Multi-Stage Rapid Drawdown

When the water level at a dam drops, the stabilizing force due to the weight of the water is removed. If the dam material has a low permeability and the water level drops quickly, then excess pore pressures will be slow to dissipate. This causes reduced stability in the slope. This tutorial describes how to use *Slide* to model rapid drawdown and examine the effect on dam stability and factor of safety.

The finished product of this tutorial can be found in the **Tutorial 17 Rapid Drawdown.slim** data file. All tutorial files installed with *Slide* 6.0 can be accessed by selecting File > Recent Folders > Tutorials Folder from the *Slide* main menu.

**Topics Covered**

- Rapid Drawdown: Duncan, Wright and Wong
- Rapid Drawdown: Lowe and Karafiath
- Rapid Drawdown: Army Corps of Engineers

**Geometry**
Full Reservoir, Steady State

The model is based on the Pilarcitos Dam analysis as described in Duncan, Wright and Wong (1990). The dam failed due to rapid drawdown of the water level in November, 1969.

Start the *Slide* Model program.

**Project Settings**

Open the *Project Settings* dialog from the *Analysis* menu. Set the Stress Units to Imperial. The time units do not matter since we are not doing a transient finite element groundwater analysis. Ensure the Failure Direction = Right to Left. The dialog should look like this:

![Project Settings dialog](image)

Click OK to close the Project Settings dialog.

**Boundaries**

First add an external boundary. Select the *Add External Boundary* option in the *Boundaries* menu and enter the following coordinates:

- 0, 0
- 260, 0
- 260, 78
- 205, 78
Hit Enter to finish entering points. This defines the external boundary, which defines the dam. The dam is assumed to sit upon a high strength material that is not included in the model. The dam should look like this:

**Material Properties**

Select Define Materials from the Properties menu. The dam is a homogeneous rolled earthfill embankment with the following drained material properties:

\[
\begin{align*}
\gamma &= 135 \text{ pcf} \\
\cprime &= 0 \text{ ksf} \\
\phi &= 45^\circ.
\end{align*}
\]

So enter the material properties for Material 1 as shown.
Click OK to close the dialog.

**Water Table**

To add the water table, select **Boundaries → Add Water Table**. Enter the following coordinates:

\[
\begin{align*}
0 & , 72 \\
260 & , 72
\end{align*}
\]

Hit Enter to finish entering coordinates. When the ‘Assign Water Table to Materials’ dialog appears, ensure that Material 1 is selected and click OK. The model should look like this:
Slip Surfaces

Select **Surfaces → Auto Grid** to automatically generate a grid of slip centres. Leave the default grid spacing as 20 in the X direction and 20 in the Y direction.

Click OK in the dialog and the model will look like this:
You are now ready to compute the results for the full reservoir.

**Compute**

Save the model using the **Save As** option in the **File** menu. Choose **Compute** from the **Analysis** menu to perform the analysis and choose **Interpret** from the **Analysis** menu to view the results.

**Interpret**

The Interpret program shows the results of the Bishop Simplified analysis by default. You can see that the factor of safety is 2.5 and that this is for a very small surface slip at the toe. (You can prevent *Slide* from generating these shallow failure surfaces by going to Surfaces → Surface Options and selecting a minimum depth greater than 0. See the help files for more details.) Essentially, this model can be considered stable.
Model with Rapid Drawdown

Go back to the *Slide* Model program. We now wish to simulate the rapid lowering of the water table. First we have to enable rapid drawdown analysis.

Open the **Project Settings** dialog from the **Analysis** menu. On the left side click on **Groundwater**. Click the **Advanced** check box and select **Rapid Drawdown Method**. We will look at three different methods in this tutorial but first we will examine the Duncan, Wright and Wong method so choose this method in the drop down menu.
Click OK to close the dialog.

You will now see that the water table appears as a dashed line and is annotated with the word ‘Initial’. We now need to add the final water table position. Go to **Boundaries → Add Drawdown Line**. Enter the following coordinates:

0 , 37
260 , 37

Hit Enter to stop entering points. The model will now look like this:

There is one more thing that must be done before running the drawdown analysis, and that is to define the undrained material properties.

Select **Define Materials** from the **Properties** menu. Under Rapid Drawdown Parameters check the box for Undrained Behaviour. Click the Define Strength button. Select the ‘Total Stress R Envelope – Linear’ option. Enter a Cr of 60 psf and an angle of 23°.
Click OK to close the dialog. Click OK to close the Define Material Properties dialog.

The total stress $R$ envelope is a way of representing the undrained strength of the material. It is also possible to specify a $K_c = 1$ envelope. For details about the meaning of these different envelopes, and their relationship to each other, see the information below.
**About Strength Envelopes:**

For undrained material, the shear strength can be determined from isotropic consolidated undrained (IC-U) laboratory tests. The total stress envelope can be constructed as shown below.

