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GeoStudio Example File
Slope stabilization with piles

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Introduction

Piles can be used to stabilize a slope under certain circumstances. Analyzing the effect of piles on stability using SLOPE/W requires knowledge of the shear mobilized within the piles. This is a difficult value to determine because the bending moments and shear stresses within the pile depend on the stress-strain characteristics of the soil, geometry and structural properties of the piles, and depth of installation. SLOPE/W cannot consider these factors. The alternative approach requires a soil-structure interaction analysis using SIGMA/W. This example illustrates how to model the stabilizing effect of a sheet pile wall on a marginally stable slope using the Strength Reduction Stability (SRS) analysis in SIGMA/W.

Numerical Simulation

Figure 1 shows the problem configuration. The slope is marginally stable due to the underlying weak layer that causes periodic movement when the pore-water pressures increase in the slope. The objective is to stabilize the slope by installing piles from the lower bench through the weak layer and into the underlying stiff competent material.

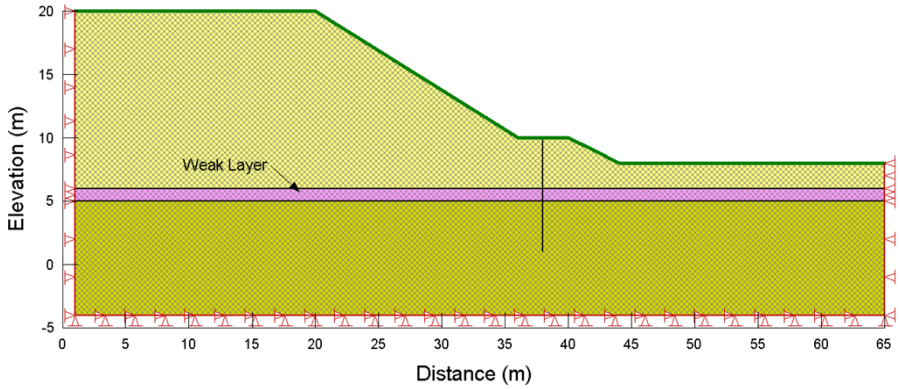

Figure 1. Problem configuration.

Table 1 presents the material properties used in the analyses. All of the materials use the saturated-unsaturated material model with an arbitrary volumetric water content and hydraulic conductivity function. An isotropic linear elastic material model is used for the bedrock material for all SIGMA/W analyses. A Mohr-Coulomb constitutive model with a friction angle of 10° and 30° represents the weak layer and sandy clay, respectively. The weak layer has zero cohesion. The response type of all materials is set to Drained.

Table 1. Material properties.

Material	Unit Wt. (kN/m3)	Elastic Modulus (kPa)	Poisson's Ratio	Cohesion (kPa)	Friction Angle	VWC Function	Saturated Hydraulic Conductivity (m/s)
OC Soil	20	500,000	0.4			Silty Clay	1e-5
Sandy Clay	20	10,000	0.4	20	30	Gravel	1e-5
Weak Clay	20	5000	0.4	0	10	Silty Clay	1e-5

Figure 2 presents the analysis tree for the GeoStudio project. A steady-state SEEP/W seepage analysis is used to establish the pore-water pressure distribution within the slope. It is assumed that the water table decreases from 14 m on the left edge of the domain to the ground surface elevation on the right. The SEEP/W results are used in the subsequent SIGMA/W *In situ* analysis to establish the initial stress-state in the ground.

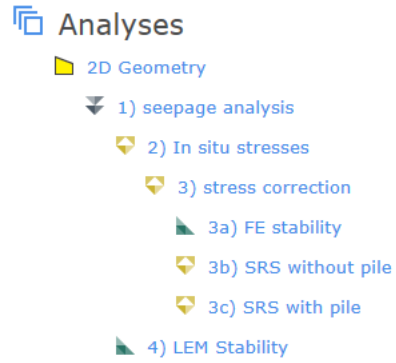

Figure 2. Analysis tree for the GeoStudio project.

The *In situ* analysis uses the Gravity Activation procedure (see SIGMA/W Reference Book). The key soil properties required for this analysis type are the total unit weight and Poisson's ratio. The specified soil stiffness (E) is arbitrary for an *In situ* analysis because the displacements are inconsequential. Poisson's ratio governs the amount of stress that develops in the horizontal direction.

An *In situ* analysis requires the assumption of linear elasticity, which can result in over-stressing; that is, stress states that sit above the Mohr-Coulomb failure surface. Stress states can be returned to the failure surface by means of a Stress Correction analysis (analysis #3).

There are three children analyses beneath the Stress Correction analysis. A Finite Element (FE) Stability analysis is first conducted using the stress field from the Parent analysis. The stability analysis is then repeated using the Strength Reduction Stability (SRS) procedure. An SRS analysis involves a gradual increase in the safety factor (i.e. reduction in strength) until failure in the soil is fully mobilized, which should correspond to a fully developed global rupture zone.

For comparison purposes, a limit equilibrium stability analysis is also included using the Morgenstern-Price method (analysis #4). The initial pore water pressure condition of this analysis is provided by its parent analysis; that is, the steady-state SEEP/W seepage (analysis #1).

Finally, the SRS procedure is used to induce stresses within the sheet pile wall that is installed to restrict deformation (analysis #3c). The sheet pile wall has an elastic modulus of 200 GPa, a cross-sectional area of 0.02 m^2, a moment of inertia equal to 0.0005 m^4, and a spacing of 1 m in the out-of-plane direction (i.e. it is continuous). The advantage of this type of analysis, compared to limit equilibrium or FE Stability methods, is that soil-structure interaction is analyzed simultaneously and the critical mode of failure evolves naturally.

Results and Discussion

Figure 3 presents contours of the vertical effective stresses for the *In situ* analysis, and Figure 4 shows the stress profiles along the left edge. The y-effective stress equals the total stress throughout the unsaturated zone, where the pore-water pressures are negative. If a volumetric water content function is defined for an *In Situ* or Load-Deformation analysis, the negative pore-

water pressure is weighted according to Effective Degree of Saturation for the calculation of effective stress (see SIGMA/W Reference Book). In this case, the volumetric water content function for the sandy clay was intentionally set to a 'gravel' to minimize the effect of negative pore-water pressure on the effective stress. The effective stress would have exceeded the total stress near the ground surface if the silty clay volumetric water content function had been used.

