Segmental Liner Design and Construction

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Agenda

1. Background / Terminology
2. Segmental Lining Types
3. Design Considerations
4. Fabrication
5. Construction
6. Project Examples
   • SR99 – Seattle
   • Eurasia – Istanbul
7. Summary
Background / Terminology

Early Segmental Lining

Roman Aqueduct ~ 300 B.C.
Background / Terminology

Stacked Drift Tunnel

Mount Baker Ridge Tunnel for I-90 in Seattle, WA, USA  1984
Background / Terminology

Segmental Tunnel Lining

SR99 Tunnel - Seattle, WA, USA  2017
Background / Terminology

Tunnel Anatomy

- Crown
- Invert
- Springline
- Ring
- Segment
- Longitudinal joint
- Circumferential joint
Background / Terminology

Rules of Thumb¹

1. Liner thickness approximately 3%-4% of tunnel diameter
2. Min ground cover over crown of tunnel ~ 1 diameter
3. Min Separation of bored twin tunnels ~ ½ diameter
4. Min radius of horizontal curvature ~ 20 diameters
5. Max vertical grade ~ 6%
6. Max external water pressure on a TBM ~ 15 bar (216 psi)
7. Average advance rate in soft ground ~ 30-50 feet / day
8. Average advance rate in hard rock ~ 25-75 feet / day
9. Average advance rate in soft rock ~ 100-200 feet / day

¹For every rule there is an exception – valid for planning stage of project.
## Design Considerations

### Lined Tunnel Applications

<table>
<thead>
<tr>
<th>Application</th>
<th>Diameter (feet)</th>
<th>Lining</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highway</td>
<td>35-60</td>
<td>Single</td>
</tr>
<tr>
<td>Railroad</td>
<td>30-45</td>
<td>Single</td>
</tr>
<tr>
<td>Transit</td>
<td>20-22</td>
<td>Single/ Double</td>
</tr>
<tr>
<td>Water</td>
<td>10-20</td>
<td>Single/ Double</td>
</tr>
<tr>
<td>Sewer</td>
<td>10-20</td>
<td>Double</td>
</tr>
</tbody>
</table>
Segmental Lining Types

One-Pass System

Tunnel Lining - One Pass
Segmental Lining Types

Two-Pass System

Tunnel Lining - Two Pass
Segmental Lining Types

Double ‘O’ Lining
Design Considerations

Loads

A tunnel lining is not an independent structure acted upon by well defined loads, and its deformation is not governed by its own internal elastic resistance. The loads acting on a tunnel are ill defined, and its behavior is governed by the properties of the surrounding ground. Design of a tunnel lining is not a structural problem, but a ground-structure interaction problem with an emphasis on ground.

## Design Considerations

### Loads

<table>
<thead>
<tr>
<th>Order of Application</th>
<th>Loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Handling / Lifting / Assembly</td>
</tr>
<tr>
<td>2.</td>
<td>Tunnel Boring Machine Jacking</td>
</tr>
<tr>
<td>3.</td>
<td>Segment Misalignment</td>
</tr>
<tr>
<td>4.</td>
<td>Bolts and Shear Dowels</td>
</tr>
<tr>
<td>5.</td>
<td>Soil / Rock Overburdon</td>
</tr>
<tr>
<td>6.</td>
<td>Groundwater Pressure</td>
</tr>
<tr>
<td>7.</td>
<td>Grout Pressure</td>
</tr>
<tr>
<td>8.</td>
<td>Internal Structures</td>
</tr>
<tr>
<td>9.</td>
<td>Rail Expansion / Contraction</td>
</tr>
<tr>
<td>10.</td>
<td>Earthquake</td>
</tr>
<tr>
<td>11.</td>
<td>Heat – Fire</td>
</tr>
<tr>
<td>12.</td>
<td>Explosion</td>
</tr>
</tbody>
</table>
Design Considerations

Loads

 Loads vary along tunnel length – generally all segments designed for most severe case.
Design Considerations

Earth - Structure Analysis

Empirical Formulas are good place to start sizing liner dimensions

Finite Element Analysis can account for ground structure interaction and adjacent structures
Design Considerations

