

Slide

2D limit equilibrium slope stability
for soil and rock slopes

User's Guide

Part 3

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Excess Pore Pressure (B-bar method)

This tutorial will demonstrate the Excess Pore Pressure (Undrained Loading) feature of SLIDE, which allows you to account for short term (transient) changes in pore pressure due to rapidly applied loading conditions.

The method used in SLIDE is the so-called “B-bar” method, in which the change in pore pressure (excess pore pressure) is assumed to be directly proportional to a change in vertical stress. The excess pore pressure is simply given by:

$$\Delta u = \bar{B} \Delta \sigma_v \quad \text{Equation 1}$$

where \bar{B} (B-bar) is the overall pore pressure coefficient for a material. The change in vertical stress can be due to the weight of added layers of material, vertical external loads, vertical seismic loads, or a combination of these factors.

For example, if an embankment is constructed over a clay foundation, this can create a temporary condition of “excess pore pressure” within the clay. Due to low permeability, the excess pore pressure within the clay cannot readily dissipate. A non-steady state situation then exists, in which the elevated pore pressure can lead to lower safety factors, and possible failure.

The calculation of the pore pressure with the SLIDE B-bar method, may be thought of as a 2-stage analysis:

1. Stage 1 - an initial pore pressure distribution is determined, using any of the available methods in SLIDE (eg. water surfaces, R_u coefficient, pressure grid, finite element analysis).
2. Stage 2 - the excess pore pressure is then determined from the change in vertical stress, and the B-bar coefficient for a material, according to Equation 1.

The final pore pressure which is used in the stability calculations, is the sum of the Initial Pore Pressure + Excess Pore Pressure. NOTE: the safety factor is only calculated at the “final” stage, after the final pore pressure (initial + excess) has been determined for all materials.

The following embankment model will demonstrate the Excess Pore Pressure (B-bar method) in SLIDE. The tutorial consists of 4 steps:

STEP 1: First, the stability of the embankment will be determined for long-term (steady state) conditions, without accounting for undrained loading.

STEP 2: Next, we will assume undrained loading conditions. The embankment material will be specified as “causing excess pore pressure”, and the clay foundation layers will be assigned B-bar pore pressure coefficients.

STEP 3: Next, we will add an additional load on the embankment. The load will also be specified as “causing excess pore pressure”.

STEP 4: Finally, we will demonstrate that the embankment material can also be assigned an initial pore pressure distribution, even though it is assumed to be added in “stage 2”.

Step 1 – no excess pore pressure

Read in the file “embank1.sli”, from the Examples folder of your SLIDE installation folder. Run Compute. View the results in Interpret. You will see that the minimum safety factor slip surface (FS = 2.50), passes only through the embankment material, and does not extend into the supporting clay layers.

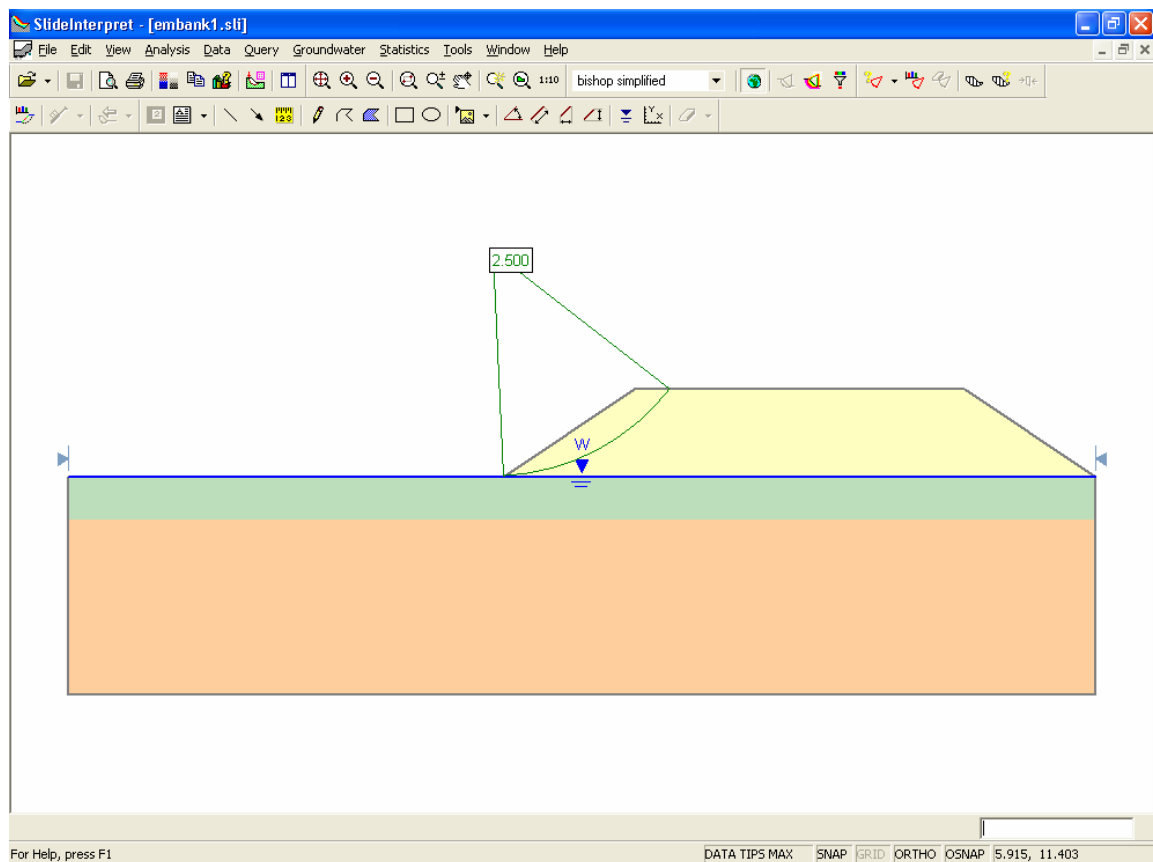


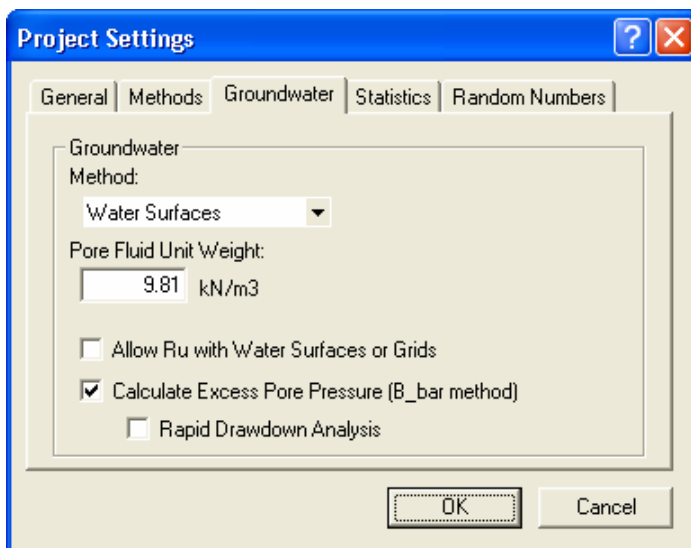
Figure 1: Critical slip surface, steady state pore pressure conditions.

Step 2 – excess pore pressure due to embankment weight

Read in the file “embank2.sli”.

Project Settings

- Select Project Settings > Groundwater
- Notice that the “Calculate Excess Pore Pressure (B-bar method)” checkbox has been selected. This checkbox must be selected in order to compute excess pore pressure using the B-bar method.
- Select Cancel in the Project Settings dialog.



Material Properties

- Select Define Materials.
- For the first material (“embankment”), notice that the “Material weight creates excess pore pressure” checkbox is selected. This means that, for the purpose of the excess pore pressure calculation, the weight of the “embankment” material will create excess pore pressure in any material underneath the embankment which has a B-bar > 0 coefficient specified. The excess pore pressure will be calculated according to Equation 1.
- Select the second material (“upper clay”). Notice that B-bar = 1 has been specified.
- Select the third material (“lower clay”). Notice that B-bar = 1 has been specified.
- Select Cancel in the Define Material Properties dialog.


Define Material Properties

☐ embankment
 ☐ upper clay
 ☐ lower clay
 ☒ Material 4

Name:
 Colour:
 Hatch:

Unit Weight: kN/m³
 Saturated U.W.: ☐ kN/m³

Strength Type:
 $\tau = c' + \sigma'_n \tan \phi'$

Strength Parameters: 

Cohesion: kN/m²
 Phi: degrees

Water Parameters (Initial Pore Pressure)

Water Surface:
 Hu:

Excess Pore Pressure

B_bar:
☒ Material weight creates excess pore pressure

Now Run Compute, and view the results in Interpret. You should see the following critical slip surface (FS = 1.80). As you can see, the critical slip surface now extends into the upper clay layer.

