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.
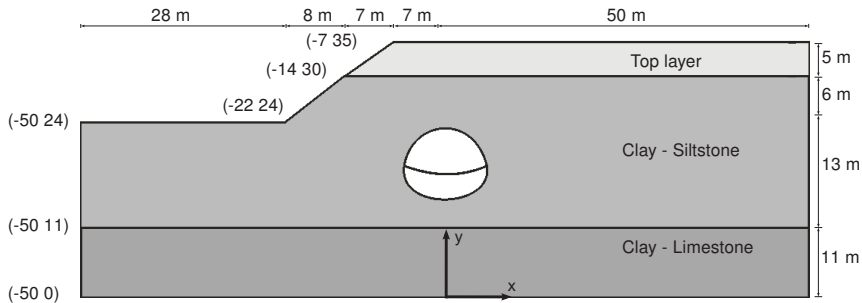

Figure 7.1 Geometry of the project

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 $x_{min} = -50.0$, $x_{max} = 50.0$, $y_{min} = 0.0$ and $y_{max} = 35.0$.

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 ($y_{min} = 0$). 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 thicknesss 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

Parameter	Name	Top layer	Clay-siltstone	Clay-limestone	Unit
General					
Material model	*Model*	Hardening soil	Hoek-Brown	Hoek-Brown	-
Type of material behaviour	*Type*	Drained	Drained	Drained	-
Soil unit weight above phreatic level	γ_{unsat}	20	25	24	kN/m^3
Soil unit weight below phreatic level	γ_{sat}	22	25	24	kN/m^3
Initial void ratio	e_{init}	0.5	0.5	0.5	-
Parameters					
Secant stiffness in standard drained triaxial test	E_{50}^{ref}	$4.0 \cdot 10^4$	-	-	kN/m^2
Tangent stiffness for primary oedometer loading	E_{oed}^{ref}	$4.0 \cdot 10^4$	-	-	kN/m^2
Unloading / reloading stiffness	E_{ur}^{ref}	$1.2 \cdot 10^5$	-	-	kN/m^2
Power for stress-level dependency of stiffness	m	0.5	-	-	-
Young's modulus	E'_{rm}	-	$1.0 \cdot 10^6$	$2.5 \cdot 10^6$	kN/m^2
Poisson's ratio	ν'_{ur}	0.2	0.25	0.25	-
Uniaxial compressive strength	σ_{ci}	-	$2.5 \cdot 10^4$	$5.0 \cdot 10^4$	kN/m^2
Material constant for the intact rock	m_i	-	4.0	10.0	-
Geological Strength Index	GSI	-	40.0	55.0	-
Disturbance factor	D	-	0.2	0.0	-
Cohesion	c'_{ref}	10.0	-	-	kN/m^2
Friction angle	φ'	30	-	-	°
Dilatancy parameter	ψ_{max}	-	30.0	35.0	°
Dilatancy parameter	σ_ψ	-	400	1000	kN/m^2
Interfaces					
Interface strength	—	Rigid	Manual	Rigid	-
Strength reduction factor	R_{inter}	1.0	0.5	1.0	-
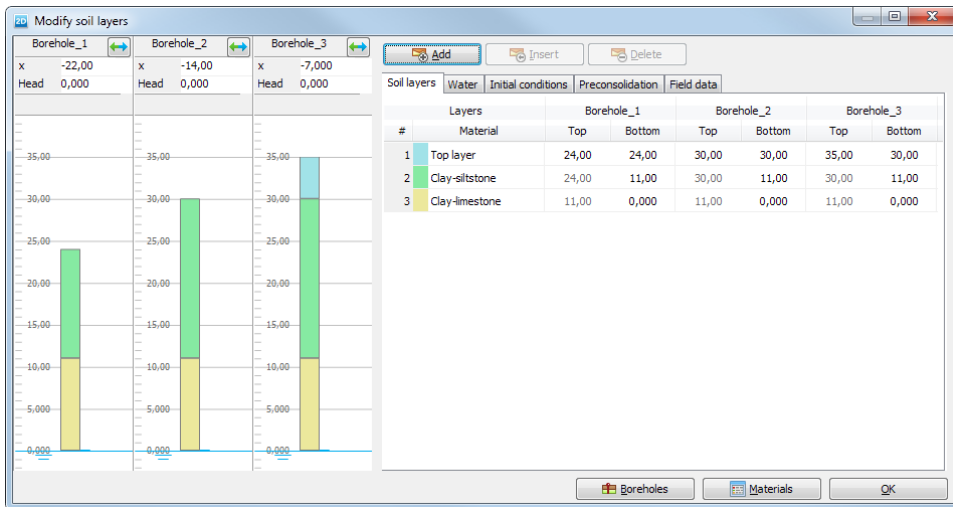
Figure 7.2 Soil layer distribution

