7

Rapid drawdown analysis [ULT]

7.1 Introduction

This example concerns the stability of a reservoir dam under conditions of drawdown. Fast reduction of the reservoir level may lead to instability of the dam due to high pore water pressures that remain inside the dam. The dam consists of a clay core with a well graded fill at both sides. The subsoil consists of overconsolidated silty sand.

Objectives

- Performing fully coupled flow deformation analysis.
- Defining time-dependent hydraulic conditions.
- Using unsaturated flow parameters.

7.2 Geometry

The dam to be considered is 30m high. The top width and the base width of the dam are 5m and 172.5m respectively. The geometry of the dam is depicted below. The normal water level behind the dam is 25m high. A situation is considered where the water level drops 20m. The normal phreatic level at the right hand side of the dam is 10m below ground surface.

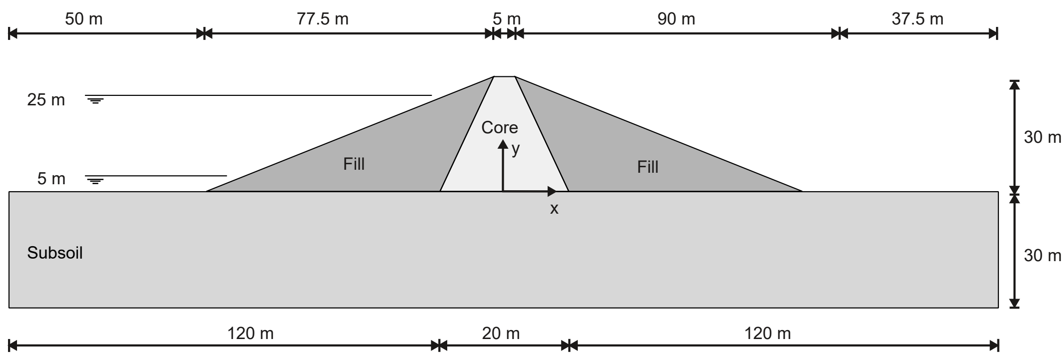

Figure 7–1: Geometry of the project

7.3 Create a new project

Assuming the dam is located in a wide valley, a representative length of 50 m is considered in the model in order to decrease the model size.

To create the geometry model, follow these steps:

1. Start the Input program and select **Start a new project** from the **Quick select** dialog box.
2. In the **Project properties** window, enter an appropriate title.
3. Keep the default units and set the model dimensions to:
   - **a.** x_{min} = -130.0m, x_{max} = 130.0m
   - **b.** y_{min} = 0m and y_{max} = 50.0m

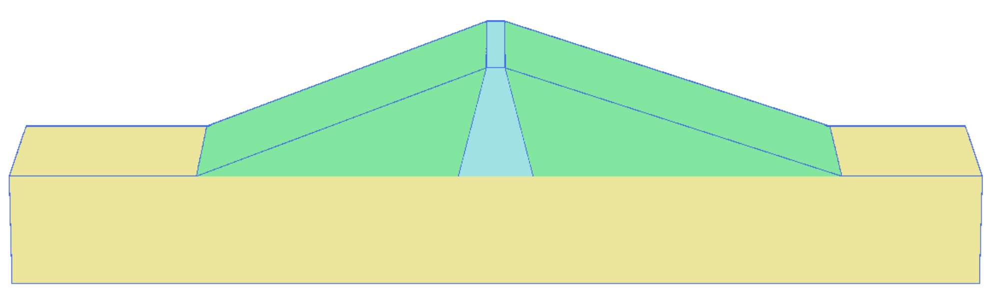

Figure 7–2: The geometry of the model

7.4 Define the soil stratigraphy

In order to define the underlying foundation soil, a borehole needs to be added and material properties must be assigned. A layer of 30m overconsolidated silty sand is considered as sub-soil in the model.

1. Create a borehole at (0.0 0.0).

   The **Modify soil layers** window pops up.

2. Add a soil layer extending from ground surface (z = 0) to a depth of 30m (z= -30).
3. Set the **Head** in the borehole to -10m. A horizontal water level will be automatically generated. This water level in combination with surface groundwater flow boundary conditions will be used in the **Fully coupled flow deformation** analyses.

7.5 Create and assign material data sets

Three material data sets need to be created for the soil layers.

The layers displayed on Table 7–1 (p. 134) have the properties:

Table 7–1: Material properties of the dam and subsoil

Property	Name	Core	Fill	Subsoil	Unit
General					
Soil model	Model	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	-
Draining type	Type	Undrained (B)	Drained	Drained	-
Unsaturated unit weight	γ_{unsat}	16.0	16.0	17.0	kN/m^3
Saturated unit weight	γ_{sat}	18.0	20.0	21.0	kN/m^3
Mechanical					
Young's modulus	E'_{ref}	$1.5 \cdot 10^3$	$2.0 \cdot 10^4$	$5.0 \cdot 10^4$	kN/m^2
Poisson's ratio	$\nu (nu)$	0.35	0.33	0.3	-
Young's modulus inc.	E'_{inc}	300	-	-	$kN/m^2/m$
Reference level	z_{ref}	30	-	-	m
Undrained shear strength	$s_{u,ref}$	5.0	-	-	kN/m^2
Cohesion	c'_{ref}	-	5.0	1.0	kN/m^2
Friction angle	φ'	-	31	35.0	°
Dilatancy angle	ψ	-	1.0	5.0	°

