4

Stabilisation of a rock slope

4.1 Introduction

This tutorial illustrates the use of PLAXIS 2D for simulating the excavation of a road in a siltstone rock mass. This tutorial introduces the *Discontinuity* and *Cable* elements in order to model the road cut.

Objectives:

- Use the **Gravity loading** method to generate the initial stresses.
- Model the fault using the **Discontinuity** feature.
- Model the reinforcement with the **Cable** feature.
- Determine the influence of reinforcements on the factor of safety.

4.2 Geometry

In this tutorial, the geometry of a natural sloping ground is considered, in which a road cut slope is excavated. An unsupported excavation of the road cut will cause instability of the rock slope and therefore, the excavation is conducted in two stages. After the first 9 m of excavation, the excavated slope is reinforced with two rows of cables with 3 m spacing. The third row of cables is installed after the final excavation of 6 m is completed. The final excavation is then additionally reinforced with the construction of a 3 m retaining wall with backfill. The retaining wall acts a rock fall barrier to avoid the rocks rolling onto the road.

A fault at a dip angle of 38.7^{o} is located within the rock mass, and the fault daylights near the toe of the slope due to the excavation. The distance between the fault and the slope face at the top is 12 m. The geometry of the rock slope, along with the fault and reinforcements, is shown in Figure 4–1 (p. 73).

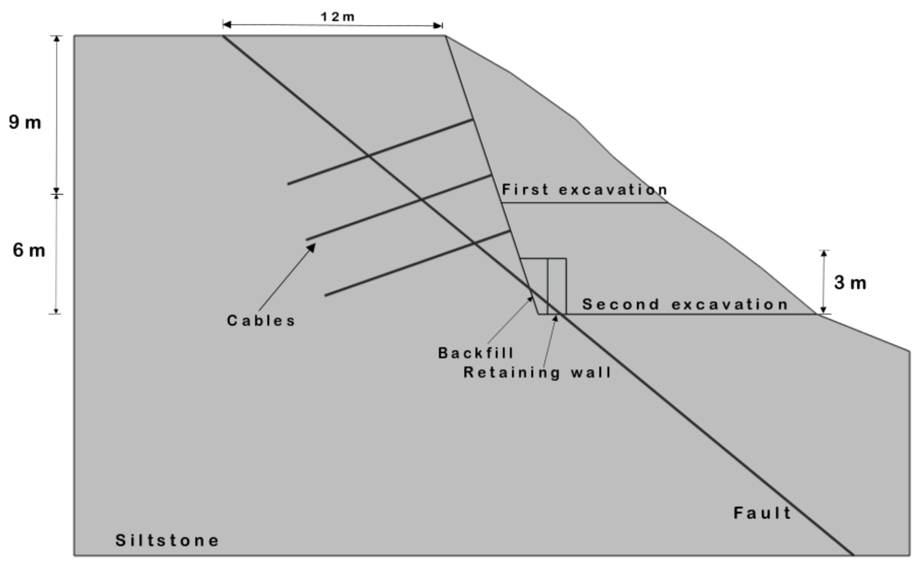

Figure 4–1: Geometry of the rock slope with reinforcement

4.3 Create a new project

To create a new project, follow the following steps:

1. Start the **Input program** and select **Start a new project** from the **Quick Start** dialog box.
2. In the **Project** tabsheet of the **Project properties** window, enter an appropriate title.
3. In the **Model** tabsheet keep the default options for **Model (Plane strain)**, and **Elements (15-Noded)**.
4. Set the model **Contour** to: x_{min} = 0 m, x_{max} = 45 m, y_{min} = -13 m and y_{max} = 15 m.
5. Keep the default values for units, constants, and general parameters and click **OK** to close the **Project properties** window.

4.4 Create and assign material data sets

In this tutorial, the rock mass is a siltstone modelled using the Hoek-Brown constitutive model. To create a material set for the rock mass, follow these steps:

1. Select the **Show materials** button and the **Material sets** window will pop up.
2. Click the **New** button in the **Material sets** window to create the data set as shown in the Table 4–1 (p. 74).

Table 4–1: Material properties of the siltstone

Parameter	Name	Value	Unit
General			
Soil model	-	Hoek Brown	-
Drainage type	-	Drained	-
Unsaturated unit weight	γ_{unsat}	24	kN/m^3
Saturated unit weight	γ_{sat}	24	kN/m^3
Mechanical			
Young's modulus	E_{rm}	$1 \cdot 10^6$	kN/m^2
Poisson's ratio	ν	0.25	-
Uni-axial compressive strength intact rock	$\lvert\sigma_{ci}\rvert$	$25 \cdot 10^3$	kN/m^2
Intact rock parameter	m_i	10	°
Geological strength index	GSI	39	-
Disturbance factor	D	0	-
Tension cut-off	-	True	-
Tensile strength	-	30	kN/m^2
Dilatancy angle	ψ_{max}	10	°
Dilatancy parameter	σ_ψ	50	kN/m^2

3. Select the created polygon and assign the Material to the soil polygon as shown in Figure 4–2 (p. 75).

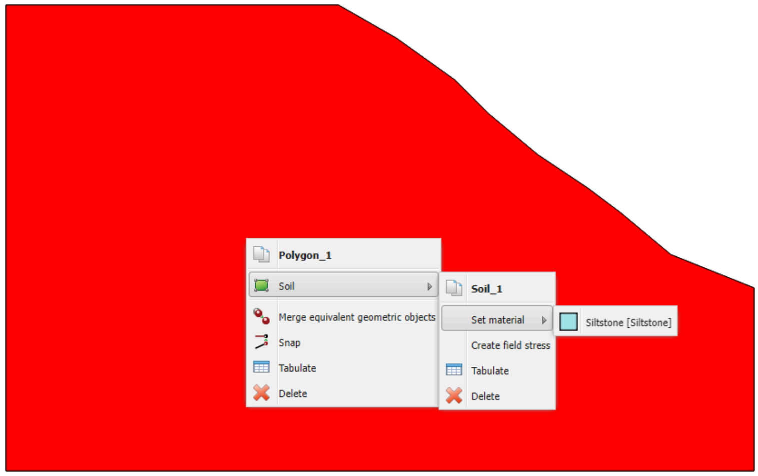

Figure 4–2: Assigning soil material to the created polygon

4.4.1 Define the rock mass stratigraphy

The geometry of the natural slope must be defined. To do so, follow these steps:

1. Click the **Structures** tab to proceed with the input of structural elements in the **Structures mode**.
2. Click the **Snapping options** button in the bottom toolbar. In the appearing window, set the **Spacing** to 0.5 and the **Number of snap intervals** to 1 as shown in Figure 4–3 (p. 75).