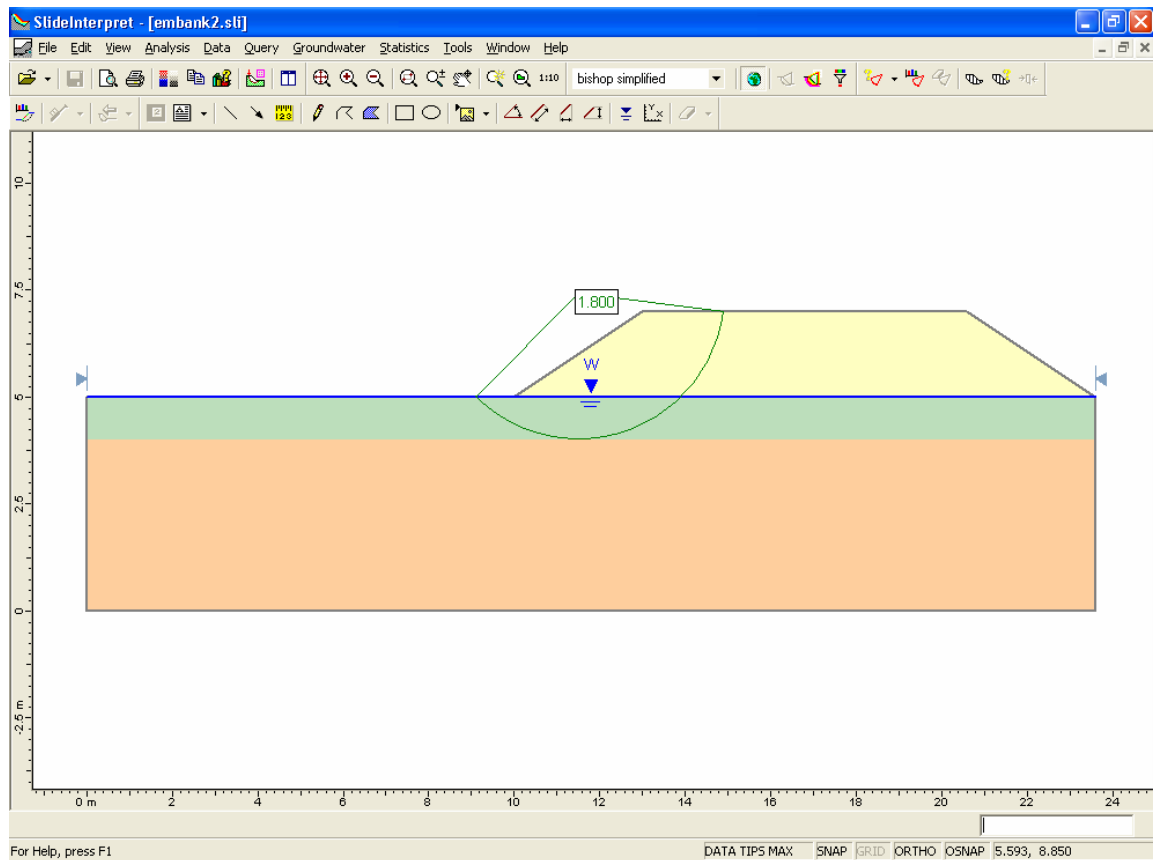
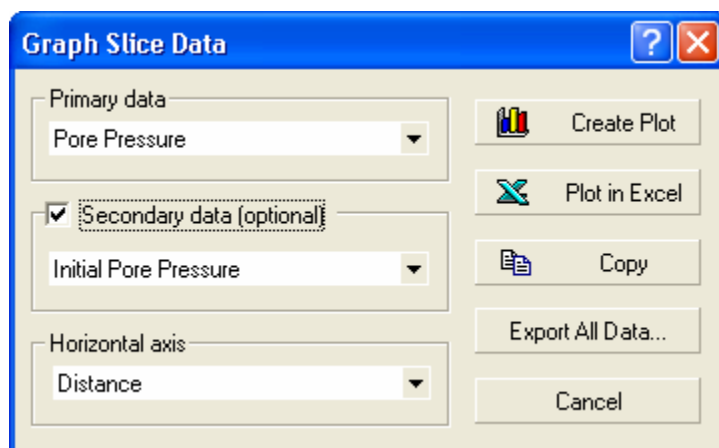


Figure 2: Embankment creates undrained loading in clay foundation.

Right-click on the critical slip surface and select “Add Query and Graph” from the popup context menu. In the dialog, select “Pore Pressure” as the primary data, and “Initial Pore Pressure” as the secondary data. Select Create Plot, and you should see the graph in Figure 3.



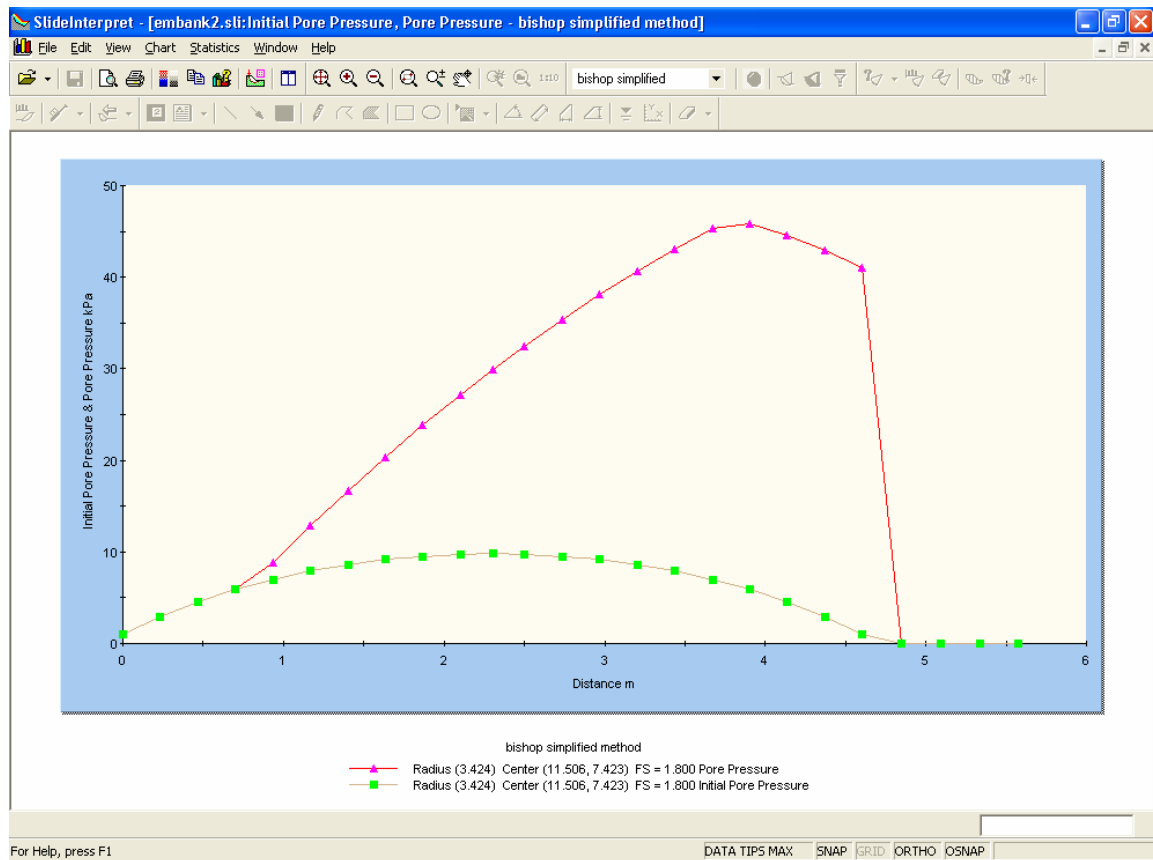


Figure 3: (Final) Pore pressure and Initial Pore pressure for file “embank2.sli”

The Initial Pore Pressure is due to the water table located at the original ground surface. The (final) Pore Pressure is the sum of the Initial Pore Pressure, and the Excess Pore Pressure created by the weight of the embankment. As you can see for this example, the Excess Pore Pressure is quite significant, and greater than the Initial Pore Pressure.

You can plot Excess Pore Pressure. Right-click on the graph and select “Change Plot Data” from the popup menu. Select “Excess Pore Pressure” as the secondary data. Select Create Plot and you should see Figure 4.

