



8 STABILITY OF DAM UNDER RAPID DRAWDOWN

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.

The dam to be considered is 30 m high and the width is 172.5 m at the base and 5 m at the top. The dam consists of a clay core with a well graded fill at both sides. The geometry of the dam is depicted in Figure 8.1. The normal water level behind the dam is 25 m high. A situation is considered where the water level drops 20 m. The normal phreatic level at the right hand side of the dam is 10 m below ground surface. The data of the dam materials and the sub-soil are given in Table 1.

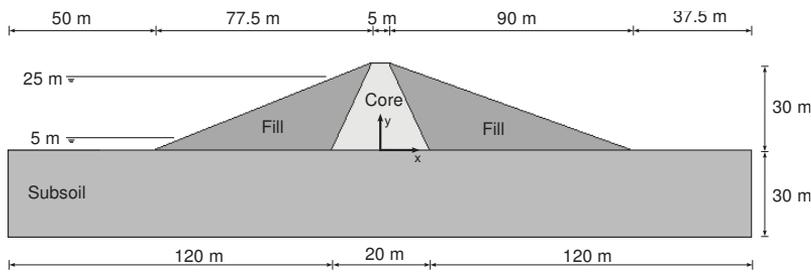


Figure 8.1 Geometry of the dam

Objectives:

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

8.1 INPUT

- Start the Input program and select the *Start a new project* from the *Quick select* dialog box.
- In the *Project properties* window enter an appropriate title.
- Keep the default units and constants and set the model dimensions to $x_{min} = -130.0$, $x_{max} = 130.0$, $y_{min} = -30.0$ and $y_{max} = 30.0$.

8.1.1 DEFINITION OF 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 sub-soil in the model.

- Create a borehole at $x = 0$. The *Modify soil layers* window pops up.
 - Add a soil layer extending from ground surface ($y = 0.0$) to a depth of 30 m ($y =$

-30.0).



Open the *Material sets* window.

- Create data sets under *Soil and interfaces* set type according to the information given in Table 8.1. Note that the *Thermal*, *Interfaces* and *Initial* tabsheets are not relevant (no thermal properties, no interfaces or *K0 procedure* are used).
- Assign the *Subsoil* material dataset to the soil layer in the borehole.

Table 8.1 Material properties of the dam and sub-soil

Parameter	Name	Core	Fill	Subsoil	Unit
General					
Material model	<i>Model</i>	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	-
Drainage type	<i>Type</i>	Undrained (B)	Drained	Drained	-
Soil unit weight above p.l.	γ_{unsat}	16.0	16.0	17.0	kN/m ³
Soil unit weight below p.l.	γ_{sat}	18.0	20.0	21.0	kN/m ³
Parameters					
Young's modulus	E'	1.5·10 ³	2.0·10 ⁴	5.0·10 ⁴	kN/m ²
Poisson's ratio	ν'	0.35	0.33	0.3	-
Cohesion	c'_{ref}	-	5.0	1.0	kN/m ²
Undrained shear strength	$s_{u,ref}$	5.0	-	-	kN/m ²
Friction angle	φ'	-	31	35.0	°
Dilatancy angle	ψ	-	1.0	5.0	°
Young's modulus inc.	E'_{inc}	300	-	-	kN/m ² /m
Reference level	y_{ref}	30	-	-	m
Undrained shear strength inc.	$s_{u,inc}$	3.0	-	-	kN/m ²
Reference level	y_{ref}	30	-	-	m
Groundwater					
Flow data set	<i>Model</i>	Hypres	Hypres	Hypres	-
Model	-	Van Genuchten	Van Genuchten	Van Genuchten	-
Soil	-	Subsoil	Subsoil	Subsoil	-
Soil coarseness	-	Very fine	Coarse	Coarse	-
Horizontal permeability	k_x	1.0·10 ⁻⁴	1.00	0.01	m/day
Vertical permeability	k_y	1.0·10 ⁻⁴	1.00	0.01	m/day

8.1.2 DEFINITION OF THE DAM

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



Define a polygon by specifying points located at (-80.0 0.0), (92.5 0.0), (2.5 30.0) and (-2.5 30.0).



