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GeoStudio Example File
Critical Slip Surface Position

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Introduction

The position of the critical slip surface depends on the parameters used to describe the shear strength of the modeled domain. For example, the critical slip surface may vary when using effective stress strength parameters instead of equivalent total stress parameters. This phenomenon is not always obvious in slope stability analyses and, consequently, can be the source of some consternation when interpreting the computed factors of safety. This document seeks to address this issue and give recommendations on selecting shear strength parameters when the position of the critical slip surface is of importance in a stability analysis.

Numerical Simulation

There are 5 analyses included in the project (Figure 1), each representing a different set of material properties as indicated by the analysis name. The modeled domain includes a 2h:1v slope, corresponding to an inclination of 26.57 degrees (Figure 2). The slip surface definition and pore water pressures are the same for all analyses, where the slip surfaces are created by the Entry and Exit method and the pore-water pressures are defined by a piezometric line.

Figure 1. Project Analysis Tree.

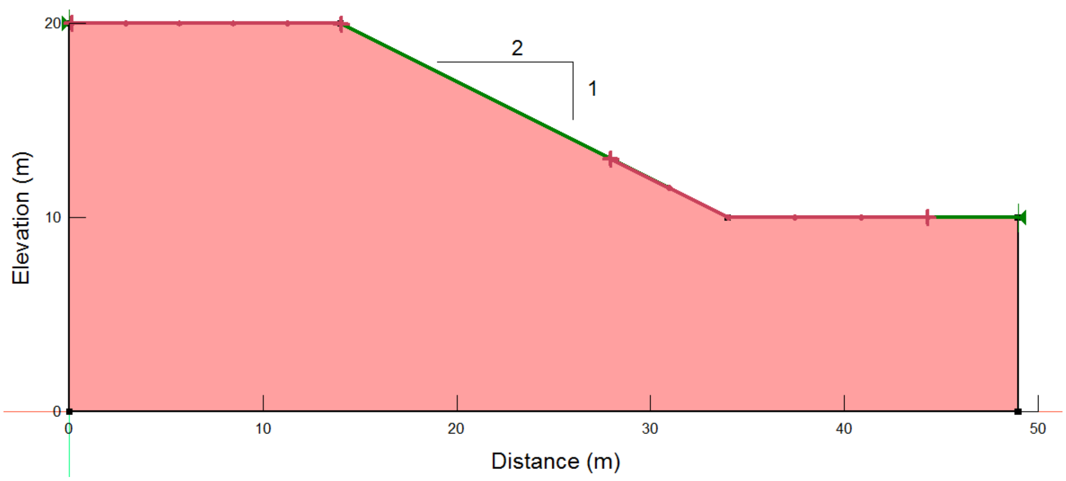

Figure 2. Problem configuration.

The material applied to the domain is different for each analysis. Table 1 outlines the inputted soil strength parameters, excluding the unit weight as it is the same for all materials (20 kN/m^3). All analyses, excluding Analysis 2, use the Mohr-Coulomb material model. Analysis 2 uses the Undrained (Phi=0) material model to illustrate the stability of the slope when a soil with constant undrained strength is used. The material defined for Analysis 3 includes suction strength by selecting a volumetric water content function under the Suction tab of the Define Materials window. The volumetric water content function was created with the sample functions estimation method (in the Define Volumetric Water Content Functions window), using a silt material with a saturated water content of 0.5 (Figure 3). The residual water content for this material was assumed to be 20% of the saturated water content.

Table 1. Soil properties for each analysis.

Analysis Name	Cohesion (kPa)	Phi (degrees)
1 – Purely frictional	0	30
2 – Undrained	40	-
3 – Suction effects	0	30
4 – High phi, low c	5	28
5 – Low phi, high c	21	15

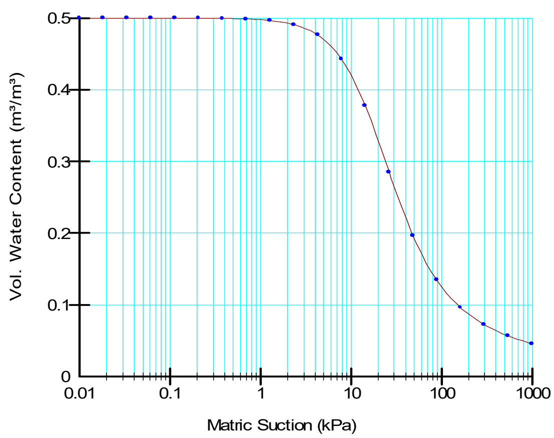

Figure 3. Volumetric water content function for the analysis including suction strength (Analysis 3).

