14

Stability of dam under rapid drawdown [ULT]

14.1 | 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. To analyse such a situation using the finite element method, a fully coupled flow-deformation analysis is required. Time-dependent pore pressure is coupled with deformations development and used in a stability analysis. This example demonstrates how coupled analysis and stability analysis can interactively be performed in PLAXIS 2D.

Objectives

- Defining time-dependent hydraulic conditions (Flow functions).
- Defining transient flow conditions using water levels.

14.2 | Geometry

The dam to be considered is 30m high and the width is 172.5m at the base and 5m at the top. The dam consists of a clay core with a well graded fill at both sides. 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. The geometry of the dam is shown in .
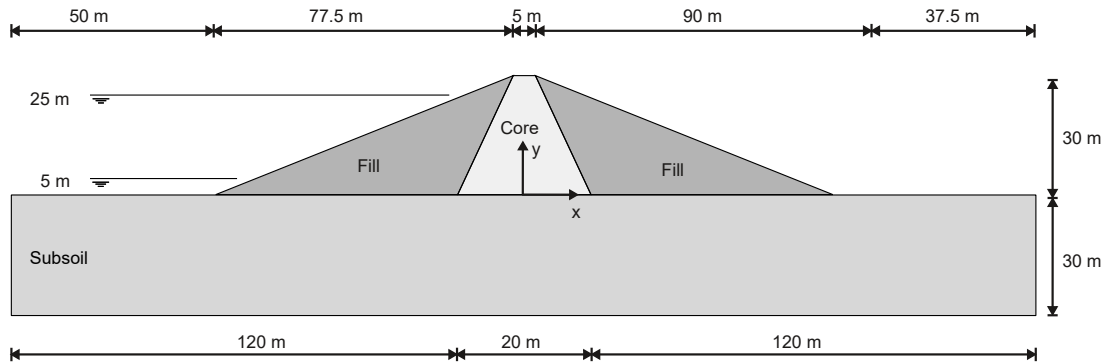

Figure 14–1: Geometry of the project

14.3 | Create new project

To create the new project, follow these steps:

1. Start the Input program and select **Start a new project** from the **Quick start** dialog box.

2. In the **Project** tabsheet of the **Project properties** window, enter an appropriate title.

3. Keep the default units and constants and set the model **Contour** to x_{min} = -130 m, x_{max} = 130 m, y_{min} = -30 m and y_{max} = 30 m.

14.4 | 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 30 m overconsolidated silty sand is considered as subsoil in the model.

1. Click the **Create borehole** button ⬛ and create a borehole at x = 0.

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

2. Add a soil layer extending from ground surface (y = 0) to a depth of 30 m (y = -30).

14.5 | Create and assign material data sets

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

The layers have the following properties as shown in :

Table 14–1: Material properties of the dam and subsoil

Parameter	Name	Core	Fill	Subsoil	Unit
General					
Soil model	Model	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	-
Drainage type	Type	Undrained (B)	Drained	Drained	-
Unsaturated unit weight	γ_{unsat}	16	16	17	kN/m^3
Saturated unit weight	γ_{sat}	18	20	21	kN/m^3
Mechanical					
Young's modulus	E'_{ref}	$1.5 \cdot 10^3$	$20 \cdot 10^3$	$50 \cdot 10^3$	kN/m^2
Poisson's ratio	ν	0.35	0.33	0.3	-
Cohesion	c'_{ref}	-	5	1	kN/m^2
Young's modulus increment	E'_{inc}	300	-	-	$kN/m^2/m$
Undrained shear strength	$s_{u,ref}$	5	-	-	kN/m^2
Friction angle	φ'	-	31	35	°
Dilatancy angle	ψ	-	1	5	°
Undrained shear strength increment	$s_{u,inc}$	3.0	-	-	kN/m^3
Reference level	y_{ref}	30	-	-	m
Groundwater					
Classification type	-	Hypres	Hypres	Hypres	-
SWCC fitting method	-	Van Genuchten	Van Genuchten	Van Genuchten	-
Subsoil /Topsoil	-	Subsoil	Subsoil	Subsoil	-
Soil class(standard)	-	Very fine	Coarse	Coarse	-
Flow parameters - Use defaults		None	None	None	-
Horizontal permeability	k_x	$0.1 \cdot 10^{-3}$	1.00	0.01	m/day
Vertical permeability	k_y	$0.1 \cdot 10^{-3}$	1.00	0.01	m/day

To create the material sets, follow these steps:

1. 🖽 Open the **Material sets** window.

