner leaking shallow (30-ft) cover
Protection of Existing Structure
1. I-880 Nimitz Freeway Overpass, Shallow cover (+/- 40 FT) embankment footing and adjacent pile foundation.
2. Shallow cover (+/- 40 FT) overlying single-story building i.e., All-World Furniture and Deka Batteries settlement potential.
Building Impact Evaluation

SETTLEMENT-SINGLE TBM TUNNEL - 45 FT OD (30 FT & 40 FT COVER)

RELATIONSHIP OF DAMAGE TO ANGULAR DISTORTION AND HORIZONTAL STRAIN FOR SINGLE LARGE TUNNELS
Further evaluation of specific existing structures based upon ground conditions and as-built foundation data, potential mitigation options could feature:

- Structural Underpinning,
- Grouted Canopy spiling and lattice girder
- Rigid Support of Excavation Systems (Secant pile walls, etc.)
- Ground treatment

“A critical issue in design of mitigation measures is avoiding the creation of hard points in the building that can focus and amplify building response or damage.” (Boscardin and Walker, 1998)
Summary

- Project-specific ground characterization
- Compatible excavation methodology
  - Hard rock tunnel: rock mass discontinuities, strength and abrasion
  - Soft-ground tunnel: continuous face and periphery support / GW control / monitoring
- Contingency – Risk Mitigation measures: pre-support / ground treatment / temporary invert support
- Optimize support design evaluate results from several analytical approaches
Mile-high thank you for your attention!