

PLAXIS

Tied-back excavation with Mohr-Coulomb

PLAXIS 2D 2023.1

Introduction

A building pit was constructed in the south of the Netherlands. The pit is 15 m deep and 30 m wide. A diaphragm wall is constructed using 100 cm diameter bored piles; the wall is anchored by two rows of pre-stressed ground anchors. In this exercise the construction of this building pit is simulated and the deformation and bending moments of the wall are evaluated.

The upper 40 m of the subsoil consists of a more or less homogeneous layer of medium dense fine sand with a unit weight of 18 kN/m^3 . Triaxial test data of a representative soil sample is given in figure 1.2. Underneath this layer there is very stiff layer of gravel, which is not to be included in the model. The groundwater table is very deep and does not play a role in this analysis.

1.1 Aims

- Using interface elements
- Using ground anchors
- Pre-stressing of anchors
- Combination of structural elements

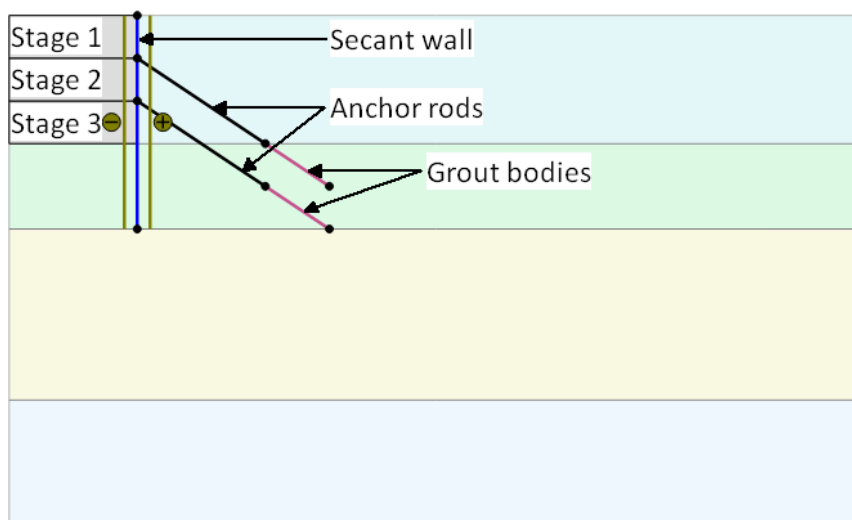


Figure 1.1: Geometry for tied-back excavation

1.2 Material parameters

1.2.1 Determination of stiffness & strength (sand)

In this exercise the Mohr-Coulomb model is used and the model parameters for the sand layer have been extracted from the triaxial test data (see figure 1.2). Concerning stiffness behaviour, it must be taken into account that the excavation involves unloading rather than primary loading. It is preferred to divide the sub-soil into several regions, this allows for the input of an average stiffness in each individual region. As the simple Mohr-Coulomb model cannot take into account the stress-dependency of the stiffness, the input

of an average stiffness per region, by the user, is the next best option to enhance the model. Please note there are other models (HS, HSsmall and SS model) available in PLAXIS that take into account the stress-dependency of the soil stiffness. In this exercise we will use 4 regions:: Top Sand (0m to -15m), Middle Sand (-15m to -25m), Lower Sand (-25m to -45m) and Deep Sand (-45m to -60m). The soil parameters can be found in table 1.1, while the determination of the soil parameters can be found in appendix A.