Color	Name	Material Model	Unit Weight (kN/m³)	Response Type	Effective Elastic Modulus (kPa)	Effective Poisson's Ratio	Effective Cohesion (kPa)	Effective Friction Angle (°)	Dilation Angle (°)	Tensile Strength (kPa)	Vol. WC. Function
	Bedrock	Isotropic Elastic	20	Drained	500,000	0.4					SiltyClay
	SandyClay	Mohr-Coulomb	20	Drained	10,000	0.4	20	30	0	0	Gravel
	WeakClay	Mohr-Coulomb	20	Drained	5,000	0.4	0	10	0	0	SiltyClay

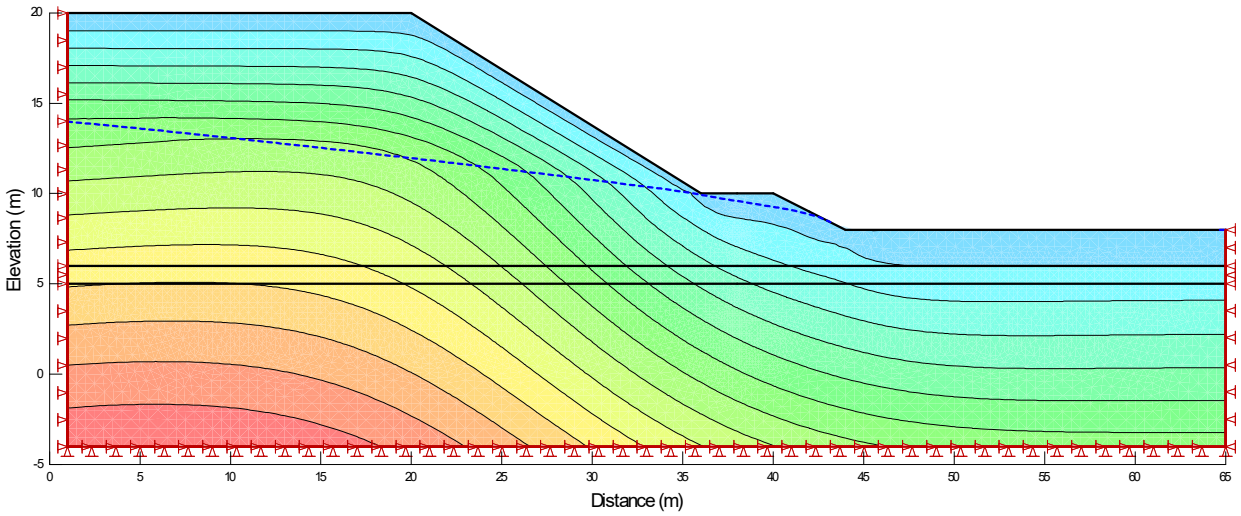

Figure 3. Computed vertical effective stress.

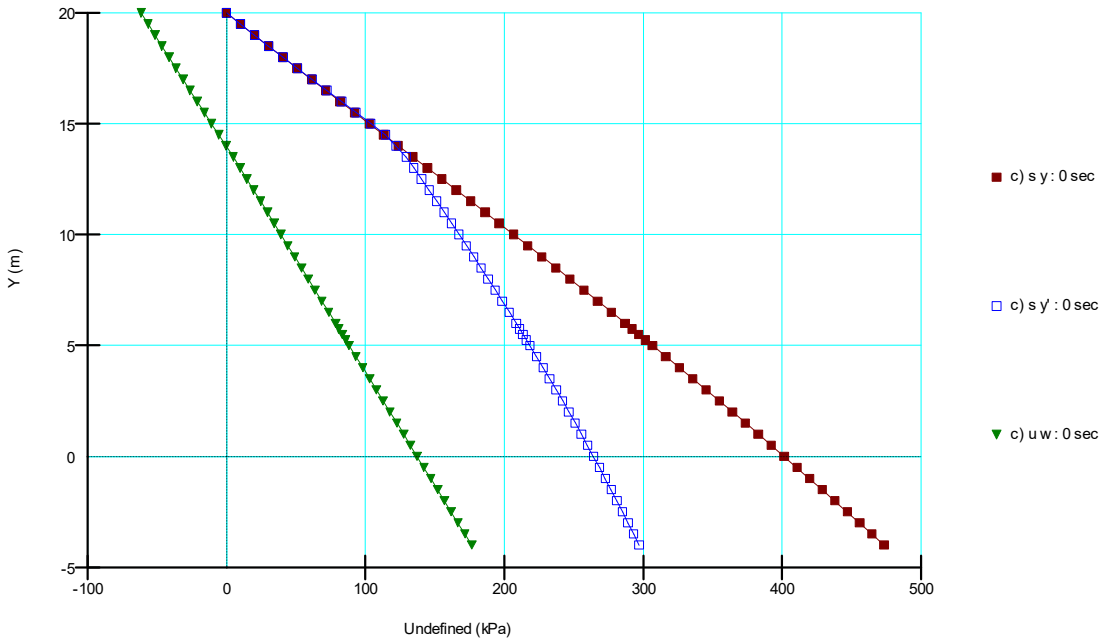

Figure 4. Stress profiles on left edge.

Figure 5 displays gauss regions that have reached a failure condition in the Stress Correction analysis. The entire weak clay layer has yielded due to the amount of shear stress that developed due to gravity activation and stress correction. The superimposed contours of deviatoric strain inidcate a regressional scenario in which mutiple rupture zones are propogating twoard the crest. The Finite Element Stability analysis indicates that the safety factor is 1.035 (see Figure 6) and that the critical rupture zone is closest to the slope face.

