7 EXCAVATION OF AN NATM TUNNEL

This tutorial illustrates the use of PLAXIS for the analysis of the construction of a NATM tunnel. The NATM is a technique in which ground exposed by excavation is stabilised with shotcrete to form a temporary lining.

![Figure 7.1 Geometry of the project](image)

Objectives:
- Modelling the construction of an NATM tunnel using the Deconfinement method.
- Using Gravity loading to generate initial stresses.

7.1 INPUT

General settings
- Start the Input program and select Start a new project from the Quick select dialog box.
- In the Project tabsheet of the Project properties window, enter an appropriate title.
- In the Model tabsheet make sure that Model is set to Plane strain and that Elements is set to 15-Noded.
- Define the limits for the soil contour as \( x_{\text{min}} = -50.0 \), \( x_{\text{max}} = 50.0 \), \( y_{\text{min}} = 0.0 \) and \( y_{\text{max}} = 35.0 \).

Definition of soil stratigraphy
The basic stratigraphy will be created using the Borehole feature. In the model 11 m of the Clay-limestone layer is considered. The bottom of this layer is considered as reference in y direction (\( y_{\text{min}} = 0 \)). To define the soil stratigraphy:
- Create the first borehole \( x = -22.0 \).
- In the Modify soil layers window create three soil layers. The layer number 1 has a depth equal to zero in Borehole_1. Assign 24.00 to Top and Bottom of the layer 1. The layer number 2 lies from Top = 24.00 to Bottom = 11.00. The layer number 3 lies from Top = 11.00 to Bottom = 0.00.
- Click the Boreholes button at the bottom of the Modify soil layers window.
• In the appearing menu select the Add option. The Add borehole window pops up.
• Specify the location of the second borehole (X = -14).
• Note that the soil layers are available for Borehole_2. The layer number 1 has a depth equal to zero in Borehole_2. However as the depth of layer 2 is higher assign 30.00 to Top and Bottom of the layer 1. The layer number 2 lies from Top = 30.00 to Bottom = 11.00. The layer number 3 lies from Top = 11.00 to Bottom = 0.00.
• Create a new borehole (Borehole_3) at X = -7.
• In Borehole_3 the layer number 1 has a non-zero thickness and lies from Top = 35.00 to Bottom = 30.00. The layer number 2 lies from Top = 30.00 to Bottom = 11.00. The layer number 3 lies from Top = 11.00 to Bottom = 0.00.
• In all the boreholes the water level is located at y = 0 m.
• Specify the soil layer distribution as shown in Figure 7.2.
• Create soil material data sets according to Table 7.1 and assign them to the corresponding layers (Figure 7.2).
• Close the Modify soil layers window and proceed to the Structures mode to define the structural elements.

Note that the layering of the model left from the first borehole is based on Borehole_1 and the layering right from the last borehole is based on Borehole_3. Hence, no borehole is needed at x = -50 m or x = 50 m.