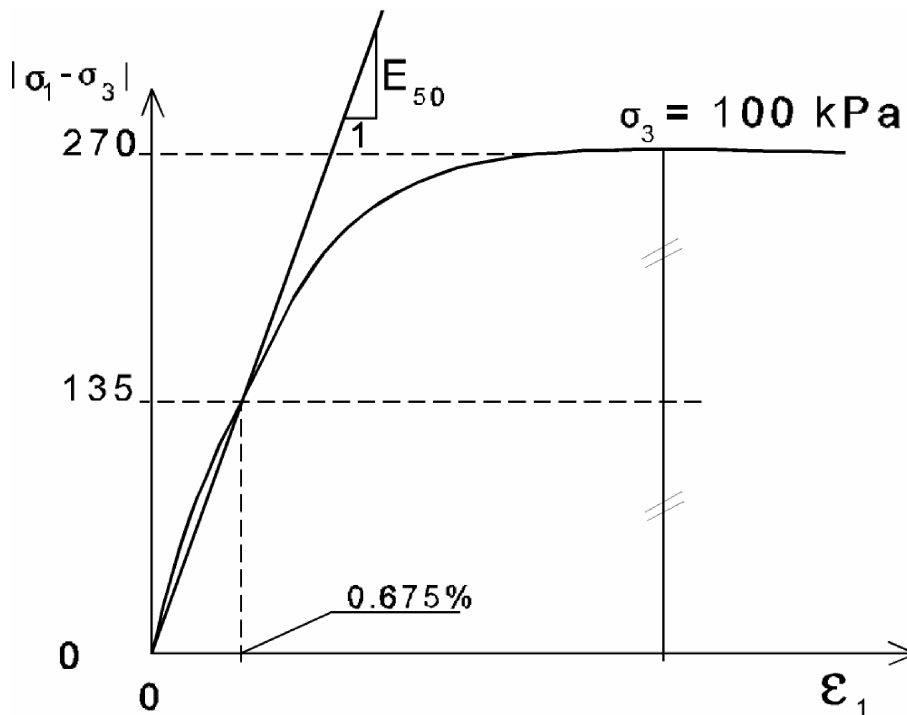


Figure 1.2: Triaxial test data for the sand layer

1.2.2 Secant wall

The secant wall consists of 100cm diameter bored piles with an intermediate distance of 80cm, hence there is a 20cm overlap of the piles. This configuration is taken into account for the determination of the cross sectional area (A) and moment of inertia (I) per meter out-of-plane (see Appendix B). The concrete stiffness is $E_c = 2.7 \cdot 10^7 \text{ kN/m}^2$ with a specific weight $\gamma = 16 \text{ kN/m}^3$, which leads to the material parameters as given in table 1.2. The determination of the stiffness parameters can be found in Appendix A.

1.2.3 Ground anchors

The anchors are made of 32mm diameter steel bars at an intermediate distance of 1m. The steel bars have a stiffness of $E_s = 2.1 \cdot 10^8 \text{ kN/m}^2$. The anchors have an representative capacity of 605 kN per anchor. In combination with a secant wall the anchors may be prestressed to a maximum level of 80% of the design capacity, which is the representative capacity divided by a partial safety factor that has been determined at 1.5. This leads to a maximum prestress force of 322 kN per anchor. The maximum compression force of the anchor is not important as the anchors will not be loaded under compression. The grout body that forms the bonded length of the anchor behaves relatively weak under tension compared to the steel bar inside. Therefore it is assumed that both stiffness and strength of the bonded part of the anchor are fully determined by the steel bar. This leads to the material properties for both the anchor rod (free length) and grout body (bonded length) as given in tables 1.3 and 1.4. Note that it is chosen to use the representative capacity of the anchors as maximum anchor force.

It is assumed that the anchor rod is present inside the full length of the grout body, hence the properties of the embedded beam are based on the composite properties of anchor rod and grout, which are considered to be mainly determine the stiffness and strength properties of the anchor rod.

Table 1.1: Soil parameters for the Mohr-Coulomb model

PARAMETER	SYMBOL	TOP SAND	MIDDLE SAND	LOWER SAND	DEEP SAND	UNIT
General						
Soil model		Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	–
Drainage behaviour		Drained	Drained	Drained	Drained	–
Unsaturated weight	γ_{unsat}	18.0	18.0	18.0	18.0	kN/m^3
Saturated weight	γ_{sat}	18.0	18.0	18.0	18.0	kN/m^3
Mechanical						
Young's modulus	E'_{ref}	$6.0 \cdot 10^4$	$1.0 \cdot 10^5$	$1.3 \cdot 10^5$	$4.8 \cdot 10^5$	kN/m^2
Poisson's ratio	ν'	0.2	0.2	0.2	0.2	–
Cohesion	c'_{ref}	1.0	1.0	1.0	1.0	kN/m^2
Friction angle	φ'	35	35	35	35	°
Dilatancy angle	ψ	5	5	5	5	°
Interfaces						
Interface reduction factor	R_{inter}	0.6	0.6	rigid	rigid	–
Initial						
K_0 determination		automatic	automatic	automatic	automatic	–

Table 1.2: Properties of the secant wall (plate)

PARAMETER	SYMBOL	SECANT WALL	UNIT
General			
Material type		Elastic	–
Weight	w	15.0	$kN/m/m$
Prevent punching		No	
Mechanical			
Isotropic		Yes	–
Axial stiffness	EA_1, EA_2	$2 \cdot 10^7$	kN/m
Bending stiffness	EI	$1.67 \cdot 10^6$	$kN/m^2/m$
Poisson's ratio	ν	0.15	–

Furthermore, it is assumed that the shear resistance between grout body and soil is sufficient and so the skin resistance of the grout body is set to a very high value.

