Pressure Tunnel Design
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Outline: Pressure Tunnel Design

1) Introduction
   Definitions
   Load Sharing

2) Case Histories Low Pressure Tunnels

3) Case Histories High Pressure Tunnels
1) Introduction
1) Introduction – Definitions

- **Low pressure < 55 psi**
  - Outfall, low pressure sewer, water supply
  - RCP/RCCP/PCCP (AWWA M9), FRP, Cast-in-Place
  - Soil, weak rock
  - Precast with continuous reinforcing hoop steel
    - Various
    - Rebar or Prestressing steel with Bearing-Transfer Plates

- **Moderate Pressure >> 55 psi to 200 psi** (not discussed)
  - Water supply, hydroelectric
  - Post tensioned CIP concrete

- **High Pressure  200 psi >1000 psi steel**
  - Medium strong to strong rock, \( E_{r,\text{min}} = 500,000 \) psi
  - Unlined, Cast-in-Place, Steel
1) Introduction
Load sharing – Internal Water Pressure

Load Sharing is defined as sharing of the internal pressure in a water system between the ground and the liner. The pressure is transmitted from the liner to the ground through the annular backfill. The ability of the ground to handle these loads is determined by verification of rock modulus using in-situ testing, verifying sufficient ground cover, control of the annular backfill strength/stiffness, and proper liner design.
Load Sharing Extent: 0 (lined) to 100% (unlined)
2) Low Pressure Tunnels
## 2) Low Pressure Segmented Lining Pressure Confinement Strategies

<table>
<thead>
<tr>
<th>Alt.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Use annular and secondary grouting to ensure thrust is applied on the liner to close cracks and to lock in thrust, and provide instrumentation to monitor the liner load.</td>
</tr>
<tr>
<td>2*</td>
<td>Provide hoop re-bar steel to accommodate tension and limit crack widths</td>
</tr>
<tr>
<td>3</td>
<td>Provide a secondary internal liner such as steel or precast concrete cylinder pipe (PCCP).</td>
</tr>
<tr>
<td>4</td>
<td>Provide coatings and/or embedded plastic linings; the embedded liner could be directly bonded to the segments or the plastic liner could be cast-in-place inside the segments (e.g., plastic internal liner such as PVC, HDPE, or equal).</td>
</tr>
<tr>
<td>5</td>
<td>Provide a steel shell in composite action with the segments.</td>
</tr>
<tr>
<td>6*</td>
<td>Provide hoop wire steel in the form of pre-stressing tendons to post-tension the concrete, thus eliminating the development of potential cracks.</td>
</tr>
</tbody>
</table>
2) Low Pressure Segmental Liner Case Histories

Preloading by External Grout pressure
- DE, Keiser’s method, 1952

Preloading by Jacks
- DE, 1960, Dusseldorf sewage tunnel under Rhine, 14.8’ OD

Rebar steel
- US, 1995-2000, South Bay Tunnel Outfall, San Diego, 12.5’ OD
- JP, 1999-2009, Metropolitan Area Outer Underground Discharge Channel, Tokyo, 17.7 to 34’? OD

Post tensioning / Pre-stressing steel
- FR, 1949, Subaqueous tunnel under Seine, 14’ & 16’ dia., steel bands
- JP, ca. 1999-2003 (Osaka area)
  - Onchigawa-Higashi Trunk Line, 9.7 ft OD,
  - Yao-Hiraoka Trunk Line, 11.6 ft OD
  - Shitanoya Trunk Line, 9 ft OD
  - Midorigaoka Rainwater Trunk Line, 10.2 ft OD
- CH, 2008, Thun Flood Relief Tunnel, 19.7’ OD
Water Leakage Criteria through micro cracks in concrete

ACI 224 Control of Cracking in Concrete Structures limiting $f_s < 20$ ksi

$W = 0.10 \ f_s \ (d_c \ A)^{1/3} \times 10^{-3}$

Where

$A = 2d_c S$

$d_c = \text{bar cover}$

$S = \text{Bar Spacing}$

$W = 0.008 \ \text{in. crack width for water retaining structures}$
As reported by Szechy (1966)

1. circumferential concrete bedding is placed, providing a smooth surface and grout barrier
2. grout fissures in rock and annular space
3. concrete segments erected
4. 1-1/4” gap use low pressure grouted until return in adjacent hole
5. finally pressure grouted to 150% of working load until cement suspension is hardened.
As reported by Szechy (1966)

