# PLAXIS

## Slope stability for a road construction project

Using PLAXIS and SLOPE/W

SEEQUENT

Last updated: October, 2022

# 1 Introduction

On the North Island of New Zealand a new road section has to be constructed along the shore line of a tidal bay, see figure 1.1.

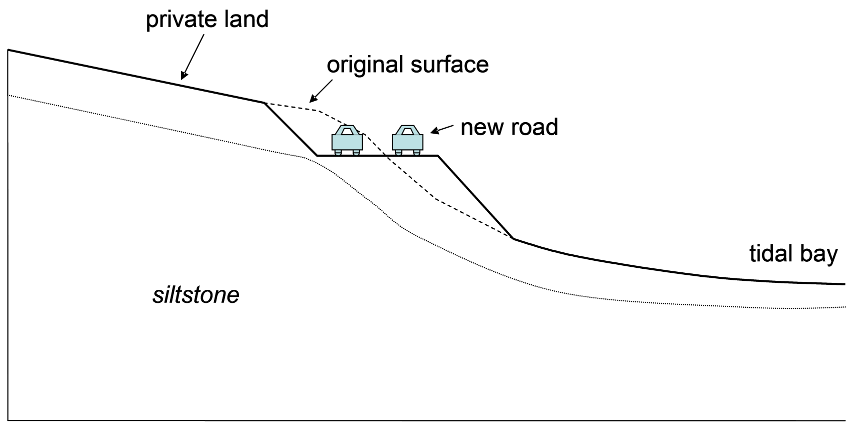



Figure 1.1: Situation overview for the newly constructed road

Though the easiest solution would have been to construct the road at a larger distance from the bay as the slope gradients are easier there, this is not possible as the upper land is privately owned which for historic reasons cannot be changed. The new road therefore had to be constructed along the steeper gradient just next to the shore line of the tidal bay.

The hillside is mainly siltstone, weathered at the surface but intact at certain depth. Construction will take place in summer when the ground water level is low. However, in winter the hillside side almost fully saturates due to heavy rainfall, which has a significant influence on the stability. For the construction of the new road part of the slope was excavated. The excavated material is crushed and mixed with sand and gravel to make fill material to support the road.

During the first winter after the road construction the road started to tilt towards the tidal bay and after assessing the winter situation the factor of safety was considered too low. The decision was taken to stabilize the fill and hillside below the road using so-called launched soil nails: long steel reinforcement bars that are shot with high speed into the ground.

Additionally concerns have raised about rock fall and land slides above the road and thus an additional analysis of the slope stability above the road must be performed. The strength reduction method in Finite Elements gives the most critical slip surface, but it's not so easy to determine a factor of safety for a specific area and therefore for the slope stability above the road a Limit Equilibrium analysis is used.

## 1.1 Main goal of the analysis

- Determine the factor of safety of the original hillside
- Construct the new road under dry (summer) conditions and calculate its factor of safety
- Simulate wet (winter) conditions and calculate its factor of safety
- Apply stabilising soil nails and calculate the factor of safety in wet conditions
- Calculate the slope stability above the road using SLOPE/W

# 2 Input

## 2.1 Project properties

Start a new project and select appropriate *Dimensions* according to the size of the geometry (see figure 2.1). After closing the *Project properties* window, open the *Snapping options* and make sure to use a snap distance of 0.25m.

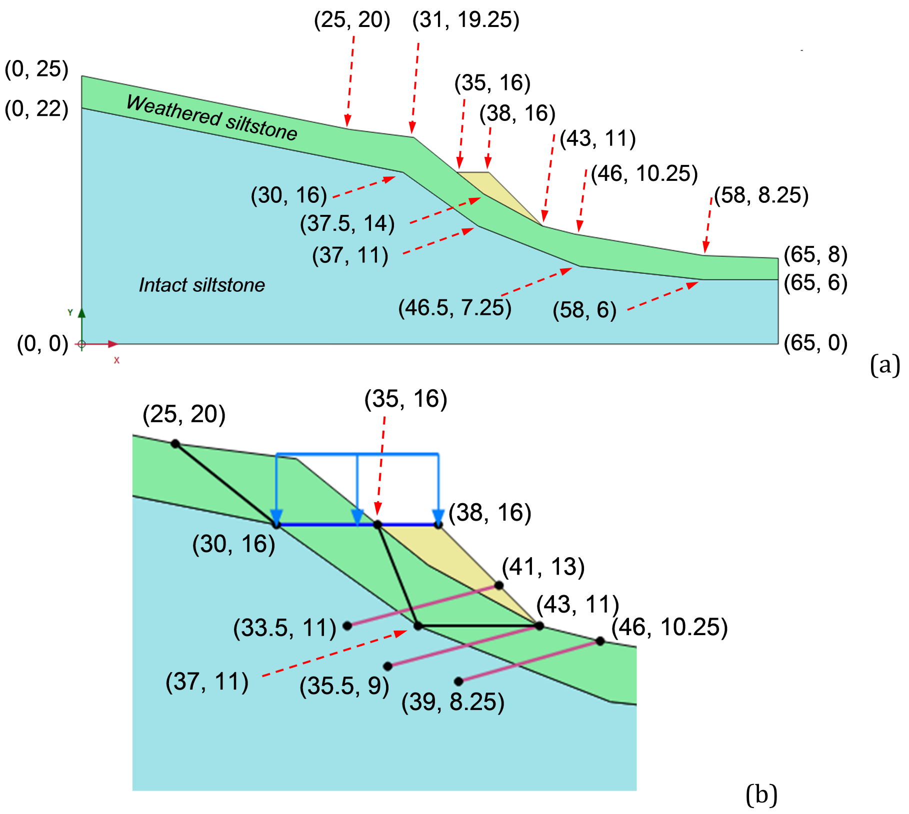



Figure 2.1: Soil model (a) and position of the road surface, construction details and soil nails (b)

## 2.2 Soil mode

Due to the complexity of the model the geometry will not be defined using boreholes, but through soil polygons in *Structures mode.* Therefore, move directly to *Structures mode*.

## 2.3 Structures mode

- First the intact siltstone is modelled.
  - Select the *Create soil polygon* button () and from the submenu that opens, select the *Create soil polygon* option.
  - Now draw a soil polygon starting from (x y) = (0 0) and then to (0 22), (30 16), (37 11), (46.5 7.25), (58 6), (65 6) and finally to (65 0).
- Secondly, the weathered siltstone layer will be added. As the bottom of weathered siltstone layer coincides with the top of the intact siltstone layer it's not needed to draw the complete soil polygon.
  - From the *Create soil polygon* submenu now select the option *Follow contour*.
  - Click at (x y) = (0 22) and draw a line to (0 25), (25 20), (31 19.25), (35 16), (37.5 14), (43 11), (46 10.25), (58 8.25), (65 8) and finally to (65 6).
  - Now right click to end the drawing. A soil polygon will be created from the line that was just drawn and the upper contour of the intact siltstone layer below.
- The last part of soil missing is the new fill that will be constructed for the road.
  - Select again the *Create soil polygon* option and draw a soil polygon from (x y) = (35 16) to (38 16), (43 11) and (37.5 14)
- Now some additional lines must be specified in order to model the construction sequence.
  - From the *Create line* menu choose the option *Create line*.
  - Draw a line from (x y) = (25 20) to (30 16)
  - Draw a line from (x y) = (35 16) to (37 11) and finally to (43 11)
- The road must be added, including the traffic load:
  - From the *Create line* button choose the option *Create plate*.
  - Draw a plate from (x y) = (30 16) to (38 16).
  - Choose the *Select* button () in order to stop drawing plates.
  - Right-click on the just created plate and from the popup menu select the option *Create* $\rightarrow$ *Line load*
  - In the *Selection explorer,* make sure the line load *Distribution* is set to *Uniform* and $q_{y,start,ref}$ = -10 kN/m/m to create a vertical line load of 10 kN/m downwards, per meter out-of-plane.
- And finally the 3 soil nails are added as well:
  - From the *Create line* button menu choose the option *Create embedded pile row*.
  - Insert 3 embedded pile rows according to the coordinates given in figure 2.1.

