Earth Pressure Coefficients using the Generalized Limit Equilibrium Method

The distribution and magnitude of lateral earth pressure acting on Earth Retaining Systems (ERS) are required by the Bridge Designer (BD) to perform design analyses.

When conventional earth pressure theory is applicable, providing soil properties for each soil layer (friction angles, unit weight, and interface friction angle) is sufficient because the soil properties can be directly entered by the bridge designer into design software, and the corresponding earth pressures are automatically generated.

However, Earth Retaining System (ERS) complex geometry and/or when the soil layers include some cohesion, Generalized Limit Equilibrium method (GLE) analyses are typically required for calculating static/seismic earth pressure coefficients. Complex geometry is defined as conditions where the Conventional Earth Pressure Theory (CEPT) including the log-spiral method is not applicable. Another application is when the ERS is to be used for remedying slope failures.

This module presents a method for determining earth pressure coefficients (*K*) using the GLE and is intended to supplement the following modules:

- Conventional Retaining Walls
- Mechanically Stabilized Embankments
- Non-Gravity Cantilever Retaining Walls
- Ground Anchor Earth Retaining Walls
- Seismic Design of Earth Retaining Systems

Included are a step-by-step calculation procedure and an appendix presenting examples of the GLE analyses. The examples were analyzed by using the slope stability analysis software, which applied the GLE method.

Definitions

- Long-Term Strength: Strength represented by only effective friction angles (ϕ').
- Short-Term Strength: Strength represented by undrained shear strength (S_u).
- K_a: Static active earth pressure coefficient back-calculated from GLE analyses with a Factor of Safety (*FoS*) of 1.0. In the GLE model, a potential failure mass movement is set in the opposite direction to applying forces on a vertical cut/wall.
- K_p: Static passive earth pressure coefficient back-calculated from GLE analyses with a Factor of Safety (*FoS*) of 1.0. In the GLE model, a potential failure mass movement is set in the same direction as applying forces on a vertical cut/wall.
- K_{ae}: Seismic active earth pressure coefficient from GLE analysis.
- K_{pe}: Seismic passive earth pressure coefficient from GLE analysis.

- K_{FoS}: Earth pressure coefficient back-calculated from GLE analysis based on *FoS* other than 1.0
- K_{min}(Refer to AASHTO-CA-BDS-8 (3.11.5.6)): Minimum lateral earth pressure applied to the soil represented by S_u or any combination of friction and cohesion: 0.25 or 0.035/γ_{ave}, whichever is greater: $\gamma_{ave} = \frac{\sum_{i=1}^{n} \gamma_i h_i}{H}$ (Refer to Figure 1)

Effect of Cohesion on Lateral Earth Pressure

In GLE, cohesion can reduce earth pressures acting on ERS to an extent that a vertical cut may stand without any support for a limited period, and hence the improper use of it can lead to long-term instability of ERS. As time passes the soil undergoes cycles of wetting and drying, which causes the cohesion to decrease resulting in higher earth pressures and larger strain. In general, cohesion decreases with increasing moisture content and soil displacement. Therefore, precautions should be taken when recommending or using cohesion in earth pressure calculations.

Based on recommendations provided in AASHTO-CA-BDS-8 (3.11.5.6) and a 75-year design life, the following recommendations are provided for earth pressure calculations.

<u>Recommendations</u>

Cohesionless/Granular Soil (ϕ = ϕ’)

- Static – Calculate K_a using ϕ’

- Seismic – K_{ae} can be calculated using S_u or *c’* and *ϕ’* but precautions should be taken when applying cohesions (refer to AASHTO 11.6.5.3) and K_{ae} should not be less than K_{min}.

c’-*ϕ’* Soil

- Static

  - If K_a calculated using ϕ’ only (zero cohesion) is greater than K_{min}, calculate K_a using *c’*-*ϕ’*. However, it should not be greater than K_{min}.

  - If K_a calculated using ϕ’ only (zero cohesion) is less than K_{min} calculate K_a using ϕ’only.

- Seismic – K_{ae} can be calculated using S_u or *c’* and *ϕ’*, but precautions should be taken when applying cohesions (refer to AASHTO 11.6.5.3) and K_{ae} should not be less than K_{min}.

Cohesive Soil (S_u for short-term strength and ϕ' for long-term strength)

- Static

  - Use short-term or long-term strength, whichever yields greater resulting earth pressures/coefficients.

  - K_a should be greater than K_{min}

- Seismic – K_{ae} can be calculated using S_u, but precautions should be taken when applying cohesions (refer to AASHTO 11.6.5.3), and K_{ae} should not be less than K_{min}.

Highly Weathered or Decomposed Rock

- Static/Seismic – K_{min} does not apply when cohesion is used in K_a or K_{ae} calculations.

GLE for Determining Earth Pressure Coefficients

Table 1 summarizes the application of GLE and CEPT for determining K_a/K_p.

Table 1: Recommended Method for Determining K_a and K_p

Cases	CEPT	GLE
Cohesive Soil or Strength with Cohesion	Only Rankine can be used	Preferred method
Cohesionless Soil	Preferred method if applicable	Preferred method if CEPT is not applicable
Complex Geometry and Strength with Cohesion	No	Yes

GLE can apply to all cases, but CEPT is preferred to GLE whenever it is applicable because of its ease of application.

GLE can be applied to all types of ERS that require the calculation of earth pressures and coefficients. For the design of ground anchor ERS using the GLE method, refer to the *Ground Anchor ERS* module.

If GLE is selected for calculating earth pressure coefficients, use the Spencer or Morgenstern-Price options to calculate a *FoS* that satisfies both force and moment equilibrium of potential failure mass.

In some cases where the back-calculation of K_{FoS} is required such as slope stabilization or at-rest earth pressure coefficient calculations, one can also use GLE by setting an *FoS* to any target value greater than 1.0. However, for the at-rest earth pressure coefficient, precautions should be taken when setting a target *FoS*.

Proposed Method for Calculating Earth Pressure Coefficients using GLE

This section presents a step-by-step procedure for determining earth pressure coefficients using GLE. As discussed in the previous sections, the following proposed method can apply to the back-calculation of various earth pressure coefficients such as K_a, K_p, K_{ae}, K_{pe}, and K_{FoS}. A wall friction angle (δ) does not change the calculation procedure presented below so the back-calculation procedure of K_a with zero δ is only presented in this module. Note that all earth pressure coefficients except K_{pe} increase with a wall friction angle, and an appropriate wall friction angle should be selected according to AASHTO 3.11.5, 11.6.5.5., and 11.8.6.3. As opposed to other earth pressure coefficients, K_{pe} may decrease with a wall friction angle due to potential failure mass that is larger under seismic conditions.

The following step-by-step procedure for back-calculating K_a using GLE is based on the vertical cut/wall model with three soil layers (Figure 1). The proposed procedure can apply to any number of soil layers.

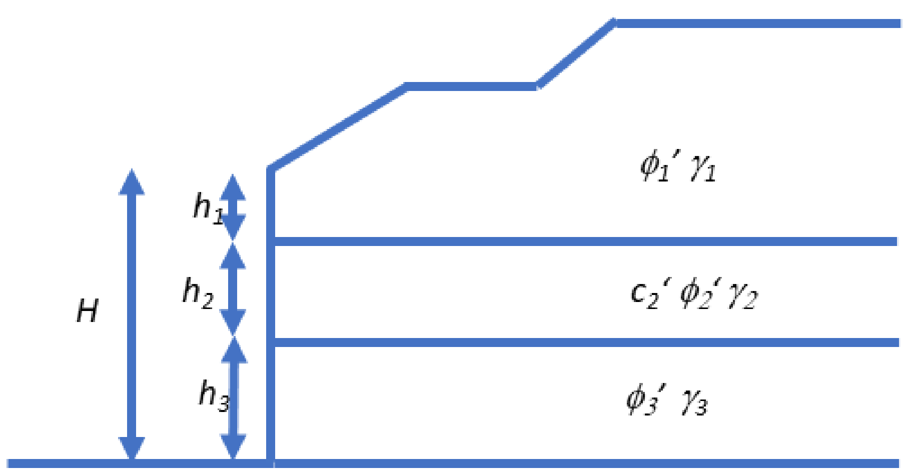

Figure 1: GLE Model for Step-by-Step Procedure

Step 1: Create a vertical cut/wall (H) in the GLE model that consists of three soil layers (refer to Figure 1)

Step 2: Calculate the locations (x_i) of applying Forces (F_i) using the following Equations (refer to Figure 2)

$$x_1 = \frac{h_1}{3} \quad \text{Eq. 1}$$

$$x_2 = \frac{h_2\left(\gamma_1 h_1 + \frac{\gamma_2 h_2}{3}\right)}{(2\gamma_1 h_1 + \gamma_2 h_2)} \quad \text{Eq. 2}$$

$$x_3 = \frac{h_3\left\{(\gamma_1 h_1 + \gamma_2 h_2) + \frac{\gamma_3 h_3}{3}\right\}}{2(\gamma_1 h_1 + \gamma_2 h_2) + \gamma_3 h_3} \quad \text{Eq. 3}$$

The generalizable equation for x of n^th^ layer is

$$x_n = \frac{h_n\left(\sum_{i=1}^{i=n-1} \gamma_i h_i + \frac{\gamma_n h_n}{3}\right)}{2\sum_{i=1}^{i=n-1} \gamma_i h_i + \gamma_n h_n} \quad \text{Eq. 4}$$

The above equations can be derived by taking moment equilibrium at the bottom of each layer with the lateral earth pressure distribution presented in Figure 3.

Step 3: Apply a force, F_1 at x_1 calculated in Step 2, and adjust the magnitude of F_1 until achieving a *FoS* value of 1.0 by trial and error. (Refer to Figure 2a). Note the critical failure surface should exit at the bottom of the first layer.

Step 4: Apply a force, F_2 at x_2 calculated in Step 2, and adjust the magnitude of F_2 until achieving a *FoS* value of 1.0 by trial and error. (Refer to Figure 2b). Note that F_1 and x_1 calculated from Step 3 must be kept during adjusting the F_2 and the critical failure surface should exit at the bottom of the second layer.

As the 2^nd^ layer is c'-ϕ' soil, the following sub-steps are required to ensure K_{a2} calculated from Step 4 is not less than K_{min}.

Step 4a: Calculate K_{a2} using Eq. 7 and compare with K_{min}. If $K_{a2} \geq K_{min}$, move on to Step 5. Otherwise go to the next sub-step, Step 4b.