Results and Discussion

When a soil has negligible cohesion, as in the first analysis, the minimum factor of safety will approach the infinite slope case where the factor of safety, FS, is:

$$FS = \frac{\tan \phi}{\tan \alpha}$$ Equation 1

given the specified soil friction angle, ϕ, and slope inclination, α. As the minimum factor of safety approaches the infinite slope case, the radius of the slip surface approaches infinity. Thus, the minimum factor of safety is generally produced by the slip surface associated with the greatest radius. The slip surface contour map from the first analysis demonstrates this trend, as the slip surfaces with the lowest factor of safety are parallel and immediately next to the slope face where the slip surface radius is the greatest (Figure 4). The computed factor of safety is 1.165, which is just over the infinite slope factor of safety calculated by Equation 1 (1.15).

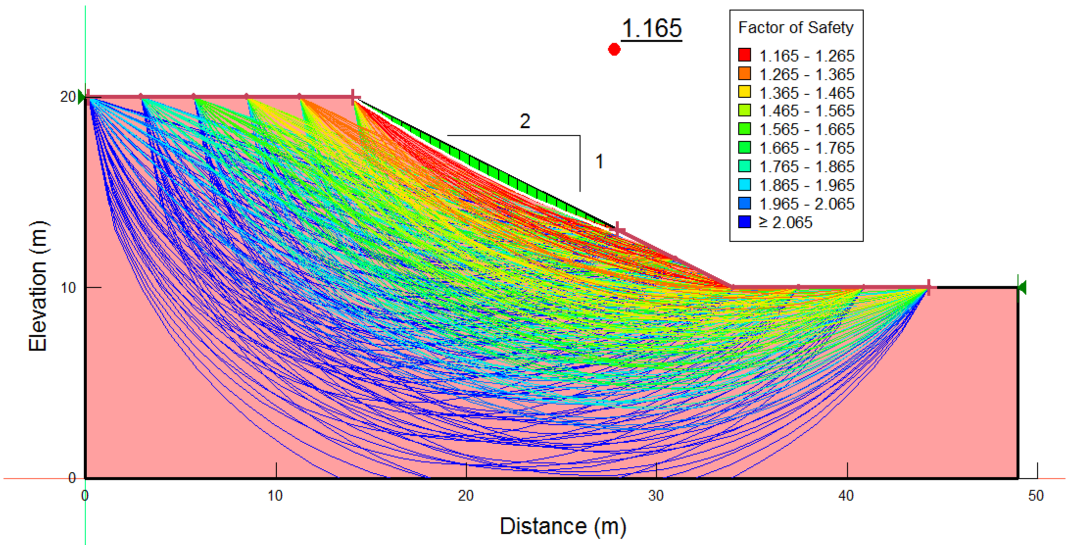

Figure 4. Shallow slip for Analysis 1, the purely frictional case (c=0).

The opposite occurs when the undrained material model is used to define the soil strength. In this case, the friction angle is zero, which generally causes the critical slip surface to extend to greater depths (Figure 5). Thus, the minimum factor of safety is associated with the slip surface having the smallest radius.

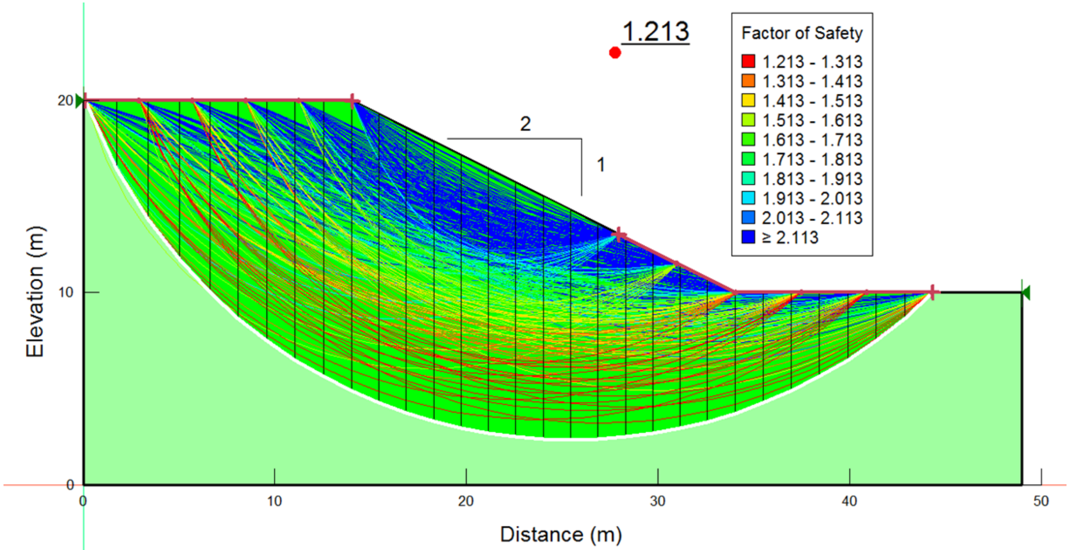

Figure 5. Deep slip surface from Analysis 2, the homogeneous undrained case.

