4

Stability of a diaphragm wall excavation

This lesson is concerned with a diaphragm wall that is constructed in a stiff sandy clay layer with a groundwater level at 1.0 m below the surface. The excavation process of a diaphragm wall is executed in a specific sequence to obtain the maximum support from the surrounding soil and to prevent soil collapse. A diaphragm wall consists of a number of individually constructed sections. The construction of one such section is modelled in this exercise.

Objectives

- Defining user-defined water conditions
- Modelling of diaphragm walls installation

Geometry

A single diaphragm section is excavated in three parts, and the construction can be modelled in five phases. In the first three phases, the wall is excavated part by part in the sequence as shown in Figure 51 (on page 74). During the excavation, fluid bentonite with a unit weight of 11 kN/m^3 is simultaneously pumped in the trench so that the bentonite pressure and the arching in the soil prevents the surrounding soil from collapse. After digging of the trench has been completed, in the fourth phase, fluid concrete is poured in the trench replacing the bentonite. In the fifth phase the concrete hardens, and the diaphragm wall section is complete. The stability of the excavation is lowest in the third phase, when the section is entirely excavated and filled with bentonite. A safety factor is calculated through a phi-c reduction procedure after each phase to observe the stability of the excavation.

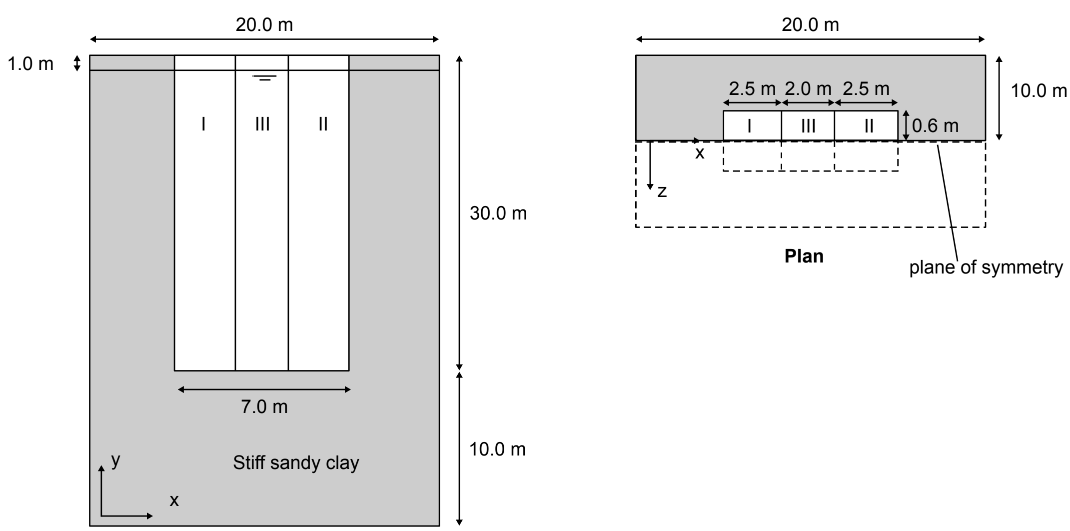

Figure 51: Geometry of the diaphragm wall

4.1 Create a new project

The diaphragm wall considered in this exercise is 30 m deep and 1.2 m thick. One section is 7.0 m wide and consists of three excavation parts; part I and II are 2.5 m wide and part III is 2.0 m wide. The wall is symmetric about its central plane, so only one half of the thickness needs to be modelled. The interaction between the wall and the soil is considered to be fully rough, therefore interfaces are not required.

To define the geometry for this exercise, follow these steps:

1. Start the **Input** program and select **New project** from the **Create/Open project** dialog box.
2. Enter an appropriate title for the project.
3. Keep the standard units and set the model dimensions to:
   a. x_{min} =0 and x_{max} = 20,
   b. y_{min} = 0 and y_{max} = 10.
4. Click **OK**.

4.2 Define the soil stratigraphy

In the current example only one horizontal soil layer is present. A single borehole is sufficient to define it.