Mechanical					
Undrained shear strength inc.	$s_{u,inc}$	3.0	-	-	kN/m^3
Groundwater					
Classification type	Model	Hypres	Hypres	Hypres	-
SWCC fitting method	-	Van Genuchten	Van Genuchten	Van Genuchten	-
Subsoil/Topsoil	-	Subsoil	Subsoil	Subsoil	-
Soil class	-	Very fine	Coarse	Coarse	-
Permeability in horizontal direction	k_x	$1.0 \cdot 10^{-4}$	0.25	0.01	m/day
Permeability in horizontal direction	k_y	$1.0 \cdot 10^{-4}$	0.25	0.01	m/day
Permeability in vertical direction	k_z	$1.0 \cdot 10^{-4}$	0.25	0.01	m/day

To create the material sets, follow these steps:

1. Open the **Material sets** window.
2. Create data sets under **Soil and interfaces** set type according to the information given in Table 7–1 (p. 134). Note that the **Interfaces** and **Initial** tabsheets are not relevant (no interfaces or **K0 procedure** used).
3. Assign the **Subsoil** material dataset to the soil layer in the borehole.

7.6 Define the dam

The dam will be defined in the **Structures mode** .

1. Define a surface by specifying points located at (-80 0 0), (92.5 0 0), (2.5 0 30) and (-2.5 0 30).
2. Define a surface by specifying points located at (-10 0 0), (10 0 0), (2.5 0 30) and (-2.5 0 30).
3. Multi-select the created surfaces and right-click on the drawing area. Select the **Intersect and recluster** menu item.
4. Multi-select the surfaces and extrude along (0 50.0 0) The volumes representing the dam are generated.
5. Delete the surfaces used to create the soil volumes.
6. Assign the corresponding material data sets to the soil volumes.
7. Time dependent conditions can be assigned to surface groundwater flow boundary conditions. Define surface groundwater flow boundary conditions (under the **Create hydraulic conditions** tool) according to the information in Table 7–2 (p. 136).

Table 7–2: Surface groundwater flow boundary conditions

Surface	Points
1	(-130 0 0), (-80 0 0), (-80 50 0), (-130 50 0)
2	(-80 0 0), (-2.5 0 30), (-2.5 50 30), (-80 50 0)
3	(-130 0 0), (-130 0 -30), (-130 50 -30), (-130 50 0)

7.7 Generate the mesh

For the generation of the mesh it is advisable to set the **Element distribution** parameter to **Fine**.

To modify the global coarseness:

1. Click the **Generate mesh** button in the side toolbar. The **Mesh options** window is displayed.
2. Select the **Fine** option form the **Element distribution** drop-down (See Figure 7–3 (p. 136)):

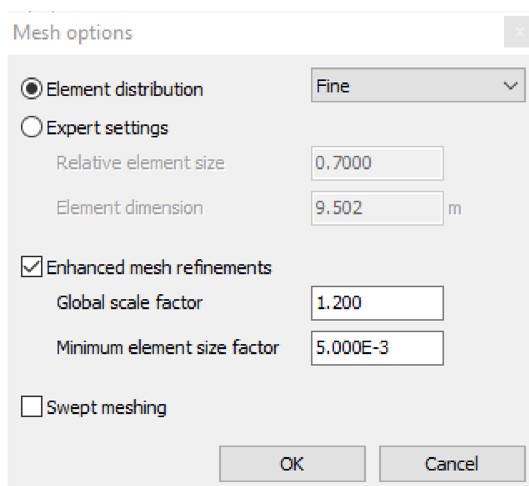

Figure 7–3: Modification of the Global coarseness

3. Click **OK** to close the **Mesh options** window and to generate the mesh.
4. Click the **View mesh** button in the side toolbar to preview the mesh. The resulting mesh is displayed on Figure 7–4 (p. 137):

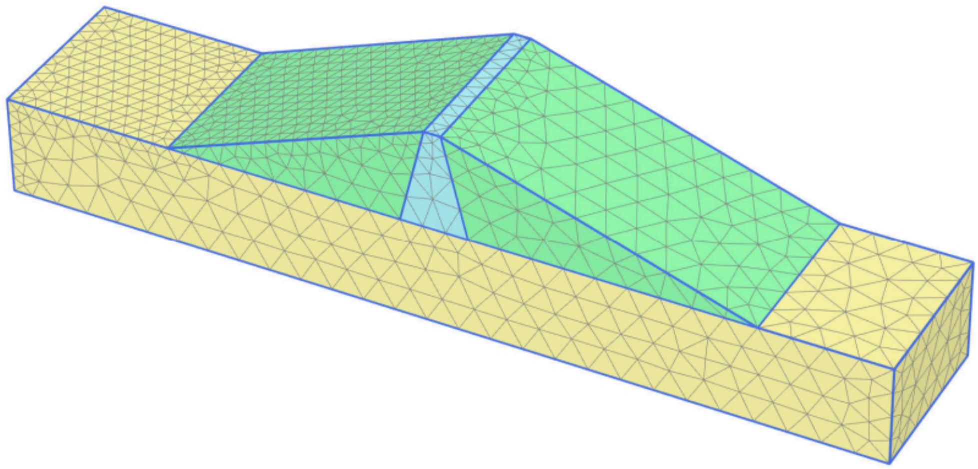

Figure 7–4: The generated mesh

7.8 | Define and perform the calculation

In the calculation process the following cases will be considered:

- Initial state (high reservoir) - A long term situation with water level at 25m.
- The rapid drawdown case - A quick drop of the water level from 25 to 5m.
- The slow drawdown case - A slow drop of the water from 25 to 5m.
- The low water level case - A long term situation with water level at 5m.