Step 4b: Calculate F_{min} using Eq. 5

$$F_{i\_min} = \frac{k_{i\_min}\left(2\sum_{i=1}^{i=n-1} \gamma_i h_i + \gamma_n h_n\right) h_n}{2} \quad \text{Eq. 5}$$

Step 4c: Replace F_2 in the GLE model with F_{min} calculated from Step 4b, apply an equivalent friction angle (ϕ_{equ}) and zero cohesion value to the 2^nd^ c'-ϕ' soil layer, and adjust ϕ_{equ} until achieving a *FoS* of 1.0 in the GLE analysis.

Step 4d: Replace c' and ϕ' with ϕ_{equ} and keep F_{min} in place of F_2 in the GLE model.

Step 5: Apply a force, F_3 at x_3 calculated in Step 2, and adjust the magnitude of F_3 until achieving an *FoS* value of 1.0 by trial and error (Refer to Figure 2c). Note that F_1, x_1, F_2, and x_2 calculated from Steps 3 and 4 must be kept during adjusting the F_3 and the critical failure surface should exit at the bottom of the third layer.

Step 6: Calculate lateral earth pressure coefficient, K_{ai} for each layer using the following equations.

$$K_{a1} = \frac{2F_1}{\gamma_1 h_1^2} \quad \text{Eq. 6}$$

$$K_{a2} = \frac{2F_2}{(2\gamma_1 h_1 + \gamma_2 h_2)h_2} \quad \text{Eq. 7}$$

$$K_{a3} = \frac{2F_3}{(2\gamma_1 h_1 + 2\gamma_2 h_2 + \gamma_3 h_3)h_3} \quad \text{Eq. 8}$$

The generalized equation for K of n^{th} layer is

$$K_{an} = \frac{2F_n}{\left(2\sum_{i=1}^{i=n-1}\gamma_i h_i + \gamma_n h_n\right)h_n} \quad \text{Eq. 9}$$

The above equations can be derived by taking the lateral force equilibrium for each layer with the lateral earth pressures presented in Figure 3.

Step 7: Develop an earth pressure diagram using the calculated K_{ai} from above Steps (refer to Figure 3).

For cohesive soil, the following additional steps are required to ensure K_{ai} is not less than either K_{min} or long-term K_a.

Step a: Calculate K_{ai} using Eq. 9 and compare with K_{min}. If $K_{ai} \geq K_{min}$, go back to the next main Step. Otherwise go to the next sub-step, Step Xb.

Step b: Calculate F_{i_min} using Eq. 5

Step c: Replace F_i in the GLE model with F_{min} calculated from Step Xb, apply an equivalent friction angle (ϕ_{equ}) and zero cohesion value to the i^{th} cohesive soil layer (S_u), and adjust ϕ_{equ} until achieving a *FoS* of 1.0 in the GLE analysis.

Step d: Compare ϕ_{equ} with the drained friction angle, ϕ' of cohesive soil. If $\phi' \geq \phi_{equ}$, go back to the next main Step. Otherwise go to the next sub-step, Step Xe.

Step e: Replace S_u with the friction angle calculated from Step Xd and run the GLE analysis to adjust F_i until achieving a *FoS* value of 1.0.

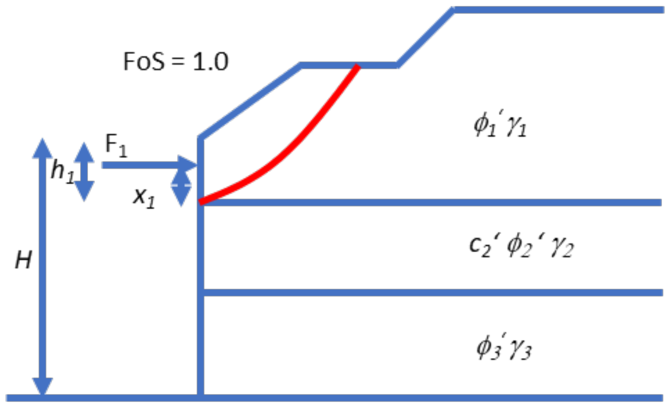

Figure 2a: 1st Layer GLE Analysis

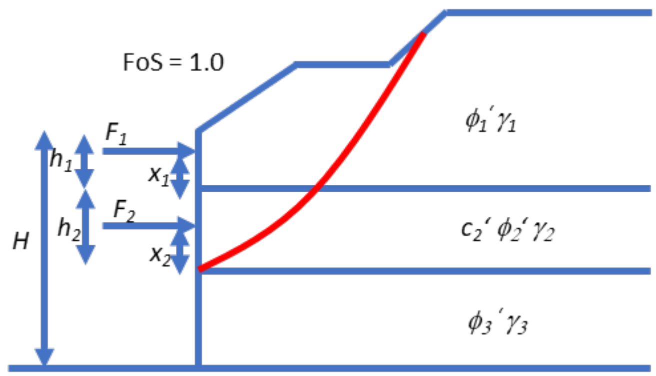

Figure 2b: 2nd Layer GLE Analysis

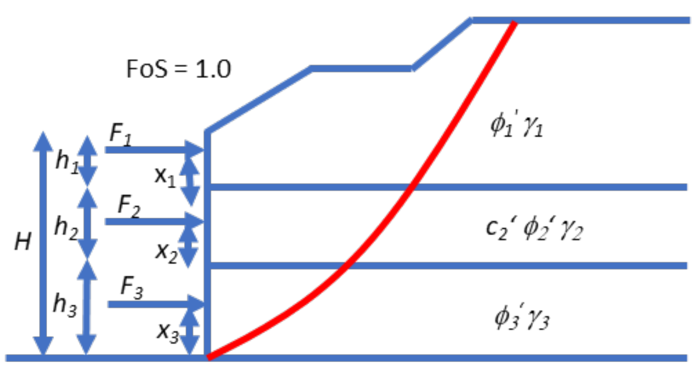

Figure 2c: 3rd Layer GLE Analysis

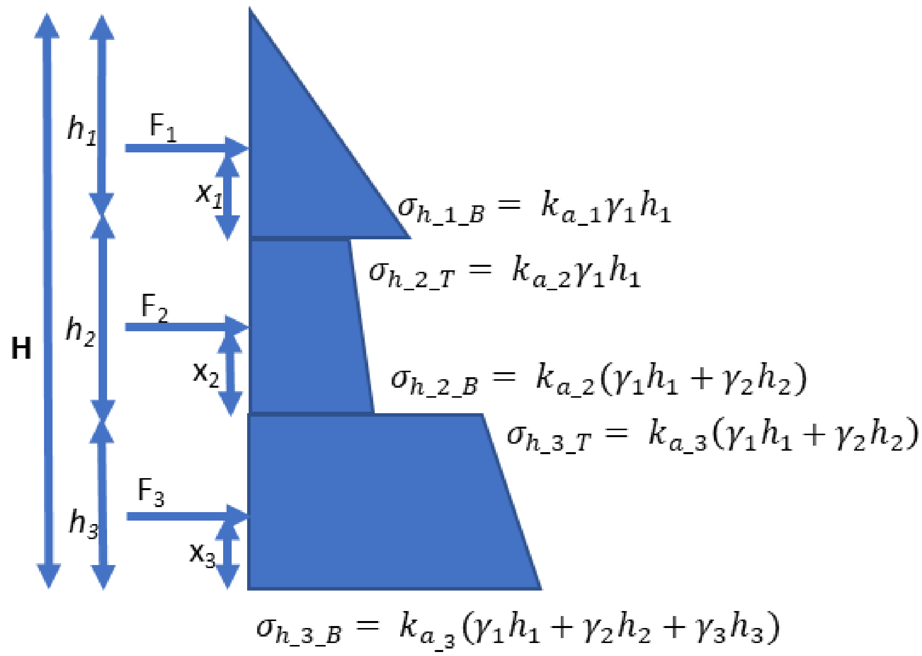

Figure 3: Resulting Earth Pressure Distribution for Three Soil Layers

Note that K_{min} only applies to the calculation of K_a and K_{ae} for c'-ϕ', and cohesive soil.

APPENDIX

I. Verification

II. Examples

- Profile 1: Mixed soils with a *c'*-ϕ' soil layer (with a cohesion of 200 psf) interbedded between sand layers
- Profile 2: Soil with a *c'*-ϕ' soil layer (with a cohesion of 300 psf) interbedded between sand layers
    - Static with zero wall friction
    - Static with non-zero wall friction
    - Seismic with zero wall friction
- Profile 3: Mixed Soil with a clay layer (S_u = 700 psf) interbedded between sand layers
- Profile 4: Sand Soil

APPENDIX I - Verification of Proposed Methods

This appendix presents the verification of the proposed lateral earth pressure calculation method using GLE method. For verification, a vertical cut of 30 feet with homogeneous soil was modeled in GLE analyses to compare with a Rankine active earth pressure coefficient that can be easily calculated using the Rankine earth pressure theory. The analyses used (1) Spencer and (2) Morgenstern-Price methods and a homogeneous soil was divided into three layers for the verification purpose. The soil strength parameters and geometry in GLE models are shown in Table AI-1 and Figure AI-1.

Table AI-1: Soil Parameters

Layer No.	Soil	Layer Thickness (feet)	Unit Weight (pcf)	Soil Strength Parameters	
				Friction Angle, ϕ (deg.)	Cohesion (psf)
1	Sand	10	120	30	0
2	Sand	10	120	30	0
3	Sand	10	120	30	0

<u>Static Condition</u>

The models and results of GLE analyses for the proposed method are presented in Figure AI-11 through Figure AI-33. The soil parameters presented in Table AI-1 were used for the GLE models. The locations (x_i) of applying Forces (F_i) are calculated as follows:

$$x_1 = \frac{h_1}{3} = \frac{10}{3} = 3.33 \text{ ft.}$$

$$x_2 = \frac{h_2\left(\gamma_1 h_1 + \frac{\gamma_2 h_2}{3}\right)}{(2\gamma_1 h_1 + \gamma_2 h_2)} = \frac{10\left(120\cdot 10 + \frac{120\cdot 10}{3}\right)}{(2\cdot 120\cdot 10 + 120\cdot 10)} = 4.44 \text{ ft.}$$

$$x_3 = \frac{h_3\left\{(\gamma_1 h_1 + \gamma_2 h_2) + \frac{\gamma_3 h_3}{3}\right\}}{2(\gamma_1 h_1 + \gamma_2 h_2) + \gamma_3 h_3} = \frac{10\left\{(120\cdot 10 + 120\cdot 10) + \frac{120\cdot 10}{3}\right\}}{2(120\cdot 10 + 120\cdot 10) + 120\cdot 10} = 4.67 \text{ ft.}$$

The required forces (F_i) to achieve *FoS* value of 1.0 in GLE analyses are as follows:

F_1 = 2,000 lbs/ft., F_2 = 6,000 lbs/ft., F_3 = 10,000 lbs/ft.