1. Click the **Create borehole** button and create a borehole at (0 0 0).
   The **Modify soil layers** window pops up.
2. In the **Modify soil layers** window add a soil layer with top boundary at z = 40m and bottom boundary at z = 0m.
3. Set the **Head** to 39m.

4.3 Create and assign the material data sets

The material properties for the data sets are shown in Table 12 (on page 75).

Table 12: Material properties for the soil and concrete

Property	Name	Stiff sandy clay	Concrete	Unit
General				
Soil model	Model	Mohr-Coulomb	Linear Elastic	-
Drainage type	Type	Drained	Non-porous	-

Property	Name	Stiff sandy clay	Concrete	Unit
General				
Unsaturated unit weight	γ_{unsat}	15	24	kN/m^3
Saturated unit weight	γ_{sat}	20	-	kN/m^3
Mechanical				
Young's modulus	E'_{ref}/ E_{ref}	$50 \cdot 10^3$	$2.6 \cdot 10^7$	kN/m^2
Poisson's ratio	ν *(nu)*	0.3	0.2	kN/m^2
Cohesion	c'_{ref}	15	-	kN/m^2
Friction angle	φ' *(phi)*	30	-	°
Dilatancy angle	ψ *(psi)*	0.0	-	°
Interfaces				
Strength determination	-	Rigid	Rigid	-
Initial				
K_0 determination	-	Automatic	Automatic	-

1. Click the **Materials** button.
2. Create the data sets for the soil layer and the concrete as specified in Table 12 (on page 75).
3. Assign the 'Stiff sandy clay' material data set to the soil layer and close the **Material sets** window.

4.4 Definition of the diaphragm wall

The diaphragm wall is modelled in the **Structures mode.** The volume elements composing the diaphragm wall are generated by extruding rectangular surfaces.

The coordinates for the surfaces are given in Table 13 (on page 77):

Table 13: Surfaces composing the diaphragm wall

Segment	Point coordinates
I	(6.5 0 40) (9 0 40) (9 0.6 40) (6.5 0.6 40)
II	(11 0 40) (13.5 0 40) (13.5 0.6 40) (11 0.6 40)
III	(9 0 40) (11 0 40) (11 0.6 40) (9 0.6 40)

1. Click the **Create surface** button in the side toolbar and create three surfaces accordingly to Table 13 (on page 77).
2. Select the created surfaces by keeping the **<Ctrl>** key pressed while clicking them in the model.
3. Click the **Extrude object** button in the side toolbar. Set the extrusion vector to (0 0 -30) and the extrusion vector length to 30 as displayed in Figure 52 (on page 77).

