GeoStudio Example File
Material Model: Mohr Coulomb

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Introduction

The shear strength of a soil comprises three components: 1) frictional; 2) cohesive; and, 3) suction. In a SLOPE/W analysis, the limit equilibrium formulation requires that the frictional and cohesive components are defined regardless of the material model selected. The user can elect to set either value to zero for modeling certain pore-water pressure conditions. In contrast, suction strength is only included if the parameters are explicitly defined. The objective of this example is to review the fundamental theory, discuss various loading conditions, and then demonstrate how the strength inputs are manifest in the software.

Background

The primary material property in a SLOPE/W analysis is the shear strength of the soil or rock. The shear strength can be defined by the Mohr-Coulomb equation as:

$$\tau = c^{'} + (\sigma - u_w)\tan\phi^{'} \qquad \text{Equation 1}$$

where σ is the stress, u_w is the pore-water pressure, and c' and ϕ' are the intercept on the shear-stress axis and the slope of the Mohr-Coulomb failure envelope, respectively. This equation is used when the pore-water pressure is positive. The pore-water pressure is assumed to be zero in the unsaturated zone. The Mohr-Coulomb equation can also be modified to account for suction strength as:

$$\tau = c^{'} + (\sigma - u_a)\tan\phi^{'} + (u_a - u_w)\left[\frac{\theta_w - \theta_r}{\theta_s - \theta_r}\right]\tan\phi^{'} \qquad \text{Equation 2}$$

where u_a is the pore-air pressure, $(u_a - u_w)$ is the soil suction, θ_w is the volumetric water content, θ_r is the residual water content and θ_s is the saturated water content. By default, suction strength is excluded from an analysis unless the suction strength inputs are defined. The suction strength is discussed in another SLOPE/W example file.

SLOPE/W does not distinguish between total stress and effectives stress cohesion and friction angle when the Mohr-Coulomb material model is selected. The usage is inferred from the pore-water pressure. If the pore-water pressure is defined, it is implied that the strength parameters are effective stress parameters; that is, the parameters are c´ and ϕ’, and the shear strength is computed from:

$$\tau = c^{'} + (\sigma - u_w)\tan\phi^{'} \qquad \text{Equation 3}$$

If the pore-water pressure is undefined, it is implied that the parameters are total stress parameters; that is, c and ϕ, and the shear strength is computed from:

$$\tau = c + (\sigma)\tan\phi \qquad \text{Equation 4}$$

The shear strength parameters are generally measured using a direct shear test or triaxial cell. The latter is discussed below.

Consolidated Undrained (CU) Tests

Effective stress parameters c´ and ϕ' are generally determined from consolidated-undrained (CU) triaxial tests with pore-water pressure measurements. Effective stress cannot be measured and are always computed from total stresses together with pore-water pressures. As a result of this requirement, triaxial test results are often presented as giving a total stress strength envelope and an effective stress strength envelope.

In general, the procedure involves testing three (or more) different samples at three different consolidation pressures. Each sample is allowed to come to equilibrium with full drainage at different cell pressures. After having come to complete consolidation, the pore-water pressure drainage valve is shutoff and the sample is slowly loaded vertically. During the loading, the magnitude of the vertical load and responding pore-water pressures are measured.

In a triaxial test, the cell pressure is the minor principal stress (σ_3) and the vertical stress is the major principal stress (σ_1). From this Mohr circles of stress can be drawn (Figure 1). First, the total stress Mohr circles are drawn. Each of the total stress circles is then shifted to the left by the amount of the pore-water pressure at failure, then becoming the effective stress Mohr circles (dashed-line circles in Figure 1). A best fit line tangent to the stress circles becomes the failure envelope.