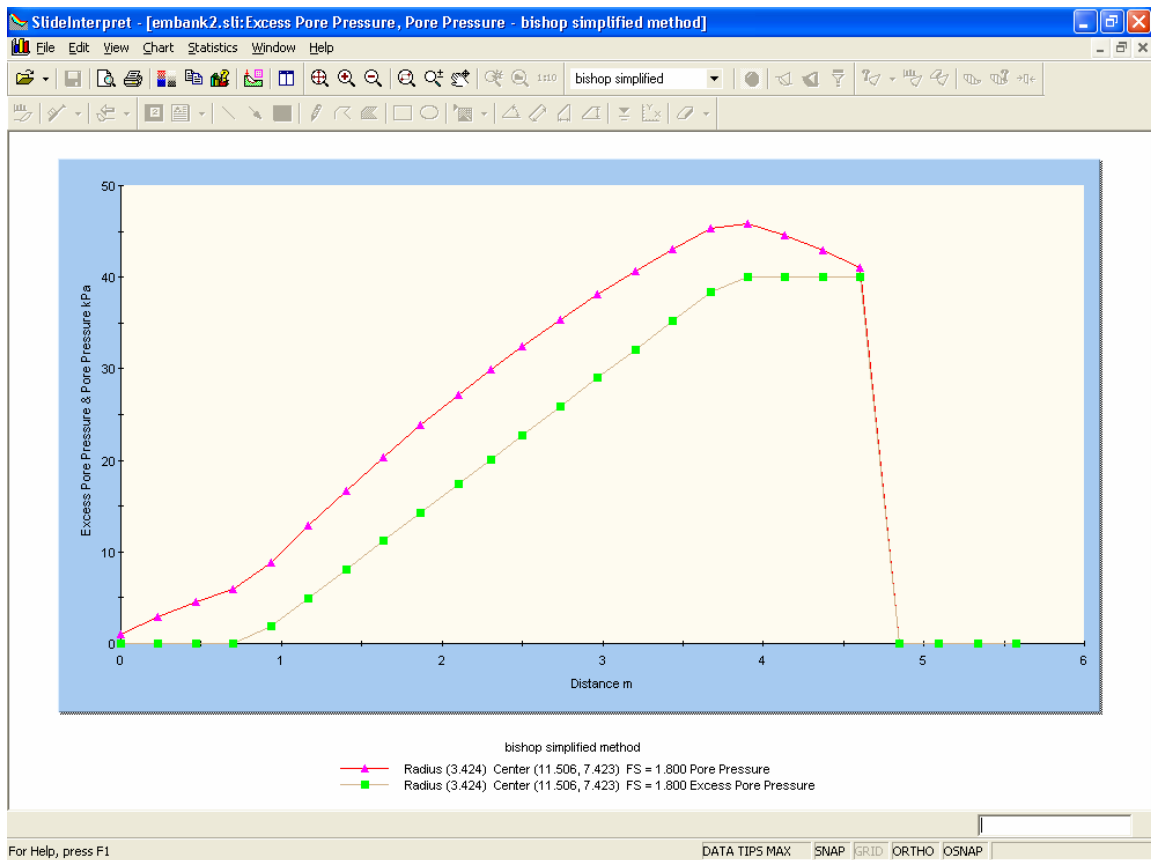


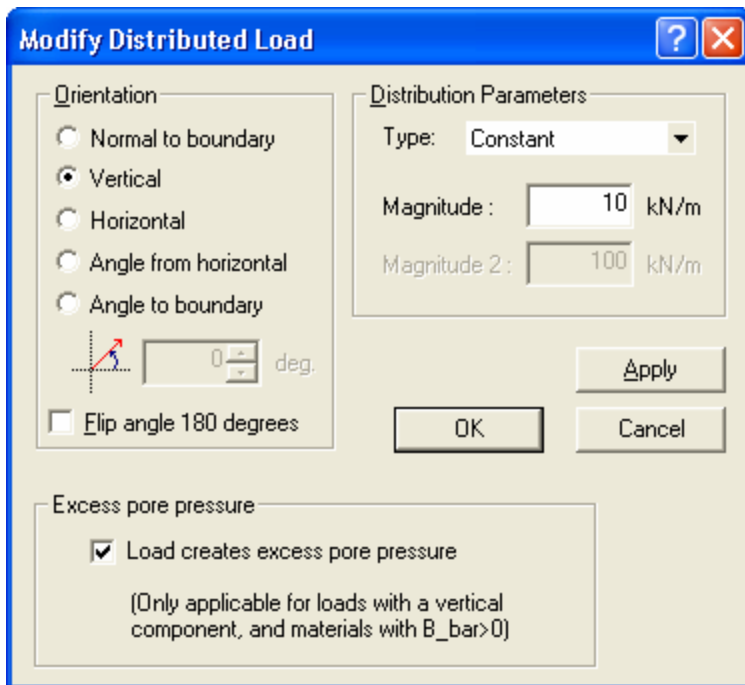
Figure 4: (Final) Pore pressure and Excess Pore pressure for file “embank2.sli”.

The Excess Pore Pressure curve displays only the excess pore pressure calculated along the slip surface, due to the weight of the embankment acting on the upper clay layer.

Step 3 – excess pore pressure due to embankment and load

In SLIDE, material weight is not the only mechanism which can cause undrained loading. External loads can also be specified as “causing excess pore pressure”. To demonstrate this, read in the file “embank3.sli”.

This file is identical to “embank2.sli”, with the addition of a 10 kN/m distributed load added to the top of the embankment. Right-click on the load and select “Modify Load” from the popup menu. You will see the following dialog.



Notice that the “Load creates excess pore pressure” checkbox has been selected.

This means that, for the purpose of the excess pore pressure calculation, the load (vertical component only) will create excess pore pressure in any material underneath the load which has a $B\text{-bar} > 0$ coefficient specified. The excess pore pressure will be calculated according to Equation 1.

Select Cancel in the Modify Load dialog.

Now Run Compute, and view the results in Interpret. You should see the following critical slip surface ($FS = 1.496$).

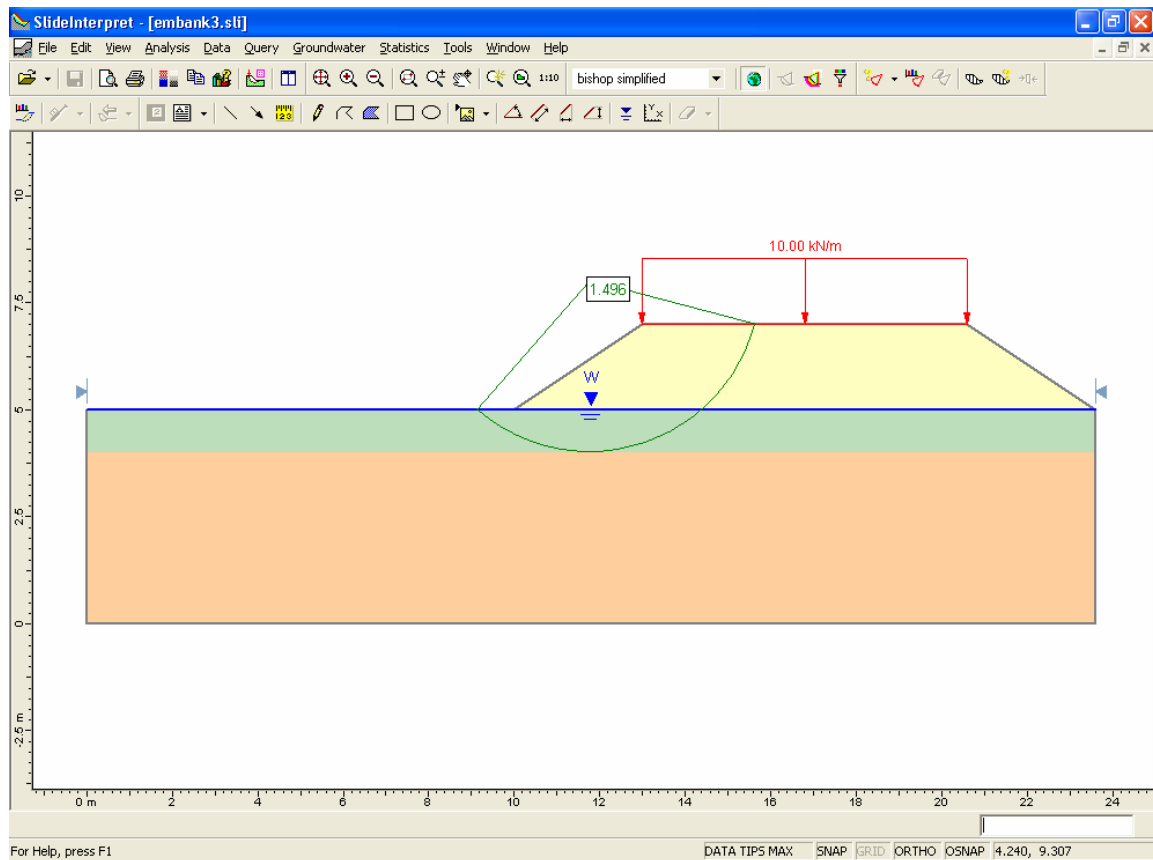


Figure 5: Distributed load contributes to additional excess pore pressure in clay foundation.

A different critical slip surface has been determined, with an even lower safety factor.

Right-click on the critical slip surface and select “Add Query and Graph” from the popup menu. In the dialog, select “Pore Pressure” as the primary data, and “Initial Pore Pressure” as the secondary data. Select Create Plot, and you should see the graph in Figure 6.

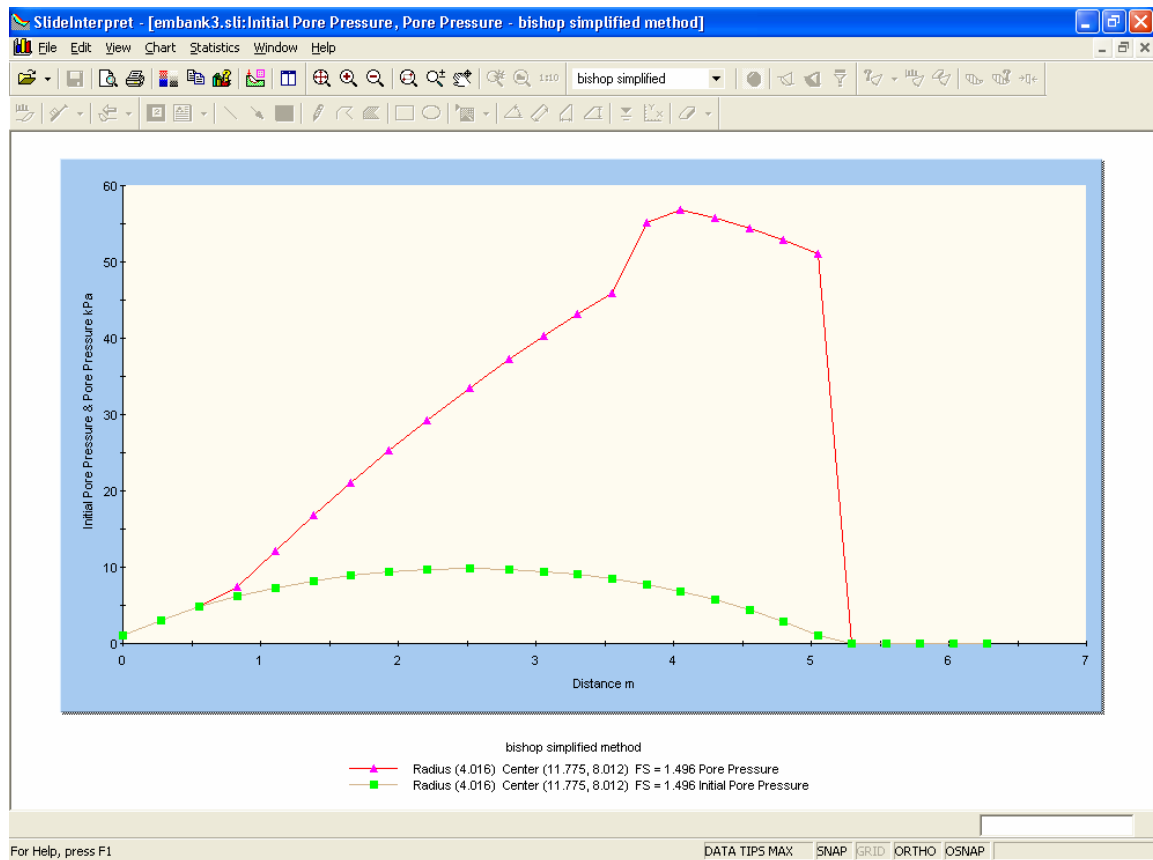


Figure 6: (Final) Pore pressure and Initial Pore pressure for file “embank3.sli”.