Color	Name	Stress Material Model	Unit Weight (kN/m³)	Response Type	Effective Elastic Modulus (kPa)	Effective Poisson's Ratio	Effective Cohesion (kPa)	Effective Friction Angle (°)	Dilation Angle (°)	Tensile Strength (kPa)	Vol. WC. Function
	Overconsolidated Soil	Isotropic Elastic	20	Drained	500,000	0.4					SiltyClay
	SandyClay	Mohr-Coulomb	20	Drained	10,000	0.4	20	30	0	0	Gravel
	Weak Clay	Mohr-Coulomb	20	Drained	5,000	0.4	0	10	0	0	SiltyClay

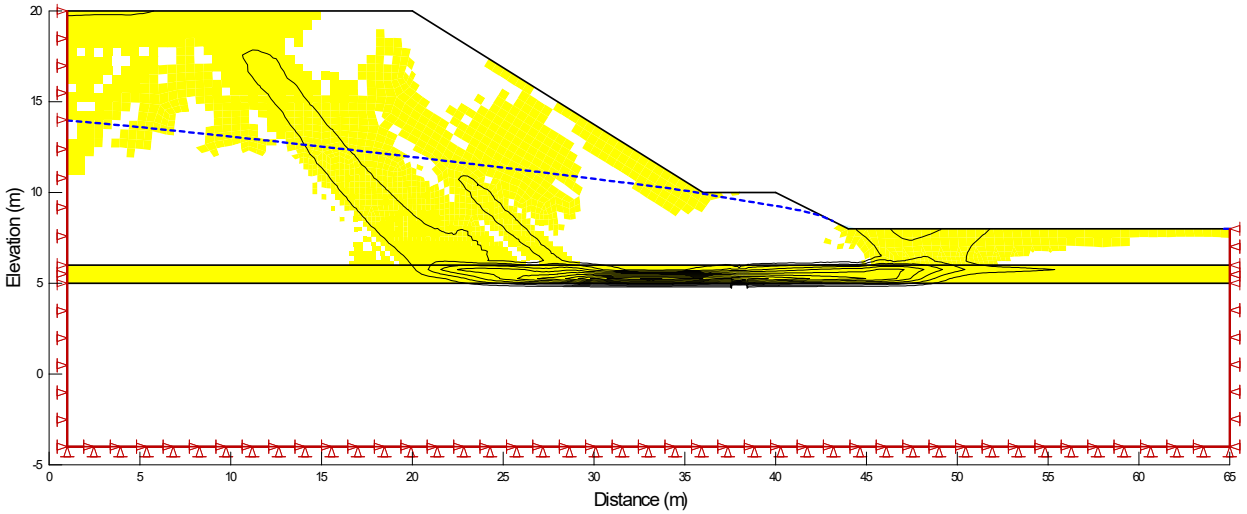

Figure 5. Plastic states for the Stress Correction analysis.

Color	Name	Slope Stability Material Model	Unit Weight (kN/m³)	Effective Cohesion (kPa)	Effective Friction Angle (°)	Phi-B (°)
	Overconsolidated Soil	Bedrock (Impenetrable)				
	SandyClay	Mohr-Coulomb	20	20	30	0
	Weak Clay	Mohr-Coulomb	20	0	10	0

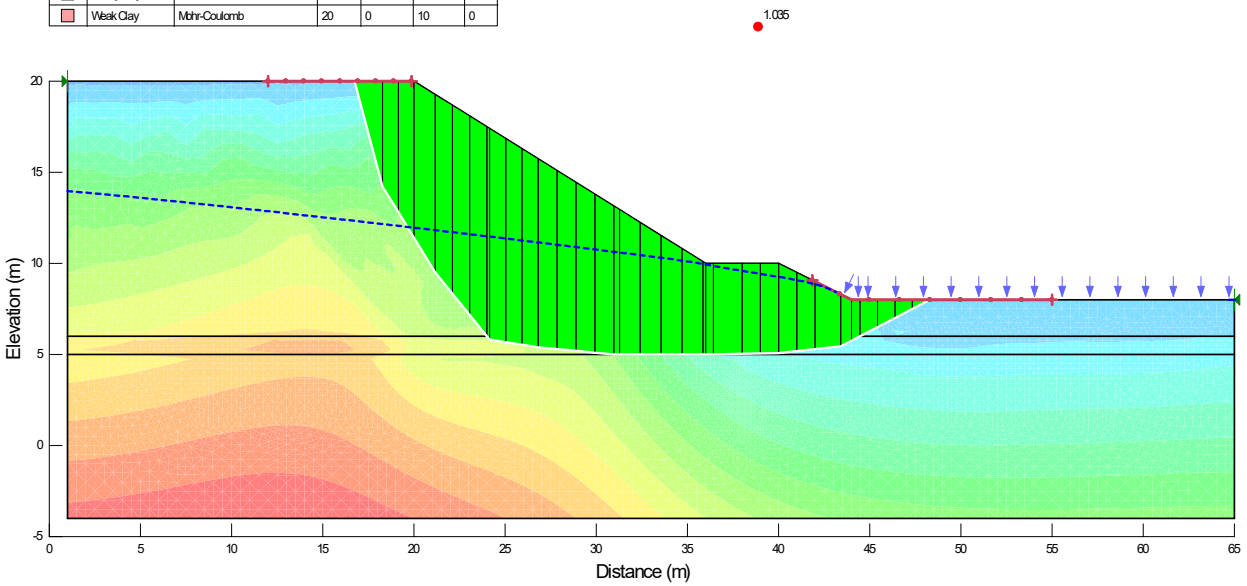

Figure 6. FE Stability results using the Stress Correction stresses.

As shown in Figure 7, the limit equilibrium analysis (analysis #4) gives a safety factor of 1.033, which is similar to the finite element stability analysis. Both the FE stress and LE stability analyses confirm the critical model of failure.