## 2.3.1 Material properties

### Soil

- Enter the material properties for the three soil data sets specified in table 2.1.
- After entering all properties for the three soil types, drag and drop the properties to the appropriate clusters, as indicated in figure 2.1.

Table 2.1: Soil material set parameters

| **Parameter** | **Symbol** | ***Intact siltstone*** | ***Weathered siltstone*** | ***Reinforced fill*** | **Units** |
|---|---|---|---|---|---|
| *General* | | | | | |
| Material model | Model | Mohr-Coulomb | Mohr-Coulomb | Mohr-Coulomb | |
| Type of behaviour | Type | Drained | Drained | Drained | |
| Dry weight | $\gamma_{unsat}$ | 16.0 | 16.0 | 19.0 | $kN/m^3$ |
| Wet weight | $\gamma_{sat}$ | 17.0 | 17.0 | 21.0 | $kN/m^3$ |
| *Mechanical* | | | | | |
| Young's modulus | $E'_{ref}$ | 12,000 | 12,000 | 20,000 | $kN/m^2$ |
| Poisson's ratio | $\upsilon'$ | 0.3 | 0.3 | 0.3 | – |
| Cohesion | $c'_{ref}$ | 12 | 10 | 8 | $kN/m^2$ |
| Friction angle | $\varphi'$ | 35 | 19 | 30 | $^\circ$ |
| Dilatancy angle | $\psi$ | 0 | 0 | 0 | $^\circ$ |
| Tension cut-off | Tension cut-off | Disabled | Enabled | Enabled | |
| *Groundwater* | | | | | |
| Permeabilities | $k_x, k_y$ | $1 \cdot 10^{-3}$ | 0.01 | 0.1 | $m/d$ |

### Road surface

The road surface is modelled with a plate element. Therefore, create a new plate material set using the parameters as specified in table 2.2 and assign it to the plate representing the road surface.

Table 2.2: Properties of the road surface (plate)

| **Parameter** | **Symbol** | ***Road surface*** | **Unit** |
|---|---|---|---|
| *General* | | | |
| Material type | | Elastic | – |
| Weight | $w$ | 3.0 | $kN/m/m$ |
| Prevent punching | | No | |
| *Mechanical* | | | |
| Isotropic | | Yes | – |
| Axial stiffness | $EA_1$, $EA_2$ | $250 \cdot 10^3$ | $kN/m$ |
| Flexural stiffness | $EI$ | 500 | $kNm^2/m$ |
| Poisson's ratio | $\nu$ | 0.0 | – |

### Soil nails

The 3 soil nails are modelled using embedded pile row elements. Hence, create a new embedded pile row material set with parameters as specified in table 2.3 and assign the material to all 3 soil nails.

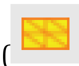
Table 2.3: Properties of the soil nails (embedded beams)

| **Parameter** | **Symbol** | ***Grout body*** | **Unit** |
|---|---|---|---|
| *General* | | | |
| Material type | | Elastic | - |
| Material weight | $\gamma$ | 60 | $kN/m^3$ |
| *Mechanical* | | | |
| Spacing | $L_{spacing}$ | 1.0 | $m$ |
| Cross section type | | Predefined | - |
| Predefined cross section type | | Solid circular beam | - |
| Diameter | Diameter | 0.032 | $m$ |
| Modulus of elasticity | $E$ | 210*10$^6$ | $kN/m^2$ |
| Axial skin resistance | | Linear | |
| Skin resistance | $T_{skin,start,max}$, $T_{skin,end,max}$ | 1000 | $kN/m$ |
| Lateral skin resitance | | Unlimited | |
| Base resistance | $F_{max}$ | 0 | $kN$ |
| Interface stiffness factor | | Default values | - |

## 2.4 Mesh mode

The road surface and the soil nails are automatically refined. However, as possible failure would be expected in the weathered siltstone layer, this layer has to be refined as well.

The *Coarseness factors* as specified in figure 2.2 should be applied to the indicated areas. This can be done in 2 ways:

1. From the vertical toolbar select the *Refine mesh* button () and click on the areas to be refined. For every click on an area or object its coarseness factor will become 70% of it's current value. Hence, to reach a coarseness factor of 0.5 it's necessary to click twice on the area, for a coarseness factor of 0.35 one has to click 3 times on the same area.

2. Select the areas and in the *Selection explorer* directly enter the appropriate coarseness factors.

Now select the *Generate mesh* button () and make sure the *Element distribution* is set to *Medium*. After mesh generation, view the mesh (see figure 2.3)

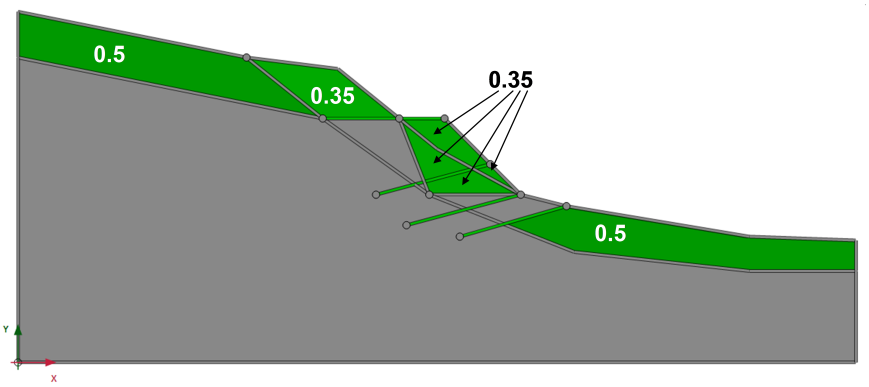



Figure 2.2: Areas of the mesh to be refined

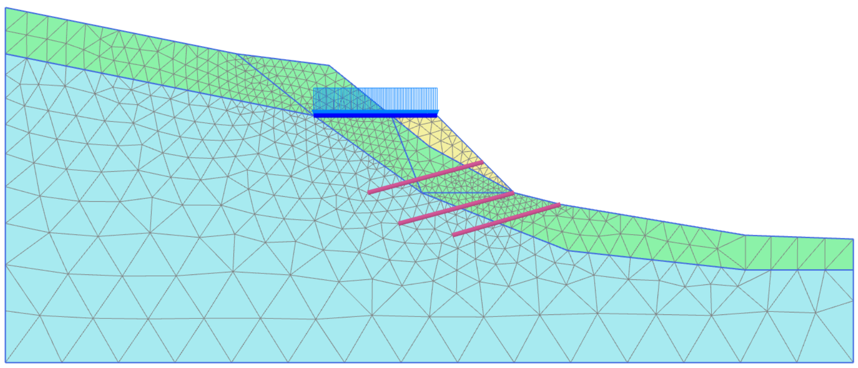


Figure 2.3: Generated mesh with refinement

## 2.5 Flow conditions mode and Staged construction mode

The calculation consists of the initial phase and 12 calculation phases more in order to model the proper construction sequence and the determination of the factors of safety at key moments in the construction process.

### 2.5.1 Initial phase

The initial situation consists of the intact hill side and a phreatic level representing typical summer conditions as construction starts in summer. In order to define the initial situation, follow these steps:

- **Flow conditions mode**
  - From the vertical toolbar select the *Create water level* button ( ) and then the option *Create water level.*
  - Draw a water level from (x y) = (-1 10) to (66 10). This water level will automatically become the global water level.
- **Staged construction mode**

- The geometry has a non-horizontal soil layering, hence the $K_0$-procedure cannot be used. Open the *Phases* window and for the initial phase set the *Calculation type* to *Gravity loading*.
- Make sure only the clusters representing the original hillside are activated and the parts of reinforced soil are switched off.

