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GeoStudio Example File
Multi-stage Pseudo-static Analysis

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Introduction

The pseudo-static method is used to analyze the stability of slopes during earthquake shaking. The seismic loading is represented by a static force acting on each slice of the discretized sliding mass. In SLOPE/W, there are two options to accommodate the development of excess pore-water pressures during shaking: an undrained method and an effective stress method. This example illustrates the pseudo-static implementation in SLOPE/W and provides some recommendations on the appropriate usage.

Background

Earthquake motion will create an inertial force that is proportional to the mass of the sliding body. In SLOPE/W, the inertial force acting on each slice is calculated as:

$$F = kW \quad \text{Equation 1}$$

where k is as a pseudo-static seismic coefficient, which is equivalent to a ratio of the earthquake acceleration (a) over the gravitational acceleration constant (g). This inertial force is applied at the centroid of each slice in the potential sliding mass. Both a horizontal and vertical seismic load can be included, however, the vertical seismic force is generally not included because it counteracts the effect of the horizontal seismic force by increasing the normal force, and therefore shear resistance, at the base of each slice.

Free standing ponded surface water does not enter into the seismic force calculations. Free standing ponded surface water gets added to the weight of each slice under the water, but the surface water weight is not included in the seismic force calculations. The portion of the slice weight arising from the surface water is subtracted from the slice weight before the seismic force is computed. The reason for this is that water has no shear strength and any seismic motion of the surface water will therefore not create any additional forces.

Figure 1 presents the free body diagram for a slice with k_h equal to 0.10. The seismic force is a horizontal force applied during the force resolution of the slice. In this case, it is 10% of the slice weight (203.31 kN x 0.1 = 20.331 kN). A vertical seismic force is not depicted directly on the free body diagram. A specified vertical seismic force is algebraically added to the slice weight.

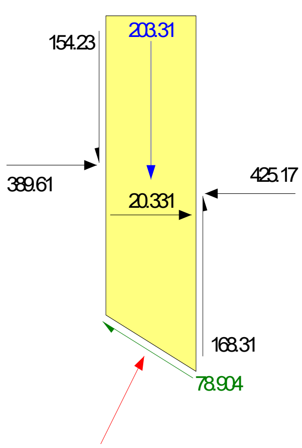

Figure 1. Illustration of the horizontal seismic slice force.

Seismic loading can lead to the generation of excess pore-water pressure. Although the mechanism for the generation of excess pore-water pressure during shaking is complicated, the undrained shear strength of the soil can be used to represent the loading conditions. There are two options in SLOPE/W found on the Define Analysis | Settings tab (Figure 2): an undrained strength method and an effective stress strengths method.

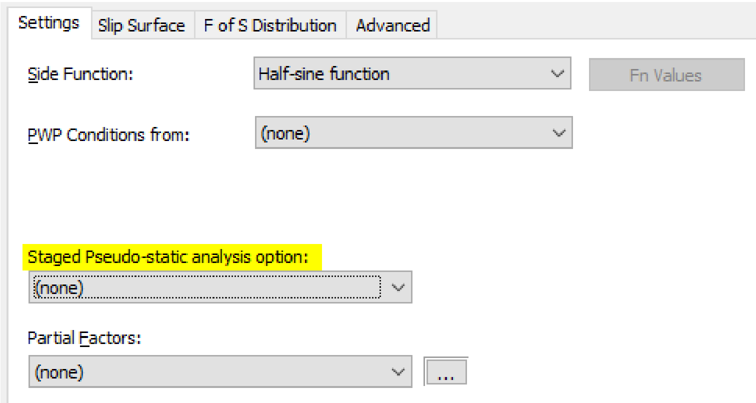

Figure 2. Staged psuedo-static options in SLOPE/W.

SLOPE/W first completes an analysis without any seismic forces to establish the effective normal stress at the base of each slice. The shear strength is then calculated based on the staged pseudo-static method selected. If the option to use undrained strengths is selected, then the method proposed by Duncan et al. (1990) is used to calculate the undrained strength (see SLOPE/W Engineering Book). Conversely, the effective stress strength method uses the effective strength properties, c' and φ', to calculate the shear strength according to the Mohr-Coulomb strength equation.

The shear strength at the base of each slice is then converted into an equivalent undrained (cohesive) strength. The analysis is then repeated (stage two) with the seismic loading. The undrained shear strength is not a function of the normal stress and, consequently, the seismic loads do not alter the shear strength.

Numerical Simulation

The example configuration is shown in Figure 3. The geometry comprises an earth dam with a clay core designed to retain a reservoir. The clay cores is keyed into the foundation soil. A steady-state SEEP/W is used to establish the pore-water pressure conditions. Seepage at the downstream toe is controlled using a pore-water pressure head boundary of 0 m to represent a drain. A total head of 8 m is applied to the upstream face.

