NATM / SEM From Design to Construction

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Gall Zeidler Consultants
Geotechnics | Tunnel Design | Engineering

Elevated Thinking, Underground.
Agenda

1. Design and Range of Applications
   • Background and Principles
   • SEM Regular Cross Section
   • Ground Classification and SEM Excavation and Support Classes
   • Ground Support Elements
   • Structural Design
   • Instrumentation and Monitoring
   • Contractual Aspects, Risk Management

2. Case Histories
   • Dulles Corridor Metrorail Project, Washington Metropolitan Area Transit Authority (WMATA)
   • Caldecott 4th Bore Tunnel, Caltrans

3. Conclusions and Outlook
NATM / SEM

• Sequential Excavation Method (SEM), Shotcrete Method, Shotcrete Support Method, Observational Method, Sprayed Concrete Lining (SCL), Conventional Tunneling (Working Group 19 of ITA)

• Referred to as SEM in Federal Highway Administration (FHWA)
  • "Technical Manual for Design and Construction of Road Tunnels" Chapter 9
  • First Publication of a Tunnel Design Manual by FHWA

• NATM is a concept that is based on the understanding of:
  • Interaction of Ground - Creation of Tunnel Opening - Ground Support While Attempting to:
  • Mobilize the Optimum Ground Self-Support

and involves:
  • Practical Experience and Earth/Engineering Sciences alike
NATM / SEM – Principles
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• Mobilization of the Self Supporting Capability of Surrounding Ground
  • Recognition of Ground Characteristics
  • Define Ground Response Classes

• Adjust Construction in Terms of:
  • Round Length (Maximum Unsupported Length)
  • Type of Support Measures (Shotcrete Lining and Ground Reinforcement) and Timing of Installation
  • Subdivision of Heading into Multiple Drifts (as needed)
  • Ring Closure
  • Develop Excavation and Support Classes

for Ground Stability and Support Economy

• Risk Management / Robust Designs
Prototypical Cross Section
Prototypical Longitudinal Excavation and Support Class (ESC)
# Prototypical Longitudinal Section

<table>
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<tr>
<th>Expected Station</th>
<th>Station</th>
<th>200</th>
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<td><strong>Ground Response Class</strong></td>
<td>RT-M5</td>
<td>RT-M5</td>
<td>RT-MB3</td>
<td>RT-Q2</td>
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<td><strong>Description</strong></td>
<td>Weathered Metasediments</td>
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<td>Fractured Quartzite</td>
<td>Partially Weathered to Fresh Metasediments</td>
<td>Weathered Metasediments</td>
<td>Weathered Metasediments</td>
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<tr>
<td><strong>Excavation &amp; Support Class</strong></td>
<td>IV</td>
<td>III</td>
<td>III</td>
<td>III</td>
<td>II</td>
<td>I</td>
<td>II</td>
<td>III</td>
<td>IV</td>
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Regular Cross Section

- Geometry
- Dual Lining Character
- Initial Lining
Regular Cross Section

• Cast-in-Place Concrete Lining
• Shotcrete Final Lining
• Water Impermeable Concrete Lining
• Single Pass Linings
NATM/SEM – Recent Developments and Range of Applications

• Ground Improvement
• Shotcrete Material
• Urban Tunneling
• Procurement and Contractual Requirements in Design and Construction
• Derivatives: CombiShell and LaserShell
Design Elements – Ground Classification

• Ground Classification Systems (Rock, Mixed, Soils)
• Ground Support Systems
  • Geological Model
  • Geotechnical Model: Ground Response Class (GRC)
  • Tunnel Support Model: Excavation and Support Class (ECS)
Design Elements – Excavation & Support Classes

• Example in Competent Rock Mass
Design Elements – Excavation & Support Classes

• Example in Soft Ground
Design Elements – Excavation & Support Classes

• Example in Soft Ground – Crossrail Stepney Greene Crossover Cavern
Design Elements – Excavation & Support Classes

• Example in Soft Ground – Crossrail Bond St. Station SEM Enlargement
Excavation Methods

• Drill-and-Blast - Hard Rock
• Road Header - Medium Hard Jointed Rock
• Backhoe - Soft Ground
Shotcrete

• Effects of Shotcrete
  • Flashcrete
  • Face Support
  • Initial Shotcrete Lining
  • Temporary Support Walls
Pre-Support Measures & Ground Improvement

• Pre-Support Measures
  • Pre-Support in Rock Tunneling
  • Pre-Support in Soft Ground (Soil) Tunneling
Pre-Support Measures & Ground Improvement

• Pre-Support Measures
  • Grouted Pipe Arch Canopy
  • Face Doweling
Pre-Support Measures & Ground Improvement