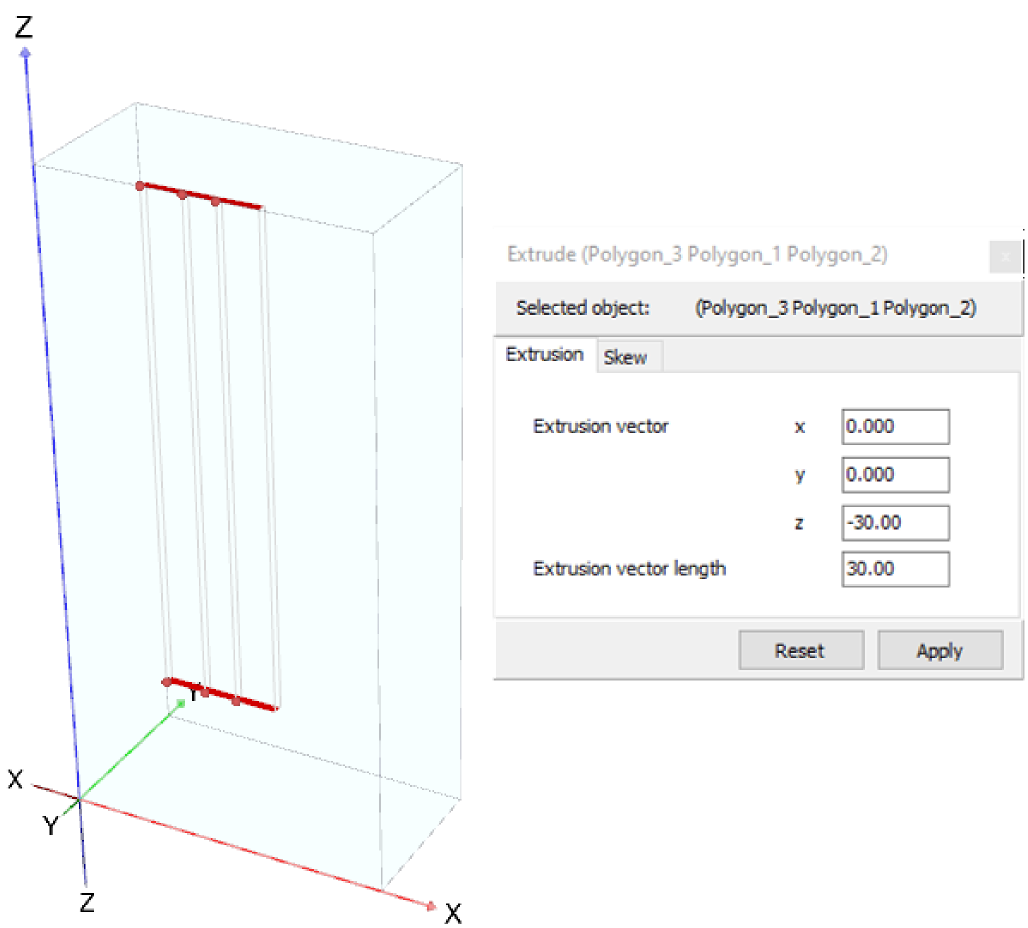

Figure 52: Extruded surfaces

4. Delete the surfaces.

4.5 Generate the mesh

In order to generate the mesh:

1. Click on the **Mesh** tab to proceed to the **Mesh mode**.
2. Multi-select all the volume elements of the diaphragm wall.
3. In the **Selection explorer** set the value of **Coarseness factor** to 0.50.
4.  Click the **Generate mesh** button. The default option (**Medium**) is used to generate the mesh.
5.  Click the **View mesh** button to inspect the generated mesh (See Figure 53 (on page 78)).

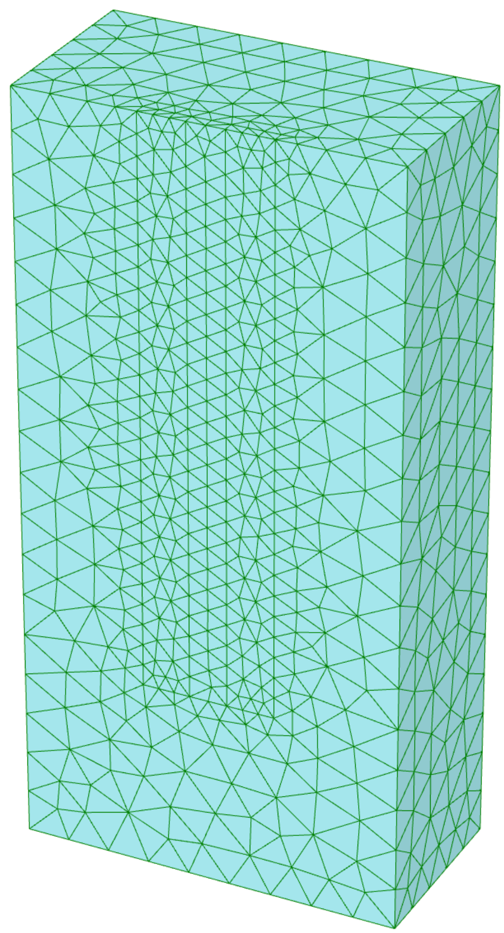

Figure 53: The generated mesh

6. Proceed to the **Staged construction mode**.

4.6 Define the calculation

The calculation consists of five phases. In the first phase, part I of the excavation is removed and simultaneously filled with bentonite. The bentonite, with a unit weight of 11 kN/m^3, is simulated employing an artificial 'water' pressure that increases linearly with depth. This pressure replaces the original water pressure inside the excavation. In the second and third phases of the excavation parts, II and III are removed and filled with bentonite. In the fourth phase, the entire excavated trench is filled with fluid concrete. The fluid concrete with a unit weight of 24 kN/m^3 is simulated by a change in the artificial 'water' pressure. In phase 5, the hardening of the concrete is simulated by removing the artificial pressures, reactivating the excavated clusters and assigning the concrete material set to these clusters.