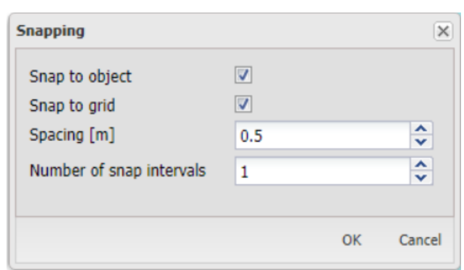

Figure 4–3: Window showing Snapping options

3. Click the **Create soil polygon** button in the side toolbar and select the **Create soil polygon** option.
4. Create the rock mass either in the command line or by clicking on points at coordinates:

```
(0 -13) (0 15) (20 15) (23.5 13) (27 10.5) (29 8.5) (32 6) (35 4) (37
 2.5) (40 0) (42.5 -1) (45 -2) (45 -13)
```

4.5 Define the structural elements

The creation of the fault, the cable elements, and the retaining wall are described below.

4.5.1 Define the fault

The fault is modelled using a discontinuity, and its material properties are defined in Table 4–2 (p. 76) below:

Table 4–2: Material properties of the fault (discontinuity)

Parameter	Name	Value	Unit
General			
Material model	-	Mohr-Coulomb	-
Drainage type	-	Drained	-
Mechanical			
Normal stiffness	k_n	$1 \cdot 10^6$	kN/m^3
Shear stiffness	k_s	$100 \cdot 10^3$	kN/m^3
Strength method	-	Peak	
Cohesion	c'	8	kN/m^2
Friction angle	φ'	20	o
Dilatancy angle	ψ	0	o
Consider gap closure	-	True	-

1. In the **Structures** mode, click the **Create line** button and select the **Create discontinuity** option .
2. Draw the discontinuity through the points (8 15) and (42 -13).
3. Select the discontinuity, then in the **Selection explorer** click on **Material**. This will display a drop-down list.
4. Click the **Add** button to create and assign a new material set for the discontinuity as shown in Figure 4–4 (p. 77).
5. Define the material data set for the discontinuity based on the properties listed in Table 4–2 (p. 76).

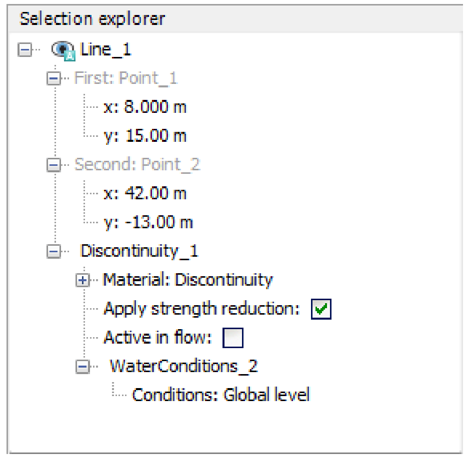

Figure 4–4: Material assignment of discontinuity in the Selection explorer

4.5.2 | Define the excavation of the road cut

The road cut is excavated in two stages with a total height of 15 m. The first excavation stage corresponds to the upper 9 m and the remaining 6 m is the second excavation stage. To define the excavation follow these steps:

1. Define the slope face of the road cut by drawing a line passing through points (20 15) and (25 0).
2. Define the bottom of excavation (roadway) by drawing a line through points (25 0) and (40 0).
3. Define the upper 9 m of excavation by drawing a horizontal line from (23 6) to the point where it intersects with the initial slope surface at (32 6).

4.5.3 | Define the cables

The reinforcement of the upper slope after the first excavation stage is achieved by creating two rows of 25.4 mm diameter grouted cable elements. The lower slope after the second excavation is reinforced by the third row of cables. The three rows of cables are 3 m above each other.

The coordinates of the cables and the material properties of the cables are listed in Table 4–3 (p. 77) and Table 4–4 (p. 78) respectively.

Table 4–3: Cable element coordinates

Cable location	First point	Second point
Top	(21.5 10.5)	(11.5 7)
Middle	(22.5 7.5)	(12.5 4)
Bottom	(23.5 4.5)	(13.5 1)

Table 4–4: Properties of the cables

Parameter	Name	Value	Unit
General			
Material type	-	Elastoplastic	-
Mechanical			
Cable bolt spacing	$L_{spacing}$	3	m
Cross section type	-	Predefined	-
Predefined cross section type	-	Solid circular beam	-
Diameter	D	0.0254	m
Stiffness	E	$98.6 \cdot 10^6$	kN/m^2
Compressive yield strength	$N_{p,comp}$	0	kN
Tensile yield strength	$N_{p,tens}$	548	kN
Shear stiffness	k_s	$15 \cdot 10^6$	kN/m^2
Strength distribution	-	Uniform	-
Cohesive strength	-	800	kN/m
Bond frictional angle	φ_{bond}	20	o
Failure surface perimeter	-	Predefined	-

1. In the side tool bar click on the **Create line** button and then select the **Create cable** option .
2. Draw a line from (21.5 10.5) to (11.5 7) to create the first row of cables.
3. Repeat step 2 to define the middle and bottom rows of the cables using the coordinates given in Table 4–3 (p. 77).
4. Click on **Material sets** **> Set type** > **Cables** and click on **New** to create the cable material data set based on the parameters listed in Table 4–4 (p. 78).
5. Multi-select all the cables in the drawing area, then in the **Selection explorer** assign the cable material by choosing the corresponding option in the **Material** drop-down menu.