- Ground Improvement Measures
  - Grouting (Systematic or Local)
    - Jet, Permeation
  - Dewatering (Systematic or Local)
  - Ground Freezing
Structural Design

- Use Ground-Structure Interaction Models to account for Stress and Deformation in the Surrounding Ground
- Finite Element Methods (since about 1965 in NATM Tunnel Designs), Finite Difference Methods
- Use of Ground Material Constitutive Models to Describe Deformation, Yielding and Post-yielding Behavior
  - Mohr-Coulomb
  - Drucker-Prager
  - Hoek and Brown
  - Others
- 2-D for Line Structures and 3-D Modeling for Junctions, Intersections, Caverns or Approximations
- “Avoid” Embedded Frame Modeling
Structural Design 2D

Stage 1: in-situ stresses

Stage 2: soften top heading

Stage 3: excavate and install initial support

N and M - top heading excavation

N - top heading excavation
Structural Design

- Ground Stresses and Deformations / Surface Settlements
- Lining Design – Initial and Final
- Design of Rock Reinforcement
Structural Design - 3D, Complex 2D
Instrumentation and Monitoring

- **Tunnel:**
  - Convergence Bolts
  - Roof Leveling Points
  - Shotcrete and Ground Load Cells

- **Surrounding Ground / Geotechnical:**
  - Multiple Point Borehole Extensometer (MPBX)
  - Inclinometer
  - Piezometer

- **Surface:**
  - Settlement Points
  - Shallow Subsurface Settlement Points

- **Structures:**
  - Deformation
  - Leveling

- **Real Time, Remotely Monitored and Evaluated**
Instrumentation and Monitoring

• Tunnel:
  • Convergence Bolts
  • Roof Leveling Points

• Surrounding Ground / Geotechnical:
  • Multiple Point Borehole Extensometer (MPBX)
Instrumentation and Monitoring

![Graph showing surface settlement above centerline at STA. 223.50]

- Settlement above Sta. 223.50
- Top Heading Face Progress
- Excavation Faces @ Sta. 223.50
- Bench/Invert Face Progress

Legend:
- Blue line: Surface Settlement
- Green line: Excavation Face Top Heading
- Blue line: Excavation Face Bench/Invert
Instrumentation and Monitoring
Instrumentation and Monitoring
Instrumentation and Monitoring
Contractual Aspects, Risk Management

• Design and Risk Management by Design
  • Experienced Designer

• GDR and GBR

• Ground and Support Classification
  • From Ground behavior to Support requirements
  • Develop Distributions of Support Classes along Tunnel Alignment

• Unit Pricing to Suit Classification of Ground and Support
  • Support Classes
  • Local Support Measures
  • Pre-Support Measures
  • Ground Improvement Measures
Contractual Aspects, Risk Management

• Contractor Pre-qualification
• Strict Quality Control Requirements: Experienced NATM Personnel - Each Shift
• CM Representation
• Instrumentation
• Geologic Mapping
• Required Excavation and Support Sheet (RESS): Daily
• Formal Risk Assessment (multiple levels)
• Implementation of the "Right Support"
CASE HISTORY:
Dulles Corridor Metrorail Project; Vienna, VA
Tunnel Alignment & Adjacent Structures
Cross Section, Excavation & Support
Ground Conditions

• Cap of ancient Coastal Plain sediments
  • Bands of clay with silty sands, gravels, and cobbles

• Residual soils and soil-like decomposed rock
  • Fine sandy silts, clays, and silty fine sands

• Decomposed rock
  • Soil-like with higher strength

• Groundwater
  • Invert level at Portal locations
  • Tunnel spring line at mid-point of tunnel alignment
Excavation and Support

- Use of Steel Grouted Pipe Arch Canopy Pre-Support due to Soft Ground and Shallow Overburden
  - Gradual Increase in Tunnel Size to Allow for Subsequent Pipe Drilling Resulted in a Saw Tooth Effect
- Excavation: Typical Conventional Method Sequence with two 3-foot Top Heading Rounds, Followed by a single 6-foot Bench/Invert Round
Pre-Support Installation
Very Shallow Tunnel vs. Utilities & Roadway

- Shortening of IB sawtooth length due to very shallow overburden at International Drive and high density of utilities
  - Six sawteeth reduced from 14 m to 7 m
  - One sawtooth reduced from 14 m to 11 m

- Utilities abandoned prior to excavation including gas lines, communication ducts, and electrical lines

- Majority of utilities remained active during excavation
**Instrumentation & Monitoring**

- Surface Monitoring
  - Threshold levels
  - Contingency plan in place
  - Angular distortion measurements