Table 1.3: Properties of the anchor rods (node-to-node anchors)

PARAMETER	SYMBOL	ANCHOR ROD	UNIT
General			
Material type		Elastoplastic	–
Mechanical			
Spacing	$L_{spacing}$	1.0	m
Axial stiffness	EA	$1.7 \cdot 10^5$	kN
Max. tension force	$ F_{max,tens} $	605	kN
Max. compression force	$ F_{max,comp} $	605	kN

Table 1.4: Properties of the grout bodies (embedded beams)

PARAMETER	SYMBOL	GROUT BODY	UNIT
General			
Material type		Elastic	-
Unit weight	γ	60	kN/m^3
Mechanical			
Spacing	$L_{spacing}$	1.0	m
Cross section type		Predefined	-
Predefined cross section type		Solid circular pile	-
Diameter		0.032	m
Stiffness	E	$2.1 \cdot 10^8$	kN/m^2
Axial skin resistance		Linear	kN/m
Skin resistance at start, end	$T_{skin,start,max}, T_{skin,end,max}$	1000	kN/m
Lateral skin resistance		Unlimited	-
Base resistance	F_{max}	0	kN
Interface stiffness factor		Default values	-

Input

Start PLAXIS Input and start a new project.

2.1 Project properties

- For the dimensions of the project, enter $x_{min} = 0$, $x_{max} = 100$, $y_{min} = -60$ and $y_{max} = 0$ in the *Model* tabsheet of the *Project properties* window, see figure 2.1.
- Accept all other settings as their defaults and press the <OK> button.

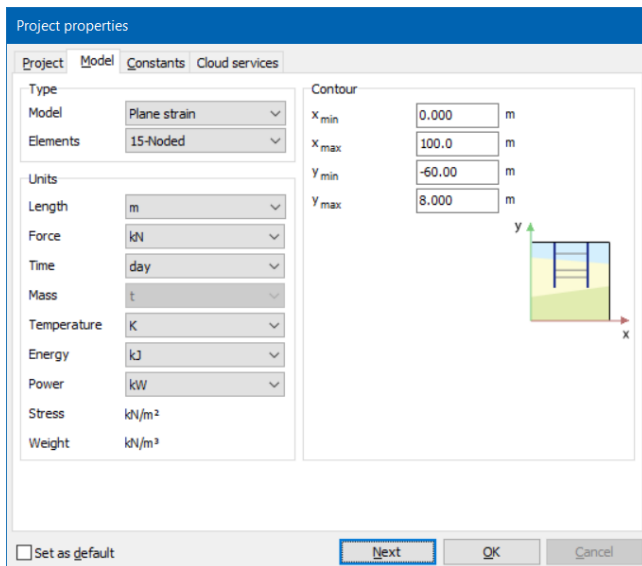


Figure 2.1: Project properties, Model tabsheet

2.2 Soil mode

- Select the *Create borehole* button (🚧) and insert a borehole at (x y) = (0 0)
- In the *Modify soil layers* window define a first layer in the borehole with *Top* = 0m and *Bottom* = -15m.
- Additionally, define 3 more layers with *Bottom* = -25m, -45m and -60m
- The phreatic level in the project area is very deep and so the excavation is done completely above the phreatic line. Set the *Head* of the borehole to -60m to indicate that the phreatic levels is at the far bottom of the borehole.
- Close the *Modify soil layers* window.

The drawing area now shows the subsoil of 100m wide and 60m deep in grey colour.

- Select the *Show materials* button (📦) so that the *Materials* window opens.

- Create 4 soil material sets according to the parameters given in table 1.1. Any parameter not specified in this table should be left at its default value.
- Assign the material sets to the soil layer where *Top Sand* is the topmost layer, followed by *Middle Sand*, *Lower Sand* and finally *Deep Sand* is the deepest layer.
- This will lead to the subsoil as given in figure 2.2.

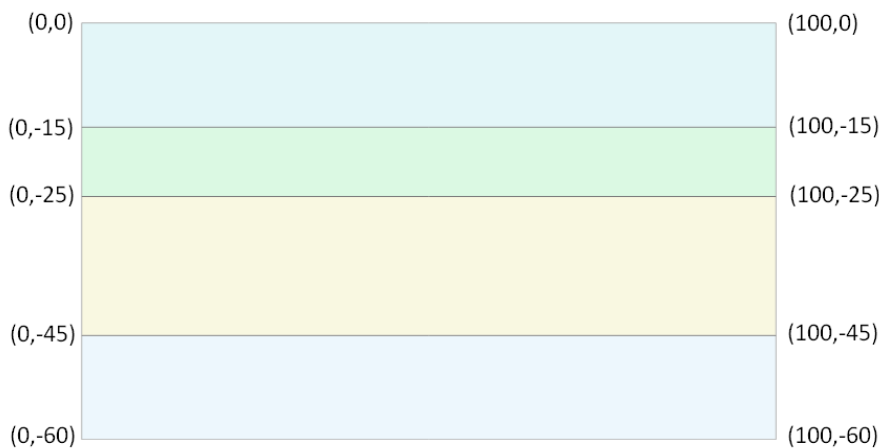


Figure 2.2: Subsoil of the model

2.3 Structures mode

In *Structures* mode we will now define the structural elements such as the wall and the anchors as well as the levels of excavation.

First we will draw the wall:

- Select the *Create line* button () and from the menu that opens select the *Create plate* button
- Draw the wall as a plate element from (x y) = (15 0) to (15 -25).