## 2.5.2 Phase 1 - Stability prior to the construction

Before the construction is started the factor of safety is determined of the initial situation

- **Staged construction mode**
  - Open the *Phases* window and change the *Calculation type* of this phase to *Safety*.

## 2.5.3 Phase 2 - Road excavation

The road excavation should continue from the initial situation and not from the results of the safety factor determination. To do so:

- Select the Initial phase.
- Select the *Add phase* button (). A new phase (phase 2) will now be created that starts from the initial phase.

Now we will define the phase:

- **In Staged construction mode**
  - In the *Phases* window, set the *Calculation type* to *Plastic* of loading type *Staged construction*.
  - In order to discard the displacements during gravity loading make sure the option *Reset displacements to zero* is selected under the *Deformation control parameters.*
  - Switch off the upper part of the road excavations, see figure 2.4.

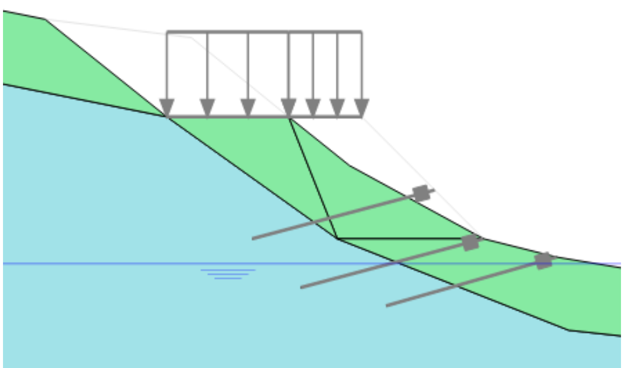


Figure 2.4: Phase 2, road excavation

### 2.5.4 Phase 3 - Construction of the fill

- This calculation phase that starts from Phase 2 is again a *Plastic* calculation, loading type *Staged construction*.
- **In Staged construction mode**
  - Switch on the additional fill
  - Assign the "reinforced fill" material set to the 4 clusters of the fill area, see figure 2.5.

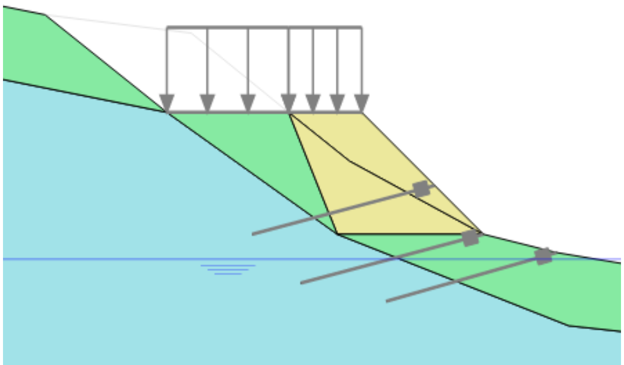


Figure 2.5: Phase 3, Construction of the fill

### 2.5.5 Phase 4 - Construction of the road

- This calculation phase that starts from Phase 3 is another *Plastic* calculation, loading type *Staged construction*.
- **In Staged construction mode**
  - Switch on the plate representing the road. Make sure the distributed load representing the traffic load remains switched off.

### 2.5.6 Phase 5 - Apply the traffic load

- Again a *Plastic* calculation of loading type *Staged construction*.
- **In Staged construction mode**
  - Switch on both parts (left ánd right) of the distributed load representing the traffic load. The plate representing the road surface remains switched on.

We are now finished with the road construction.

### 2.5.7 Phase 6 - Factor of safety of the road in summer conditions

- In order to determine the factor of safety directly after constructing the road use a *Safety* phase starting from Phase 5.

### 2.5.8 Phase 7 - Winter conditions

In winter, the water level inside the hill gradually increases due to rainfall. Only the highest water level in winter will be modelled, for which a steady-state groundwater flow analysis must be performed.

The increase of water level should occur after finishing the road construction and not after determination of the factor of safety of this situation:

- Select Phase 5 and press the *Add phase* button ( ). Now Phase 7 will be created, starting from Phase 5.

- **In Flow conditions mode**

  – Select the *Create water level* button and draw a new water level from (x y) = (-1 20) to (1 20) and further to (37 11), (47.5 10) and finally (66 10).

  – Choose the *Select* button ( ) in order to stop drawing water levels.

  – Right-click on the newly created water level and select the option *Make global* to make this new water level the global water level.

- **In Staged construction mode**

  – Open the *Phases* window and in the *General* section set the *Pore pressure calculation type* to *Steady-state groundwater flow.*

### 2.5.9 Phase 8 - Factor of safety of the road in winter conditions

- In order to determine the factor of safety directly in winter conditions create a *Safety* phase starting from Phase 7.

### 2.5.10 Phase 9 - Apply top level soil nails

In winter conditions the factor of safety appears to be rather low and therefore it is decided to improve stability by applying launched soil nails.

- The application of the first level of soil nails should occur after calculating winter conditions and not after determination of the factor of safety of this situation : select phase 7 and create a new phase

- **Staged construction mode**

  – Switch on the topmost soil nail, see figure 2.6.

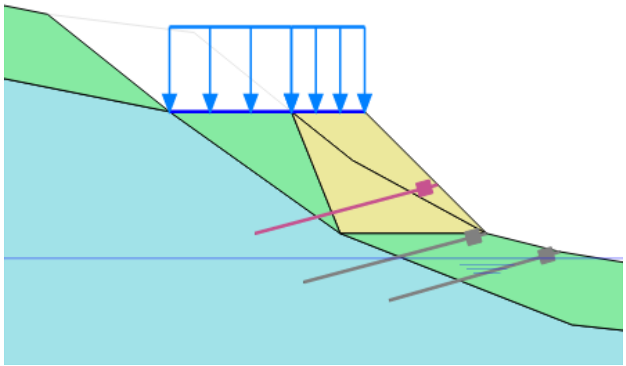


Figure 2.6: Phase 9, Road construction with traffic load and topmost level of soil nails

### 2.5.11 Phase 10 - Factor of safety in winter conditions with top level soil nails

- In order to determine the factor of safety directly in winter conditions with the topmost level of soil nails installed create a *Safety* phase. Keep all default settings

### 2.5.12 Phase 11 - Apply additional soil nails

- The application of the remaining soil nails should occur after installing the top level of soil nails and not after determination of the factor of safety of this situation. Therefore, create a phase starting from Phase 9
- In Staged construction mode
  - Switch on the 2 other soil nails

### 2.5.13 Phase 12 - Factor of safety in winter conditions with all soil nails installed

- In order to determine the factor of safety directly in winter conditions with the all soil nails installed create a final *Safety* phase.
- For this *Safety* phase, set in the *Phases* window the amount of calculation steps (*Max steps*) to 200 in the *Numerical control parameters* section.

## 2.6 Load-displacement curves

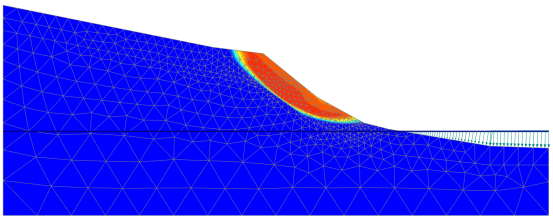
Before starting the calculation choose some points for node-displacement curves. In order to check failure for the phi/c reduction phases the chosen points should be in the expected failure zone. As there are several possible slope instabilities, chose at least points at (25 20), (35 16), (38 16) and (43 11).