To create the sub-clusters in the dam define two cutting lines from (-10.0 0.0) to (-2.5 30.0) and from (10.0 0.0) to (2.5 30.0).

- Assign the corresponding material datasets to the soil clusters.

8.2 MESH GENERATION

- Proceed to the *Mesh* mode.



Create the mesh. Use the *Fine* option for the *Element distribution* parameter.



View the generated mesh. The generated mesh is shown in Figure 8.2.

- Click on the *Close* tab to close the Output program.

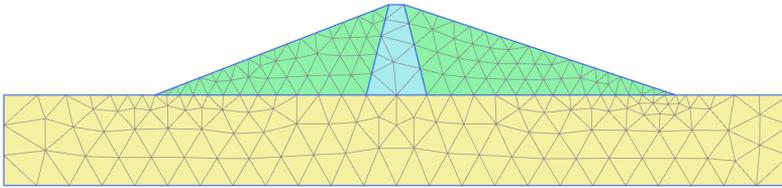


Figure 8.2 Finite element mesh

8.3 CALCULATION

The following cases will be considered:

- long term situation with water level at 25 m.
- water level drops quickly from 25 to 5 m.
- water level drops slowly from 25 to 5 m.
- long term situation with water level at 5 m.

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 25 m) 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.

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

Initial phase: Gravity loading

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

- Activate *Fill* and *Core*.
- In the *Phases explorer* double-click *Initial phase*.
- In the *General* subtree specify the name of the phase (e.g. High reservoir).

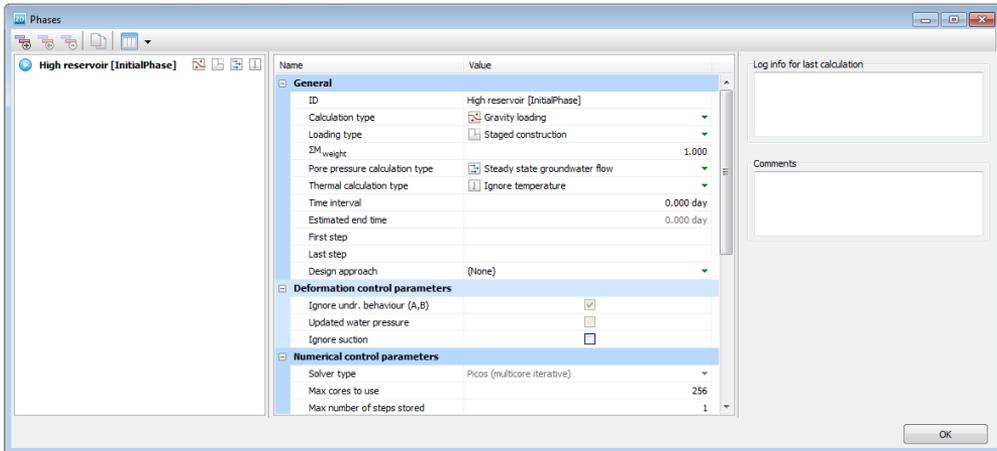


Select the *Gravity loading* option as calculation type.



Select the *Steady state groundwater flow* option as *Pore pressure calculation type*.

- Uncheck the *Ignore suction* option in the *Deformation control parameters* subtree.
- The *Phases* window is displayed (Figure 8.3). Click *OK* to close the *Phases* window.

Figure 8.3 The *Phases* window

Hint: 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.

- 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 (-132.0 25.0); the second point is just inside the dam at a level of 25 m (-10.0 25.0); the third point is near the dam toe (93.0 -10.0) and the fourth point just outside the right boundary at a level of 10 m below the ground surface (132.0 -10.0). The defined water level is shown in Figure 8.4.
- 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 by selecting the corresponding option in the *GlobalWaterLevel* menu in the *Water* subtree in the *Model conditions*.

Hint: Straight lines can be defined by keeping the <Shift> key pressed while defining the geometry.

- In the *Model explorer* expand the *Attributes library*.
- Expand the *Water levels* subtree. The levels created in the *Flow conditions* mode are grouped under *User water levels*.
- 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 8.5.