The (final) Pore Pressure is the sum of the Initial Pore Pressure and the Excess Pore Pressure. The Excess Pore pressure is now due to the change in vertical stress created by both the embankment weight AND the distributed load. Compare Figure 6 with Figure 3.

Right-click on the graph and select “Change Plot Data” from the popup menu. Select “Excess Pore Pressure” as the secondary data. Select Create Plot and you should see Figure 7.

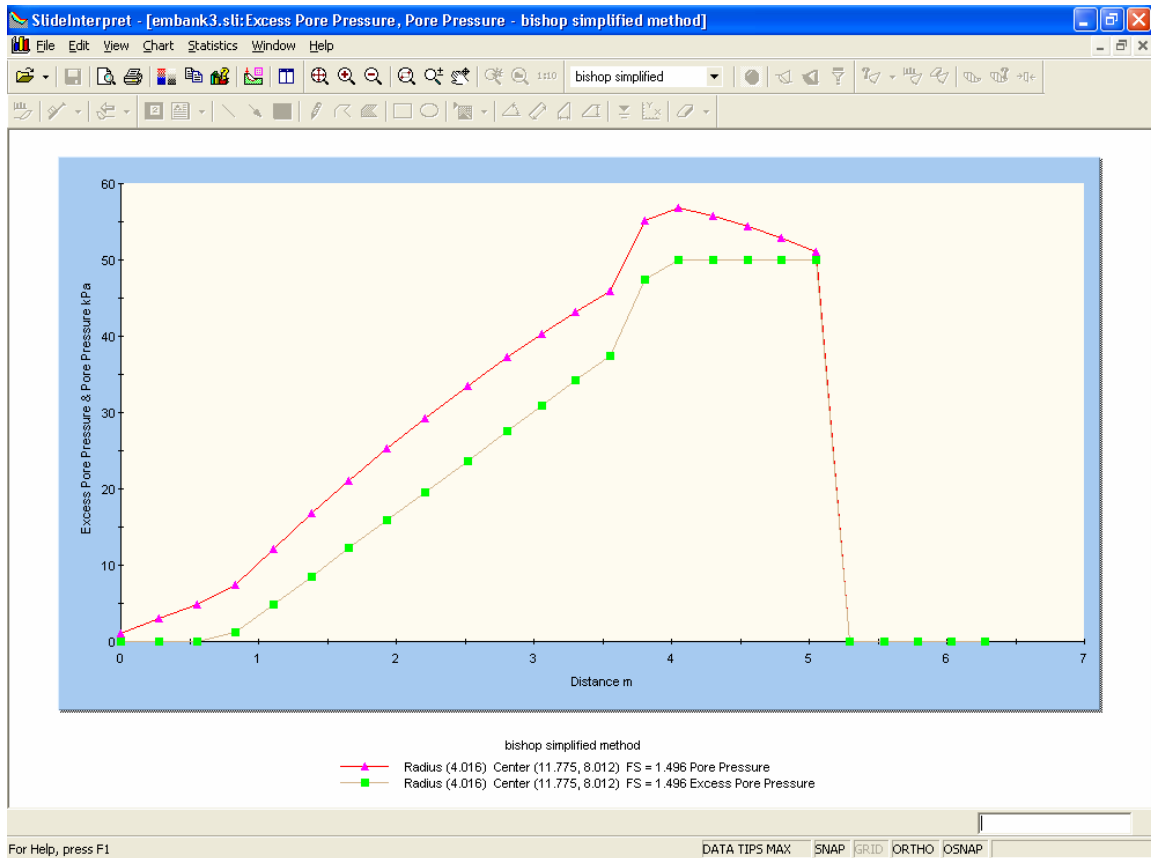


Figure 7: (Final) Pore pressure and Excess Pore pressure for file “embank3.sli”. Excess pore pressure due to embankment weight and distributed load.

Step 4 – include initial pore pressure within embankment

In this tutorial, we have so far not considered any pore pressure within the embankment material (pore pressure = 0). The embankment material can also have an initial pore pressure distribution.

Read in the file “embank4.sli”. This file is identical to “embank3.sli”, except we will now also consider pore pressure within the embankment material.

Project Settings

- Select Project Settings > Groundwater
- Notice that the “Allow Ru with Water Surfaces or Grids” checkbox has been selected. This option allows you to use the Ru method of pore pressure calculation for selected materials, even though the primary Groundwater Method = Water Surfaces.
- Select Cancel in the Project Settings dialog.

Material Properties

- Select Define Materials.
- For the first material (“embankment”), notice that Water Surface = None, and an R_u coefficient = 0.4 has been specified. The R_u coefficient will be used to calculate pore pressure within the embankment material.
- Select Cancel in the Define Material Properties dialog.

Run Compute, and view the results in Interpret. You should see the following critical slip surface (FS = 1.357). The safety factor is now lower than the “embank3.sli” file, because pore pressure is now calculated for the embankment material, as well as the clay layers.

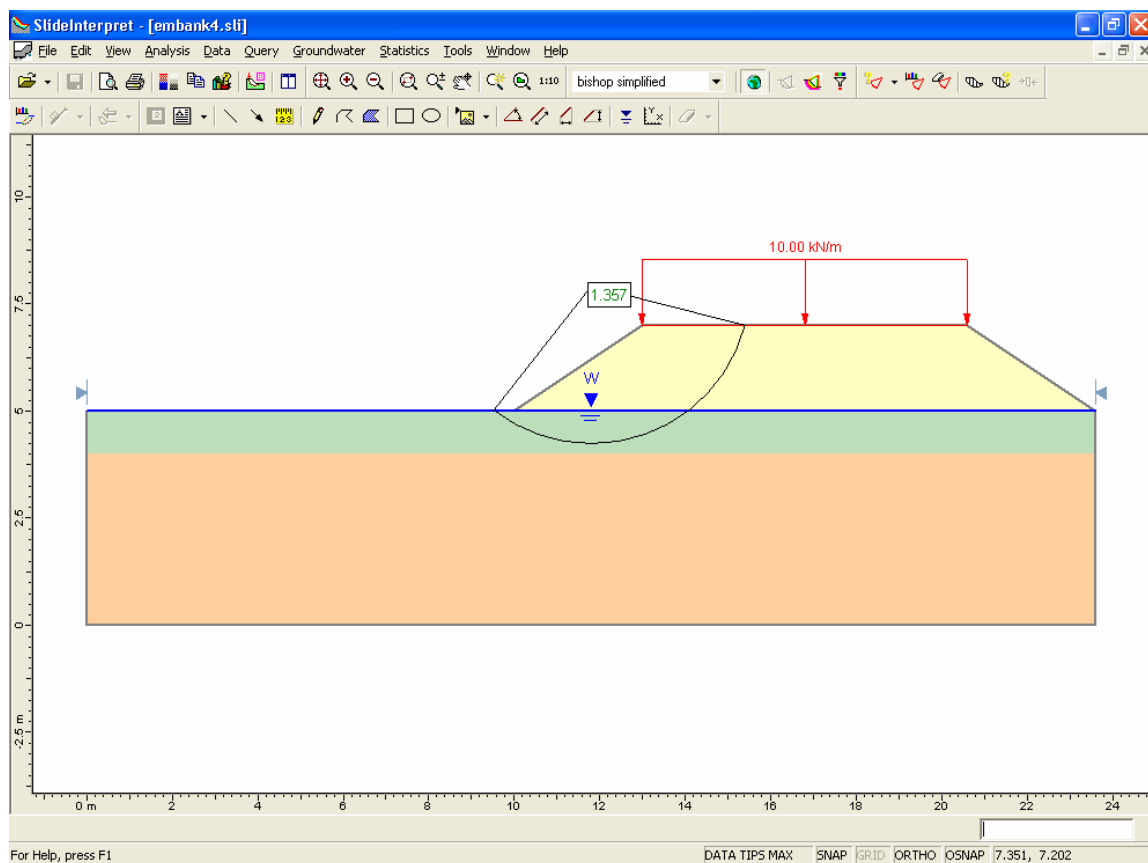


Figure 8: Initial pore pressure considered for embankment material.

Right-click on the critical slip surface and select “Add Query and Graph” from the popup context menu. In the dialog, select “Pore Pressure” as the primary data, and “Initial Pore Pressure” as the secondary data. Select Create Plot, and you should see the graph in Figure 9.

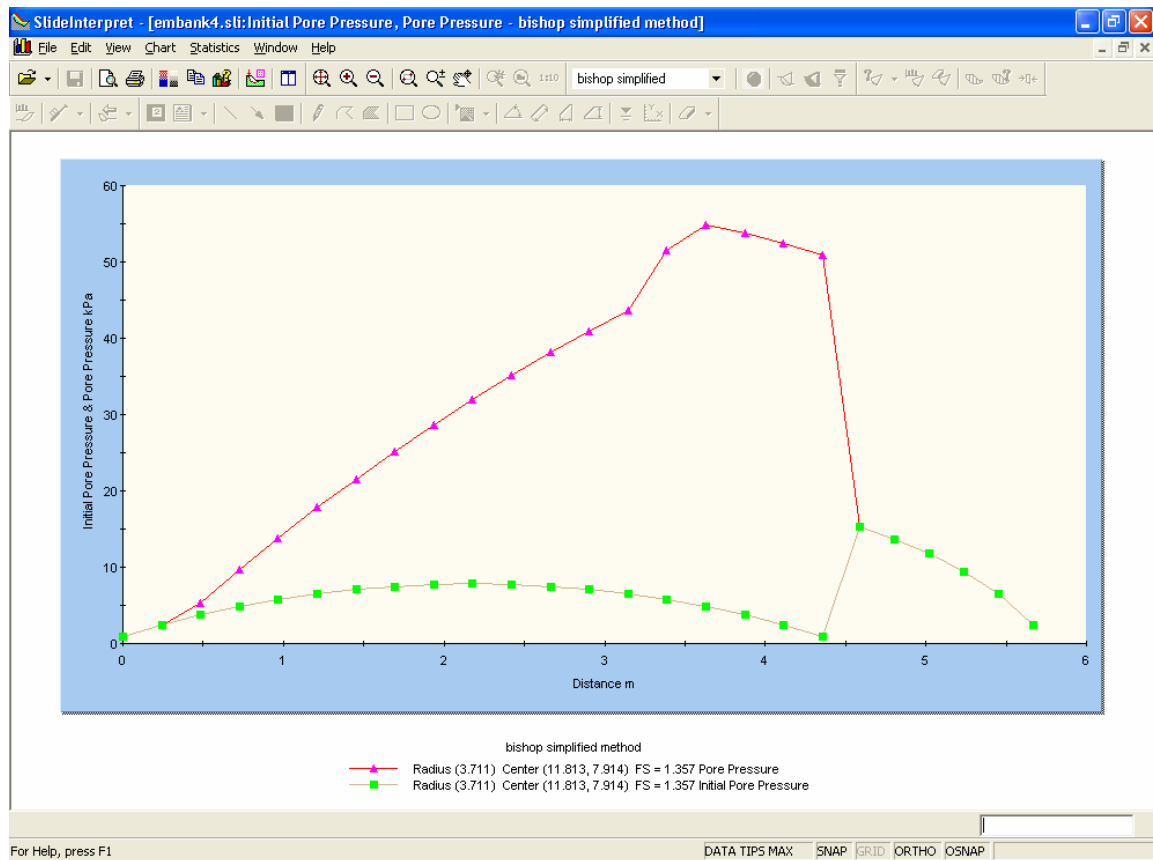


Figure 9: (Final) Pore pressure and Initial Pore pressure for file “embank4.sli”.