In addition to **Initial phase**, the calculation consists of eight phases. In the initial phase, initial stresses and initial pore water pressures of the dam under normal working conditions are calculated using **Gravity loading**. For this situation the water pressure distribution is calculated using a steady-state groundwater flow calculation. The first and second phases both start from the initial phase (i.e. a dam with a reservoir level at 25m) and the water level is lowered to 5m. A distinction is made in the time interval at which this is done (i.e. different speeds of water level reduction; rapid drawdown and slow drawdown). In both cases the water pressure distribution is calculated using a fully coupled flow-deformation analysis. The third calculation phase also starts from the initial phase and considers the long-term behaviour of the dam at the low reservoir level of 5m, which involves a steady-state groundwater flow calculation to calculate the water pressure distribution. Finally, for all the water pressure situations the safety factor of the dam is calculated by means of phi-c reduction.

1. Proceed to the **Flow conditions mode**.
2. Create water levels corresponding to the full reservoir and the low water level cases according to the information given in Table 7–3 (p. 137).

Table 7–3: Water levels

Level	Points
High reservoir	(-130 0 25), (-10 0 25), (93 0 -10), (130 0 -10), (130 50 -10), (93 50 -10), (-10 50 25), (-130 50 25)
Low reservoir	(-130 0 5), (-10 0 5), (93 0 -10), (130 0 -10), (130 50 -10), (93 50 -10), (-10 50 5), (-130 50 5)

3. In the **Model explorer** under **Attributes library** rename the created user water levels as `High_Reservoir` and `Low_Reservoir`.

> **Note:**
>
> No modifications, such as **Time dependency** is possible for **Borehole water levels** and non-horizontal **User water levels**.

7.8.1 Initial phase: High reservoir

1. Proceed to the **Staged construction mode**.
2. Double-click the initial phase in the **Phases explorer**.
3. In the **General** subtree of the **Phases** window rename the phase as `High reservoir`.
4. as **Calculation type** select the **Gravity loading** option.

   Note that **Staged construction** is the only option available for **Loading type**.
5. As **pore pressure calculation type** select the **Steady state groundwater flow** option.
6. Note that the options **Ignore undr. behaviour (A,B)** and **Ignore suction** are by default selected in the **Deformation control parameters** subtree. The default values will be used for the parameters in the **Numerical control parameters** and **Flow control parameters** subtrees.
7. Click **OK** to close the **Phases** window.
8. In the **Staged construction mode** activate the soil clusters representing the embankment.
9. In the **Model explorer** expand the **Model conditions** subtree.
10. In the **GroundwaterFlow** subtree set **BoundaryYMin**, **BoundaryYMax** and **BoundaryZMin** to **Closed**. The remaining boundaries should be **Open** (See Figure 7–5 (p. 139)).
11. In the **Water** subtree select the high reservoir water level (High_Reservoir) as **GlobalWaterLevel**.

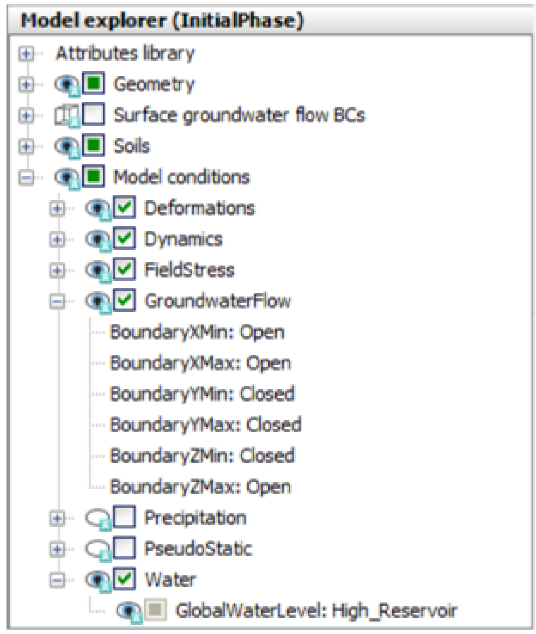

Figure 7–5: Boundary conditions for groundwater flow

7.8.2 Phase 1: Rapid drawdown

In the rapid drawdown phase the water level in the reservoir will be lowered from z = 25m to z = 5m in a period of 5 days. To define the function describing the fluctuation of the water level:

1. Add a new calculation phase.
2. In the **Phases explorer** double-click the newly added phase.

   The **Phases** window is displayed.
3. In the **General** subtree specify the name of the phase (e.g. `Rapid drawdown`).
4. Set the **Calculation type** to **Fully coupled flow-deformation**.
5. In the **Include reference flow analysis** option keep the checkbox unselected. This sets the non-steady state boundary conditions.
6. Set the **Time interval** to 5 days.
7. The **Reset displacements to zero** option is automatically selected in the **Deformation control parameters** subtree.
8. Click **OK** to close the **Phases** window (see Figure 7–6 (p. 140)).