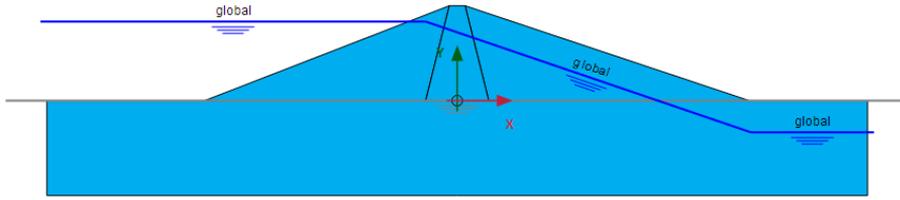


Figure 8.4 High water level in the reservoir

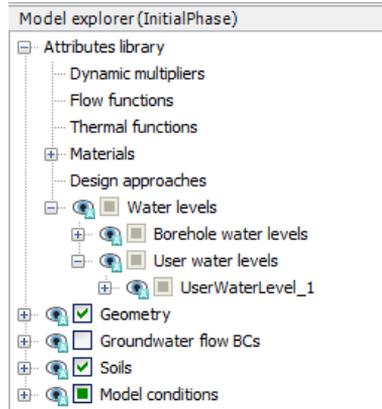


Figure 8.5 Water levels in *Model explorer*

- 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).
- Expand the *Model conditions* subtree.
- Expand the *GroundWaterFlow* subtree. Note that by default the boundary at the bottom of the model is set to *Closed*. This is relevant for this example (Figure 8.6).

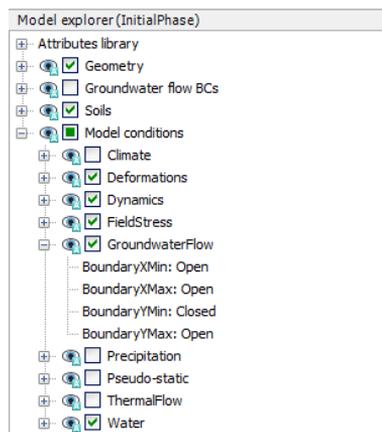


Figure 8.6 *GroundwaterFlow* boundary conditions in *Model explorer*

Phase 1: Rapid drawdown

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



Add a new calculation phase.

- In *Phases explorer* double-click the newly added phase. The *Phases* window is displayed.
- 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.



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

- Assign a value of 5 days to the *Time interval* parameter.
- 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.
- Click *OK* to close the *Phases* window.
- 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 *Model explorer* right-click on *FullReservoir_Steady* and select the *Duplicate* option in the appearing menu (Figure 8.7). A copy of the water level is created.

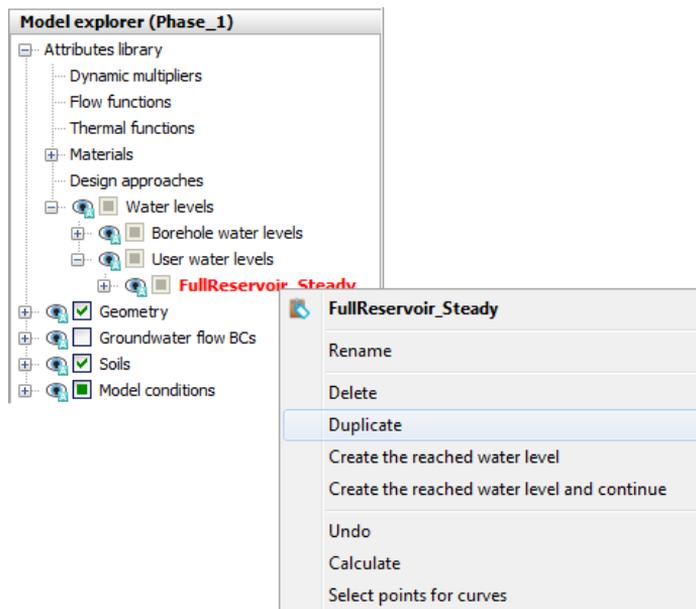


Figure 8.7 Copying water levels in *Model explorer*

- 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 under the *Attributes library* in *Model explorer*. To define the flow functions:

- Right-click the *Flow functions* option in the *Attributes library* in the *Model explorer* and select the *Edit* option in the appearing menu. The *Flow functions* window is displayed.
- ✚ 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.
- Specify a proper name to the function for the rapid drawdown (e.g. Rapid).
- Select the *Linear* option from the *Signal* drop-down menu.
- Specify a time interval of 5 days.
- Assign a value of -20 m to $\Delta Head$, representing the amount of the head decrease. A graph is displayed showing the defined function (Figure 8.8).