**Now save the project and start the calculation by pressing the *Calculate* button.**

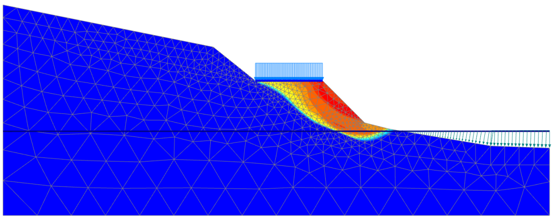
# 3 Output

## 3.1 Failure mechanisms

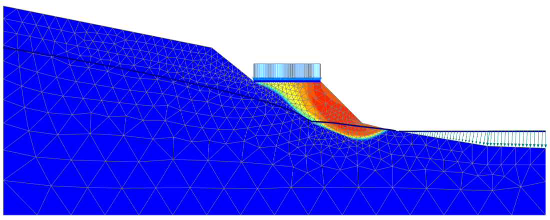
Figure 3.1 shows the failure mechanisms for all 5 conditions. Note that only for the winter condition with all soil nails installed, the failure mechanism is different depending on whether suction was taken into account. For all other conditions the failure mechanism is the same with or without suction, though the actual factor of safety is different.



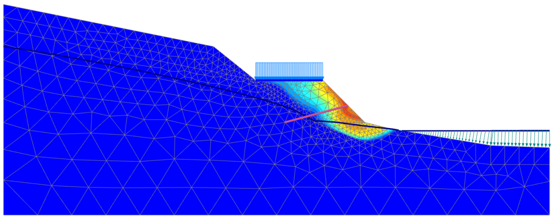
(a) Before construction



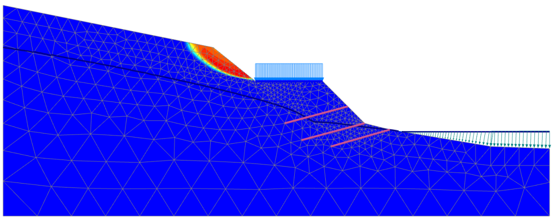
(b) Summer conditions



(c) Winter conditions (no nails)



(d) Winter conditions (top nails)



(e) Winter conditions (all nails)

Figure 3.1: Incremental displacements showing failure mechanisms

## 3.2 Factors of safety

In order to check the factors of safety, strength reduction curves ($\Sigma Msf$ vs. displacement of a control point) must be made in the Curves module. As can be seen from figure 3.1 it is not possible to use the same control point for all 6 factors of safety in case we ignore suction, as the failure mechanisms are in different locations for different situations. Therefore we choose the control points as:

- (x y) = (25 20) for the winter conditions with all nails installed
- (x y) = (35 16) for all other conditions.

To create the curve as shown in figure 3.2 follow these steps:

- Open the Curves manager () and choose to start a new chart.
- Set the x-axis values to the total displacement of point (x y) = (35 16) and the y-axis values to the *Project* multiplier $\Sigma Msf$.
- Right-click on the chart and choose the option *Settings.*
- In the *Settings* window, on the tabsheet representing the curve, click the *Phases...* button and in the *Select phases* window that opens, deselect phase 12 (factor of safety of the winter conditions with all nails installed) so that it will not appear in the graph. To clean up the graph a bit more, one can decided to deselect all phases that are not Safety phases as well.
- Close the *Select phases* window but do not close the *Settings* window.
- In the *Settings* window now select the *Add curve* button and then from the popup menu select *From current project*.
- Add a new curve, but now with the total displacements of point (x y) = (25 20) on the x-axis. The y-axis values remain the *Project* multiplier $\Sigma Msf$.
- Back in the *Settings* window, on the tabsheet representing the newly added curve, click again the *Phases...* button. Now deselect all phases but keep phase 12 selected.
- Close the *Phases* window
- Addittionally, on the *Chart* tabsheet of the *Settings* window one can set the scaling of the axes. For instance the x-axis from 0 to 2 m. Press the *Apply* button to confirm this.

We now have a graph with the strength reduction curves for point (x y) = (25 20) for the final phases and for point (x y) = (35 16) for all other calculation phases.

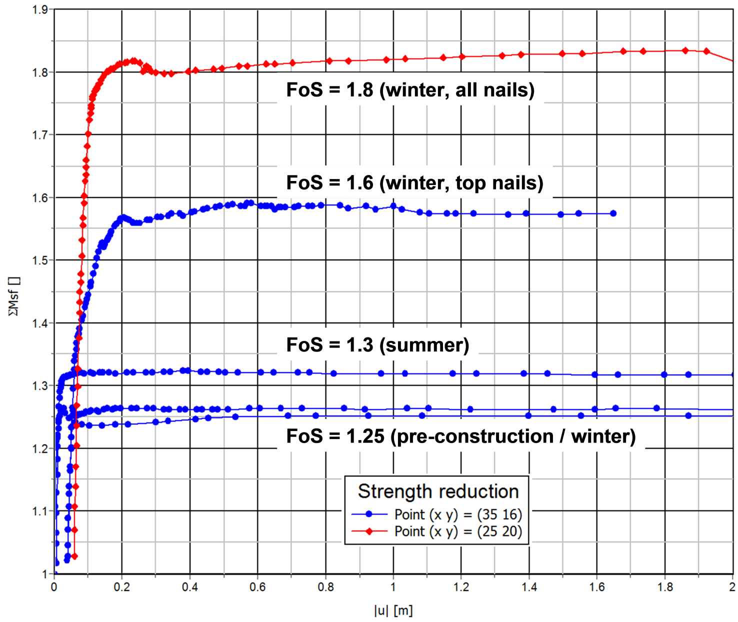



Figure 3.2: Factors of safety for key moments in the project without taking into account suction.

From figure 3.2 the effect of installing the nails on the factor of safety can be seen.

# 4 Additional analysis: Local slope stability

## 4.1 Introduction

The results of the FEM analysis show that after all nails have been installed and in winter conditions the slope above the road is the most critical whereas in other conditions the slope below the road is the most critical. With respect to the serviceability of the road the following requirements have been made by the Highway Authority:

- Total loss of the road: reached when either the slope below the road fails or when a failure of the whole hill side occurs. The minimum required factor of safety against total loss is 1.8.
- Temporary loss of service: reached when the slope above the road fails and soil/rocks block the traffic temporarily. This failure is considered less severe, hence the minimum required factor of safety against loss of service is 1.6.

Using the strength reduction method, it is quite difficult to determine the safety factor of local failure mechanisms as the method by concept gives only the most critical mechanism. Therefore we will do a Limit Equilibrium (LE) analysis to determine the factors of safety against total loss and of the road and temporary loss of service.

## 4.2 Safety factor prior to construction

As a first calibration between FEM results and LE results we will first determine the factor of safety prior to construction using Limit Equilibrium:

1. In PLAXIS 2D, select Phase 1 in the *Phase explorer*
2. From the *Expert* menu choose the option *Run Python script*. The first time the option *Open* must be chosen to select the script that will open the project in SLOPE/W. This script is called "lem_converter".
3. Running the script it will first give a message if the Remote Scripting server is not running yet (see figure 4.1). Press *Start server* to start the remote scripting server and then press *Close* to continue running the script.

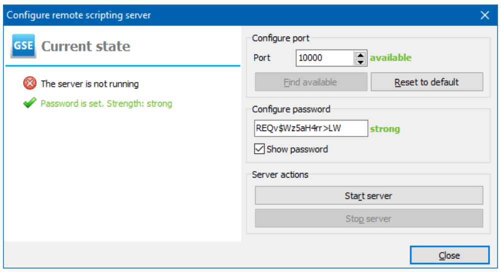



Figure 4.1: Starting the remote scripting server

4. Conversion starts and the *PLAXIS 2D to Limit Equilibrium model converter* dialog will open (see figure 4.2).

5. In this dialog, set the *Slip surface direction* to *Left to Right* and the *LEM solution* to *SLOPE/W*. Then click the *Convert* button. Note that some messages and warnings on possibilities and limitations appear in the *Conversion log*.