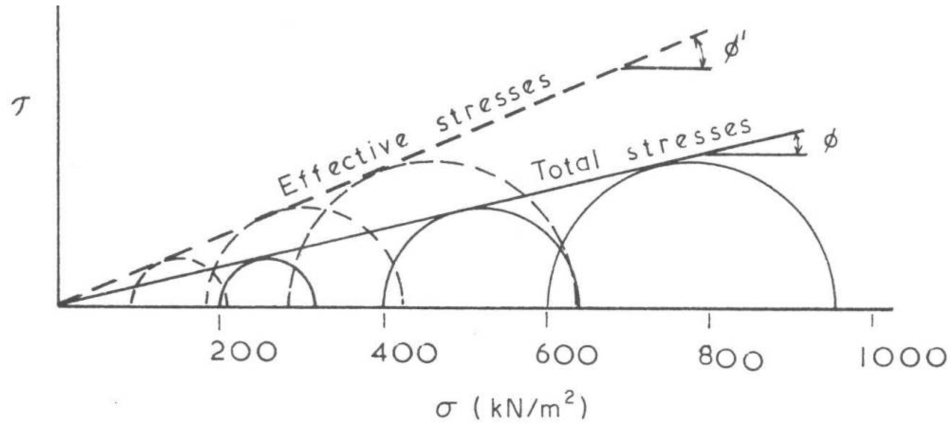

Figure 1. Results of consolidated undrained triaxial tests with pore-water pressure measurements (after Smith, 1974, p. 118).

Consolidated Drained (CD)Tests

To avoid the process of measuring the pore-water pressure, samples are consolidated at various cell pressures and then loaded very slowly. The idea is that any excess pore-water pressure created by the loading will dissipate during the loading. This makes the total and effective stress the same, and consequently c´ is equivalent to c and ϕ' is equivalent ϕ.

The slope of the failure envelope from tests like this is sometimes designated ϕ_S. The subscript S refers to 'Slow'. It is important to be cognizant of the fact that ϕ_S is an effective stress parameter.

CU Tests without PWP Measurement

In an effort to do triaxial tests more quickly, the samples are consolidated and then loaded very rapidly without making any pore-water pressure measurements. The slope of the failure envelope from tests like this is sometimes designated ϕ_R. The subscript R refers to 'Rapid'. All of the measured stresses are total stresses and the results are consequently total stress parameters. In a SLOPE/W analysis, ϕ_R needs to be thought of as ϕ. The designations ϕ_S and ϕ_R are used in the literature describing the Staged Rapid Drawdown analysis procedure.

Undrained Strengths

Another triaxial testing variation is to run a series of unconsolidated-undrained tests. This means each sample is placed in the cell, but not allowed to consolidate after the cell pressure is applied. After the cell pressure is applied, the sample is loaded rapidly without allowing any drainage and without collecting any pore-water pressure measurements (Figure 2). The cohesion intercept *c* is a constant, and the failure envelope is flat making it appear as if ϕ is zero.

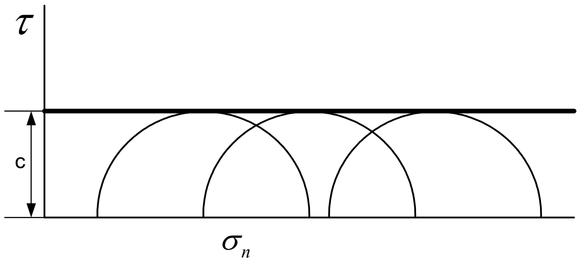

Figure 2. Undrained triaxial test results.

The cohesion intercept c is called the undrained strength and is often designated in the literature by symbols like C_u and/or S_u. Undrained strength in SLOPE/W can be specified by setting c (cohesion) to S_u and setting ϕ to zero in the Mohr-Coulomb material model. Conversely, the Undrained material model can be selected.

Commentary on undrained strength

It is important to understand that S_u is not a fundamental soil property. It is a strength value in response to a particular loading condition and loading sequence. Different loading conditions and sequences will result in different undrained strengths. Stated another way, undrained strength are stress-path dependent.

Effective stress strength parameters are, however, fundamental soil properties and consequently are not stress path dependent. The test results presented in Figure 2 make it appear that ϕ is zero. This is only a response to a particular testing procedure. This does not mean that the frictional resistance between the soils particles is zero. The frictional resistance between the soils particles is always represented by ϕ', even during undrained loading conditions.