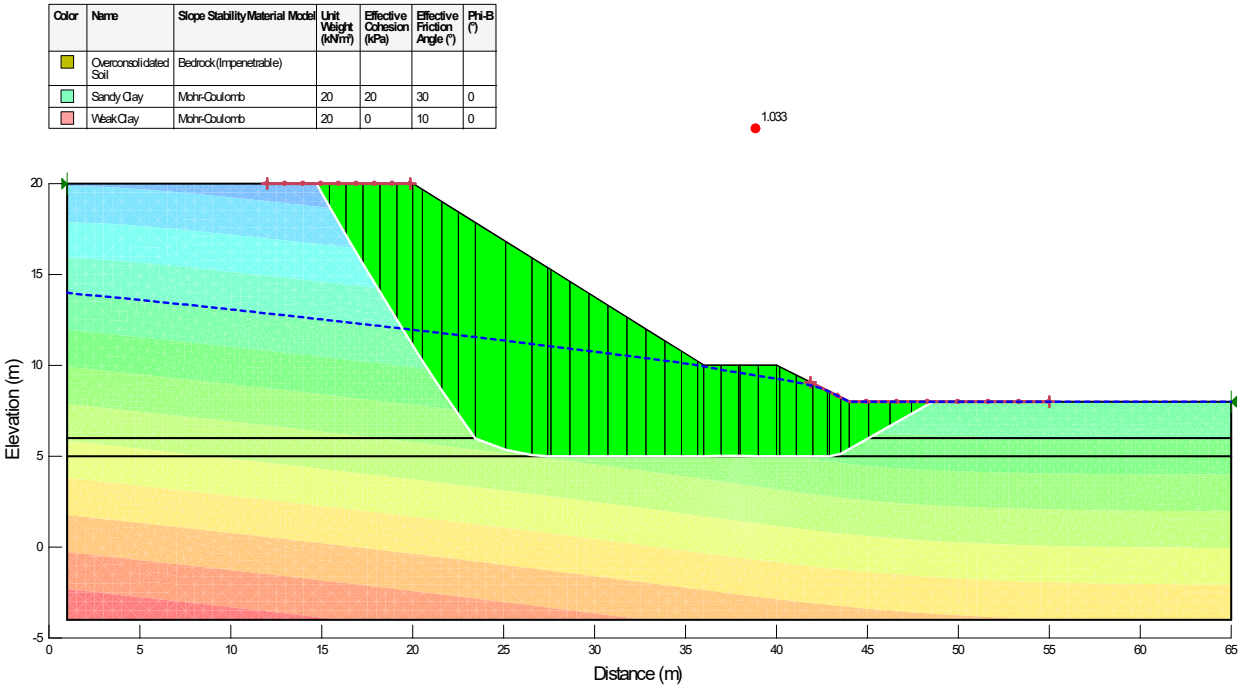

Figure 7. Limit equilibrium stability results using the Morgenstern-Price analysis type.

Figure 8 to Figure 10 present the SRS results for Analysis 3b, which excludes the sheet pile wall. Unlike the FE Stability and Limit Equilibrium methods, the factor of safety has to be interpreted from the results of the SRS analysis. The aforementioned stability analyses revealed that the slope was near a state of limiting equilibrium; consequently, two rupture zones immediately propagate (i.e. fully form) when the strength reduction factor is incremented from 1.0 to 1.025. The fully formed rupture zones are revealed by the plastic states and deviatoric strain contours (Figure 8). The deformation vectors are contained within the rupture zones and confirm the critical mode of failure and retrogressive nature of the slope failure (Figure 9). The Relative Unbalanced Energy Error and iteration count both increase abruptly when the strength reduction factor increases from 1.0 to 1.025 (Figure 10), confirming that equilibrium cannot be established. The SRS safety factor is therefore around 1.025, which is in keeping with the FE and LE stability analyses, thereby confirming the SRS interpretation and improving confidence in the subsequent analysis.

Color	Name	Stress Material Model	Unit Weight (kN/m³)	Response Type	Effective Elastic Modulus (kPa)	Effective Poisson's Ratio	Effective Cohesion (kPa)	Effective Friction Angle (°)	Dilation Angle (°)	Tensile Strength (kPa)	Vol. WC. Function
	Overconsolidated Soil	Isotropic Elastic	20	Drained	500,000	0.4					Silty Clay
	Sandy Clay	Mohr-Coulomb	20	Drained	10,000	0.4	20	30	0	0	Gravel
	Weak Clay	Mohr-Coulomb	20	Drained	5,000	0.4	0	10	0	0	Silty Clay

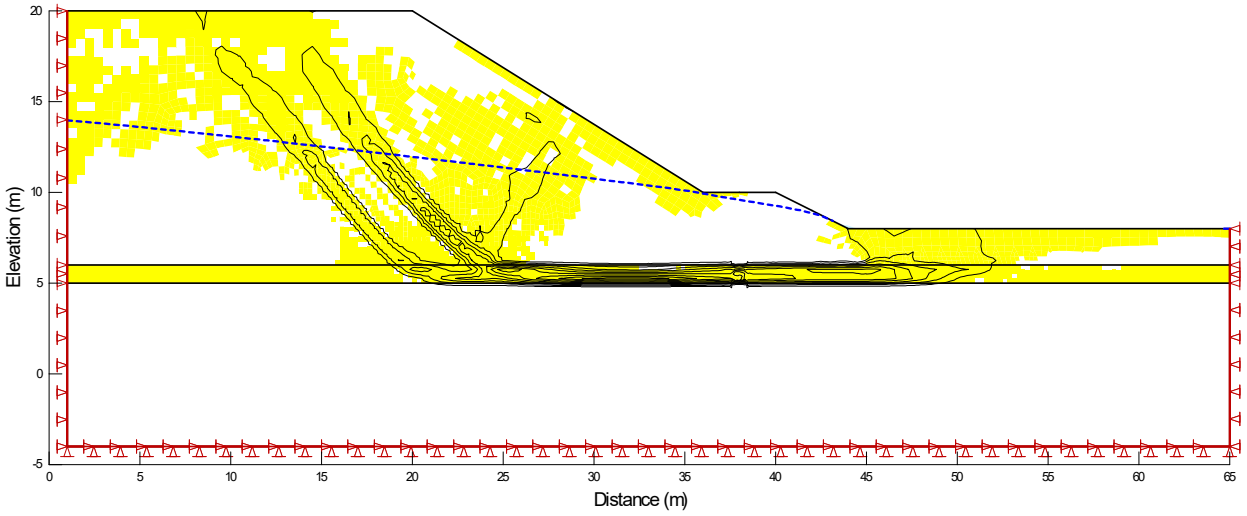

Figure 8. SRS without sheet pile wall (3b): plastic states at a safety factor of 1.025.