Seismic Analysis

Simulation of EQ pressure wave passing through segmental liner
Design Considerations

Blast Analysis
### Design Considerations

#### Blast Analysis

##### Effect of Charge Weight

<table>
<thead>
<tr>
<th>W (lbs)</th>
<th>Damage Area</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Liner</td>
<td>Interior</td>
<td></td>
</tr>
<tr>
<td>5,000</td>
<td>xxx ft²</td>
<td>xx ft</td>
<td></td>
</tr>
<tr>
<td>2,000</td>
<td>xx ft²</td>
<td>xx ft</td>
<td></td>
</tr>
<tr>
<td>1,000</td>
<td>x ft²</td>
<td>xx ft</td>
<td></td>
</tr>
</tbody>
</table>

##### Effect of Reinforcing Ratio

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Damage Area</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Liner</td>
<td>Interior</td>
<td></td>
</tr>
<tr>
<td>1.5 %</td>
<td>xxx ft²</td>
<td>xx ft</td>
<td></td>
</tr>
<tr>
<td>1.0 %</td>
<td>xxx ft²</td>
<td>xx ft</td>
<td></td>
</tr>
<tr>
<td>0.5 %</td>
<td>xxx ft²</td>
<td>xx ft</td>
<td></td>
</tr>
<tr>
<td>0%</td>
<td>xxx ft²</td>
<td>xx ft</td>
<td></td>
</tr>
</tbody>
</table>
Construction

Liner Segment Construction

Concrete for Precast Liner Segments
• High Strength – typically Type 3
• Dense - fly ash or silica fume added
• Durable and impermeable
Liner Segment Reinforcement

1. Conventional Rebar
2. Epoxy Coated Rebar
3. Welded Wire Fabric
4. Steel Fiber
5. Poly Fiber
6. Hybrid of Fiber & Rebar
Design Considerations

Segment Anatomy

- Key Segment
- Longitudinal Dowel
- Segment Gasket
- Radial Bolt Pocket
- Grout Duct and lifting eye
- Curved & Straight bolts
- Longitudinal Dowel
- Radial Bolt Pocket
Design Considerations

Segment Shape

- Expanded
- Trapazoid
- Rectangular
- Rhomboid
- Honeycomb
- Tapered Ring

Reflected Ceiling Plan

Direction TBM Advances

Jacked Closure Strip

Key Segment

Reverse Key Segment

Direction TBM Advances

Diameter

Straight (alternating)
Curved (non alternating)
Construction

Tunnel Liner Construction

(a) Tunnel cross section
(b) Reinforcement arrangement
(c) Radial joint
(d) Circumferential joint
Construction

Liner Segment Fabrication
Construction

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Liner Segment Fabrication
Construction

Tunnel Liner Construction
Construction

Tunnel Liner Construction
Construction

Tunnel Liner Construction

Alignment Dowels

Shear Key (male)

Rubber Gaskets

Shear Key (female)
Construction

Tunnel Liner Construction

TBM shoving off newly placed liner segments
A 1250 feet south approach, 9300 feet bored tunnel, and 450 feet north approach, and two operations buildings

Significant tunnel deformation mitigation and buoyancy resistance measures provided at the south end

Numerous buildings, elevated roadways, sewer tunnels and utilities along the alignment
Design Criteria

- 100-year design life
- Consider 7 ksf future building loading
- Expected Earthquake (100-year event)
- Operational performance objectives
- Rare Earthquake (2500-year event)
- Life safety performance objectives
- Minimum liner requirement
  - Thickness – 2 feet
  - Steel Reinforcement – 1% of gross volume
- AASHTO LRFD Bridge Design Specifications

Project Examples

SR99 – Seattle
Cross Section Control Points

1. Inside shoulder width
2. Outside shoulder width
3. Egress walkway width
4. Vertical clearance + Signage
5. Cross section area of vent
Project Examples

