



GeoStudio Example File Rapid Drawdown with Consolidation

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Introduction

This example is about the rapid drawdown of a reservoir and the excess pore-water pressures that remain in the ground once the ponded water has been removed. The excess pore-water pressures can cause slope instability and, consequently, this is an important issue in the operation of water retention structures, such as embankment dams.

There are many ways to approach rapid drawdown, as indicated by the significant number of papers in the research literature. The purpose here is not to do a review of what has been done in the past, but to demonstrate how this issue can be addressed using GeoStudio.

One way of computing the changes in pore-water pressures resulting from the drawdown is to do a water transfer analysis. Another way is to do a fully coupled stress/pore-water pressure analysis using SIGMA/W. The results from these two types of analyses are presented and compared here.

Background

As noted in the introduction, many different methods have been proposed over the years in the research literature for evaluating the effects of rapid drawdown. Some are based on dealing with effective stresses, while others attempt to use total stresses and undrained strengths. The purpose here is not to review all of the methods that have been proposed, but to briefly comment on the methods available in GeoStudio, which range from the simple to the complex. There are essentially four methods available in GeoStudio which are:

- SLOPE/W alone with an assumption about the post-drawdown piezometric line position;
- SLOPE/W alone with total stress staged analysis;
- SEEP/W computed pore-water pressures in a SLOPE/W analysis; and
- SIGMA/W stress/pore-water pressure computed results in a SLOPE/W analysis.

The latter two methods are presented in this document. The other two methods are discussed and presented in the Stability Modeling with GeoStudio Book.

The simplest approach in SLOPE/W is to remove the weight of the reservoir water and assume that the post-drawdown water table is at the ground surface where the reservoir was in contact with the ground surface, and keep the water table inside the earth structure at the long-term steady-state condition. This procedure, in essence, means the change in pore-water pressure is equal to the vertical change in water level, and it means that the total stress change is equal to the pore-water pressure change so that the effective stress remains unchanged. Another way to describe this simple approach is that it is equivalent to a B-bar of 1.0. The following equation is a common way of looking at changes in pore-water pressure with changes in total stress:

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

When B-bar is 1.0, the change in pore-water pressure is equal to the change in vertical total stress.

The simplest SLOPE/W-alone analysis is based on an instantaneous drawdown assumption. As we demonstrate in this example, this may result in a highly conservative picture of the stability condition after drawdown. Fortunately, in this case, simplicity errs on the safe side.

Numerical Simulation

The problem configuration is shown in Figure 1. The embankment has a height of 10 m with 2h:1v side slopes and sits on 10 m of foundation soil. The reservoir depth is 9 m. On the

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downstream toe is a granular under-drain which keeps the water table at the tail water elevation for a distance of 5 m under the embankment toe (the actual granular layer is not required to achieve this effect; the desired effect can be achieved with a specified boundary condition). The + mark on the drawing is a reference point for later discussion on the pore-water pressure response.

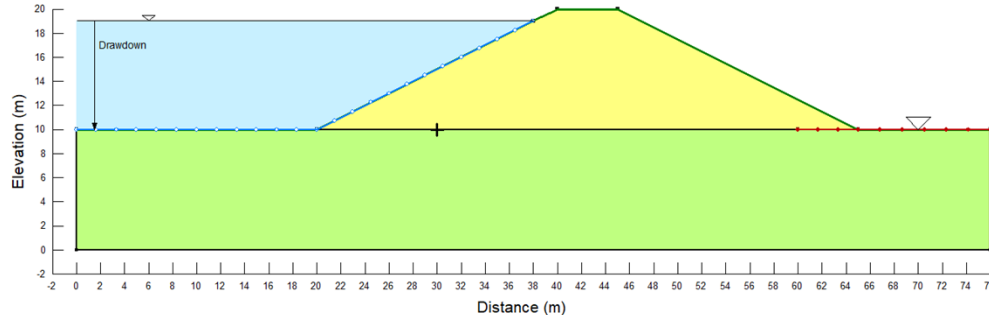


Figure 1. Problem configuration and setup.