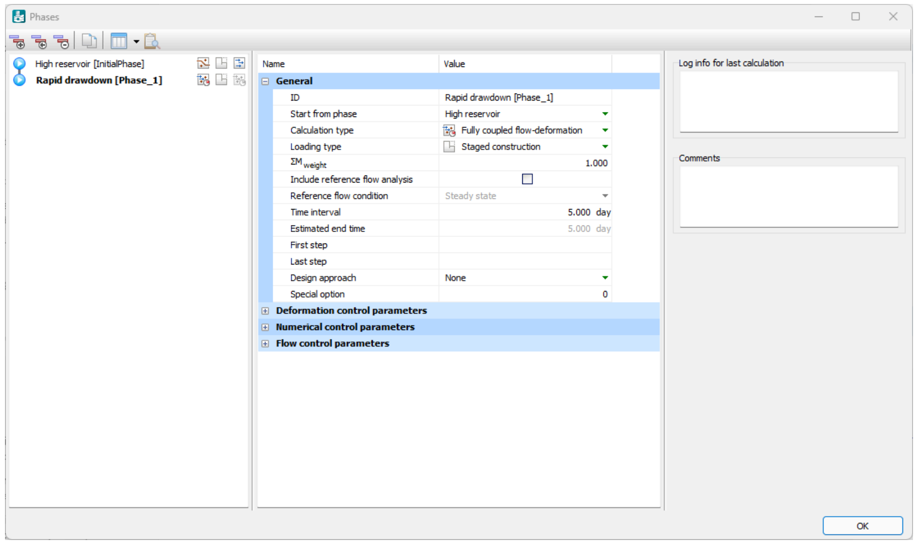

Figure 7–6: Phases window for the Rapid drawdown phase with - fully coupled flow-deformation calculation

9 Expand the **Attributes library** in the **Model explorer**.

10 Right-click on **Flow functions** and select the **Edit** option in the appearing menu.

The **Flow functions** window is displayed.

11  In the **Head functions** tabsheet add a new function by clicking the corresponding button. The new function is highlighted in the list and options to define the function are displayed.

a. Specify a proper name to the function for the rapid drawdown (e.g. `Rapid`).
b. Select the **Linear** option from the **Signal** drop-down menu.
c. Assign a value of -20m to **ΔHead**, representing the amount of the head decrease.
d. Specify a time interval of 5 days. Figure 7–7 (p. 141) shows the defined function.

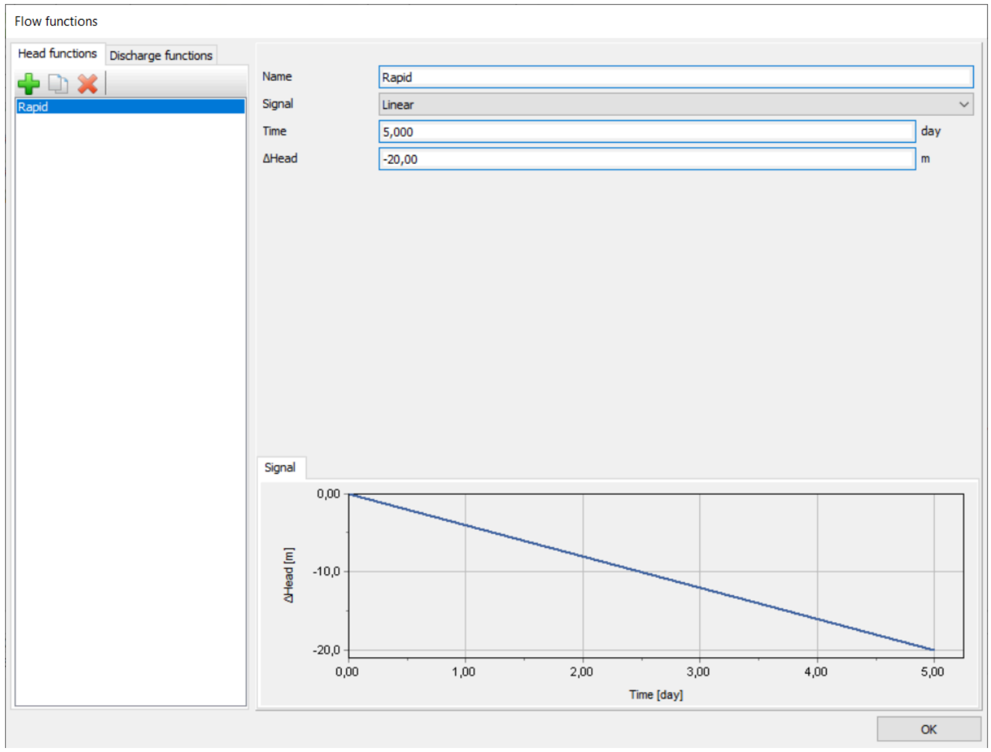

Figure 7–7: The flow function for the rapid drawdown case

e. Click **OK** to close the **Flow functions** window.

