Unit Weight Definition

GEO-SLOPE International Ltd. | www.geo-slope.com

1200, 700 - 6th Ave SW, Calgary, AB, Canada T2P 0T8
Main: +1 403 269 2002 | Fax: +1 888 463 2239

Introduction

The primary means of defining the weight of the soil in a slope stability analysis is to specify the total unit weight. Generally, unit weight is seen as being substantially less above the water table, given that, this soil is unsaturated. In reality, there is no sharp break in unit weight at the water table as the soil remains saturated in the capillary zone (above the water table) and diminishes with distance above this zone. Ultimately, the unit weight above the water table is variable because it depends on the water content. This example considers three different options for defining the total unit weight of a soil in SLOPE/W analyses.

Background

The total unit weight specified in SLOPE/W is assumed to be the saturated unit weight, γ_{sat}, corresponding to the saturated volumetric water content (VWC), θ_s. However, SLOPE/W can compute the unit weight of an unsaturated soil based on its VWC, θ. In order to do so, a VWC function for the soil must be specified, such that the change in water content is known over a range of pore water pressures (Figure 1). Consequently, if the (negative) pore-water pressure above the water table is known, the water content can be determined from the VWC function and the soil unit weight is calculated by:

$$\gamma = \gamma_{sat} - [\gamma_w * (\theta_s - \theta)] \quad \text{Equation 1}$$

where γ_w is the unit weight of water.

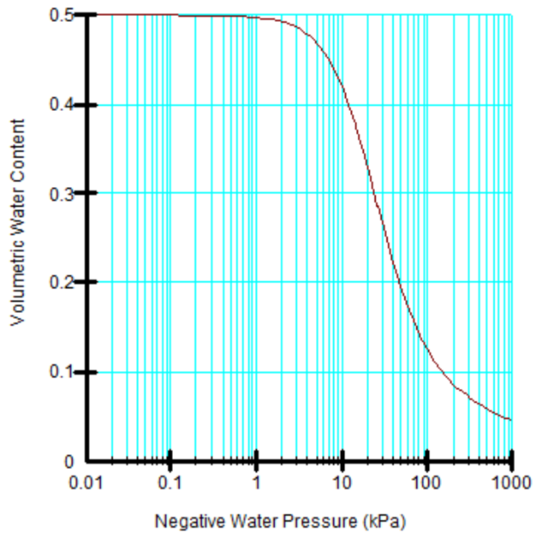

Figure 1. Volumetric water content function.

Consider a soil with a total unit weight of 20 kN/m^3 and a saturated water content of 0.5. At a water content of 0.4, the soil unit weight is:

$$\gamma = 20 - [9.81 * (0.5 - 0.4)] = 19.02\ kN/m^3 \quad \text{Equation 2}$$

If the soils were bone dry (θ = 0.0), the soil unit weight would be:

$$\gamma = 20 - [9.81 * (0.5 - 0)] = 15.10\ kN/m^3 \quad \text{Equation 3}$$

The soil unit weight is used to compute the total weight of each slice along a trial slip surface. The slice weight is determined by integrating the soil unit weight in increments over the height of the slice. There are three options available in SLOPE/W for handling the soil unit weight:

1. The unit weight is treated as a constant (the saturated unit weight), regardless of the pore-water pressure conditions;
2. The unit weight below the water table represents the saturated unit weight, while the unit weight above the water table can be specified as a different (but still constant) value; or
3. The unit weight can be a function of the soil water content as described above.

These three options will be explored in this example.

Numerical Simulation

The stability of a homogeneous dam with steady-state flow can be assessed by using pore water pressures computed by a steady-state SEEP/W analysis in SLOPE/W. The SEEP/W analysis includes a constant head boundary condition along the upstream face of the embankment to represent a constant reservoir level (of 9 m), and a zero pressure head boundary condition along the bottom toe of the dam (from x = 44 m to x = 52 m) to represent a toe drain (Figure 2). This seepage analysis provides the pore water pressure definition for all of the SLOPE/W analyses in the project file (Figure 3).