- 14 and 16 ft dia.
- compressed air
- hand excavation methods
- 11” x 0.20” steel bands/grouted
- segments 4’10” l, 1’10’ wd, 1’4” thk

1. two 50 ton jacks at two half rings
2. jacks tensioned and steel wedges installed to hold pretension
3. jacks removed and space filled with concrete
4. Joints clipped and band grouted
5. Interior gunite layer

**FIG. 6/141. FREYSSINET’s prestressing method with external flat-steel hoop bandage**
As reported by Szechy (1966)

- 14’8” OD
- 2’3’ wide x 10’ thk segments
- Prestressing keys at Qtr Arches

1. Prestressing bar tensioned against shoulders in joint with asbestos bearing pads
2. Joints filled with grout
3. Followed by annular grout
Continuous Hoop Re-bar Joined by Bearing/Transfer Plates

San Diego’s SBOO Tunneled Outfall
Continuous Hoop Re-bar Fastened by C- and H-shape connectors

Metropolitan Area Outer Discharge Channel, JP

Cement Paste Gap Filling
The gap will be filled with quick-set non-shrink cement paste mainly for corrosion resistance, and H-shaped connectors will be encased permanently at approx. 120m behind the heading.

Circumference Joint
Tongue and Groove
Shear force is transferred through tongue and groove.

Hoop Re-bar fastened to C-shaped connectors which are in turn butted together and fastened with H-shape connectors at the segment Joint. (Miyao et al., 1999).

Push Grip
Push Grips (Wedge Pins) retain the expansion force of the seals between the rings, so that water tightness is assured both in normal times and in an earthquake.

Radial Joint
The joint with wedges inserted along the tunnel axis

C-shaped connectors are embedded on the joint surface. When two segments are butted together, those create an H-shapped space. Then an H-shaped connector is inserted into the space to fasten the two segments together.
Continuous Tendons
Post Tensioned/Prestressed

Construction Sequence

1. Assembling segments
2. Inserting prestressing strand
3. Tensioning and fastening
4. Grouting and filling up hollows

Construction Experiments

- On'chigawa-Higashi Trunk Line of Sewage System in Lower Stream of Neyagawa Basin, Sewage Pipe Construction Work (Lining Outer Diameter: 2,950 mm)
- Yao-Hiraoka Trunk Line of Sewage System in Lower Stream of Neyagawa Basin, Sewage Pipe Construction Work (Lining Outer Diameter: 3,550 mm)
- Shitanoya Trunk Line of Yokohama City Northern Treatment District Construction Work (Lining Outer Diameter: 2,750 mm)
- Midorigaoka Rainwater Trunk Line of Sagamihara City Public Drain Construction Work (Lining Outer Diameter: 3,120 mm)
Continuous Tendons
P&PC Segment Lining Method

Unbonded prestressing strand

X anchor

Unbonded prestressing strand

Center holed jack

A-T

X anchor
Thun Flood Relief Tunnel, CH

Anchoring niche

Two monostrands in PE protective casing

Haefilger, 2009; Kohler and Rupp, 2008
Thun Flood Relief Tunnel, CH

Haefilger, 2009; Kohler and Rupp, 2008
South Bay Tunnel Ocean Outfall (ca. 1995-2000)
Hydrotest of Hoop Tendons or Bars (SBTO, ca. 1994)
Outside Face of Tunnel

Indicators numbering order:
- Start at keystone
- Clockwise (outside face)
- Bottom to top ring

Approx. Location of Stressing Pocket

Photo 1

Photo 2

Photo 3

Photo 1

LEGEN

A LVDT
1 Dial Indicator

1A Segment Type

Indicators numbering order:
- Start at keystone
- Clockwise (outside face)
- Bottom to top ring
Issues and Conclusions
Low Pressure One Pass Segmented Liner

Alternatives
- Two Pass
- Load Sharing
- Plastic liner

Bearing Transfer
- Anchorage/Liner thickness

Hoop Bars
- Steel vs. Carbon
- Bonded vs. Unbonded
- Anchorage

Constructability

Example Trade Off Analysis

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Description</th>
<th>Relative Reliability</th>
<th>Relative Cost</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Secondary grout, lock in thrust</td>
<td>1</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>Hoop steel</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>Two-pass w/steel or PCCP</td>
<td>5</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>Embedded plastic linings</td>
<td>3</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>5</td>
<td>Steel shell</td>
<td>4</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>6</td>
<td>Pre-stressing tendons</td>
<td>3</td>
<td>4</td>
<td>12</td>
</tr>
</tbody>
</table>
2) References