Color	Name	Model	K-Function	Ky'/Kx' Ratio	Rotation (°)	Vol. WC. Function
(orange)	Clay core	Saturated / Unsaturated	Core K function	1	0	Core W/C
(light green)	Foundation	Saturated / Unsaturated	Shell K function	1	0	Shell W/C
(dark green)	Shell	Saturated / Unsaturated	Shell K function	1	0	Shell W/C

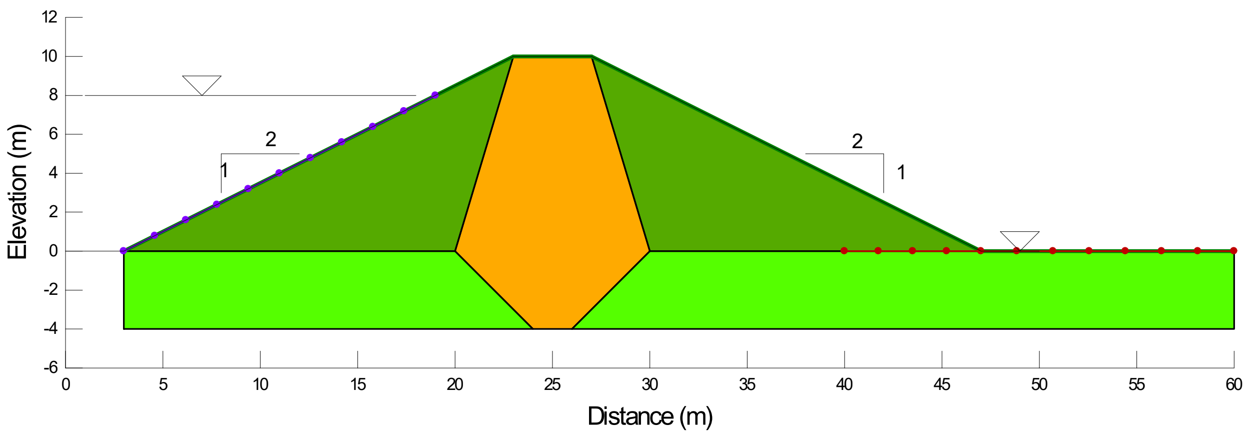

Figure 3. Example configuration.

There are four SLOPE/W analyses in the GeoStudio project (Figure 4). The first analysis is used to establish the factor of safety under static conditions. The last three analyses include horizontal seismic coefficients (k_h) of 0.05, 0.10 and 0.15, respectively. The Staged Pseudo-static Analysis option is set to 'Effective Stress Strengths' for all three analyses.

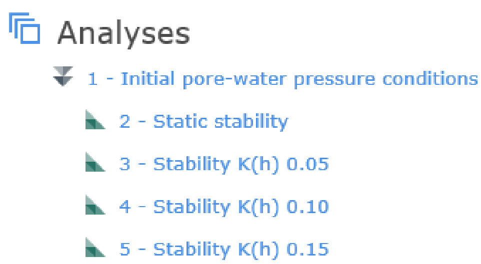

Figure 4. Analysis Tree for the Project.

Results and Discussion

The initial pore-water pressure conditions from the SEEP/W analysis are shown in Figure 5. Figure 6 presents the factor of safety under static conditions (Analysis 2). The shear strength for the critical slip surface is shown in Figure 7. The shear strength distribution for each slip surface is the same in all stability analyses because the staged pseudo-static option is selected for Analyses 3 to 5.

Color	Name	Model	K-Function	Ky'/Kx' Ratio	Rotation (°)	Vol. WC. Function
	Clay core	Saturated / Unsaturated	Core K function	1	0	Core WC
	Foundation	Saturated / Unsaturated	Shell K function	1	0	Shell WC
	Shell	Saturated / Unsaturated	Shell K function	1	0	Shell WC

