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GeoStudio Example File

Submerged Slope with Excess Pore-Water Pressure

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Introduction

Analyzing the stability of subaqueous slopes and embankments requires some special considerations in SLOPE/W, particularly if excess pore-water pressures due to loading are involved. This illustrative example highlights the issues and discusses techniques available in SLOPE/W.

Background

A key concept for modeling a submerged ground profile is that the depth of submergence does not alter the effective stress in the ground. Consider a point that is 5 m below the ground surface and under 2 m of water. The total vertical stress (σ_v) is calculated as:

$$\sigma_v = \gamma_s z_s + \gamma_w z_w \quad \text{Equation 1}$$

where z_s is the depth below the soil surface and z_w is the submergence depth. Given that the total unit weight of the soil is 20 kN/m^3 and the unit weight of the water is 10 kN/m^3, the total vertical stress becomes:

$$\sigma_v = (5\ m * 20\ {}^{kN}/_{m^3}) + (2\ m * 10\ {}_{kN}/_{m^3}) = 120\ kPa$$

The pore pressure is:

$$u = z_s \gamma_w + z_w \gamma_w \quad \text{Equation 2}$$

$$u = (5\ m * 10\ {}^{kN}/_{m^3}) + (2\ m * 10\ {}_{kN}/_{m^3}) = 70\ kPa$$

The effective stress (σ') is calculated as:

$$\sigma' = 120\ kPa - 70\ kPa = 50\ kPa \quad \text{Equation 3}$$

If the water depth is changed to 6 m, the effective stress is calculated as:

$$\sigma_v = (5\ m * 20\ {}^{kN}/_{m^3}) + (6\ m * 10\ {}_{kN}/_{m^3}) = 160\ kPa$$

$$u = (5\ m * 10\ {}^{kN}/_{m^3}) + (6\ m * 10\ {}_{kN}/_{m^3}) = 110\ kPa$$

$$\sigma' = 160\ kPa - 110\ kPa = 50\ kPa$$

The effective stress is calculated as 50 kPa in both cases, showing that the soil effective stress is not altered by the submergence depth.

Numerical Simulation

Figure 1 shows the model domain with a simple 3:1 slope that is completely submerged. A piezometric line is drawn at an elevation of 25 m. This results in positive pore-pressures along the ground surface line; consequently, the water surchage is automatically included in the analysis. For spot checking convenience, the total unit weight of the soil (γ_s) is set to 20 kN/m^3 and the unit weight of water (γ_w) is set to 10 kN/m^3.

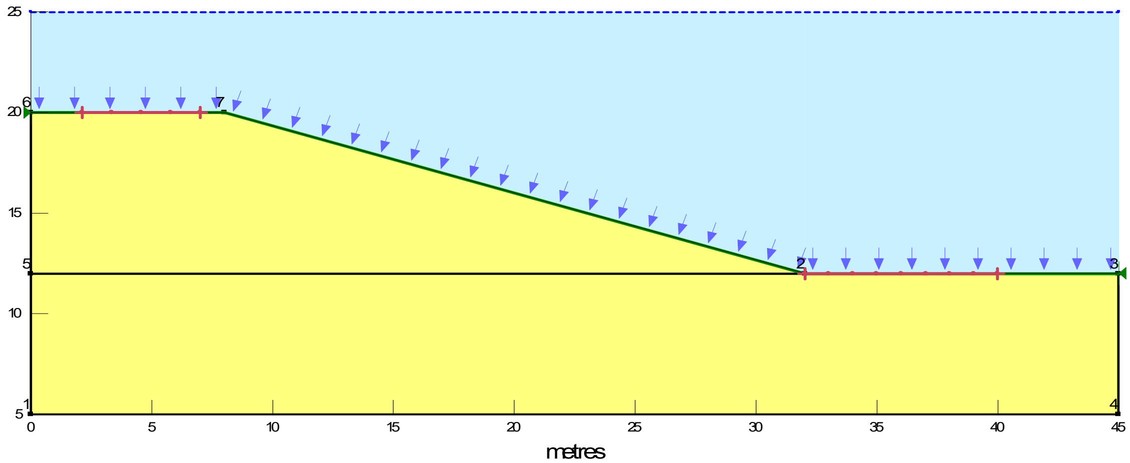

Figure 1. **Example problem configuration.**

Figure 2 presents the Analysis Tree for the GeoStudio Project. The first case models the stability of the submerged slope using total unit weights, while the second case makes use of buoyant unit weights. The third case models the generation of excess pore-water pressure in the foundation due to placement of the embankment. This cases makes use of total unit weights and B-bar, which must be adjusted accordingly (discussed below). The fourth case uses buoyant unit weights and B-bar to replicate Case 3.

