Rapid Drawdown with Effective Stress

1 Introduction

Stability analysis during rapid drawdown is an important consideration in the design of embankment dams. During rapid drawdown, the stabilizing effect of the water on the upstream face is lost, but the pore-water pressures within the embankment may remain high. As a result, the stability of the upstream face of the dam can be much reduced. The dissipation of pore-water pressure in the embankment is largely influenced by the permeability and the storage characteristic of the embankment materials. Highly permeable materials drain quickly during rapid drawdown, but low permeability materials take a long time to drain.

Using SLOPE/W, stability during rapid drawdown can be analyzed in two approaches; namely the “effective strength” approach and the “staged undrained strength” approach. The purpose of this example is to show how to conduct a rapid drawdown analysis using the effective stress approach. The followings are considered:

Upstream stability before drawdown

Upstream stability after rapid drawdown

SEEP/W initial condition

SEEP/W transient analysis

Multiple time step stability analysis after drawdown

2 Configuration and setup

The cross-section of the slope is shown in Figure 1. Note that in this example, the reservoir is not modeled. SLOPE/W will automatically add the weight of the reservoir to the upstream slope based on the position of the piezometric line when the reservoir is not modeled with a no strength material or a pressure boundary.

Figure 1 shows the assumed piezometric surface of the embankment before drawdown when the reservoir is at full supply level. In this case, water is ponded up against the upstream slope and the assumption is that the pore-water pressure conditions in the slope have reached some steady-state conditions. The ponded water results in both a vertical force and a horizontal hydrostatic force, which is distributed as individual line loads acting normal to the embankment face. The piezometric line is used during the analysis to compute the pore-water pressures that exist at the base of each slice.

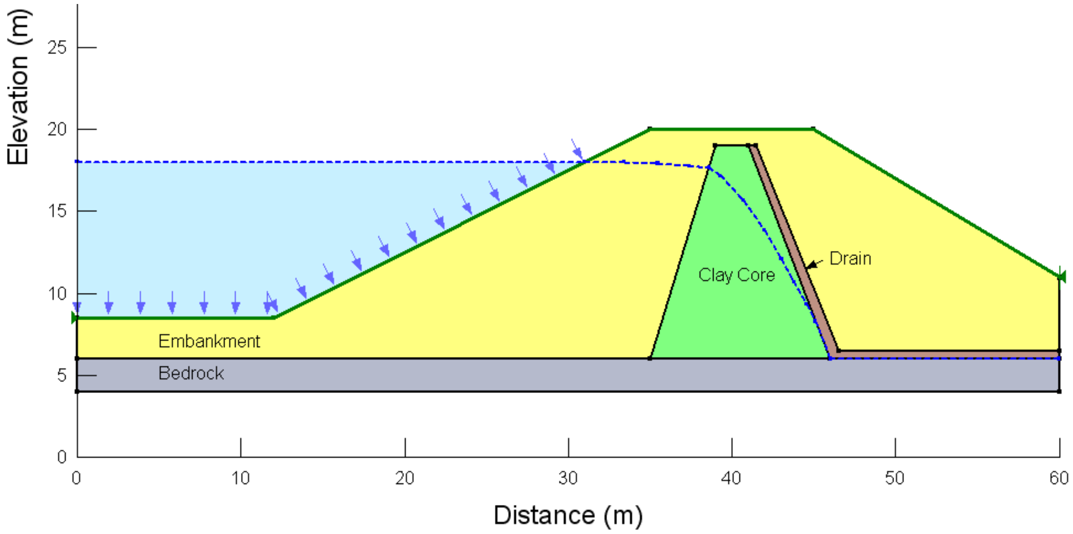

Figure 1 Profile used and assumed piezometric line before drawdown

To model the rapid drawdown conditions in SLOPE/W, we need to remove the ponded water and place the piezometric line along the ground surface. Figure 2 shows the piezometric surface of the embankment under rapid drawdown conditions. The piezometric line is assumed to follow the upstream ground surface, but remains unchanged inside the embankment.