12. Activate all the surface groundwater flow boundary conditions.
13. Multi-select the surface groundwater flow BCs in the drawing area.
14. In the **Selection explorer** as **behaviour** select the **Head** option. The distribution of the head is **Uniform**. Assign a value of 25m to h_{ref}.
15. Set the time dependency to **Time dependent** and as **Head function** select the **Rapid** option.

    Information related to the head function is displayed in the **Object explorers** as well.
16. In the **Model explorer** > **Model Conditions** > **Water** as **GlobalWaterLevel** select the BoreholeWaterLevel_1 option.

7.8.3 Phase 2: Slow drawdown

In the slow drawdown phase the water level in the reservoir will be lowered from z = 25m to z = 5m in a period of 50 days. To define the function describing the fluctuation of the water level:

1. Select the initial phase (High reservoir) in the **Phases explorer**.
2.  Add a new calculation phase.
3. In the **Phases explorer** double-click the newly added phase. The **Phases** window is displayed.
4. In the **General** subtree specify the name of the phase (e.g. `Slow drawdown`).

5  Set the **Calculation type** to **Fully coupled flow-deformation**.

6 Set the **Time interval** option to 50 days.

7 The **Reset displacements to zero** option is automatically selected in the **Deformation control parameters** subtree.

8 Click **OK** to close the **Phases** window.

9 Create a new flow function (see Figure 7–8 (p. 142)) following the steps previously described.

a. Specify a proper name to the function for the slow drawdown (e.g. Slow).
b. Select the **Linear** option from the **Signal** drop-down menu.
c. Assign a value of -20m to **ΔHead**, representing the amount of the head decrease.
d. Specify a time interval of 50 days.

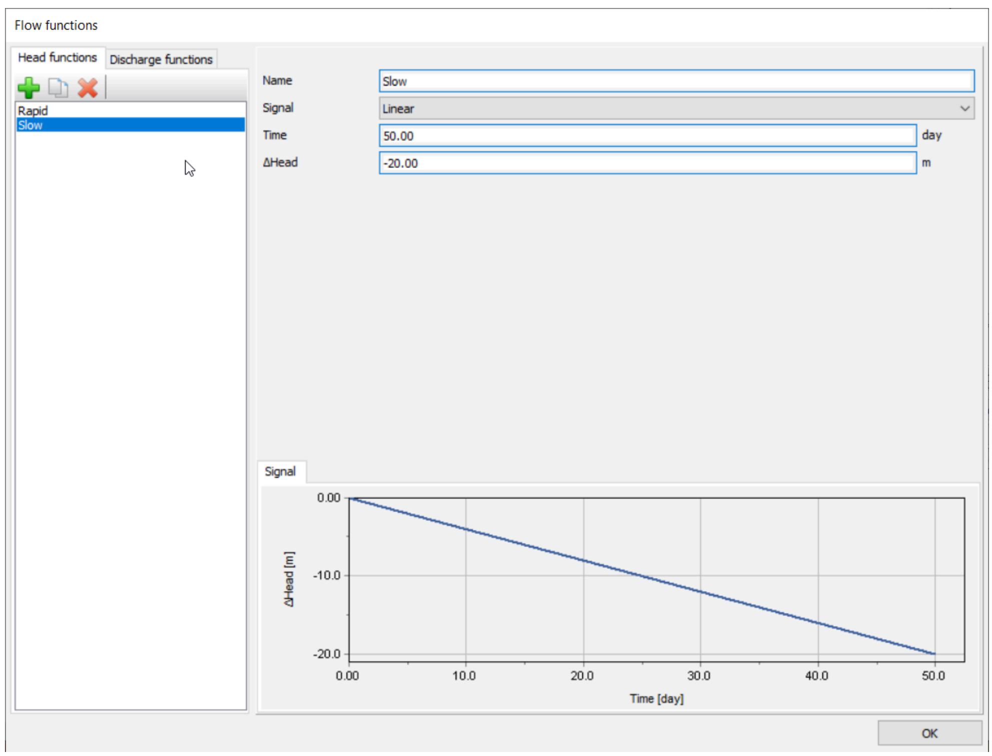

Figure 7–8: The flow function for the slow drawdown case

10 Activate all the surface groundwater flow boundary conditions and multi-select them in the drawing area.

11 In the **Selection explorer** select the **Head** option as behaviour. The distribution of the head is **Uniform**. Assign a value of 25m to h_{ref}.

12 Set the time dependency to **Time dependent** and as **Head function** select the **Slow** option.

13 In the **Water** subtree in the **Model explorer** as **GlobalWaterLevel** select the **BoreholeWaterLevel_1** option.

7.8.4 Phase 3: Low level

This phase considers the steady-state situation of a low reservoir level.

1. Select the initial phase (High reservoir) in the **Phases explorer**.
2. Add a new calculation phase.
3. In the **Phases explorer** double-click the newly added phase.