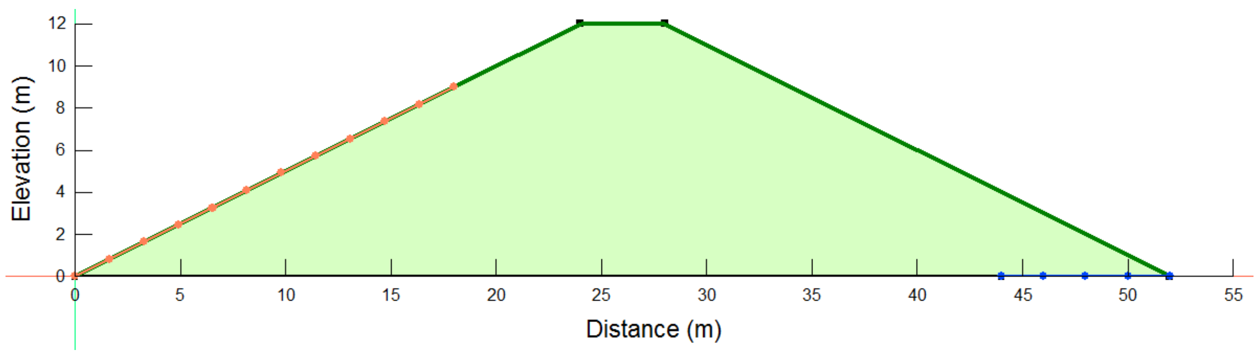

Figure 2. Domain configuration and SEEP/W boundary conditions for a constant reservoir level (orange) and toe drain (blue).

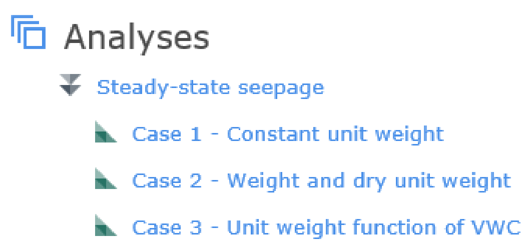

Figure 3. Analysis Tree for the project.

The material properties in the SEEP/W analysis are defined using the Saturated / Unsaturated material model. The VWC function is estimated for a silty soil using the sample functions provided in SEEP/W and a saturated water content of 0.5 (Figure 1). The air entry value is approximately 1 kPa, above which the soil drains rapidly. This indicates that the saturated capillary zone will extend approximately 0.1 m above the water table.

As described above, the unit weight definition varies in the three SLOPE/W analyses for comparison purposes. The unit weight definition in each of the three cases is as follows:

1. A constant saturated unit weight of 20 kN/m^3;
2. A saturated unit weight of 20 kN/m^3 and an unsaturated unit weight of 16 kN/m^3 above the water table (i.e., where the pore-water pressure is negative); and
3. A unit weight computed from Equation 1 based on the computed pore-water pressure and specified VWC function.

The other soil properties are similar for all three SLOPE/W analyses. The friction angle is defined as 30° and cohesion is 5 kPa, both specified under the Basic tab of the Define Materials window. A unit weight of 20 kN/m^3 is also specified under the Basic tab for all three analyses, as all of the materials have the same saturated unit weight. In Case 2, a constant unsaturated unit weight of 16 kN/m^3 is entered under the Advanced tab (Figure 4). In Case 3, the VWC function used to determine the unsaturated unit weight is specified under the Advanced tab (Figure 5).