6. Now click the button *Open SLOPE/W* and the converted project will open in *SLOPE/W* (see figure 4.3).

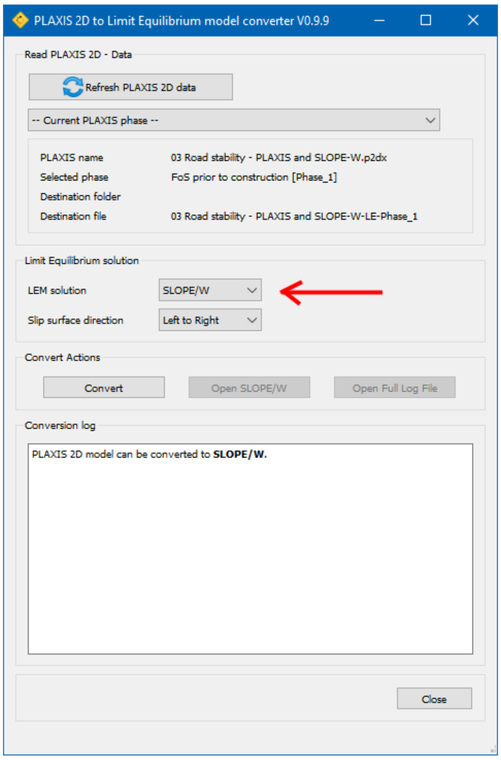



Figure 4.2: Conversion window for PLAXIS FE to LE phase conversion

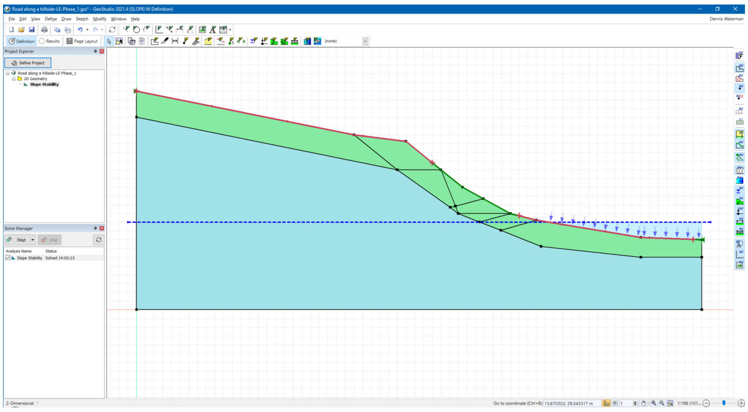


Figure 4.3: Model for Phase 1 in SLOPE/W

7. In SLOPE/W there are several options to specify possible slip surfaces, for instance through the definition of a grid of center points and radii, but also by specifying a range at the surface where the slip surface may begin (Entry) and end (Exit). This is the option we will use in this exercise as we're interested in the failure in different parts of the model. Before construction we expect the slip surface to include the entire slope, hence it will start somewhere above the slope (Entry) and end somewhere beyond the toe of the slope (Exit). We can specify this as follows:

   (a) In *Definition* mode, choose from the *Define* menu the option *Slip Surface* and then the suboption *Entry and Exit*. A window to define the Entry and Exit range opens, see figure 4.4.

   (b) For the *Entry Range*

      i. set the *Type* to *Range*

      ii. specify for the *Left Point* X = 0 and for the *Right Point* x = 35 to assure the slip surface will start somewhere above the slope. The Y-coordinates of both the left and right point are filled in automatically.

   (c) For the *Exit Range*

      iii. set the *Type* to *Range*

      iv. specify for the *Left Point* X = 36 and for the *Right Point* x = 65 to assure the slip surface will end somewhere below the slope. Again, the Y-coordinates of both points are filled in automatically.

   (d) Note that for both within the *Entry Range* and *Exit Range* a limited amount of points is taken into account where the slip surface can start or end. This amount of points is given by the parameter *Number of increments over range* and is by default set to only 4 points. This means that for instance for the top of the slip surface only X = 0, X = 9, X = 18, X = 26 and X = 34 is considered. In order to refine the search we set increments of 1 meter, hence the Number of increments over range should be $X_{righ} - X_{left}$ for both the *Entry Range* and *Exit Range*.

      v. For the *Entry Range* set the *Number of increments over range* to 35

      vi. For the *Exit Range* set the *Number of increments over range* to 30

   (e) Additionally, the *Number of radius increments* determines how many slip surfaces are taken into account between eacht Entry point and Exit point. The default setting is 4 slip surfaces per combination of Entry point and Exit point and in order to refine the search this number is increased to 25.

      vii. Hence , set the *Number of radius increments* to 25.

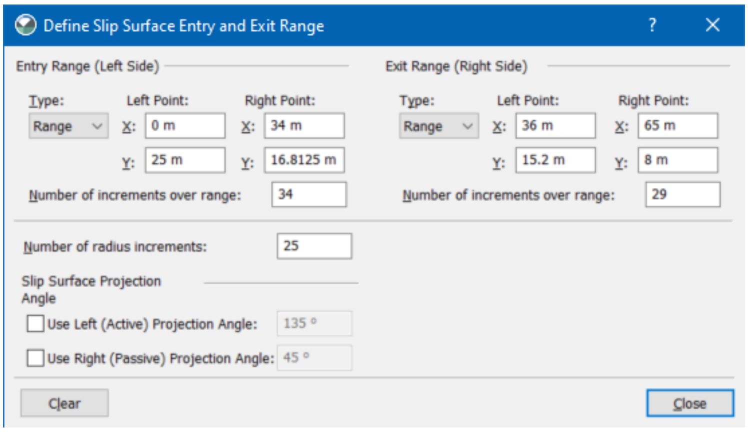



Figure 4.4: Setting the slip surface Entry and Exit ranges

8. Additionally, it is important to optimize the critical slip surface location in order to find a non-circular slip surface. This is done by right-clicking on the project in the *Project Explorer* and choose the option *Define project*, see figure 4.5:
   (a) Above the tabsheet the *Analysis Type* can be chosen. Here we will keep the first option: *Morgenstern-Price*.
   (b) On the *Slip Surface* tabsheet keep the default *Direction of movement* (Left to right) and *Slip Surface Option*: *Entry and Exit*.
   (c) Select the option *Optimize critical slip surface location*. It is not needed to change the *Optimization Settings*.
   (d) Now close the *Define Project* window

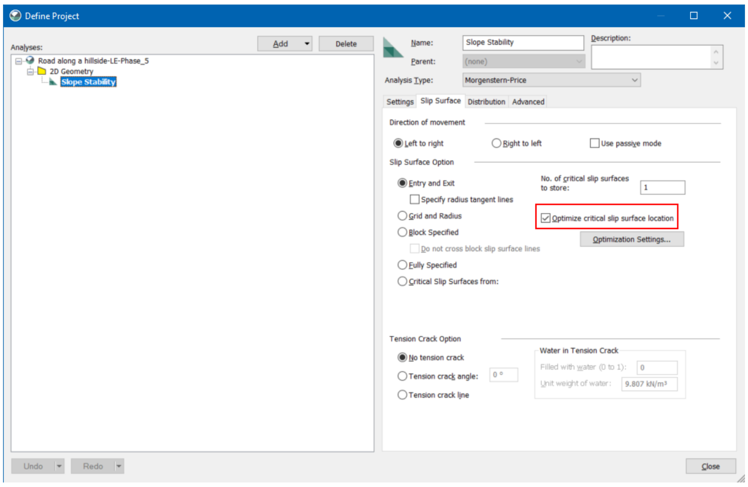



Figure 4.5: Project Slip Surface settings in SLOPE/W

9. Now start the calculation by clicking the *Start* button in the *Solve manager*.

## 4.2.1 Results of the LE analysis

After the calculation ends, the program will automatically switch to the *Results* view. By default the slip surface with the lowest calculated factor of safety is shown. In order to see other slip surfaces and the corresponding factor of safety, select the slip surface of interest from the *Slip Surfaces* list on the left.