2. Create data sets under the **Soil and interfaces** set type according to the information given in [Table 14–1 (p. 216)](#). Note that the **Thermal**, **Interfaces** and **Initial** tabsheets are not relevant (no thermal properties, no interfaces or **K0 procedure** are used).

3. Assign the **Subsoil** material dataset to the soil layer in the borehole.

14.6 | Define the dam

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

In order to draw the dam with the mouse it is necessary to decrease the snap-to-grid distance. By default this distance is 1 m, but in this tutorial it should be 0.5m. In order to change the snap-to-grid distance, select the **Snapping options** button below the drawing area. The **Spacing** defines the distance between 2 grid points and the *Intervals* defines the amount of snap-to-grid intervals between 2 grid points. In order to have a snap-to-grid distance of 0.5m we can set either the **Spacing** to 0.5m and leave the **Intervals** to 1, or we can leave the **Spacing** at 1 m and set the amount of **Intervals** to 2.

1. Click on the **Polygon** button to define a polygon through the points located at (-80 0), (92.5 0), (2.5 30) and (-2.5 30).

2. Click again on the **Polygon** button, and this time select the **Cut polygon** button to create the sub-clusters in the dam. Define two cutting lines from (-10 0) to (-2.5 30) and from (10 0) to (2.5 30).

3. Assign the corresponding material datasets to the soil clusters.

14.7 | Generate the mesh

1. Proceed to the **Mesh mode** .

2. Click the **Generate mesh** button in the side toolbar. For the **Element distribution** parameter, use the option **Fine**.

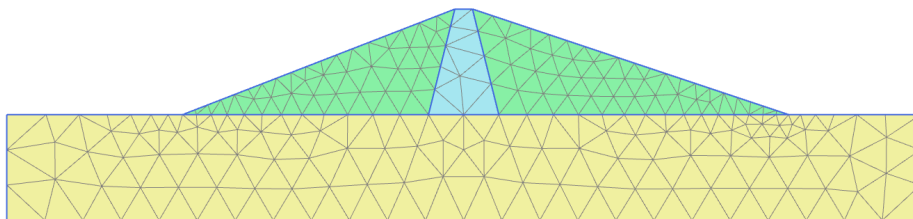3. Click the **View mesh** button to view the mesh which is shown in [Figure 14–2 (p. 217)](#).

Figure 14–2: The generated mesh

4. Click the **Close** tab to close the Output program.

14.8 | Define and perform the calculation

The following cases will be considered:

- A long term situation with water level at 25m.
- A quick drop of the water level from 25 to 5m.
- A slow drop of the water from 25 to 5m.
- 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 5 m. 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 5 m, 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.

Note that only the water conditions will be defined for different calculation phases. The model requires no changes in the geometry. Water levels can be defined in the **Flow conditions mode**.

## 14.8.1 | Initial phase: Dam construction & high reservoir

By default the initial phase is added in the **Phases explorer**.

1. Proceed to the **Flow conditions mode** by clicking the corresponding tab.

2. Activate **Fill** and **Core**.

3. In the **Phases explorer** double-click **Initial phase**.

    The **Phases** window is displayed.

4. In the **General** subtree specify the name of the phase (e.g. High reservoir).

5. Select the **Calculation type** > **Gravity loading** option ![icon] .

6. Select the **Pore pressure calculation type** > **Steady state groundwater flow** option ![icon]

7. In the **Deformation control parameters** subtree, uncheck the **Ignore suction** option.

> ⓘ **Note:** Note that in this exercise we will do a fully coupled flow-deformation analysis and this type of analysis always takes into account suction in the unsaturated zone. Therefore, it is advised to also take into account suction in calculation phases prior to the fully coupled flow deformation analysis (like the initial phase in this tutorial) to avoid the unbalance in soil stresses that would occur when changing between phases with and without suctions.

The phases window after putting all the parameters is shown in :

