Example Application 11

Multistage Tunnel Excavation and Support
Multi-Stage Tunnel Construction
Multistage Tunnel Conditions

Rock Mass Properties – Mohr-Coulomb Model

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>unit weight</td>
<td>27,000 N/m³</td>
</tr>
<tr>
<td>bulk modulus</td>
<td>0.555 GPa</td>
</tr>
<tr>
<td>shear modulus</td>
<td>0.417 GPa</td>
</tr>
<tr>
<td>cohesion</td>
<td>10,000 Pa</td>
</tr>
<tr>
<td>friction angle</td>
<td>33°</td>
</tr>
<tr>
<td>tensile strength</td>
<td>1000 Pa</td>
</tr>
</tbody>
</table>

In-Situ Stress State

\[ K_o = 0.5 \]
Rockbolt Properties

cross-sectional area $5.0 \times 10^{-4} \text{ m}^2$

spacing 1.0 m

Young’s modulus 2.05 GPa

tensile yield strength 0.5 MN

grout shear stiffness 15 GN/m/m

grout shear strength 800,000 N/m
### Shotcrete Liner Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus</td>
<td>5.28 GPa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.2</td>
</tr>
<tr>
<td>thickness</td>
<td>0.3 m</td>
</tr>
<tr>
<td>moment of inertia</td>
<td>$2.25 \times 10^{-3} \text{ m}^4$</td>
</tr>
<tr>
<td>compressive strength</td>
<td>10.0 MPa</td>
</tr>
<tr>
<td>tensile strength</td>
<td>1.0 MPa</td>
</tr>
</tbody>
</table>
Stress Relaxation due to Tunnel Advancement
# Tunnel Construction Sequence

<table>
<thead>
<tr>
<th>Percent Relaxation</th>
<th>Side Excavation (I &amp; II)</th>
<th>Top-heading Excavation (III)</th>
<th>Bench Excavation (IV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100%</td>
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</tr>
<tr>
<td>50%</td>
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<td></td>
</tr>
<tr>
<td>75%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Excavation Stages

- **Stage I:** right-side excavation
- **Stage II:** left-side excavation
- **Stage III:** top-heading excavation
- **Stage IV:** bench excavation

## Construction Steps

- **Step a:** initial excavation
- **Step b:** installation of rockbolt support
- **Step c:** installation of a shotcrete lining

Rockbolts are installed at a distance to the face corresponding to 50% relaxation of tunnel loads, and shotcrete lining is installed at a distance to the face corresponding to 75% relaxation of tunnel loads.
Modeling Procedure

Step 1 Generate model grid and assign material models and properties and boundary conditions to represent the in-situ conditions.

Step 2 Determine the initial in-situ stress state of the ground prior to construction.

Step 3 Perform an unsupported tunnel excavation calculation to develop a ground reaction curve for the given conditions.

Step 4a Excavate the right-side excavation with rockbolts installed after 50% relaxation of the tunnel load (construction step a).

Step 4b Install the shotcrete support after 75% relaxation of the tunnel load (construction step b).

Step 4c Relax the tunnel load 100% for complete excavation of the right-side (construction step c).

Step 5a-c Repeat construction steps a, b and c for excavation of the left side.

Step 6a-c Repeat construction steps a, b and c for excavation of the top heading.

Step 7a-c Repeat construction steps a, b and c for excavation of the bench.
**Step 1-1**  Draw model boundary with [Box] edge option in [Geometry Builder]
Step 1-2 Import TUNNEL.DXF, a sketch of tunnel excavation boundaries.
Step 1-3  Add construction lines to divide model into quad blocks.
Step 1-4 Add a box around tunnel to facilitate creation of quad blocks and control zoning.
**Step 1-5** Add additional construction lines to divide model into quad blocks
Step 1-6 Use [Cleanup] stage to clean up bad vertices and edges
Step 1-7 Check that model is divided into 4-sided blocks in [Blocks] stage. Extract 10 quad blocks for building FLAC grid by pressing [Build]. Press [OK] to exit the [Geometry builder].
Step 1-8 Enter the [Edit] tool. Select [Transform region] and right-click on the model. Select [Add and merge mirrored copy left] from the menu.
Step 1-9  The full tunnel geometry is created, as shown.
Step 1-10 Select the [Boundary] stage and assign standard boundary conditions using [Automatic boundary cond.] mode.
Step 1-11 Use manual zoning to create a fine mesh density in the bench excavation region
Step 1-12  Use density multiplier to create a uniform zoning around the tunnel
Step 1-13 Use the density multiplier to extend the uniform zoning to the model boundaries.
Step 1-14  Use [Adjust ratios] to gradually increase zone size away from the tunnel.
Step 1-15  Define regions for multi-stage excavation using [Define regions] mode in [Materials] stage
Step 16  In the [Assign] mode, click on [Database] and load in the MSTUNNEL.GMT material database
Step 1/17 Assign materials to regions in the [Assign] mode
Step 1-18  Click [OK] to exit the [Edit] tool, click [Execute] to create commands and send to FLAC, and click [Save] to save the model state (ms1.sav)
Step 2-1 Assign initial stress state