4.6.1 Initial phase

The initial phase consists of the generation of the initial stresses using the **K0 procedure**. The default settings for the initial phase are valid.

4.6.2 Phase 1 - Excavation of part I

1. Add the first calculation phase.
2. Select the first excavation volume (part I).
3. In the selection explorer (see Figure 54 (on page 79)), deactivate the soil volume. Set the water condition to **User-defined** and enter z_{ref} = 40 m, p_{ref} = 0.0 kN/m^2 and p_{inc} = -11 kN/m^2/m.

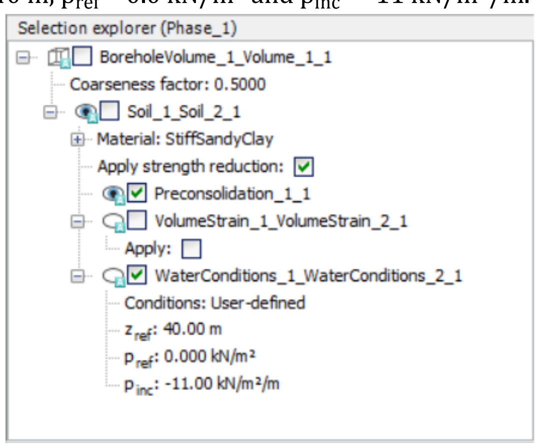

Figure 54: User-defined water condition in part I

A bentonite pressure is now defined in part I of the excavation, starting at 0 kN/m^2 at the reference level of 40 m and increasing at 11 kN/m^2 per m depth, resulting in 330 kN/m^2 at the bottom of the excavation.

4. Click the **Preview phase** button to check the settings for the current phase.

4.6.3 Phase 2 - Excavation of part II

1. Add a new phase.
2. Select the second excavation volume (part II).
3. In the selection explorer, deactivate the soil volume. Set the water condition to **User-defined** and enter z_{ref} = 40 m, p_{ref} = 0.0kN/m^2 and p_{inc} = -11 kN/m^2/m.

4.6.4 Phase 3 - Excavation of part III

1. Add a new phase.
2. Select the third excavation volume (part III).
3. In the selection explorer, deactivate the soil volume. Set the water condition to **User-defined** and enter z_{ref} = 40 m, p_{ref} = 0.0kN/m^2 and p_{inc} = -11kN/m^2/m.

4.6.5 Phase 4 - Fluid concrete

The bentonite in the excavation is now replaced by fluid concrete with a weight of 24.0kN/m^3.

1. Add a new phase.
2. Select the three excavation volumes.
3. In the selection explorer, change the **User-defined** water conditions and enter p_{inc}= -24kN/m^2/m. The other parameters must be kept at their original values (z_{ref} = 40m, p_{ref} = 0.0kN/m^2).

4.6.6 Phase 5 - Cured concrete

1. Add a new phase.
2. Select the three excavation volumes.
3. the selection explorer, reactivate the soil volumes and set the material to concrete.
4. Set the water condition to **Dry**.

Note:

Although the concrete is non-porous and the calculation program will automatically assume zero pore pressures in these elements, it is a good practise to regenerate the water pressures such that the generated pore pressures correspond to those used in the calculation program.

4.6.7 Phase 6 to 9 - Safety analysis

In Phases 6 to 9, stability calculations are defined for the previous phases respectively except for the fluid concrete phase (less critical than the bentonite phase thanks to the higher unit weight). Phase 3 should be the most critical because the support pressure from the bentonite is low. Also, the excavation is at its full width, which reduces the possibility for lateral arching. A check on whether Phase 3 is the most critical stage can be carried out by calculating the safety factors for the first three phases through a **Safety** analysis.

