Segmental Concrete Tunnel Liners
(Precast Concrete Tunnel Linings)

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Agenda

1. Overview
2. Materials and Design Features
3. Design
4. Manufacture
5. Installation
6. Seismic Performance
7. References and Conclusions
1 Overview
Segmental Tunnel Linings

- Steady development in shielded tunnel excavation rates
- TBM capital and labor costs mandate that support installation not control the mining cycle
- PCTL are an innovative and efficient segment system
New Geometry
• Lining and TBM are interdependent
What We Want in a Lining

- Structural capacity – includes static, seismic, and fire
- Water-tightness
- Maneuverability
- Ease of installation
- Settlement control
- Seismic stability
- **PCTL linings provide all of the above**
Materials and Design Features
Materials

• Start with purpose – Water / Transportation / Other

• High performance concrete
  – Rebar or wire
  – Steel fibers
  – Admixtures for strength and corrosion resistance (internal and external)

• Polypropylene fibers (fire resistance)

• Steel / Iron
Structural Capacity

- Fiber or Rebar
  - Rebar: High structural capacity
  - Rebar: High cost
  - Rebar: Control of crack size
Structural Capacity – SF

- Fiber or Rebar
  - Fiber: ease of installation
  - Fiber: corrosion advantages
Water-tightness - Gaskets

Single

Double
Corrosion Resistance – Water Applications

<table>
<thead>
<tr>
<th>Description</th>
<th>Advantages and Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrosion Resistance: The cast in place plastic lining will protect the PCTL segments from internal corrosion. A sacrificial concrete layer can be added to protect PCTL from external corrosion.</td>
<td>Cost: Additional cost for PCTL manufacturing and installation. Durability: Potential for small defects resulting in separation of plastic liner and corrosion of PCTL. Schedule: Combi-segments allow for a single pass lining while others require a second pass.</td>
</tr>
<tr>
<td>2. Two pass lining system with Hobas pipe installed within PCTL</td>
<td></td>
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<tr>
<td>Corrosion Resistance: Use of Hobas has a proven long design life in corrosive environments, both internally and externally.</td>
<td>Cost: Additional cost for the installation of Hobas pipe in a double-pass configuration is currently estimated at up to $xx Million. Schedule: Additional project schedule for the installation of Hobas pipe in a double-pass configuration is currently estimated at up to x months.</td>
</tr>
<tr>
<td>3. High performance concrete and corrosion and odor control</td>
<td></td>
</tr>
<tr>
<td>Corrosion Resistance: The corrosion resistant concrete mix design will deliver improved corrosion resistance to the PCTL. Additional measures and concrete thickness will further improve performance.</td>
<td>Cost: Additional cost for testing and simulation of the corrosion resistant mix, lining manufacture, enhanced air flow, and chemical dosing. Durability: Verification/proof-of-concept for a corrosion resistant mix with a 100 year design life is reliant on simulation and verification testing. Other modifications for increased air flow and chemical dosing improve overall performance. Schedule: Some additional design time is required to assess the estimated useful performance life of the HPC mix.</td>
</tr>
</tbody>
</table>
Fire Resistance – Transportation Applications

Images from: Channel Tunnel Rail Link
3 Design
Conceptual Design

- **Dead and Live Loads** – ground, groundwater, buoyancy, traffic

- **Variable Loading** –
  - Internal pressure (PCTL may need special considerations for internal pressure)
  - TBM thrust from rams

- **Temporary Load** – form removal / stripping, stacking, transportation, assembly, grouting

- **Seismic** – check, usually this does not govern
  - Fault rupture if applicable
Conceptual Design

- Stacking / Transport
Forms of Analysis

• Elastic closed form solutions per Muir Wood
  - Fast – can used for loads, deflections and parametrics

• Beam-spring models
  - Not so much – limited SSI

• Finite Element / Difference
  - FLAC, Phase 2/RS2, PLAXIS
  - Nice looking output

• Like any calc – garbage in = garbage out
Manoeuvrability = Ring Taper
Settlement Control

- Grouting provisions

Partial Penetration (grout through TBM shield)
Settlement Control

- Grouting provisions

**Full penetration (grout through segments)**
4 Manufacture
Process

- Plant location and qualifications
- Batch / mix
- Pour / form
- Cure (steam)
- Remove from forms
- Stockpile
- Transport to site
Steam Curing

- Crack control is important
Highlights of Manufacturing Process

- Controlled process
- Specialized molds
- Tight tolerances
- Quality – RFID or Bar Codes
  - Scanners on delivery and on installation with logs of problems if any
5 Installation
Ease of Installation

- Ring build time is critical to overall productivity
- Rail cars
- TBM handling
- Segment conveyor
- Segment erector
- Build order (L / R)
Ease of Installation