The lateral earth pressure coefficient, K_{ai} for each layer is estimated as shown below:

$$K_{a1} = \frac{2F_1}{\gamma_1 h_1^2} = \frac{2\cdot 2{,}000}{120\cdot 10^2} = 0.333$$

$$K_{a2} = \frac{2F_2}{(2\gamma_1 h_1 + \gamma_2 h_2)h_2} = \frac{2 \cdot 6{,}000}{(2 \cdot 120 \cdot 10 + 120 \cdot 10) \cdot 10} = 0.333$$

$$K_{a3} = \frac{2F_3}{(2\gamma_1 h_1 + 2\gamma_2 h_2 + \gamma_3 h_3)h_3} = \frac{2 \cdot 10{,}000}{(2 \cdot 120 \cdot 10 + 2 \cdot 120 \cdot 10 + 120 \cdot 10) \cdot 10} = 0.333$$

The calculated K_{ai} for each layer is the same as the value calculated using Rankine's theory with f = 30 degrees.

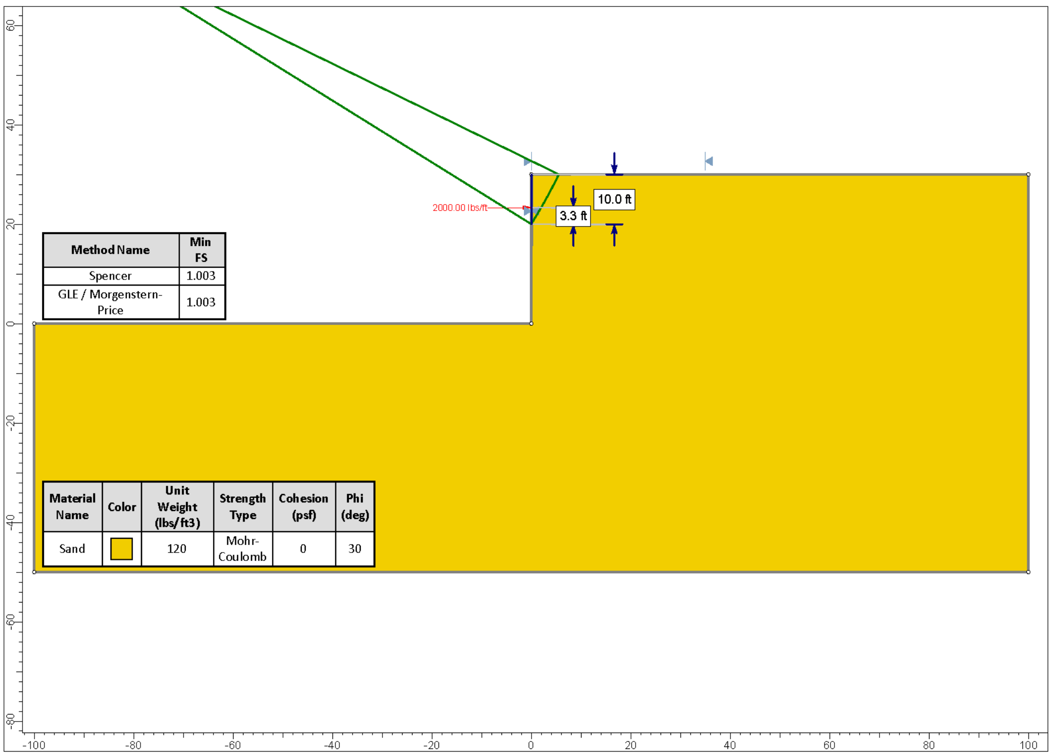

Figure AI-1: GLE Result for 1st layer

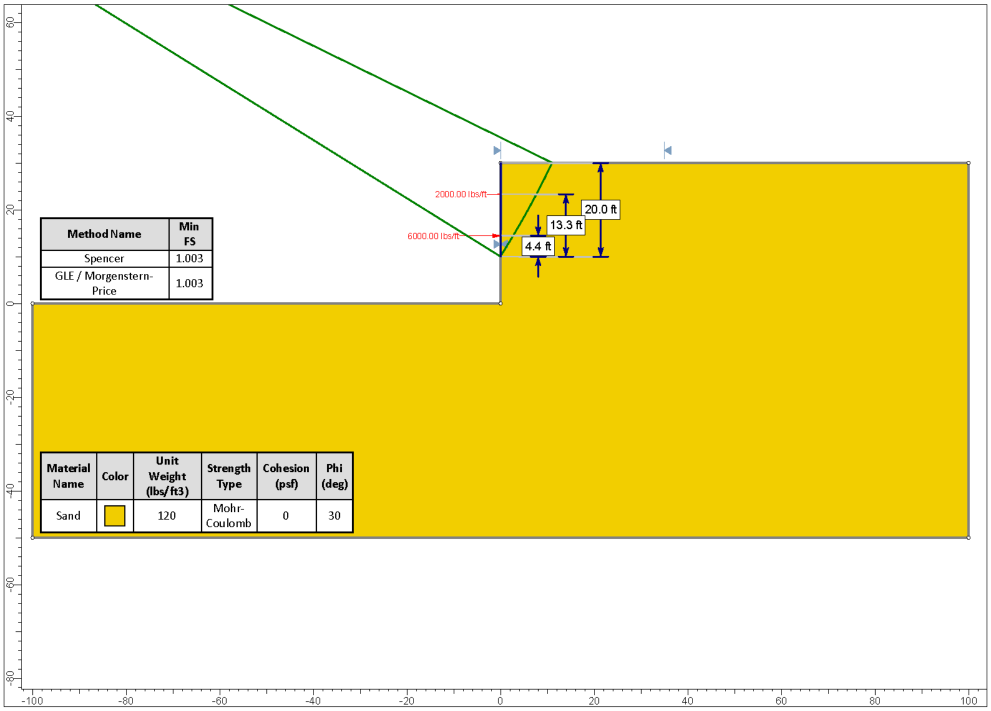

Figure AI-2: GLE Result for 2nd layer

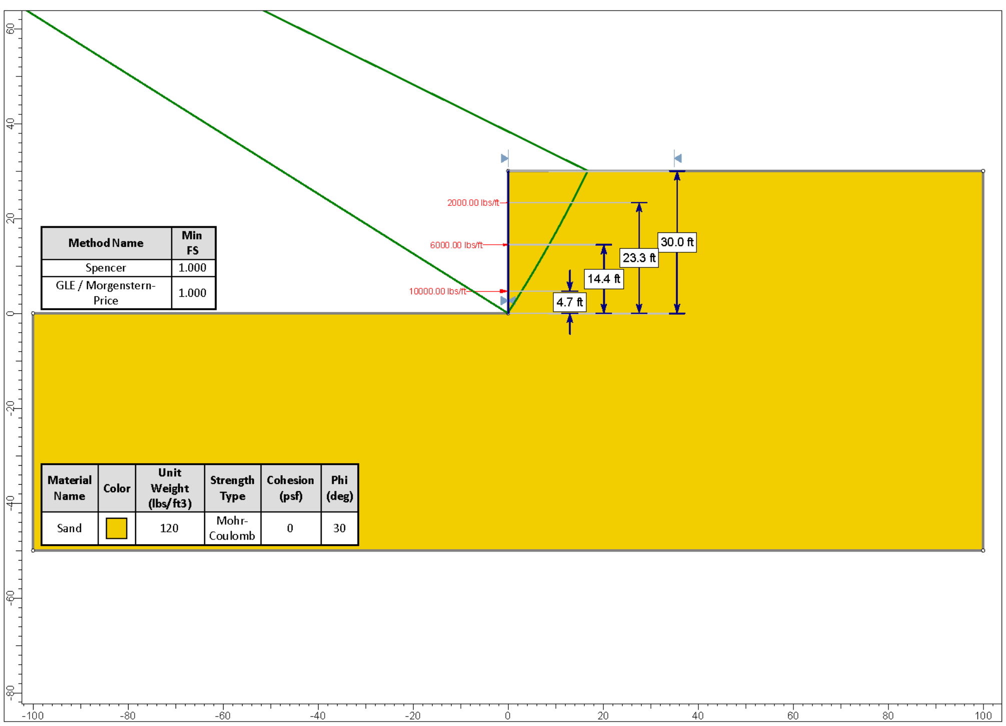

Figure AI-3: GLE Result for 3rd layer

Seismic Condition

The models and results of GLE analyses for the proposed method are presented in Figure AI-4 through Figure AI-6. The soil parameters presented in Table AI-1 were used for the GLE models. The horizontal acceleration coefficient (*k_h*) is assumed as 0.2 in this verification. The locations (*x_i*) of applying Forces (*F_i*) are calculated as follows:

$$x_1 = \frac{h_1}{3} = \frac{10}{3} = 3.33 \text{ ft.}$$

$$x_2 = \frac{h_2\left(\gamma_1 h_1 + \frac{\gamma_2 h_2}{3}\right)}{(2\gamma_1 h_1 + \gamma_2 h_2)} = \frac{10\left(120 \cdot 10 + \frac{120 \cdot 10}{3}\right)}{(2 \cdot 120 \cdot 10 + 120 \cdot 10)} = 4.44 \text{ ft.}$$

$$x_3 = \frac{h_3\left\{(\gamma_1 h_1 + \gamma_2 h_2) + \frac{\gamma_3 h_3}{3}\right\}}{2(\gamma_1 h_1 + \gamma_2 h_2) + \gamma_3 h_3} = \frac{10\left\{(120 \cdot 10 + 120 \cdot 10) + \frac{120 \cdot 10}{3}\right\}}{2(120 \cdot 10 + 120 \cdot 10) + 120 \cdot 10} = 4.67 \text{ ft.}$$

The required forces (*F_i*) to achieve *FoS* value of 1.0 in GLE analyses are as follows:

F_1 = 2,840 lbs/ft., F_2 = 8,520 lbs/ft., F_3 = 14,200 lbs/ft.