1. Select Phase_1 in the **Phases explorer**.
2. Add a new calculation phase and proceed to the **Phases** window.
3. Set **Calculation type** to **Safety**. The **Incremental multipliers** option is valid as **Loading type.**
4. In the **Deformation control** subtree select the **Reset displacements to zero** option.
5. In the **Numerical control parameters** subtree set the **Max steps** parameter to 40.
6. Follow the same procedure to add **Safety** analysis phases following phases 2, 3 and 5.

4.6.8 Execute the calculation

1. In the **Staged construction mode** select some nodes near (10 1 40) and (10 4.5 40) for curves.
2. Start the calculation process.
3. Save the project when the calculation is finished.

4.7 Results

The stability of the excavation can be evaluated from the calculated safety factor after each excavation stage. Use the Curves program to plot ΣMsf (the safety factor) as a function of the displacements |u| (see Figure 55 (on page 82)). In Phase 3, the stability is the lowest. However, ΣMsf remains greater than 1 and so collapse would not be expected.

In order to evaluate the safety factors for the three situations in this way, follow these steps:

1. Click the **Curves manager** button in the toolbar.
2. Click **New** in the **Charts** tabsheet.
3. In the **Curve generation** window, select one of the two nodes for the x-axis. Select **Deformations** > **Total displacements** > **|u|**.
4. For the **y**-axis, select **Project** and then select **Multiplier** > **ΣMsf**. The Safety phases are considered in the chart. As a result, the curve of Figure 55 (on page 82) appears.
5. Set x-axis interval maximum to 0.1 and for y-axis set 7.0 in **Chart** tab.

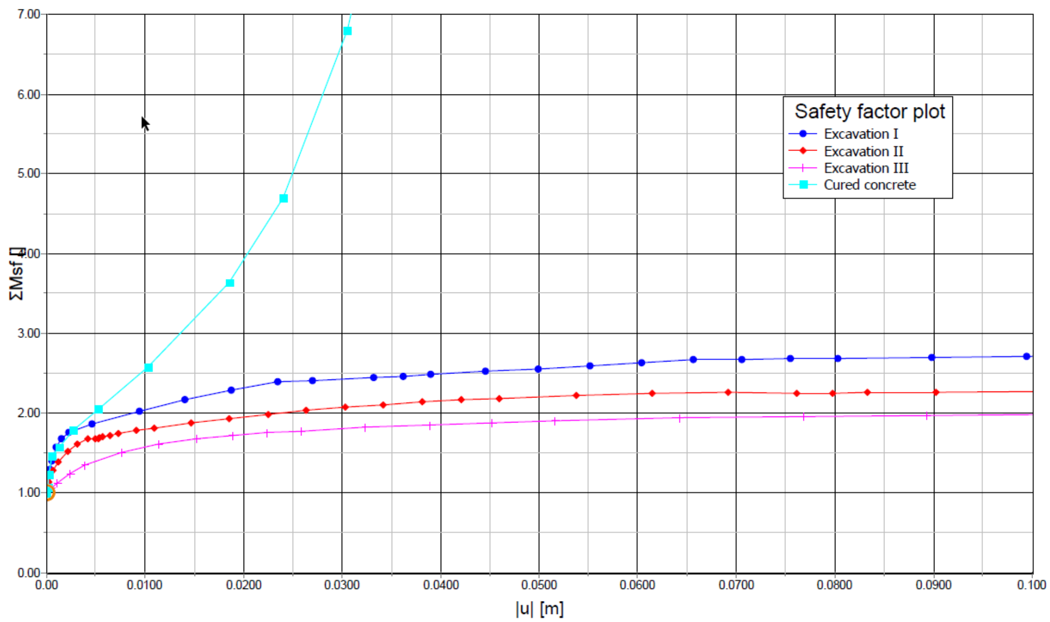

Figure 55: ΣMsf (safety factor) as a function of the total displacement

An important phenomenon that keeps the excavation stable is arching in the soil. This phenomenon is shown in Figure 56 (on page 82), Figure 57 (on page 83) and Figure 58 (on page 83). To see the principal stresses directions at a chosen depth, make a horizontal cross section by clicking the **Horizontal cross section** button.