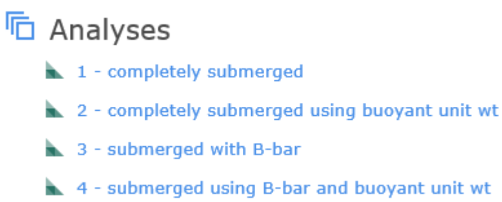

Figure 2. Analysis tree for GeoStudio file.

Results and Discussion

Case 1 and 2

Figure 3 presents the factor of safety and critical slip surface for Case 1. Notice that the water weight is represented by the vectors on the ground surface and that the vectors are perpendicular to the ground surface. This means that the vectors on the slope have a horizontal component in the up-slope direction that creates a stabilizing effect.

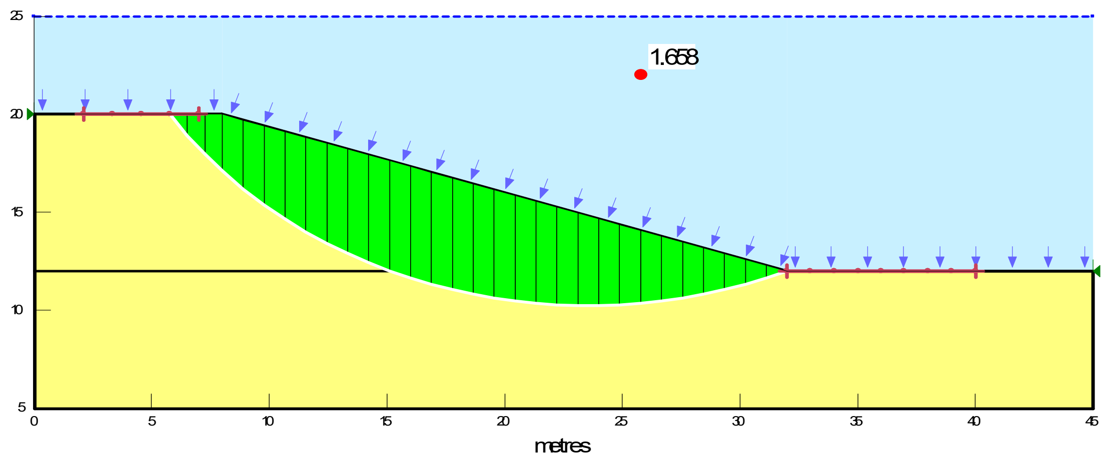

Figure 3. Factor of safety for Case 1.

The water weight is shown on the free-body diagram as a vector at the top of each slice (Figure 4). When the water weight approaches or exceeds the slice weight, the force polygon becomes tall and slender as illustrated in Figure 5. This change in the force polygon becomes more exaggerated as the depth of the submergence is increased. This becomes particularly pronounced in shallow trial slips as shown in Figure 5. Accordingly, deep submergence can cause numerical problems that are manifest in non-convergence.

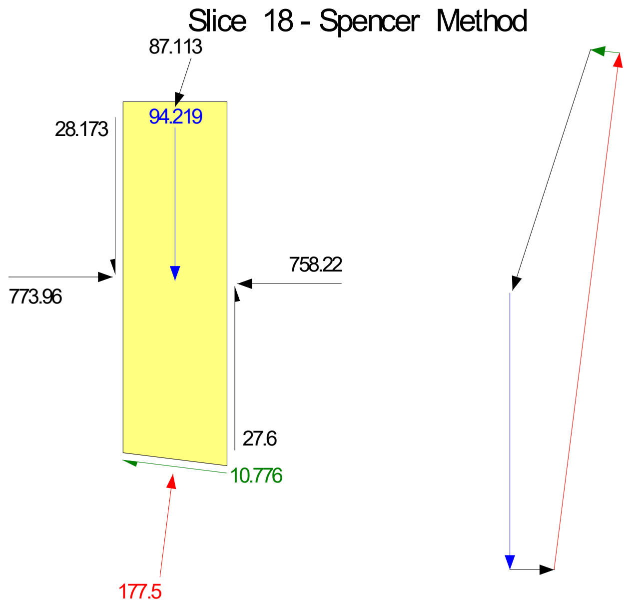

Figure 4. Free body diagram and force polygon for Slice 18 of the critical slip surface.