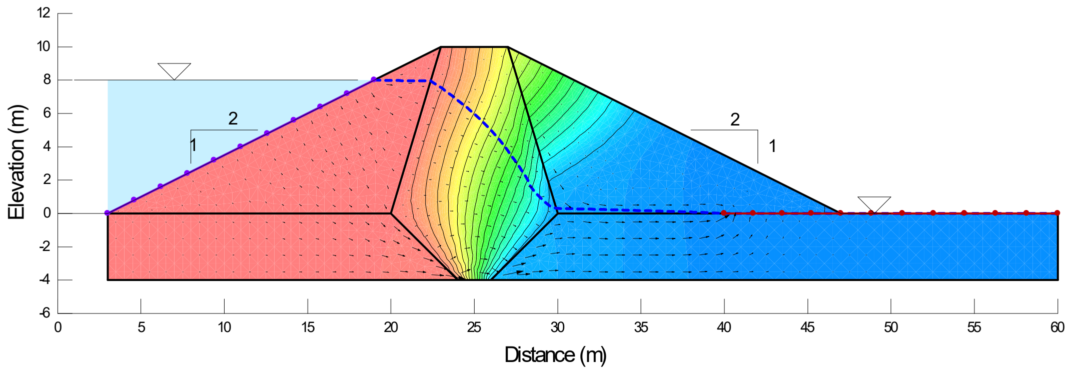

Figure 5. Initial pore-water pressure conditions of the embankment.

Color	Name	Unit Weight (kN/m³)	Cohesion' (kPa)	Phi' (°)
	Clay core	20	5	24
	Foundation	18	0	26
	Shell	20	10	32

Staged Pseudo Static Analysis Option: (none)

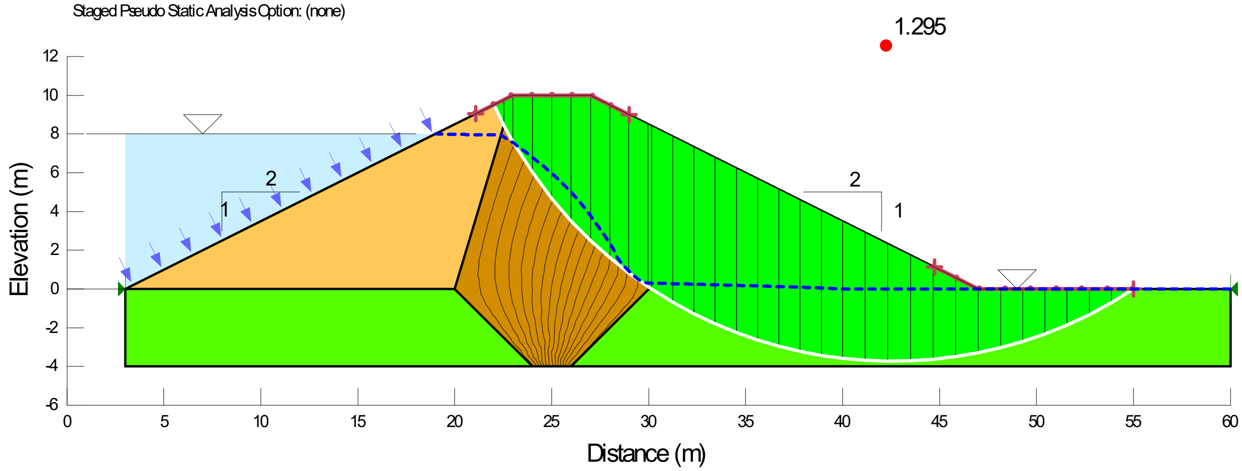

Figure 6. Stability condition under static conditions (Analysis 2).

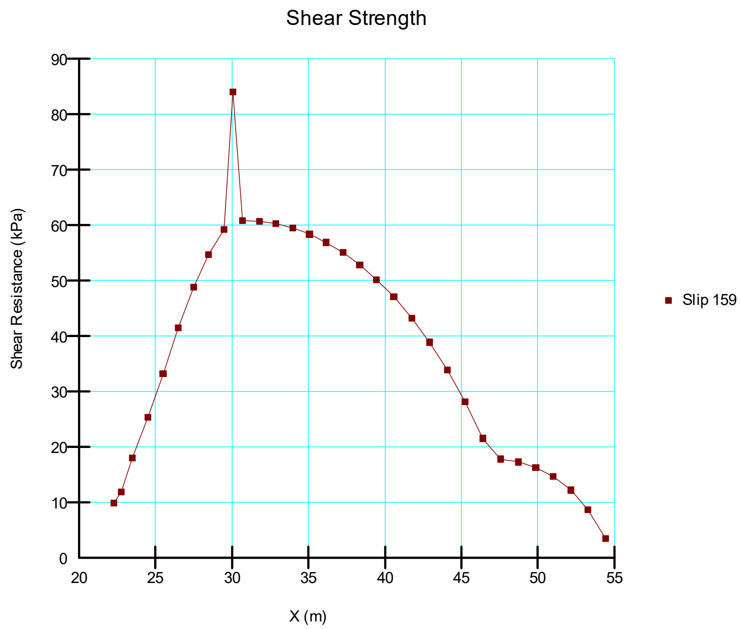

Figure 7. Shear strength for the critical slip surface: static stability.