Figure 14–3: The Phases window
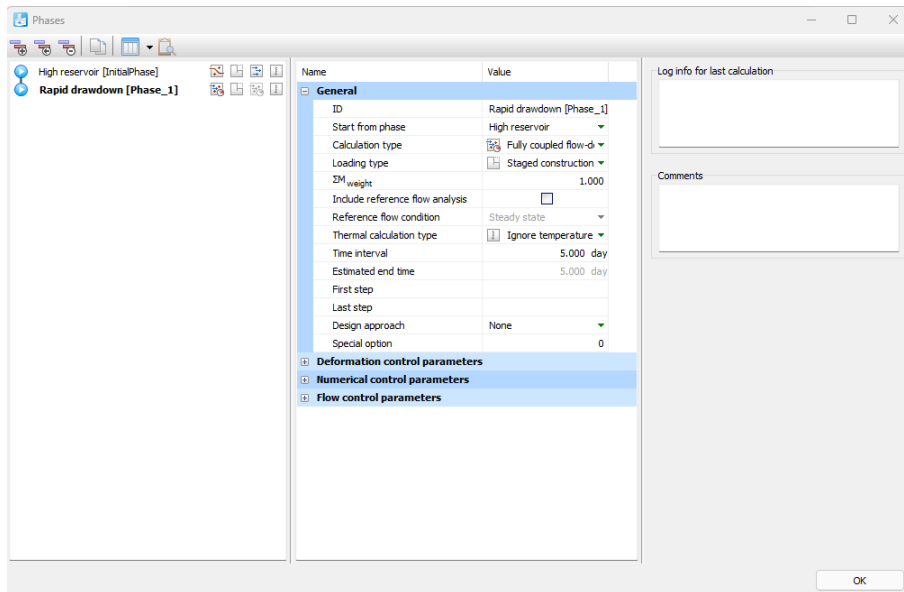
8. Click **OK** to close the **Phases** window.

> ℹ **Note:** Note that by default **Undrained behaviour (A)** and **(B)** are ignored for a **Gravity loading** calculation type. The corresponding option is available in the **Deformation control parameters** subtree in the **Phases** window

9. Define the water level corresponding to the level of water in the reservoir prior to the drawdown. The water level consists of four points:

- Starting at the very left side at a level of 25 m above the ground surface (-132 25);
- Second point just inside the dam at a level of 25 m (-10 25);
- Third point near the dam toe (93 -10);
- Forth point just outside the right boundary at a level of 10 m below the ground surface (132 -10).

> ℹ **Note:** Straight lines can be defined by keeping the **Shift** key pressed while defining the geometry.

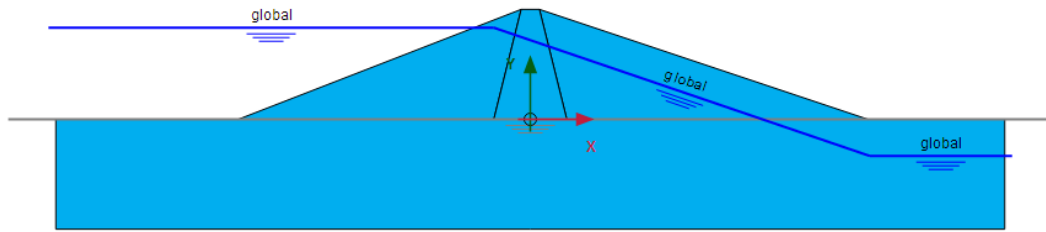The defined water level is shown in

Figure 14–4: High water level in the reservoir

(10) Right-click the created water level and select the **Make global** option in the appearing menu.

Note that the global water level can also be specified in the **Model Explorer** by selecting the corresponding option in the menu **Model conditions** > **Water** > **GlobalWaterLevel** > **UserWaterLevel_1**.

(11) In the **Model explorer** expand the **Attributes library**.

(12) Expand the **Water levels** subtree. The levels created in the **Flow conditions** mode are grouped under **User water levels**.

(13) Expand the **User water levels** subtree.

The created water level can be seen named as UserWaterLevel_1. The location of the water levels in **Model explorer** is shown in

Figure 14–5: Water levels in Model explorer

(14) Double-click on the created water level and rename it as *FullReservoir_steady*. This is a distinctive name that satisfies the naming requirements (no invalid characters).

(15) Expand the **Model conditions** subtree.

(16) Expand the **GroundWaterFlow** subtree.

Note that by default the boundary at the bottom of the model is set to **Closed** shown in . This is relevant for this example.
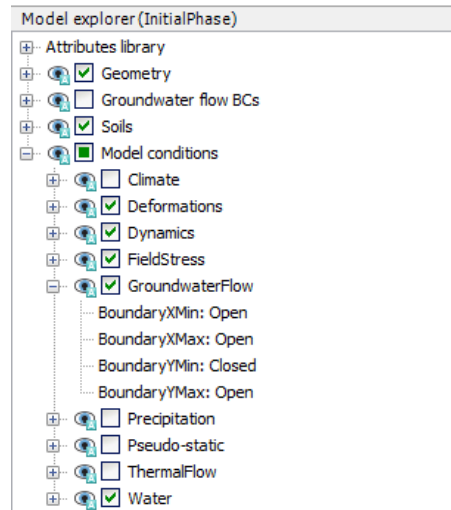
Figure 14–6: GroundwaterFlow boundary conditions in Model explorer

14.8.2 | Phase 1: Rapid drawdown

In this phase rapid drawdown of the reservoir level is considered.