Soil-structure interaction is modelled with an interface element. Since there will be interaction between soil and wall on both sides of the wall, an interface is required on both sides of the wall:

- From the *Create line* button menu now select the *Create interface* button ().
- Draw the interface for soil-structure interaction from (x y) = (15 0) to (15 -25) and back to (15 0) in order to get soil-structure interaction on both sides of the wall.

Now the anchors are added. The anchors are made out of two parts: a free length formed by just the anchor rod and modelled with a node-to-node anchor, and a bonded length which is the grout body with the anchor rod inside, modelled by an embedded beam element:

- To draw the anchor rods of the grout anchors (hence, the free length sections) select again the *Create line* button, now followed by the *Create node-to-node anchor* button ().
- Draw the upper anchor from (x y) = (15 -5) to (30 -15) and right-click to end the drawing.
- Now draw the lower anchors from (x y) = (15 -10) to (30 -20) and again right-click to end the drawing.
- Finally, insert the grout bodies (hence, the bonded length sections) using embedded beams. To do so, select the *Create embedded beam* button from the *Create line* button menu.

- Draw the upper grout body from (x y) = (30 -15) to (37.5 -20) and right-click to end drawing.
- Draw the lower grout body from (x y) = (30 -20) to (37.5 -25) and again right-click to end drawing.

Now we have to specify that the embedded beams are used as grout bodies. By defining them as grout bodies, they will be connected to the anchors and only to the anchors.

- With the <Ctrl> key pressed on the keyboard, select both embedded beams in the drawing area.
- In the *Selection explorer* change the *Behaviour* for both embedded beams from *Pile* to *Grout body*, see figure 2.3.

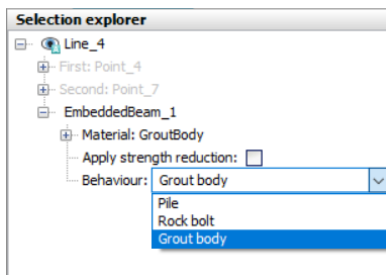


Figure 2.3: Selected embedded beams in Selection explorer

Hint: As interfaces can be introduced on both sides of a geometry line, one should pay attention to the arrows on the cursor. These arrows indicate where the program will locate the interfaces.

Hint: It is not necessary to create a geometry line before creating plates, geogrids, embedded beams or anchors. When drawing a plate, geogrid or embedded beam, a geometry line is automatically added. Anchors do not create corresponding geometry lines. This is not necessary since anchors do not interact with the underlying soil.

Finally, the levels of excavation must be defined:

- From the *Create lines* menu select the *Create line* option
- Draw a line from (x y) = (0 -5) to (15 -5) to define the first level of excavation and right-click to stop drawing.
- Now draw the second level of excavation from (x y) = (0 -10) to (15 -10).

2.3.1 Material sets

- Open the *Material sets* window by selecting the *Show materials* button ()
- In the *Material sets* window change the *Set type* to Plates and create a new plate material set according to the parameters given in table 1.2.
- Assign the material set to the wall.
- In a similar way, create material sets for the anchors and embedded beams according to the parameters given in tables 1.3 and 1.4 and assign them.

2.4 Mesh mode

- Press the *Generate Mesh* button. In the appearing window *Mesh options* set the *Element distribution* to *Medium* and press the *OK* button.
- Press *View mesh* to inspect the resulting mesh as shown in figure 2.4.

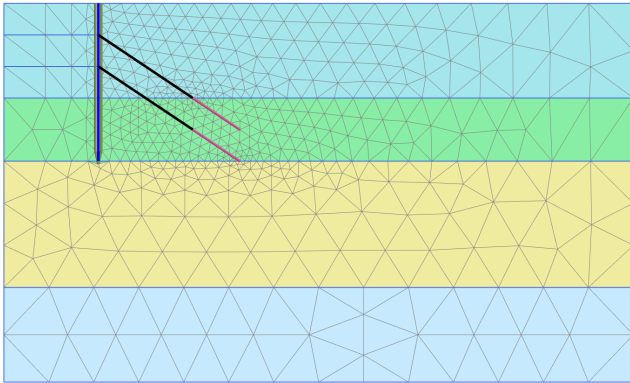


Figure 2.4: Medium finite element mesh

The mesh is automatically refined around the wall and anchors and needs no further refinement.

2.5 Staged construction mode

Change to the *Staged construction* mode to define the construction phases for this project. The entire construction process consists of five phases. Define the phases, as shown graphically below.

2.5.1 Initial phase

For the initial phase make sure that:

- all the the soil layers are activated (coloured)
- all stuctures are deactivated (grey)

2.5.2 Phase 1: First excavation

In the first calculation phase, the diaphragm wall is activated and the first excavation takes place. See figure2.5.