Notice that the pore pressure is no longer zero, for the portion of the slip surface within the embankment material (right hand side of the curves in Figure 9).

Right-click on the graph and select “Change Plot Data” from the popup menu. Select “Excess Pore Pressure” as the secondary data. Select Create Plot and you should see Figure 10.

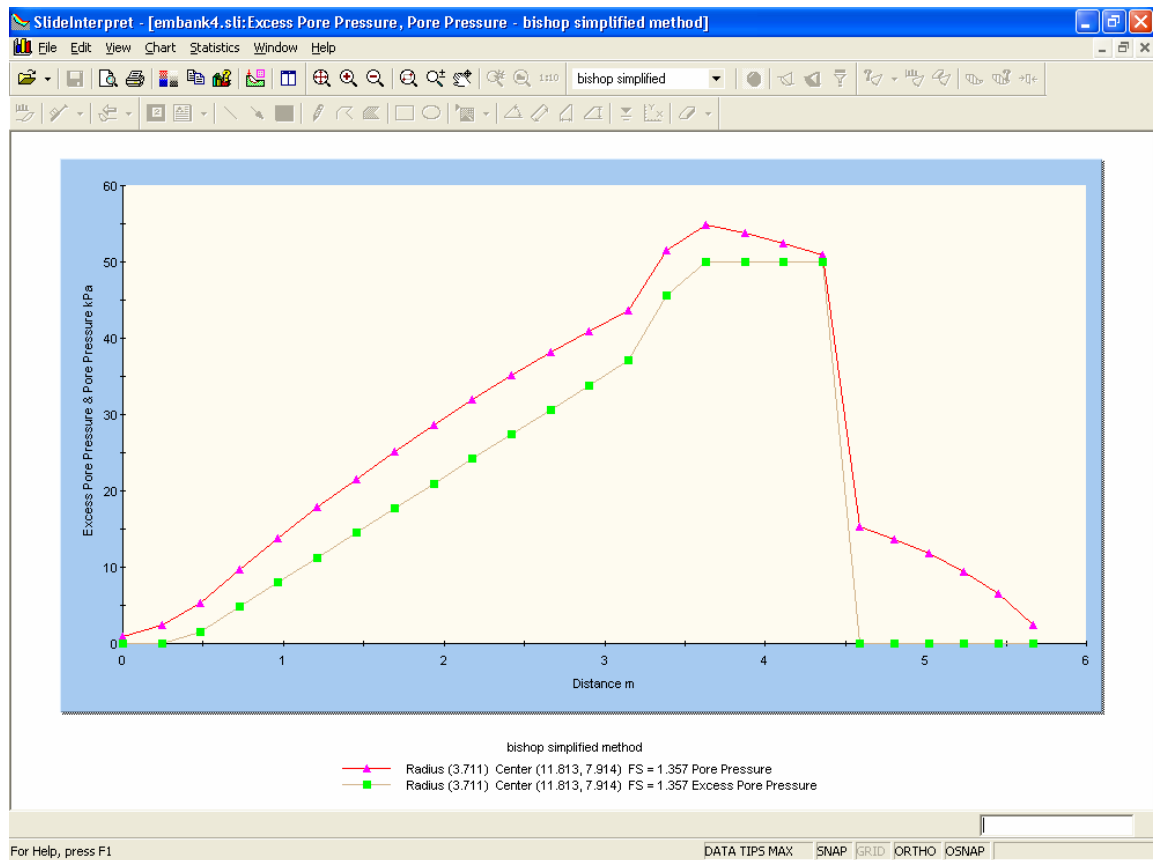


Figure 10: (Final) Pore pressure and Excess Pore pressure for file “embank4.sli”.

Notice in Figure 10, that the Excess Pore Pressure within the embankment is ZERO. Although the embankment weight creates excess pore pressure within the clay layers beneath, the embankment weight DOES NOT create excess pore pressure within itself (as this does not make physical sense). The final Pore Pressure in the embankment material, is equal to the initial pore pressure, with no contribution from excess pore pressure.

Additional Exercises

1. Re-run this example using ONLY the distributed load to create excess pore pressure, and NOT the material weight. Hint: simply turn OFF the checkbox for “Material weight creates excess pore pressure”, for the embankment material, in the Define Material Properties dialog. Graph the Final and Excess Pore pressure for the critical slip surface.
2. In this tutorial we have demonstrated that Excess Pore Pressure (Undrained Loading) can be generated by material weight and / or distributed loading. In SLIDE, Excess Pore Pressure can also be generated by Seismic Loading (vertical coefficient only), or Line Loads (vertical component only). Just select the “Load creates excess pore pressure” checkbox in the Seismic Load dialog or the Line Load dialog, when you define Seismic or Line loads.
3. One final observation – you may have noticed, in the Define Material Properties dialog, that for the embankment material, the B-bar parameter was still enabled, even though we have stated (in Step 4), that a material’s own weight, cannot create excess pore pressure within itself (does not make physical sense). So why is B-bar still enabled for such “stage 2” materials?

Answer: this is to account for the possibility that Distributed, Line or Seismic Loads, may create excess pore pressure within a “stage 2” material. In effect, you have a 3-stage pore pressure calculation:

- i. Calculation of initial pore pressure for all materials
- ii. Calculation of excess pore pressure for stage 1 materials, due to added material weight or loading (distributed, line or seismic).
- iii. Calculation of excess pore pressure for stage 2 materials, due to loading (distributed, line or seismic).

Just remember that the safety factor is only calculated at the “final” stage, after the final pore pressure (initial + excess) has been determined for all materials.

Rapid Drawdown Analysis (B-bar method)

The concept of excess pore pressure using the B-bar method, can also be applied to unloading scenarios. If a load is removed quickly from a low permeability material, a “negative excess pore pressure” can be induced.

The change in pore pressure is given by:

$$\Delta u = \bar{B} \Delta \sigma_v \quad \text{Equation 1}$$

where \bar{B} (B-bar) is the overall pore pressure coefficient for a material. In SLIDE, this can be used to simulate the pore pressure changes due to rapid drawdown of ponded water in earth dams.

In the SLIDE Rapid Drawdown analysis:

1. The initial pore pressure distribution is determined, using any of the available methods in SLIDE (eg. water surfaces, Ru coefficient, pressure grid, finite element analysis).
2. The weight of the ponded water is computed. The change in pore pressure (B-bar method) can then be calculated, due to the removal (unloading) of the ponded water, according to Equation 1. The final pore pressure at any point (for B-bar materials), is the sum of the initial pore pressure and the (negative) excess pore pressure.
3. For the purpose of the safety factor calculation, ALL ponded water is then removed from the model.

This tutorial will demonstrate rapid drawdown analysis using the B-bar method in SLIDE. The following scenarios will be analyzed: full reservoir, complete drawdown, partial drawdown.

Full Reservoir, Steady State

First we will analyze a dam with a full reservoir.

Read in the SLIDE file “drawdown1.sli”.

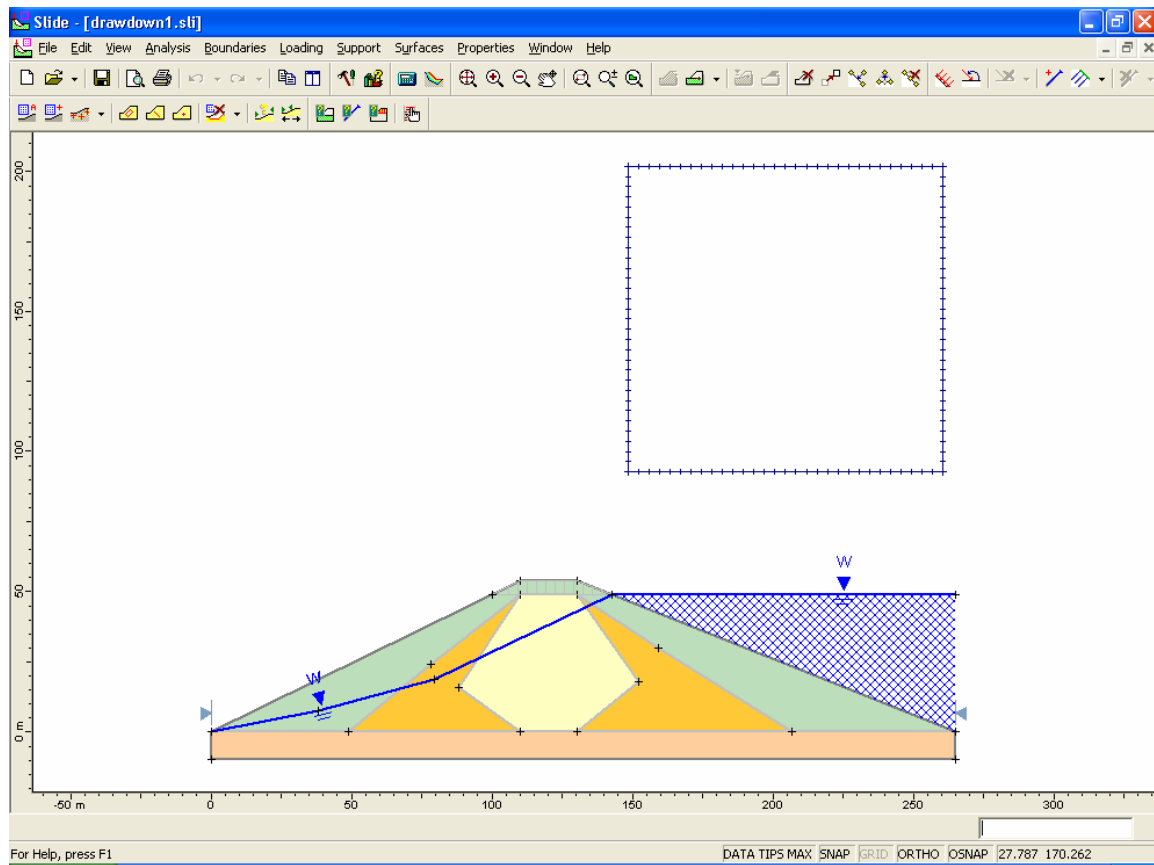


Figure 1: Dam with full reservoir.