1. Click the **Add phase** button ⬚ to create a new 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). Note that the **High reservoir** phase is automatically selected in the **Start from phase** drop-down menu.

4. As **Calculation type**, select the **Fully coupled flow-deformation** option ⬚ .

5. In the **Include reference flow analysis** option keep the checkbox unselected. This sets non-steady state boundary conditions.

6. To the **Time interval** parameter assign a value of 5 days .

7. In the **Deformation control parameters** subtree, make sure that the **Reset displacements to zero** and **Reset small strain** options are selected.

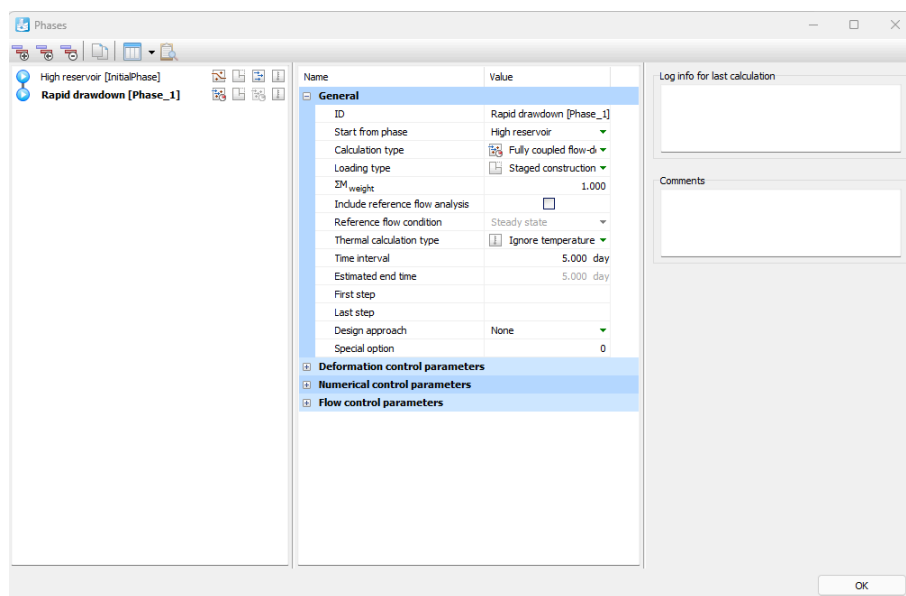8. Click **OK** to close the **Phases** window (see Figure 14–7 (p. 222)).

**Figure 14–7: Phases window for the Rapid drawdown phase
with - fully coupled flow-deformation calculation type**

⑨ Due to the global nature of the water levels, if an attribute is assigned to a water level in the model it will affect it in all phases. The water level in this phase has the same geometry with the one previously defined, however it is time dependent and a function needs to be assigned to it. As a result, it is required to create a new water level with the same geometry and different attributes. In the **Model explorer** go to the **Attributes library** > **Water levels** > **User water levels** and right-click on FullReservoir_Steady as shown in <u>Figure 14–8 (p. 223)</u>. Then select the **Duplicate** option in the appearing menu.

A copy of the water level is created.

Figure 14–8: Duplication of water level

(10) Rename the newly created water level as *FullReservoir_Rapid*. The behaviour of the water levels can be described by specifying **Flow functions**. Note that **Flow functions** are global entities and are available in the **Model explorer** under the **Attributes library**. To define the flow functions:

a. In the **Model explorer** go to the **Attributes library** and right-click the **Flow functions** option. Select the **Edit** option in the appearing menu. The **Flow functions** window is displayed.

b. 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.

c. Specify a proper **Name** to the function for the rapid drawdown (e.g. Rapid).

d. From the **Signal** drop-down menu, select the **Linear** option .

e. Specify a time interval of 5 days.

f. As **ΔHead** assign a value of -20 m representing the amount of the head decrease.