Color	Name	Stress Material Model	Unit Weight (kN/m³)	Response Type	Effective Elastic Modulus (kPa)	Effective Poisson's Ratio	Effective Cohesion (kPa)	Effective Friction Angle (°)	Dilation Angle (°)	Tensile Strength (kPa)	Vol. WC. Function
	Overconsolidated Soil	Isotropic Elastic	20	Drained	500,000	0.4					Silty Clay
	Sandy Clay	Mohr-Coulomb	20	Drained	10,000	0.4	20	30	0	0	Gravel
	Weak Clay	Mohr-Coulomb	20	Drained	5,000	0.4	0	10	0	0	Silty Clay

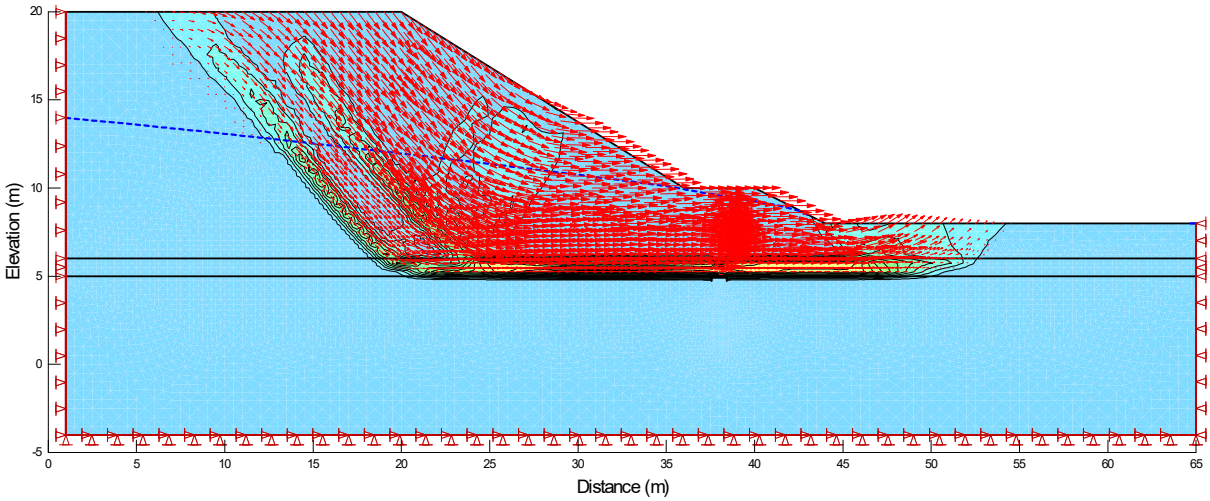

Figure 9. SRS without sheet pile wall (3b): deformation vectors at a safety factor of 1.025.

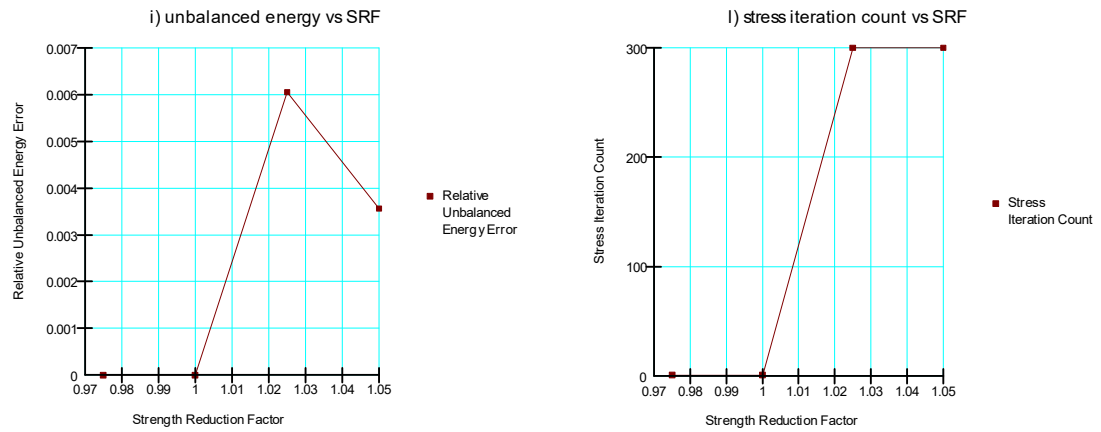

Figure 10. SRS without sheet pile wall (3b): relative unbalanced energy error (left) and iteration count (right) vs safety factor.

Figure 11 to Figure 14 present the SRS results for Analysis 3c, which includes the sheet pile wall. As the SRF is incremented upwards, the slope continues to deform and transfer load onto the wall, which is where our primary interest resides. Regardless, the global stability calculated by a SRS analysis remains of interest. In this particular case, the SRS analysis reveals a new critical mode of failure develop with the wall in place. Figure 11 and Figure 12 reveal that a fully developed rupture zone propagates along the deepest pre-existing back-scarp and now daylights in front of the wall. The Relative Unbalanced Energy Error increases at a strength reduction factor of about 1.4; that is, the factor of safety with the wall in place is about is about 1.4. The interpreted factor of safety is confirmed by the graph of crest displacement vs SRF, which reveals an inflection point at an SRF of 1.4. Figure 15 shows the effect of the wall by contrasting the lateral displacements that are simulated without the wall in place.

Color	Name	Stress Material Model	Unit Weight (kN/m³)	Response Type	Effective Elastic Modulus (kPa)	Effective Poisson's Ratio	Effective Cohesion (kPa)	Effective Friction Angle (°)	Dilation Angle (°)	Tensile Strength (kPa)	Vol. WC. Function
	Overconsolidated Soil	Isotropic Elastic	20	Drained	500,000	0.4					SiltyClay
	Sandy Clay	Mohr-Coulomb	20	Drained	10,000	0.4	20	30	0	0	Gravel
	Weak Clay	Mohr-Coulomb	20	Drained	5,000	0.4	0	10	0	0	SiltyClay