- Click on the *Add phase* button () in the *Phases explorer* to add the first calculation phase.
- Select the *Activate* button () and click on the 4 parts of the wall to activate the complete wall. Note that this will automatically also activate the interfaces on both sides of the wall.
- Also click on the soil representing the first excavation to deactivate the soil.

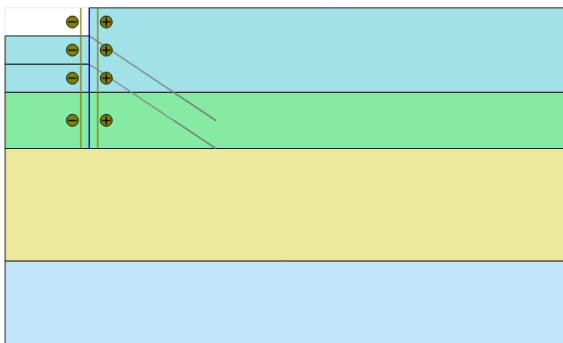


Figure 2.5: Phase 1: activation of the wall and 1st excavation

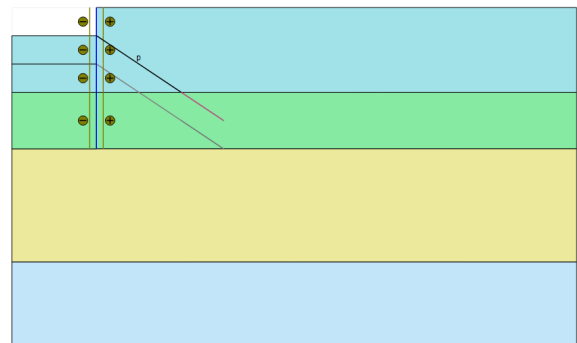


Figure 2.6: Phase 2: activation and prestressing of the 1st anchor

2.5.3 Phase 2: Install first anchor

In the second phase a new option is used: the prestressing of anchors.

- Add a new calculation phase in the *Phases explorer*.
- Select the *Activate* button () and click on the grout body (the embedded beam) of the upper anchor to activate it.
- Then click on the anchor rod (node-to-node anchor) to also activate the anchor rod.

Now that the grout anchor is active, it needs to be prestressed:

- Select the *Select* button () and select the anchor rod of the upper anchor, hence the node-to-node anchor.
- In the *Selection explorer* click on the option *Adjust prestress* that can be found as part of the node-to-node anchor. A checkbox now appears.
- Select the checkbox (so that it's checked). An extra input field $F_{prestress}$ now appears. Fill in a prestress of 300 kN, see figure 2.7.

In the geometry a black node-to-node anchor indicates that the anchor is activated. The letter "p" indicates that a prestress force will be active in the anchor.

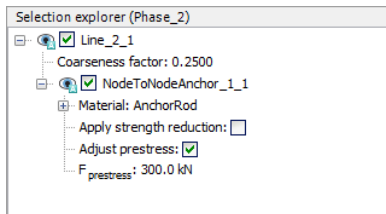


Figure 2.7: Adjusting the prestress force of a node-to-node anchor

2.5.4 Phase 3, 4 and 5

Now define the remaining phases according to figures 2.8, 2.9 and 2.10.

- In phase 3 excavate the second part of the excavation
- In phase 4 activate the lower anchor and prestress it to 300 kN/m
- In phase 5 excavate the remaining 3rd part.

Hint: When processing an anchor in a certain calculation phase the anchor force will exactly match the prestress force at the end of that phase. In following calculation phases without prestressing, the anchor force will be influenced by the excavation process.

2.5.5 Calculate

When all phases are defined, press the *Calculate* () button. Ignore the warning to select nodes for curves.