4.5.4 Define the retaining wall and backfill

The retaining wall is modelled with a thickness of 1 m, constructed at the toe of the rock slope. The backfill is provided between the slope face and the retaining wall, with its thickness varying along the height. The material properties of the retaining wall and the backfill are shown in Table 4–5 (p. 79) and Table 4–6 (p. 79) respectively.

Table 4–5: Material properties of the retaining wall

Parameter	Name	Value	Unit
General			
Soil model	-	Mohr-Coulomb	-
Drainage type	-	Non-porous	-
Unsaturated unit weight	γ_{unsat}	24	kN/m^3
Mechanical			
Young's modulus	E_{ref}	27·10^6	kN/m^2
Poisson's ratio	ν	0.15	-
Cohesion	c_{ref}	500	kN/m^2
Friction angle	φ	35	°
Dilatancy angle	ψ	5	°
Tension cut-off	-	True	
Tensile strength	-	750	kN/m^2

Table 4–6: Material properties of the backfill

Parameter	Name	Value	Unit
General			
Soil model	-	Mohr-Coulomb	-
Drainage type	-	Drained	-
Unsaturated unit weight	γ_{unsat}	20	kN/m^3
Saturated unit weight	γ_{sat}	20	kN/m^3
Mechanical			
Young's modulus	E'_{ref}	100·10^3	kN/m^2
Poisson's ratio	ν	0.3	-
Cohesion	c'_{ref}	5	kN/m^2
Friction angle	φ'	45	°
Dilatancy angle	ψ	15	°

To define the geometry of the retaining wall and backfill, follow these steps:

1. Click on the **Create line** button and then select the **Create line** option .
2. Draw the retaining wall by defining lines through the points (25.5 0), (25.5 3) then (25.5 3), (26.5 3) and (26.5 3), (26.5 0).

3 Define the backfill by drawing a line from (25.5 3) at the retaining wall to the sloping face of the rock cut at (24 3).

4 Create the separate materials for the retaining wall and the backfill in the **Material sets** > **Soil and interfaces** using the parameters listed in Table 4–5 (p. 79) and Table 4–6 (p. 79). These materials will be assigned later in the **Staged construction** mode.

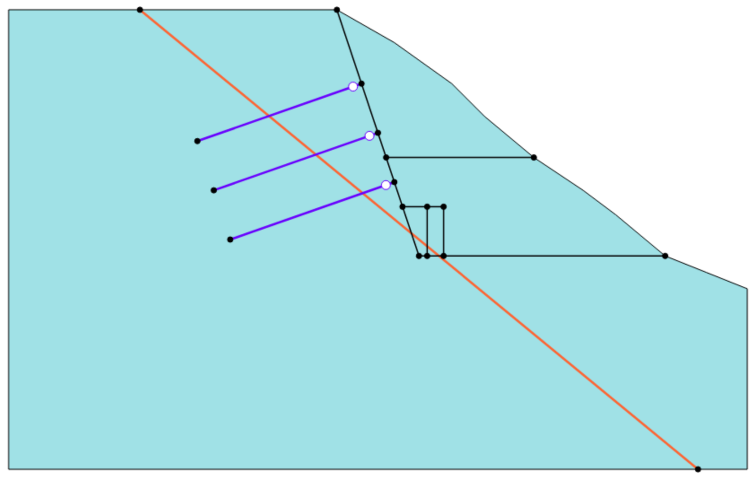

Figure 4–5: Final geometry of the model

4.6 Generate the mesh

1. Proceed to the **Mesh mode**.
2. Select the soil polygon enclosed between the lower slope, the discontinuity and the third cable row as shown in Figure 4–6 (p. 80). In the **Selection explorer** set the coarseness factor to 0.5.

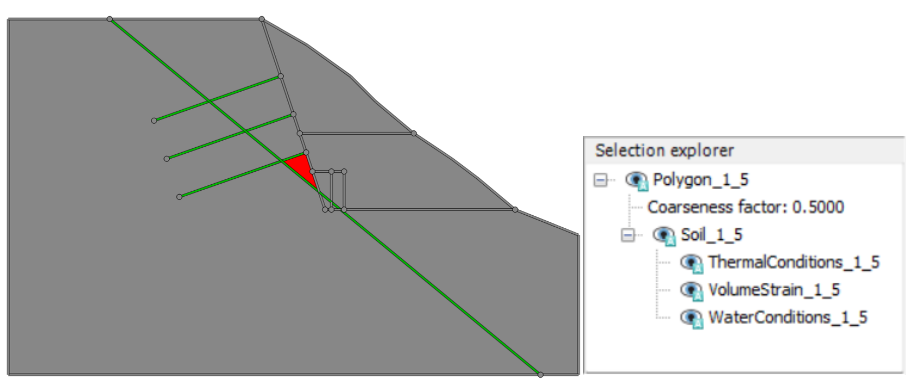

Figure 4–6: Refining the mesh for the selected soil polygon

3. Click the **Generate mesh** button to generate the mesh. The **Mesh options** window will appear.
4. Select the **Medium** option in the **Element distribution** list, and generate the mesh.
5. Click the **View mesh** button to view the mesh. The generated mesh is shown in Figure 4–7 (p. 81).
6. Select the **Close** button on the top left of the Output program to close the mesh view.