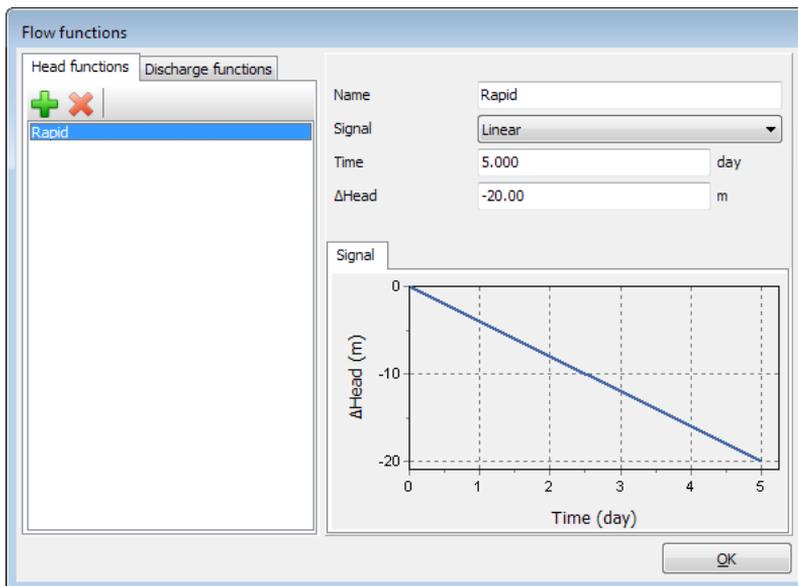


Figure 8.8 The flow function for the rapid drawdown case

- Click *OK* to close the *Flow functions* window.
- In the *Model explorer* right-click on *FullReservoir_Rapid* and select the *Use as global water level* option in the appearing menu.
- 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).
- Expand the subtree of the selected segment and select the *Time dependent* option for the *TimeDependency* parameter.
- Select the *Rapid* option for the *HeadFunction* parameter. Figure 8.9 shows the

selected water segment in *Model explorer*.

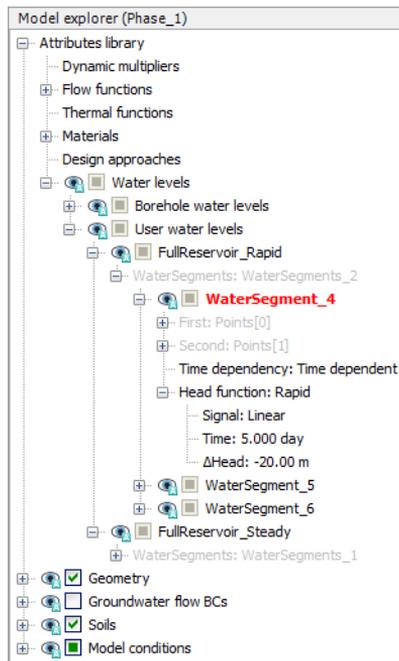


Figure 8.9 Properties of the lowering water segment

- In the *Water* subtree under the *Model conditions* in the *Model explorer* note that the new water level (FullReservoir_Rapid) is assigned to *GlobalWaterLevel*.

The configuration of the phase is shown in Figure 8.10. Note that the shadow under the water level segment in the upstream shoulder indicates the variation of the water level during the phase.