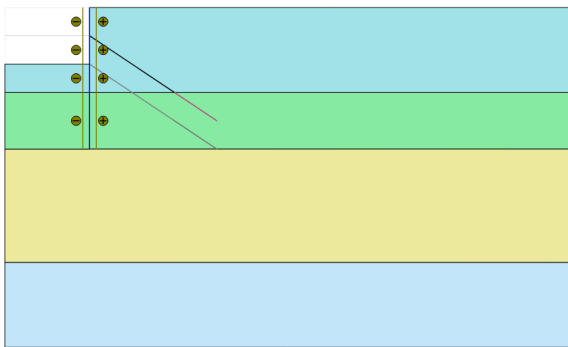


Figure 2.8: Phase 3: Second excavation

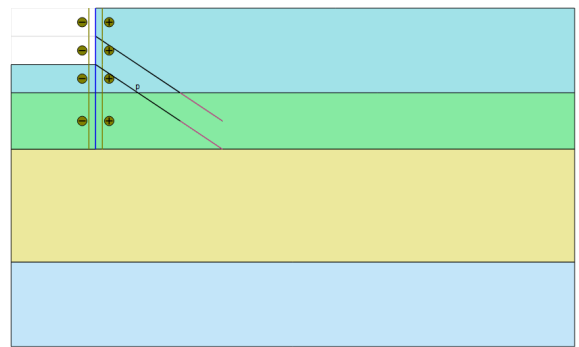


Figure 2.9: Phase 4: Activation and prestressing of 2nd anchor

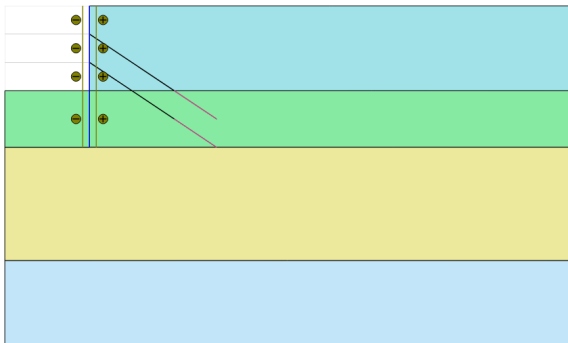


Figure 2.10: Phase 5: Final excavation

Output

3.1 Deformations and structural forces

After calculation, press the *View calculation results* button () to inspect the results.

The results of phase 5 are presented in figure 3.1. After this final stage the calculated excavation bottom heave is 5-6 cm.

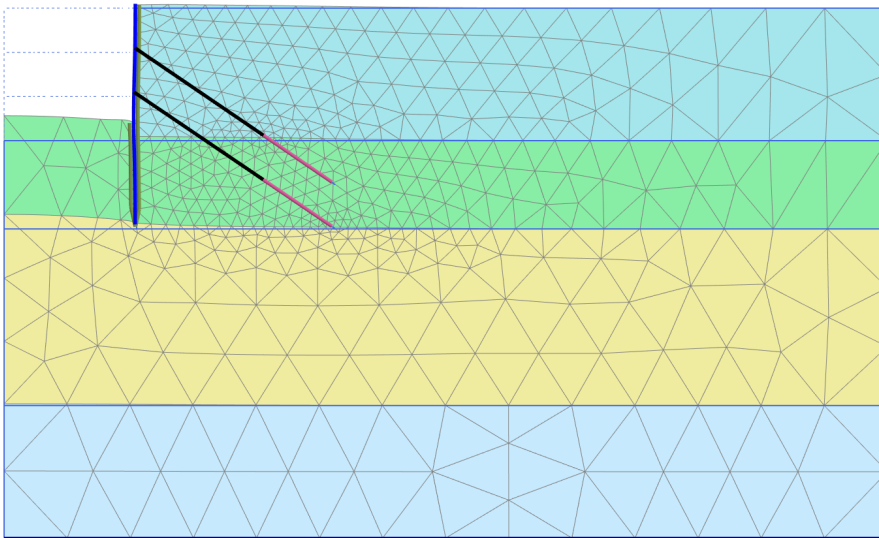


Figure 3.1: Deformed mesh (phase 5)

- Select the button *Select structures* () and double click on a node-to-node anchor. Plaxis will present a table in which the stress of the anchor can be inspected. Anchor forces are approximately 330 kN where the lower anchor has a slightly higher anchor force than the upper anchor.
- When double-clicking on one of the embedded beams the change of axial forces within the grout body can be investigated. For both grout bodies the axial forces equals the anchor force where it's connected to the node-to-node anchors. The axial decreases almost linearly over the length of the grout body.
- By double-clicking on the wall the structural forces in the wall can be inspected. The maximum bending moment should be in the order of 350 kNm/m (figure 3.2)
- When double-clicking on an interface only the results of part of the interface can be seen. In order to see the results for the whole interface chain without the extension below the wall, keep <Shift> pressed on the keyboard while selecting the parts of the interface that are next to the wall on both sides. After selecting all parts, double-click on the interface while keeping the <Shift> key pressed. In figure 3.3 the left side are the passive earth pressures and the right side are the active earth pressures. It can be seen that only a small part of the maximum passive earth pressures has been mobilized at this stage.