The model represents a dam with a clay core, a transition zone, and a granular fill outer layer.

Run Compute and then view the results in Interpret. You should see Figure 2. The critical slip circle has a safety factor = 1.99.

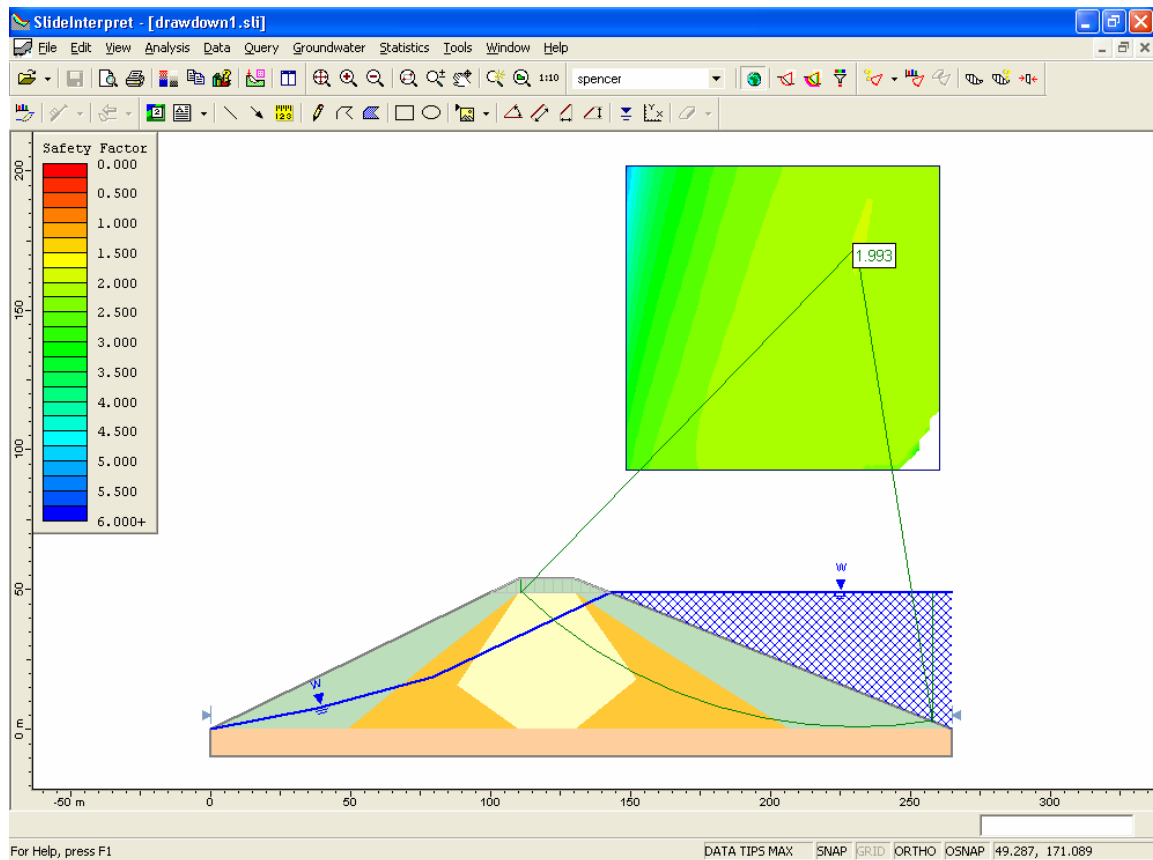


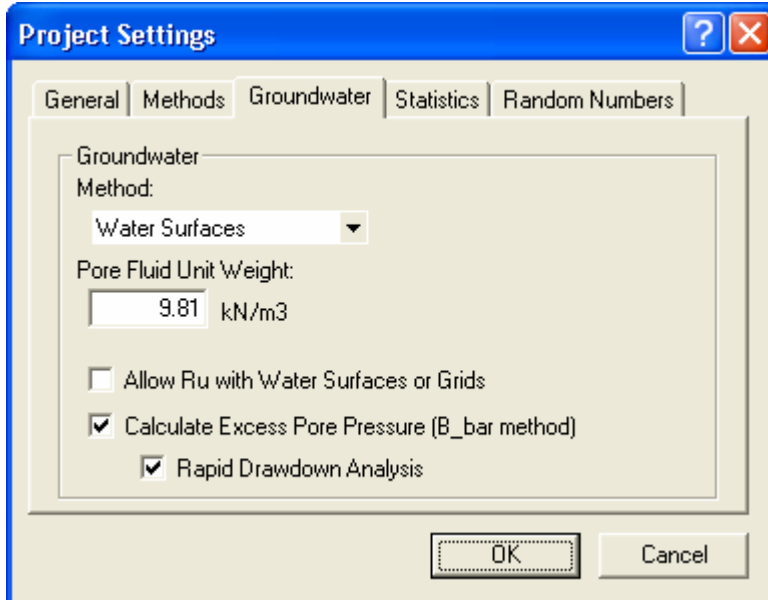
Figure 2: Critical slip circle with full reservoir.

Rapid Drawdown of entire reservoir

Read in the SLIDE file “drawdown2.sli”. This file simulates complete drawdown of the reservoir. Note that the ponded water is displayed with a gray hatched pattern, rather than the usual blue hatched pattern. This is to indicate that a drawdown state exists, ie. the ponded water will be removed for the final stage of the analysis (ie. the safety factor calculation).

Project Settings

- Select Project Settings > Groundwater
- The “Calculate Excess Pore Pressure (B-bar method)” checkbox has been selected. This checkbox must be selected in order to compute pore pressure change using the B-bar method.
- The “Rapid Drawdown Analysis” checkbox is also selected. When this checkbox is selected, this has the effect of removing ALL ponded water from the final stability analysis. The change in pore pressure due to removal of the ponded water will be calculated using the B-bar method.
- Select Cancel in the Project Settings dialog.



Material Properties

- Select Define Materials
- For the “clay core”, “transition” and “hard bottom” materials, a B-bar coefficient of 1 has been entered. This will result in a negative pore pressure change for any of these materials which is located beneath the ponded water, calculated according to Equation 1.
- The “granular fill” is assumed to be free-draining. For this complete drawdown analysis, we would like to specify zero pore pressure in this material, so Water Surface = None (ie. no pore pressure will exist in the “granular fill” for the stability analysis). Also note that B-bar = 0 for the granular fill material (ie. the removal of the ponded water will not affect the pore pressure in this material).
- Select Cancel in the Define Material Properties dialog.

Run Compute, and view the results in Interpret. You should see the following critical slip surface (FS = 1.44).