The first two analyses demonstrate the large variation in the position of the critical slip surface given different material properties. However, the generated critical slip surfaces are unrealistic due to the unrealistic strength parameters used for both cases. For example, undrained strength generally increases with depth. If these conditions were applied to the modeled domain in Analysis 2, the deep slip surfaces would not have the lowest factor of safety. In addition, cohesion is rarely zero near the ground surface, as a desiccated layer or root zone often forms near the soil surface with higher strength properties. If the soil strength increases towards the ground surface, the critical slip surface will be at some depth, unlike the critical slip surface generated by Analysis 1.

GeoStudio Example - Critical Slip Surface Position

There are multiple ways of avoiding very shallow slip surfaces. One is to specify a minimum sliding mass depth under the advanced tab in the analysis settings (Figure 6). At least one slice within the potential sliding mass must have a height greater than or equal to the specified value. Thus, trial slip surfaces where all slice heights are less than the specified value are ignored. This prevents SLOPE/W from analyzing very shallow slips; however, the slip surface with the minimum factor of safety may still be the shallowest one analyzed. As a result, this parameter does not address the underlying issue of unrealistic soil strength properties. Alternatively, a surface region could be included in the geometry with a stronger desiccated layer or root zone. This approach may also fail to address the issue as the slip surface with the minimum factor of safety may simply move to the bottom of the strong surface region.

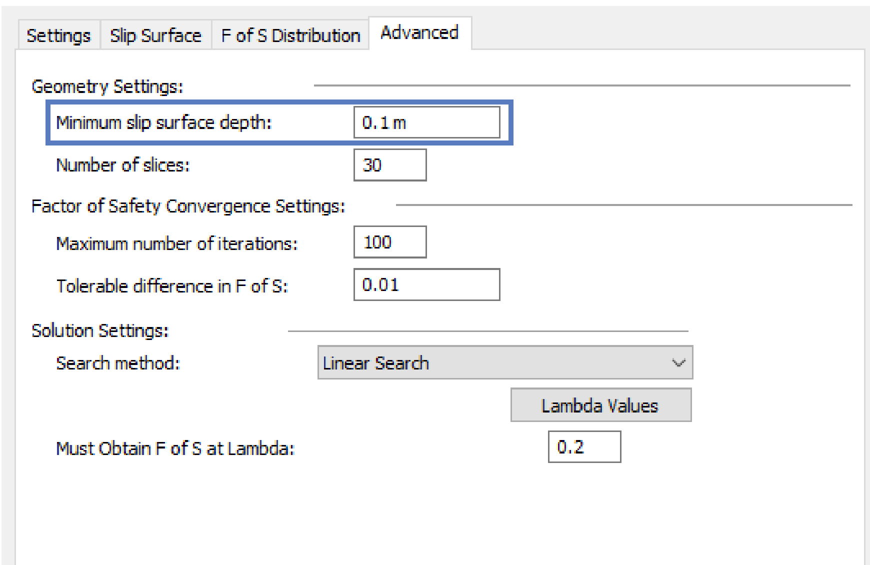

Figure 6. Minimum slip surface depth specified as 0.1 m.

The best way to avoid shallow, near-surface critical slip surfaces is to incorporate suction (negative pore-water pressures) into a SLOPE/W analysis, as in Analysis 3. In the capillary zone (the saturated region above the water table where the pore-water pressure is negative), the full effect of the negative pore-water pressure increases the effective stress and, thereby, increases the shear strength of the soil. Once air enters the soil, only a portion of the negative pore-water pressure contributes to increasing the shear strength. Thus, the increase in soil strength due to suction peaks at the top of the capillary zone, decreases as the soil dries out and is zero when the volumetric water content of the soil reaches the residual water content. In Analysis 3, a residual volumetric water content of 0.2 is specified in the Suction tab under the material properties.

The materials associated with Analysis 1 and Analysis 3 have the same properties, except for the inclusion of suction strength in Analysis 3. A comparison of the results indicates that the factor of safety and the position of the critical slip surface are very different when suction is incorporated (Figure 7). The strength contributed by suction is relatively small compared to the frictional strength (Figure 8); however, the critical slip surface position is more realistic when suction strength was included (even though the cohesive strength is zero). The suction strength peaks and then decreases as the pore-water pressure becomes more negative towards the ground surface.