The lateral earth pressure coefficient, *K_{ai}* for each layer is estimated as shown below:

$$K_{a1} = \frac{2F_1}{\gamma_1 h_1^2} = \frac{2 \cdot 2{,}840}{120 \cdot 10^2} = 0.473$$

$$K_{a2} = \frac{2F_2}{(2\gamma_1 h_1 + \gamma_2 h_2)h_2} = \frac{2 \cdot 8{,}520}{(2 \cdot 120 \cdot 10 + 120 \cdot 10) \cdot 10} = 0.473$$

$$K_{a3} = \frac{2F_3}{(2\gamma_1 h_1 + 2\gamma_2 h_2 + \gamma_3 h_3)h_3} = \frac{2 \cdot 14{,}200}{(2 \cdot 120 \cdot 10 + 2 \cdot 120 \cdot 10 + 120 \cdot 10) \cdot 10} = 0.473$$

The value of *K_{ai}* for each layer matches the value calculated using M-O as shown below:

$$K_{ae} = \frac{\cos^2(\phi - \theta_{MO} - \beta)}{\cos(\theta_{MO}) \cdot \cos^2\beta \cdot \cos(\delta + \beta + \theta_{MO})} \times \left[1 + \sqrt{\frac{\sin(\phi + \delta)\sin(\phi - \theta_{MO} - i)}{\cos(\delta + \beta + \theta_{MO})\cos(i - \beta)}}\right]^{-2} = 0.473$$

Where $\theta_{MO} = \tan^{-1}[k_h/(1 - k_v)]$, δ = wall backfill interface friction angle (deg.),

i = backfill slope angle (deg.), and β = slope of wall to the vertical (deg.)

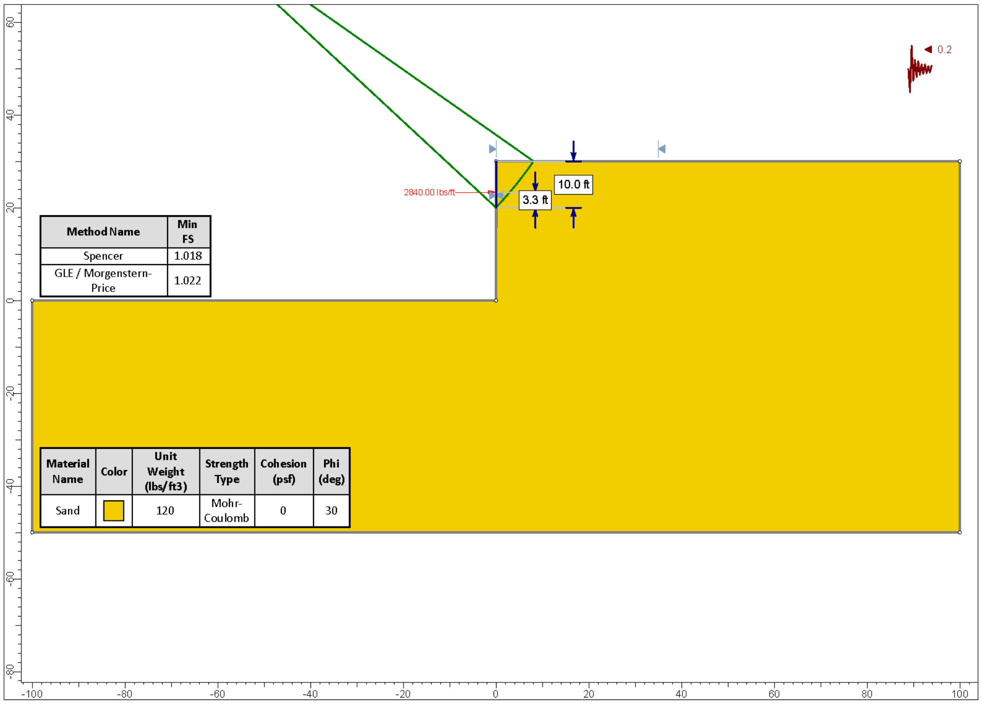

Figure AI-4: GLE Result (Seismic Condition) for 1st layer

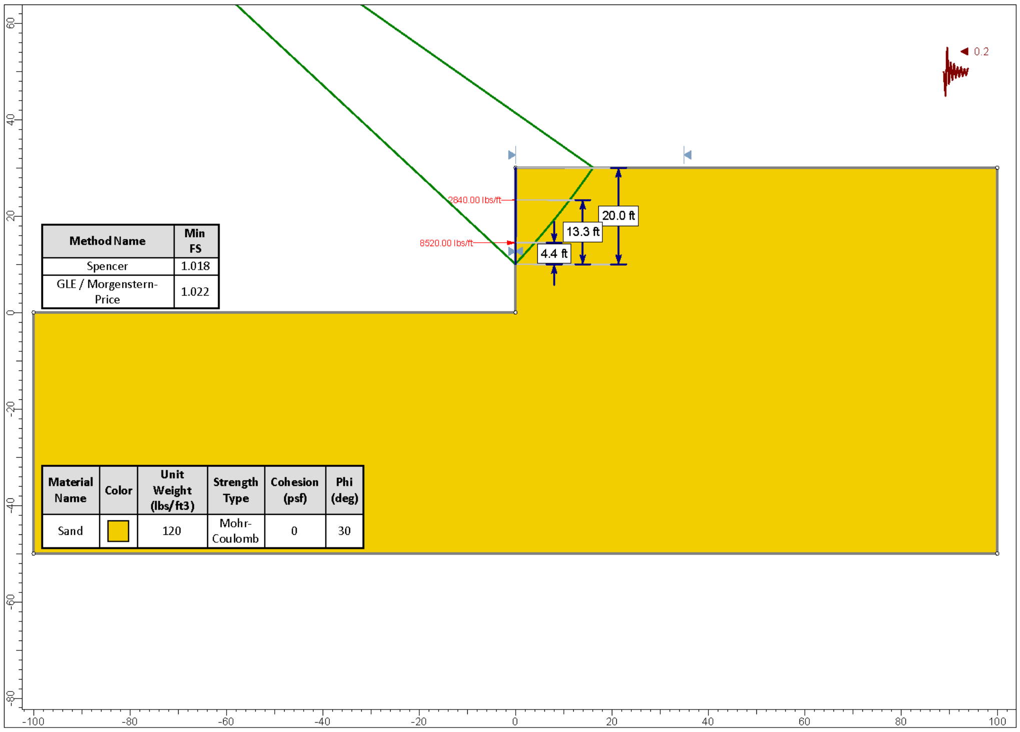

Figure AI-5: GLE Result (Seismic Condition) for 2nd layer

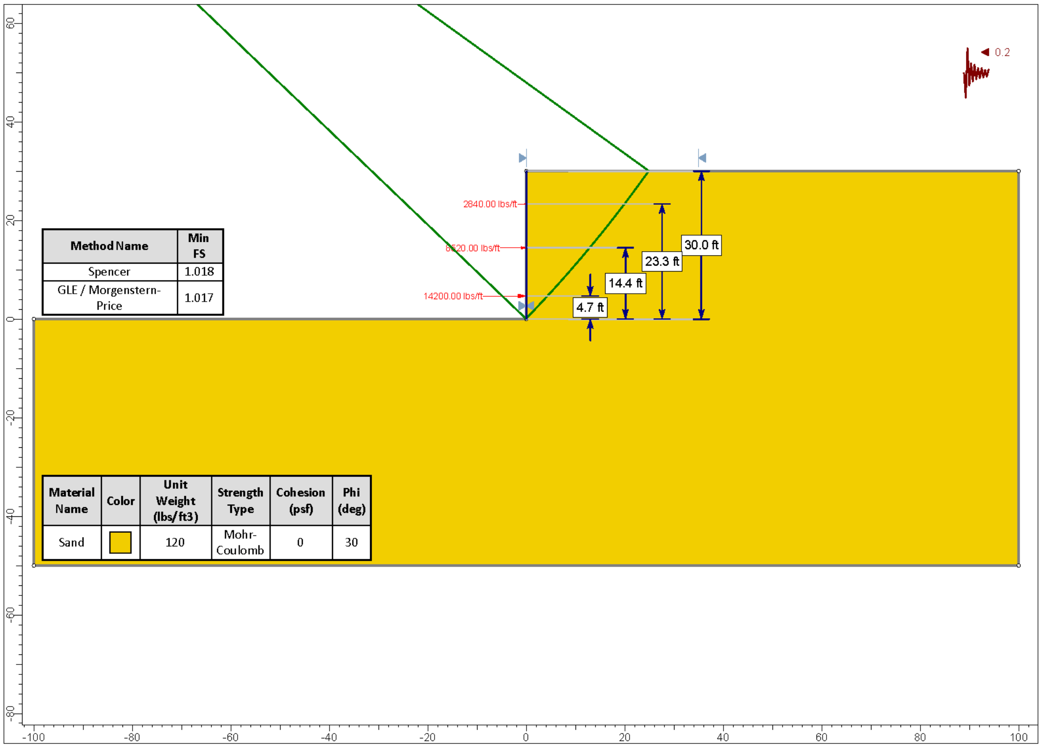

Figure AI-6: GLE Result (Seismic Condition) for 3rd layer

<u>Non-zero wall friction angle</u>

The models and results of GLE analyses for non-zero wall friction angle case are presented in Figure AI-17 through Figure AI-39. The soil parameters presented in Table AI-1 were used for the GLE models. The wall friction angle (δ) is assumed as 15 degrees. The locations (x_i) of applying Forces (F_i) are calculated as follows:

$$x_1 = \frac{h_1}{3} = \frac{10}{3} = 3.33 \text{ ft.}$$

$$x_2 = \frac{h_2\left(\gamma_1 h_1 + \frac{\gamma_2 h_2}{3}\right)}{(2\gamma_1 h_1 + \gamma_2 h_2)} = \frac{10\left(120 \cdot 10 + \frac{120 \cdot 10}{3}\right)}{(2 \cdot 120 \cdot 10 + 120 \cdot 10)} = 4.44 \text{ ft.}$$

$$x_3 = \frac{h_3\left\{(\gamma_1 h_1 + \gamma_2 h_2) + \frac{\gamma_3 h_3}{3}\right\}}{2(\gamma_1 h_1 + \gamma_2 h_2) + \gamma_3 h_3} = \frac{10\left\{(120 \cdot 10 + 120 \cdot 10) + \frac{120 \cdot 10}{3}\right\}}{2(120 \cdot 10 + 120 \cdot 10) + 120 \cdot 10} = 4.67 \text{ ft.}$$

The forces are applied at an angle of 15 degrees to the horizontal.