\[ S_{yy} = -1.589 \text{ MPa} \]

\[ K_0 = 0.5 \]
Step 2-2 Initialize stress state using the [Insitu]/[Initial] tool
Step 2-3 Assign gravity with the [Settings]/[Gravity] tool.
Step 2-4  Check that model is at equilibrium state using the [Run]/[Solve] tool.
Step 2-5  Save the state as ms2.sav.
Step 3-1 Excavate tunnel for ground reaction curve calculation in the [Material]/[Assign] tool by using the [Region] range to set null materials.
**Step 3-2** Initialize displacements to zero in the [In Situ]/[Initial] tool by pressing the Clear? [Displmt & velocity] button.
Step 3-3 Create a ground reaction table. FISH function closure.fis is used to calculate tunnel closure. Closure, closure, is defined here by the sum of the vertical displacement at the tunnel crown (at i=39,j=53) plus the invert (at i=39, j=21). Horizontal closure, closure_side, is also monitored as horizontal displacement at the left side (at i=21, j=37) plus the right side (at i=57, j=37).
Step 3-4 The FISH variable, closure, is recorded as a history by selecting [Fish>History] in the [Utility]/[History] tool.
**Step 3-5** The ground reaction table is generated using the [In Situ/Apply] tool. Select [Relax] and [Long] and drag the mouse along the tunnel boundary. Then, press [Assign] to open the Apply relax dialog. The boundary tractions will be reduced in 10 increments until reaching an end factor of 0.2 (i.e., 80% relaxation). The vertical closure versus tunnel relaxation is recorded to table 1 by checking the [Generate Ground Reaction Table] box, and entering Table No. 1. The horizontal closure versus tunnel relaxation is recorded to table 2.
Step 3-6  Calculate the effect of relaxation of the tractions around the tunnel using the [Run]/[Solve] tool.
Step 3-7 Plot the table of relaxation factor vs vertical closure. (Note that relaxation factor is the ratio of current tunnel traction to the initial tunnel traction.) Rockbolts will be installed at tunnel advance corresponding to 1.2 cm vertical closure (50% relaxation), and liner will be installed at tunnel advance corresponding to 2.8 cm vertical closure (75% relaxation). Save the state as ms3.sav.
Step 4-1 Create a new branch starting from ms2.sav and perform a side excavation by nulling mstunnel:right side region in [Material]/[Assign] tool.
Step 4-2  Initialize the displacements and velocities in the [In Situ]/[Initial] tool.
**Step 4-3**  Return to the [In Situ]\[Apply] tool and select [Relax] and [Long]. Drag the mouse around the tunnel side boundary. Press [Assign] to open the *Apply relax* dialog. Relax the tractions in 5 increments and set the end factor to 0.5 (50% relaxation).
Step 4-4  Record a stress history near the tunnel springline in the [Utility]/[History] tool.
Step 4-5  Select [Run]/[Solve] to relax the tractions around the side tunnel by 50%.
Step 4-6  Save the state as ms4.sav. The syy stress history plot, created in the [Plot]/[History] tool, indicates a gradual change in the stress resulting from the excavation.
Step 4-7  Import the sketch of the rockbolt pattern (rockbolts.dxf) in the [Build]/[Sketch] tool.
**Step 4-8** Using the rockbolt.dxf sketch as a background image, install nine rockbolts (with 5 segments each) around the right-side excavation using the [Structure]/[Rockbolt] tool. (Five segments are sufficient to place at least one rockbolt node within every zone along the bolt length.) Position rockbolts to coincide with the sketch of rockbolt pattern. (The rockbolt pattern sketch is made visible by right-clicking to open the drop-down menu and selecting [Show sketch].)
Step 4-9 Assign rockbolt properties in [Structure]/[SEProp] tool. (Note that a high value for element compressive yield strength is set to prevent compressive failure during initial transient load change.)
Fig. 4-10  Return to the [In Situ]/[Apply] tool, press [Relax] and drag the mouse along the side boundary again. Set the number of relaxation increments to 5 and set end factor to 0.5. The tractions are relaxed an additional 50%.
Step 4-11  Select [Run]/[Solve] to calculate the equilibrium state with rockbolt support for the side excavation. The state is saved as ms5.sav.
