Chapter 1
Planning
- Definition of Tunnels
- Shapes and Construction Types
- Alternative Analysis
- Operational and Financial Planning
- Tunnel Type Study
- Risk Analysis and Management

Tunnel and Underground Space Uses...
- Transportation
  - Vehicular (road tunnels)
  - Transit and rail (subway, freight, passenger rail, etc...)
- Water Conveyance
  - Water supply
  - Waste water (storm, sanitary, combined sewers, CSO, etc...)
- Utilities (electrical, steam, communications, etc...)

...Tunnel and Underground Space Uses
- Power stations, valve chambers, substations, etc...
- Storage (cold storage, document storage, nuclear waste, liquid storage, oil, wine, etc...)
- Mines
- Defense and National Security projects
- Commercial, residential, institutional facilities, etc...
- Unique projects/Applications (SMART Tunnel)

Storm water Management and Road Tunnel or (SMART) Kuala Lumpur Malaysia

Definition of Road Tunnels
- Road Tunnels:
  “Road tunnels (as defined by AASHTO Technical Committee for Tunnels (T-20)) are enclosed roadways with vehicles access that is restricted to portals regardless of type of the structure or method of construction.”

Tunnel Types
- Planning/ Route Selection
- Water
  - Immersed Tunnels
  - Mined/Bored Tunnels
- Land
  - Rock Tunneling
  - Soft Ground Tunneling
  - Difficult Ground Tunneling
  - SEM/NATM Tunneling
Examples of Road Tunnels

Fort McHenry Tunnel - Baltimore
Highway H-3 Oahu, Hawaii

Road Tunnels

Hanging Lake Tunnel Colorado
Cumberland Gap Tunnel Kentucky/Tennessee

Tunnel Shapes
- Rectangular
- Circular
- Horseshoe, Curvilinear
- Other Shapes:
  - Cavern shapes
  - Unique shapes (elliptical, double-o-tube, etc...)
  - Shafts – (circular, square, rectangular, elliptical)
- Configuration depends
  - Type of Construction
  - Uses
  - Liner and Finishes

Rectangular Tunnels
- Most common for road tunnels
- Cut and Cover
- Immersed Tube Tunnels

Fort Point Channel - Boston
2nd Elizabeth River Tunnel Norfolk (cut and cover segment)

Rectangular Tunnels
- Cut and Cover and Immersed Tunnels

Circular Tunnels
- Road tunnels
- Other uses:
  - Transit and rail tunnels
  - Water conveyance
  - Most suited for TBM construction
Circular Tunnels

- Bored (mined) Tunnels
  - Rock
  - Soft Ground
  - TBM

Examples of Circular Road Tunnels

Largest Bored Circular Road Tunnel
Chongming under Yangtze River Tunnel, Shanghai – 15.43 m TBM

Horseshoe Tunnels

- Rock Tunnel (Drill and Blast)
- SEM/NATM (Conventional Tunneling)
- Cut and Cover
- Immersed Tunnel
- Conventional Excavation
- Mechanized (Road Header)

Devil Slide Tunnel – San Francisco

Glenwood Canyon Colorado

2nd Downtown Tunnel Norfolk
Classes of Roads

- Accommodate all vehicle sizes permitted on the road
- Cost Conscious

Alternative Analysis

- Route Study
- Type Study
  - Cut & cover, bored, immersed tube, SEM/NATM, etc.
- Financial Evaluations
  - Capital cost and maintenance/operational costs
  - Life cycle cost
- Geological and Site Constraints
- Environmental Issues
  - Sustainability
- Operational Issues
  - Traffic control, ventilation, fire-life safety, maintenance, etc.

Route Study

- Subsurface, geological, and geo-hydraulic conditions
- Constructibility
- Long-term environmental impact
- Seismicity
- Land use restrictions
- Potential air right developments
- Life expectancy
- Economical benefits and life cycle cost
- Operation and maintenance
- Security
- Sustainability

Tunnels Enhance Sustainability

Tunnel Construction Types

- Cut-and-Cover
- Bored or Mined Tunnels
  - Rock Tunnels
  - Soft Ground Tunnels
  - Mechanized (TBM)
  - Conventional (NATM/SEM, Drill and Blast)
- Immersed Tunnels
- Specialty (Jacked Tunnels)

Cut and Cover Tunnels
Bored Tunnels – Soft Ground

M30 Madrid 13.45 m Diameter

Immersed Tunnels

Ft McHenry Tunnel, Baltimore

Specialty Type Construction
Stacked Drifts

Mt Baker Ridge Tunnel - Seattle

Specialty Type Construction
Tunnel Jacking

Central Artery Under South Station - Boston

Design Process

- Define Functional Requirements
- Perform Surveys and Investigations
- Perform Environmental Studies
- Prepare Tunnel Type Study
- Establish Alignment, Profile and Cross Section
- Establish Design Criteria, and perform the design various elements: preliminary and final designs
- Conduct Risk Analyses
- Prepare Construction Contract Documents including drawings, specs, cost estimates, GBR, etc...

Groundwater Control

- Open System (drained)
- Closed System (un-drained)

Drained waterproofing system

Un-drained waterproofing system
Fire Life Safety Aspects
- NFPA 502
- Refuge Space
- Emergency Walkway – 3.3 ft (1m)
- Exits Spacing 1000 ft (300 m)
- Cross Passages 650 ft (200m)
- Fire Rating -2 hr Minimum
- Signage
- Emergency Lighting, Fire Detection (or suppression), Fire Lines, Hydrants, communications, etc...
- Emergency Ventilation and Control Systems

Fire-Life Safety System

Tunnel Fires
- Roughly one-third of all tunnel fatalities are from fires
- Fires have the ability to quickly spread engulfing tunnel
- Fires affect all tunnel occupants
- Fires require evacuation and management to prevent loss of life and structural damage
- Structural damage often results in tunnel closure and revenue loss.