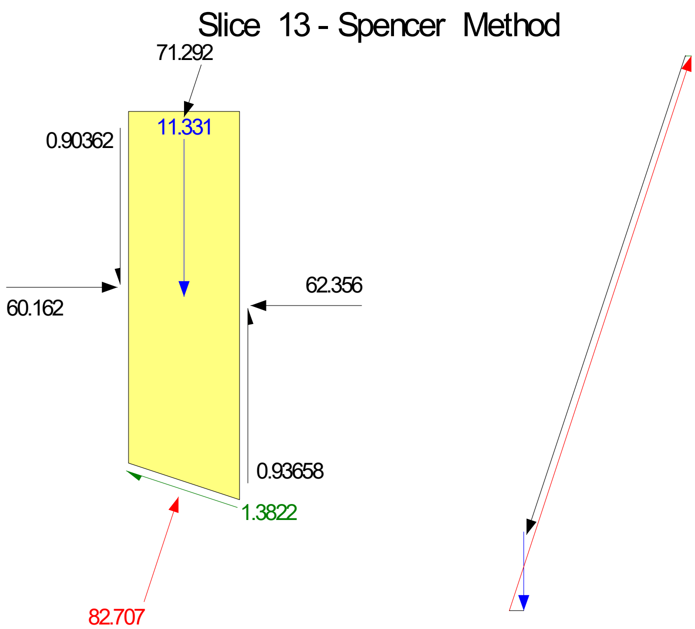

Figure 5. Free body diagram and force polygon for a shallow slip surface (Slip 181).

Numerical issues associated with submergence, especially very deep submergence, can be mitigated by omitting the surface water and assigning the soil a buoyant unit weight. Figure 6 presents the results for Case 2, which assigning the soil a buoyant unit weight of 10 kN/m^3 (20 kN/m^3 – 10 kN/m^3) and omitted the piezometric line. The overall factor of safety is essentially the same, but the force polygons are formed much better. This is observed by comparing the results in Figure 7 to those obtained in Figure 5, where the submergence was included in the model.

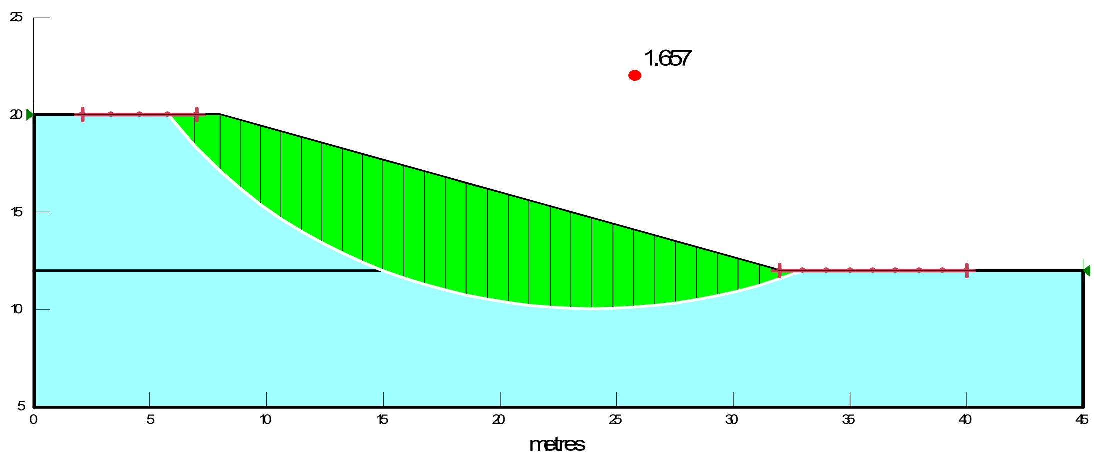

Figure 6. Stability results for Case 2 using a buoyant unit weight.