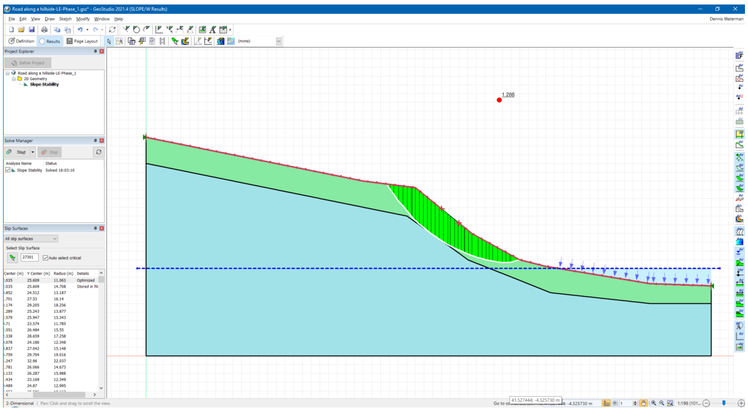


Figure 4.6: Minimum factor of safety slip surface using LE

Comparing the failure mechanisms and factors of safety of the FEM and LE calculation we can see that they are in fact very close, see figure 4.7.

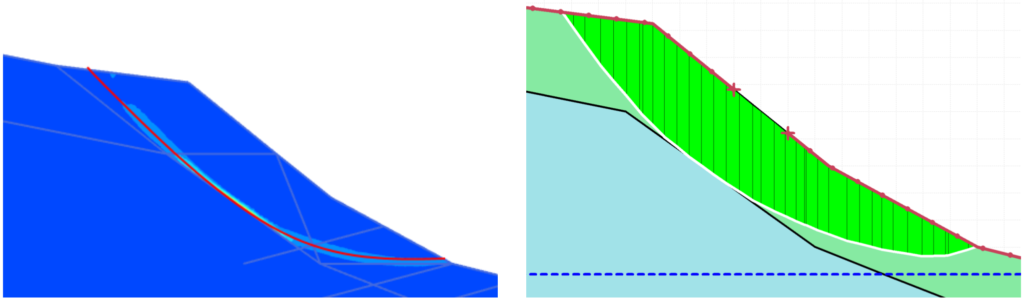


Figure 4.7: Slip surface with FEM (FoS = 1.25) and LE (FoS = 1.29)

## 4.3 Safety factor after construction, summer conditions

- In PLAXIS 2D choose Phase 6 (FoS Summer conditions) and export the model to SLOPE/W again.
- Apply the same *Project settings* as before:
  - *Analysis Type: Morgenstern-Price*
  - *Slip Surface Option: Entry and Exit*
  - *Optimize critical slip surface location*

In order to compare our model with the PLAXIS model we're first interested in the failure of the lower slope, hence below the road. The road constructed as a tarmac layer on top of a compacted gravel bed and the total road construction works as a stiff and strong reinforcement layer. Where in PLAXIS this is automatically taken into account for the Safety analysis as the road is modelled as elastic plate element, such element is not created in the SLOPE/W model. Therefore we will consider 2 situations:

1. The road is stiff/strong enough to force the slip surface towards the leftmost tip of the road at (X Y) = (30 16)
2. The road surface can easily break and thus has no influence on the failure mechanism: hence the entry of the slip surface can be anywhere from X = 30 to X = 38m.

The easiest way to calculate both alternatives is to clone the current analysis. This can be done by right-clicking on the analysis in the *Project Explorer* and choose the option *Add Analysis* → *Clone* → *Analysis.*

For the first of the two analyses we assume the road is infinitely strong and so we set the *Entry and Exit Range* according to:

- *Entry Range* as a *Point* at X = 30
- *Exit Range* as a *Range* from X = 38 to X = 65 and 27 increments over this range
- *Number of radius increments* : 25

For the second of the two analyses we assume the road is not limiting the slip surface in anyway way and so we set the *Entry and Exit Range* according to:

- *Entry Range* as a *Range* fromt X = 30 to X = 38.
- *Exit Range* as a *Range* from X = 38 to X = 65 and 27 increments over this range
- *Number of radius increments* : 25

From the results we can see that the LE analysis confirms that the failure of the slope underneath (and including) the road is the most critical with a factor of safety of 1.32 for FEM and for both LE analysis we find 1.36 and 1.29. The slip surfaces of the FEM analysis and the LE analysis with strong road are very much alike, see figure 4.8 the left and middle figures. It can also be seen from the factors of safety that the resistance of the road surface has no major influence on the factor of safety.

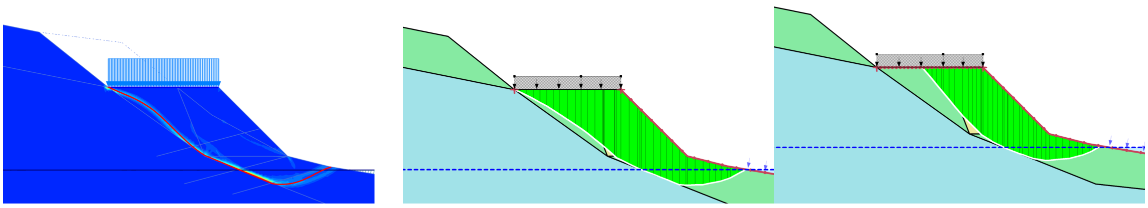


Figure 4.8: Slip surfaces for summer conditions using FEM (left) and LE (middle and right)

It's clear that both FEM and LE show that the minimum required factor of safety of 1.8 is not met.

- Now we want to calculate the factor of safety of the slope above the road, something that is harder to achieve with a FEM analysis.
- Go back to the *Definition* mode of SLOPE/W .
- We could now simply choose to change the *Entry and Exit* range again, but then if we would like to review the slip surface below the road we would have to reset the *Entry and Exit Range* again. It is more practical to make another slope stability analysis for the upper slope by cloning the current analysis
  - In the Project Explorer, right-click on the Slope Stability analysis
  - From the menu that appears, select the option *Add analysis* → *Clone* → *Analysis.* The anaylis will be copied as "Slope Stability (2)".
  - If preferred, the name can be changed
- For the cloned analysis we will limit the search for a slip surface to just the upper slope. To do so, we have to modify the *Entry and Exit Range*:

- Specify the *Entry Range* as a *Range* with the *Left Point* at X = 15 and the *Right Point* at X = 30 with 15 increments
- Specify the *Exit Range* as a *Point* at X = 30
- Set the *Number of radius increments* to 25

- Now analyze the model again and view the results. Of course there is no need to re-run the analysis for the lower slope, so this analysis can first be deselected in the *Solve Manager*.
- Figure 4.9 shows the slip surface with the lowest factor of safety for the upper slope. The factor of safety is 1.8 and thus fulfills the minimum requirement of 1.6.