Figure 8 summarizes the results for the various seismic coefficients. The factor of safety is less than 1.0 for horizontal seismic coefficients greater than about 0.14. It should be noted that this type of graph could have also been created by doing a sensitivity analysis in a single analysis.

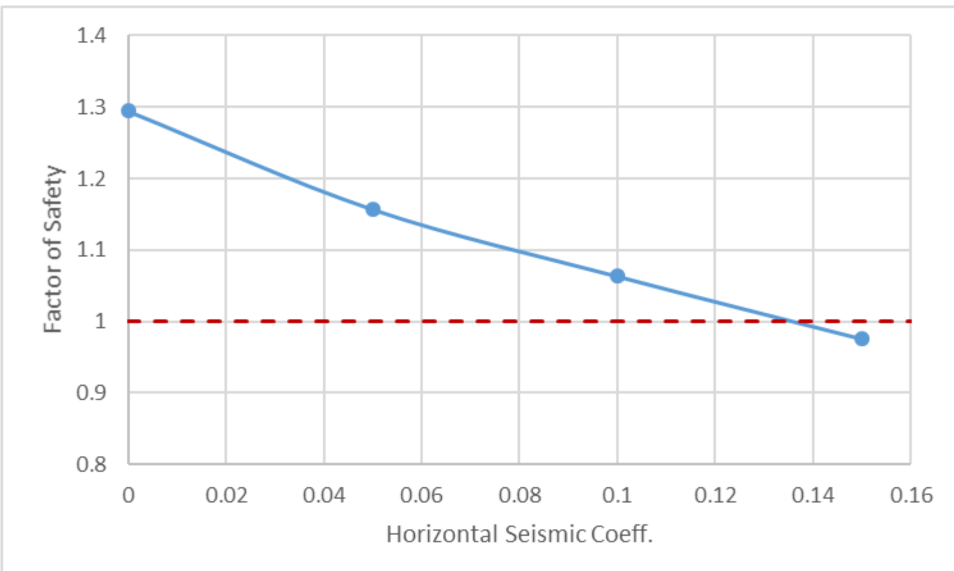

Figure 8. Factor of safety as a function of seismic coefficient.

Applying a high seismic coefficient can lead to convergence difficulties; that is, the moment and force factor of safety verses lambda lines do not crossover. As such, it is good modeling practice to incrementally increase the seismic coefficient(s) toward a target rather than starting with a large value. For example, assume that the design coefficient for a site is 0.3. Instead of using that value directly in SLOPE/W, it is better to increase the coefficient from 0 to 0.3 in a number of small increments, generating a graph like Figure 8. If a coefficient of 0.2 yields a factor of safety around 1.0, then it is already known that the structure does not meet the design criteria.

Generally, it is assumed that the soil behaves in an undrained manner during the earthquake shaking and the SLOPE/W staged option needs to be selected. There are, however, some cases where this may not be required. If the sloping ground consists primarily of broken rock or coarse gravel, then it may be more appropriate to allow the seismic loads to be reflected in the slice base shear strength.

Summary and Conclusions

A pseudo-static seismic analysis can sometimes be useful as a screening tool to judge the severity of potential problems associated with an earthquake. Pseudo-static seismic analyses, however, should only be used as a design criterion in some specific cases. A pseudo-static seismic analysis is only appropriate if there will be no significant loss of shear strength during the shaking. This would be the case for well compacted and over-consolidated soils or free draining granular soils and broken rock.

If there is chance that the shaking will generate excess pore-water pressures which could, in the worst case, lead to liquefaction, then a pseudo-static seismic analysis is not appropriate. Case history studies of the San Fernando dam liquefaction failures are included with the QUAKE/W detailed examples. The Lower San Fernando dam at the design stage was deemed to have an adequate margin of safety against failure with a seismic coefficient of 0.15, and yet the upstream face failed catastrophically due to liquefaction. This is a case history where the use of a pseudo-static seismic analysis was entirely inappropriate.

It is important to comprehend that a pseudo-static seismic analysis only deals with inertial forces. There are other issues, such as the generation of excess pore-water pressures, the loss of strength due to the collapse of the grain structure and post-earthquake deformations that cannot be addressed with a pseudo-static seismic analysis. These issues can be examined with QUAKE/W in conjunction with SEEP/W, SIGMA/W and SLOPE/W.

References

Duncan, J.M and Wright, S.G. (2005). Soil Strength and Slope Stability, John Wiley & Sons, Inc.

Duncan, J.M., Wright S.G. and Wong, K.S. (1990). “Slope Stability during Rapid Drawdown”. Proceedings of H. Bolton Seed Memorial Symposium. Vol. 2.