Segmented Liners designed for low pressure

- Haefliger, P., 2009, Thun Flood Relief Tunnel, Sept. 22 Presentation to D. Klug European Tunnel Tour.
  - Hochtief Nachrichten (Newsletter), 1960, Rheintunnel Dusseldorf, Aug/Sept
  - Keiser, A., 1960, Druckstollenbau (Pressure Tunnel Construction), Springer-Verlag
3) High Pressure Tunnels
   a) Geotech. Inv. for Design of Press. Tunnels & Shafts
   b) Water Pressure Testing
   c) Rock Cover and Minimum Stress
   d) Lining Design and Lessons Learned
3a) Geotechnical Investigations for Design of Pressure Tunnels and Shafts
Calaveras Power Tunnel

Potential water loss or gain

Landslide potential

McKAY’S POINT
ARCH DAM

CREST OF DAM
EL. 1033.3 m

STATIC HEAD
EL. 1027.2 m

MILL CREEK

SURGE TANK
EL. 1048.2 m (MAX. SURGE)

EL. 1041.2 m

EL. 923.2 m

TUNNEL ADIT

1%

TUNNEL ADIT

UPPER TUNNEL

LOWER TUNNEL

PRESSURE SHAFT

EL. 335.0 m

1292 m

844 m

11770 m

SECTION 2 AS LOCALLY REQUIRED

1 UNLINED SECTION

2 CONCRETE LINED TUNNEL SECTION

3 CONCRETE LINED TUNNEL & SURGE SHAFT SECTION

4 STEEL LINED TUNNEL SECTION
Landslide Potential

k of rock > k of deposit
Issues

- Groundwater infiltration (construction considerations or permit requirements)
- Water exfiltration from pressurized, unlined waterways due to:
  - hydraulic conductivity of rock mass
  - hydraulic jacking of discontinuities
- Design of the lining system (load sharing with surrounding rock)
Field Exploration Program

- Water pressure testing (WPT) of boreholes
- Minimum stress measurement by hydraulic jacking (WPT to higher pressures) and/or hydraulic fracturing
- Rock mass modulus of deformation (for load sharing calculations)
Foliation can trap fracture
3b) Water Pressure Testing (WPT)
WPT – Typical Setup

Parameters:

- Q = 10 - 20 gpm
- L = 10 - 20 ft
- \( h_t = h_w + h_p \)
Water Pressure Testing (WPT)

- Estimating water inflow is major issue in design of rock tunnels
- Heuer’s method (RETC, 1995 & 2005) commonly employed
- Problem with method not so much empirical approach, but quality of WPT data, as indicated by Heuer:
  
  “…accuracy of the estimate will be limited by the nature of the preconstruction exploration program.”
Estimating inflow:
Heuer’s empirical approach
(modified radial flow equation)

Flow = 1/8 to 1/4 q_s
Issues (WPT)

- No down-the-hole (DTH) pressure measurement (transducer)
- Inadequate testing of the bore hole interval and/or development of statistical baseline
Permeability Histogram

![Histogram of Packer Test Permeability](image)

Missing data ????
WPT – Unfilled Standpipe

System resolution for:

\[ Q = 10 - 20 \text{ gpm} \]
\[ L = 10 - 20 \text{ ft} \]
\[ h_t = h_w + h_p = 0 \]

<table>
<thead>
<tr>
<th>( h_t &lt; h_w ) (ft)</th>
<th>( K ) (cm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>( 1 \times 10^{-2} )</td>
</tr>
<tr>
<td>100</td>
<td>( 1 \times 10^{-3} )</td>
</tr>
<tr>
<td>500</td>
<td>( 3 \times 10^{-4} )</td>
</tr>
</tbody>
</table>
Permeability Histogram

Estimated Flow, $Q^{31} \approx 5Q^{30}$
3c) Rock Cover and Minimum Stress
Rock Cover: Norwegian Criteria

\[ C_{RM} = \frac{h_s \gamma_w F}{\gamma_R \cos \beta} \]

- \( C_{RM} \) = MINIMUM ROCK COVER
- \( h_s \) = STATIC HEAD
- \( \gamma_w \) = UNIT WEIGHT OF WATER
- \( \gamma_R \) = UNIT WEIGHT OF ROCK
- \( \beta \) = SLOPE ANGLE (VARIES ALONG SLOPE)
- \( F \) = SAFETY FACTOR = 1.2 to 1.5