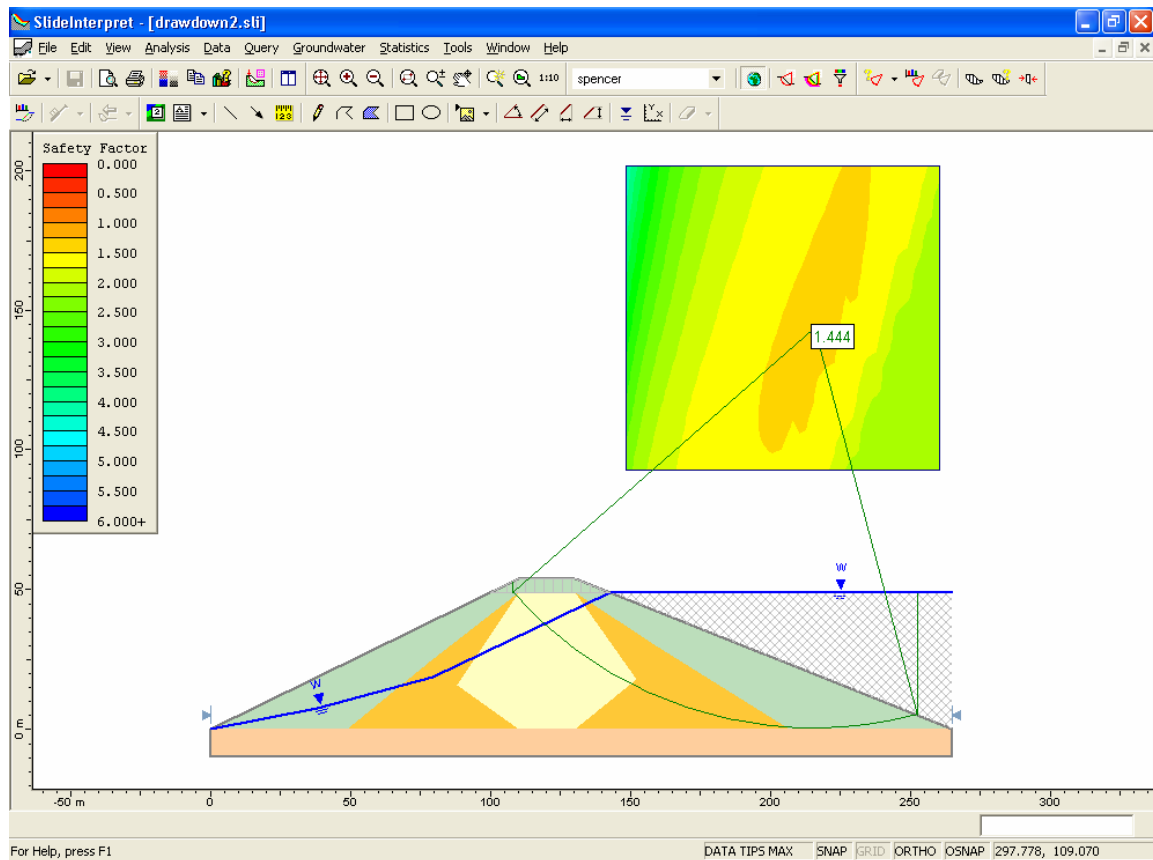
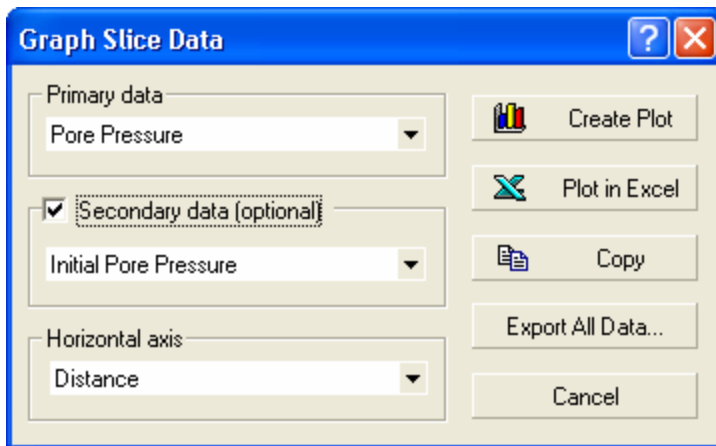


Figure 3: Critical slip surface after rapid drawdown.

The critical safety factor after rapid drawdown is significantly lower than the safety factor of the full reservoir, as we would expect, due to the removal of the support provided by the ponded water against the slope. For this example, the critical slip circles, before and after drawdown, are quite similar (ie. large, deep seated surfaces passing through the core of the dam).

Let's examine the pore pressure along this slip surface. Select Graph Query from the toolbar. You will see the following dialog:



Select Pore Pressure as the primary data, and Initial Pore pressure as the secondary data, and select Create Plot. You should see the following plots.

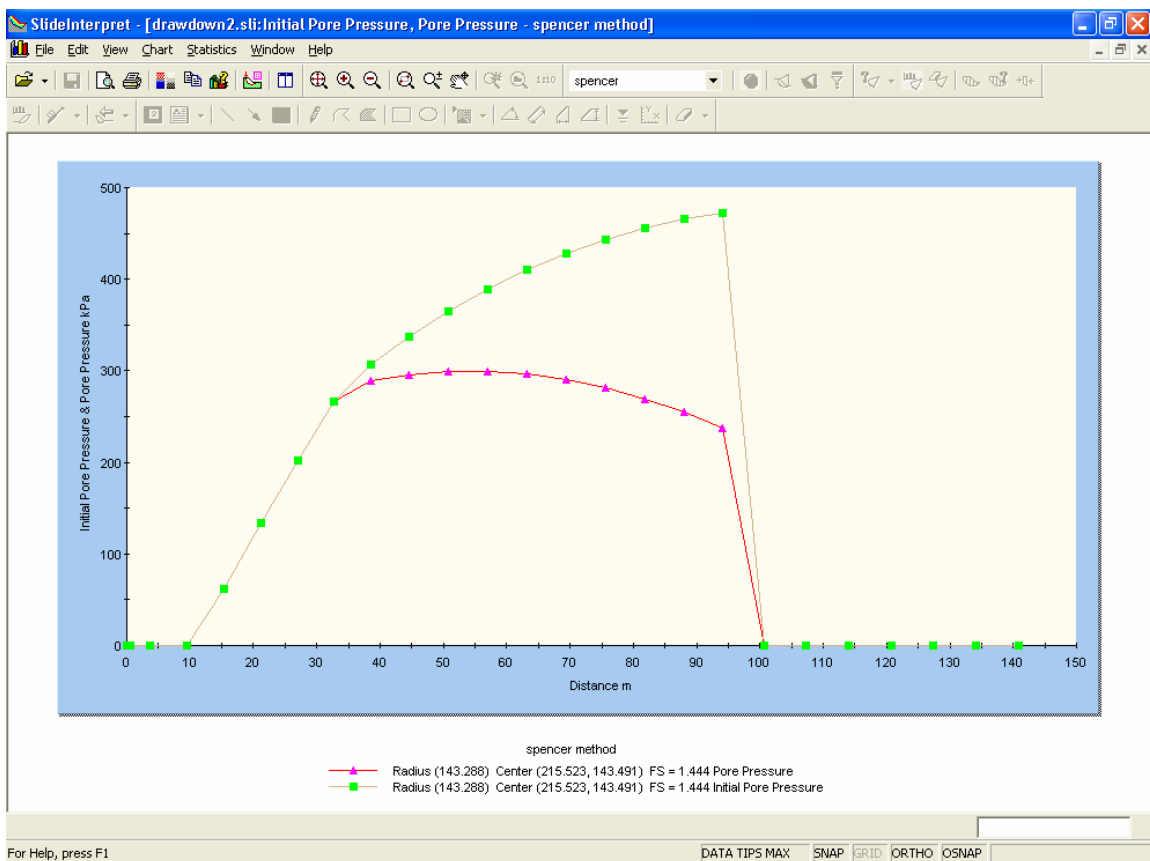


Figure 4: Final Pore Pressure and Initial Pore pressure.

Notice that the (final) Pore Pressure is actually lower than the Initial Pore Pressure. This is due to the negative change in pore pressure, due to removal of the ponded water, above the “transition” material ($B\text{-bar} = 1$). Let’s plot the Excess Pore pressure.

Right-click on the graph, and select “Change Plot Data” from the popup menu. Select Excess Pore Pressure as the secondary data, and select Create Plot. You should see the following plot.

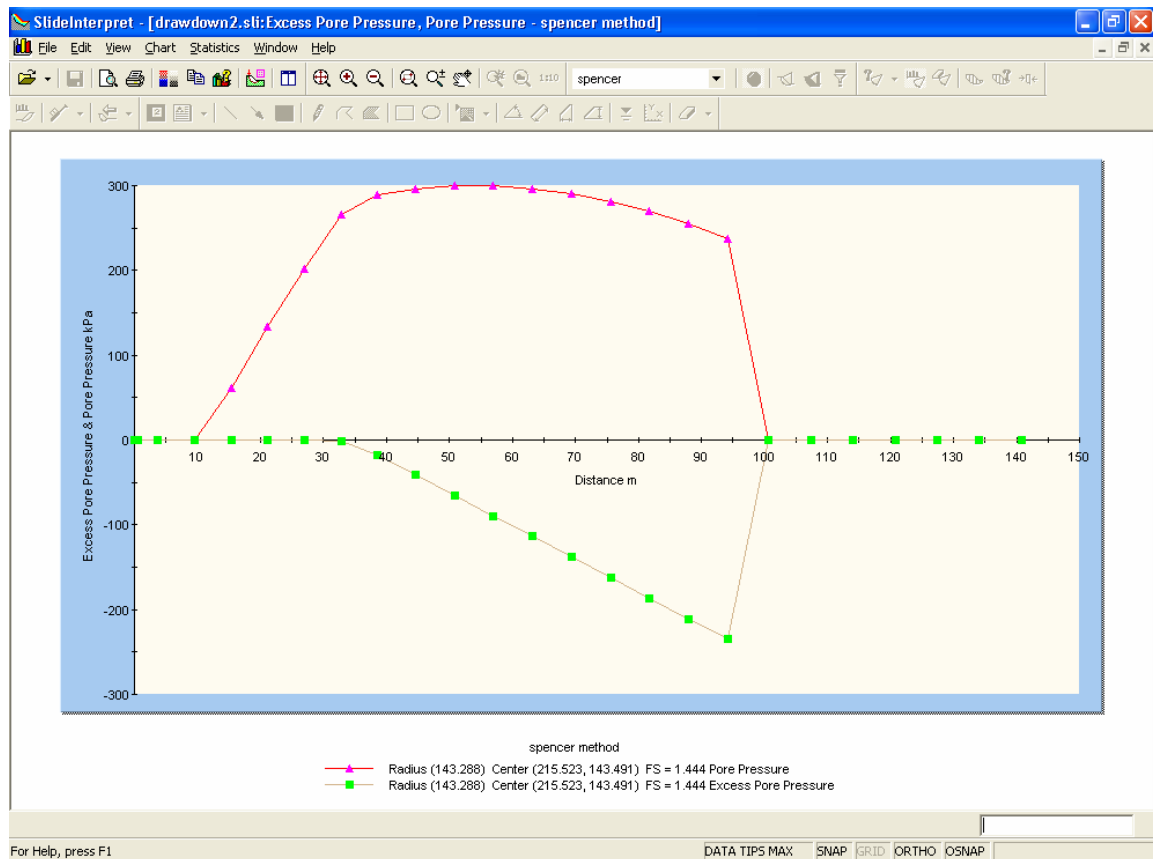


Fig. 5: Final pore pressure and excess pore pressure, rapid drawdown analysis.

The negative excess pore pressure is clearly visible on the plot, and corresponds to the removal of the ponded water, over the portion of the slip surface which passes through the “transition” material.

Also notice that the pore pressure in the “granular fill” material is zero (right side of plot in Figure 5), because this is what we specified in the Define Materials dialog, to represent a complete drawdown state, for the granular fill material.