Table 7.1 Material properties of the soil layers

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Name</th>
<th>Top layer</th>
<th>Clay-siltstone</th>
<th>Clay-limestone</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>General</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material model</td>
<td>Model</td>
<td>Hardening soil</td>
<td>Hoek-Brown</td>
<td>Hoek-Brown</td>
<td>-</td>
</tr>
<tr>
<td>Type of material behaviour</td>
<td>Type</td>
<td>Drained</td>
<td>Drained</td>
<td>Drained</td>
<td>-</td>
</tr>
<tr>
<td>Soil unit weight above phreatic level</td>
<td>(\gamma_{\text{unsat}})</td>
<td>20</td>
<td>25</td>
<td>24</td>
<td>kN/m(^3)</td>
</tr>
<tr>
<td>Soil unit weight below phreatic level</td>
<td>(\gamma_{\text{sat}})</td>
<td>22</td>
<td>25</td>
<td>24</td>
<td>kN/m(^3)</td>
</tr>
<tr>
<td>Initial void ratio</td>
<td>(e_{\text{int}})</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>-</td>
</tr>
<tr>
<td>Parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Secant stiffness in standard drained triaxial test</td>
<td>(E_{\text{ref}}^{\text{50}})</td>
<td>4.0 (\cdot) 10(^4)</td>
<td>-</td>
<td>-</td>
<td>kN/m(^2)</td>
</tr>
<tr>
<td>Tangent stiffness for primary oedometer loading</td>
<td>(E_{\text{ref}}^\text{oed})</td>
<td>4.0 (\cdot) 10(^4)</td>
<td>-</td>
<td>-</td>
<td>kN/m(^2)</td>
</tr>
<tr>
<td>Unloading / reloading stiffness</td>
<td>(E_{\text{ref}}^\text{ur})</td>
<td>1.2 (\cdot) 10(^5)</td>
<td>-</td>
<td>-</td>
<td>kN/m(^2)</td>
</tr>
<tr>
<td>Power for stress-level dependency of stiffness</td>
<td>(m)</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>(E_{\text{rm}})</td>
<td>-</td>
<td>1.0 (\cdot) 10(^6)</td>
<td>2.5 (\cdot) 10(^6)</td>
<td>kN/m(^2)</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>(\nu_{\text{ur}})</td>
<td>0.2</td>
<td>0.25</td>
<td>0.25</td>
<td>-</td>
</tr>
<tr>
<td>Uniaxial compressive strength</td>
<td>(\sigma_{\text{ci}})</td>
<td>-</td>
<td>2.5 (\cdot) 10(^4)</td>
<td>5.0 (\cdot) 10(^4)</td>
<td>kN/m(^2)</td>
</tr>
<tr>
<td>Material constant for the intact rock</td>
<td>(m_i)</td>
<td>-</td>
<td>4.0</td>
<td>10.0</td>
<td>-</td>
</tr>
<tr>
<td>Geological Strength Index</td>
<td>GSI</td>
<td>-</td>
<td>40.0</td>
<td>55.0</td>
<td>-</td>
</tr>
<tr>
<td>Disturbance factor</td>
<td>(D)</td>
<td>-</td>
<td>0.2</td>
<td>0.0</td>
<td>-</td>
</tr>
<tr>
<td>Cohesion</td>
<td>(c_{\text{ref}})</td>
<td>10.0</td>
<td>-</td>
<td>-</td>
<td>kN/m(^3)</td>
</tr>
<tr>
<td>Friction angle</td>
<td>(\varphi')</td>
<td>30</td>
<td>-</td>
<td>-</td>
<td>°</td>
</tr>
<tr>
<td>Dilatancy parameter</td>
<td>(\psi_{\text{max}})</td>
<td>-</td>
<td>30.0</td>
<td>35.0</td>
<td>°</td>
</tr>
<tr>
<td>Dilatancy parameter</td>
<td>(\sigma_{\psi})</td>
<td>-</td>
<td>400</td>
<td>1000</td>
<td>kN/m(^2)</td>
</tr>
<tr>
<td>Interfaces</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interface strength</td>
<td>(R_{\text{inter}})</td>
<td>Rigid</td>
<td>Manual</td>
<td>Rigid</td>
<td>-</td>
</tr>
<tr>
<td>Strength reduction factor</td>
<td>-</td>
<td>1.0</td>
<td>0.5</td>
<td>1.0</td>
<td>-</td>
</tr>
</tbody>
</table>
7.1.1 DEFINITION OF TUNNEL

In the Structures mode click the Create tunnel button in the side toolbar and click on (0.0 16.0) in the drawing area to specify the location of the tunnel. The Tunnel designer window pops up.

• The default shape option (Free) will be used. The default values of the rest of the parameters defining the location of the tunnel in the model are valid as well.

• Click on the Segments tab.

Click the Add button in the side toolbar.

• In the segment info box set the Segment type to Arc. Set Radius to 10.4 m and the Segment angle to 22°. The default values of the remaining parameters are valid.

Add a new arc segment. Set Radius to 2.4 m and the Segment angle to 47°. The default values of the remaining parameters are valid.

Add a new arc segment. Set Radius to 5.8 m and the Segment angle to 50°. The default values of the remaining parameters are valid.

Click the Extend to symmetry axis option to complete the right half of the tunnel. A new arc segment is automatically added closing the half of the tunnel.

Click the Symmetric close button to complete the tunnel. Four new arc segment are automatically added closing the tunnel.

• Click on the Subsections tab.

Add a new subsection. This subsection will be used to separate the top heading (upper excavation cluster) from the invert (lower excavation cluster).

• Set Offset 2 to 3 m. Select the Arc option from the Segment type drop-down menu. Set Radius to 11 m and Segment angle to 360°.
Select all the geometric entities in the slice.

Click the *Intersect* button.

Delete the part of the subsection outside of the slice by selecting it in the display area and clicking the *Delete* button in the side toolbar.

- Proceed to the *Properties* mode.
- Multi-select the polycurves in the display area and select the *Create plate* option in the appearing menu.
- Press <Ctrl> + <M> to open the *Material sets* window. Create a new material dataset for the created plates according to Table 7.2.
- Multi-select the created plates and in the *Selection explorer*, assign the material *Lining* to the selected plates.

Table 7.2 Material properties of the plates

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Name</th>
<th>Lining</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material type</td>
<td>Type</td>
<td>Elastic; Isotropic</td>
<td>-</td>
</tr>
<tr>
<td>Normal stiffness</td>
<td>(EA)</td>
<td>(6.0 \times 10^6)</td>
<td>kN/m</td>
</tr>
<tr>
<td>Flexural rigidity</td>
<td>(EI)</td>
<td>(2.0 \times 10^4)</td>
<td>kNm²/m</td>
</tr>
<tr>
<td>Weight</td>
<td>(w)</td>
<td>5.0</td>
<td>kN/m/m</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>(\nu)</td>
<td>0.15</td>
<td>-</td>
</tr>
</tbody>
</table>

- Assign negative interfaces to the lines defining the shape of the tunnel (not the excavation levels). The final tunnel view in the *Tunnel designer* window is given in Figure 7.4.