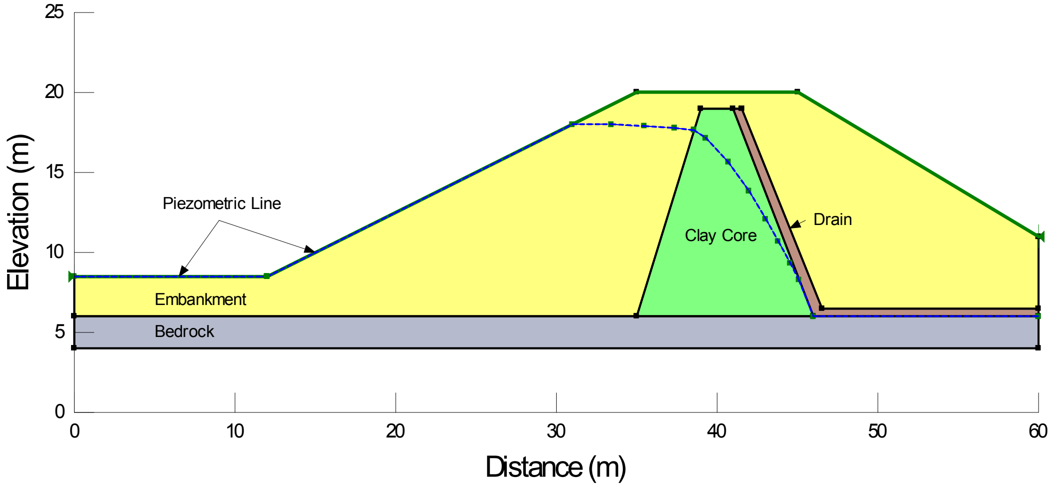

Figure 2 Profile used and assumed piezometric line after rapid drawdown

By removing the ponded water through adjusting the piezometric line, the hydrostatic force offered by the ponded water is gone, but the effective stress remains the same at the base of each slice, as indicated by the following equation:

$$\sigma_v^{'} = \sigma - u$$

$$\sigma_v^{'} = H_s\gamma_s - H_w\gamma_w$$

$$H_w = H_s$$

$$\therefore \sigma_v^{'} = H_s\left(\gamma_s - \gamma_w\right)$$

Note that the height of the soil and water are the same, since the piezometric line is on the ground surface. When effective stress does not change, the shear resistance to sliding does not change as a result of the rapid drawdown.

3 Upstream stability before drawdown

A limit equilibrium stability analysis using the Morgenstern-Price method results in a factor of safety of 1.977. The critical slip surface is shown in Figure 3. A grid of centers was defined and the slip surface was forced to exit at the toe of the upstream embankment by collapsing the search radii into a single point.