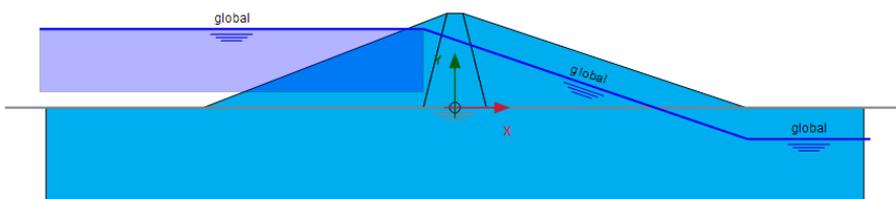


Figure 8.10 Configuration of the rapid drawdown phase

Phase 2: Slow drawdown

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

- Select the *High reservoir* phase in the *Phases explorer*.
- Add a new calculation phase.
- In *Phases explorer* double-click the newly added phase. The *Phases* window is displayed.

- 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.



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

- Assign a value of 50 days to the *Time interval* parameter.
- 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.
- Click *OK* to close the *Phases* window.
- 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.
- Rename the newly created water level as 'FullReservoir_Slow'.



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

- Specify a proper name to the function for the slow drawdown (e.g. Slow).
- Select the *Linear* option from the *Signal* drop-down menu.
- Specify a time interval of 50 days.
- Assign a value of -20 m to $\Delta Head$, representing the amount of the head decrease. A graph is displayed showing the defined function (Figure 8.11).
- Click *OK* to close the *Flow functions* window.

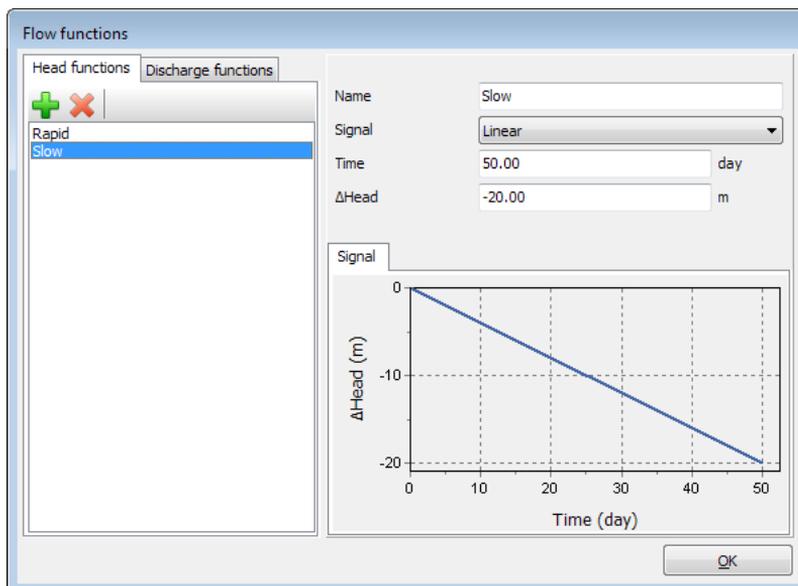


Figure 8.11 The flow function for the slow drawdown case

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

- 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.
- Expand the subtree of the selected segment and select the *Time dependent* option for the *TimeDependency* parameter.
- Select the *Slow* option for the *HeadFunction* parameter.
- In the *Water* subtree under the *Model conditions* in the *Model explorer* note that the new water level (*FullReservoir_Slow*) is assigned to *GlobalWaterLevel*.

Phase 3: Low level

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

- Select the *High reservoir* phase in the *Phases explorer*.
-  Add a new calculation phase.
- In *Phases explorer* double-click the newly added phase. The *Phases* window is displayed.
- 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.
-  Make sure that the *Plastic* option is selected as calculation type.
-  Make sure that the *Steady state groundwater flow* option is selected as *Pore pressure calculation type*.
- In the *Deformation control* subtree, select *Ignore und. behaviour (A,B)* and make sure that the *Reset displacements to zero* and *Reset small strain* options are selected in the *Deformation control parameters* subtree.
- Uncheck the *Ignore suction* option in the *Deformation control parameters* subtree.
- Click *OK* to close the *Phases* window.
-  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 (-132.0 5.0); the second point is inside the dam at a level of 5 m (-60.0 5.0); third point at (93.0 -10.0) and the fourth point just outside the right boundary at a level of 10 m below the ground surface (132.0 -10.0).
- Rename the newly created water level as 'LowLevel_Steady'.
- In the *Water* subtree under the *Model conditions* in the *Model explorer* assign the new water level (*LowLevel_Steady*) to *GlobalWaterLevel*. All the defined water levels are shown in Figure 8.12.