- Click on *Generate* to update the tunnel in the model and press *Close*. 
7.2 MESH GENERATION

The default global coarseness parameter (Medium) can be accepted in this case.

- Proceed to the Mesh mode.

Create the mesh. Use the default option for the Element distribution parameter (Medium).

View the mesh. The generated mesh is shown in Figure 7.5.

- Click on the Close tab to close the Output program.

7.3 CALCULATIONS

To simulate the construction of the tunnel it is clear that a staged construction calculation is needed.
• Click on the *Staged construction* tab to proceed with the definition of the calculation phases.

  The initial phase has already been introduced. Note that the soil layers are not horizontal. It is not recommended in this case to use the *K0 procedure* to generate the initial effective stresses. Instead *Gravity loading* will be used. This option is available in the *General* subtree of the *Phases* window.

• Water will not be considered in this example. The general phreatic level should remain at the model base.

• Make sure that the tunnel is inactive.

### 7.3.1 SIMULATION OF THE CONSTRUCTION OF THE TUNNEL

A staged construction calculation is needed in which the tunnel lining is activated and the soil clusters inside the tunnel are deactivated. The calculation phases are *Plastic analyses*, *Staged construction*. The three-dimensional arching effect is emulated by using the so-called *β*-method. The idea is that the initial stresses $p_k$ acting around the location where the tunnel is to be constructed are divided into a part $(1 - \beta) p_k$ that is applied to the unsupported tunnel and a part *Deconfinement* method that is applied to the supported tunnel. To apply this method in PLAXIS, one can use the *Deconfinement* option, which is available for each de-activated soil cluster in the model explorer. *Deconfinement* is defined as the aforementioned factor $(1 - \beta)$. For example, if 60% of the initial stresses in a de-activated soil cluster should disappear in the current calculation phase (so the remaining 40% is to be considered later), it means that the *Deconfinement* $(1 - \beta)$ parameter of that inactive cluster should be set to 0.6. The value of *Deconfinement* can be increased in subsequent calculation phases until it reaches 1.0.

To define the calculation process follow these steps:

**Phase 1: First tunnel excavation (deconfinement)**

• Add a new calculation phase.

  • In the *Staged construction* mode deactivate the upper cluster in the tunnel. Do NOT activate the tunnel lining. The model for Phase 1 is displayed in Figure 7.6.

  • While the de-activated cluster is still selected, set in the *Selection explorer* *Deconfinement* $(1 - \beta)$ to 60%.

![Figure 7.6 Configuration of Phase 1](image)
**Phase 2: First (temporary) lining**

Add a new calculation phase.

- In the *Staged construction* mode activate the lining and interfaces of the part of the tunnel excavated in the previous phase (Figure 7.7).
- Select the de-activated cluster. In the *Selection explorer* set *Deconfinement* to 100%.

![Figure 7.7 Configuration of Phase 2](image)

**Phase 3: Second tunnel excavation (deconfinement)**

Add a new calculation phase.

- In the *Staged construction* mode deactivate the lower cluster (invert) and the temporary lining in the middle of the tunnel (Figure 7.8).
- While the lower de-activated cluster is still selected, set in the *Selection explorer* *Deconfinement* to 60%.

![Figure 7.8 Configuration of Phase 3](image)

**Phase 4: Second (final) lining**

Add a new calculation phase.

- Activate the remaining lining and interfaces. All the plates and interfaces around the full tunnel are active (Figure 7.9).
- Select the lower de-activated cluster. In the *Selection explorer* set *Deconfinement* to 100%.
- Select a node at the slope crest point and the tunnel crest. These points might be of...
interest to evaluate the deformation during the construction phases.

Calculate the project.

Save the project after the calculation has finished.

7.4 RESULTS

After the calculation, select the last calculation phase and click the View calculation results button. The Output program is started, showing the deformed mesh at the end of the calculation phases (Figure 7.10).

To display the bending moments resulting in the tunnel:

- To select the lining of all the tunnel sections, click the corresponding button in the side toolbar and drag the mouse to define a rectangle where all the tunnel sections are included. Select the Plate option in the appearing window (Figure 7.11) and press View. Note that the tunnel lining is displayed in the Structures view.
- From the Forces menu select the Bending moment M option. The result, scaled by a factor of 0.5 is displayed in Figure 7.12.
Figure 7.11  Select structures window

Figure 7.12  Resulting bending moments in the NATM tunnel