Rapid Drawdown to specified level

Finally, let's demonstrate how we can model rapid drawdown to a specified water level, rather than a full drawdown.

Read in the file “drawdown3.sli”.

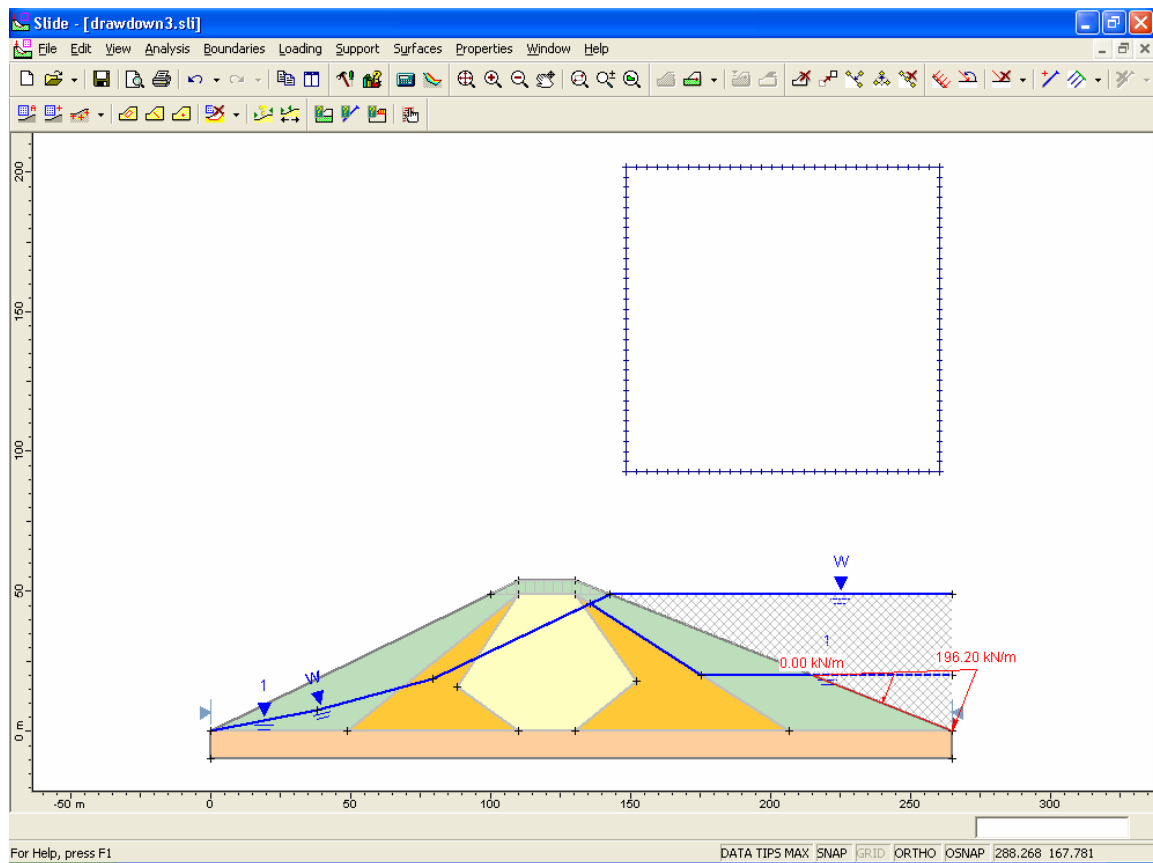


Figure 6: Partial drawdown of reservoir.

For this file, note the following:

1. We have added a Piezometric Line, to represent the pore pressure at the drawdown level, for the “granular material”. The Piezometric line has been assigned to the granular material in the Define Material Properties dialog. The Piezometric line does NOT affect pore pressure in the other materials.
2. We have added a triangular distributed load, to model the force of the ponded water on the slope, at the drawdown level. See the note at the end of this tutorial for details about how this load is determined.

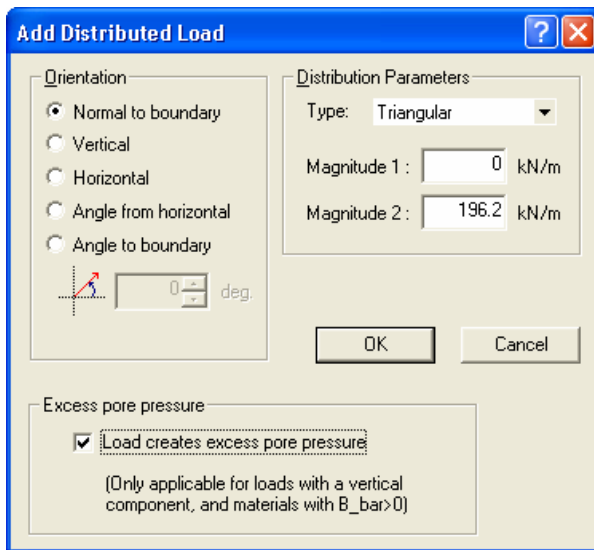


Figure 7: Equivalent distributed load for 20 meter depth of ponded water.

Run Compute, and view the results in Interpret.

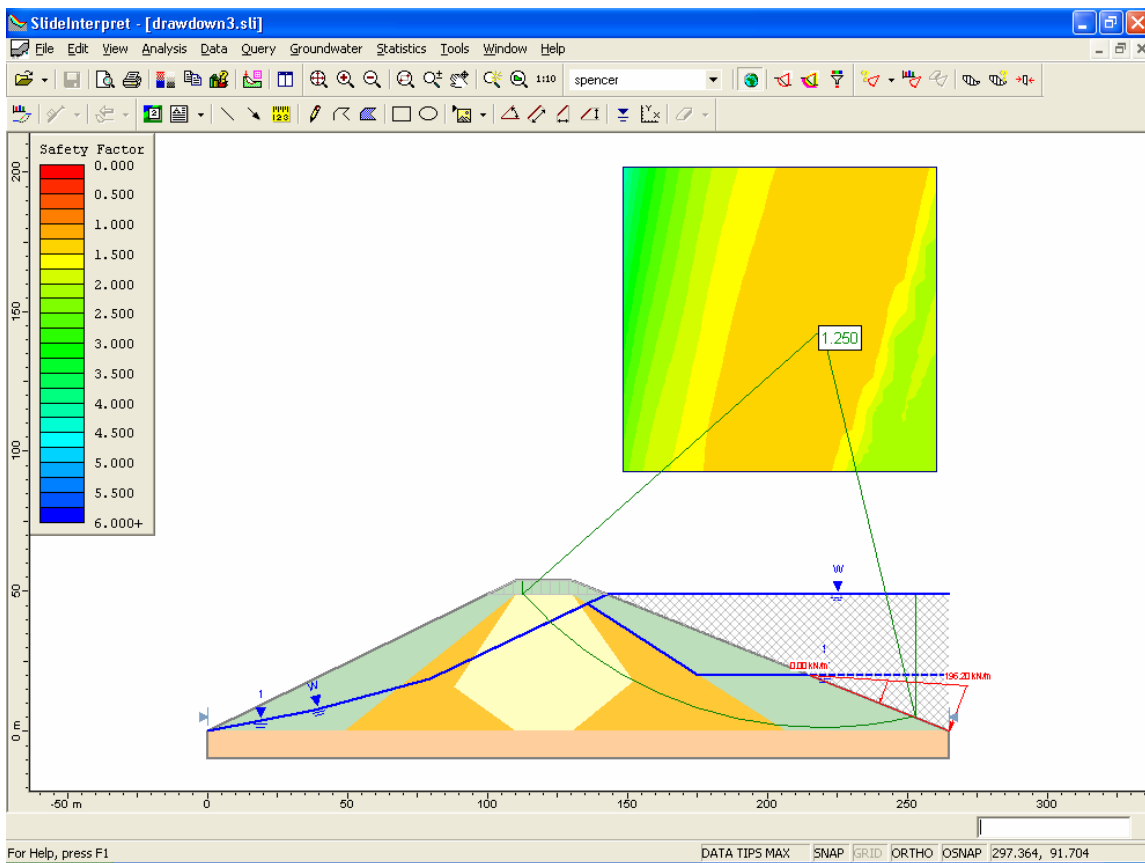


Figure 8: Critical slip surface for partial drawdown of reservoir.

For this example, the minimum safety factor at partial drawdown is lower than the minimum safety factor at full drawdown. This is due to the material properties and geometry of the slope – eg. complete drainage (zero pore pressure), assumed for the granular material for the complete drawdown state. At partial drawdown, the Piezometric line creates significant pore pressure in the granular material, towards the toe of the slope, and this leads to the lower safety factor. For this particular model, a minimum safety factor therefore exists at some intermediate drawdown level.

Equivalent distributed load to represent ponded water

To calculate the equivalent distributed load to represent a given depth of ponded water against the slope:

1. Add a Triangular Distributed load along the slope surface, which has the same extent as the ponded water you wish to replace.
2. The orientation of the load must be Normal to the slope surface.
3. The magnitude of the triangular load = 0 at the water surface.
4. The magnitude of the triangular load at a given depth below the water level, is simply given by: $\text{Magnitude} = (\text{unit weight of water}) * (\text{depth})$. For this example, $\text{Magnitude} = 9.81 * 20 = 196.2 \text{ kN/m}$ (see Figure 7).
5. This will create a distributed load with the equivalent load of the ponded water on the slope.
6. If the slope surface beneath the ponded water consists of multiple line segments, you will have to define individual triangular distributed loads, for each segment of the slope. The load magnitude at each end of the triangular load is equal to $(\text{unit weight of water}) * (\text{depth})$.
7. Finally, note that it is important to select the “Load creates excess pore pressure” checkbox for the distributed load. This is necessary to counteract the effect of the complete removal of the ponded water, so that the total excess pore pressure is correctly calculated for that part of the slope. For this example, it does not make any difference, because the granular material ($B\text{-bar} = 0$) exists at this location. However, if a material with $B\text{-bar} > 0$ was used, then this checkbox must be selected for the distributed load.