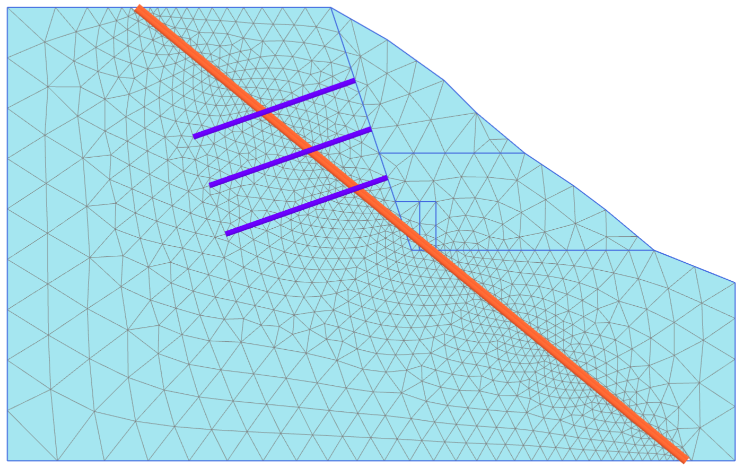

Figure 4–7: The generated mesh

> **Note:**
>
> In areas where large stress concentrations or large deformation gradients are expected, it is desirable to have a more accurate (finer) finite element mesh, whereas other parts of the geometry might not require a fine mesh. Such a situation often occurs when the geometry model includes edges or corners or structural objects. Local refinement is based on a local coarseness factor that can be specified for each geometry entity.

4.7 Define and perform the calculation

The construction of this project consists of the initial phase and eight phases.

- In the **Initial phase**, the initial stresses are generated using the **Gravity loading** method.
- **Phase 1** involves the excavation of the top 9 m.
- **Phase 2** includes the installation and connection of the first two rows of cables to the face of the rock cut.
- **Phase 3** entails a further 6 m excavation to reach the designed level of the roadway.
- **Phase 4** includes the installation of the third row of cable to the face of the rock cut.
- **Phase 5** involves the construction of the retaining wall near the toe of the road cut.
- **Phase 6** involves placing the backfill between the slope face and the retaining wall.

Additionally, a safety analysis is performed for both **Phase 3** and **Phase 6** respectively.

4.7.1 Initial phase: Initial conditions

The initial stress field is generated by means of the **Gravity loading** method.

1. Proceed to the **Staged construction** mode.
2. Activate all the polygons of the original sloping rock mass.
3. Activate the discontinuity by selecting it in the **Model explorer**. All other structural components (cables) should remain deactivated.

4. In the **Phases explorer**, double-click the initial phase and for **Calculation type** select the **Gravity loading** option. The other default parameters for the initial phase remain the same.
5. Click **OK** to close the **Phases** window.

> **Note:** The water conditions are not considered in this tutorial example, therefore the pore pressure calculation options are neglected.

4.7.2 Phase 1: First excavation stage

1. Click the **Add phase** button to create a new phase.
2. Deactivate the upper 9 m cluster of the excavation.

The model for the Phase 1 is shown in Figure 4–8 (p. 82) below:

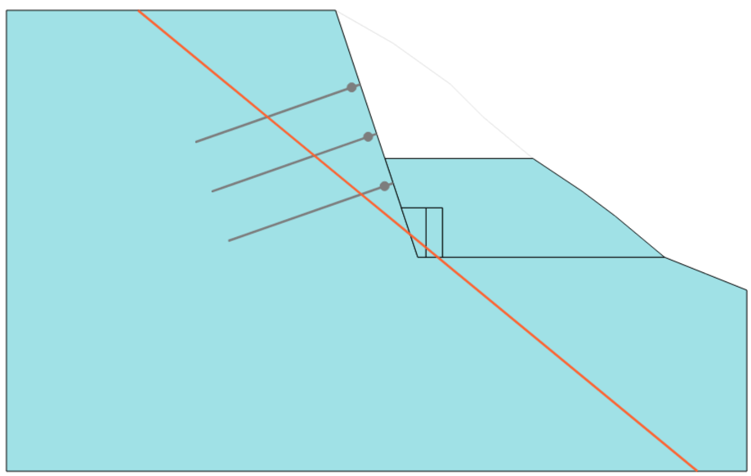

Figure 4–8: Configuration of Phase 1

4.7.3 Phase 2: Installation of the first two rows of cables

1. In the **Phases explorer**, click on the **Add phase** button .
2. Select the first two cables and activate them in the **Selection explorer** by clicking on the checkbox in front of the **Cables**.
3. In the **Selection explorer**, click the checkbox for **Adjust prestress** and assign a pre-stress force of **200 kN**.

The model for the Phase 2 is shown in Figure 4–9 (p. 83) below:

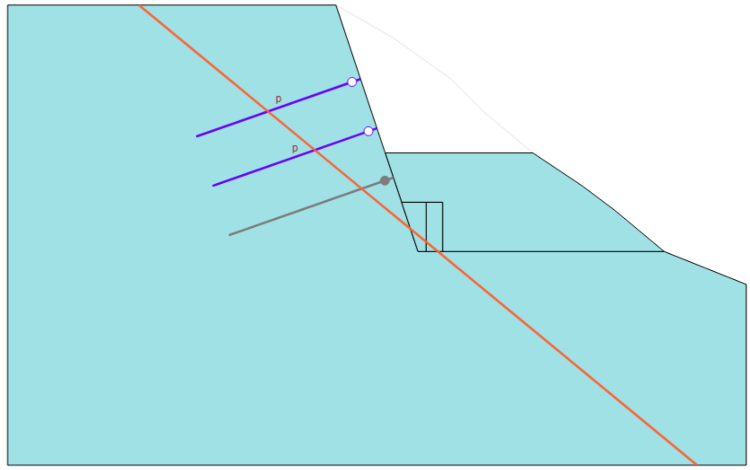

Figure 4–9: Configuration of Phase 2

> **Note:** When the **Adjust prestress** box is selected, a prestress force (per cable, force unit) is applied to the cable, while bond shear force is assumed to be zero [State: Unbonded]. When the **Adjust prestress** box is unselected, in a subsequent phase, it is assumed that bond interaction with the surrounding rock is developed [State: Bonded]. By default, in a calculation phase following a phase in which an anchor or a cable was prestressed, the prestress setting is NOT continued but the prestressing force is maintained. In this way, the existing cable force is used as a start condition and will develop 'naturally' based on changes of stresses and forces in the model.