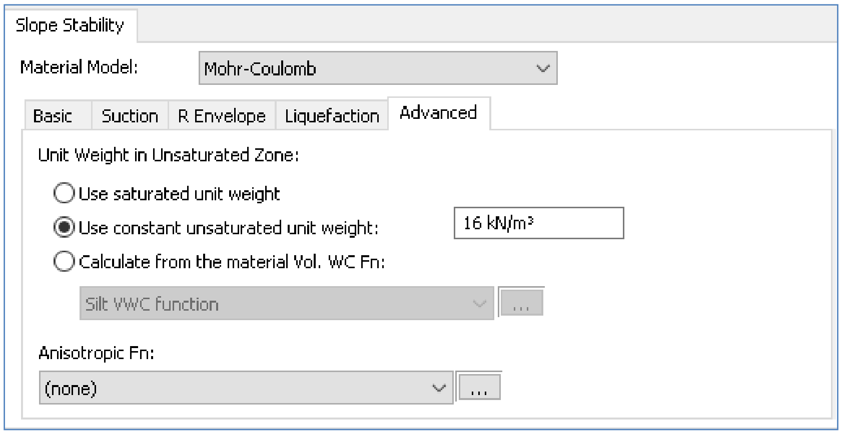

Figure 4: Constant unsaturated unit weight definition in Case 2.

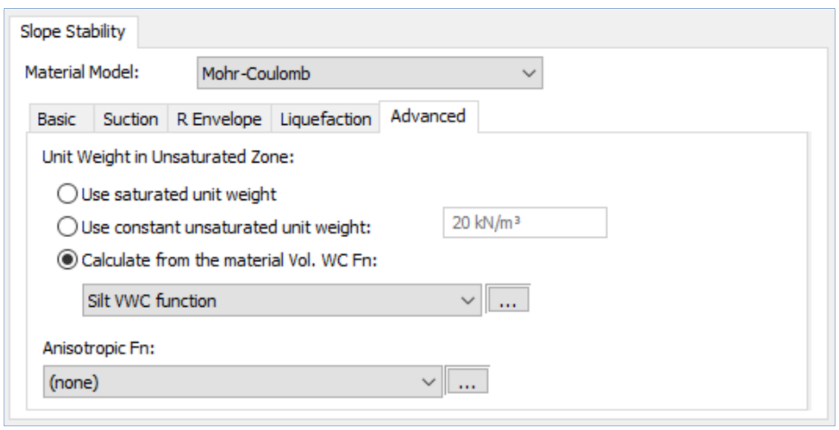

Figure 5: Unit weight defined as a function of water content for Case 3.

The trial slip surfaces are defined with the Entry and Exit method. The entry range includes the crest and top part of the upstream face of the dam. A single point at the toe of the dam defined the exit. The slip surface definition is the same in all three SLOPE/W analyses.

Results and Discussion

The pore water pressures generated by a SEEP/W analysis can be contoured throughout the domain as illustrated in Figure 6. Each contour represents a range of 10 kPa. Given an air entry value of approximately 1 kPa, the capillary zone will only be a small portion of the domain above the water table (approximately 0.1 m as previously mentioned). The capillary zone also extends over the toe drain on the right side of the domain. Further above the water table, the water content decreases and, consequently, the total unit weight decreases. Some flow does occur above the water table – as indicated by the flow vectors – though much of this flow is within the saturated capillary zone or the near-saturated zone just above it (Figure 6).

