Tunnel Lining Design and Construction

Verya Nasri, PhD, PE

10th Annual Breakthroughs in Tunneling Short Course
August 15, 2017
Cast-in-Place Final Lining

❖ Design Considerations
  ➢ Strength
  ➢ Serviceability
  ➢ Durability

❖ Plain concrete versus reinforced concrete
❖ Fiber versus rebar
❖ Spray on concrete versus CIP concrete
Final Tunnel Linings

- Liner Geometry
- Construction Method
- Area of Application
# Road Tunnels

**World Road Association (PIARC)**

<table>
<thead>
<tr>
<th>Country and name of guidelines or other source</th>
<th>Design Speed or Reference Speed [km/h]</th>
<th>Width of Traffic Lane [m]</th>
<th>Width of Traffic Lane Marking [m]</th>
<th>Width of Carriageway [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria RVS 9.232</td>
<td>80 - 100</td>
<td>3.50</td>
<td>0.15</td>
<td>7.00</td>
</tr>
<tr>
<td>Denmark (practice)</td>
<td>90 - 120</td>
<td>3.60</td>
<td>0.10</td>
<td>7.20</td>
</tr>
<tr>
<td>France CETU</td>
<td>80 - 100</td>
<td>3.50</td>
<td>?</td>
<td>7.00</td>
</tr>
<tr>
<td>Germany</td>
<td>100 (26t, 26Tr)</td>
<td>3.50</td>
<td>0.15</td>
<td>7.00</td>
</tr>
<tr>
<td>Germany RAS-Q 1996</td>
<td>70 (26t)</td>
<td>3.50</td>
<td>0.15</td>
<td>7.00</td>
</tr>
<tr>
<td>Germany RABT 94</td>
<td>110 (29.5T)</td>
<td>3.75</td>
<td>0.15</td>
<td>7.50</td>
</tr>
<tr>
<td>Japan</td>
<td>80 - 120</td>
<td>3.50</td>
<td></td>
<td>7.00</td>
</tr>
<tr>
<td>Japan Road Structure Ordinance</td>
<td>60</td>
<td>3.25</td>
<td>6.50</td>
<td></td>
</tr>
</tbody>
</table>
Rail Tunnels
Subway Stations

Mined

Cut and Cover
Ventilation
Station Cross Section

Strength of shape reduces material consumption

Precast panels finish surface & in-situ formwork

"Green" concrete

Derive acoustic advantage from form

Drained cavern
Caverns in Competent Rock
Permanent SOE Wall

Munich
Underground Parking
Cut and Cover, Top-Down and Bottom-Up
Cut and Cover Tunnels
Immersed Tunnels
Final Tunnel Linings

- Liner Loading
- Structural Analysis
- Design
Uniform Rock Load

Unbalanced Rock Load
Groundwater Pressure
Drained and Undrained Concepts

WATER TABLE (HWL)

CROWN OF ARCH

W.25 "Wbase"

.25Wcrown

EFFECTIVE PRESSURE DISTRIBUTION

.25Wbase

.10Wbase

.25Wbase

HYDROSTATIC PRESSURE
Beam Spring Method

US Army Corps of Engineers

\[ K_r = \frac{E_g}{R(1+v)} \]

\[ K_t = 0.5K_r/(1+v) \]
2D Structural Analysis

Cut & Cover Box

Mined Cavern

Beam-Spring Model
3D Structural Analysis

Mined Cavern

Beam-Spring Model

Cut & Cover Box
Road Deck

Central LRT Precast Unit

In-situ Deck

Construction in Parallel with Excavation & Lining

Pavement
Stacked Subway
Design Pressure Envelopes for Braced Cuts (Peck, 1969)

- **Sand**
  \[ p_a = 0.65 \gamma H K_a \]

- **Soft-Medium Clay**
  \[ p_a = \gamma H \left[ 1 - \left( \frac{4c}{\gamma H} \right) \right] \]

- **Stiff Clay**
  \[ p = 0.2 \gamma H \text{ to } 0.4 \gamma H \]
Excavation Sequence, Support Installation and Flow Analysis
Convergence Confinement Method

(a) Direction of excavation
- Final settlement
- > 5R excavation radius
- < 2R tunnel face
- Onset of change of geostatic stress

(b) Tunnel face specific section
- \( \sigma_r = p = \sigma^0 \)
- \( \sigma_r^0 = p = (1 - \lambda) \sigma^0 \)
- \( \sigma_r = p = 0 \)
- \( p = 0 \)

(c) Geostatic stress
- \( p = (1 - \lambda) \sigma^0 \) support pressure
- \( p = 0 \)

(d) Ground reaction line
- Support reaction line
- Assumed elastic response

\( \lambda = 0 \)
\( \lambda_1 \)
\( \lambda_2 \)
\( \lambda_3 \)
Initial Ground Support Design

➢ Empirical Method (e.g. Q-System)
➢ Analytical Method (e.g. Key-Block)
➢ Numerical Method (Continuum and Discontinuum Modeling)
Continuum Analysis

- 2D modeling
- Hoek-Brown Failure Criterion
- 50% Relaxation,
- Shotcrete Strength Varied With Excavation Sequence
Rock Mass Parameters

- **Input**
  - Intact Uniaxial Compressive Strength (UCS)
  - Intact Rock Modulus (Ei)
  - Disturbance Factor (D)
  - Geological Strength Index (GSI)
  - Intact Rock Parameter (mi)