Where \(\sigma'_{sc}\) is the effective stress during (isotropic) consolidation and \((\sigma_1 - \sigma_2)_f\) is the principal stress difference at failure.

From the same laboratory test data, it is possible to construct a \(K_c = 1\) envelope instead as shown below.

These two different envelopes are related through the following equations:

\[
\phi_{c_{fc}=1} = \psi_{r} \left( \frac{\cos \phi_r \cos \phi'}{1 - \sin \phi_r} \right)
\]

\[
\psi_{c_{fc}=1} = \tan^{-1} \left( \frac{\sin \phi_r \cos \phi'}{1 - \sin \phi_r} \right)
\]
Where $\phi'$ is the undrained friction angle.

**Army Corps method**

To perform the limit equilibrium analysis, the Army Corps method requires the $R$ envelope. If the $K_c = 1$ envelope is entered instead, then it is converted using the above equations. The $R$ envelope is then combined with the effective stress envelope to avoid relying on elevated shear strengths that result from negative pore pressures. The composite envelope is shown below.

*Other methods*

The Lowe and Karafiath (1960) and the Duncan Wright and Wong (1990) methods require the $K_c = 1$ envelope. If the $R$ envelope is entered instead, then it is converted using the above equations. $K_c = 1$ refers to an isotropically consolidated state. To get the envelope for an anisotropically consolidated material (where $K_c \neq 1$) the drained failure envelope is plotted on the same graph. The drained envelope is assumed to represent the undrained shear strength of the soil at maximum allowable $K_c$ (i.e. the value of $K_c$ that results in failure during consolidation). The envelope to be used in the analysis is then interpolated between the two, using the value of $K_c$ for each slice in the limit equilibrium analysis of the slope prior to drawdown.
Once the envelope is defined, the limit equilibrium analysis is performed for the second stage (after drawdown) using the new shear strengths. In the Duncan, Wright and Wong (1990) method, a third stage of computation is also performed. In this stage, the effective stress on the bottom of each slice (after drawdown) is calculated and if the drained shear strength is less than the undrained shear strength, then the drained shear strength is used instead.

**Compute**

Save the model using the Save option in the File menu.

Choose Compute from the Analysis menu to perform the analysis and choose Interpret from the Analysis menu to view the results.
Interpret

As before, the Interpret program shows the results of the Bishop Simplified analysis.

You can see that the factor of safety is now approximately 1, corresponding to a slope failure as observed at the actual Pilarcitos dam.

Lowe and Karafiath method

Go back to the Slide Model program. Open the Project Settings from the Analysis menu. Click on the Groundwater link on the left side. Beside Rapid Drawdown Method, select Lowe and Karafiath (1960).

The Lowe and Karafiath method is essentially the same as the Duncan, Wright and Wong method. The difference is that the Duncan, Wright and Wong method performs a third stage of calculation in which it checks if the effective stress after drawdown produces a drained strength that is less than the undrained strength. If any slices are found for which this is the case, then the drained strength is substituted and the analysis is rerun.
Click OK to close the dialog.

**Compute**

Save the model using the *Save As* option in the *File* menu. You may want to choose a different name so you can compare the results of this model with the results from the Duncan, Wright and Wong model. Choose *Compute* from the *Analysis* menu to perform the analysis and choose *Interpret* from the *Analysis* menu to view the results.

**Interpret**

You can see that the factor of safety for the Lowe and Karafiath method is 1.052. This is slightly higher than the value of 1.047 obtained with the Duncan, Wright and Wong method. This indicates that some of the slices must have had lower drained strengths than undrained strengths. Therefore the third stage of analysis in the Duncan, Wright and Wong method resulted in a slightly lower factor of safety.
Army Corps method

Go back to the *Slide* Model program. Open the **Project Settings** from the **Analysis** menu. Click on the Groundwater link on the left side. Beside Rapid Drawdown Method, select Army Corps. Eng. 2 Stage (1970).

As described above, the Army Corps method uses a different failure envelope than the other methods. However we do not need to change the material properties since *Slide* automatically performs any required conversions.
Compute

Save the model using the **Save As** option in the **File** menu. Choose **Compute** from the **Analysis** menu to perform the analysis and choose **Interpret** from the **Analysis** menu to view the results.

Interpret

The factor of safety for the Army Corps method is 0.824 – significantly lower than the other methods. This agrees with the general belief that the Army Corps method gives results that are too conservative.

This concludes the tutorial.

Additional Exercise

Instead of using the R envelope, try entering a $K_c = 1$ envelope instead. If you specify $d = 64 \text{ lb/ft}^2$ and $\psi = 24.4^\circ$ then you should get the same results.
References