The required forces (F_i) to achieve *FoS* value of 1.0 in GLE analyses are as follows:

$F_1 = 1{,}850$ lbs/ft., $F_2 = 5{,}400$ lbs/ft., $F_3 = 9{,}100$ lbs/ft.

The lateral earth pressure coefficient, K_{ai} for each layer is estimated as shown below:

$$K_{a1} = \frac{2F_1}{\gamma_1 h_1^2} = \frac{2 \cdot 1{,}850}{120 \cdot 10^2} = 0.308$$

$$K_{a2} = \frac{2F_2}{(2\gamma_1 h_1 + \gamma_2 h_2)h_2} = \frac{2 \cdot 5{,}400}{(2 \cdot 120 \cdot 10 + 120 \cdot 10) \cdot 10} = 0.300$$

$$K_{a3} = \frac{2F_3}{(2\gamma_1 h_1 + 2\gamma_2 h_2 + \gamma_3 h_3)h_3} = \frac{2 \cdot 9{,}100}{(2 \cdot 120 \cdot 10 + 2 \cdot 120 \cdot 10 + 120 \cdot 10) \cdot 10} = 0.303$$

The calculated K_{ai} for each layer is the same as the value calculated using Coulomb's theory with ϕ = 30 degrees and δ = 15 degrees as shown below:

$$K_a = \frac{\cos^2(\phi - \omega)}{\cos^2\omega \cdot \cos(\delta + \omega)} \times \left[1 + \sqrt{\frac{\sin(\delta + \phi)\sin(\phi - \beta)}{\cos(\delta + \omega)\cos(\omega - \beta)}}\right]^{-2} = 0.301$$

Where ω = angle from the face of wall to the vertical (deg.) and β = angle from backfill surface to the horizontal (deg.)

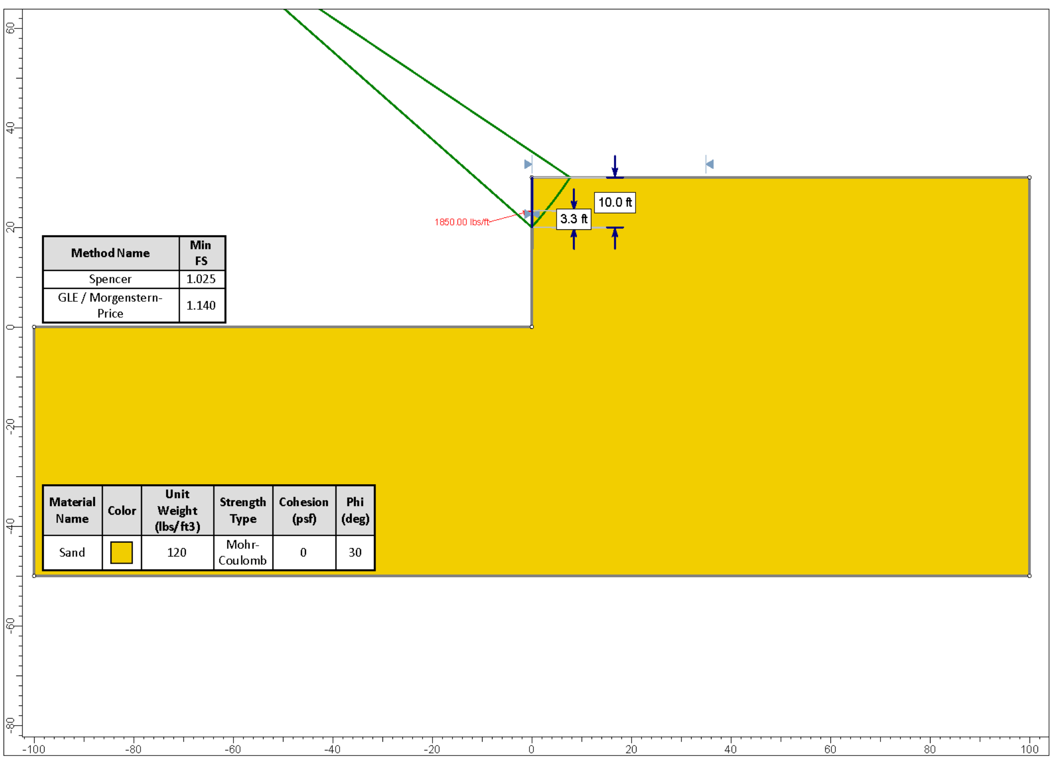

Figure AI-7: GLE Result for 1st layer

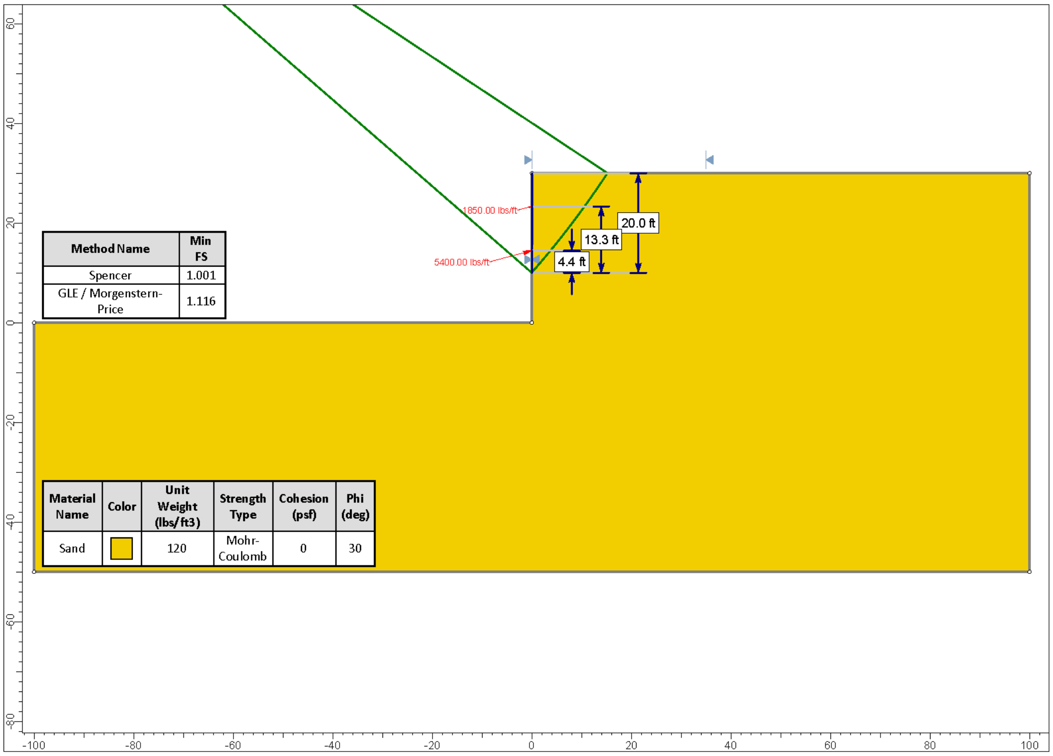

Figure AI-8: GLE Result for 2nd layer

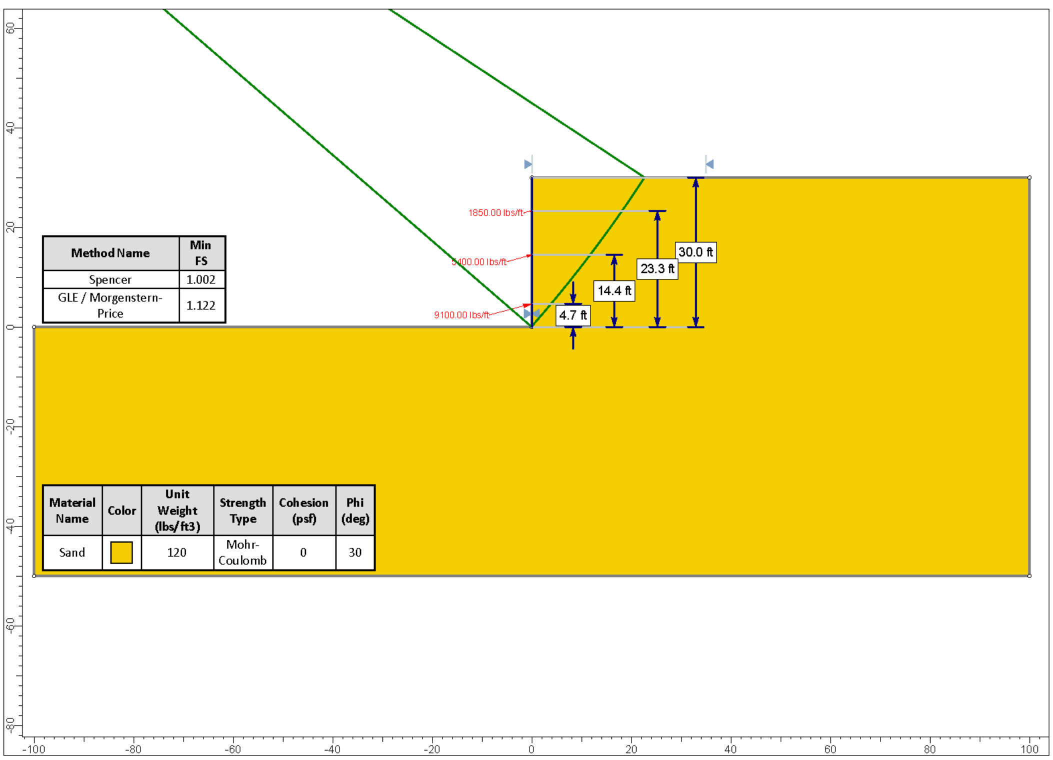

Figure AI-9: GLE Result for 3rd layer

APPENDIX II - Examples of Proposed Methods

This appendix presents example GLE analyses that calculate K_a using the proposed method. The examples analyzed a complex wall geometry with three soil layers where the conventional earth pressure method cannot be used. The wall was modeled with a vertical cut of 25 feet and groundwater was not considered in the model. In addition, a *c′-ϕ′*/cohesive layer was assumed to be interbedded between sand soil layers, and various effective cohesion values were applied to the *c′-ϕ′* soil layer as shown in Table AII-1a to show the effect of cohesion and how to incorporate the minimum K_a value into K_a calculations. Table AII-1b shows assumed short-term and long-term soil strength parameters for a clay layer. Spencer and Morgenstern-Price methods were selected for GLE analyses.