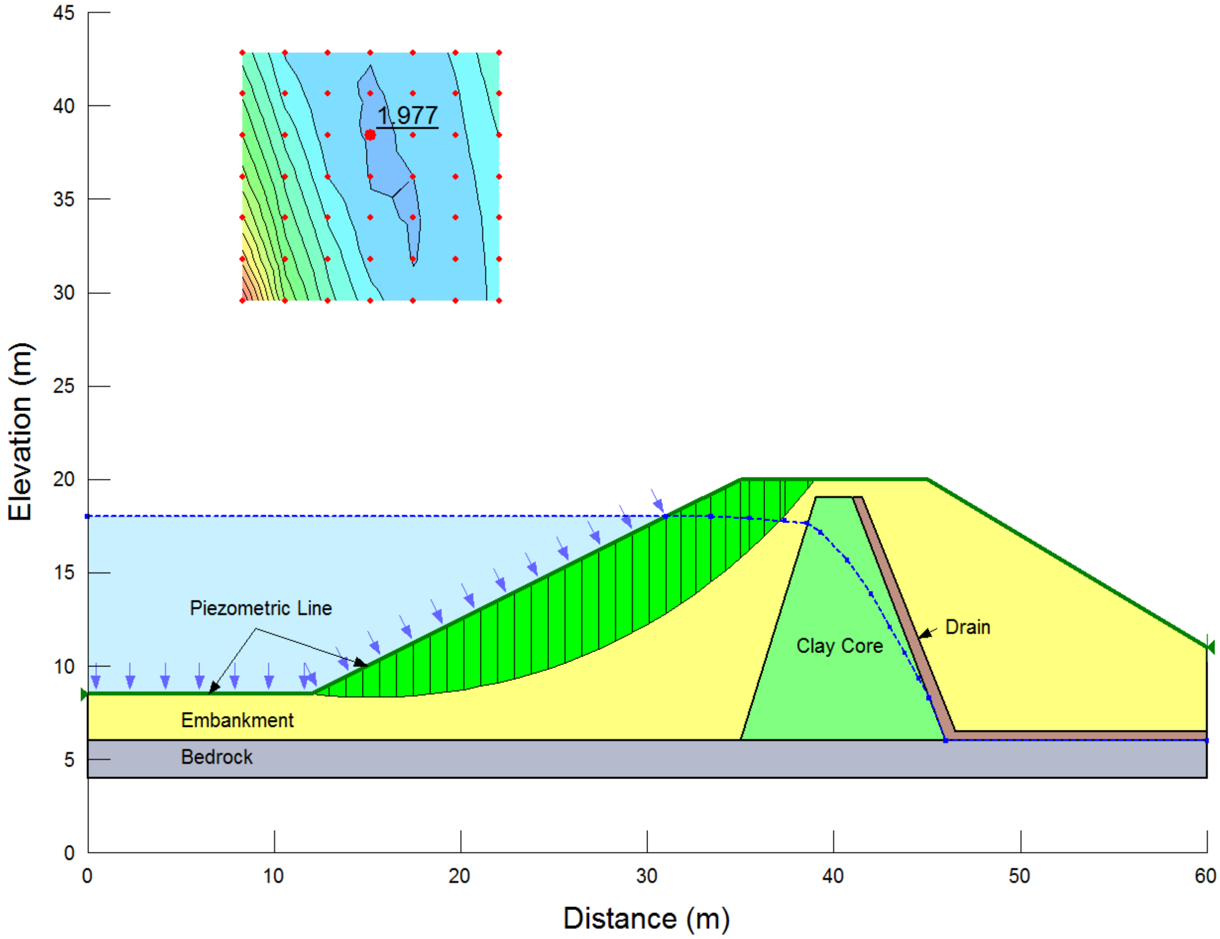

Figure 3 Critical slip surface and factor of safety before drawdown

Within SLOPE/W Result View, you can generate a graph of the pore-water pressures versus distance across the critical slip surface, as shown in Figure 4. The pore-water pressures are high at the toe of the embankment and decrease as they should with elevation until they are set equal to zero for those slices that exist above the piezometric line.

