Coupled Stress-Seepage Numerical Design of Pressure Tunnels

Afis Olumide BUSARI, Prof. C.W. LI
Department of Civil and Environmental Engineering, the Hong Kong Polytechnic University, HKSAR, China

Abstract: The design and construction of pressure tunnels are most complicated among all types of tunnels. Therefore, special attention is required in the design and construction of these tunnels to prevent failure. This research introduces PLAXIS 2D finite element program as a tool for numerical modeling of plain concrete pressure tunnels. The numerical model cannot completely portray the nature, but should have the capability to simulate the materials and the loading cases. The rock behaviour is approximated by using the elasto-plastic Mohr - Coulombs model. The shotcrete and final lining are assumed permeable and elastic. The structural analysis is based on plain strain condition. Different phenomena in terms of loading cases during construction stage and operational loading case with internal water pressure are simulated. Special concern is taken on the modeling of the contact between the shotcrete and the final lining where during shrinkage and temperature change by first filling with cold water a gap can open and later closed during prestressing. Plain concrete lining of pressure tunnels is not absolutely tight and water seeps out of the tunnel. The seeped water losses energy, but can also cause stability problems in the surrounding rock mass. Additionally, if the rock mass around the tunnel is tight (originally or tightened by grouting) the seeped water stays in the vicinity of the tunnel and increases the external water pressure. Such increased external water pressure decreases the gradients between internal and external pressure and reduces the seepage and losses. Modeling of this phenomenon is performed by coupled stress-seepage calculation performed by the same model. The coupling of stress-seepage is carried out by superimposing results of consolidation and water flow analyses. The pressure tunnel of the HPP Ermenek Turkey is taken as a practical example in the numerical simulation. The results illustrate the applicability of the present method.

Keywords: pressure tunnel, plain concrete lining, internal water pressure, stress-seepage analysis
Coupled stress-seepage numerical design of pressure tunnels

Presented by
BUSARI, Afis Olumide
OUTLINE

• Introduction

• Research objectives

• Methodology

• Results and discussion of results

• Conclusions

• Recommendations
INTRODUCTION

- Design and construction of pressure tunnels are among the most complicated of tunnels.
- The construction of the power waterway for high-head hydro-power plants is generally one of the most expensive project parts.
- Special attention is required to prevent failure.
- Most especially the used of plain concrete as a liner in pressure tunnels.
- No method have been found to include all important parameters for its construction and operational loading.
- The bearing of IWP is limited by low tensile strength of concrete.
- Plain concrete lining of pressure tunnels is not absolutely tight and water seeps out of the tunnel.
- The seeped water is lost of energy, but can also cause stability problems in the surrounding rock mass.
- If the rock mass around the tunnel is tight (originally or tighten by grouting) the seeped water stays in the vicinity of the tunnel and increases the external water pressure. Such increased external water pressure decreases the gradients between internal and external pressure and reduce the seepage and losses.
RESEARCH OBJECTIVES

- **Overall objective**
  To review common practice design methods with special attention on plain concrete lined power waterways.

- **Specific objectives**
  - To define a numerical methods that include all important parameters and loading cases occurring during excavation, lining construction, grouting and operational loading by internal water pressures.
  
  - To give a unique and effective method for design of the permeable pressure tunnel linings.
Material and Loading Modelling

- Material behaviour
  - Understanding the behaviour of rock mass and concrete will allow proper modelling of the materials and well as the interaction during and after loading.

- (Material and loading) Modelling

Schematic diagram of material & loading Modelling
**Methodology I**

Methodology flow chart:

1. Model set up - PLAXIS 2D
   - Model 1-Full mesh
   - Model testing
   - Sensitivity study (SS)
   - Model calibration/Parametric study
   - Correlation
   - Model 1
   - Model 2
2. Model 2-Distributed load
   - Model testing
3. Numerical Simulation of pressure tunnel

Full model (FE meshing)

Distributed load (FE meshing)
Flow chart for the numerical analysis of pressure tunnels

1. Initial state of stresses
2. Excavation modelling
3. Shotcrete installation
4. Final lining/shotcrete decay
5. Grout modelling
6. Shrinkage effect
7. Internal pressure (Pi)