Table AII-2a: Soil Parameters for sand and c′-ϕ′ soil layers

Layer No.	Soil	Layer Thickness (feet)	Unit Weight (pcf)	Soil Strength Parameters	
				Effective Friction Angle, ϕ’ (deg.)	Effective Cohesion (psf)
1	Sand	5	120	32	0
2	c′-ϕ′	10	115	27	Varied: 200 and 500
3	Sand	10	125	34	0

Table AII-3b: Soil Parameters for sand and clay soil layers

Layer No.	Soil	Layer Thickness (feet)	Unit Weight (pcf)	Soil Strength Parameters		Long-Term Strength Parameter	
				Effective Friction Angle, ϕ’ (deg.)	Undrained Shear Strength (psf)	Effective Friction Angle, ϕ’ (deg.)	Effective Cohesion (psf)
1	Sand	5	120	32	0	32	0
2	Clay	10	115	0	S_u = 700	32	0
3	Sand	10	125	34	0	34	0

Profile No. 1

The soil parameters of Profile No. 1 used for the example analyses are presented in Table AII-4.

Table AII-4: Soil Parameters - Profile No. 1

Layer No.	Soil	Layer Thickness (feet)	Unit Weight (pcf)	Soil Strength Parameters	
				Effective Friction Angle, ϕ' (deg.)	Effective Cohesion (psf)
1	Sand	5	120	32	0
2	c'-ϕ'	10	115	27	200
3	Sand	10	125	34	0

The model and result of GLE analysis for the proposed method are presented in Figure AII-1 through Figure AII-3. The locations (x_i) of applying Forces (F_i) are calculated as follows:

$$x_1 = \frac{h_1}{3} = \frac{5}{3} = 1.67 \text{ ft.}$$

$$x_2 = \frac{h_2\left(\gamma_1 h_1 + \frac{\gamma_2 h_2}{3}\right)}{(2\gamma_1 h_1 + \gamma_2 h_2)} = \frac{10\left(120 \cdot 5 + \frac{115 \cdot 10}{3}\right)}{(2 \cdot 120 \cdot 5 + 115 \cdot 10)} = 4.18 \text{ ft.}$$

$$x_3 = \frac{h_3\left\{(\gamma_1 h_1 + \gamma_2 h_2) + \frac{\gamma_3 h_3}{3}\right\}}{2(\gamma_1 h_1 + \gamma_2 h_2) + \gamma_3 h_3} = \frac{10\left\{(120 \cdot 5 + 115 \cdot 10) + \frac{125 \cdot 10}{3}\right\}}{2(120 \cdot 5 + 115 \cdot 10) + 125 \cdot 10} = 4.56 \text{ ft.}$$

The required force (F_1) to achieve *FoS* value of 1.0 for 1st layer from GLE analyses is obtained as follows (See Figure AII-AII-1):

$$F_1 = 750 \text{ lbs/ft.}$$

The lateral earth pressure coefficient, K_{a1} for 1st layer is calculated as follows:

$$K_{a1} = \frac{2F_1}{\gamma_1 h_1^2} = \frac{2 \cdot 750}{120 \cdot 5^2} = 0.5$$

For 2nd layer, the required force (F_2) to achieve *FoS* value of 1.0 from GLE analyses is as follows (See Figure AII-AII-2):

$$F_2 = 4{,}000 \text{ lbs/ft.}$$

The lateral earth pressure coefficient, K_{a2} for 2nd layer is calculated as follows:

$$K_{a2} = \frac{2F_2}{(2\gamma_1 h_1 + \gamma_2 h_2)h_2} = \frac{2 \cdot 4{,}000}{(2 \cdot 120 \cdot 5 + 115 \cdot 10) \cdot 10} = 0.340$$

As 2nd layer is c'-ϕ' soil, $K_{\min}$ is checked/calculated using the following:

$$K_{\min} = \frac{0.035}{(5 \cdot 0.120 + 10 \cdot 0.115 + 10 \cdot 0.125)/25} = 0.292\ (\geq 0.25)$$

Therefore, K_{a2} is taken as 0.340 ($K_{a2} \geq K_{\min}$).

The required force (F_3) to achieve *FoS* value of 1.0 for 3rd layer from GLE analyses is as follows (See Figure AII-3):

$F_3 =$ 8,500 lbs/ft.

The lateral earth pressure coefficient, K_{a3} for 3rd layer is calculated as follows:

$$K_{a3} = \frac{2F_3}{(2\gamma_1 h_1 + 2\gamma_2 h_2 + \gamma_3 h_3)h_3} = \frac{2 \cdot 8{,}500}{(2 \cdot 120 \cdot 5 + 2 \cdot 115 \cdot 10 + 125 \cdot 10) \cdot 10} = 0.358$$

The values of K_a determined using GLE are summarized in Table AII-33.

Table AII-3: Summary of K_a determined using GLE - Profile No. 1

Layer No.	Soil	Layer Thickness (feet)	Unit Weight (pcf)	Soil Strength Parameters		Applied Force, F_i (lbs/ft)	K_a
				Effective Friction Angle, ϕ' (deg.)	Effective Cohesion (psf)		
1	Sand	5	120	32	0	750	0.5
2	c'-ϕ'	10	115	27	200	4,000	0.340
3	Sand	10	125	34	0	8,500	0.358