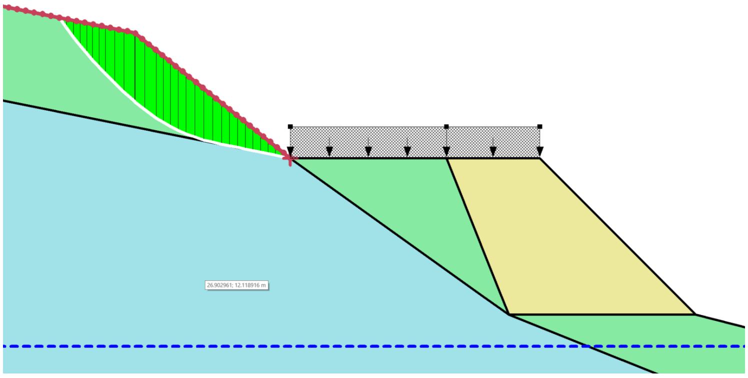


Figure 4.9: Upper slope slipsurface

## 4.4 Safety factor after construction, winter conditions

Similar to the summer conditions we will now perform an LE analysis for both the lower and upper slope. To do so, export phase 8 from PLAXIS to SLOPE/W.

Note: after converting the phase to SLOPE/W the conversion shows log info at the bottom of the window to which, until now, we didn't pay much attention. However, the first warning is important here (see figure 4.10):

- It states that the converted phase has pore pressures from the previous phase, which is not yet supported in the conversion to SLOPE/W. Hence the defined global water level in PLAXIS 2D will be used as the water level for the LE analysis.
- Note that in the FE analysis the pore pressures come from a groundwater flow analysis, which is not (yet) supported in SLOPE/W. Hence, the global water level as drawn in PLAXIS is taken for hydrostatic pore pressures in SLOPE/W. This is a fairly good approximation here, as can be seen from the FEM calculation results:
  - The global water level drawn in PLAXIS matches quite well the real resulting water level from the groundwater flow analysis
  - Flow velocities are small, hence the influence of groundwater flow on the results should be small
  - Figure 4.11 shows the calculated water level from the groundwater flow analysis in PLAXIS (left) and the water level taken into account in SLOPE/W (right).

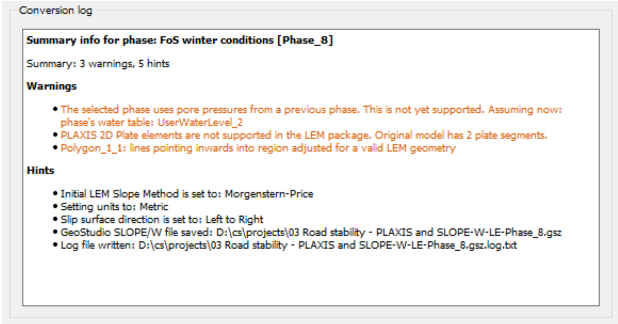



Figure 4.10: Conversion log

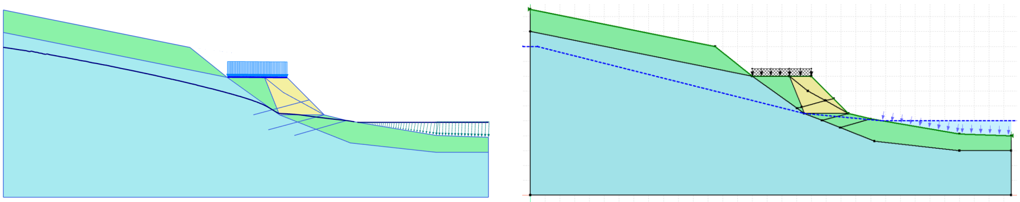


Figure 4.11: Phreatic level in FEM analysis (left) and LE analysis (right)

- In *Project Definition* set the same *Analysis Type* and *Slip Surface Options* as for previous phases.

- We will now analyze the model for 3 different slip surfaces: failure of the upper slope, the lower slope with both strong and weak road surface, and the entire slope. To do so, create 3 clones of the analysis and set the *Entry and Exit Range* as:

  - Upper slope : *Entry* from X = 15 to X = 30 with 15 increments and *Exit* at X = 30
  - Lower slope with very strong road : *Entry* at X = 30 and *Exit* from X = 38 to X = 65 with 27 increments
  - Lower slope with weak road : *Entry* from X = 30 to X = 38 with 8 increments and *Exit* from X = 38 to X = 65 with 27 increments
  - Entire slope : Entry from X = 0 to X = 25 with 25 incremetns and Exit from X = 38 to X = 65 with 27 increments
  - In all 4 cases set the *Number of radius increments* to 25

The factors of safety found are 1.81 (Upper slope), 1.32 (Lower slope with strong road), 1.25 (Lower slope with weak road) and 1.6 (Entire slope, see figure 4.12). As expected, the lower slope is found as the most critical one with a factor of safety of comparable to that of the FEM analysis (1.27). It is also interesting to see that neither the stability of the lower slope nor the stability of the entire slope fulfill the requirement of having a factor of safety larger than 1.8

The upper slope in winter conditions fullfills the requirement of being larger than 1.6.

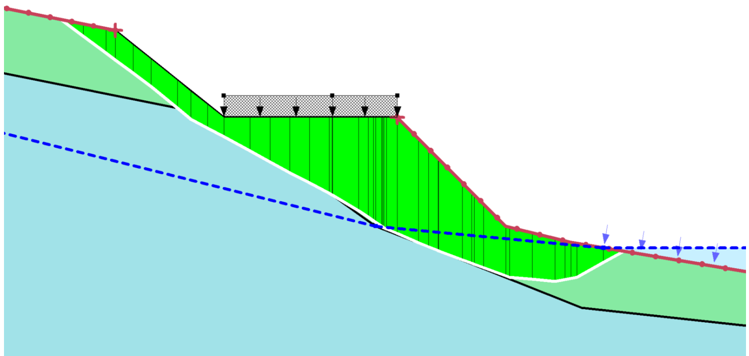


Figure 4.12: Slip surface for the stability of the entire slope

## 4.5 Safety factor with top nails installed, winter conditions

Again we will perform an LE analysis for the lower and upper slope as well as for the entire slope. To do so, export phase 9 from PLAXIS to SLOPE/W.

For the top nails an adjustment must be made with respect to the pullout resistance. In the FE analysis a skin resistance is specified, but the amount of skin resistance that is really mobilized depends on the deformation. In the LE analysis, however, the specified pullout resistance is assumed to be fully mobilised. In the conversion from PLAXIS to SLOPE/W the skin resistance as defined for the embedded beam in PLAXIS will be converted to the pullout resistance in SLOPE/W, but this will probably result in a (large) overestimation of the pullout resistance in SLOPE/W.

Therefore we should modify the pullout resistance in SLOPE/W to the mobilised skin resistance obtained from PLAXIS. When looking at the PLAXIS results we can see that the mobilised skin resistance (skin friction $T_{skin}$) is about 26 kN/m/m inside the failure zone and 45 kN/m/m outside the failure zone. Since the embedded beam is for about 60% inside and 40% outside the failure zone we will use the weighted average value of 33 kN/m/m as the mobilised skin resistance. Note that this is the skin friction per meter embedded beam, per meter out-of-plane.

The *Pullout Resistance* (PR) as specified in SLOPE/W is the pullout force per anchor divided by the contact area between nail and surrounding soil. The relation between these two values is given by:

$PR = \frac{T_{skin}}{\pi D} \cdot L_s$ where $L_s$ is the out-of-plane spacing of the embedded beams / nails and D is the (bond) diameter.

Hence, in order to match the mobilised resistance from PLAXIS a *Pullout Resistance* of approximately 330 kPa must be specified in SLOPE/W:

- In the *Definition* mode choose the option *Reinforcements* from the *Define* menu. The *Define Reinforcement* window now opens.
  - Select the *Soil nails* reinforcement, the properties will now show (see figure 4.13)
  - Set the *Pullout Resistance* to 330 kPa. Check at the bottom of the window the *Factored Pullout Resistance* (FPR) as this value is per meter anchor length per meter out-of-plane and thus comparable with the $T_{skin}$ in PLAXIS. The FPR should be about 33 kN/m/m.
- In *Project Definition* set the same *Analysis Type* and *Slip Surface Options* as for previous phases.
- Create again the 3 cases and set the *Entry and Exit Range* as well as the increments as in the previous phase and analyze the 3 situations.