SR99 – Seattle

Proposed Alaskan Way Bored Tunnel - Systems

3D Modeling of Systems to space proof and detect clashes
Project Examples

SR99 – Seattle

Geologic Profile

- Poor, unconsolidated soils
- Till deposits
- Cohesionless sand and gravel – regional aquifer
- Cohesionless silt and fine sand
- Cohesive clay and silt
- Till-like deposits
Seismic Hazards in Seattle

Project Examples

SR99 – Seattle

Magnitude 7.1
Olympia Earthquake, 1949

Magnitude 6.5
Seattle-Tacoma Earthquake, 1965

Magnitude 6.8
Nisqually Earthquake, 2001

Note: Base map prepared from drawing provided by USGS and the University of Washington, 2001.

Source

- Cascadia Subduction Zone - Interplate: 9.0
- Cascadia Subduction Zone - Intraplate: 7.5
- Crustal Faults: 7.5


Crustal earthquakes (900AD, 1872)
Project Examples

SR99 – Seattle

15 STATIC SECTIONS
8 SEISMIC SECTIONS
Liner Design

SR99 – Seattle

Project Examples

Static Analysis

1. Soil and hydrostatic loads
2. Static SSI springs

Seismic Analysis

1. Displacement time histories
2. Dynamic SSI springs

FLAC2D

STEP 1
Geotechnical

CSiBridge

STEP 2
Structural

1. Static analysis
2. Load combinations
3. Structural design

Radial spring

$F \rightarrow K_r \rightarrow d$

Tangential spring

$F_t \rightarrow d_t$

1. Dynamic time history analysis
2. Check seismic performance for two levels of earthquakes
Project Examples

SR99 – Seattle

Seismic Design

2D Section Model

- Study ovalling effect
- Determine liner internal forces
- Determine transverse deformations
- Model with and without interior structures

3D Spine Model

- Study longitudinal behavior
- Determine displacements at interfaces between liner and headwalls
- Determine longitudinal deformations

3D FE Model

- Predict gasket behavior at the circumferential and radial joints by imposing transverse and longitudinal deformations
Seismic Design – Ovaling

- Determine the shape corresponding to maximum curvature
- Maximum ovaling is 1.5 inches from Rare Earthquake

Project Examples

SR99 – Seattle
Project Examples

SR99 – Seattle

Seismic Design – Displacement and curvature

- Determine the closing/opening at the ends for seismic joint design
- Determine the curvature to evaluate the joint opening between the rings for gasket design.

<table>
<thead>
<tr>
<th>Gap</th>
<th>Expected EQ</th>
<th>Rare EQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opening</td>
<td>0.1”</td>
<td>6.6”</td>
</tr>
<tr>
<td>Closing</td>
<td>0.2”</td>
<td>8.6”</td>
</tr>
</tbody>
</table>
Project Examples

SR99 – Seattle

Seismic Design – Gasket

Segment Gasket

Key

Joint

Long. Bolt

Radial Bolt

Gasket/Seal Opening of Ring 1 - Back

Gasket/Seal Opening of Ring 1 - Back

J02 J08 J14 J20 J26 J32 J38 J44 J50 J56

Joint Opening (mm)

Gasket-Back

Seal-Back
Project Examples

SR99 – Seattle

Tunnel Construction

Bertha on its public opening – July 2013
Project Examples

SR99 – Seattle

Tunnel Construction

Tunnel interior – July 2016
Project Examples

SR99 – Seattle

Tunnel Construction

Casting of top decks of the future roadway – August 2016
Project Examples

SR99 – Seattle

Tunnel Construction

TBM Breakthrough - April 2017
Conclusions

1. Preliminary design is critical in meeting overall design requirements.
2. Tunnel diameter will change several times as requirements identified and new Geotech and Seismic data became available.
3. Seismic loads and deformations did not govern liner thickness or reinforcement, but did govern size of the shear cones at the circumferential joints and the size and type of the gaskets.
4. Hitachi EPB TBM finished tunnel bore with less than ¼” settlement.
Project Examples

Eurasia - Istanbul

In-Line Seismic Joints
for a Large Diameter Tunnel
Istanbul is 5th largest city in the world
Population of city estimated at 15 Million
City is in Europe and Asia – both sides of Bosphorus