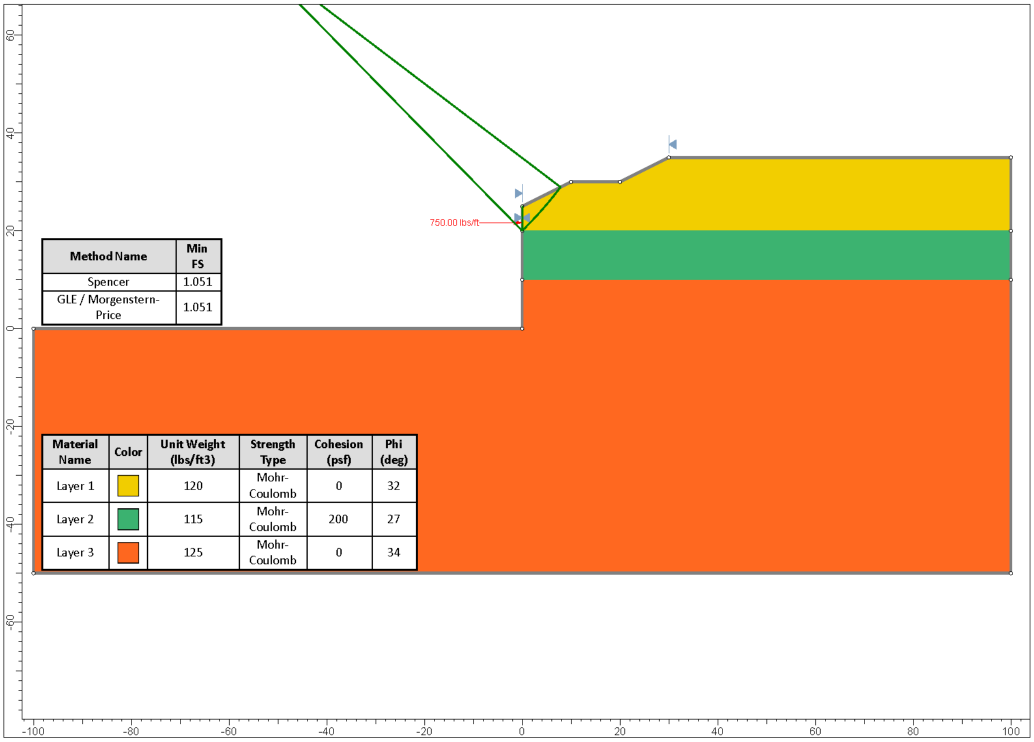

Figure AII-1: GLE Result for Profile No. 1, 1st layer

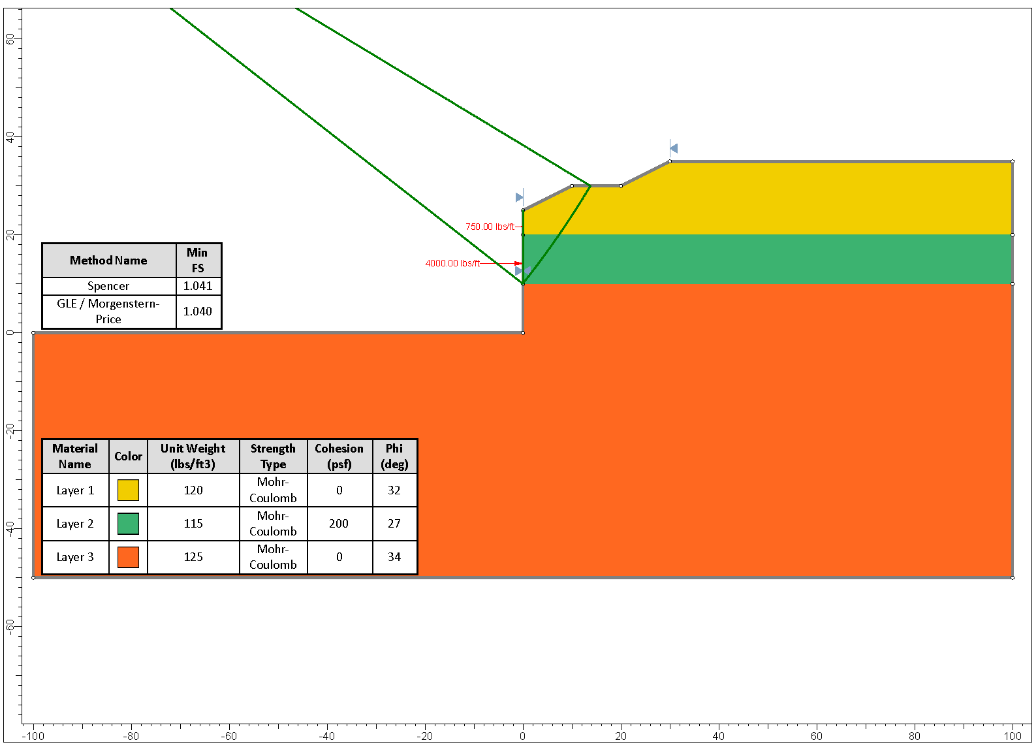

Figure AII-2: GLE Result for Profile No. 1, 2nd layer

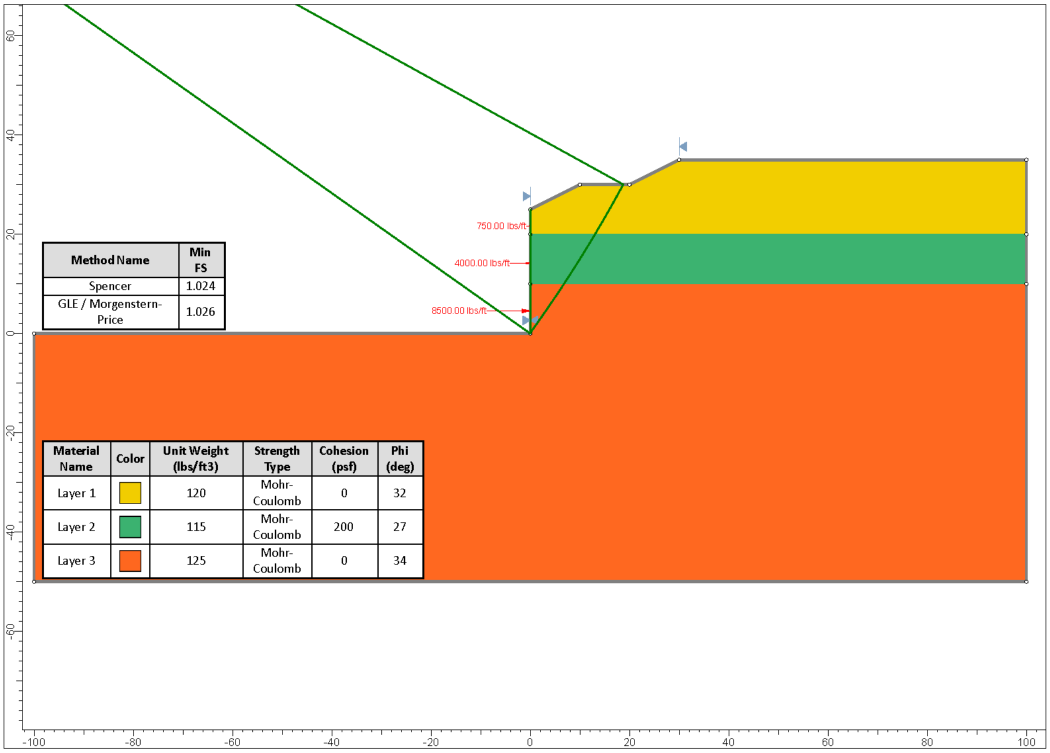

Figure AII-3: GLE Result for Profile No. 1, 3rd layer

Profile No. 2

The soil parameters of Profile No. 2 used for the example analyses are presented in Table AII-4.

Table AII-4: Soil Parameters - Profile No. 2

Layer No.	Soil	Layer Thickness (feet)	Unit Weight (pcf)	Soil Strength Parameters	
				Effective Friction Angle, ϕ' (deg.)	Effective Cohesion (psf)
1	Sand	5	120	32	0
2	c'-ϕ'	10	115	27	500
3	Sand	10	125	34	0

The model and result of GLE analyses for the proposed method are presented in Figure AII-4 through Figure AII-AII-7. The locations (x_i) of applying Forces (F_i) are calculated as follows:

$$x_1 = \frac{h_1}{3} = \frac{5}{3} = 1.67 \text{ ft.}$$

$$x_2 = \frac{h_2\left(\gamma_1 h_1 + \frac{\gamma_2 h_2}{3}\right)}{(2\gamma_1 h_1 + \gamma_2 h_2)} = \frac{10\left(120 \cdot 5 + \frac{115 \cdot 10}{3}\right)}{(2 \cdot 120 \cdot 5 + 115 \cdot 10)} = 4.18 \text{ ft.}$$

$$x_3 = \frac{h_3\left\{(\gamma_1 h_1 + \gamma_2 h_2) + \frac{\gamma_3 h_3}{3}\right\}}{2(\gamma_1 h_1 + \gamma_2 h_2) + \gamma_3 h_3} = \frac{10\left\{(120 \cdot 5 + 115 \cdot 10) + \frac{125 \cdot 10}{3}\right\}}{2(120 \cdot 5 + 115 \cdot 10) + 125 \cdot 10} = 4.56 \text{ ft.}$$

The required force (F_1) to achieve *FoS* value of 1.0 for 1st layer from GLE analyses is obtained as follows (See Figure AII-4):

$$F_1 = 750 \text{ lbs/ft.}$$

The lateral earth pressure coefficient, K_{a1} for 1st layer is calculated as follows:

$$K_{a1} = \frac{2F_1}{\gamma_1 h_1^2} = \frac{2 \cdot 750}{120 \cdot 5^2} = 0.5$$

For 2nd layer, the required force (F_2) to achieve *FoS* value of 1.0 from GLE analyses is as follows (See Figure AII-5):

$$F_2 = 0 \text{ lbs/ft.}$$

The lateral earth pressure coefficient, K_{a2} for 2nd layer is calculated as follows:

$$K_{a2} = \frac{2F_2}{(2\gamma_1 h_1 + \gamma_2 h_2)h_2} = \frac{2 \cdot 0}{(2 \cdot 120 \cdot 5 + 115 \cdot 10) \cdot 10} = 0$$

As 2nd layer is c'-ϕ' soil, $K_{\min}$ is checked/calculated using the following:

$$K_{\min} = \frac{0.035}{(5 \cdot 0.120 + 10 \cdot 0.115 + 10 \cdot 0.125)/25} = 0.292\ (\geq 0.25)$$

Therefore, K_{a2} is taken as 0.292 ($K_{a2} < K_{\min}$).

As K_{min} controls K_a, a force (F_{2_min}) corresponding to K_{min} is calculated using $K_{min} = K_{a2} = 0.292$ by assuming a linear distribution of the lateral earth pressure for this layer:

$$F_{2\_\min} = \frac{K_{a2} \cdot (2\gamma_1 h_1 + \gamma_2 h_2)h_2}{2} = \frac{0.292 \cdot (2 \cdot 120 \cdot 5 + 115 \cdot 10) \cdot 10}{2} = 3{,}431 \text{ lbs/ft.}$$

After replacing F_2 with F_{2_min} in the GLE model, the equivalent friction angle (ϕ_{equ}) to achieve *FoS* value of 1.0 for 2nd layer is 41 degrees (See Figure AII-6).

The required force (F_3) to achieve *FoS* value of 1.0 for 3rd layer from GLE analyses is as follows (See Figure AII-7):

F_3 = 8,500 lbs/ft.

The lateral earth pressure coefficient, K_{a3} for 3rd layer is calculated as follows:

$$K_{a3} = \frac{2F_3}{(2\gamma_1 h_1 + 2\gamma_2 h_2 + \gamma_3 h_3)h_3} = \frac{2 \cdot 8{,}500}{(2 \cdot 120 \cdot 5 + 2 \cdot 115 \cdot 10 + 125 \cdot 10) \cdot 10} = 0.358$$

The values of K_a determined using GLE are summarized in 5.

Table AII-5: Summary of K_a determined using GLE - Profile No. 2

Layer No.	Soil	Layer Thickness (feet)	Unit Weight (pcf)	Soil Strength Parameters		Applied Force, F_i (lbs/ft)	K_a
				Effective Friction Angle, ϕ' (deg.)	Effective Cohesion (psf)		
1	Sand	5	120	32	0	750	0.5
2	c'-ϕ'	10	115	41	0	3,431	0.292
3	Sand	10	125	34	0	8,500	0.358