The embankment and foundation soils are, in essence, treated as being one and the same for this illustrative example. The soil has a saturated hydraulic conductivity K_{sat} of 0.1 m/day (about 1×10^{-4} cm/sec). The E -modulus is 5000 kPa and Poisson's ratio ν is 0.334 (1/3). The equivalent m_v is 0.000133/kPa.

The first step is to establish the long-term steady-state conditions using a water transfer analysis. The next step is to complete a transient water transfer analysis to investigate the changes in pore-water pressure with time during and after the drawdown of the reservoir.

It is assumed that the reservoir will be drained over a period of five (5) days. This is modeled with the time-dependent boundary condition shown in Figure 2.

The process is modeled for 30 days after the reservoir has been removed using 10 exponentially spaced time steps. The previous "Parent" steady-state conditions become the initial or starting conditions for the transient drawdown analysis.

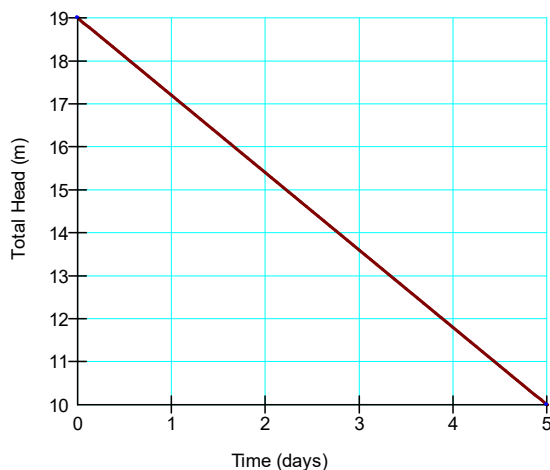


Figure 2. Reservoir elevation with time during drawdown.

The slope stability analysis is then used to model the changing factor of safety with changing pore-water pressure conditions simulated in the water transfer analysis. The key to doing this type of analysis is to select **all** time steps in the Parent Analysis (Figure 3).

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Figure 3. Using all time steps from the water transfer analysis in the slope stability analysis.

To do a coupled stress/pore-water pressure analysis, we need to first establish the *in situ* stress state conditions. The pore-water pressure conditions come from the “Parent” steady-state water transfer analysis.

This is done with a SIGMA/W In Situ type of analysis. An important component of this type of analysis is to ensure that the reservoir pressure (weight) is included. This is applied as a Hydrostatic Pressure boundary condition.

Now that the long-term steady-state and *in situ* conditions have been established, a Consolidation analysis can be completed, which simulates the removal of the reservoir.

Removing the reservoir is like removing a weight from the upstream face of the structure. This can be done with a fluid pressure type of boundary function (Figure 4). Recall that the reservoir is being drawn down over a period of 5 days. This is like applying an uplift force which represents the unloading. The uplift force per day is $(10-19)/5 = -1.8$ m /day. Due to the incremental formulation in SIGMA/W, the surface pressure change is the current elevation minus the previous elevation. And since the current elevation is lower than the previous elevation, it is a negative fluid pressure, or a negative normal stress.

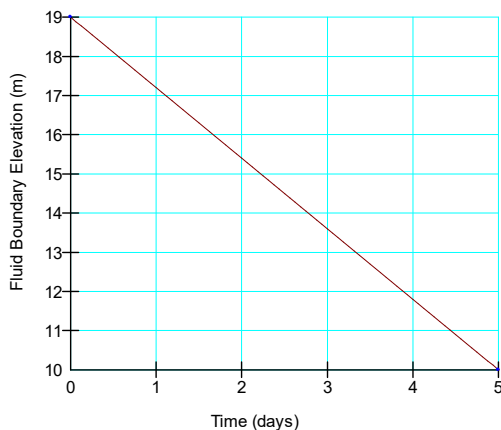


Figure 4. Fluid boundary function representing the reservoir drawdown.

Two boundary functions need to be applied on the upstream face of the dam and the ground surface under the reservoir. These are the stress-strain fluid pressure boundary function and the hydraulic boundary function representing the changing pore-water pressure conditions.