4.7.4 Phase 3: Second excavation stage

1. Click the **Add phase** button to add a new phase.
2. Deactivate the soil polygon of the second excavation.
3. Deactivate the lines of the discontinuity that are inside the second excavation.

The model configuration for Phase 3 is shown in Figure 4–10 (p. 83) below:

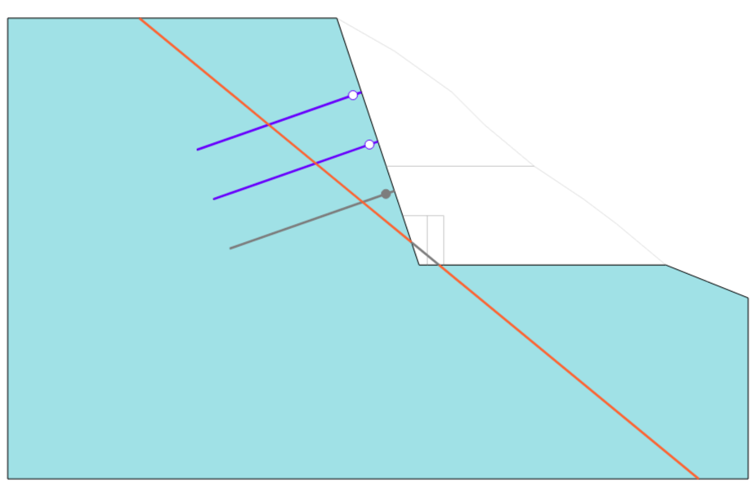

Figure 4–10: Configuration of Phase 3

4.7.5 | Phase 4: Installation of the third cable

1. Click the **Add phase** button to create a new phase.
2. Select the third cable and activate it in the **Selection explorer** by clicking on the checkbox in front of the **Cables**.
3. In the **Selection explorer**, click the checkbox for **Adjust prestress** and assign a pre-stress force of **200 kN**.

The model configuration for Phase 4 is shown in Figure 4–11 (p. 84).

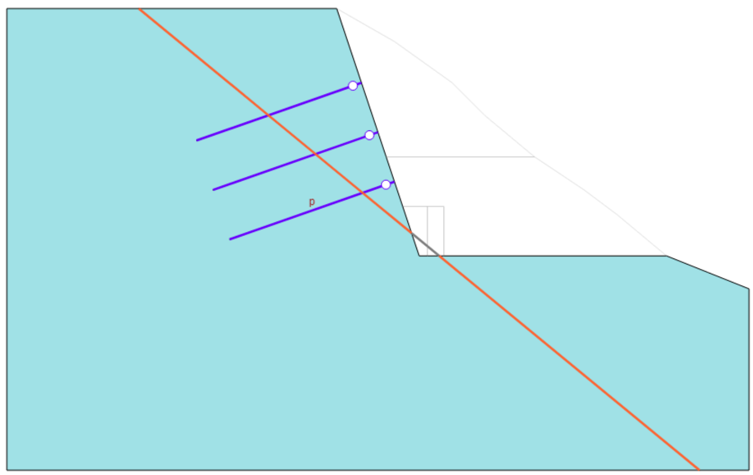

Figure 4–11: Configuration of Phase 4

4.7.6 | Phase 5: Construction of the retaining wall

1. Click the **Add phase** button to add a new phase.
2. Activate the retaining wall and assign the material to the retaining wall according to Table 4–5 (p. 79).

The model configuration for Phase 5 is shown in Figure 4–12 (p. 84) below:

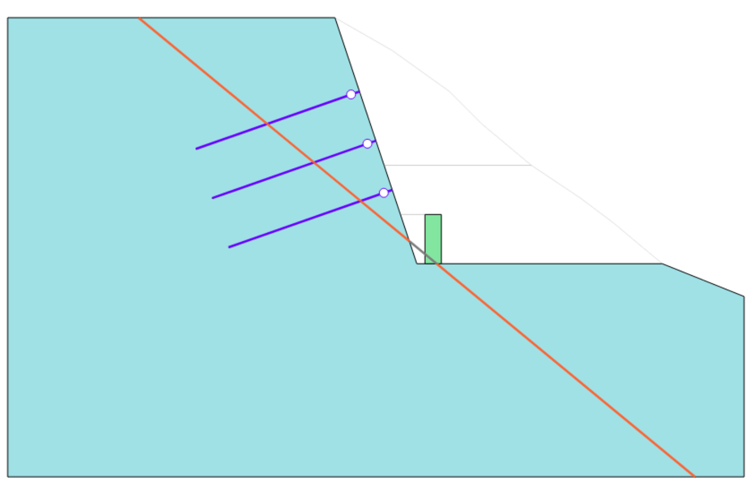

Figure 4–12: Configuration of Phase 5

4.7.7 Phase 6: Backfilling

1. Click the **Add phase** button to add a new phase.
2. Activate the backfill and assign the material to the backfill according to Table 4–6 (p. 79).

The model configuration for Phase 6 is shown in Figure 4–13 (p. 85) below:

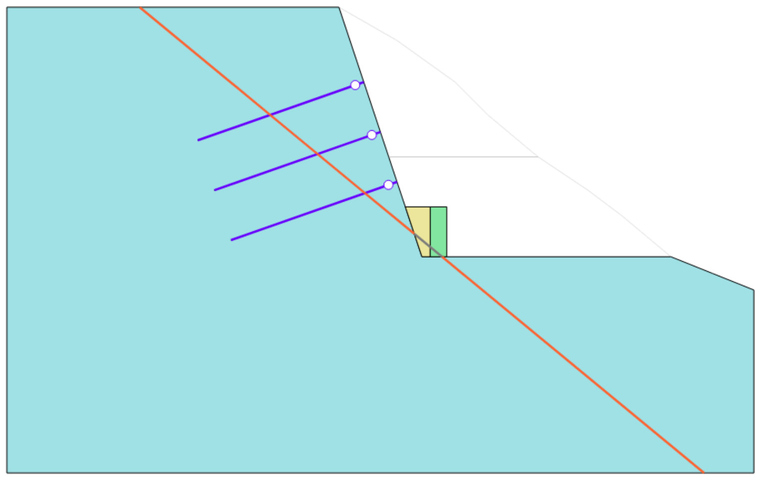

Figure 4–13: Configuration of Phase 6

4.7.8 Phase 7 and Phase 8: Safety analysis

To design the road cut slope, it is important to consider the stability during the excavation and also after the completion of construction. Therefore, it is necessary to evaluate the global safety factor of Phase 3 (second excavation stage), and Phase 6 (After backfilling). To calculate the global safety factor for these two situations, follow these steps:

1. Select Phase 3 in the **Phases** explorer.
2. Add a new calculation phase.
3. Double-click on the new phase to open the **Phases** window.
4. In the **Phases** window, Phase 3 is automatically selected from the **Start from phase** drop-down menu.
5. In the **Calculation type** box, select **Safety** .
6. In the **Deformation control parameters** section select the **Reset displacements to zero** option in order to exclude the existing deformations from the previous calculations.
7. In the **Numerical control parameters** section leave selected the **Use default iter parameters**. The safety calculation is now defined for Phase 3.
8. Follow the same steps as mentioned above to create a new calculation phase that analyses the stability of the final phase after the construction of the retaining wall and the backfill (Phase 6).

The phases after defining the safety calculations are displayed in Figure 4–14 (p. 86).

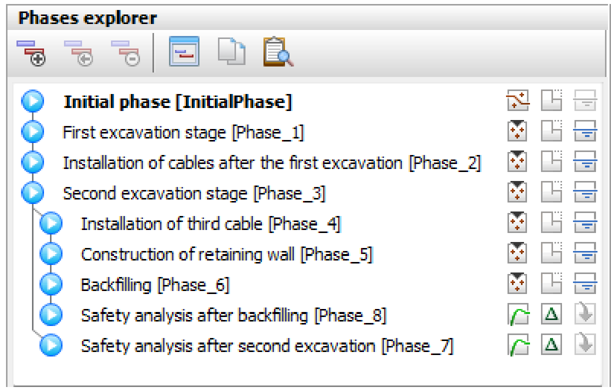

Figure 4–14: Safety calculation phases

4.8 Calculate

Before initiating the calculation, it is recommended to select some nodes in order to generate the plots to determine the factor of safety at a later stage. To do this, follow these steps.

1. Click on the **Select points for curves** button in the side toolbar.
2. Select the characteristic point (23 6) for curves and click on **Update**.
3. Click on the **Calculate** button to compute the project.
4. Once the calculation is completed, save the project by clicking on the **Save** button .

4.9 Results

For this tutorial, the results for the excavation phases and the safety analysis are evaluated.

4.9.1 Evaluation of results

1. After completing the calculations, select Phase 3 (second excavation stage) and click on the **View calculation results** button . The Output program will show the deformed mesh after the second excavation stage. Then, zoom in the toe area to inspect the deformed mesh.

   Figure 4–15 (p. 87) shows the deformed mesh for the Phase 3.

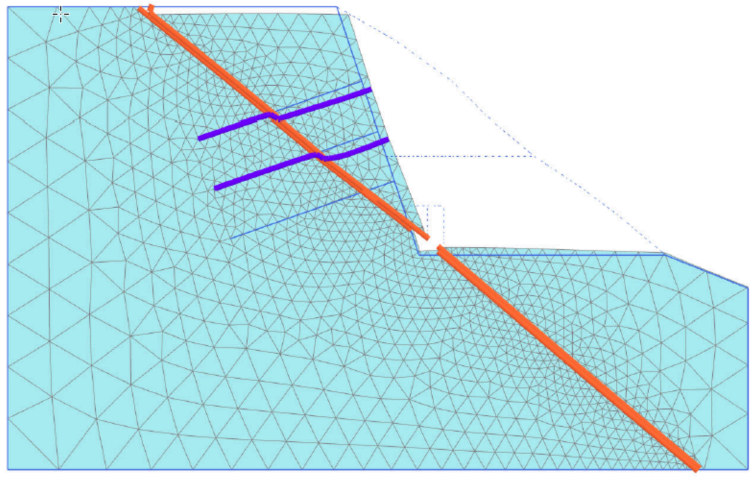

Figure 4–15: The deformed mesh after the second excavation stage

2. To inspect the resulting axial force in the cables, in the toolbar from the **Displayed step** button drop-down menu, go to Phase 6. Click on the **Drag a window to select structures** button in the side toolbar and drag the mouse to define a rectangle encompassing all the cables. Select the **Cable** option in the appearing window, as shown in Figure 4–16 (p. 87).

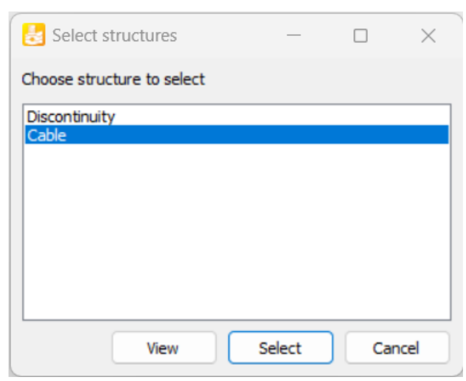

Figure 4–16: Select structures window

3. Click **View**. Note that the cables are displayed in the Structures view.
4. From the **Forces** menu, select the $T_{s,bond}$ option to view the shear force developed in the grouted segments as displayed in Figure 4–17 (p. 88).