Phase 4 to 7:

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

- Select the parent phase in the *Phases explorer*.
-  Add a new calculation phase and proceed to the *Phases* window.
-  Set *Calculation type* to *Safety*.

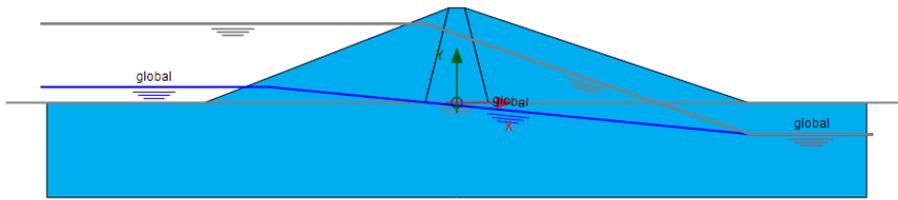


Figure 8.12 Model for the low level case in the *Flow conditions* mode

- In the *Deformation control* subtree, select *Reset displacements to zero*.
- In the *Numerical control parameters* subtree, uncheck *Use default iter parameter* box and set the *Max steps* parameter to 30 for Phase 4 and to 50 for phases 5 to 7. The final view of *Phases explorer* is given in Figure 8.13.
- In the *Deformation control parameters* subtree, check the *Ignore suction* option for all the safety analyses.

Hint: 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, 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.

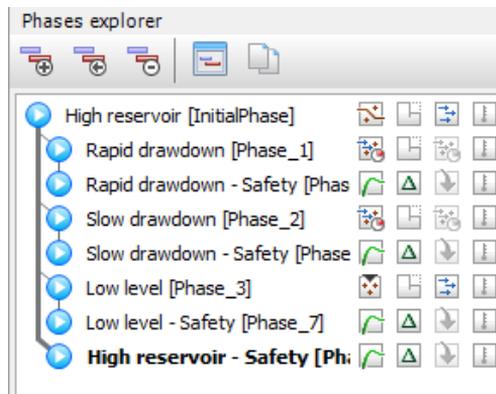


Figure 8.13 The final view of *Phases explorer*

- Proceed to the *Staged construction* mode.
- 🔧 Select nodes located at the crest (-2.5 30.0) and at the toe of the dam (-80.0 0.0).
- 🖨️ Click *Calculate* button and ignore the warnings regarding the influence of suction in the *Safety* analysis.
- 💾 Save the project after the calculation has finished.

8.4 RESULTS

The results of the four groundwater flow calculations in terms of pore pressure distribution are shown in Figures 8.14 to 8.17. Four different situations were considered:

- The steady-state situation with a high (standard) reservoir level (Figure 8.14).

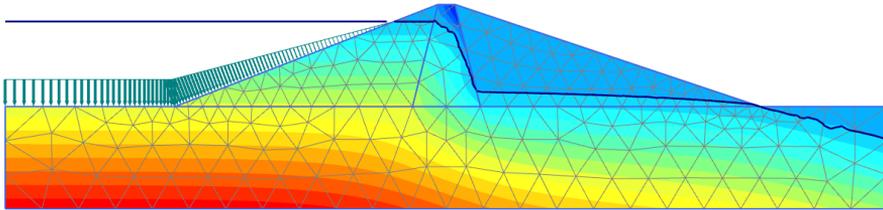


Figure 8.14 Pore pressure distribution, (p_{active}), for high reservoir level

- The pore pressure distribution after rapid drawdown of the reservoir level (Figure 8.15).

