Segmental lining design

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Outline

• Ring materials, geometry; constructability
• Selection of ground and groundwater loads for analysis
• Construction loads (TBM thrust, demoulding, handling, stacking, transport etc)
• Grouting loads
• Lining stiffness and shear/slip between lining and ground
• Calculation of bending and thrust (Muir Wood/Curtis and others) Development of Moment Thrust Diagrams (Steel Reinforced, SFRC)
• Bursting due to joint opening
• Gasket design
• Earthquake loading and earthquake design
Typical form – One-pass system:

- Series of rings, consisting of 5+ segments
- Segments assembled at/in tail of TBM. Joints between segments sub-parallel to tunnel axis (longitudinal joint)
- Circumferential joints between rings. Rings typically rolled relative to previous such that longitudinal joints are staggered
Inputs

- Tunnel space-proofing
- Alignment
- Machine type
- Ground and groundwater model

LINING ARRANGEMENT, MATERIALS, DETAILS
“Typical” design process

**Tender**
DD90% Spaceproofing
DD30% Lining design

- Ring geometry
- Lining thickness
- Gasket design

Cost estimate

**Immediately Post-Award**
DD100% Spaceproofing
DD70% Lining design

- Ring geometry
- Lining thickness confirmed
- Refinement of structural design
- Gasket design
- Connectors

Mould procurement
TBM procurement

**DD100% Lining design**

- Finalize structural analyses and reinforcement
- Allowance for internal structures
- Specifications

Materials finalized
Fire testing

Other design elements recognize lining design as an input, constraint.

- At each stage, quantity and quality of input data increases
- Design typically finalized prior to completion of other studies
Ring materials, geometry

1. Boring Mechanics drive a circular profile – Concrete segments typical; steel and cast iron now usually only adopted for special applications, e.g. cross-passage openings

2. Segmental linings typically installed as a single-pass lining system at the rear of the TBM. Double-layer systems (i.e. via beam + gripper) can result in thinner secondary linings, but do involve an additional process (i.e. temporary support).

3. Alignment: Typically achieved via tapered segments; or packers between rectangular segments. Impact on segment width – Smaller width and constant taper allows lining to achieve tighter radius.

4. Two significant drivers with respect to segment length:
   a. Reinforcement – Typically a considerable advantage to avoid the need for conventional reinforcement where feasible and use steel fibres – This typically limits the length of segments
   b. Limiting number of segments – Fewer segments leads to faster build and potentially shorter schedule

5. Typical geometries: Rectangular; rectangular with key, counter-keys; trapezoidal, hexagonal
Geometries

- Rectangular Segment
- Tapered Segment
- Trapezoid Segment
- Hexagon Segment
- Universal Taper
- Left-Right Taper

Outer Diameter of Segmental Lining Width
## Geometries

<table>
<thead>
<tr>
<th>Type</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular segments</td>
<td>Most commonly adopted – With key and counter key</td>
</tr>
<tr>
<td>Trapezoid</td>
<td>Variation on rectangular system; all longitudinal joints angled</td>
</tr>
<tr>
<td>Hexagonal</td>
<td>Typically used as first pass of a second-pass system; Results in stiffer longitudinal lining; Suitable for diameters &lt; approx. 4.5m</td>
</tr>
</tbody>
</table>

1. Geometries a balance of structural requirements and efficiencies with respect to build
2. TBM Specification must respond to ring geometry and vice-versa
Turning radius

• Proposed tunnel alignment will determine taper
• Need to allow for tighter radius than design value to allow for correction for out-of-alignment

\[ k = \frac{\varnothing_A b_m}{R} \]

with:
- \( k \) tapering (difference of maximum to minimum ring width)
- \( \varnothing_A \) outer diameter of the segment ring
- \( b_m \) mean ring width
- \( R \) minimum curve radius

Recommendations for the design, production and installation of segmental rings; DAUB; 2013
Design sections

• Segment design often an early activity – Inputs for long-lead items:
  • Segment moulds
  • TBM Specification

• Often achieve IFC status prior to completion of ground investigations; and ahead of the design of other elements, and in therefore in some cases design must often accommodate flexibility with respect to:
  • Alignment (e.g. marginally deeper/shallower, closer/further from existing/proposed sub-structures)
  • Variations in ground and groundwater conditions
  • Arrangement, detailing and intensity for internal structure loads
Selecting ground and groundwater loads

1. Ground loads a function of material types; depth of cover; stress regime

2. Groundwater loads dependent of tunnel-type; groundwater regime

3. Imposed loads; anticipated future loads/changes in loads

Characterize scheme in terms of anticipated design sections
Design to resist ground loads – Consider scenarios

- Shallow tunnel in soil; full overburden pressure
- Deep tunnel in soil; full overburden pressure or some arching depending on consistency
- Tunnel in saprolite; soil-like, rock-like behaviours to be assessed
- Tunnel in rock; consider intact properties, mass properties
Design to resist groundwater loads – Consider scenarios

Design groundwater levels may vary widely along the alignment
Design to resist ground and groundwater loads – Consider scenarios

Cluster design cases that are associated with comparable design actions

Designs to suit the entire alignment; or sets of designs for particular sections of the alignment

Typically geometry, thickness set; reinforcement details can change
Applied loads and changes to applied loads

- Allowance for loads associated with existing buildings, structures and utilities
- Allowance for additional tunnel, other scheme elements
- Allowance for future excavations, development loads
Construction loads