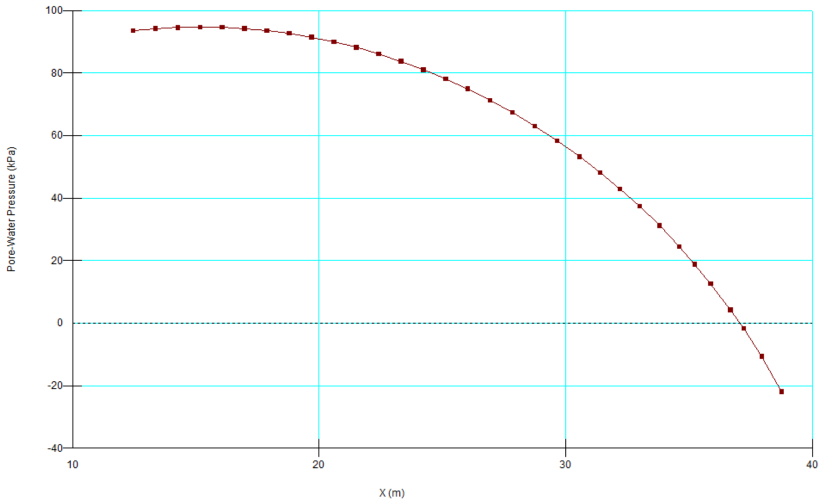

Figure 4 Pore-water pressures across the slip surface before rapid drawdown

The portion of the water weight acting vertically downward on each slice is computed, as is the horizontal hydrostatic force. Figure 5 shows the force polygon for slice 18, whose location is shown in Figure 6. The weight of the water and the hydrostatic water force acting on each slice are resolved into a resultant force that is applied normal to the top of the slice. The resultant force (F_R) appearing on slice 18 is 15.707 kN and the angle of the slope is 26.57°. To confirm this line load, you can do the following hand-calculation. The width of the slice is 0.90476 m and the rise over the slice width is 0.4525 m as shown in Figure 5. The reservoir is 1.584 m deep at the top of this slice, so the water pressure at this point is γ_w*H = 9.807 x 1.584 = 15.53 kPa. The vertical water force (F_V) applied over the area of the slice is therefore 15.53 x width of the slice x unit depth = 15.53 kPa x 0.90476 m x 1 m = 14.0509 kN. The horizontal hydrostatic force (F_H) over the area of the slice is 15.53 kPa x 0.4525 m x 1 m = 7.0273 kN. The resultant Force (F_R) = $\sqrt{}$(F_H^2 x F_V^2) = $\sqrt{}$(7.0273^2 x 14.0509^2) = 15.71 kN, which agrees with the line load appearing in the slice force information.

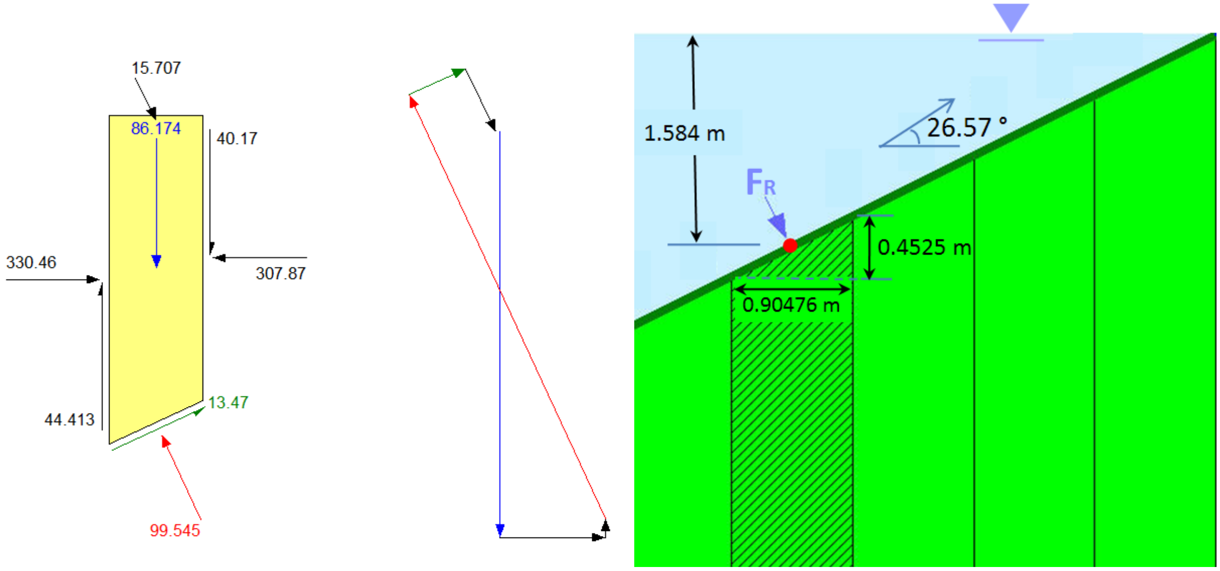

Figure 5 Slice force information and a schematic representation of some slice dimensions for slice 18