Fire Heat Release Curves
- The Cellulosic Curve
- Hydrocarbon (HC) curve
  - Simulates fires in tankers
- The RABT-ZTV curve (Germany)
  - Represents shorter duration fire
  - Rapid rise in temperature
- The RWS Curve (Netherlands)
  - Represents 300MW fire load
  - Trapped heat cannot easily dissipate

Fire Heat Release Curves

Tunnel Ventilation
- Transverse
- Semi Transverse
- Longitudinal (jet fans)
- Push-Pull
- Seccardo Nozzle
Tunnel Ventilation

Typical Vane Axial Fans
Jet Fans – Detroit Metro Airport Tunnel

Operational and Financial Planning
- Traditional Funding Sources (Federal, State, Local, Bonds, etc.)
- Alternative Funding
  - Public Private Partnership (PPP)
  - DBOM
- Operational and Maintenance Cost Planning
- Cost Analysis and Cash Flow
- Project Delivery
  - Design-Bid-Build
  - Design-Build
- Procurement Options
  - Competitive Bid (low price – Lump Sum, Unit Prices)
  - Quality Based Selection
  - Best and Final Offer (BAFO)
  - Cost Plus Fee
  - Negotiated Procurement

Chapter 2
Geometrical Configuration
- Horizontal and Vertical Alignment
- Clearances
- Cross Section Elements

Geometrical Configuration
- General Geometrical Requirements
- Horizontal and Vertical Alignments
- Cross Section Clearances
- Cross Section Elements
- AASHTO Green Book
- Standards by States and Localities
- NFPA 502

Horizontal and Vertical Alignment
- Maximum Effective Grade 4%
- Horizontal and Vertical Curves
  - Meet Green Book Requirements
  - Minimum Radius 1000 ft
  - Superelevation 1% to 6%
- Sight and Breaking Distance
- Design Flood Level (500 Year Occurrence)

Minimum and Desirable Travel Clearance
- Clearance Diagram using Vehicle Dynamic Envelopes
- Min Vertical Clearance 14 ft
- Future Resurfacing
- Truck Mounting the Curb
- Military Cargo
- Desirable Vertical Clearance 16 ft
- Lane Width 12 ft
- Shoulders Minimum 0 ft to 1.5 ft
### Modified Shoulders

![Diagram of modified shoulders]

### Typical Cross Section Elements
- Travel Lanes – Shoulders - Sidewalks/Curbs
- Tunnel Drainage
- Tunnel Ventilation
- Tunnel Lighting
- Signals and Signs Above Roadway Lanes
- Tunnel Utilities and Power
- Water Supply Pipes for Firefighting
- Cabinets For Hose Reels and Fire Extinguishers
- CCTV Surveillance Cameras
- Emergency Telephones/ Communication Equipment
- Monitoring Equipment Of Noxious Emissions And Visibility
- Emergency Egress Illuminated Signs

### Tunnel Width

#### Travel Lanes 12 ft
- Full vs Reduced Shoulders
- Barriers
- Sidewalks/Emergency Egress

![Diagram of tunnel width]

---

### Table 5.5: Dimensions of Cross Section Elements

<table>
<thead>
<tr>
<th>Component</th>
<th>Design Length (m)</th>
<th>Width of Cross Section (m)</th>
<th>Width of Shoulder (m)</th>
<th>Width of Water Supply Pipes (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel Lanes</td>
<td>12.00</td>
<td>3.65</td>
<td>0.78</td>
<td>1.15</td>
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<tr>
<td>Barriers</td>
<td>0.60-1.50</td>
<td>1.50</td>
<td>1.00</td>
<td>1.50</td>
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<tr>
<td>Sidewalks</td>
<td>0.60-1.50</td>
<td>0.70</td>
<td>0.50</td>
<td>1.00</td>
</tr>
<tr>
<td>Emergency Egress</td>
<td>0.60-1.50</td>
<td>0.70</td>
<td>0.50</td>
<td>1.00</td>
</tr>
</tbody>
</table>

*In exceptional cases, secondary emergency exits are to be provided.*

---

**Parsons Brinckerhoff**

---

**Cumberland Gap Tunnel**

---

**Miami Port Tunnel**
Lighting Requirements

- ANSI/IESNA RP 22 “Recommended Practice for Tunnel Lighting”
- Black Hole Effect

Portals

- Location and Orientation
- Functionality
  - Dividing walls
  - Flood Level
  - Traffic Control
  - Emergency Access
- Environmental
- Aesthetics

H3 Tetsuo Harano Tunnel
Chapter 3
Geotech Investigations

- Introduction
- Information Study
- Surveys and Site Reconnaissance
- Geologic Mapping
- Subsurface Investigations
- Environmental Issues
- Seismicity
- Additional Investigations During Construction
- Geospatial Data Management System

As stated in Section 2.4.6 of AASHTO Manual on Subsurface Investigations (1988), "Design for underground construction is basically a geotechnical engineering effort, with project configuration being subject to the limitations imposed by soil and rock conditions and properties."

Phased Geotech Investigations

Conceptual Planning
Feasibility
Alternative/Route Study
Environmental Study/Conceptual Design
Preliminary Design
Final Design
Construction

References

- FHWA Geotechnical Engineering Circular No. 5 (FHWA, 2002a)
- FHWA Reference Manual for Rock Slopes (FHWA, 1999), and

Tunnel Types

Planning/Route Selection
Water
Immersed Tunnels
Rock Tunneling
SEM Tunneling
Land
Mined/Bored Tunnels
Soft Ground Tunneling
Difficult Ground Tunneling
Cut & Cover Tunnels
Components of Geotechnical Investigation Program

- Information study
- Survey
- Site reconnaissance
- Geologic mapping
- Subsurface exploration
- In-situ and laboratory testing
- Instrumentation, and
- Other investigations made during and after construction

Geologic Mapping

- Discontinuity type
- Discontinuity orientation
- Discontinuity infilling
- Discontinuity spacing
- Discontinuity persistence
- Weathering

Geologic Mapping

- Slides, new or old, particularly in proposed portal and shaft areas
- Major faults
- Rock weathering
- Sinkholes and karstic terrain
- Groundwater springs
- Volcanic activity
- Anhydrite, gypsum, pyrite, or swelling shales
- Stress relief cracks
- Presence of talus or boulders
- Thermal water (heat) and gas

Subsurface Investigations

- Typically 3% to 5% of Construction Cost
- Phased Investigations
- Define subsurface profile
- Estimate geomaterial properties
- Identify hydrogeological conditions
- Identify potential adverse geotechnical features (difficult ground issues)

Example Interpretive Profile

Geological Setting
Subsurface Explorations and Field/Laboratory Testing

- Borings to identify the subsurface stratigraphy and to obtain disturbed and undisturbed samples.
- In situ tests to obtain useful engineering and index properties.
- Geophysical tests to obtain subsurface information (stratigraphy and general engineering characteristics).
- Laboratory tests to provide a wide variety of engineering properties and index properties.