Plastic calculations

Consolidation & flow Analyses

Flow chart for the numerical analysis of pressure tunnels
DESIGN DATA

Material properties

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Rock mass</th>
<th>Shotcrete</th>
<th>Final lining</th>
<th>Unit</th>
</tr>
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<tbody>
<tr>
<td>Modulus of elasticity</td>
<td>E</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>GPa</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>ν</td>
<td>0.20</td>
<td>0.22</td>
<td>0.22</td>
<td>-</td>
</tr>
<tr>
<td>Unit weight</td>
<td>γ</td>
<td>26</td>
<td>24</td>
<td>24</td>
<td>kN/m³</td>
</tr>
<tr>
<td>Frictional angle</td>
<td>φ</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>°</td>
</tr>
<tr>
<td>Cohesion</td>
<td>C</td>
<td>1000</td>
<td>1000</td>
<td>1500</td>
<td>kN/m²</td>
</tr>
<tr>
<td>Thickness of lining</td>
<td>d</td>
<td>-</td>
<td>0.1</td>
<td>0.3</td>
<td>m</td>
</tr>
<tr>
<td>Weight</td>
<td>w</td>
<td>-</td>
<td>2.4</td>
<td>7.2</td>
<td>kN/m/m</td>
</tr>
<tr>
<td>Thermal coefficient</td>
<td>α</td>
<td>-</td>
<td>-</td>
<td>1.2 × 10⁻⁵</td>
<td>/°C</td>
</tr>
</tbody>
</table>

(Source: Ermenek Pressure Tunnel Project, Turkey, 2003)

Overburden height = h = 200m

Material properties of shotcrete (calculated values)

<table>
<thead>
<tr>
<th>Nr</th>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Type</td>
<td>Elastic</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>EA</td>
<td>2,000,000</td>
<td>kN/m</td>
</tr>
<tr>
<td>3</td>
<td>EI</td>
<td>1666.67</td>
<td>kNm²/m</td>
</tr>
<tr>
<td>4</td>
<td>w</td>
<td>2.4</td>
<td>kN/m per metre</td>
</tr>
</tbody>
</table>
MODEL ASSUMPTIONS

- Rock mass behaviour is assumed to be in drained conditions.
- Lining material is elastic.
- The model is based on condition of plane strain.
- Rock mass is defined as elasto-plastic material, with yield functions defined by Mohr-Coulomb strength law.
- The stresses existing in the rock mass are related to the weight of the overlying strata and geological history. No geotechnical stresses are expected and the vertical stress is assumed as a weight of overburden. The horizontal stress is defined as a portion of the vertical stress for elastic solution with restrained horizontal movements.

**Boundary condition:**

Horizontal fixity, $U_x = 0$
Vertical fixity, $U_y = 0$
RESULTS AND DISCUSSION OF RESULTS

Numerical Simulation of pressure tunnel

- Initial state of stresses
- Excavation modelling
- Shotcrete installation
- Final lining/shotcrete decay
- Grout modelling
- Shrinkage effect

Stresses and Deformations

- Plastic calculations

Consolidation & flow Analyses

- Internal pressure ($P_i$)
- $K_{c1}$
- $K_{c2}$
- $K_{c3}$
- $K_{c4}$
- $K_{c5}$

Stresses and Seepage

Flow chart for results of numerical design of plain concrete pressure tunnels
RESULTS AND DISCUSSION OF RESULTS

1. Initial state of stress

1.1 Vertical stresses ($\sigma_{yy}$)

Cross section

Deformation is uniform and equals to zero
RESULTS AND DISCUSSION OF RESULTS

1. Initial state of stress

1.2 Horizontal stresses ($\sigma_{xx}$)

Cross section
RESULTS AND DISCUSSION OF RESULTS

1. Initial state of stress

1.3 Horizontal stresses ($\sigma_{zz}$)

Cross section
RESULTS AND DISCUSSION OF RESULTS

**Loading -1- Stress relief**

**Model calibration (β- method)**

Excavation and shotcrete installation (2D simulation of 3D arching effect).

Before excavation, initial radial stress = initial state of stress in the rock.

As excavation starts, the reduction factor applies because the natural equilibrium of the rock is disturbed.

\[ \beta \] increases as the excavation progresses leading to decrease in deformation around the opening as the shotcrete takes part of the rock pressure.

The load reduction factor, \( \beta \) defines the degree to which the lining is unloaded due to rock mass being allowed to converge.

This implies that the shotcrete lining partly confines the convergence and reduces deformation.

[Diagram showing stress relief and rock mass-lining characteristic curve (Element 7, Node 2873, Crown).]
RESULTS AND DISCUSSION OF RESULTS

Model calibration (β-method)

β in the range of (0.6 - 0.64) is found to have given a normal compressive force in range of 1000kN as measured at the project site and in the geological conditions similar to the selected rock mass parameters.