<table>
<thead>
<tr>
<th>Description</th>
<th>Level 1</th>
<th>Level 2</th>
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<tbody>
<tr>
<td>Ground surface settlements (1st tunnel excavation)</td>
<td>3/4-inch</td>
<td>1-1/4-inch</td>
</tr>
<tr>
<td>Ground surface settlements (1st + 2nd tunnel excavation)</td>
<td>1-0-inch</td>
<td>1-1/2-inch</td>
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<tr>
<td>Horizontal ground movement at tunnel elevation (at 25 feet distance from tunnel)</td>
<td>1/8-inch</td>
<td>1/8-inch</td>
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<tr>
<td>Tunnel roof settlement</td>
<td>1/2-inch</td>
<td>3/4-inch</td>
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<tr>
<td>Horizontal movement of tunnel sidewalls</td>
<td>1/3-inch</td>
<td>1/2-inch</td>
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<tr>
<td>Maximum utility settlement and slope of settlement trough</td>
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<td>1-1/2-inch</td>
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<td>Maximum utility settlement and slope of settlement trough</td>
<td>1/250</td>
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<tr>
<td>Maximum bridge foundation settlement</td>
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<tr>
<td>Maximum surface settlement trough of road surfaces</td>
<td>1-0-inch</td>
<td>1-1/2-inch</td>
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</table>
As-Built Surface Settlements

• No Surface Settlements Surpassed Maximum Threshold Values
  • Maximum Value Realized 1 ¼ “ vs. 1 ½ “
• Maximum Observed Slope of 1/300
• All Settlement Data Jointly Evaluated by Construction, Engineering, and Owner’s Representatives at Daily RESS Meeting
As-built Surface Settlements
Final Lining (CIP) – Ready For Installations

ASCE Automation Award
NCE International Tunneling Award Nomination in Category < $ 100 million
CASE HISTORY
Caldecott 4th Bore Tunnel (Oakland, CA)
Project Overview

- **Length**: 1036 meters (3400 feet)
- **Cover**: 7-165 meters (24-541 feet)
- **Pillar widths**:
  - West: 16 meters (54 feet)
  - Center: 35 meters (115 feet)
  - East: 22 meters (72 feet)
Typical Section

• Horseshoe-shaped tunnel
  • Width: 15 meters (50 feet)
  • Height: 9.7 meters (32 feet)

• Two lanes
  • Width: 3.6 meters (12 feet)

• Two shoulders
  • 3 meters (10 feet) and 0.6 meters (1 foot)
Geologic Structure

- The four major faults are all inactive and strike to the northwest. Fault contacts defined by lithologic changes and bedding orientation.
- Minor faults, shears, crushed zones also occur along the alignment away from the major fault zones.
- Igneous Dikes also encountered, most frequently in the Claremont Formation.
NATM / SEM Design

• Most favorable conditions – SC IA:
  • 6 foot advance length
  • Face support shotcrete and dowels as required
  • 8 inch shotcrete lining
  • Radial dowel spacing of 6 feet

• Least favorable conditions – SC IV:
  • 3.3 foot advance length
  • Pipe canopy pre-support
  • Systematic face support core and shotcrete
  • 12 inch shotcrete lining
  • Invert arch on top heading and bench
NATM / SEM Design

• Baseline of anticipated distribution of GC/SC for bidding
• Detailed description of anticipated behaviors in GBR
• **Application criteria:**
  • Encountered ground conditions and behaviors, measured lining movements, observed lining performance
  • Daily meetings to determine support application – proposed by Contractor, approved by Engineer
Support Measures

CLAREMONT CHERT & SHALE

ORINDA FORMATION

Geologic Unit
SEM Meeting
Ground Class
Support Category
Rock Mass Type

Support Measures

Bore No. 4 Tunnel 1036.00
Measured along "ZN" Line

Dore No. 4 Bored Tunnel 980.35
Measured along "ZN" Line

EXISTING GROUND
Approximate Location of contact, 770'

Top of Tunnel Excavation

Geologic Unit

Support Category

SEM Meeting

Rock Mass Type

Ground Class
Excavation
Rock / Face Dowels and Spiling
Benching by Center Cut in East Heading
Excavated Faces and Laser Scanning
Final Lining

• Final lining production system in 3 operations: waterproofing, reinforcement and concrete
NATM/SEM – Conclusions and Outlook

• Design and Risk Management by Design (ITA WG 19)
• Contractual Framework
• Experienced Design, Construction, and Inspection
• Wide Range of Applications and Flexibility
  • Complex Geometries
  • Difficult Ground Conditions
  • Urban Settings
• Outlook
  • Increased Application (Projects and in More Challenging Conditions)
  • Increased Experience
  • Refinements in:
    • Exploration Techniques to Identify Ground Conditions
    • Ground Improvement Methods
    • Close Cooperation of Modeling-Instrumentation-Excavations and Support Adjustment-As Built Conditions
    • More Efficient Materials Including Shotcrete and Waterproofing