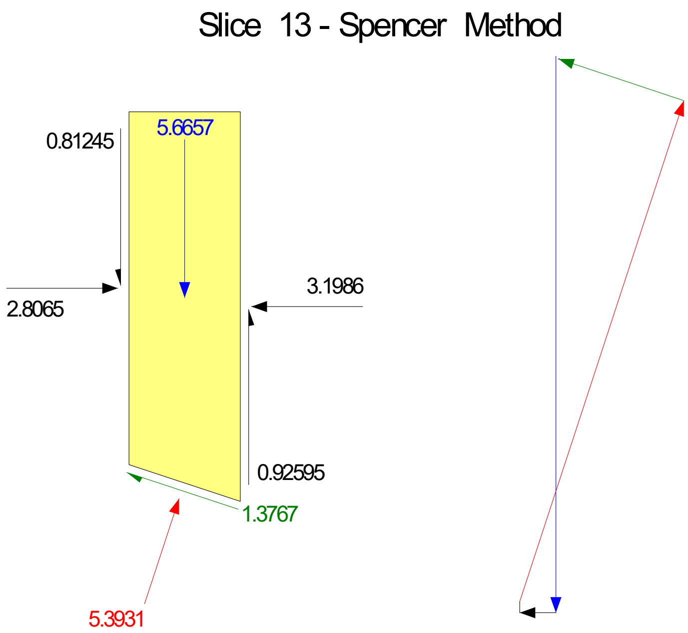

Figure 7. Free body diagram and force polygon for a shallow slip surface (Slip 181) when using a buoyant unit weight.

Case 3 and 4

During subaqueous construction, it is possible that excess pore-pressures will develop in the foundation. Such excess pore pressures can be considered in a stability analysis using B-bar ($\bar{B}$) coefficient. It is important to remember that the generation of excessive pore-water pressures in a submerged slope is due to the replacement of water by fill. In order to correctly calculate the pore-water pressure, the B-bar value must be manipulated to reflect the effect of replacing water by fill. The following is the relationship between input B-bar and design B-bar:

$$Input\ \bar{B} = Design\ \bar{B} \cdot \left(\frac{soil\ unit\ weight - water\ unit\ weight}{soil\ unit\ weight}\right)$$ **Equation 4**

Assuming a design B-bar value equal to 1, the input value is calculated as 0.5. Figure 8 presents the results for Case 3 and Figure 9 presents the pore-water pressure along the critical slip surface. Note that the pore-water pressures in this figure are the total values consisting of the initial static component and the excessive pore-water pressures calculated using B-bar.

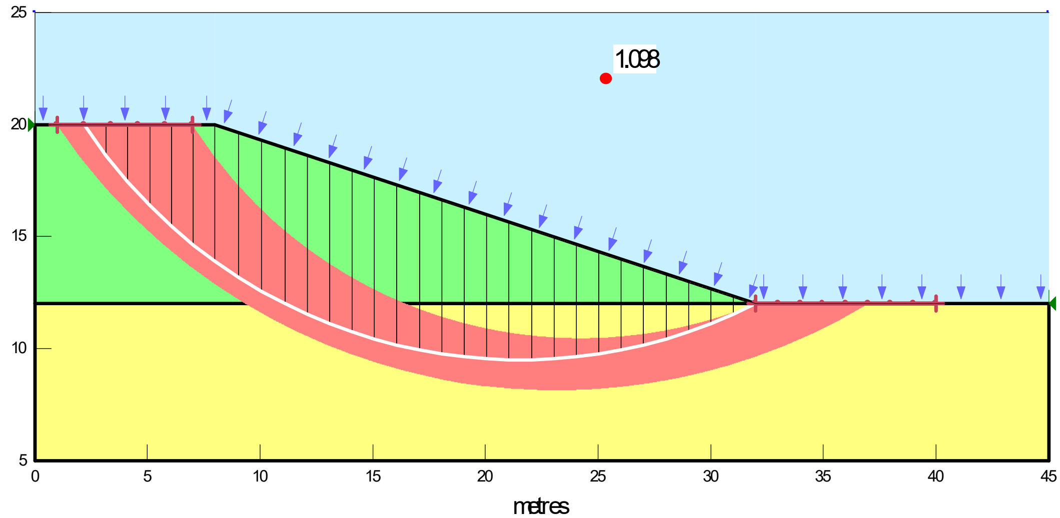

Figure 8. Stability with water weight included and a B-bar value of 0.5.

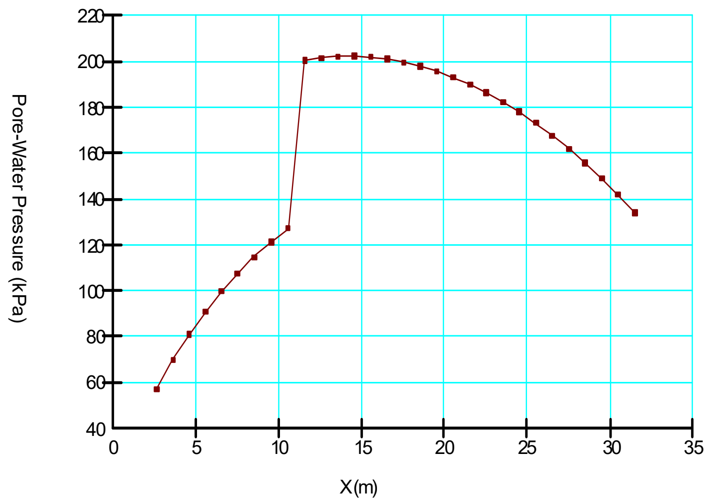

Figure 9. Total pore pressures along the critical slip surface.