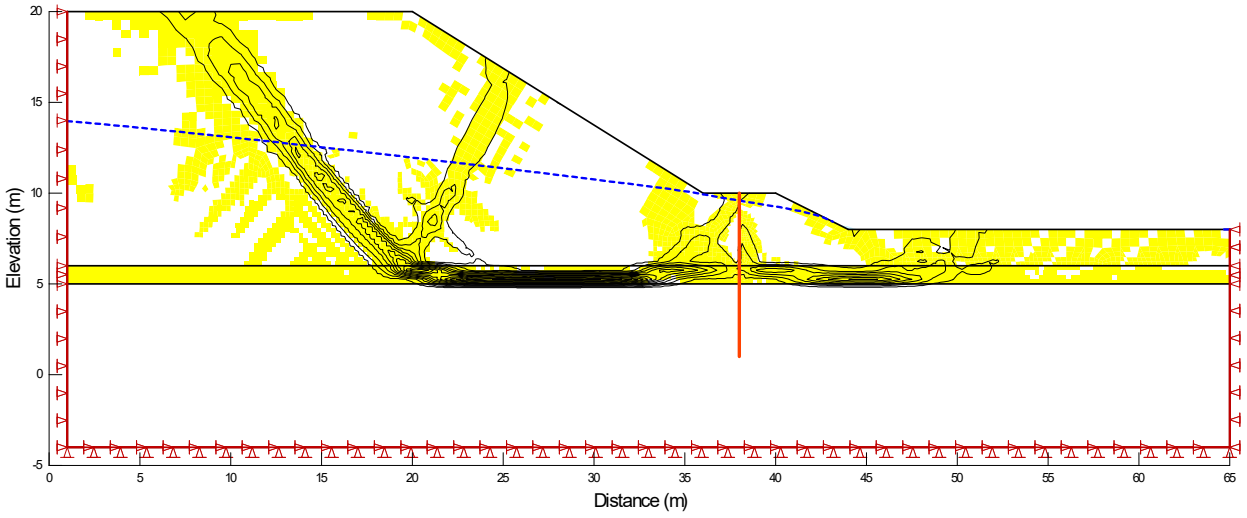

Figure 11. SRS with sheet pile wall (3c): plastic states at a safety factor of 1.4.

Color	Name	Stress/Material Model	Unit Weight (kN/m³)	Response Type	Effective Elastic Modulus (kPa)	Effective Poisson's Ratio	Effective Cohesion (kPa)	Effective Friction Angle (°)	Dilation Angle (°)	Tensile Strength (kPa)	Vol. WC. Function
	Overconsolidated Soil	Isotropic Elastic	20	Drained	500,000	0.4					Silty Clay
	Sandy Clay	Mohr-Coulomb	20	Drained	10,000	0.4	20	30	0	0	Gravel
	Weak Clay	Mohr-Coulomb	20	Drained	5,000	0.4	0	10	0	0	Silty Clay

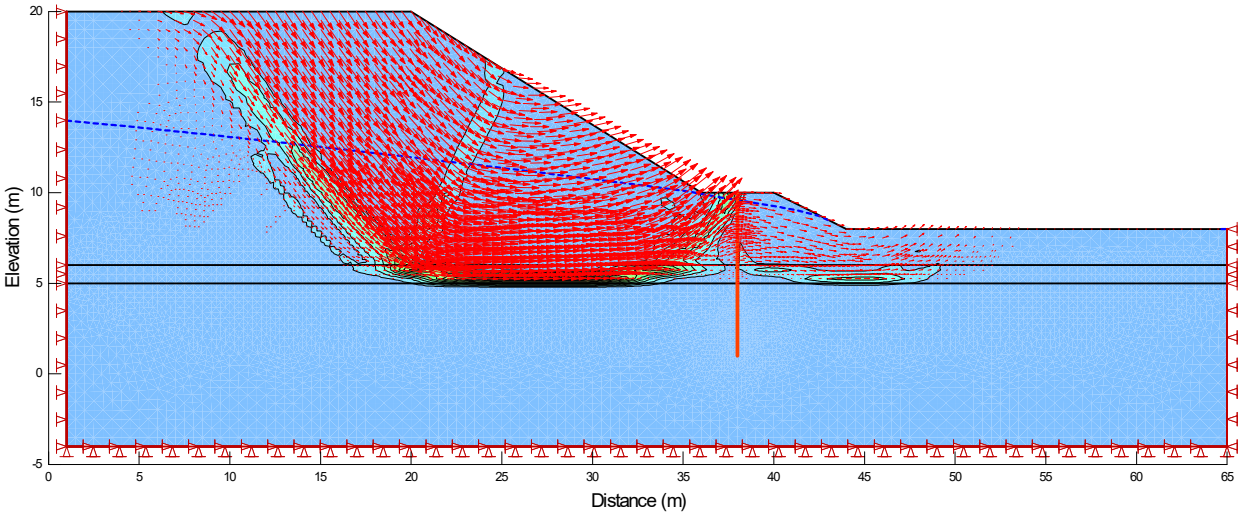

Figure 12. SRS with sheet pile wall (3c): deformation vectors at a safety factor of 1.4.

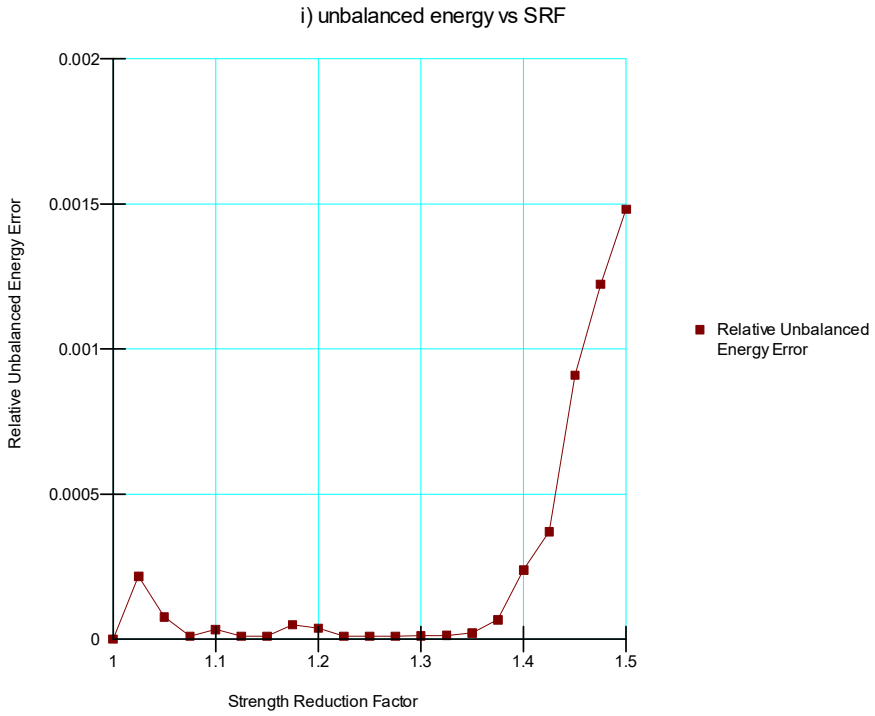

Figure 13. SRS with sheet pile wall (3c): Relative Unbalanced Energy Error vs safety factor.