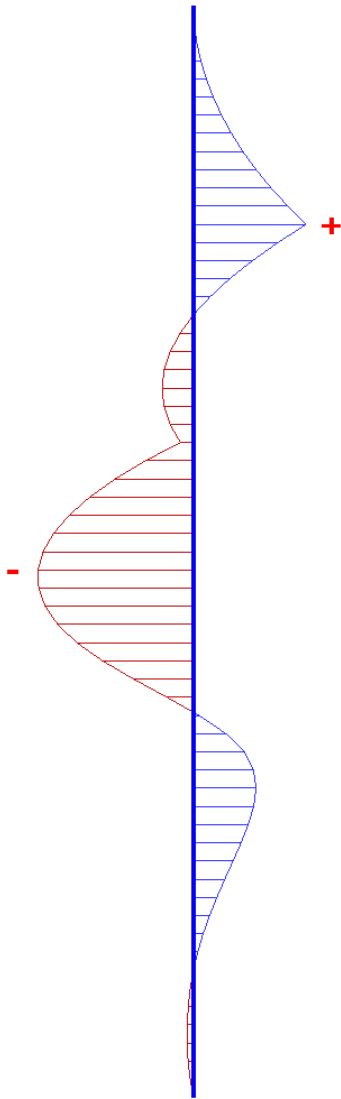


Figure 3.2: Bending moments in the secant wall

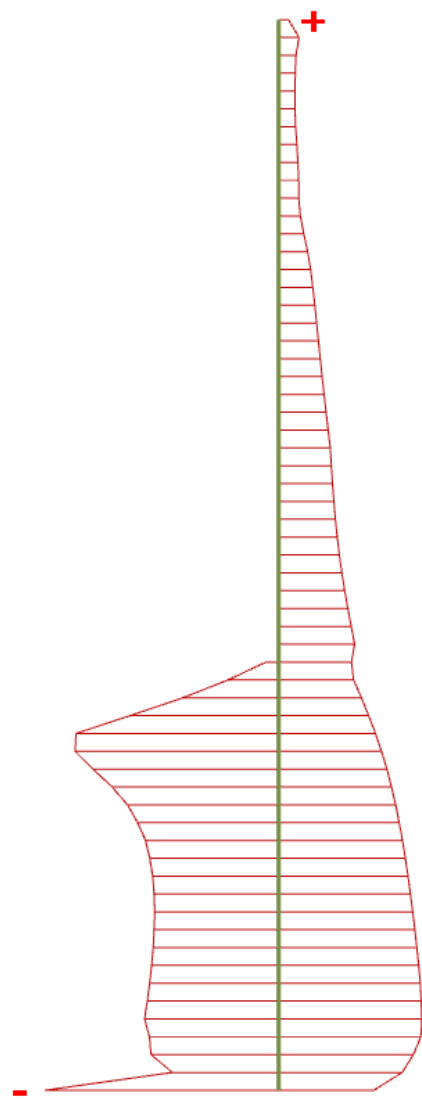


Figure 3.3: Effective normal stresses in the interface

A

Determination of soil parameters from triaxial test

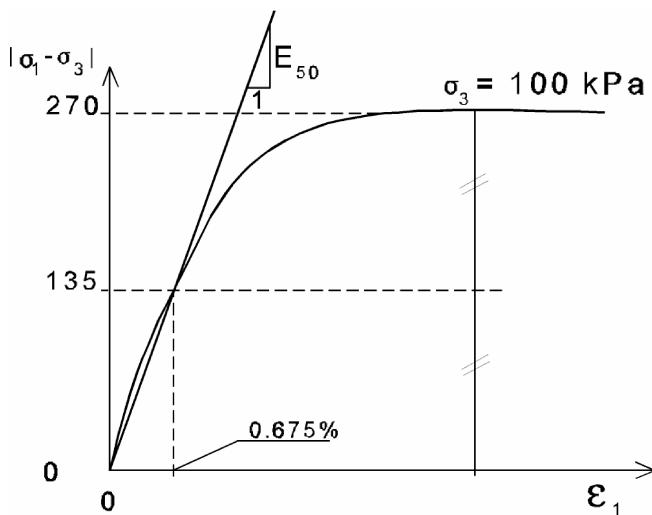


Figure A.1: Triaxial test for sand layer

A.1 Strength parameters

Fill in σ_1 and σ_3 in the Mohr-Coulomb criteria:

$$\sigma_1 - \sigma_3 = (\sigma_1 + \sigma_3) \sin \varphi + 2c \cos \varphi$$

Since the cohesion will be small, assume $c = 0$:

$$\frac{\sigma_1 - \sigma_3}{\sigma_1 + \sigma_3} = \sin \varphi$$

$$\frac{370 - 100}{370 + 100} = \sin \varphi$$

$$\varphi = 35^\circ$$

$$\psi = \varphi - 30 = 5^\circ$$

For reasons of numerical stability, use $c = 1$ kPa

A.2 Stiffness parameters

Since excavation is considered in this exercise, the input of Young's modulus E should be based on unloading, rather than on primary loading. For the same reason, Poisson's ratio should also be based on unloading, which results in a somewhat lower value.