Figure 10 and Figure 11 present the factor of safety and pore-water pressure distribution for Case 4, respectively. In this case, the design B-bar of 1 can be directly used as the input value because buoyant unit weights are used. The factor of safety remains unchanged. However, it is important to recognize that Figure 11 represents excess pore-pressures, not the pore pressures that would be measured in a piezometric instrument reading. The actual pore pressure would be the excess pressure plus the static free-standing water pressure.

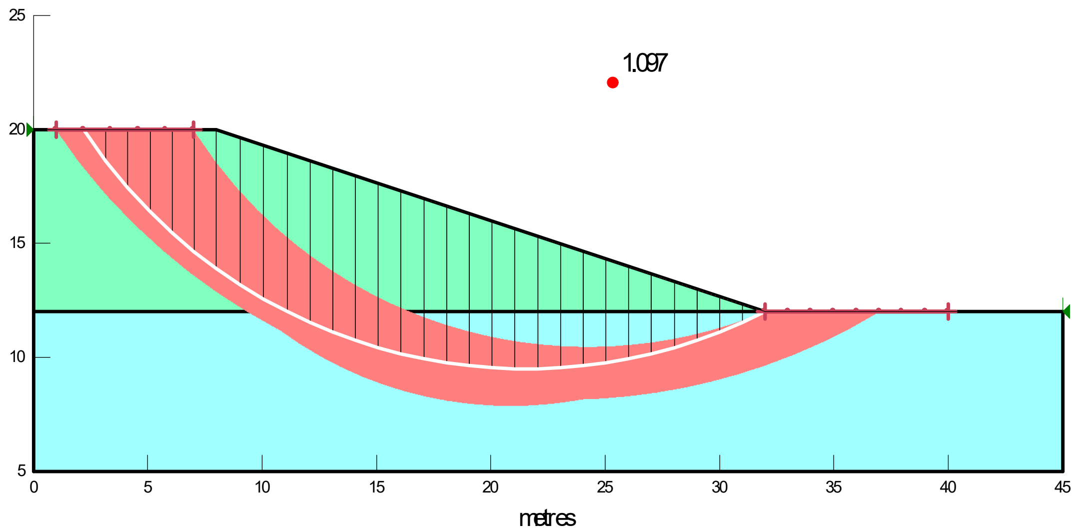

Figure 10. Stability with a buoyant weight and a B-bar value of 1.

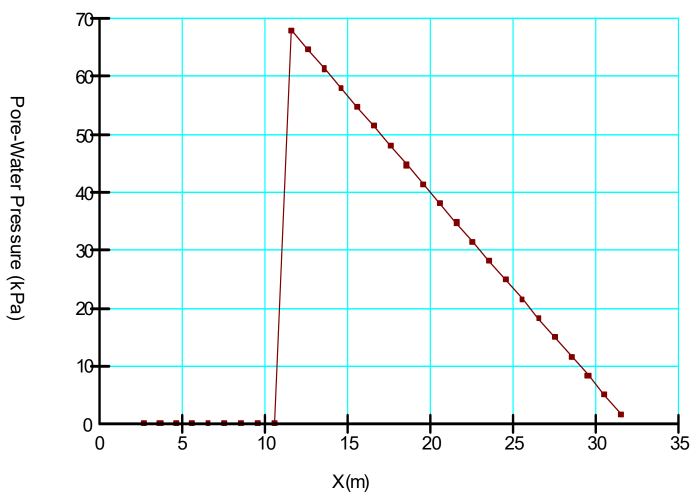

Figure 11. Excess pore pressures along the critical slip surface.

Summary and Conclusions

Submerged slopes can be analysed using either total unit weights or buoyant unit weights. In the latter case, the water surcharge load must be omitted from the analysis. It is sometimes necessary to use buoyant unit weights to avoid numerical problems. Modeling the generation of excess pore-water pressures also requires special consideration. The value for B-bar must be calculated realizing that the excess pore-water pressures in the foundation are generated due to the water being replaced by soil. If buoyant unit weights are used directly and the water surcharge load is omitted, then the pore-water pressures along the slip surface represent the excess pore pressures and not the actual pore-water pressures.