Results and Discussion

Figure 5 shows the long-term total head (H) contours.

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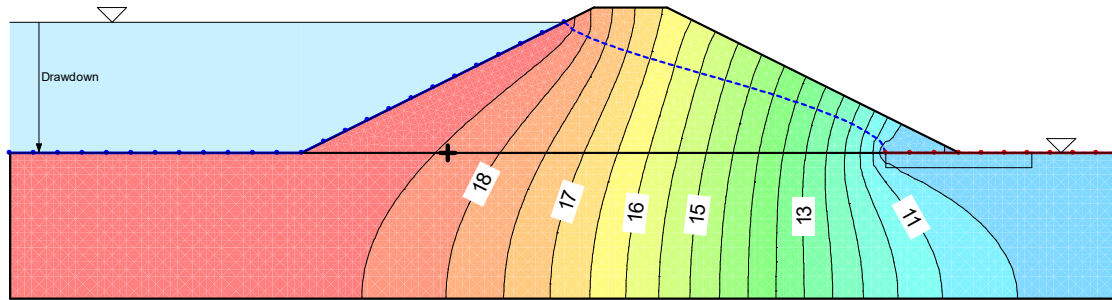


Figure 5. Long-term steady-state conditions.

Figure 6 shows the dissipation of the excess pore-water pressures 2 days after the start of the drawdown. Of interest is the flow in the upstream direction into the remaining reservoir and the continuing flow in the downstream direction towards the toe under-drain.

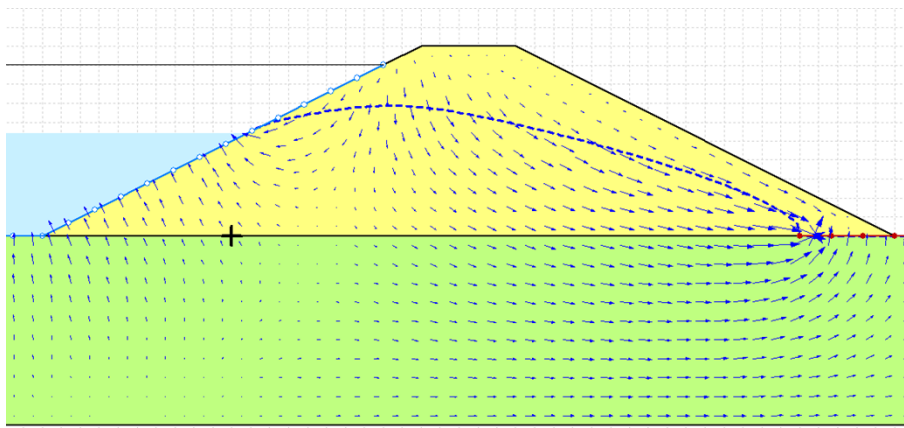


Figure 6. Conditions 2 days after start of the drawdown.

The resulting positions of the water table (zero pressure contours) with time is shown in Figure 7.

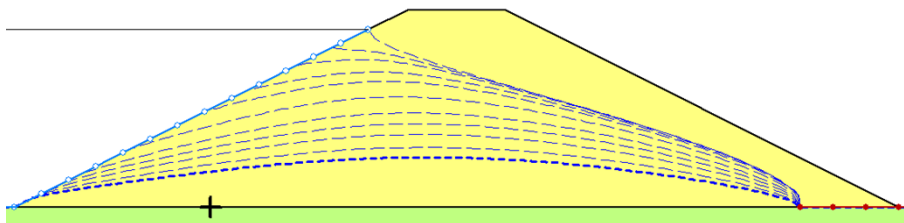


Figure 7. Changing positions of the water table after reservoir drawdown.

Figure 8 shows the decreasing pore-water pressure at Point + during and after the drawdown.