Project Examples

Eurasia - Istanbul

- Istanbul is 5th largest city in the world
- Population of city estimated at 15 Million
- City is in Europe and Asia – both sides of Bosphorus

Designer: Parsons Brinckerhoff
Independent Design Verifier: HNTB
DB Contractor: Yapı Merkezi – SK
Each Roadway deck has 10 foot vertical clearance
- Cars and minivans only – no heavy goods vehicles
- Subject to 11.0 bar of water pressure
- 43 foot outer diameter 39 foot inner diameter
- 23.5 inch thick precast segmental liner (8+1 configuration) (7000 psi concrete.) 6.6 feet wide
- Double gaskets 1.5” EPDM
- Radial and circumferential bolts,
- Upper roadway deck cast in place and lower roadway deck precast concrete (6000 psi concrete)
- Emergency Egress: 44” wide walkway and escape stairs at 660 feet
- Vehicle Lay-by emergency stops every 1970 feet
- Longitudinal ventilation with vent plants at each portal
- Design life of 100 years
Project Examples

Eurasia - Istanbul
Geotechnical Conditions

- **Trakya formation** sedimentary inter-layered sandstone, siltstone and mudstone. Highly fractured, folded, faulted, weathered, and intruded with very abrasive volcanic dykes every 100-200 feet.
- **Soft ground:** Alluvial deposits consisting of coarse-grained soils (gravels and sands) to fine-grained soils (silts and clays) with beds of gravel and cobbles.
- **Mixed Face:** mixed face conditions rock to soft ground, soft ground to rock, and within the rock strata itself.

![Geotechnical Conditions Diagram](image-url)
Seismic Conditions

- Istanbul is in one of the most active seismic zones in the world
- Three Tectonic Plates: African, Anatolian, and Eurasian generate seismic activity
- Tunnel within 10 miles of Marmara fault system
- At least one medium intensity earthquake has affected Istanbul every 50 years.
- Thorough assessment of earthquake hazard critical
- Performance of the tunnel in the mixed face condition for seismic displacement is critical
Seismic Joint Design Displacements
- 3” Expansion
- 3” Contraction
- 2” Shear

✓ 3D analysis of earthquake induced Tunnel Ovaling
Project Examples

Eurasia - Istanbul

Seismic Joint

Flexible Segment Configuration
Seismic Joint Installation

Installation Steps

Stage 1 – within shield of TBM
1. Assemble 3 transition segment rings
2. Assemble seismic joint ring
3. Remove thrust blocks and install 1\textsuperscript{st} seal and barrier
4. Re-install thrust blocks
5. Assemble 3 transition segment rings

Stage 2 – prior to building roadway
1. Remove thrust blocks
2. Install support bars
3. Install 2\textsuperscript{nd} Seal

Project Examples
Eurasia - Istanbul
Project Examples

Eurasia - Istanbul

Seismic Joint Installation

Transport Segments to TBM
Assemble seismic joint ring
Seismic Joint Installation

Remove Thrust Blocks
Project Examples

Eurasia - Istanbul

Seismic Joint Installation

Install 1st Seal
Project Examples

Eurasia - Istanbul

Seismic Joint Installation

Install Barrier to protect 1st Seal
Project Examples

Eurasia - Istanbul

Seismic Joint Installation

Re-Install Thrust Blocks
Project Examples

Eurasia - Istanbul
Seismic Joint Installation

Thrust Blocks Re-Installed to allow TBM to shove forward
Project Examples

Eurasia - Istanbul

Insitu Seismic Joint – 3 months prior to opening to traffic
Conclusions

1. Large diameter tunnel with double deck roadway configuration
2. 11 bars of water pressure, complex and variable ground conditions
3. Specialized MixShield TBM equipped to mine highly abrasive ground
4. Liner designed for demanding seismic environment with nearby active faults
5. Seismic Joints required at rock soil interfaces to limit liner stress
6. Seismic Joints had to be installed in-line with segmental lining
7. Tunnel completed and open to traffic ahead of schedule
Thank you

Questions