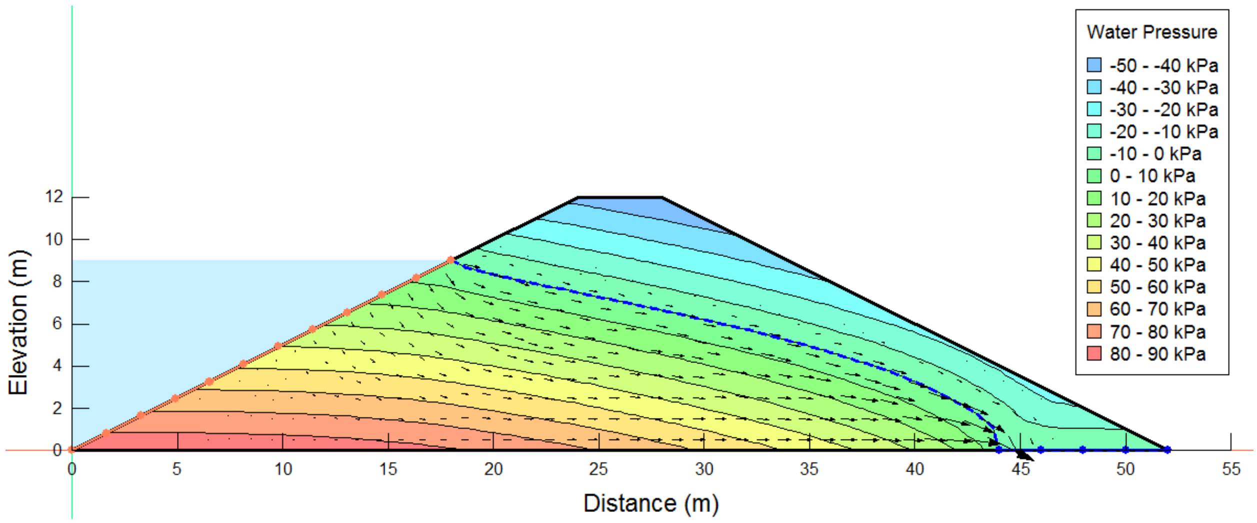

Figure 6. Total head contours and flow vectors produced by the steady-state SEEP/W analysis.

The critical slip surface shape was the same for each of the three stability analyses (Figures 7, 8, and 9). The factor of safety for the critical slip surface is the lowest for Case 1, when the saturated unit weight is applied to the entire domain (Figure 7). The factor of safety increases slightly when a lower unit weight is used above the water table (Figure 8), and again when unit weight is computed as a function of the soil water content (Figure 9). For the cases with reduced unit weight in the unsaturated zone (Cases 2 and 3), the driving force causing instability decreases due to the lighter slices at the upper end of the slip surface. This reduced driving force is greater than the reduced shear resistance near the toe, and so the factor of safety is higher.

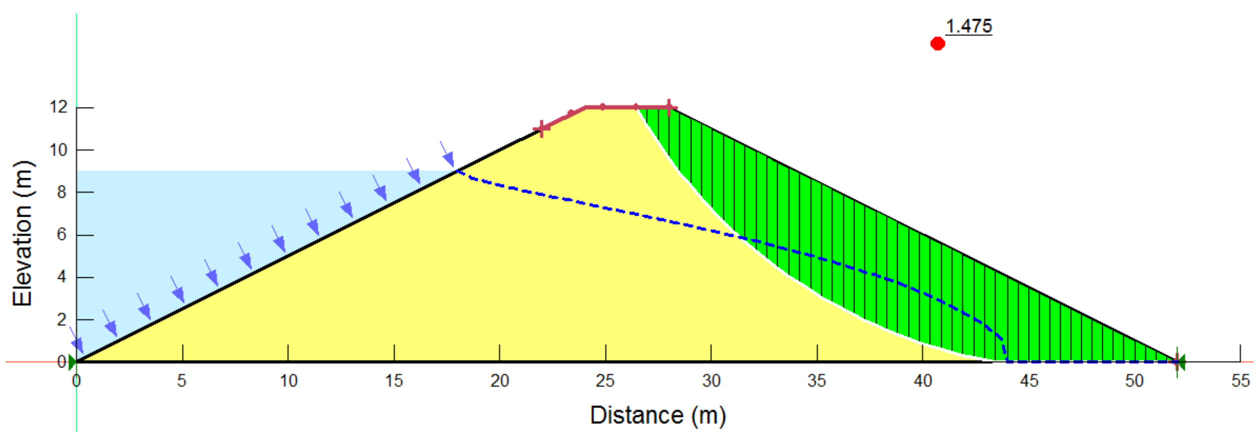

Figure 7. Factor of safety for the critical slip surface given a constant unit weight (Case 1).