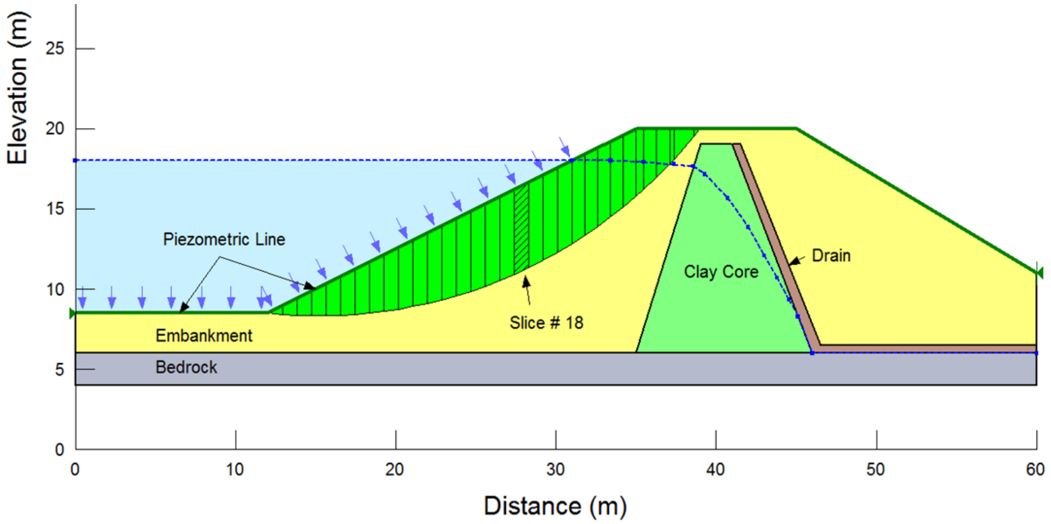

Figure 6 Position of slice 18 as used in the hand calculation of the water force acting on the slice

4 Upstream stability after rapid drawdown

Figure 7 shows the critical slip surface and factor of safety after rapid drawdown. Recall that the factor of safety before drawdown was 1.977. Following rapid drawdown, the factor of safety has been reduced to 0.956.