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 °.
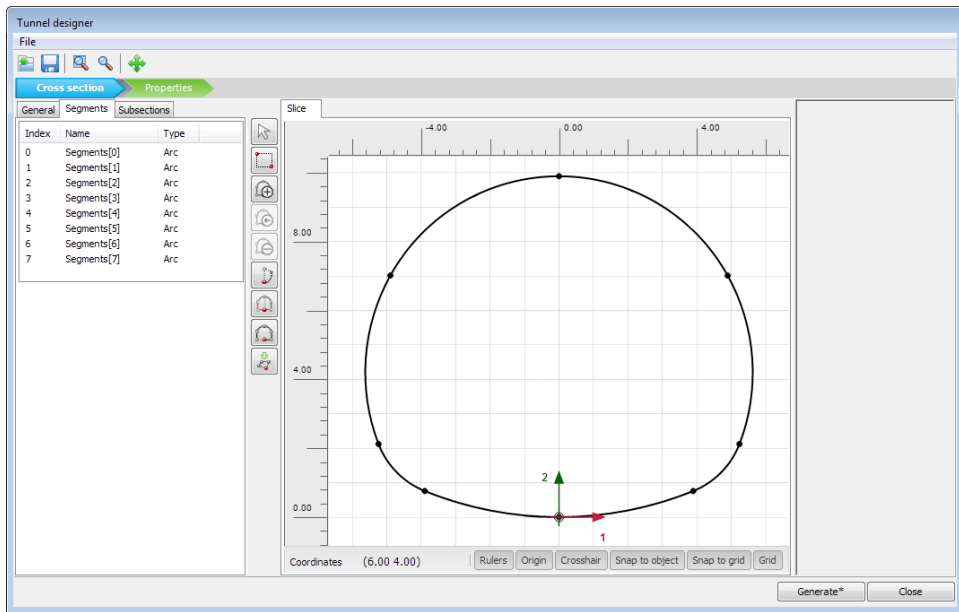
Figure 7.3 Segments in the tunnel cross section

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

Parameter	Name	Lining	Unit
Material type	*Type*	Elastic; Isotropic	-
Normal stiffness	*EA*	$6.0 \cdot 10^6$	kN/m
Flexural rigidity	*EI*	$2.0 \cdot 10^4$	kNm^2/m
Weight	*w*	5.0	kN/m/m
Poisson's ratio	ν	0.15	-

- 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.