(Assumes minimum stress is vertical)
3d) Lining Design and Lessons Learned
Load Sharing

Compatible radial strains at each interface
Steel Liner Design Flow Chart
(mod. after Schleiss, 1988)

1. Working Stresses and Deformations in Steel Lining
   - Design Loads
   - Assume Steel Grade Quality and Liner Thickness
     - Safety Factor Against Buckling
       SF>1.5 (no gap) or >1.3 (with gap)?
       Y
       - Assumption
         Full Load Sharing including Cracked Zone
       - Stresses and Deformations in Steel Liner and Rock Mass
         - Safety Factor Against Yield
           SF>1.7?
           Y
           - Maximum Width of Crack in Rock Mass
             - Safety of Steel Liner for Crack Bridging
               w < t/2?
               Y
               - Increase Thickness of Steel Liner
           N
           - Increase Thickness of Steel Liner
             or
             Steel liner with stiffners
             or
             Steel liner with drainage system
               N
               - Can Alignment be Modified to allow for Increased Rock Cover?
                 Y
                 - Maximum Rock Participation
                   1.2*Required Rock Cover
                 N
                 - Modify Alignment
                   Maximum Rock Participation
                   1.2*Required Rock Cover
               N
               - Control of Rock Participation or Cover
                 SF>2.0
               N
               - Carrying Capacity of the Tunnel at Failure, Yielding of Steel Liner at Rock Mass Failure
                 Y
                 - Carrying Capacity of the Static System Liner-Rock SF>2.0
               N
               - Requirements 1. and 2. are satisfied
                 Y
                 - End of Flow Chart
Steel Liner Design – Seeber Diagram

Fig. 7. Steel liner thickness design diagram. \( r_i = \text{radius of steel liner}; r_f = \text{radius of cracked zone}; k_o = \text{ratio between minimum horizontal and vertical rock stress}. \)
Graphical Line Method, Seeber Diagram

\[
z = \frac{FS P_t}{3 k_o \gamma} + 3r_t
\]

Effective Depth of Cover (ft)

Internal Pressure in Steel Liner (psi)

Internal Pressure in Rock (psi)

Effective Modulus of Rock and Backfill

\[
\frac{u_r}{r_t} = P_t \left[ \frac{(1 - \nu_c^2)}{E_c} \ln \left( \frac{r_a}{r_t} \right) + \frac{(1 - \nu_s^2)}{E_s} \ln \left( \frac{r_f}{r_s} \right) + \frac{(1 + \nu)}{E_T} \right] + \text{GAP}
\]

GAP

Radial Strain

Hoop Stress (ksi)

Steel Liner

Steel

Rock

Effective Modulus of Rock and Backfill

\[
f_{\text{allow}} \geq f_s = \frac{P D}{2 t_{\text{wall}}}
\]

\( f_y / 2 \text{ LIMIT} \)
Rock Load Carrying Capacity – Cracked Zone Analysis

\[ \sigma_h = k_o \times \sigma_v = k_o \times \gamma \times H \]

CRACKED ZONE
INDUCED TENSION

\[ x < 3 \text{ to } 4 \, \text{r} \]

\( \sigma_x, \sigma_v, \sigma_h \)
Rock Mass Modulus of Deformation

Methods:

- Seismic
- Flat jack / plate load
- Borehole dilatometer (Goodman jack or rock pressure meter)
- Instrumented TBM gripper pads
Borehole WPT Interval

Typical approaches:
• Tunnel diameter or envelope
• ± 1 tunnel diameter beyond envelope
• 100 ft overall interval

Recommendation: Test entire borehole below weathering profile for statistically representative sampling (unless geology dictates otherwise)
Unlined waterways – confined and unconfined hydraulic jacking

Unlimited leakage (improvement by grouting – no)

Minimum stress governs

Cover = minimum stress

Leakage function of joint aperture, stiffness and erosion
Hydraulic Jacking Tests

- WPT at higher pressures
- Results depend on representative statistical sampling to define lower bound results or minimum stress
- Exercise the fractures to confirm the results
- “Breakdown” healed fractures or intervals with intact rock (need higher pressure packers and pump)
Hydraulic jacking to determine normal stress across fracture

\[ P_j = h \gamma_w \sim \sigma_n \]