Step 4-12  Install liner around side excavation in [Structure]/[Liner] tool by dragging the mouse around the excavation boundary. Liner nodes are attached directly to the grid
Step 4-13  Assign liner properties in [Structure]/[SEProp] tool
Step 4-14 Return to the [In Situ]/[Apply] tool and relax tractions 100% (end factor = 0.0) in 5 increments.
Step 4-15 Use [Run]/[Solve] and solve to equilibrium. Save the state as ms6.sav.
Step 4-16  The moment-thrust diagram for the liner is created with the [Plot]/[Mom-P] tool.
Step 5-1  Excavate the left side using the [Material]/[Assign] tool.
Step 5-2 Return to the [In Situ]/[Apply] tool and select [Relax]. Press [Long] path and drag the mouse around the tunnel side boundary. Press [Assign] to open the Apply relax dialog. Relax the tractions in 5 increments and set the end factor to 0.5 (50% relaxation).
Step 5-3  Record a stress history near the left-side tunnel springline in the [Utility]/[History] tool.
Step 5-4  Select [Run]/[Solve] to relax the tractions around the left-side tunnel by 50%.
Step 5-5  Plot stress tensors and displacement vectors in the [Plot]/[Model] tool. Save the state as ms7.sav.
**Step 5-6**  Using the rockbolt.dxf sketch, install nine rockbolts (with 5 segments each) around the left-side excavation in the [Structure]/[Rockbolt] tool.
Step 5-7 Return to the [In Situ]/[Apply] tool, press [Relax] and [Long] path and drag the mouse along the side boundary. Press [Assign] to open the Apply relax dialog. Relax the tractions in 5 increments and set the end factor to 0.5 (75% relaxation).
Step 5-8 Select [Run]/[Solve] to calculate the equilibrium state with the rockbolt support.
Step 5-9  Save the state as ms8.sav.
Step 5-10  Install liner around the left-side excavation in [Structure]/[Liner] tool by dragging the mouse around the excavation boundary. Liner nodes are attached directly to the grid.
Step 5-11 Return to the [In Situ]/[Apply] tool and relax tractions 100% (end factor = 0.0) in 5 increments.
Step 5-12 Use [Run]/[Solve] and calculate the equilibrium state.
Step 5-13  Save the state as ms9.sav.
Step 5-14  Check the moment-thrust diagram.
Step 6-1 Perform the top excavation by nulling the top excavation region in the [Material]/[Assign] tool.
**Step 6-2** Also, delete liner segments between the sides and top excavations in the [Structure]/[Segments] tool.
Step 6-3  Tractions are reduced by 50% in 5 increments along the top excavation boundary in the [In Situ]/[Apply] tool.
Step 6-4 Calculate equilibrium using the [Run]/[Solve] tool.
Step 6-5  Save the state as ms10.sav.
Step 6-6 Using the rockbolt.dxf sketch as a background image, install 8 rockbolts (with 5 segments each) around the top excavation in the [Structure]/[Rockbolt] tool.
Step 6-7  Tractions are reduced by an additional 50% in 5 increments along the top excavation boundary in the [In Situ]/[Apply] tool.
Step 6-8  Calculate equilibrium with tractions relaxed 75% using the [Run]/[Solve] tool.
Step 6-9  Save this state as ms11.sav.
Step 6-10  Install liner around top excavation in [Structure]/[Liner] tool
Step 6-11  Tractions are reduced 100% \((r_{stop} = 0.0)\) in 5 increments along the top excavation boundary in the [In Situ]/[Apply] tool.
Step 6-12 Calculate equilibrium with tractions relaxed 100% using the [Run]/[Solve] tool.
Step 6-13  Save this state as ms12.sav.
Step 6-14  Check the moment-thrust diagram.
Step 7-1 Excavate the bench using the [Material]/[Assign] tool.
Step 7-2  Delete liner segments between the bench and side excavation in the [Structure]/[Segments] tool.
Step 7-3  Relax tractions along bench excavation boundary by 75% using the [In Situ]/[Apply] tool.
Step 7-4  Calculate equilibrium with tractions relaxed 75% using the [Run]/[Solve] tool.
Step 7-5  Save this state as ms13.sav
**Step 7-6** Install liner along bench excavation boundary in [Structure]/[Liner] tool.
Step 7-7 Relax tractions along bench boundary 100% in the [In Situ]/[Apply] tool.
Step 7-8  Solve to equilibrium with tractions relaxed 100% along bench excavation.
Step 7-9  Save this state as ms14.sav.
Step 7-10  Check the moment-thrust diagram.
**Step 7-11** Surface settlement after completion of Step 7 using SETTLE.FIS (Gridpoint I,j values are adjusted to correspond to values along the top of grid.) Save the state as ms15.sav.