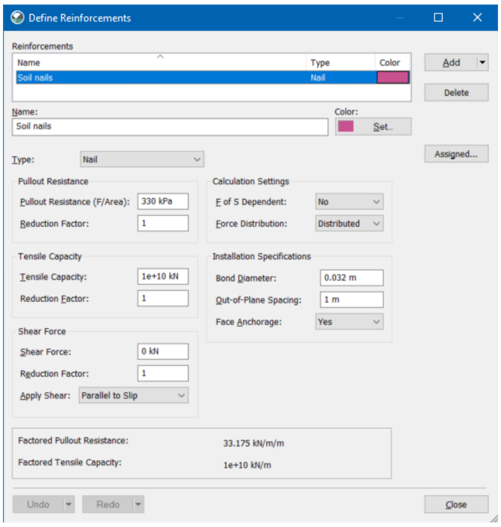



Figure 4.13: Adjusting reinforcement properties

The factors of safety found are 1.81 (Upper slope), 2.1 (Lower slope with strong road), 1.60 (Lower slope with weak road) and 2.06 (Entire slope). The difference is quite large in the factor of safety for the lower slope. Examining the slip surface in the FEM analysis in more detail it can be seen (figure 4.14a) that in fact the slip surface starts underneath the road, but cannot break through the road. Therefore the slip surface is forced to the left tip of the road which practically means that the road will slip off the cut.

In SLOPE/W we also forced the slip surface to start from the leftmost point of the road, but the result is that the slip surface will go all around the reinforcement (see figure 4.14b), which leads to a higher factor of safety than in the the FE analysis whereas the solution in which we allow the slip surface to pass through the road (see figure 4.14c) gives a slip surface much closer to the FEM solution but with a lower factor of safety.

It is clear from the results that the stability of the lower slope is now quite sensitive for the possible stabilizing effect of the road and its foundation, which is an unfavourable situation.

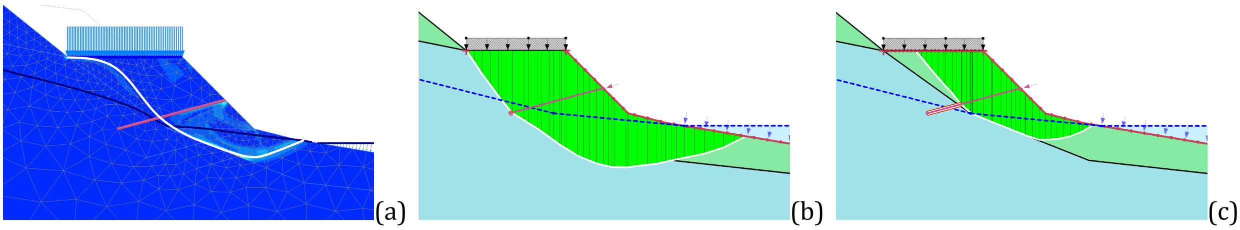



Figure 4.14: Slip surface in FEM (a), and LE (b,c)

## 4.6 Safety factor with all nails installed, winter conditions

Finally we will perform an LE analysis for both the lower and upper slope with all soil nails installed. To do so, export phase 12 from PLAXIS to SLOPE/W.

- Rename the existing reinforcement material to "Soil nails - Upper" and set the *Pullout Resistance* for the reinforcements to 300 kPa based on the $T_{skin}$ obtained from PLAXIS in phase 12.
- Duplicate the reinforcement material to "Soil nails - Middle" and "Soil nails - Lower" (Use the arrow on the right and side of the *Add* button and choose the option *Clone*) and set the *Pullout Resistance* to 175 kPa and 40 kPa respectively. Both results have been obtained from the PLAXIS analysis, phase 12.

- From the *Define* menu choose the option *Define Reinforcement Lines*. A window opens showing the 3 reinforcements that now still have all the same material set (Reinforcement Upper). Assign the correct reinforcement material to the middle and lower reinforcement line.
- In *Project Definition* set the same *Analysis Type* and *Slip Surface Options* as for previous phases.
- For the 4 cases, set the *Entry and Exit Range* as well as the increments as in the previous phase and analyze the 3 situations.
- Analyze the model and view the results.

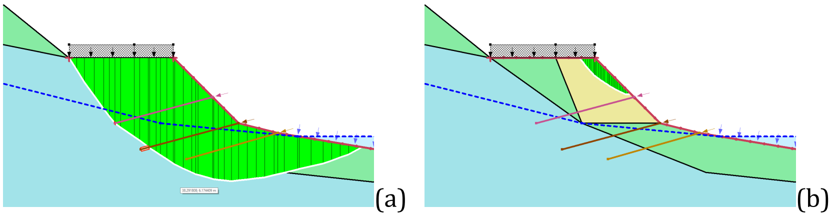



Figure 4.15: Slip surface below the road assuming strong road (a) and weak road (b)

The results of the LE analysis with the weak road (see figure 4.15b) show that a possible local failure mechanism with a factor of safety of 1.71 exists under the right edge of the road. Since this failure mechanism does not lead to loss of the road one might question whether it should indeed fulfill the requirement of a minimum safety factor of 1.8 as this failure would more lead to a loss of service rather than a loss of the road. When looking further into the different slip surfaces from this analysis (Slip Surfaces list at the left bottom side of the SLOPE/W screen) it can be seen that more substantial slip surfaces all do have safety factors of considerably higher than 1.8. Also, the LE analysis assuming a strong road (see figure 4.15a) gives a complete loss of the road with a factor of safety of 2.16.

## Additional analysis: Local slope stability

Safety factor with all nails installed, winter conditions

# 5
# Summary and conclusion

Summary of safety factors:

| | Loss of service | | Complete loss of road | |
|---|---|---|---|---|
| | LE | FEM | LE | FEM |
| Initial situation | N/A | N/A | 1.3 | 1.3 |
| Summer conditions | 1.8 | - | 1.3 | 1.3 |
| Winter conditions | 1.8 | - | 1.3 | 1.3 |
| Winter conditions with top soil nail | 1.8 | - | 1.6 - 2.1 | 1.6 |
| Winter conditions with all soil nails | 1.7 | 1.8 | 2.1 | - |

- In summer and winter conditions the required factor of safety against total loss of the road cannot be met without additional measures
- In summer and in winter conditions the required factor of safety against temporary loss of service is met, hence no additional stabilizing measures are needed for the slope above the road.
- When installing 1 row of soil nails
  - the required factor of safety may be reached according to the LE analysis but depends on the (uncertain) reinforcing influence of the road.
  - the required factor of safety is not reached according to the FEM analysis .
  - differences in the results between FEM and LE may be explained by
    * different behaviour of the soil nails in FEM and LE
    * no groundwater flow in the LE analysis (groundwater flow may lead to decreases stability of the toe of the slope thus explaining the failure there according to the FEM analysis)
- When all soil nails are installed the required safety against both total loss as well as loss of serviceability are met though some concern may remain for local failure just under the edge of the road.
- Installing all soil nails is probably the best to assure the stability of the road.

In general:

- Having different requirements for safety factors is easily solved using Limit Equilibrium analysis in combination with Finite Element analysis. Where the Finite Element analysis finds the most critical slip surface against which the Limit Equilibrium results can be validated for the same failure mechanisms, the Limit Equilibrium analysis can find the factors of safety for non-critical areas more easily than Finite Element analysis.