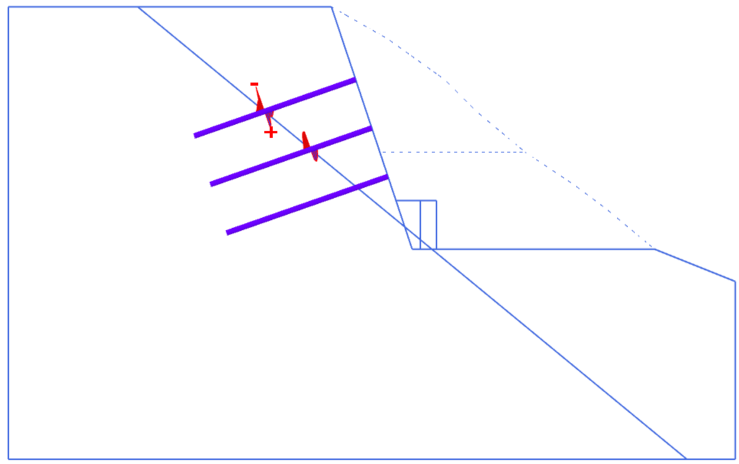

Figure 4–17: Resulting shear force in the bond $T_{s,bond}$ after backfilling

5 Again from the **Forces** menu, select the **Axial forces N** option as shown in Figure 4–18 (p. 88).

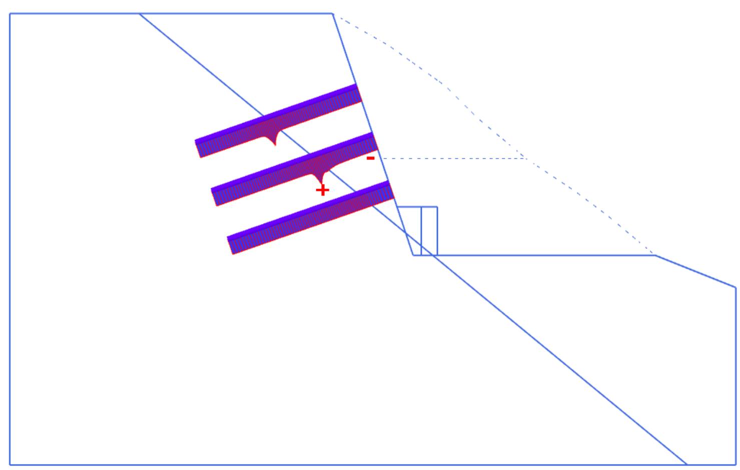

Figure 4–18: Axial forces in the cables after backfilling

Figure 4–17 (p. 88) and Figure 4–18 (p. 88) illustrates that the axial forces are considerably intensified at the intersection of cables and the fault, where the shear force in the bond also develops. The cable forces are mobilised when the rock face moves along the discontinuity. However, after the installation of the third cable there is no further movement of the rock face so the forces in the lower cable is not mobilised. The main function of the lower cable is to contribute to a higher factor of safety rather than to limit the movement of the rock face under normal conditions.

4.9.2 Evaluation of safety analysis results

To assess the stability of the road cut slope design, a safety analysis is performed for this project based on the strength reduction method. Due to the ongoing reduction of the soil strength, additional displacements are generated during a safety calculation. The incremental displacements in the final step of failure are evaluated to assess the possible failure mechanism. To view the incremental displacements of the slope resulting from the second excavation, follow these steps:

1. Select Phase 7 in the Input program, and click on the **View calculation results** button, which is the Safety phase starting from Phase 3.

2. In the Output program, select the menu **Deformations > Incremental displacements > |Δu|**, to display the contour plots of total incremental displacement of the safety calculation after the second excavation stage.

3. From the **Displayed step** drop-down menu in the toolbar, select Phase 8 to view the results of the safety calculation for the rock slope after the construction of the backfill and retaining wall.

   The results are shown in Figure 4–19 (p. 89).

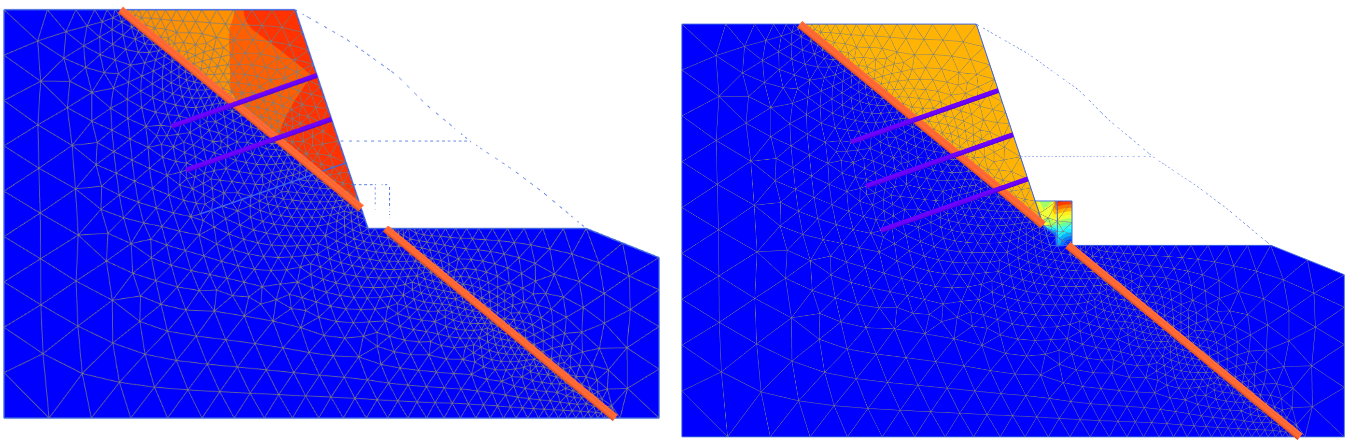

Figure 4–19: Shadings of the displacement increments indicating the most applicable failure mechanism after the second excavation stage (first) and after the backfilling (second)

4. From the top toolbar, click the **Arrows** button, and the incremental displacement movement vectors will be displayed. The length of the arrow indicates the magnitude of the specific incremental displacement, while the arrow direction indicates the displacement increment direction, as shown in Figure 4–20 (p. 89) .