- \( P_j = \text{Jacking Pressure} \)
- \( h = \text{Head} \)
- \( \gamma_w = \text{Unit Weight of Water} \)
- \( \sigma_n = \text{Normal Stress Across Jacking Surface} \)

```
Q \propto a^3
```

"knee"
Hydraulic Jacking – methodology

\[ \sigma_{\text{max}} \]

\[ \sigma_{\text{min}} \]

\[ \sigma_{\text{normal}} \]

Combine with ATV
Hydraulic Jacking - Issues

- Inadequate definition of jacking pressure or “knee”
- Failure to cycle the test interval
- Too few test to define reliable lower bound result
- Test procedures not amenable to “cookbook” approach
- Testing limited to one location or borehole
Problems: Too few points, no repeat of cycle after breakdown of healed fracture

Not the correct jacking pressure

**Graph:**
- **Y-axis:** HEAD (PSI)
- **X-axis:** STEADY STATE FLOW (GPM)
- **Notes:**
  - Pj = 229 psi
  - TOTAL OVERBURDEN AT MIDPOINT
  - STATIC HGL
  - STATIC PORE WATER PRESSURE
Hydraulic Jacking Test – two cycles

First cycle
Second cycle

Lower bound jacking pressures:
~900 psi
~800 psi
Bi-County Hydrojacking Tests
(horizontal stresses greater than vertical)

(Note: 12 tests over ~230 ft interval)

Tests on sub-horizontal joints: (4 points)

Tests on near vertical joints: (6 points)
Dinkey Creek Hydrojacking Tests
(vertical stresses greater than horizontal)

Jacking pressure (psi)

Lithostatic Pressure
(1.15 psi/ft)

Ko = 0.62
Minimum stress
(0.28 psi/ft)

Ko = 0.43

(Note: 29 tests over ~800 ft interval)
Dinkey Creek – 8 hour test

8 hr hold
(~ 1000 cf water)
Dinkey Creek – Tunnel Profiles

Low alignment

High alignment
Balsam Meadow Hydroelectric Project

- Maximum static design head: 610 psi (1400 ft)
- Stress measurements (hydro-fracture) done in powerhouse area: $\sigma_{\text{min}} = 700$ psi (1 borehole, 16 tests)
- Typical WPT (no DTH transducer) in drop shaft and elsewhere – could not fill standpipe in some tests
- Observed anomalous conditions (open joints)
- Repeated stress measurements in power tunnel area (1150 ft): $\sigma_{\text{min}} = 320$ psi (2 holes, 12 tests)
- Add steel lining
Balsam Meadow – open joints
(right photo: silt infilling)
Another Hydroelectric Project

- Stress measurements (H-F) done in trifurcation area: $\sigma_{\text{min}} =$ overburden, (1 borehole, 10 tests)
- $\sigma_{\text{min}}$ appears adequate for design
- Additional jacking tests within power tunnel reveal lower $\sigma_{\text{min}}$ mostly found on second cycles ($\sigma_{\text{min}}$ as low as 1/2 static head)
- Owner decides not to extend steel lining
- Very large leakage occurred, damage to PH, repeated shutdowns and attempts to grout leaks from within power tunnel
- Redesign and installation of steel lining
View through tunnel plug toward back wall of headrace tunnel
Hydraulic jacking of individual joint parallel to valley side

Edge of broken shotcrete

Open joint
Lessons Learned

- For improved estimates of water inflow, statistically significant number of WPTs should be performed with greater care using DTH pressure transducer.
- WPTs performed with DTH pressure transducer can be used for minimum stress measurements or to confirm other measurements.
- To provide reliable results, hydro-jacking tests should be performed to minimum standards: sufficient points to define the “knee” and multiple cycles.
- Multiple stress measurements at multiple locations are essential - ideally, both surface and underground.
References

Moderate to High Pressure

C ASCE, 1989, Civil engineering guidelines for planning and designing hydroelectric developments, Vol. 2, Waterways, Ch. 3, Tunnels and shafts, ed. E. Moore


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Fernandez, G. and T.A. Alvarez, 1994, Seepage-induced effective stresses and water pressures around pressure tunnels, ASCE J. of Geotechnical Engineering, V. 120, No. 1, Jan.


Goodall, D.C., H. Kjorholt, T. Tekle, and E. Broch, 1988, Air cushion surge chambers for underground power plants, Water Power and Dam Construction, Dec.


C = Also contains information on design of concrete pressure tunnels