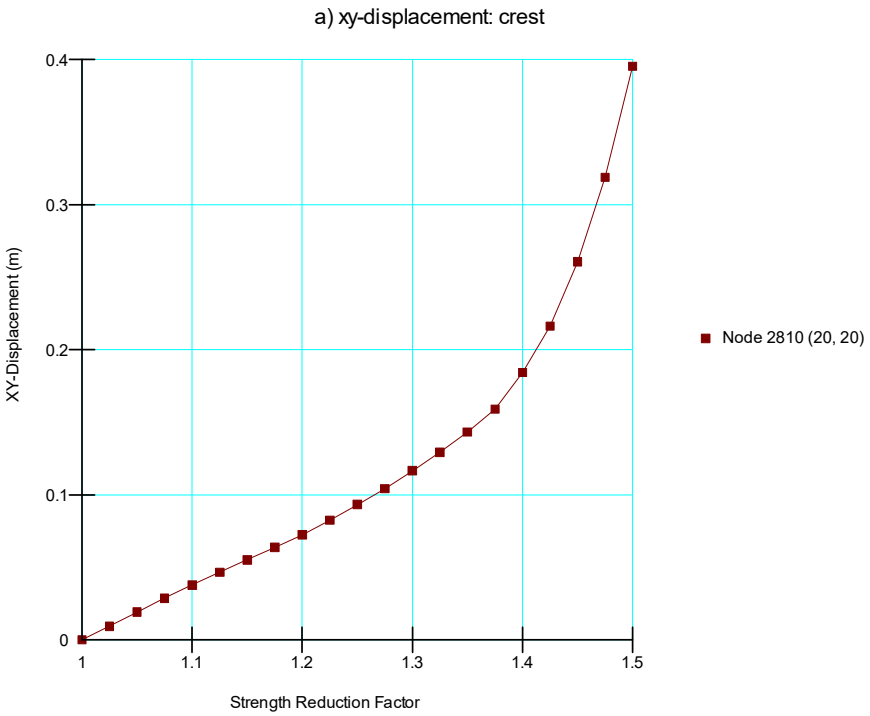

Figure 14. SRS with sheet pile wall (3c): crest displacement vs safety factor.

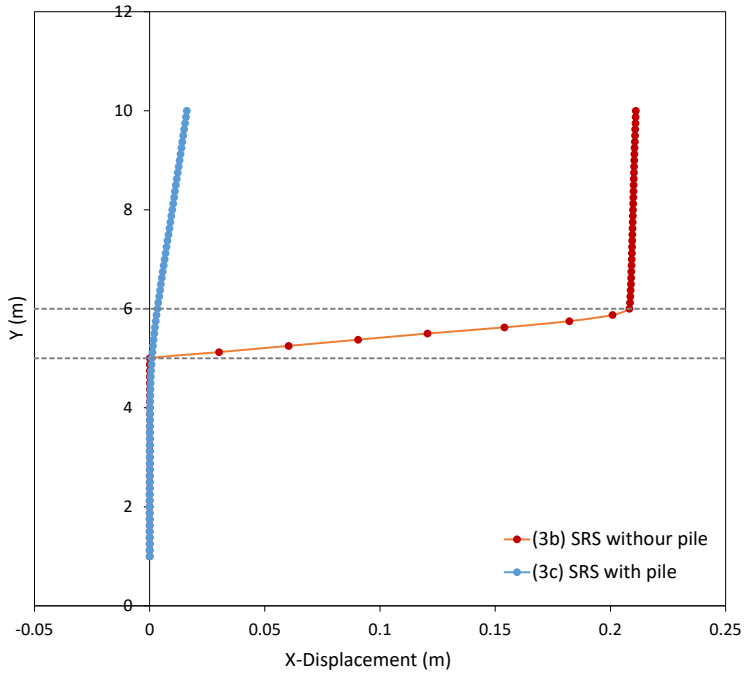

Figure 15. Comparison of simulated movements with and without the pile in place

Figure 16 shows the resulting deflection in the pile with each increment in the SRF. The curvature is the highest in the area of the weak layer, which is reflected in the moment and shear distribution shown in Figure 17 and Figure 18. Given that a global failure has developed in front of the wall at a safety factor of about 1.4, the bending moments and shear forces corresponding to this SRF represent the maximum values that could be transferred into the

structure. The maximum bending moments and shear forces could be compared to the structures capacities. Assuming that the factor of safety against bending and shear failure within the structure are acceptable, then it would be reasonable to conclude that the pile wall will effectively stabilize the slope.

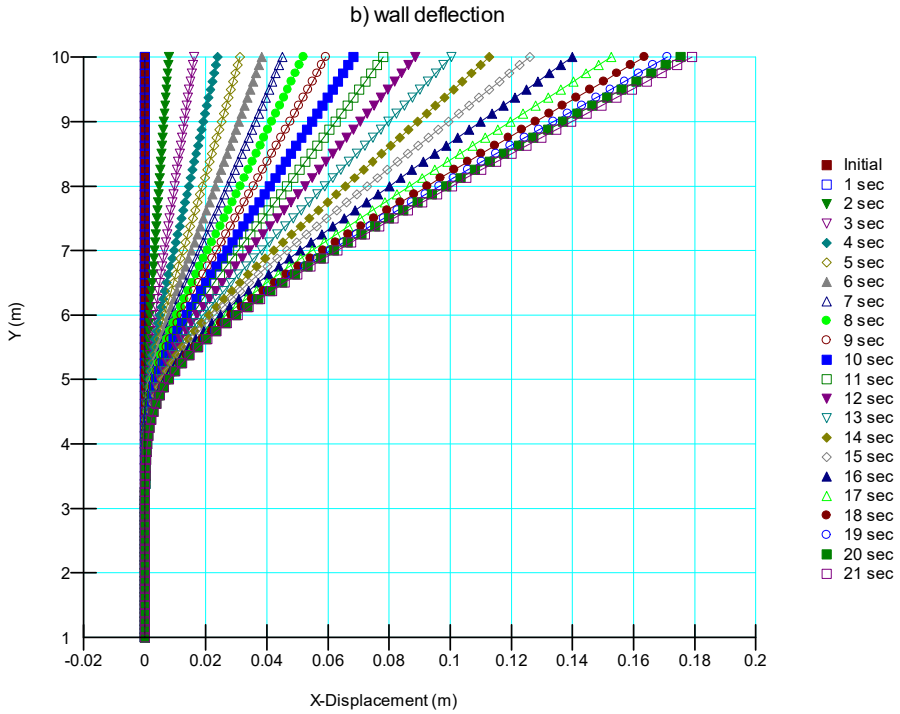

Figure 16. Lateral deflection in the pile.