- **Output**
  - Hoek-Brown Strength Parameters
  - Rockmass Deformation Modulus
Continuum Analysis Results

- No Yielding of Initial Support
- Small Ground Surface Deformations
Types of Discontinuities

- Conjugate Joints
- Foliation
- Subvertical Structure
- Fault / Shear Zone
- Cluster
Discontinuum Analysis

Rock constitutive model: Mohr-Coulomb elastic/plastic failure

Joint constitutive model: Barton-Bandis joint model
Discontinuum Analysis Results
3D Continuum Analysis

Perspective view

West entrance

East entrance

Main gallery
3D Continuum Analysis Results
3D Continuum Analysis Results
3D Discontinuum Analysis

(a) TBM tunnels
(b) Cut & cover boxes
(c) Cavern
(d) East and West ancillary penetrations
3D Discontinuum Analysis Results

Extreme fiber maximum tensile stress (psf) (Negative in tension)

Tensile capacity approx. 80 ksf
Seismic Design of Tunnel Final Lining

Design & Analysis Approach

- Force Method for surface structures
- Deformation Method for underground structures
- Two-level seismic hazard (ODE and MDE)
Seismic Design of Tunnel Final Lining

Deformation modes of tunnels due to seismic waves
Fire duration time is determined by considering the location of the nearest fire station to the tunnel.
Reduction of Strength and Stiffness of Concrete

![Graph showing reduction of strength and stiffness of concrete with temperature](image-url)
Final Lining Protection in Concrete Sewers

- Corrosion has been identified as No. 1 cause of deterioration in concrete sewers.
- Quantitative approach to assess the corrosion of the concrete final lining
- Measures to protect the concrete final lining
The life expectancy of the concrete final lining:

$$L = \frac{z}{C}$$

- $L =$ service life, yr
- $z =$ thickness of allowable loss (thickness covering the reinforcing steel), in.
- $c =$ corrosion rate, in./yr
Liners and Coatings

Example: Ameron T-Lock, a PVC sheeting that locks mechanically into the interior wall of concrete sewer pipes and tunnels
Sewers Subject to Low Corrosion Risk

❖ For a 100-year service life costly corrosion protection measures such as impermeable liners, coatings or polymer concrete are not warranted.

❖ Use calcareous aggregate and sacrificial concrete cover
Sewers Subject to High Corrosion Risk

Recommendation: A combination of corrosion protection schemes including:

- concrete with calcareous aggregates
- sacrificial concrete thickness
- protective lining
Waterproofing, Drained and Undrained Concepts
Initial Liner Smoothness Criteria

GENERAL SHOTCRETE SMOOTHNESS CRITERIA

NO SCALE

\[ T_{ds} \quad \text{DESIGN THICKNESS OF INITIAL SHOTCRETE LAYER} \]
\[ T_{al} \quad \text{ACTUAL THICKNESS OF INITIAL SHOTCRETE LAYER} \]
\[ S_{a} \quad \text{ACTUAL THICKNESS OF SMOOTHING SHOTCRETE} \]
\[ S_{s} \quad \text{DESIGN THICKNESS OF SMOOTHING SHOTCRETE} \]
\[ D_{cl} \quad \text{DEVIAITION FROM CLEARANCE LINE (mm)} \]
\[ N \quad \text{WAYINESS OF SHOTCRETE LINING (mm)} \]
\[ L \quad \text{DISTANCE BETWEEN TWO CRESTS (mm)} \]

CRITERIA:
\[ W < L / 10 \]
\[ R > 200 \text{ mm} \]
\[ W < 75 \text{ mm} \]
\[ S_{a} > S_{s} \]
\[ T_{ds} = T_{al} \]
\[ T_{as} = T_{al} + S_{a} \]
Materials: Geotextile, Membrane, and Attachment Disk
Membrane Installation and Testing
Sectioning, Water Barrier, and Remedial Grout Pipes
Sprayed on Waterproofing Membrane

- Elongation at rupture %100
- Bond strength 1 MPa
- Tensile strength 2-4 MPa

10th Annual Breakthroughs in Tunneling Short Course
New York City’s
Second Avenue Subway
72nd Street Station and Tunnels Project

Final Concrete Lining
(Waterproofing and Concrete Stages)
72nd Street Station and Tunnels Project
Station Cavern – Walls
72nd Street Station and Tunnels Project
Station Walls – Forms & Rebar
72nd Street Station and Tunnels Project
Station Cavern – Finished Walls
72nd Street Station and Tunnels Project
Station – Arch Forming System
72nd Street Station and Tunnels Project
Station – Arch Forming System
72\textsuperscript{nd} Street Station and Tunnels Project
Station – Arch Forming System
72nd Street Station and Tunnels Project
Tunnels – Invert Concrete
72nd Street Station and Tunnels Project
Tunnels – Arch Concrete
Final Tunnel Linings

Architectural Aspects
Magenta Station, Paris
Different Types of Structural and Architectural Concrete

- Light gray with satin finish for the entire structure
- Light gray with shiny finish for stair tunnels
- Light gray with rough finish for sidewalls of central cavern and side tunnels
- White only for columns and struts.
More than 10 mix designs were used to answer the structural and architectural requirements.

Large scale samples for testing the formwork surface and its accessories.
Metal (copper, aluminum ...), exotic wood, concrete with multiple finishes (white, satin, shiny ...), marble
Entrance
Thank You