Borehole Spacing

<table>
<thead>
<tr>
<th>Ground Conditions</th>
<th>Typical Borehole Spacing (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut-and-Cover Tunnels</td>
<td>100 to 500</td>
</tr>
<tr>
<td>Rock Tunnelling</td>
<td>50 to 100</td>
</tr>
<tr>
<td>Adverse Conditions</td>
<td>500 to 1000</td>
</tr>
<tr>
<td>Favorable Conditions</td>
<td></td>
</tr>
<tr>
<td>Soft Ground Tunneling</td>
<td>25 to 50</td>
</tr>
<tr>
<td>Adverse Conditions</td>
<td>300 to 500</td>
</tr>
<tr>
<td>Favorable Conditions</td>
<td></td>
</tr>
<tr>
<td>Mixed Face Tunneling</td>
<td>50 to 75</td>
</tr>
<tr>
<td>Adverse Conditions</td>
<td></td>
</tr>
<tr>
<td>Favorable Conditions</td>
<td></td>
</tr>
</tbody>
</table>

Horizontal Boring

- Observation of groundwater levels in boreholes
- Assessment of soil moisture changes in the boreholes
- Groundwater sampling for environmental testing
- Installation of groundwater observation wells and piezometers
- Borehole permeability tests (rising, falling and constant head tests; packer tests, etc.)
- Geophysical testing (see Section 3.5.4)
- Pumping tests

Groundwater Investigation

Seismic Considerations

- Large ground displacements due to ground failure, i.e., fault rupture through a tunnel
- Landslide (especially at tunnel portals)
- Soil liquefaction
- Chapter 13 – Seismic Considerations

Investigations During Construction

- Borings/probings from the ground surface
- Additional laboratory testing of soil and rock samples
- Geologic mapping of the exposed tunnel face
- Geotechnical instrumentation
- Probing/Geophysical testing in advance of the tunnel heading from the face of the tunnel
- Pilot Tunnels
- Groundwater observation wells and/or piezometers
- Environmental testing of soil and groundwater samples suspected to be contaminated or otherwise harmful
Difficult Ground Conditions
- Mixed face condition
- High groundwater pressure
- Sensitive Clays
- Running Sands
- Faults and Shear Zones
- Squeezing and Swelling Ground
- Boulders and Obstacles
- Karstic Limestone
- Gassy ground
- High Temperature

Data Management and Preservation
- It often takes decades for a tunnel to be completed
- Preservation of rock and soil samples?
- Core scanning
- Borehole video and acoustic viewer
- Geospatial Data Management System

Chapter 4
Geotechnical Reports
- Introduction
- Geotechnical Data Report
- Geotechnical Design Memorandum
- Geotechnical Baseline Report

Geotechnical Reports
- Originally based on 1997 Yellow Book – Geotechnical Baseline Reports for Underground Construction
- Revised based on Draft 2007 Geotechnical Baseline Reports for Construction – Suggested Guidelines

Geotechnical Data Reports
- Geotechnical factual data collected during investigation and design phases of the Project.
- Included as a contract document
- Do not include any interpretation of data to avoid conflict with subsequent reports.
<table>
<thead>
<tr>
<th>Geotechnical Design Memorandum</th>
<th>Geotechnical Baseline Report</th>
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<tbody>
<tr>
<td>■ Geotechnical Interpretive Reports</td>
<td></td>
</tr>
<tr>
<td>■ For internal use and considerations – NOT included in Contract Document</td>
<td></td>
</tr>
<tr>
<td>■ Not to be used or confused with Baselines</td>
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</tr>
<tr>
<td>■ Geotechnical Design Summary Reports</td>
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</tr>
<tr>
<td>■ Geotechnical Interpretive Reports</td>
<td></td>
</tr>
<tr>
<td>■ Set clear realistic baselines for conditions anticipated to be encountered during construction</td>
<td></td>
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</tbody>
</table>
Chapter 5
Cut and Cover Tunnels

- Construction Methodology
- Support of Excavation
- Structural Systems
- Loads and Load Combinations
- Structural Design
- Ground Water Control
- Maintenance and Protection of Traffic
- Utility Support/Relocation

Construction Methodology

- Bottom Up
- Top Down

Bottom Up Construction

1. Excavate Opening
2. Install Support of Excavation
3. Deck Over Excavation
4. Construct Structure
5. Backfill
6. Remove Support of Excavation
7. Restore Surface

Bottom Up Construction

- Conventional Techniques
- Waterproofing more easily Applied
- Drainage Systems more easily Installed
- Excavation Open and Accessible
- Requires Larger Footprint
- Restoration of Surface can not Occur until Completion of Construction

Bottom Up Construction
Top Down Construction

- Excavate Opening
- Install Support of Excavation
- Install Bracing Elements
- Bracing Elements and Excavation Support Walls are the Final Structure

Support of Excavation

- Deck over the Excavation
- Remove Top Portions of Support of Excavation
- Backfill
- Restore Surface