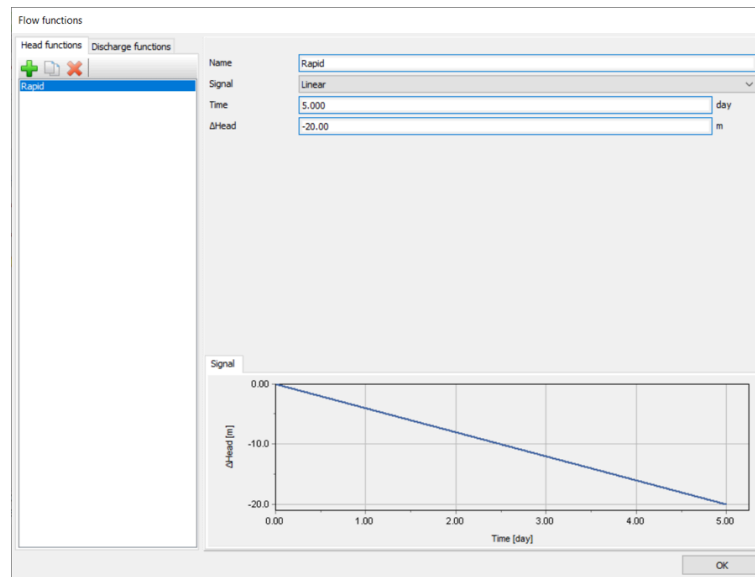A graph is displayed showing the defined function in .

Figure 14–9: The flow function for the rapid drawdown case

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

(11) In the **Model explorer** right-click on **FullReservoir_Rapid** and select the **Use as global water level** option in the appearing menu.

(12) Expand the **FullReservoir_Rapid** subtree. Note that the water level is composed of 3 water segments. Select the water segment in the upstream shoulder (left from the dam, at the reservoir side).

(13) Expand the subtree of the selected segment and from the **TimeDependency** parameter select the **Time dependent** option.

(14) For the **HeadFunction** parameter select the **Rapid** option.

shows the selected water segment in **Model explorer**.

Figure 14–10: Properties of the lowering water segment

(15) Note that in the **Model explorer** under the **Model conditions** in the **Water** subtree the **GlobalWaterLevel** gets assigned the new water level (FullReservoir_Rapid).

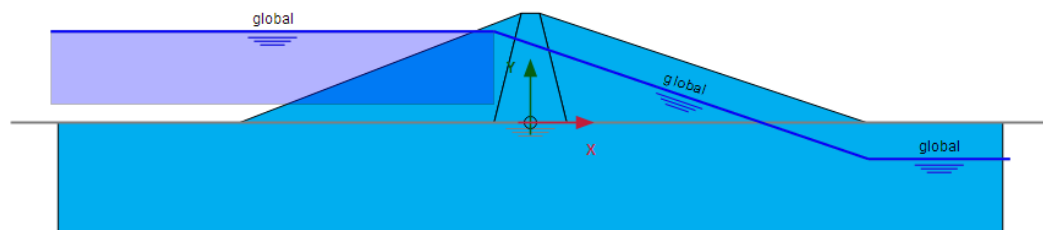The configuration of the phase is shown in .

Figure 14–11: Configuration of the rapid drawdown phase

Note that the shadow under the water level segment in the upstream shoulder indicates the variation of the water level during the phase.

14.8.3 | Phase 2: Slow drawdown

In this phase the drawdown of the reservoir level is performed at a lower rate.

(1) Select the **High reservoir** phase in the **Phases explorer**.

(2) Click the **Add phase** button ⧉ to create a new phase.

(3) In **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). The **High reservoir** phase is automatically selected for the **Start from phase** parameter.

5 Select the **Fully coupled flow deformation** option ⊞ as calculation type.

6 Assign a value of 50 days to the **Time interval** parameter.

7 Make sure that the **Reset displacements to zero** and **Reset small strain** options are selected in the **Deformation control parameters** subtree. The **Ignore suction** option is unchecked by default.

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

9 Create a new duplicate of the high water level. The newly created water level will be used as **Global water level** in the slow drawdown phase. Even though the water level in this phase has the same geometry as the previously defined ones, the flow function for the time dependency is different.