   The **Phases** window is displayed.
4. In the **General** subtree specify the name of the phase (ex: `Low level`).
5. The default calculation type (**Plastic**) is valid for this phase.
6. The default **Pore pressure calculation type** (**Steady state groundwater flow**) is valid for this phase.
7. In the **Deformation control** subtree, select **Ignore und. behaviour (A,B)** and make sure that the **Reset displacements to zero** is selected as well.
8. Click **OK** to close the **Phases** window.
9. The surface groundwater flow BCs should be deactivated in the **Model explorer**.
10. In the **Water** subtree select the low reservoir water level (Low_Reservoir) as **GlobalWaterLevel**.

7.8.5 Phase 4 to 7

In Phases 4 to 7, stability calculations are defined for the previous phases respectively.

1. Select Phase_1 in the **Phases explorer**.
2. Add a new calculation phase and proceed to the **Phases** window.
3. In the **General** subtree specify the name of the phase (ex: `Rapid drawdown - Safety`).
4. Set **Calculation type** to **Safety**. As **Loading type** select **Incremental multipliers** option.
5. Select the **Reset displacements to zero** option in the **Deformation control** subtree.
6. In the **Numerical control parameters** subtree set the **Max steps** parameter to 50 for Phase 4.
7. Follow the same procedure for Phases 5 to 7 as shown in Figure 7–9 (p. 144).

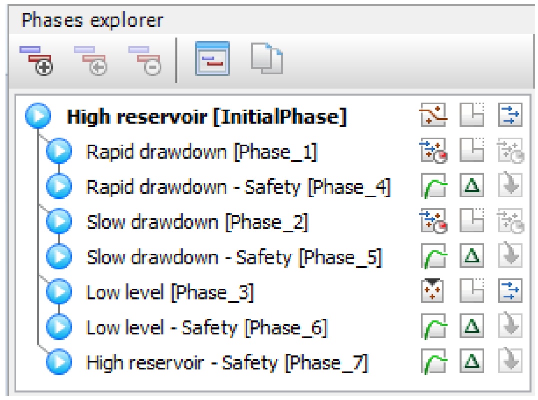

Figure 7–9: The final view of the Phases explorer

7.8.6 Execute the calculation

1. In the **Staged construction mode** select a node at the crest (-2.5 25.0 30.0).
2. Start the calculation process. Ignore the calculation warnings.
3. Save the project when the calculation has finished.

7.9 Results

1. After the calculation is finished click the **View the calculation results** button.

   The **Output** window now shows the deformed mesh for the selected phase.
2. Select the menu item **Stresses** > ***Pore pressures*** > $\boldsymbol{P}_{\text{water}}$.
3. Define a vertical cross section passing through (-130 15) and (130 15)

> **Note:**
>
> - Note that by default the legend is locked in cross section plots, meaning that the same layer distribution will be used if the cross section is relocated in the model or if the results are displayed for other phases.
> - The legend can be unlocked by clicking on the **Lock** icon under the legend. A 'free' legend is indicated by the **Open lock** icon.

The results of the four groundwater flow calculations in terms of pore pressure distribution are displayed for four conditions as follows:

- The situation with a high (standard) reservoir level - See Figure 7–10 (p. 145).
- The situation after rapid drawdown of the reservoir level - See Figure 7–11 (p. 145).
- The situation after slow drawdown of the reservoir level - See Figure 7–12 (p. 146).
- The situation with a low reservoir level - See Figure 7–13 (p. 146).

When the change of pore pressure is taken into account in a deformation analysis, some additional deformation of the dam will occur. These deformations and the effective stress distribution can be viewed on the basis of the results of phases 1 to 4.

For the phases 1 and 2 change the legend settings to **Manual** and set the values as follows:

- Minimum value: -480
- Maximum value: 200
- Number of intervals: 18

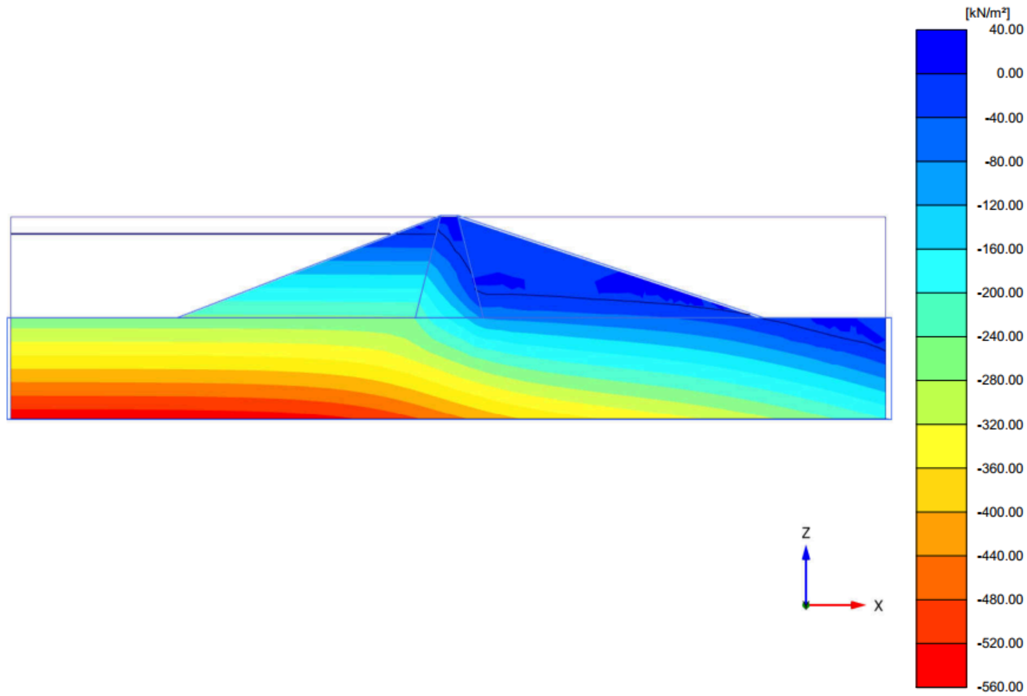

Figure 7–10: Pore water pressure distribution for high reservoir level (Initial phase)

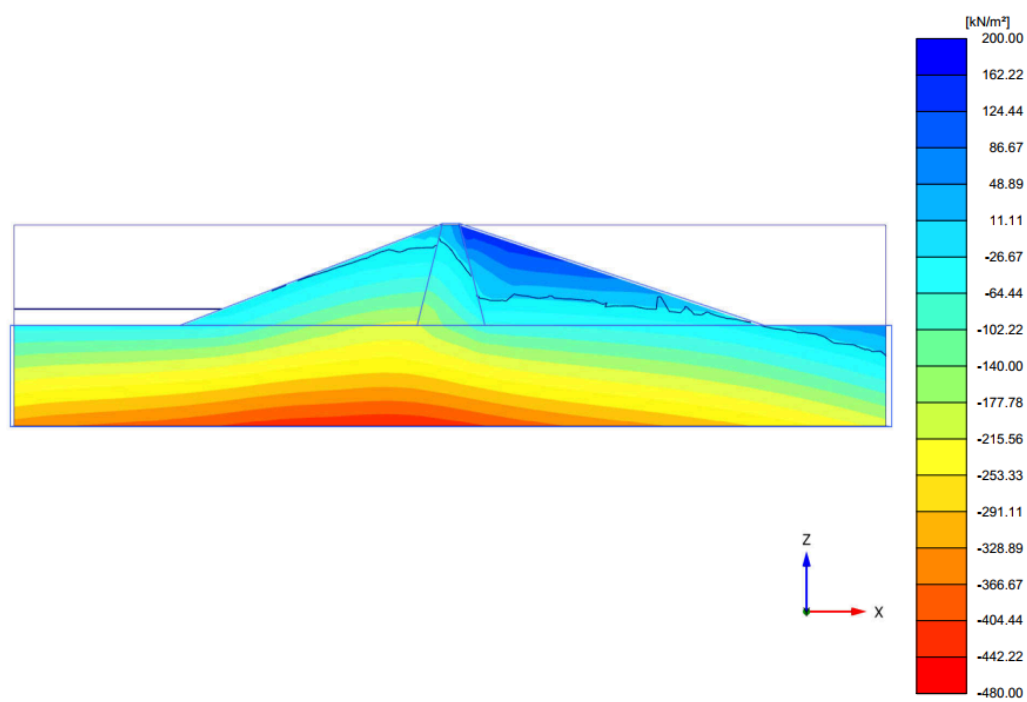

Figure 7–11: Pore water pressure distribution after rapid drawdown (Phase_1)

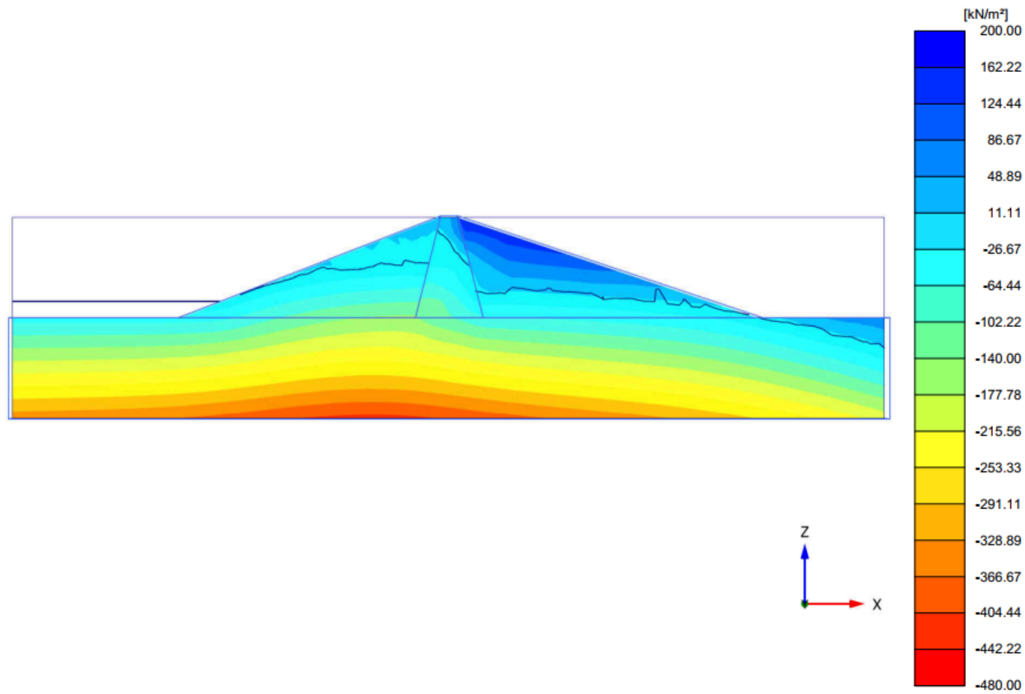

Figure 7–12: Pore water pressure distribution after slower drawdown (Phase_2)