Support of Excavation Design Issues

- Ground Movement
  - Deflection of Support of Excavation Walls
  - Deflections are Not Recoverable and Cumulative
  - Deflections must not Encroach on the Structural Envelop of the Permanent Structure
  - Wall Stiffness
  - Wall Type
  - Spacing of Bracing
  - Tie-Backs
  - Consolidation Due to Dewatering
  - Impact on Adjacent Features

Support of Excavation Design Issues

- Base Stability
  - Cohesive Soils – Heave
  - Granular Soils - Quick
- Water Tightness
  - Local draw Down of Water Table
  - Movement of Hazardous Materials in Ground
  - Dry Working Conditions
  - Flooding of Excavation
- Underpinning of Adjacent Facilities
  - Deflection of Support of Excavation Walls
  - Monitoring and Instrumentation
  - Mitigation Plans
Support of Excavation

Tangent Pile Wall

1. Install tangent piles spaced at N
2. Install tangent piles adjacent to piles installed in step 1
3. Complete wall by installing remaining piles

Secant Pile Wall

Portion of pile 1 removed during installation of pile 3 (typ.)
Portion of pile 1 removed during installation of pile 2 (typ.)
Structural Systems

- Structural Element Sizing
- Clear Space Requirements
  - Vehicular Clearance – Horizontal & Vertical
  - Clearance to Appurtenances
- Span Lengths
- Structural Depths
  - Vertical Alignment
  - Depth of Excavation
  - Length of Approaches

Loads

- Dead Loads
  - Structural Members
    - Roof
    - Ceiling
    - Walls
    - Roadway Slab
    - Floor Slab
  - Utilities
  - Drainage
  - Signs
  - Signals
  - Communications
  - Ventilation

Loads (cont’d)

- Earth Loads
  - Horizontal – At Rest
  - Vertical – AASHTO LRFD Provides Guidance
  - Surcharge – Minimum 400psf
- Live Loads
  - Over Tunnel
  - Inside Tunnel
  - Buoyancy
- Extreme Event
  - Fire
  - Earthquake
  - Blast

Loads (cont’d)

- Bottom Up Construction

Loads (cont’d)

- Top Down Construction
Load Combinations

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<th>Load Combination</th>
<th>DC</th>
<th>Dw</th>
<th>Dv</th>
<th>El</th>
<th>El</th>
<th>El</th>
<th>El</th>
<th>Vw</th>
<th>Vw</th>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
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</tbody>
</table>

At-rest earth pressure should be used for all conditions of design of cut and cover tunnel structures. Cut and cover tunnel structures are considered rigid frames.

Resistance Factors
- Reinforced Concrete (As Modified by Chapter 12 of AASHTO):
  - Flexure = 0.9
  - Shear = 0.85
  - Bearing = 0.7
  - Compression = 0.75
- Structural Steel
  - Flexure = 1.0
  - Shear = 1.0
  - Compression (Steel Only) = 0.9
  - Compression (Composite) = 0.9

Groundwater Control
- Construction Dewatering
  - Impervious Retaining Walls
  - Well Points (Drawdown)
  - Ground Improvement (Chemical or Grout Injection)
  - Pumping
  - Effects of Lowering Groundwater must be Considered
  - Base Stability
- Uplift
  - Connections to Excavation Support System
  - Thickening Structural Members to add Dead Weight
  - Widening Floor Slab to Engage Soil Weight
  - Tension Piles
  - Permanent Tie-Down Anchors
  - Permanent Pressure Relief System
  - Groundwater Discharge and Environmental Issues

Structural Design
- Load Factors and Combinations
- Resistance Factors as per AASHTO
- Ductility Factor = 1.0
- Redundancy Factor = 1.0
- Importance Factor = 1.05

Structural Analysis
- Analyze Each Stage of Construction
- Analysis Methods
  - Classical Frame Analysis
  - Soil Springs for Floor Slab
  - Soil Structure Interaction
  - 3D Models for Complex Sections
- Account for Secondary Effects

Maintenance and Protection of Traffic

Parsons Brinckerhoff
Utility Support and Relocation

- Field Locate All Utilities
- Excavate to Expose Utilities
- Identify Disposition
  - Relocate
  - Abandon
  - Support in Place
- Utility Issues
  - Long Lead Times (Energy Utilities)
  - Functioning (i.e. Gravity Sewers)
  - Hazardous Materials
  - Sensitivity to Ground Movements
  - Age and Condition

Utility Support and Relocation

- Process
  - Identify Utilities and Owners
  - Coordinate with Owners
  - Coordinate Construction Schedule and Staging
  - Survey Existing Condition
  - Establish Criteria for Allowable Movement
  - Establish Instrumentation Requirements
  - Develop Procedures for Access During and After Construction
  - Define Easements and Prior Rights

3D Phasing Example

Questions?

3D Phasing & Cut-away Views
Chapter 6
Rock Tunneling

- Introduction
- Rock Failure Mechanism
- Rock Mass Classifications
- Rock Tunneling Methods
- Types of Rock Reinforcement and Excavation Support
- Design and Evaluation of Tunnel Supports
- Groundwater Control During Excavation
- Permanent Lining Design Issues

Rock Failure Mechanism

- In Situ Stress Level and Rock Mass Characteristics
- Shallow Depths, Blocky and Jointed
  - Gravity Falls of Wedges, Blocks
- Great Depths
  - Failure of Rock Mass
  - Spalling, Slabbing, Rock Bursts

Intervention

- Analysis, Design and Construction
- Range of Behavior
  - Coherent Continuum to Discontinuum
- Stabilization
  - No Support to Bolts to Sets to Reinforced Concrete
- Vary Tunnel to Tunnel and Within A Tunnel
- Be Prepared for Change

Wedge Failure

- “Solid” Rock is a Misconception
- Usually Combination of Blocky Medium and Continuum
- Acts like Discontinuum
- Depends on Character and Spacing of Discontinuum
- Hold Rock Together, Make it Form Ground Arch

Basic Information

- Determine
  - RQD
  - Number of Joints
  - Joint Roughness
  - Joint Alteration
  - Water Condition
  - Stress Condition
Basic Information