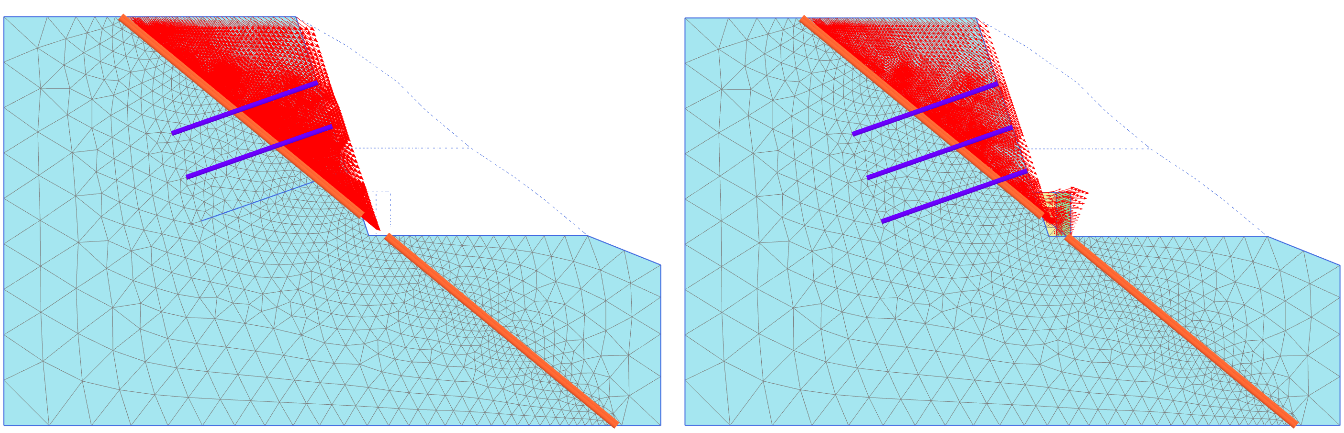

Figure 4–20: Displacement increments after the second excavation stage (first) and after the backfilling (second)

Figure 4–19 (p. 89) and Figure 4–20 (p. 89) shows the contour plots and arrows of the incremental displacement from the safety calculations for both Phases 3 and 6. The magnitude of the displacement increments is not relevant, but it indicates whether or not a failure mechanism has developed. In Figure 4–19 (p. 89), the rock slope tends to slide down along the discontinuity, indicating the need for stabilisation by constructing a retaining wall. In both the figures it is seen that the potential failure mechanism is a planar failure of the rock block sliding along the discontinuity.

It can be seen that the value of ΣMsf remains relatively constant from a certain step onwards while the displacements keep increasing. For an accurate evaluation of the safety factor, it is necessary to plot the values of parameter ΣMsf against the displacement of a node inside the failure zone. To determine the safety factors, follow these steps:

5. To evaluate the factor of safety for Phases 7 and 8 corresponding to Phase 3 and 6, click on the **Curves manager** button.
6. In the **Charts** tabsheet, click on **New** option.
7. In the **Curve generation** window, select the pre-calculation **Node** from the dropdown list for the x-axis. Select **Deformations > Total displacements > |u|**.
8. For the y-axis, select **Project > Multipliers > ΣMsf**.
9. Press **OK** to close the window and generate the chart.
10. Right-click on the chart and select the **Settings** option in the appearing menu. The **Settings** window pops up.
11. In the tabsheet corresponding to the node curve, click the **Phases** button.
12. In the **Select phases** window make sure only the safety calculation Phases are selected.
13. Click **OK** to close the **Select phases** window.
14. In the **Settings** window change the titles and colour of the curves in the corresponding tabsheet.
15. Click **Apply** to update the chart according to the changes made and click **OK** to close the Settings window. The plot is shown in Figure 4–21 (p. 90).

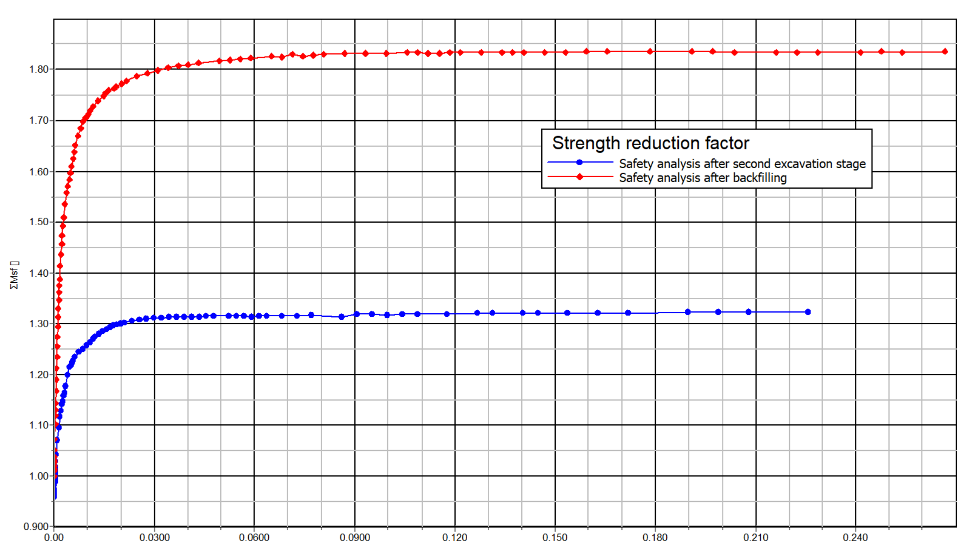

Figure 4–21: Evaluation of safety factor

In Phase 7 which represents the second excavation stage has a lower factor of safety of about 1.33. It indicates that the rock slope along the discontinuity is unstable. However, in

Phase 8 which represents the final road cut slope with the construction of retaining wall along with backfilling is stable with a higher factor of safety of about 1.83.