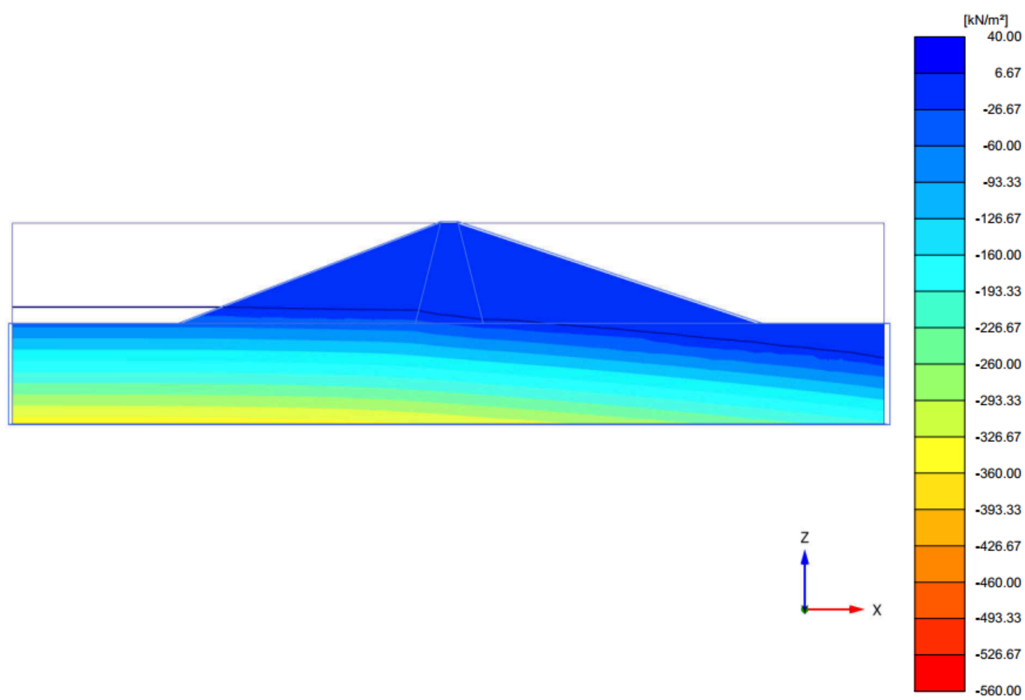

Figure 7–13: Pore water pressure distribution for low reservoir level (Phase_3)

In this tutorial attention is focused on the variation of the safety factor of the dam for the different situations. Therefore, the development of **ΣMsf** is plotted for the phases 4 to 7 as a function of the displacement of the dam crest point (see Figure 7–14 (p. 147)).

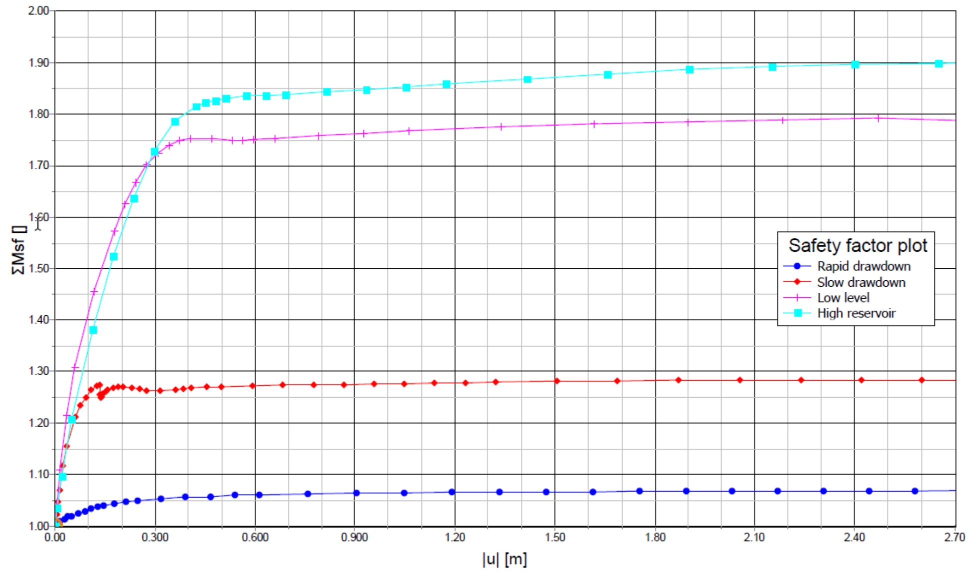

Figure 7–14: Safety factors for different situations

Rapid drawdown of a reservoir level can reduce the stability of a dam significantly. Fully coupled flow-deformation and stability analysis can be performed with PLAXIS 3D to effectively analyse such situations.