- Determine
- RQD
- Number of Joints
- Joint Roughness
- Joint Alteration
- Water Condition
- Stress Condition
- Bases for Q System
- More Later

Squeezing and Swelling

- Squeezing
  - In-Situ Uniaxial Compressive Strength << Excavation Induced Stress
- Swelling
  - Increase in Moisture of Rock
  - Can be Related But Doesn't Require Squeezing
  - Support Must Resist Full Swelling Pressure
    - It will form

The Challenge

- Prevent Natural Tendency to Unravel
- Initiated by “Keyblocks” (Goodman 1980)
- Loosen and Come Out
- Others Follow
- Until it Stabilizes or Collapses

Strain Squeezing Relationship

Stabilizing Blocks

- Step 1: Block A drops down
- Step 2: Block B rotates counterclockwise and drops out
- Step 3: Block C rotates counterclockwise and drops out
- Step 4: Block D drops out followed by block E
- Step 5: Block E drops out followed by block F
- Step 6: Block F rotates clockwise and drops out

Rock Mass Classification Systems
Terzaghi’s Rock Mass (Tunnelman’s) Classification

<table>
<thead>
<tr>
<th>Rock Condition</th>
<th>Rock Load, Mf (Mf)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard and intact</td>
<td>0</td>
<td>Failure from wedging, required only of stoping or propning</td>
</tr>
<tr>
<td>Third weak but cohesive</td>
<td>0.25 to 3.39 (0.25 - 3.39)</td>
<td>Light support. Loads may change somewhat from point to point.</td>
</tr>
<tr>
<td>Moderately weak and subuneat</td>
<td>3.30 to 1.10 (3.30 - 1.10)</td>
<td>Little or no side pressure.</td>
</tr>
<tr>
<td>Very weak and subuneat</td>
<td>2 to 1.50 (2 - 1.50)</td>
<td>Considerable side pressure. Swelling effect often causes damage. Support for lower ends of ribs or circular sections.</td>
</tr>
<tr>
<td>Completely subuneat but chemically intact</td>
<td>1 to 0.50 (1 - 0.50)</td>
<td>Heavy side pressure. Support at lower ends of ribs or circular sections.</td>
</tr>
<tr>
<td>Spacing rock, medium depth</td>
<td>1 to 0.50 (1 - 0.50)</td>
<td>Heavy side pressure. Support at lower ends of ribs or circular sections.</td>
</tr>
<tr>
<td>Spacing rock, greater depth</td>
<td>1.50 to 2.00 (1.50 - 2.00)</td>
<td>Heavy side pressure. Support at lower ends of ribs or circular sections.</td>
</tr>
<tr>
<td>Softening rock</td>
<td>0.50 to 0.25 (0.50 - 0.25)</td>
<td>Circular ribs are recommended.</td>
</tr>
<tr>
<td>Ultimate resistance of intact sound core pieces greater than Four Inches</td>
<td>0.25 to 3.39 (0.25 - 3.39)</td>
<td>Light support. Loads may change somewhat from point to point.</td>
</tr>
</tbody>
</table>

Q System

- Traditional Six-Parameter (Q-Value) for Selecting Suitable Combinations of Shotcrete and/or Bolts For Rock Mass Reinforcement
- Six Parameters
  - RQD = Quality Designation
  - Jn = Joint set Number
  - Jr = Joint Roughness Number
  - Ja = Joint Alteration Number
  - Jw = Joint Water Factor
  - SRF = Stress Reduction Factor

Q System Equation

\[ Q = \left( \frac{RQD}{J_n} \right) \times \left( \frac{J_r}{J_a} \right) \times \frac{J_w}{SRF} \]

RQD – Rock Quality Designation

- Systematic Description of Rock Mass Quality From Rock Cores
- Length, as Percentage, of Intact and Sound Core Pieces Greater than Four Inches

Q System

- Three Major Components
  - \( \frac{RQD}{J_n} \) = Measure of block size
  - \( \frac{J_r}{J_a} \) = Measure of joint frictional strength
  - \( \frac{J_w}{SRF} \) = Measure of Joint Stress

Based on more than 1000 tunnels
### Q System Table 1

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Rock Quality Designation</td>
<td>RQD</td>
<td>1. Where RQD is reported or measured, it is 10% excluding 0.</td>
</tr>
<tr>
<td>2. Porous</td>
<td>20 - 100</td>
<td>2. RQD varies between 55 and 100 are sufficiently accurate.</td>
</tr>
<tr>
<td>3. Fracture</td>
<td>55 - 75</td>
<td></td>
</tr>
<tr>
<td>4. Overburden</td>
<td>16 - 80</td>
<td></td>
</tr>
<tr>
<td>5. Structure</td>
<td>30 - 100</td>
<td></td>
</tr>
</tbody>
</table>

### Q System Table 2

<table>
<thead>
<tr>
<th>Joint Set Number</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Major</td>
<td>0 - 3</td>
<td></td>
</tr>
<tr>
<td>B. Minor</td>
<td>4 - 7</td>
<td></td>
</tr>
<tr>
<td>C. Discontinuous</td>
<td>8 - 10</td>
<td></td>
</tr>
<tr>
<td>D. Thin Planar</td>
<td>11 - 13</td>
<td></td>
</tr>
<tr>
<td>E. Thick Planar</td>
<td>14 - 16</td>
<td></td>
</tr>
</tbody>
</table>

### Q System Table 3

<table>
<thead>
<tr>
<th>Joint Discontinuity Number</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. No.</td>
<td>1 - 3</td>
<td></td>
</tr>
<tr>
<td>B. Rough or jagged, uneven</td>
<td>4 - 6</td>
<td></td>
</tr>
<tr>
<td>C. Smooth or rounded</td>
<td>7 - 9</td>
<td></td>
</tr>
<tr>
<td>D. Discontinuous</td>
<td>10 - 12</td>
<td></td>
</tr>
<tr>
<td>E. Less than 60 cm</td>
<td>13 - 15</td>
<td></td>
</tr>
<tr>
<td>F. Greater than 60 cm</td>
<td>16 - 18</td>
<td></td>
</tr>
</tbody>
</table>