GeoStudio Example - Critical Slip Surface Position

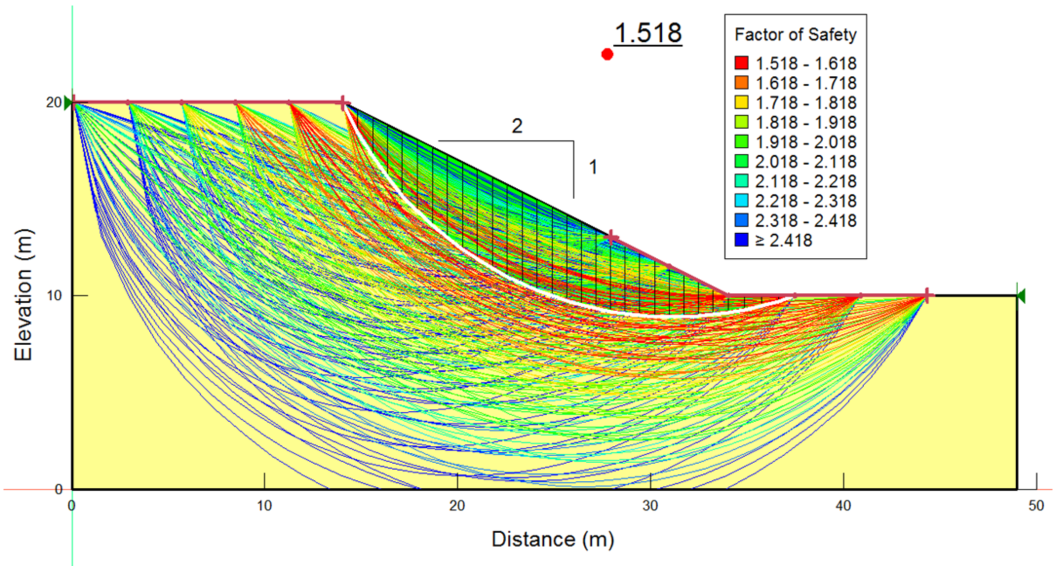

Figure 7. Analysis 3 stability result with suction strength and no cohesion.

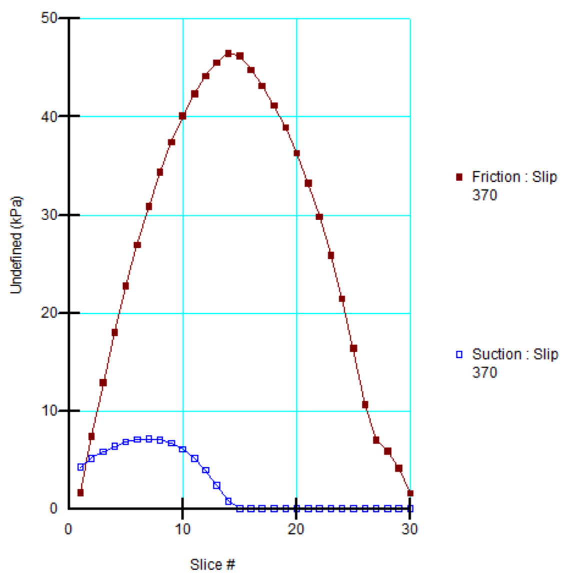

Figure 8. Frictional and suction strength components.

Stability analyses may be conducted to assess the minimum distance from the crest of a slope required for development. In these cases, the primary objective is to find the most likely position of a failure. If the design factor of safety must be 1.5 or greater, different strength parameters may achieve this factor of safety. Analyses 4 and 5 demonstrate different combinations of cohesion and the friction angle generating a similar factor of safety. However, the position of the critical slip surface in each analysis is different (Figure 9 and Figure 10). Thus, great care must be taken when selecting the shear strength parameters if the position of the critical slip surface is important to engineering design.