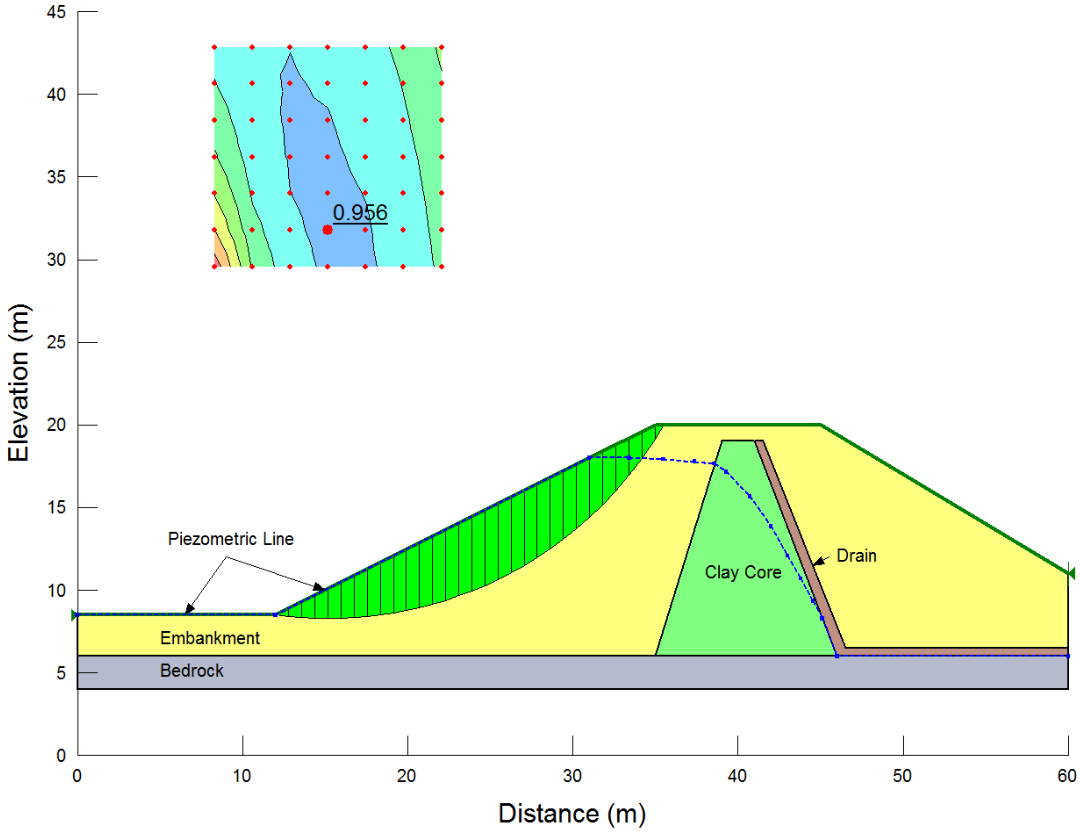

Figure 7 Critical slip surface and factor of safety after rapid drawdown

While the slip surface has still been forced to exit at the toe of the embankment, a different critical slip surface was determined. Viewing the factors of safety displayed on the search grid reveals that the same center that was used to determine the critical slip surface in the "before" analysis gave an "after" factor of safety of 0.958. The pore-water pressure distribution across the slip surface following rapid drawdown is shown in Figure 8.

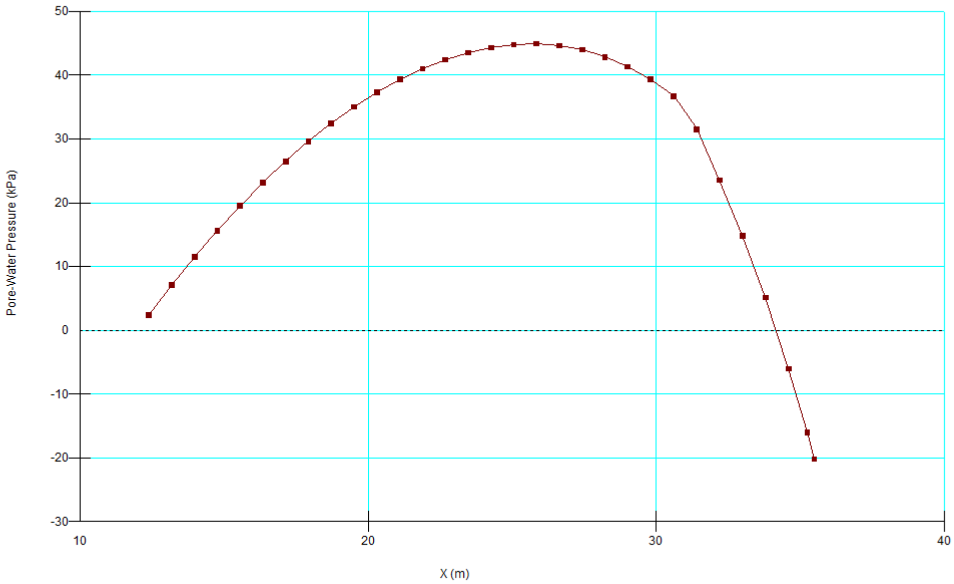

Figure 8 Pore-water pressures across the slip surface after rapid drawdown

The approach used to model rapid drawdown in this example is based on the assumption that the soil has some finite hydraulic conductivity such that the change in pore-water pressure at the base of the slice is instantaneously equal to the change in ponded water pressure head above the slice. Considering that water is incompressible and that soils near the slope face likely have at least some finite conductivity, this is not an unrealistic assumption. In most situations, this approach is likely a worst case scenario. Practically, it is not possible to draw down the water instantaneously, and to totally prevent at least some of the water from flowing out of the embankment during the drawdown. In this context, the approach presented here should be considered conservative and on the safe side.

5 Rapid drawdown with SEEP/W pore-water pressure

A more accurate way of analyzing drawdown is to use the seepage results from a SEEP/W analysis. This more advanced approach uses the exact pore-water pressures that were in the soil during the drawdown process, as opposed to simply getting the pore-water pressure from the vertical distance between the piezometric line and the base of the slice.