Numerical Simulation

Figure 3 presents the model domain. The entry-exit technique is used to search for the critical slip surface. There are three cases in the GeoStudio Project. The first case uses the Mohr-Coulomb material model for both regions with effective stress strength inputs (c' and ϕ') and the pore-water pressure defined using a piezometric line. The second case uses total stress strength inputs for the Mohr-Coulomb material model. Note that the pore-water pressure definition was set to ‘none’ in the analysis settings. As noted above, including a pore-water pressure definition would yield strength values calculated using Equation 3 instead of Equation 4. The water ponding at the toe of the slope had to be replaced with a surcharge load. The third case uses the Undrained material model to define the strength. The piezometric line is retained because it has no effect on the calculated strength while ensuring that the water surcharge load is applied.

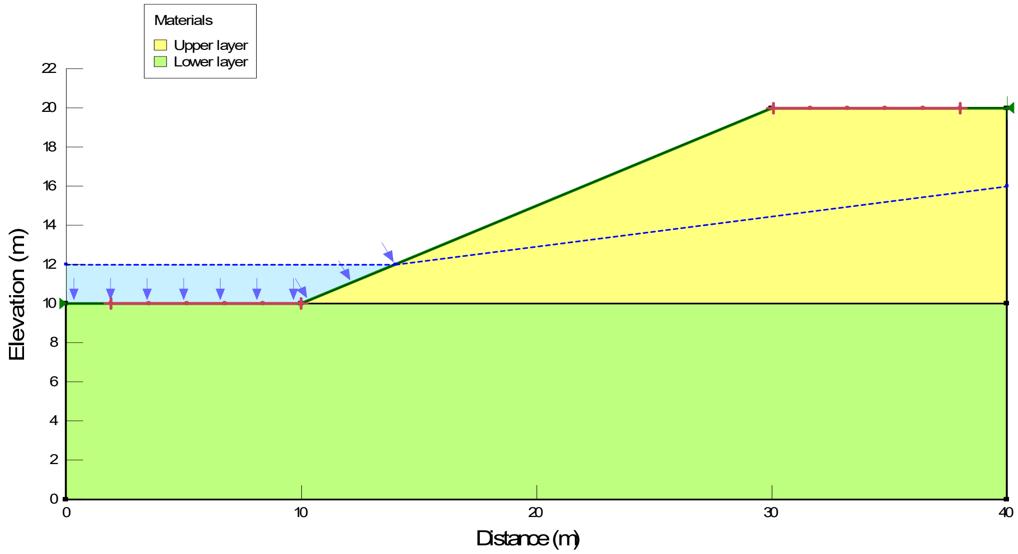

Figure 3. Model configuration.

Results and Discussion

Figure 4 presents the critical slip surface and factor of safety for Case 1 along with the color map for all valid slip surfaces. The cohesive and frictional shear strength at the base of each slice is presented in Figure 5. Note how the cohesive strength is independent of the effective normal stress along the slip surface, while the frictional strength changes with effective stress. The addition of the two strength components yields the shear resistance presented in Figure 6.