### Q System Table 4

<table>
<thead>
<tr>
<th>Joint Orientation Number</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Rock in place, non-porous</td>
<td>0.0</td>
<td>1. Values of 0.0 are assumed to be not present.</td>
</tr>
<tr>
<td>B. Porous or fractured</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>C. Fractures</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>D. Joints</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>

### Q System Table 5

<table>
<thead>
<tr>
<th>Joint Water Infiltration</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Dry</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>B. Moist</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>C. Saturated</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>D. Very Saturated</td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>

### Q System Table 6

<table>
<thead>
<tr>
<th>Stress Reduction Factor</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Dry</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>B. Wet</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>C. Very Wet</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>
Rock Mass Rating (RMR)  
(Bienewski, 1989)

- Uses Six Parameters
  - Uniaxial Compressive Strength (Intact)
  - RQD
  - Discontinuity Spacing
  - Condition of Discontinuities
  - Groundwater Conditions
  - Orientation of Discontinuities

**Numerical Modeling**

**Rock Tunneling Methods**

**Drill and Blast**

- Controlled Blasting Principles
- Relief
- Delay Sequencing
- Tunnel Blast Specifics
- Burn Cut
- Perimeter Control
- Art vs. Science
- Hire a Blast Consultant
- Hemphill (1981)
Tunnel Boring Machines (TBM)

Alkirk TBM

Cutter Wheels with Carbide Inserts or Teeth

Tunnel Advance Rate (AR) Improvements Driven by Innovation

Disk Cutters
Disk Cutters

Machine Main and Support Elements

- Complex Machine – Mechanisms for:
  - Cutting
  - Shoving
  - Steering
  - Gripping
  - Shielding
  - Exploratory Drilling
  - Ground Control and Support
  - Lining Erection
  - Muck Removal
  - Ventilation
  - Power Supply

Machine Components

- Machine Components Include Some or All:
  - Cutter
  - Gripper (Except Single Shield TBM)
  - Shield (Except Open TBM)
  - Thrust Cylinders
  - Conveyor
  - Rock Reinforcement Equipment
  - Complete Trailing Gear

Fully Equipped Up To 1000 Ft or More

Modern Rock TBM

Open Main Beam

Single Shield

Double Shield
Put It All Together

Rock Bolt Drill Rig

Mesh Erector

Mesh Installed

Shotcrete Robot

Shielded TBM
Multi Support TBM

1. Cutterhead
2. Cutterhead Support
3. Ring Erector
4. Anchor Drilling Device
5. Wire Mesh Erector

Compatible Ground Support Elements

- Roof Bolting
- Spiling/Forepoling
- Pre-Injection
- Steel Ring Beams with or without Lagging
- Invert Segment
- Shotcrete
- Precast Concrete Segment Lining

Roadheaders

Machine Utilization

When Do Roadheaders Apply

- Low Rock Strength – 20000 psi or even 15000
- Short Runs
- One of a Kind Opening
- Odd, Non-circular or Large Shapes
- Connection, Cross Passages, etc
- Low to Moderate Abrasivity
- Preferably Self-supporting Rock
- No or Small Inclusions-Chert etc
- Nominal Water Pressure
Types of Rock Reinforcement and Excavation Support

Lattice Girder

Steel Rib Support

Precast Concrete Segments
Design and Evaluation of Tunnel Supports

Tunnel Supports

Transition
- From Support – Ribs/Lagging
- To Reinforcement – Bolts, Dowels, Spiling, Lattice Girders, Shotcrete
- Hold Rocks Together
- Prevent Block Movement
- Ground Arch

Started on DC Subway

Empirical Methods

<table>
<thead>
<tr>
<th>Reinforcing Categories</th>
<th>Unsupported</th>
<th>Spot Bolting</th>
<th>Systematic Bolting with 40-100 mm unreinforced shotcrete</th>
<th>Fiber reinforced shotcrete, 50 - 90 mm, and bolting</th>
<th>Fiber reinforced shotcrete, 90 - 120 mm, and bolting</th>
<th>Fiber reinforced shotcrete, &gt; 150 mm, and bolting</th>
<th>Cast concrete lining</th>
</tr>
</thead>
</table>
Empirical Methods

Analytical Method
- Kirsch Solution

\[ \sigma = \sigma_{ff} \left(1 + \frac{a^2}{r^2}\right) \]

Rock Mass Rating (RMR)

Analytical Method
(Hoek 1999)

\[ P_{cr} = \frac{2 P_0 - \sigma_{cm}}{1 + k} \]
- \( P_{cr} \) = Critical Support Pressures - Prevents failure of rock mass around opening
- \( P_0 \) = Hydrostatic Stress
- \( \sigma_{cm} \) = Uniaxial Compressive Strength (Rock Mass)
- \( \varnothing \) = Angle of Friction (Rock Mass)
- \( k \) = XXX

\[ \frac{1 + \sin \varnothing}{1 - \sin \varnothing} \]

Analytical Methods

Rock Arch – Bischoff and Smart
Analytical Methods Unwedge

- 3-D Stability Analysis (Computer) For Blocky Ground

Analytical Methods

- Finite Element (FEM) or Finite Difference (FDM)
- Complex Computer Modeling Options
- Wide Variety of Support Types

Typical Modeling Results – Discrete Element Method (DEM)

- Large Deformation and Finite Analysis of Blocky Ground

Analytical Methods Summary

<table>
<thead>
<tr>
<th>Support System</th>
<th>Support stiffness (kN) and maximum support pressure (P_m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete/Reinforced</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( k = \frac{b}{2} \left[ \frac{b}{2} \left( \frac{b}{2} + d \right) \right] )</td>
</tr>
<tr>
<td></td>
<td>( P_m = \frac{b}{2} \left( \frac{b}{2} + d \right) )</td>
</tr>
<tr>
<td>Brick or Stone</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( k = \frac{b}{2} \left( \frac{b}{2} + d \right) )</td>
</tr>
<tr>
<td></td>
<td>( P_m = \frac{b}{2} \left( \frac{b}{2} + d \right) )</td>
</tr>
<tr>
<td>unsupported mechanical</td>
<td></td>
</tr>
<tr>
<td>or chemically anchored</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( k = \frac{b}{2} \left[ \frac{b}{2} \left( \frac{b}{2} + d \right) \right] )</td>
</tr>
<tr>
<td></td>
<td>( P_m = \frac{b}{2} \left( \frac{b}{2} + d \right) )</td>
</tr>
</tbody>
</table>