10 Rename the newly created water level as 'FullReservoir_Slow'.

11 ➕ Add a new flow function following the steps described for the previous phase.

    a. Specify a proper name to the function for the slow drawdown (e.g. Slow).
    b. From the **Signal** drop-down menu select the **Linear** option.
    c. Specify a time interval of 50 days.
    d. Assign a value of -20 m to **ΔHead**, representing the amount of the head decrease. A graph is displayed showing the defined function.
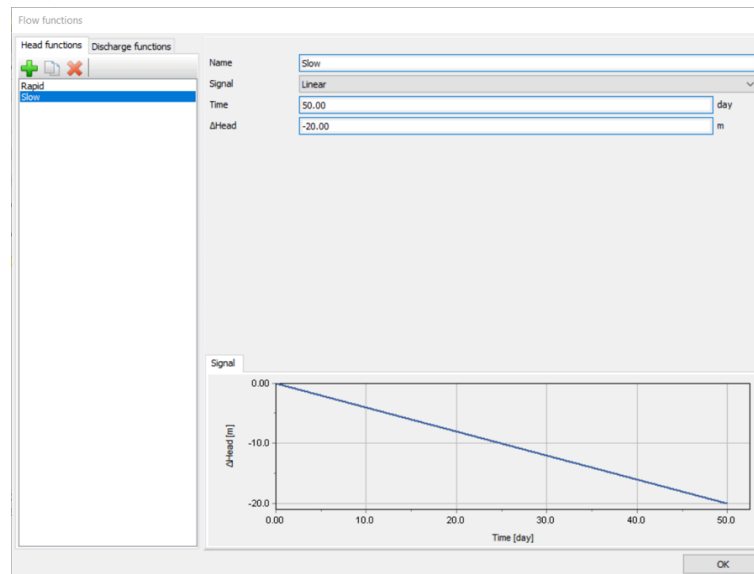   **e.** Click **OK** to close the **Flow functions** window as shown in <u>Figure 14–12 (p. 226)</u>.

Figure 14–12: The flow function for the slow drawdown case

12 In the **Model Explorer** > **Attributes library** > **Water levels** > **User water levels** right-click on **FullReservoir_Slow** and select the **Use as global water level** option in the appearing menu.

13 Expand the **FullReservoir_Slow** subtree. Select the water segment in the upstream shoulder (left from the dam, at the reservoir side).

The segment selected in **Model explorer** is indicated by a red colour in the model.

14 Expand the subtree of the selected segment and for the **TimeDependency** parameter select the **Time dependent** option.

(15) Select the **Slow** option for the **HeadFunction** parameter.

Note that in the **Model explorer** under the **Model conditions** in the **Water** subtree the **GlobalWaterLevel** gets assigned the new water level (FullReservoir_Slow).

14.8.4 | Phase 3: Low level

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

(1) Go to the **Phases explorer** and select the **High reservoir** phase.

(2) Click the **Add phase** button 🔄 to create a new phase.

(3) In **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. Low level). The **High reservoir** phase is automatically selected for the **Start from phase** parameter.

(5) In the **Calculation type** make sure that the **Plastic** option 🔳 is selected.

(6) As **Pore pressure calculation type** select the **Steady state groundwater flow** option 🔳.

(7) In the **Deformation control parameters** subtree select **Ignore und. behaviour (A,B)**. Then make sure that the **Reset displacements to zero** and **Reset small strain** options are selected. Finally, uncheck the **Ignore suction** option.

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

(9) 🔄 Define the water level corresponding to the level of water in the reservoir after the drawdown. The water level consists of four points:

- Starting at the very left side at a level of 5 m above the ground the surface (-132 5);
- Second point inside the dam at a level of 5 m (-60 5);
- Third point at (93 -10);
- Fourth point just outside the right boundary at a level of 10 m below the ground surface (132 -10).

(10) Rename the newly created water level as 'LowLevel_Steady'.

(11) In the **Model explorer** > **Model conditions** > **Water** assign to the **GlobalWaterLevel** the newly created water level (LowLevel_Steady).
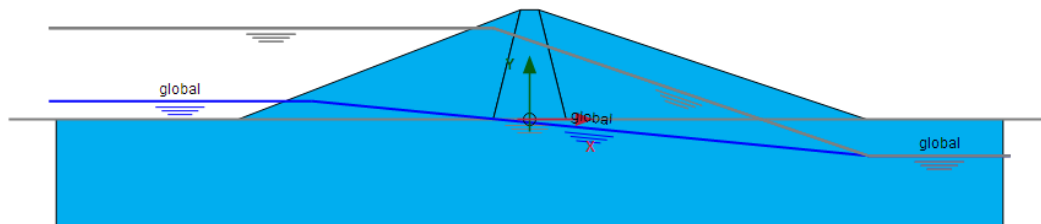

Figure 14–13: Model for the low level case in the Flow conditions mode

All the defined water levels are shown in .