Normal forces and deformations for $0 \leq \beta \leq 1$

<table>
<thead>
<tr>
<th>S/n</th>
<th>β</th>
<th>A  (kN/m)</th>
<th>Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>14.74</td>
<td>2.76</td>
</tr>
<tr>
<td>2</td>
<td>0.1</td>
<td>341.97</td>
<td>2.66</td>
</tr>
<tr>
<td>3</td>
<td>0.2</td>
<td>552.50</td>
<td>2.60</td>
</tr>
<tr>
<td>4</td>
<td>0.3</td>
<td>691.37</td>
<td>2.57</td>
</tr>
<tr>
<td>5</td>
<td>0.4</td>
<td>781.83</td>
<td>2.53</td>
</tr>
<tr>
<td>6</td>
<td>0.5</td>
<td>895.90</td>
<td>2.49</td>
</tr>
<tr>
<td>7</td>
<td>0.6</td>
<td>1010.00</td>
<td>2.46</td>
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<tr>
<td>8</td>
<td>0.64</td>
<td>1050.00</td>
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<tr>
<td>9</td>
<td>0.7</td>
<td>1120.00</td>
<td>2.43</td>
</tr>
<tr>
<td>10</td>
<td>0.8</td>
<td>1240.00</td>
<td>2.40</td>
</tr>
<tr>
<td>11</td>
<td>0.9</td>
<td>1360.00</td>
<td>2.37</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>1480.00</td>
<td>2.35</td>
</tr>
</tbody>
</table>

Normal force envelope
Note: diagram not to scale
RESULTS AND DISCUSSION OF RESULTS

Performance of models

Effect of $\beta$ on internal forces in the shotcrete lining

Effect of $\beta$ on total deformation in the tunnel

Relationship between inner forces and deformations
RESULTS AND DISCUSSION OF RESULTS

**Loading -2- Excavation**

**Stresses around excavation**

- pressure reduction in the rock mass
- transfer of stresses
- Reduction in deformation due to pressure transfer.

**Loading -3- Shotcrete lining**

**Stresses around shotcrete**

- shotcrete becomes a load bearing member.
- redistribution of stresses
- stress concentration increases due to confinement.
- stresses becomes negligible at a distance of about 3 times tunnel radius
- 12% reduction in deformation
- 25% of rock pressure taken by the shotcrete.
- rock around shotcrete in plastic point.
RESULTS AND DISCUSSION OF RESULTS

Sensitivity analysis

Effect of thickness variation on axial forces in the shotcrete

- Increase in thickness, increase in stiffness and normal comp. stresses at $E=constant$ produce increase in inner forces.

- Moment of resistance tend to increase with forces

- The forces reduced the impact of pressure from rock mass,

- Part of 3D arching effect produces deformation and stresses in shotcrete

- Decrease in total deformation unlike unsupported tunnel.

Effect of thickness variation on liner deformation
RESULTS AND DISCUSSION OF RESULTS

Loading- 4- Final lining installation

• Final lining is not subjected to any significant stresses

• Stresses in lining can be attributed to self weight of lining

• Stresses are maximum at extrados and minimum at intrados.

• Normal stresses and shear stresses at the interface boundary are negligible.
RESULTS AND DISCUSSION OF RESULTS

Loading - 5 – Temperature and shrinkage effect

**Volumetric strain calculation:**

\[
\text{The } \% \text{ volumetric strain } (e_v) = \alpha \Delta T \times 100\% = 0.022\%
\]

\[\text{where } \alpha = 1.2 \times 10^{-5}/\degree \text{C and } \Delta T = 15 \degree \text{C}\]

- Gap formation under 250 scale factor
- Zero normal stresses at the crown and sides of tunnel interface – no external forces.
- Interface as bond breaker
- Compressive normal stresses in the max range of 6kN/m² found at the invert.
- Shear stresses are negligible.

The gap indicates decoupling of the final lining from shotcrete due to temperature change – curing and initial filling with cold water.


RESULTS AND DISCUSSION OF RESULTS

Loading – 6 – Shotcrete decay

\[ \frac{E_c}{E_r} = 2 \text{ to } \frac{E_c}{E_r} = 0.2. \]

The analysis simulates the shotcrete element decay by reducing the bearing contribution of the shotcrete.

- Increase in stresses in the lining
- Increase in deformation.

- Forces in lining is approx. 30% of forces in shotcrete

- Stresses in lining is approx. 10% of shotcrete

- The lining becomes a load bearing in the long term.
RESULTS AND DISCUSSION OF RESULTS

Loading – 7 – Grouting

Contact grouting

The filling of gap by numerical simulation of injecting cement grout in the void between shotcrete and final lining was impossible.

The prestressing of rock mass behind shotcrete with 0.3% reconstituted the elements.

Contrary to expectation, the normal stress increased with volumetric strain.

Note: expected values are just arbitrary numbers
RESULTS AND DISCUSSION OF RESULTS

Loading – 7 – Grouting

Consolidation grouting

- increase the rock mass strength
- Increase the stiffness.
- Prestressing of the tunnel - increase external forces acting upon lining.
- Reduce permeability of the rock mass
- Liner becomes relatively tight.