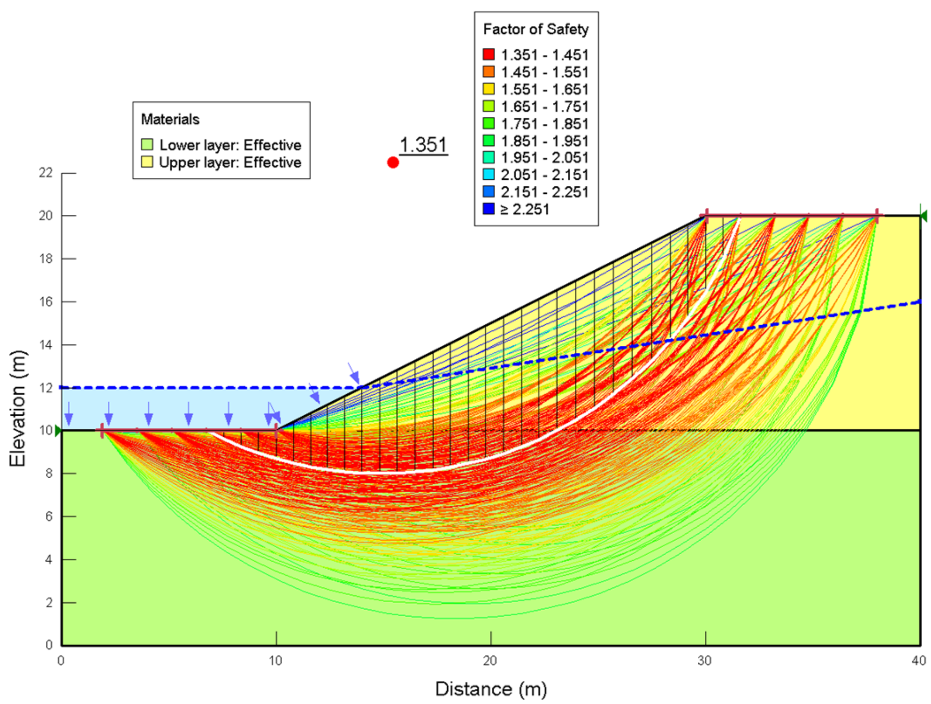

Figure 4. Critical slip surface for Case 1.

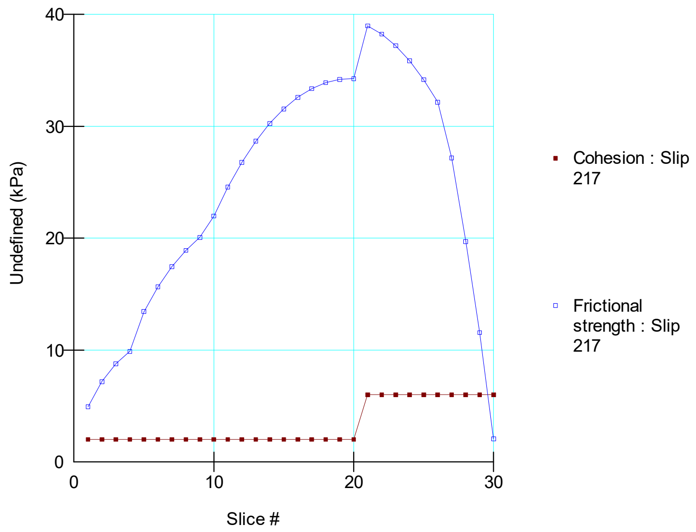

Figure 5. Cohesive and frictional strength components.

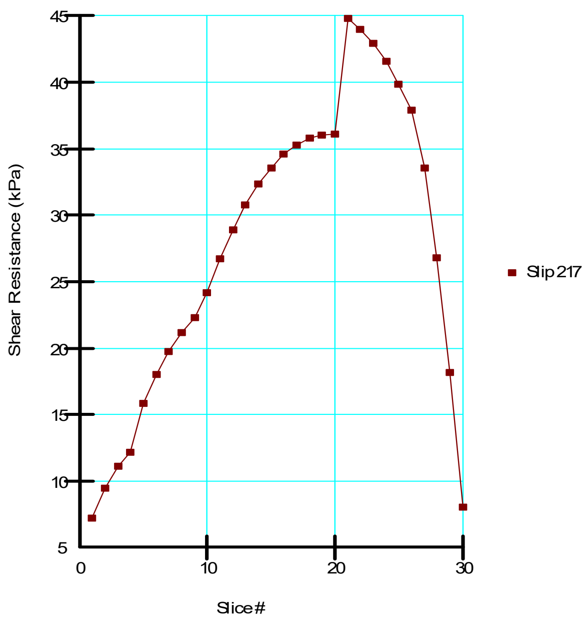

Figure 6. Shear resistance along the critical slip surface for Case 1.