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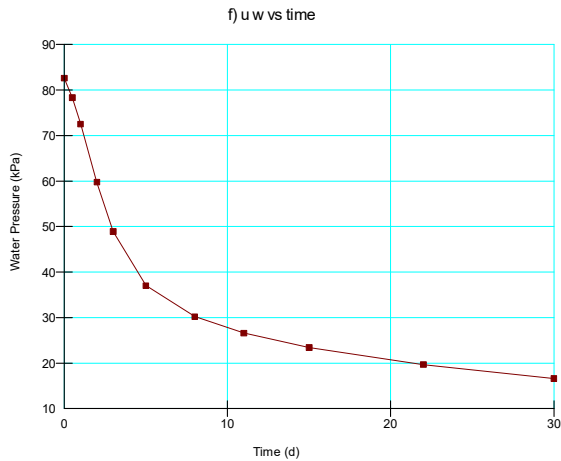


Figure 8. Pore-water pressure at Point + during and after the drawdown.

Figure 9 shows the computed critical factor of safety with time for the changing pore-water pressure conditions.

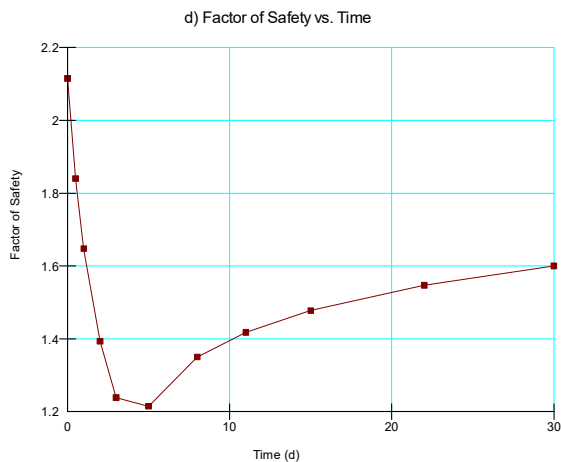


Figure 9. Factors of safety during and after drawdown.

The effect of the fluid-pressure type of boundary condition in the fully coupled SIGMA/W analysis is illustrated in Figure 10 by the small arrows normal to the surface at the bottom of the reservoir. This is important in order to compute the correct total and effective stresses. The contours in Figure 10 are the resulting *in situ* vertical effective stress contours.

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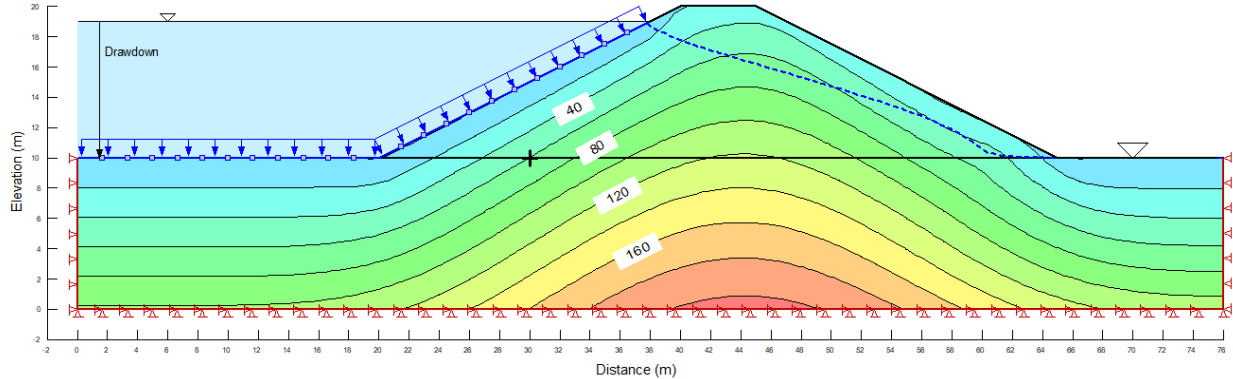


Figure 10. Vertical effective stress contours for the Insitu analysis.