Using the pore-water pressure estimated from SEEP/W, the factor of safety of the embankment dam at different times during the entire drawdown process can be evaluated. An example plot of factor of safety versus time during drawdown process is illustrated in Figure 9. In the example, the factor of safety drops to below 1.0 in the early stage of the drawdown process, but increases to above 1.7 when the pore-water pressure in the embankment dissipated with time.

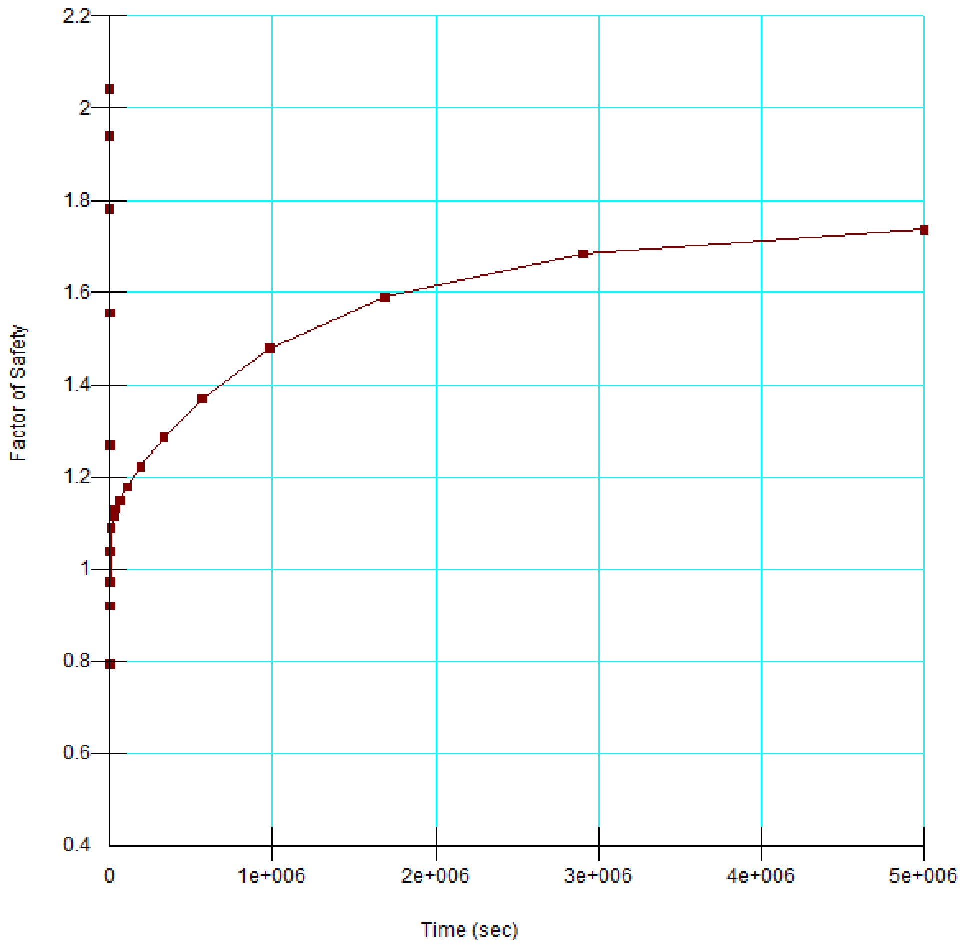

Figure 9 An example Factor of Safety Versus Time Steps during rapid drawdown

The advantage of this approach is that the hydraulic properties of the materials can be considered and time can be included in the analysis. With this approach, rapid drawdown is not just an instance in time, but is a process. The downside of this method is the extra work required to do a finite element transient seepage analysis with SEEP/W. However, in the design of an embankment dam, the hydraulic properties of the materials are usually available and a finite element seepage analysis of the embankment is likely required anyway. GeoStudio allows easy integration between SLOPE/W and SEEP/W, making this rigorous approach an attractive alternative. You must have the SEEP/W module to use this approach.