Brady & Brown 1985

Groundwater Control

- Terzaghi
- Control Takes Many Forms
- Varies Tunnel to Tunnel – Within a Tunnel

Typical Modeling Results – Continuum
Groundwater Control Methods

Usual
- At Face
- Probe Holes
- Pilot Tunnel
- Grouting
- Freezing
- Closed Face Machine

Other
- Compressed Air
- Panning
- Drain Fabric

Groundwater Control Methods

Rock Loads

- Section 6.6
- Roof, Side and Eccentric
- Empirical or Computer

Rock Loads

Permanent Lining Water Loads

- Prefer to Drain
- Many Factors
  - Relative Permeability
  - Relative Stiffness
  - Geometric (e.g., Depth Below Water)
- Empirical
- Numerical

Permanent Lining Water Loads

Empirical Water Loads

- Long Term Support
- Prepare for End Use
- Incorporate Initial Support

Empirical Water Loads
Water Loads
Numerical Methods

Closure

- Exciting Engineering
- Art and Science
- Old and New
- Rapid Changes
- Déjà Vu All Over Again
Chapter 7
Soft Ground Tunneling Outline
- Introduction
- Ground Behavior
- Excavation Methods
- Ground Loads and Ground – Support Interaction
- Settlement
- Ground Stabilization
- Ground Improvement
- Impact on and Protection of Surface Facilities

Introduction
- 1000’s of years
- Demand will Grow
- Discuss Mostly Shield Tunneling
- SEM/NATM – Chapter 9
- Problematic Ground – Chapter 8
- Data Needed – Chapter 3
- GDM and GBR – Chapter 4

Tunnelmans Ground Classification

Cohesive Soils and Silty Sand Above Water Table

$$ N_{cr} = \frac{P_z - P_a}{S_u} $$

$$ P_z = \text{Overburden Pressure} $$
$$ P_a = \text{Interior Pressure} $$
$$ S_u = \text{Undrained Shear Strength} $$

Clayey Soils and Silty Sand

<table>
<thead>
<tr>
<th>Stability Factor, $N_{	ext{cr}}$</th>
<th>Soft Ground Tunneling Behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cohesive Soils</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Stable</td>
</tr>
<tr>
<td>2-3</td>
<td>Small creep</td>
</tr>
<tr>
<td>4-5</td>
<td>Creeping, usually slow enough to permit tunneling</td>
</tr>
<tr>
<td>6</td>
<td>May produce ground shear failure. Clay likely to undulate (tunnel too quickly to handle)</td>
</tr>
<tr>
<td>Silty Sands Above Water Table (with some apparent cohesion)</td>
<td></td>
</tr>
<tr>
<td>4-6</td>
<td>Firm</td>
</tr>
<tr>
<td>6/2-1</td>
<td>Slow Raveling</td>
</tr>
<tr>
<td>1/2-1</td>
<td>Raveling</td>
</tr>
</tbody>
</table>

Modified by Heuer (1974) from Terzaghi (1950)
### Sand and Gravels

<table>
<thead>
<tr>
<th>Description</th>
<th>Degree of Coarseness</th>
<th>Tunnel Behavior Above Water Table</th>
<th>Tunnel Behavior Under Water Table</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Fine Gravel</td>
<td>Low, N&lt;10</td>
<td>Cohesive Rounding</td>
<td>Flowing</td>
</tr>
<tr>
<td>Fine Gravel</td>
<td>Low, N&lt;10</td>
<td>Dry or Sandy Rounding</td>
<td>Flowing</td>
</tr>
<tr>
<td>Sand or Gravel</td>
<td>Low, N&lt;10</td>
<td>Low Pressure Rounding</td>
<td>Flowing</td>
</tr>
<tr>
<td>Sand and Gravel</td>
<td>Low, N&lt;10</td>
<td>Dry or Sandy Rounding</td>
<td>Notopelling</td>
</tr>
</tbody>
</table>

### Brunel’s Discovery

- Maintain Stability
- Limit size
- Match size to ground behavior, support
- Many factors involved

### Tunnel Behavior

Cohesionless Soils Below Water Tables

- Can run or flow, cleaner more so

### Brunel Shield

- Maintain Stability
- Changing Stresses – Starts ahead of face
- Accompanied by Distortions
  - In medium and supports
  - Some is beneficial – too much detrimental

### Brunel Shield – Thames River
1960’s – 1970’s

Earth Pressure Balance Machine

1960’s – 1970’s

Earth Pressure Balance TBM
Earth Pressure Balance TBM

EPB Shield, Belt Conveyor Outlet

Slurry Face Machine

Slurry Face Machine

Slurry Face Machine

Slurry Separation Plant
Choosing Between EPB And SFM

EPB
- Silty Ground High Percent Fines
- Permeability less than 10 – 5 m/s
- Higher permeability requires increased percentage of conditioners

SFM
- Permeability
- Fines > 20% may rule it out
- High Plasticity clays – balling – and problems at treatment plant
- Conditioning Agents

Ground Loads and Ground – Support Interaction

- Overpressure Loading
  - Ground Isolated – Unstressed
  - Excavate Tunnel, Install Lining
  - Apply Soil (Freefield) Stresses to Boundary

- Excavation Loading
  - Ground Isolated – Unstressed
  - Apply In-situ Stresses
  - Construct Tunnel in Stressed Groundmass