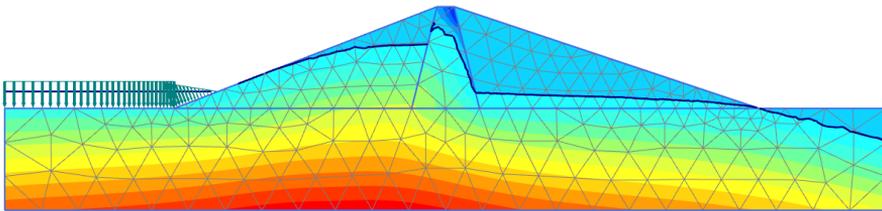


Figure 8.15 Pore pressure distribution, (p_{active}), after rapid drawdown

- The pore pressure distribution after slow drawdown of the reservoir level (Figure 8.16).

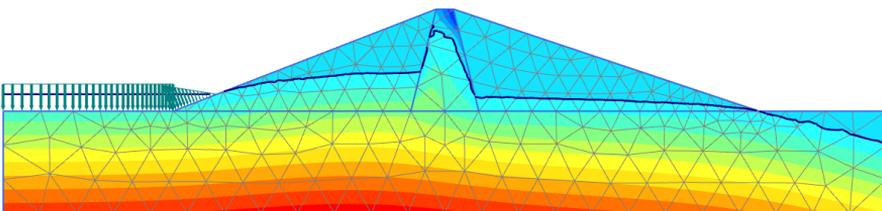


Figure 8.16 Pore pressure distribution, (p_{active}), after slow drawdown

- The steady-state situation with a low reservoir level (Figure 8.17).

Hint: 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

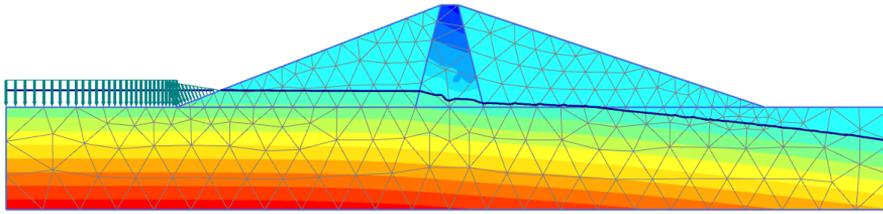


Figure 8.17 Pore pressure distribution, (p_{active}), for low reservoir level

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 ΣM_{sf} 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 8.18.

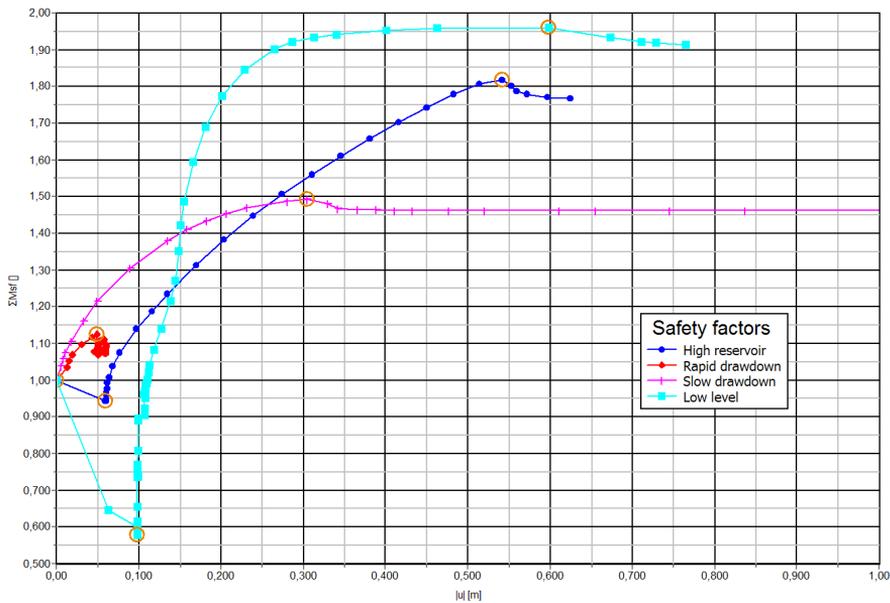


Figure 8.18 Safety factors for different situations

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 analyze such situations.

Hint: 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 ΣM_{sf} can decrease in the first part of the calculation.