- Ring build time is critical to overall productivity
- Circumferential joint connectors
- Dowels – only with trapezoidal segments
- Tension and shear
Repairs

• Need to have repair procedures
  – Manufacture
  – Construction – post installation spalling
Repairs
Repairs
Grouting is key
Inspection is key
6 Seismic Performance
Seismic Stability

- Seismic analyses - from Hashash et al, 2001

Fig. 6. Deformation modes of tunnels due to seismic waves (after Owen and Scholl, 1981).
Fault Rupture

Ring Displacements
SVRT Tunnel Lining

- Construction of the tunnels will use a single pass PCTL system
- Sometimes PCTL are owner procured
Seismic Resiliency

• Connecting devices become important

• Seismic study on the use of PCTL in tunnels in seismically active areas and the performance of such systems during seismic events
PCTL Seismic Performance Study

- With Dave Young and Gary Kramer
- PM: John Hawley, Reviewer: Andrew Hindmarsh
- Paper to be published in Sept 2006
- Presentations at NAT and IAEG
Focus of Study

- PCTL are recommended for the following reasons
  - Used worldwide in seismic areas for transit tunnels
  - Have withstood significant shaking with little to no damage
  - Preferred based on cost, ductility, water tightness, fire resistance, and other considerations
Focus of Study

- History of PCTL use in bored tunnels
- History of PCTL use in seismically active areas
- Tunnel performance criteria
- History of earthquakes in areas where PCTL were used
- PCTL performance in earthquakes
- Anticipated structural analyses for PCTL in seismic design
Performance Criteria and Ground Motions

- BFS: Trains shall be “capable of being operational” within 72 hours of the design ground motion.

- SVRT design ground motion (PGA) for the tunnel segment: 0.55g.
Seismicity and Seismic Hazards

Global Seismicity – USGS
Seismicity and Seismic Hazards

Local Seismicity, 10% in 50 years PSHA – USGS/CGS
PCTL use in the USA

• Selected examples:
  - San Diego, South Bay Outfall, Single Pass, 0.63 g
  - LA Metro Gold Line, ODE – 0.41g, MDE – 0.79 g
  - Portland, East & West Side CSO – 0.3 g
PCTL Performance in Earthquakes

- No reports of structural damage to PCTL Tunnels were found in any major earthquake since 1980, including the following events:
  - 1985 – Mexico City, Mw 8.1
  - 1993 – Hokkaido, Mw 7.7
  - 1994 – Northridge, Mw 6.7
  - 1995 – Kobe, Mw 6.9
  - 1999 – Taiwan, Mw 7.5
  - 2001 – Nisqually, Washington, Mw 6.6
Power et al Study

- Bored tunnel performance in five major seismic events – no damage occurred to PCTL tunnels

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Magnitude</th>
<th>Number of Cases Reviewed</th>
<th>Number of Cases at each Damage Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/17/89</td>
<td>Loma Prieta, CA</td>
<td>7.1</td>
<td>22</td>
<td>(22, 0, 0, 0)</td>
</tr>
<tr>
<td>4/25/92</td>
<td>Petrolia, CA</td>
<td>7.2</td>
<td>11</td>
<td>(9, 2, 0, 0)</td>
</tr>
<tr>
<td>7/12/93</td>
<td>Hokkaido, Japan</td>
<td>7.7</td>
<td>1</td>
<td>(1, 0, 0, 0)</td>
</tr>
<tr>
<td>1/17/94</td>
<td>Northridge, CA</td>
<td>6.7</td>
<td>31</td>
<td>(28, 2, 1, 0)</td>
</tr>
<tr>
<td>1/17/95</td>
<td>Kobe, Japan</td>
<td>6.9</td>
<td>97</td>
<td>(75, 14, 8, 0)</td>
</tr>
</tbody>
</table>
• Initial design is conducted for static loads

• The design is subsequently checked against dynamic (seismic) loads

• Changes rarely need to be made based on dynamic checks due to the inherent load-carrying advantages of PCTL systems
7 References and Conclusions
References

- AFTES Guidelines
- BTS – Tunnel Lining Design Guide
- Code of Practice – HS2 / BTS
- Conference Proceedings – NAT + RETC, Others
Seismic Performance Conclusions

- Tunnels perform well in earthquakes in general, because they are constrained by the ground around them.

- PCTL tunnels perform particularly well because they are: largely symmetrical, jointed and have ample flexibility.

- PCTL is the ideal lining type for many tunnel projects regardless of tunnel purpose – transportation, water/wastewater, utility, etc...
Conclusions

- PCTL are currently the conventional way TBM tunnels in soft ground are lined.
- Intricate detailing is typically done for conformance with contractor equipment and means and methods.
- Design has evolved with numerous innovations.
  - LACSD Clearwater Tunnel will have post-tensioned segments for internal pressure in soft ground, which will be the first application of this type in USA.