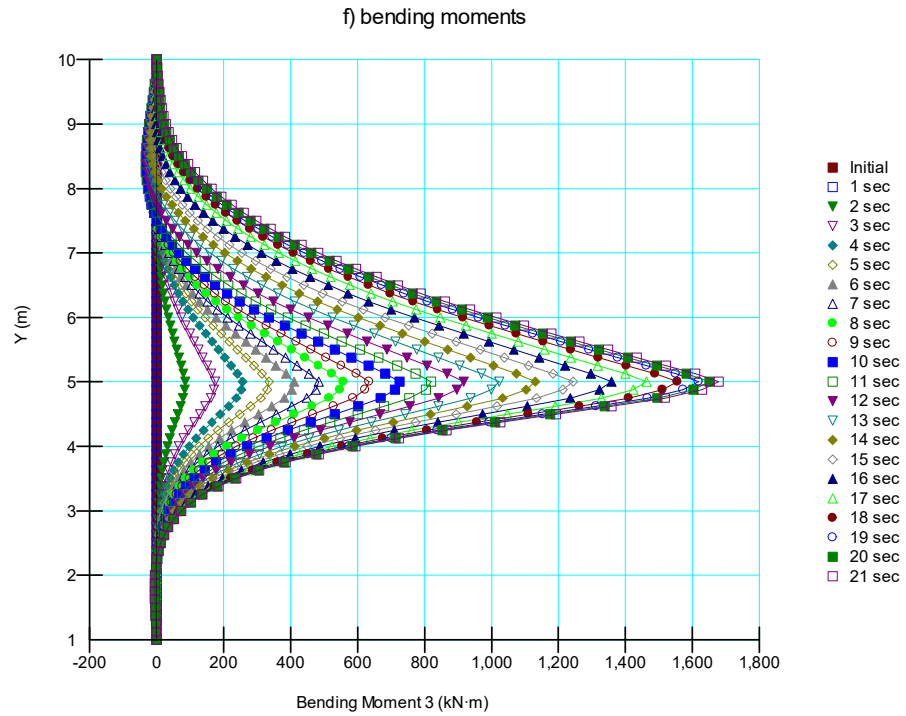

Figure 17. Pile moment distribution.

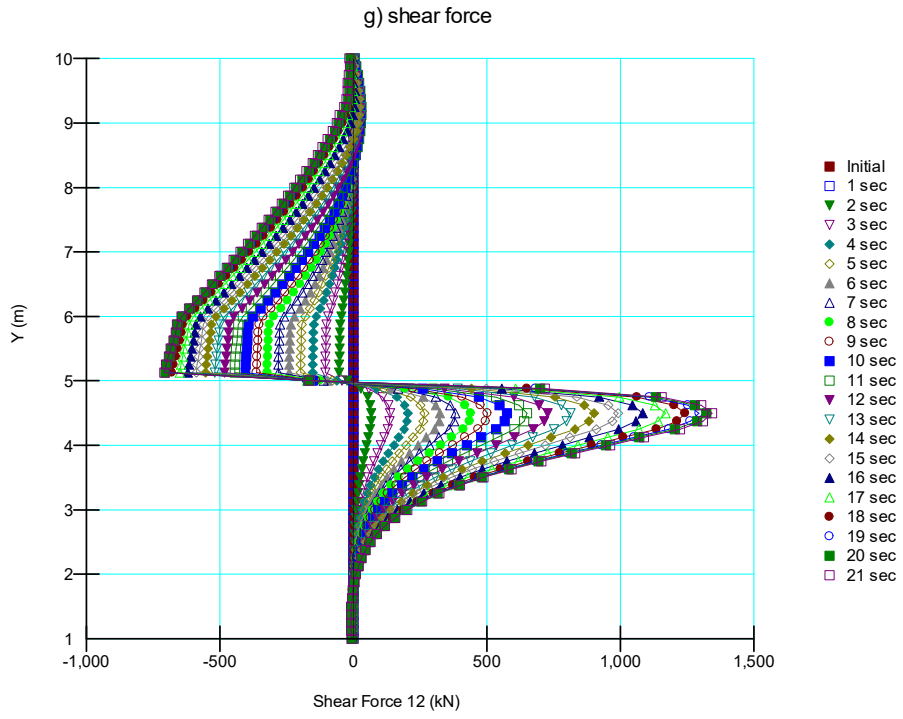

Figure 18. Pile shear distribution.

Summary and Conclusions

A pile stabilization analysis was conducted using GeoStudio. A FE stress stability analysis calculated a safety factor of approximately 1.035 before the pile was installed. A strength reduction stability (SRS) analysis, which incrementally reduces the strength of the soil until a global rupture zone forms, computed a similar safety factor. The analysis was then repeated with the pile installed, yielding a safety factor of approximately 1.4.

A comparison of the FE Stability and SRS techniques reveal the key advantages of a SRS analysis: 1) the mode of failure evolves naturally as the strength is reduced; and, 2) soil-structure interaction is simultaneously analyzed, revealing the bending moments and shear forces that develop in the structure. In traditional Limit Equilibrium stability analyses, a force is applied to the free body that represents the shear resistance in the pile needed to achieve a design factor of safety. The actual forces and moments that develop in the pile, and the anticipated displacements, are not modelled. In a FE stability analysis, the safety factor can be computed without the pile in-place, but it is not possible to include the effect of the pile.

In summary, a strength reduction stability analysis can be used to calculate the safety factor for soil-structure interaction problems, while providing information on the shear forces and bending moments that develop in the structure. If the bending capacity and shear force capacity of the structure is not exceeded, the slope is stable and deformations will cease.