- Storage and transportation
- Lifting

These loads experienced with < 28 day strength
Construction loads

- Ring build
- TBM thrust
Construction loads

- Grouting loads

Typically 1 Bar above groundwater pressure

- 1st Stage – All round
- 2nd Stage - Concentrated
Lining stiffness

- Rigidity of system a combinations of:
  - Flexural rigidity of segment
  - Flexural rigidity of joint. Longitudinal joints transfer:
    - Axial forces
    - Moments
    - Shear
- Typically longitudinal joints are hinges or partial hinges with a limited capacity to transfer bending moments.
- Depends on member stiffness; also number and type of joints
Longitudinal joint geometry

- Flat joint, rotation occurs via elastic/plastic strains
- Convex-convex joints; high rotation capacity. Minimizes potential for spalling. High curvature leads to small contact area and potential splitting. Not stable during ring build.
- Convex-concave (hinged) joints; high rotation capacity. Edges of concave section vulnerable to spalling. Good stability during assembly.
Ground-structure interface

- Nature of contact between lining and ground is an important design consideration

Annulus backfill:

- Typically grout or pea-gravel
- Grout injected within tail-skin adopted where control of ground movements critical
Ground-structure interface

- Deformations modified by support pressure (i.e. slurry, compressed air, earth pressure) if machine is pressurized.

- Grout – Low initial strength; little/no shear capacity initially
- Pea-gravel – Frictional connection between ground + lining
Analysis and design methods

1. Closed form solutions – Used to determine the design bending moments and hoop forces
2. Analysis of ground-structure system using finite-element, boundary-element, finite-difference techniques
3. Structural analysis of segments restrained by ground reactions; structural analysis for detailing

Typically design completed via a mix of iterations between #1 and #3; or #2 and #3 where mixed ground, complex loading conditions apply
Analysis and design methods

Closed form solution (Muir/Curtis equations)

Determine axial loads, moments

Numerical analyses (FEM; BEM)

Structural design – Segments modelled as short columns
Closed form solutions

- Assumes ground properties are consistent over the diameter of the tunnel
- Useful for rapid assessment of sections where ground conditions can be characterized with a simple model

<table>
<thead>
<tr>
<th>Property</th>
<th>No shear</th>
<th>Shear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending moment</td>
<td>$\frac{P_0 R_0^2}{2(3 - b_{RA} + 4 Q_2)}$</td>
<td>$\frac{P_0 R_0^2}{4(1 + Q_2(3 - 4v))}$</td>
</tr>
<tr>
<td>Axial load, N</td>
<td>$P_{cr} R_0 + \frac{P_0 R_0 (3 - 4v)}{2(5 - 6v + 4 Q_2)}$</td>
<td>$P_{cr} R_0 + \frac{P_0 R_0}{2(1 + \frac{(2v Q_2)}{(3 - 4v)(1 + Q_2)})}$</td>
</tr>
<tr>
<td>Radial deflection, $\delta$</td>
<td>$\frac{BM R_0^2}{3 E_{concrete} f_0}$</td>
<td></td>
</tr>
<tr>
<td>Relative flexibility, $Q_2$</td>
<td>$\frac{E_{concrete} R_0^3}{E_{concrete} 12(1 + v) f_0}$</td>
<td></td>
</tr>
</tbody>
</table>
Numerical analysis

Beam on spring analysis using structural software: Compression springs only

FEM, BEM where tunnel-tunnel or tunnel-other external interface; anticipated; complex geology; check of other methods
Structural design

M-N interaction diagrams developed by analysing segment as short column
Structural design – Crack width

- Segments fundamentally rely on dense, intact concrete
- Crack widths commonly limited to 0.2-0.3mm
- Assess crack width for conventionally reinforcement in line with EN 1992-1-1
- For SFRC – Limit SLS tensile stress to allowable flexural stress
Structural design – Rotation of joints

Opening of joint on outside – Loss of confinement of gasket; increased contact stress towards intrados

Opening of joint on inside – Increased contact stress towards extrados
Structural design – Rotation of joints

- Check for bursting
- Check for bearing

Design of Precast Concrete Segmental Tunnel Linings – D Gutteridge

FIG 19 - Potential failure modes at joints.
Gasket design

• Two types:
  • EPDM – Relies on rubber-rubber contact to resist inflows – Requires compression of gasket
  • Hydrophilic – Gasket swells as water is absorbed, leading to a seal
• These sometimes used in combination
Gasket design

• Compression of gasket in short-term maintained by:
  • Typically self-gripping dowels or spear bolts on circle joints
  • Joint geometry on longitudinal joints
Other design issues

- Fire resistance:
  - Spalling criteria in response to design fire.
  - Check of structural capacity in response to fire – Reduced section, reduced capacity, fire-induced actions
- Durability:
  - Aggressive ground, groundwater
  - Presence of hydrocarbons, other contaminants
  - Carbonation – Internal environment
- Other loads:
  - Resistance to machine torque
  - Internal structures
  - Seismic
Seismic loads

Earthquake design criteria: Ground accelerations, motions.

Expected ground response

Liquefaction: Tunnel must act as a pressure vessel within a dense slurry

Affected by significant deflection of active fault: Gross distortions anticipated – Avoid collapse

Likely considered as Accidental Limit State only

For segmental linings – Pseudo-static load approach (Hashash et al 2001)

Shaking, deformations
Key points

1. Design will likely commence prior to receipt of all data; early analyses must anticipate possible changes to alignment, variations in ground/groundwater conditions
2. Alignment must be characterized by a number of design profiles, cases
3. Early analyses set geometry, so key load cases must be examined in some detail. Details of edges, joints are critical
4. Segment arrangement, geometry must be compatible with TBM
5. Construction-phase loads are most often critical
Thank You!!