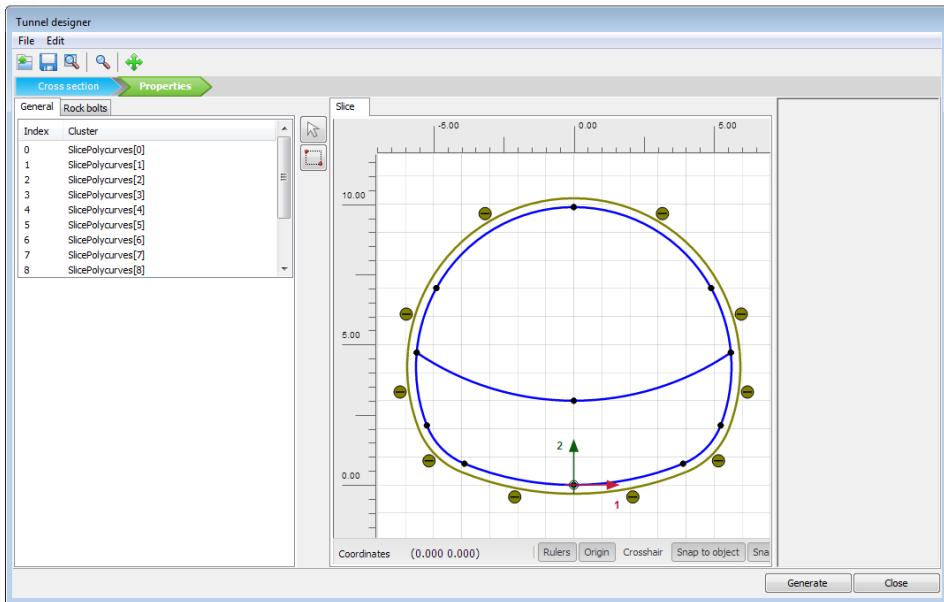- Click on *Generate* to update the tunnel in the model and press *Close*.

Figure 7.4 Final tunnel

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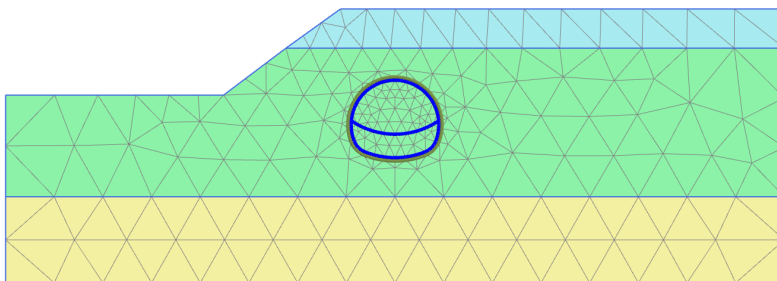
- Click on the *Close* tab to close the Output program.

Figure 7.5 The generated mesh

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%.
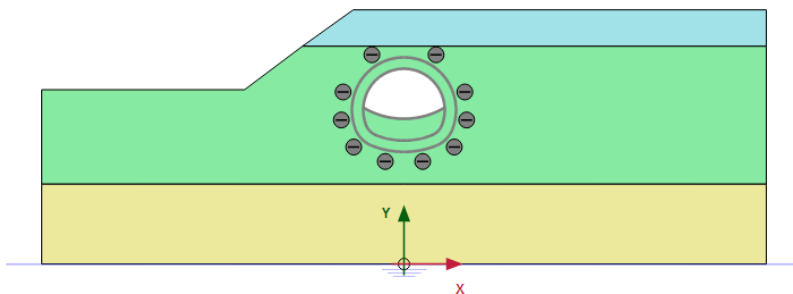

Figure 7.6 Configuration of Phase 1

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%.
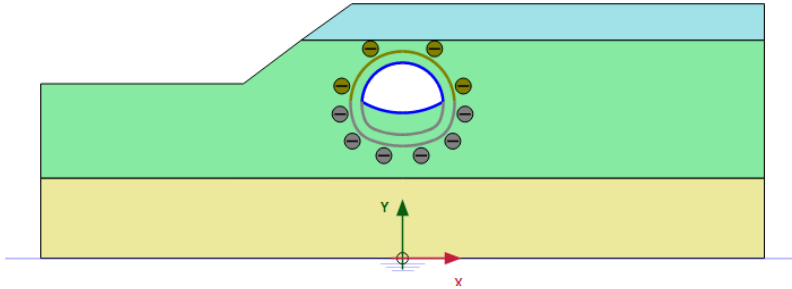