0.2% volumetric strain $\approx$ 15 bars of injection pressure
RESULTS AND DISCUSSION OF RESULTS

Loading – 8 – Internal water pressure

• at 18 bars of pressure, cracks occur as the magnitude of tensile stress in the liner is increasing.

• With the prestressing, as π increases, the net pressure drive the water through the liner.
• The magnitude of increase in hydraulic pressure start to reduce.
• The hydraulic pressure generate uniform, all round counter-pressure and increase external pressure.

• The hydraulic pressure in the grouted rock mass tend to reach equilibrium value (equilibrium of flow).

• the increased external pressure decrease the gradient between internal and external pressure.
RESULTS AND DISCUSSION OF RESULTS

Loading – 8 – Internal water pressure

Consolidation analysis

Water flow analysis
RESULTS AND DISCUSSION OF RESULTS

Loading – 8 – Internal water pressure

Water flow analysis

Seepage losses without prestressing (18 bars)
RESULTS AND DISCUSSION OF RESULTS

Loading – 8 – Internal water pressure

\[
\frac{p_i - \frac{3}{4} \rho g r_i}{\rho w g} = \frac{q}{2\pi K_r} \ln \frac{q}{\pi K_r r_g} + \frac{q}{2\pi} \ln \left( \frac{r_g}{r_i} \right) + \frac{1}{K_g} \ln \left( \frac{r_g}{r_a} \right)
\]

Internal water pressure and seepage flow in pressure tunnel

Water losses in the pressure tunnel
CONCLUSIONS

• The hydraulic-mechanical interaction due to change in stress in cracked liner change permeability which results to change seepage flow in the rock zone.

• The stress field and seepage field affect each other while trying to attain a state of equilibrium.

• The overall assessment showed that the program is capable of evaluating the rock mass behaviour around pressure tunnels in terms of stresses and deformation

• a tool for faster simulation of 3D arching effect, assessing the performance of lining, predicting the effect of internal pressure on the lining, reach of seepage through lining to the surrounding rock mass as well as estimating the leakage in pressure tunnels.

• The program remained not independent in the modeling of prestressing as the volumetric strain needs to be related to the injection pressure using analytical method.
• The method will cost effective as reduce much more expensive steel lined section in power waterways.

• Above all, this work recommends the finite element program as a tool for observing and/or predicting phenomena in pressure.
THANK YOU

New buddies, new idea
Consolidation and Water flow Analysis

Governing equations are:

**Darcy’s equation:**

\[ \nabla p_w + \rho_w g + \varphi = 0 \]

Where \((g^T = 0, -g, 0)^T\) is a vector of gravitational acceleration.

\(\varphi\) is the vector of friction force per unit volume, between flowing fluid and soil skeleton.

\[ \varphi = -m^{int} q \]

\(q\) is the specific discharge (fluid velocity) and \(m^{int}\) is:

\[ m^{int} = \begin{bmatrix} \mu / \kappa_x & 0 & 0 \\ 0 & \mu / \kappa_y & 0 \\ 0 & 0 & \mu / \kappa_z \end{bmatrix} \]

\(\mu\) is the dynamic viscosity of the fluid and \(\kappa\) is the intrinsic permeability of the porous medium.
The basic form of darcy’s equation will be of form:

\[
q = \frac{k_i}{\rho_w g} \left( \nabla p_w + \rho_w g \right)
\]

Continuity equations:

\[
\nabla^T \left( \rho_w \frac{k_{rel}}{\rho_w g} k_{sat} (\nabla p_w + \rho_w g) \right) = -\frac{\partial}{\partial t} \left( \rho_w n_S \right)
\]

Mass of water flowing out from a control volume. Change in mass concentration

For steady state:

\[
\nabla^T \left( \rho_w \frac{k_{rel}}{\rho_w g} k_{sat} (\nabla p_w + \rho_w g) \right) = 0
\]

Deformation equation:

\[
\bar{L}^T \left[ \bar{M} (\bar{L} d\mathbf{u}) + S_\rho d\rho w m \right] + d\rho g = 0
\]

And

\[
d\sigma' = \bar{M} d\bar{\varepsilon}
\]

\(\bar{M}\) is the material stress – strain matrix

\(\bar{L}\) is the differential operator

\(\rho\) is the density of multiphase medium
Consolidation theory:

Biot's theory, under assumption of Darcy's law of fluid flows and elastic behaviour of soil skeleton \( \sigma = \sigma' + m(p_{steady} + p_{excess}) \)

Where \( m \) is a vector containing unit terms of normal stress components and zero terms for shear stress components

Further detail (see scientific manual)

Coupled problem (see PLAXIS Flow 2010)