Figure 7 and Figure 8 present the cohesive and frictional strength components for Case 2 and Case 3, respectively. In case 2, the frictional component increases with increasing total overburden stress, which is equal to the effective stress because pore-water pressure conditions were not defined. It is again important to note that the surcharge load had to be applied to model the ponded water. The strength is constant at S_u for Case 3.

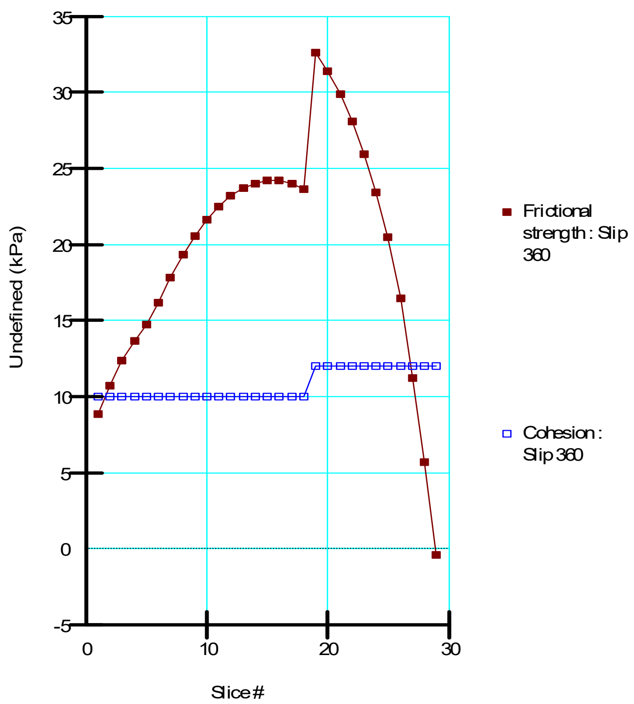

Figure 7. Frictional and cohesive strength components for Case 2.

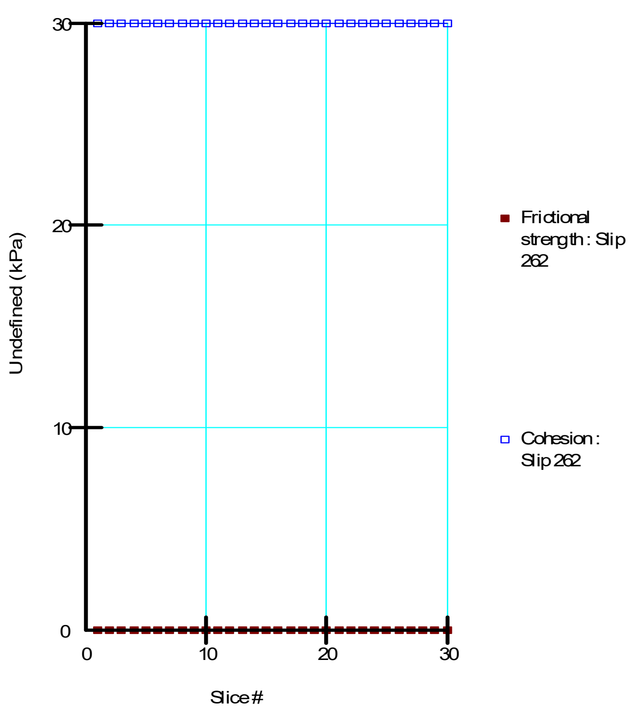

Figure 8. Frictional and cohesive strength components for Case 3.

Summary and Conclusions

SLOPE/W is formulated to always use only one of two shear strength equations. The two primary parameters are c and ϕ. All the shear strength models in SLOPE/W collapse down to one or both of these parameters. The Mohr-Coulomb input values for c and ϕ can represent either effective stress or total stress parameters depending on the definition for pore-water pressure conditions. If the pore-water pressure is undefined, c and ϕ are total stress parameters. If the pore-water pressure is defined, the specified c and ϕ are c´ and ϕ´. It is important to remember that water ponding must be represented by a surcharge load in the case of total stress inputs. In the case of the Undrained material model, ϕ is set to zero so the piezometric line can be used to model water surcharge loads.