Figure 7.7 Configuration of Phase 2

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%.
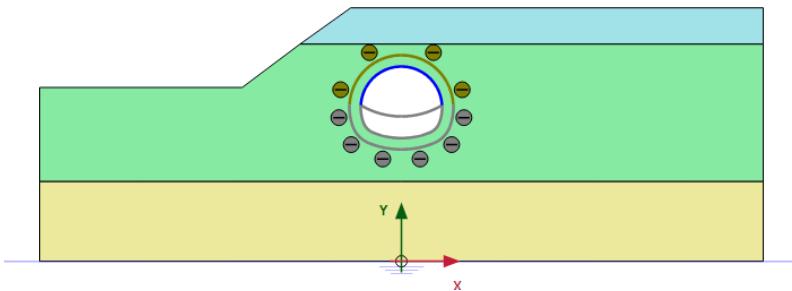

Figure 7.8 Configuration of Phase 3

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
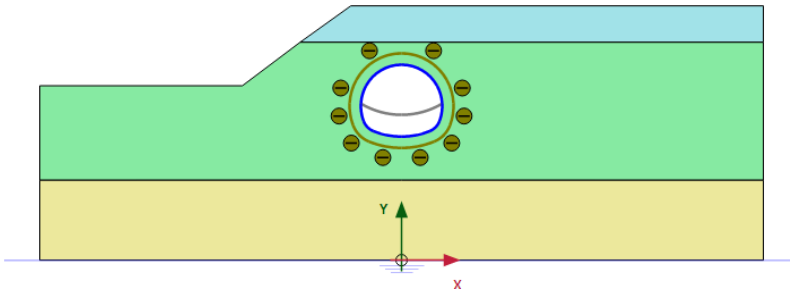
Figure 7.9 Configuration of Phase 4

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).
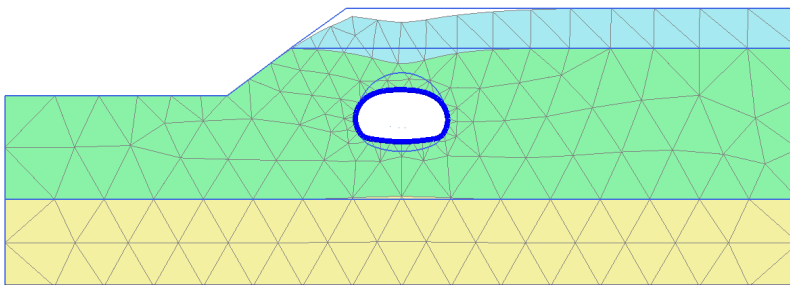

Figure 7.10 The deformed mesh at the end of the final calculation phase

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.
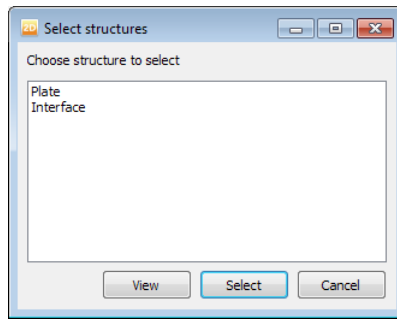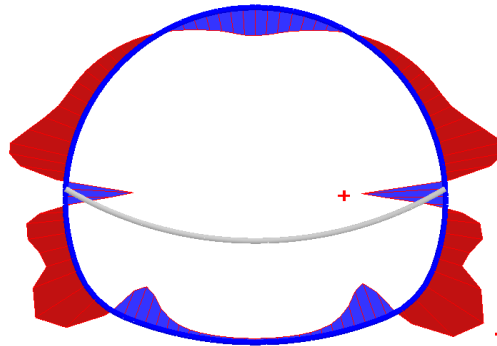
Figure 7.11 *Select structures* window

Figure 7.12 Resulting bending moments in the NATM tunnel