1.  To create such plots, make a horizontal cross-section by clicking the **Horizontal cross section** button in the side bar.
2. In the window that appears fill in a cross section height of 25 m (at the mid-height of the diaphragm wall).
3. Select the menu item **Stresses** > **Principal total stresses** > **Total principal stresses**.
4.  Select the top view in **View** > **Viewpoint** to reorientate the model in order to obtain a clearer view of the arch effect.

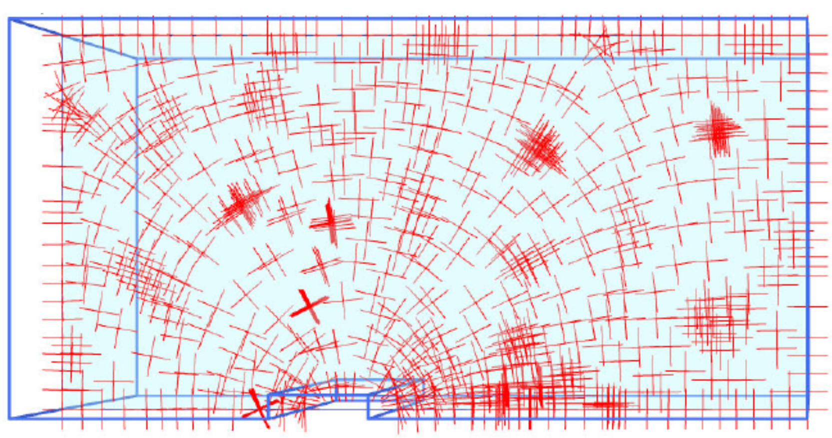

Figure 56: Principal stresses directions at z = 25 m at the end of Phase_1

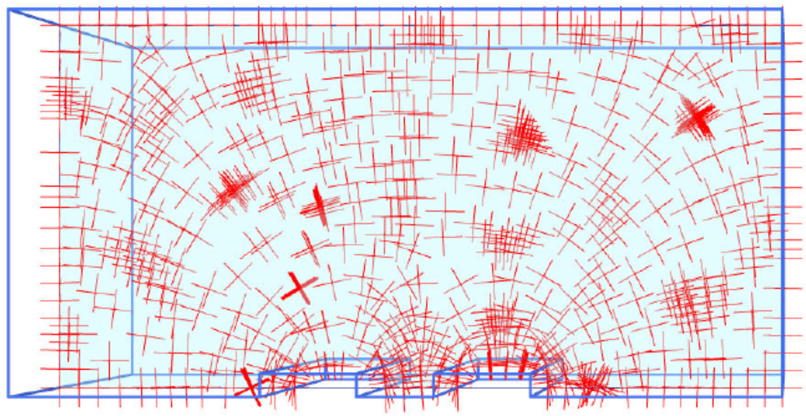

Figure 57: Principal stresses directions at z = 25 m at the end of Phase_2

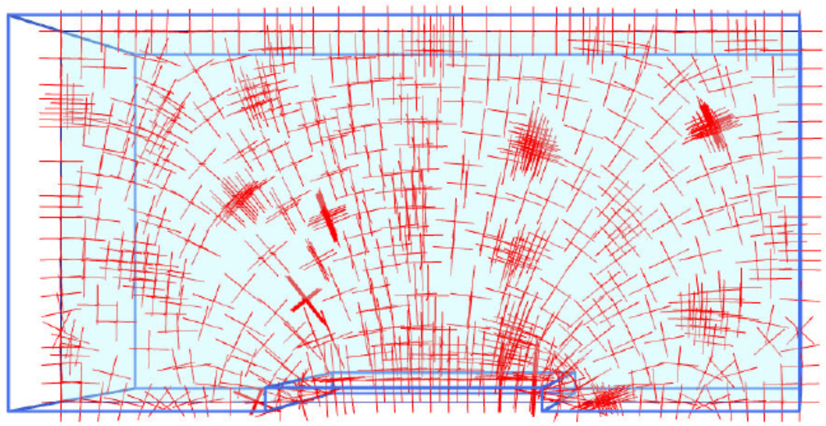

Figure 58: Principal stresses directions at z = 25 m at the end of Phase_4