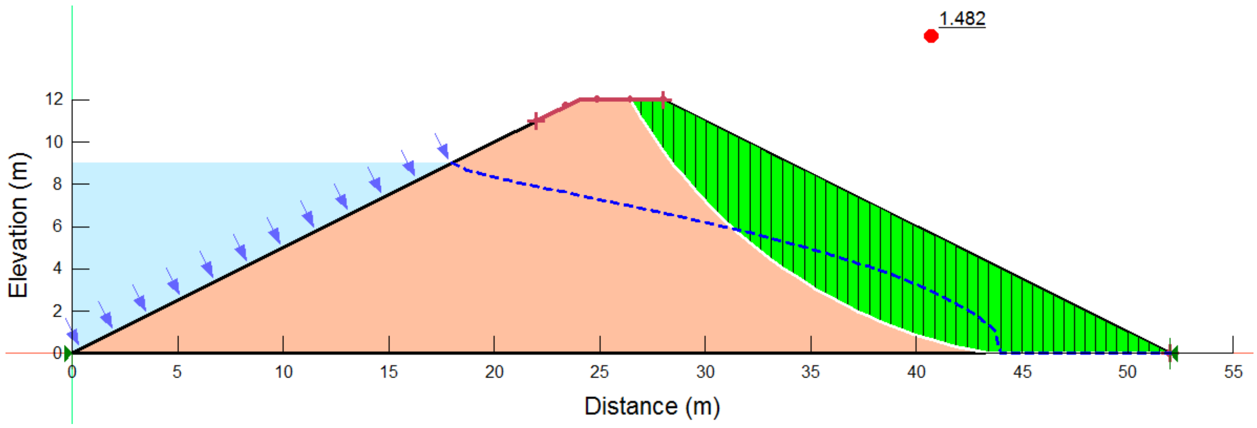

Figure 8. Critical slip surface factor of safety for constant but different wet and dry unit weights (Case 2).

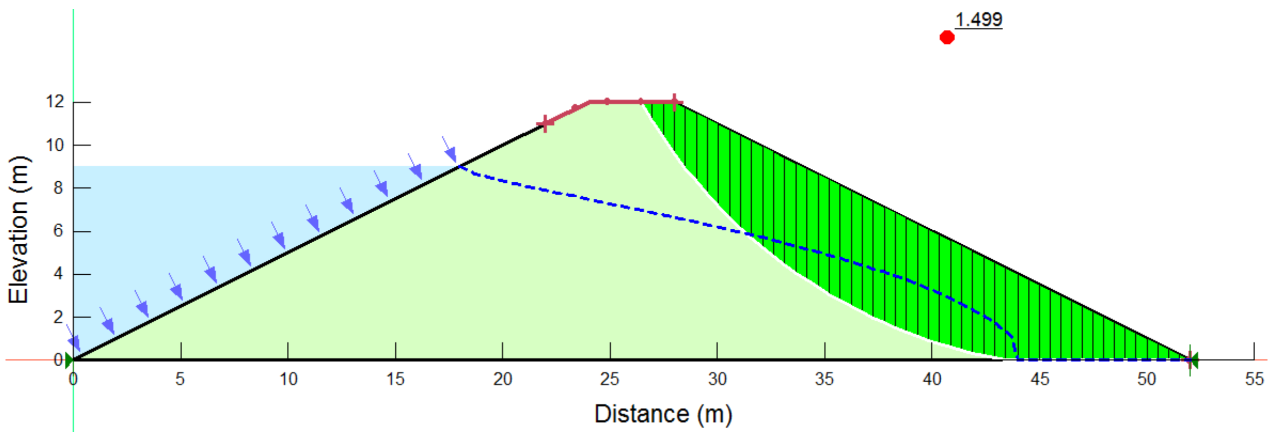

Figure 9. Critical slip surface factor of safety with variable unit weight based on water content (Case 3).