See Chapter 10

Analytical Solutions

Ground – Support Interaction
Solutions Include
1. Morgan – 1961
2. Burns and Richard – 1964
3. Hoeg – 1968
5. Dar and Bates – 1974
7. Curtis – 1976
8. Rankin, Ghabouss, and Hendrois – 1978
10. Wu and Perszien – 1997

See Appendix
**Simplified Loads for Initial Tunnel Support**

<table>
<thead>
<tr>
<th>Geological Condition</th>
<th>Circular Tunnel</th>
<th>Horsehoe Tunnel</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Racing ground</td>
<td>Some of full overbreak or 1/2 B</td>
<td>Same as full overbreak</td>
<td>Flow indicated in previous if compensated or used. Otherwise, ignore compensated.</td>
</tr>
<tr>
<td>Flowing ground in air free</td>
<td>Some of full overbreak or 1/2 B</td>
<td>Same as full overbreak</td>
<td>Flow from expansion in horsehoe.</td>
</tr>
<tr>
<td>Trenching ground</td>
<td>Some or no lining</td>
<td>Some or lining</td>
<td>Some in horsehoe ground. Flow from expansion in horsehoe.</td>
</tr>
<tr>
<td>Spreading ground</td>
<td>Depends on soil properties</td>
<td>Depends on soil properties</td>
<td>Depends on soil properties.</td>
</tr>
<tr>
<td>Settlement ground</td>
<td>Some or no lining</td>
<td>Some or lining</td>
<td>Some in horsehoe ground. Flow from expansion in horsehoe.</td>
</tr>
</tbody>
</table>

Table 7-6: Initial Support Loads for Tunnels in Soft Ground

**Sources of lost ground**

- Face – movement in front of and into shield
- Running, flowing, caving, squeezing
- Shield – Between cutting edge and tail
- Yawing, pitching, plowing, cornering
- Tail
  - Vacated by tail
  - To erect segments
  - Prevent iron binding
  - Tends to fill rapidly

**Numerical Methods**

(a) Axial Force
(b) Bending
(c) Shear

Loads on a Concrete Lining Calculated by Finite Element Analysis

**Settlement Calculations**

<table>
<thead>
<tr>
<th>Case</th>
<th>η (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good practice in fine ground or fine soil without or with close face,</td>
<td>0.5</td>
</tr>
<tr>
<td>face machine in slowly moving or stopping ground</td>
<td></td>
</tr>
<tr>
<td>Good practice with closely spaced face machine in slowly moving or</td>
<td>1.0</td>
</tr>
<tr>
<td>stopping ground</td>
<td></td>
</tr>
<tr>
<td>Poor practice with closed face in moving ground</td>
<td>2</td>
</tr>
<tr>
<td>Poor practice with closed face in poor (not moving) or stopping</td>
<td>3</td>
</tr>
<tr>
<td>Poor practice with little face control in moving ground</td>
<td>4.0 or more</td>
</tr>
</tbody>
</table>

**Tunneling Induced Settlement**

- More for soft ground
- Typically more facilities

**Approx. Settlement Curve**

Figure 7-4: Typical Settlement Profile for a Soft Ground Tunneling
Ground Stabilization/ Improvement

- Stabilize ground for excavation
- Contribute to its own stability
- Final lining is less costly

Impact, Continued

<table>
<thead>
<tr>
<th>Complexity of Potential Damage</th>
<th>Angular Displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damage to machinery sensitive to settlement</td>
<td>1/750</td>
</tr>
<tr>
<td>Damage to structures with diagonals</td>
<td>1/400</td>
</tr>
<tr>
<td>Safe limit for no cracking of building</td>
<td>1/500</td>
</tr>
<tr>
<td>First cracking of panel walls</td>
<td>1/100</td>
</tr>
<tr>
<td>Difficulties with confined courses</td>
<td>1/100</td>
</tr>
<tr>
<td>Topping of high rise building becomes visible</td>
<td>1/250</td>
</tr>
<tr>
<td>Consider for cracking of panel and block walls</td>
<td>1/150</td>
</tr>
<tr>
<td>Dampness of structural damage to general building</td>
<td>1/150</td>
</tr>
<tr>
<td>Safe limit for flexible brick walls</td>
<td>1/150</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Risk category</th>
<th>Maximum slope of building (°)</th>
<th>Minimum settlement of building (in)</th>
<th>Description of risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Less than 1/500</td>
<td>Less than 10</td>
<td>Minor structural damage unlikely, tight building materials, small relative settlement.</td>
</tr>
<tr>
<td>2</td>
<td>1/500 – 1/200</td>
<td>10 – 50</td>
<td>Moderate structural damage unlikely, tight building materials, small relative settlement.</td>
</tr>
<tr>
<td>3</td>
<td>1/200 – 1/50</td>
<td>50 – 75</td>
<td>Significant structural damage unlikely, complex building materials, moderate relative settlement.</td>
</tr>
<tr>
<td>4</td>
<td>Greater than 1/50</td>
<td>Greater than 75</td>
<td>High risk, possible structural damage to buildings. Enhanced design to resist failures in future operations.</td>
</tr>
</tbody>
</table>

Table 2: Limiting Angular Distortion (Wahls, 1981) * Safe limit includes a factor of safety.

Impact on and Protection of Surface Facilities

Tolerance to Settlement
- Architectural Damage – Appearance, not function
- Functional – Requires non-structural repair
- Structural – Affecting Stability

Structure Protection (Mitigating Settlement)

- Proper Construction Means, Methods
- Require Closed Face Machine
- Grout Annular Spale
- Control Operation (Steering) –
  - One Percent Correction = 1.5% Ground Loss
- Compaction or Consolidation Grout
- Treat (Stabilize) Loose Soil Before Tunneling
- Underpin
- Freeze

Soil nails
- Micro piles
- Grouting
  - Permeation
  - Compaction
  - Compensation
  - Jet grouting
- Ground freezing
Soft Ground Tunneling Closure

- Great Strides Forward
- Close Face Machines
- Ground Treatment
- Hold Settlement to Less than 3/8 in.