Generally, the resulting behavior of the water transfer-alone analysis and a fully coupled SIGMA/W analysis is very similar. The pore-water pressures at Point + for these analyses are compared in Figure 11. Initially, the pore-water pressures from the coupled analysis are slightly lower than from the water transfer analysis. This is due to the rebound associated with the unloading. The tendency for the volumetric expansion is offset by a greater decrease in the pore-water pressure. The water transfer and SIGMA/W analyses produce nearly identical results at later times as the same pore-water pressure distribution is obtained.

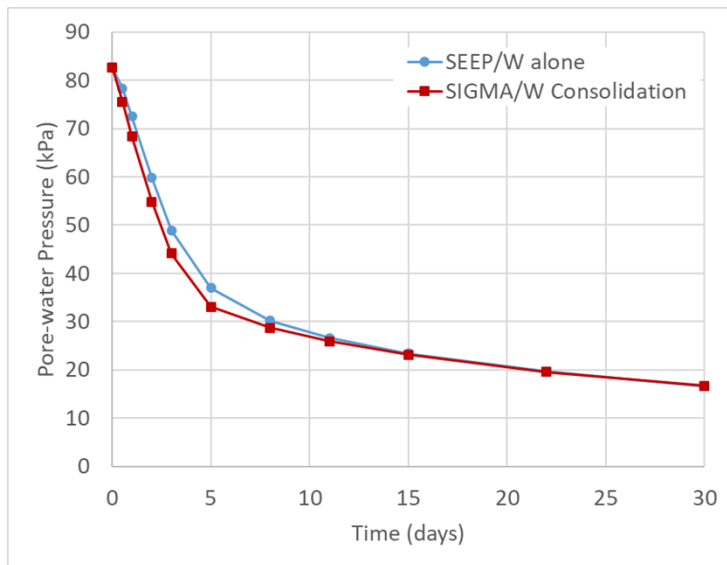


Figure 11. Comparison of pore-water pressures at Point + from the two types of analyses.

The lower pore-water pressure from the coupled analysis is reflected in the variation in the factors of safety with time (Figure 12). The minimum factor of safety for from the coupled analysis is 1.29, while the minimum from the water transfer analysis is 1.21.

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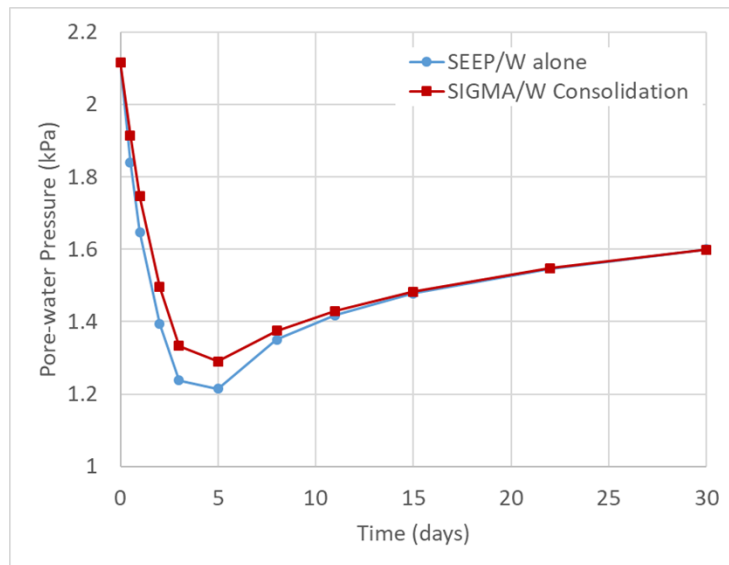


Figure 12. Comparison of factors of safety from the two types of analyses.

The minimum factor of safety tends to occur around the time of the lowest water level of the reservoir drawdown or shortly before, as illustrated in Figure 13.