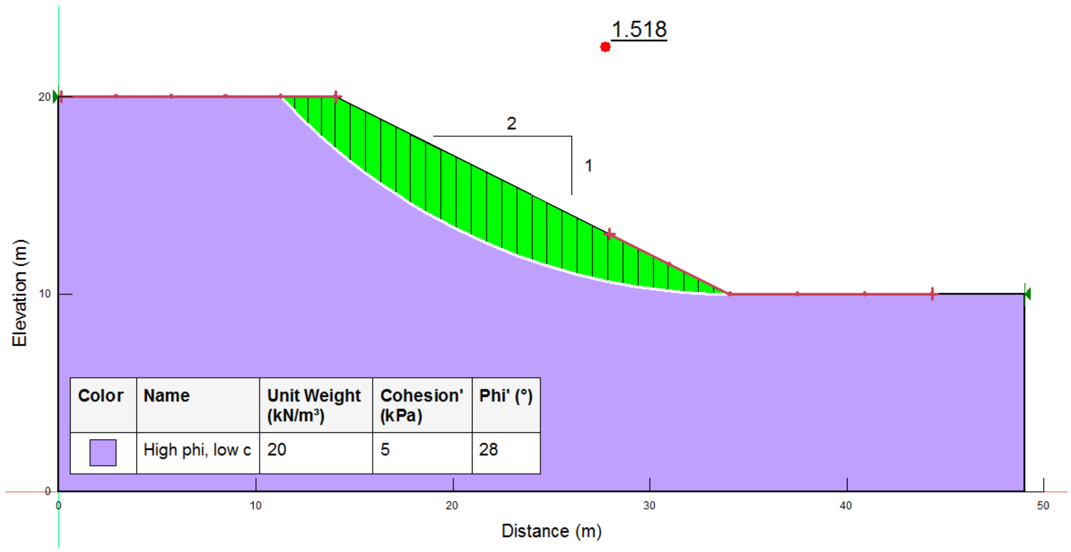

Figure 9. Analysis 4, case with high φ, low c.

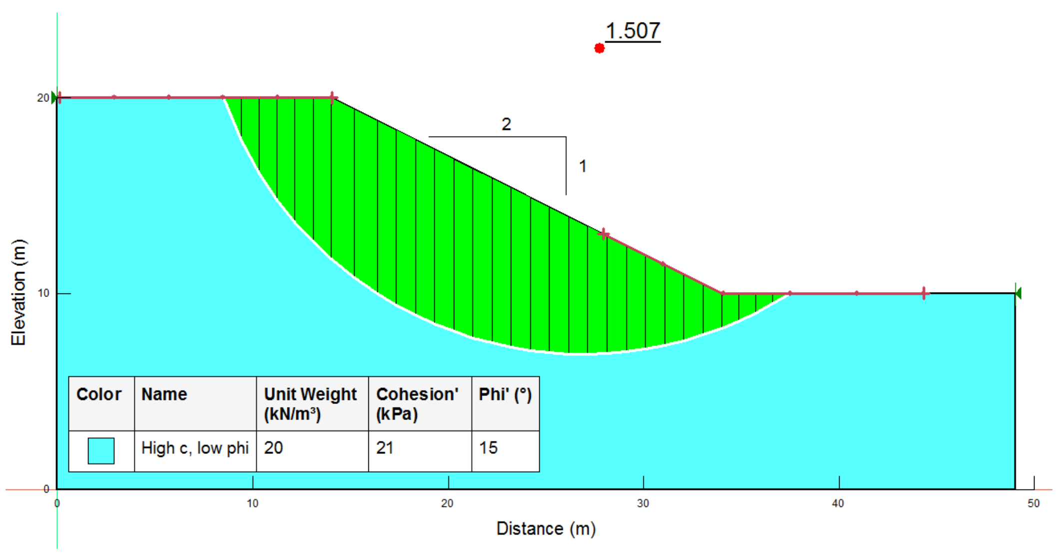

Figure 10. Analysis 5, case with low φ, high c.

The most likely position of the critical slip surface is generally computed by slope stability analyses using effective strength parameters (c´ and φ´) and realistic pore-water pressures. Effective strength parameters can be determined for most soils and rocks. Establishing realistic pore-water pressures may be more difficult; however, finite element groundwater seepage models (e.g., SEEP/W) can be used to define pore-water pressures with considerable accuracy. Total strength parameters (c and φ) should be avoided when the position of the critical slip surface is important.

Summary

The position of the critical slip surface in a limit equilibrium analysis depends on the shear strength parameters used in the material model and the pore-water pressure definition. Analyses 1 and 2 demonstrate the large variability in the critical slip surface computed by SLOPE/W. However, both modes of failure would likely never occur (i.e., very shallow or very deep failures). More realistic critical slip surfaces are produced when the shear strength parameters are more realistic. Analyses 4 and 5 also illustrate the importance of defining the shear strength parameters. Both analyses generated a similar factor of safety but dissimilar critical slip surface positioning due to the different inputted shear strength parameters. The best indication of the critical slip surface position is generally obtained when using effective stress strength parameters (c´ and φ´) with realistic pore-water pressures that include suction.