The triaxial test has a cell pressure $\sigma_3 = 100$ kPa. This corresponds with reference pressure, so $E_{50} = E_{50}^{ref}$.

$$E_{50} = \frac{\Delta \sigma_u}{\Delta \epsilon_v} = \frac{135}{0.675\%} = 2.0 \cdot 10^4$$

Assume that $E_{ur} \approx 4 \cdot E_{50}$

For improved modelling, four regions are distinguished, for each individual layer an average stiffness is determined by using:

$$E_{50} = E_{50}^{ref} \sqrt{\frac{\sigma_3}{p^{ref}}}$$

We distinguish:

- Top layer (from top to - 15 m)
- Middle layer (from -15 m to -25 m)
- Lower layer (from -25 m to -45 m)
- Deep layer (from -45 m to -60 m)

A.2.1 Top layer

- $\sigma_3 = depth \cdot \gamma_{soil} \cdot K_0$
 σ_3 = average horizontal stress (reference point at -7.5 m)
 $\sigma_3 = 7.5 \cdot 18 \cdot (1 - \sin \varphi) = \mathbf{58 \text{ kPa}}$
 $E_{50}^{top} = 2.0 \cdot 10^4 \sqrt{\frac{58}{100}} \approx 1.5 \cdot 10^4 \text{ kPa}$
 $E' = E_{ur}^{top} \approx 4 \cdot E_{50}^{top} = \mathbf{6.0 \cdot 10^4 \text{ kPa}}$

A.2.2 Middle layer

- $\sigma_3 = 20 \cdot 18 \cdot (1 - \sin \varphi) = \mathbf{153 \text{ kPa}}$
 $E_{50}^{middle} = 2.0 \cdot 10^4 \sqrt{\frac{153}{100}} \approx 2.5 \cdot 10^4 \text{ kPa}$
 $E' = E_{ur}^{middle} \approx 4 \cdot E_{50}^{middle} = \mathbf{1.0 \cdot 10^5 \text{ kPa}}$

A.2.3 Lower layer

- $\sigma_3 = 35 \cdot 18 \cdot (1 - \sin \varphi) = \mathbf{269 \text{ kPa}}$
 $E_{50}^{middle} = 2.0 \cdot 10^4 \sqrt{\frac{269}{100}} \approx 3.3 \cdot 10^4 \text{ kPa}$
 $E' = E_{ur}^{middle} \approx 4 \cdot E_{50}^{middle} = \mathbf{1.31 \cdot 10^5 \text{ kPa}}$

A.2.4 Deep layer

- $\sigma_3 = 52.5 \cdot 18 \cdot (1 - \sin \varphi) = \mathbf{403 \text{ kPa}}$
 $E_{50}^{deep} = 2.0 \cdot 10^4 \sqrt{\frac{403}{100}} \approx 4.0 \cdot 10^4 \text{ kPa}$

The deep layer is supposed to be at such a distance from the excavation that it has very small deformations resulting in a very stiff behaviour.

$$E' = E_0^{deep} \approx 12 \cdot E_{50}^{deep} = \mathbf{4.8 \cdot 10^5 \text{ kPa}}$$

Assume for all layers $\nu = 0.2$ based on unloading.

B

Material properties secant wall

For a plane strain model material properties for the secant wall have to be specified per meter length of the wall. In order to do so we first recognize the secant wall as consisting of repetitive parts at a certain intermediate distance, as shown in Figure B.1.

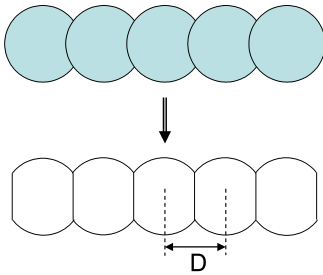


Figure B.1: Secant wall as repetitive equal sections

Compared to the original bored piles the repetitive sections have a reduced cross sectional area. Though it can be analytically derived how much the reduction is, the fastest way to determine this is to draw the repetitive section on paper with a fine grid based on the original bored piles with a diameter of 1000mm and an overlap of 200mm and count squares. Using this method the cross sectional area of the repetitive section is determined as $A_s = 0.74 \text{ m}^2$. Since the sections are at a distance D apart where D is given as 800mm, the cross sectional area of the wall per meter is given as: $A_{wall} = \frac{A_s}{D} = \frac{0.74}{0.8} = 0.93 \text{ m}^2/\text{m}$

For the moment of inertia is assumed that the influence of the reduced cross sectional area is negligible as the reduction is close to the axis of bending and symmetric. Therefore the moment of inertia per meter wall is determined as:

$$I_{wall} = \frac{I_{pile}}{D} = \frac{\pi r^4}{4D} = \frac{\pi \cdot (0.5)^4}{4 \cdot 0.8} = 61.3 \cdot 10^{-3} \text{ m}^4/\text{m}$$

With $E_{concrete} = 2.7 \cdot 10^7 \text{ kN/m}^2$ this gives

$$EA = (2.7 \cdot 10^7)(0.93) = 2.5 \cdot 10^7 \text{ kN/m}$$

$$EI = (2.7 \cdot 10^7)(61.3 \cdot 10^{-3}) = 1.67 \cdot 10^6 \text{ kNm}^2/\text{m}$$

And for the weight:

$$w = \gamma \cdot A = 16 \cdot 0.93 = 15 \text{ kN/m/m}$$