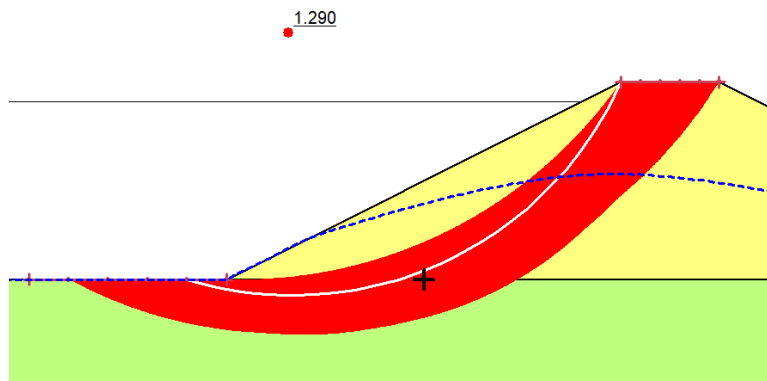


Figure 13. Minimum stability conditions.

Often the assumption is made in a rapid drawdown analysis that the reservoir disappears instantaneously. This can be readily modeled, but the results are unrealistic and unnecessarily conservative. A reservoir can never be drained instantaneously.

Figure 14 shows the factors of safety with time under instantaneous drawdown conditions. Immediately, the factor of safety is very low because the stabilizing effect of the weight of the water has been removed, but the pore-water pressures remain very high.

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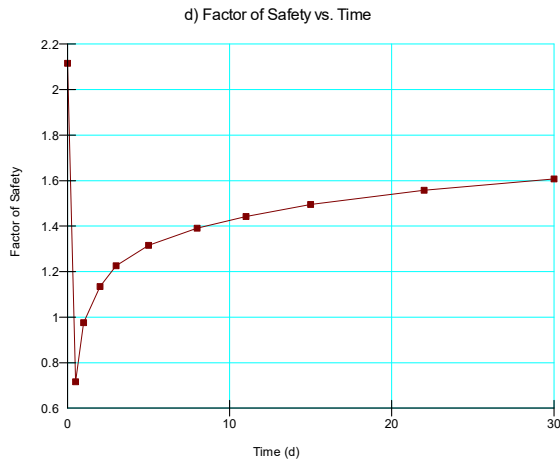


Figure 14. Factors of safety with time with instantaneous drawdown.

The minimum factor of safety from a coupled analysis is 1.29, while from an instantaneous analysis the minimum factor of safety is 0.72. A value of 1.29 may be quite acceptable, but a value of 0.72 obviously is not.

The objective of comparing the instantaneous drawdown analysis with the drawdown over time is not to suggest the appropriate procedure. Rather, the objective is to demonstrate that GeoStudio has the capability to model the drawdown in various ways.

The SIGMA/W coupled formulation requires values for the coefficient of volume change (m_v) and the stiffness properties E and ν . The coefficient m_v is computed internally from the stiffness properties to ensure compatibility between the properties. SEEP/W only requires the specification of m_v ; therefore, a compatible comparison between SEEP/W and SIGMA/W can only be accomplished if the user enters the corresponding compatible value of m_v . The relationship is:

$$m_v = \frac{(1 + \nu)(1 - 2\nu)}{E(1 - \nu)} \quad \text{Equation 2}$$

which reduces to $1/E$ when Poisson's ratio is 0.334, resulting in $m_v = 0.000133/\text{kPa}$ for $E = 5000 \text{ kPa}$.

To do a SEEP/W-alone and SIGMA/W coupled comparison, it is mandatory to ensure that the Volumetric Water Content function has a specified m_v that is consistent with the stiffness modulus E in SIGMA/W.

It is also always necessary to be mindful of the link between time step size and the accuracy of the computed pore-water pressure response. Numerical problems can be avoided by selecting a time step in accordance with the hydraulic conductivity and average element size. The procedure for selecting appropriate time steps is discussed in the Stress-Strain Modeling with GeoStudio book. Generally, very small time steps together with very low K_{sat} values can lead to numerical noise and/or erroneous results.

Summary and Conclusions

This is not an exhaustive study of rapid drawdown, and care must be exercised about drawing too many firm conclusions from the results presented here. This example does, however, demonstrate and discuss what can be done with integrated GeoStudio analyses. There should be sufficient information and ideas presented herein to perform a drawdown analysis in a manner that is appropriate to the project.