A comparison of the slice weights generated by each case provides insight on the associated factor of safety (Figure 10). Slice weights produced when the unit weight is a function of water content (Case 3) are generally lower than when the fully saturated unit weight is used throughout the domain; however, the slice weights in the toe area are very similar for Case 1 and Case 3. In the toe area, the slices are tension-saturated or near saturation and so the slice weights based on the water content (Case 3) are similar to the weights produced by the saturated unit weight (Case 1). Conversely, in the crest area the slices have sufficient suction so that the unit weight is less than the saturated unit weight. Thus, the lighter slices near the crest create a lower driving force while the resisting force from the weight at the toe remains the same. This explains the more substantial increase in factor of safety when unit weight is a function of water content.

In Case 2, when a lower (constant) unit weight is applied above the water table, the slice weights are lower across the entire slip surface. This results in lower driving forces, but also lower resisting forces. The two forces tend to cancel each other, with the result that the overall factor of safety falls in between the other two cases. It is important to note that the slice weight distribution generated by Case 2 is the least likely in the field even though the factor of safety appears to be reasonable.

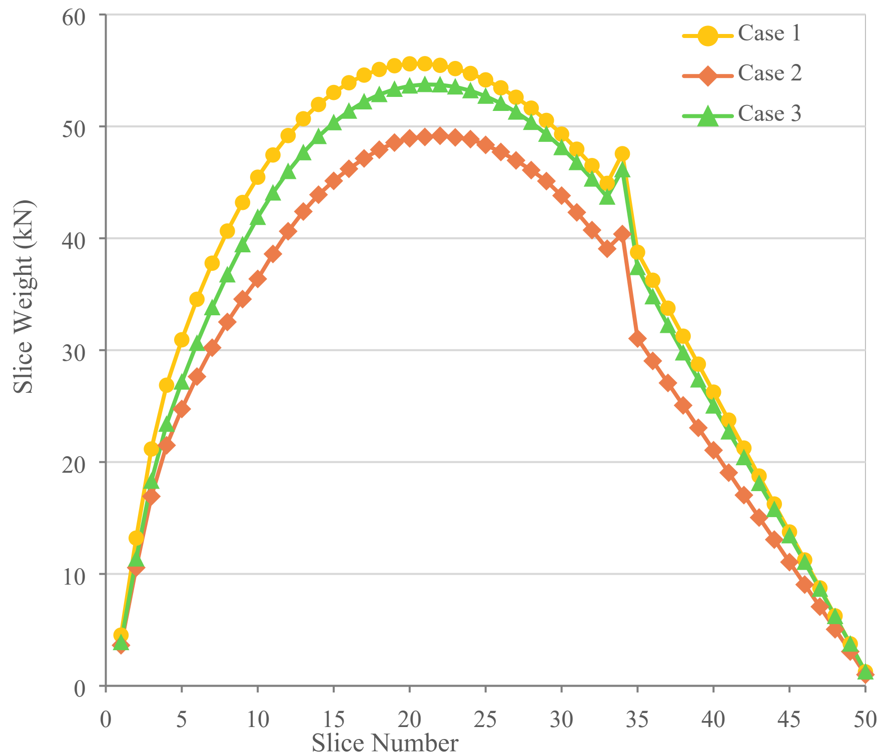

Figure 10. Slice weights generated by the three SLOPE/W cases.

Summary

This example illustrates the various methods for defining unit weight in SLOPE/W, and the influence of unit weight definition on the critical factor of safety. When a stability analysis is linked to a SEEP/W analysis for the pore water pressure definition, unit weight may be determined as a function of water content throughout the domain. A VWC function is required to define the change in water content with pore water pressure. This function can be estimated using the sample functions provided in SEEP/W. The resulting soil unit weights, and corresponding slice weights, are more representative of field conditions. This is particularly true when there is a significant tension-saturated zone.