14.8.5 | Phase 4 to 7: Safety analysis

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

1. Select the parent phase in the **Phases explorer**.

2. Click the **Add phase** button to create a new phase. Proceed to the **Phases** window.

3. Set **Calculation type** to **Safety**.

4. In the **Deformation control** subtree, select **Reset displacements to zero**.

5. In the **Deformation control parameters** subtree, check the **Ignore suction** option for all the safety analyses.

> ⓘ **Note:** Taking suction into account in a **Safety** phase gives a higher factor of safety, hence ignoring suction in a **Safety** phase is more conservative. In the **Safety** analysis of PLAXIS 2D, any unbalance due to changing from suction to no suction is first solved before the factor of safety is determined. As a result, ΣM_{sf} can decrease in the first part of the calculation.

6. The final view of the phases explorer window is shown in .
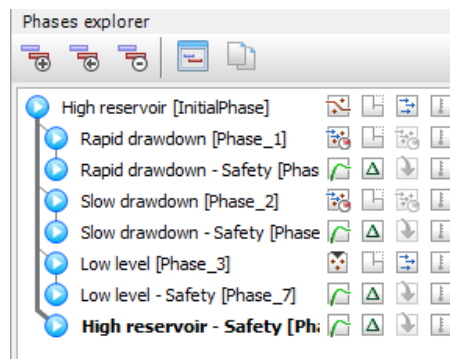

Figure 14–14: The final view of Phases explorer

14.8.6 | Execute the calculation

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

2. Select nodes located at the crest (-2.5 30) and at the toe of the dam (-80 0).

3. Click the **Calculate** button to calculate the project and ignore the warnings regarding the influence of suction in the **Safety** analysis..

4. Save the project after the calculation has finished.

14.9 | Results

The results of the four groundwater flow calculations in terms of pore pressure distribution are shown in the figures below. Four different situations were considered:

- The steady-state situation with a high (standard) reservoir level is shown in .
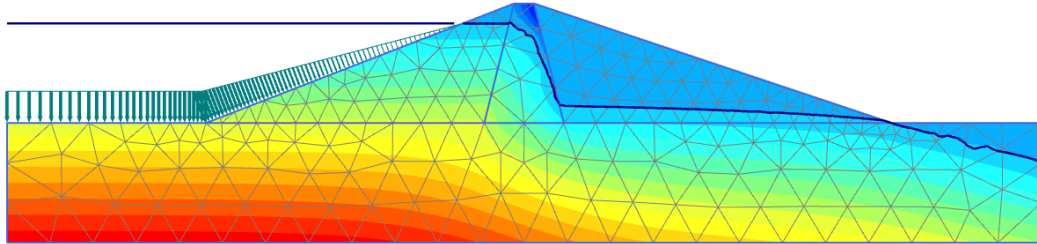

Figure 14–15: Pore pressure distribution, (p_{active}), for high reservoir level

- The pore pressure distribution after rapid drawdown of the reservoir level is shown in .
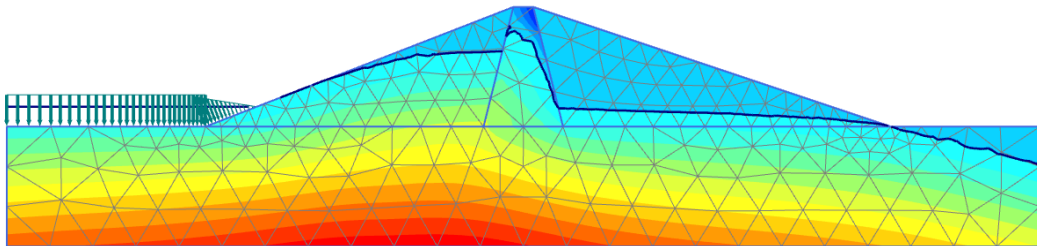

Figure 14–16: Pore pressure distribution, (p_{active}), after rapid drawdown

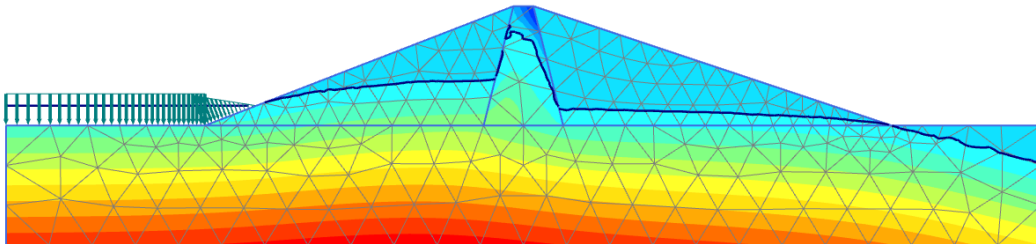- The pore pressure distribution after slow drawdown of the reservoir level is shown in .

Figure 14–17: Pore pressure distribution, (p_{active}), after slow drawdown

- The steady-state situation with a low reservoir level is shown in .

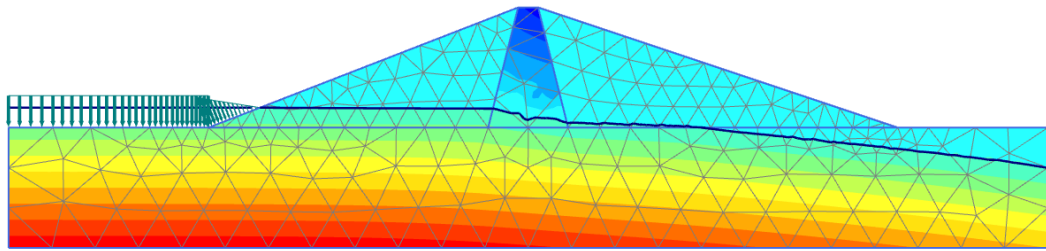**Figure 14–18: Pore pressure distribution, (p_{active}), for low reservoir level**

> **ⓘ Note:**
>
> The phreatic level can be smoother with a high refinement of the mesh in the core.

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 the first four calculation phases. Here, 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 (-2.5 30.0), see .
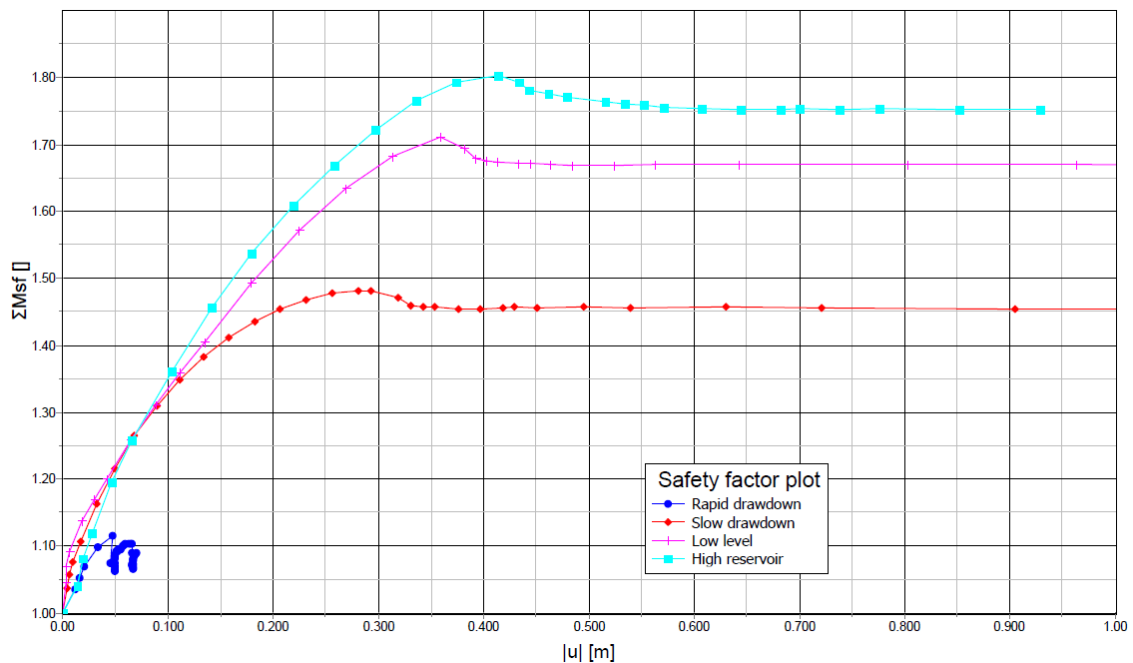

Figure 14–19: Safety factors for different situations

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 2D to effectively analyse such situations.

> **ⓘ Note:**
> - In the strength reduction method the factor of safety is considered the value of the strength reduction factor **ΣMsf** for which progressive failure occurs. Hence, a **Safety** analysis should be performed with sufficient steps to make sure that failure really occurs. This can be checked from the graph of displacement vs **ΣMsf** where the curve flattens: the strength can no longer be reduced while the displacement rapidly increase.
> - By removing the suction in the safety analysis, an out-of-balance force is introduced at the beginning of the calculation. Without the contribution of the suction, the **ΣMsf** can decrease in the first part of the calculation.