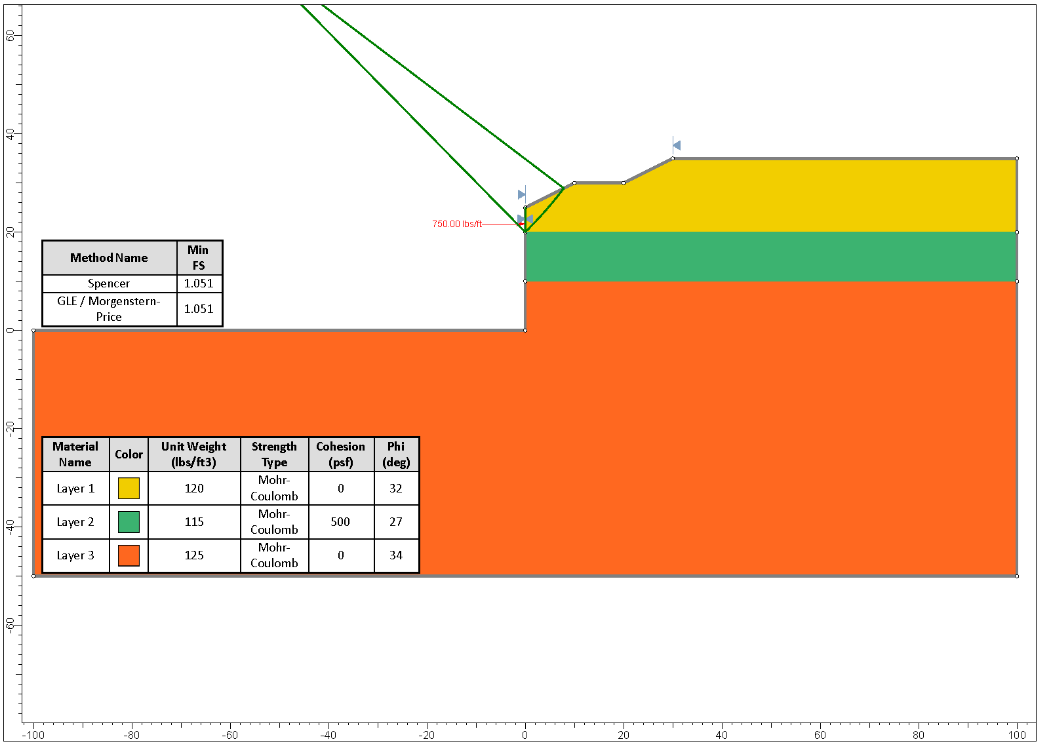

Figure AII-4: GLE Result for Profile No. 2, 1st layer

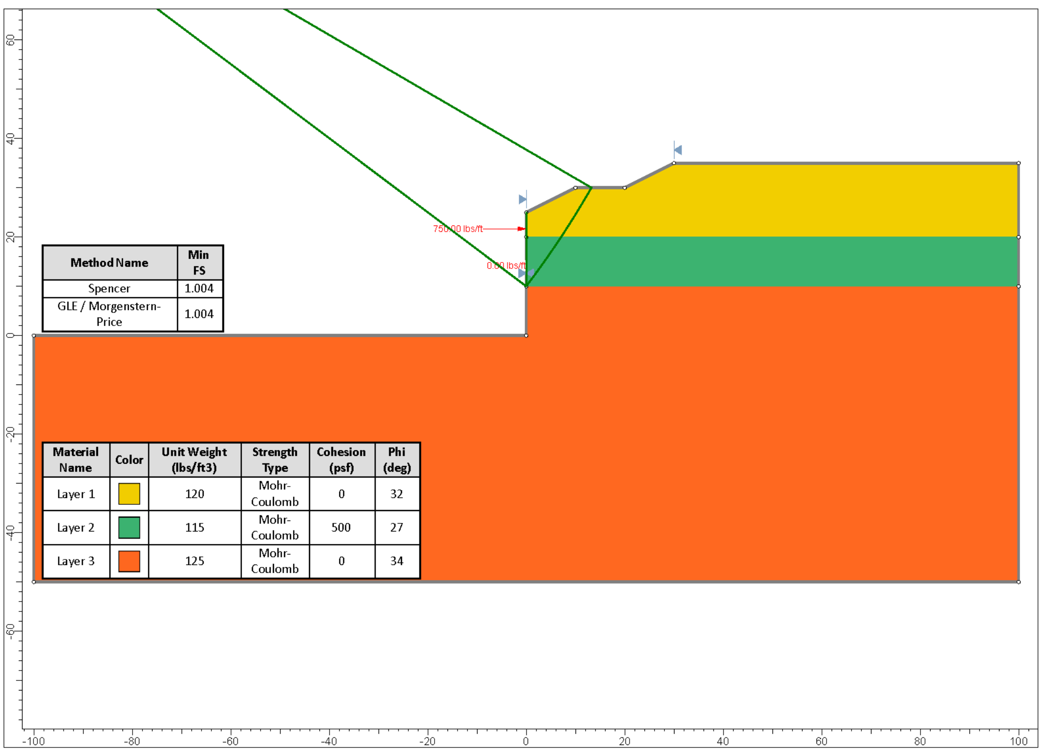

Figure AII-5: GLE Result for Profile No. 2, 2nd layer

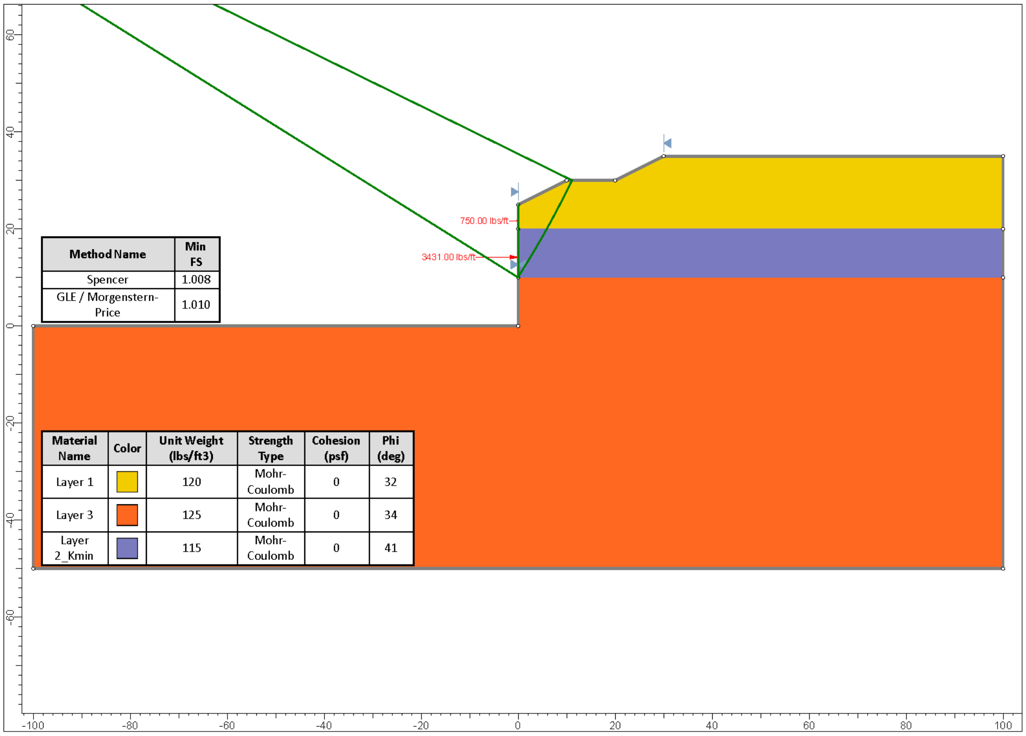

Figure AII-6 GLE Result for Profile No. 2, 2nd layer

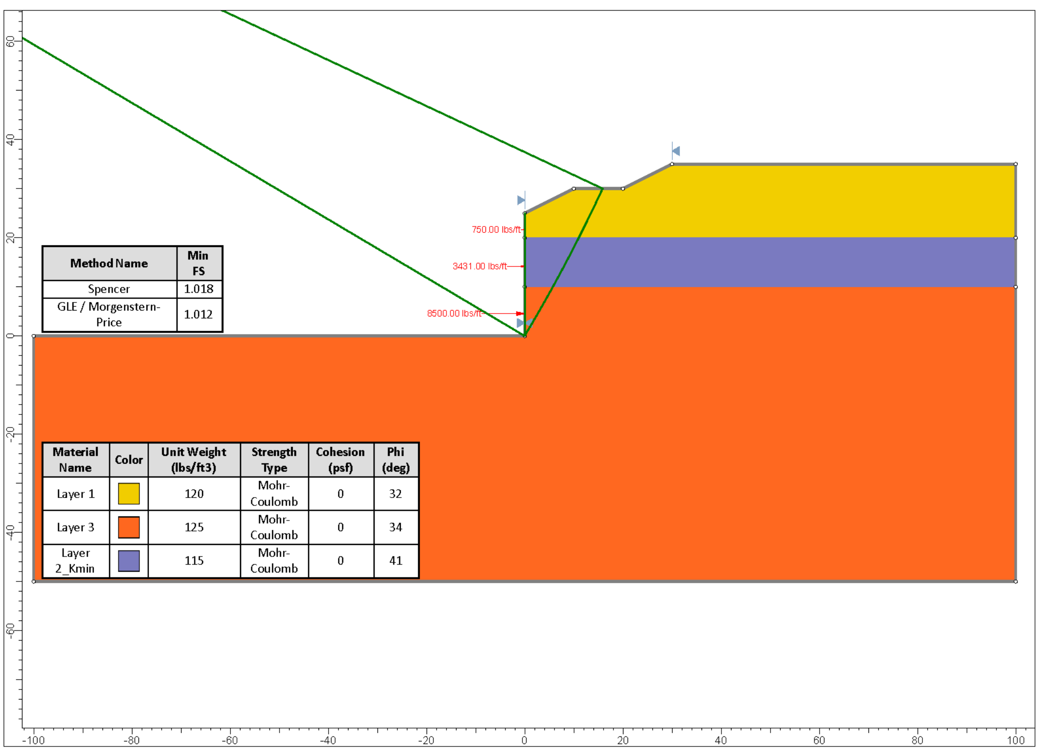

Figure AII-7: GLE Result for Profile No. 2, 3rd layer

<u>Case for non-zero wall friction angle</u>

The model and result of GLE analyses for non-zero wall friction angle case are presented in Figure AII-8 through Figure AII-AII-11. The wall friction angle (δ) is assumed as 15 degrees. The locations (x_i) of applying Forces (F_i) are calculated as follows:

$$x_1 = \frac{h_1}{3} = \frac{5}{3} = 1.67 \text{ ft.}$$

$$x_2 = \frac{h_2\left(\gamma_1 h_1 + \frac{\gamma_2 h_2}{3}\right)}{(2\gamma_1 h_1 + \gamma_2 h_2)} = \frac{10\left(120 \cdot 5 + \frac{115 \cdot 10}{3}\right)}{(2 \cdot 120 \cdot 5 + 115 \cdot 10)} = 4.18 \text{ ft.}$$

$$x_3 = \frac{h_3\left\{(\gamma_1 h_1 + \gamma_2 h_2) + \frac{\gamma_3 h_3}{3}\right\}}{2(\gamma_1 h_1 + \gamma_2 h_2) + \gamma_3 h_3} = \frac{10\left\{(120 \cdot 5 + 115 \cdot 10) + \frac{125 \cdot 10}{3}\right\}}{2(120 \cdot 5 + 115 \cdot 10) + 125 \cdot 10} = 4.56 \text{ ft.}$$

The forces are applied at an angle of 15 degrees to the horizontal.

The required force (F_1) to achieve *FoS* value of 1.0 for 1st layer from GLE analyses is obtained as follows (See Figure AII-8):

$$F_1 = 680 \text{ lbs/ft.}$$

The lateral earth pressure coefficient, K_{a1} for 1st layer is calculated as follows:

$$K_{a1} = \frac{2F_1}{\gamma_1 h_1^2} = \frac{2 \cdot 680}{120 \cdot 5^2} = 0.453$$

For 2nd layer, the required force (F_2) to achieve *FoS* value of 1.0 from GLE analyses is as follows (See Figure AII-9):

$$F_2 = 0 \text{ lbs/ft.}$$

The lateral earth pressure coefficient, K_{a2} for 2nd layer is calculated as follows:

$$K_{a2} = \frac{2F_2}{(2\gamma_1 h_1 + \gamma_2 h_2)h_2} = \frac{2 \cdot 0}{(2 \cdot 120 \cdot 5 + 115 \cdot 10) \cdot 10} = 0$$

As 2nd layer is c'- ϕ' soil, $K_{\min}$ is checked/calculated using the following:

$$K_{\min} = \frac{0.035}{(5 \cdot 0.120 + 10 \cdot 0.115 + 10 \cdot 0.125)/25} = 0.292\ (\geq 0.25)$$

Therefore, K_{a2} is taken as 0.292 ($K_{a2} < K_{\min}$).

As K_{min} controls K_a, a force (F_{2_min}) corresponding to K_{min} is calculated using K_{min} = K_{a2} = 0.292 by assuming a linear distribution of the lateral earth pressure for this layer:

$$F_{2\_\min} = \frac{K_{a2} \cdot (2\gamma_1 h_1 + \gamma_2 h_2) h_2}{2} = \frac{0.292 \cdot (2 \cdot 120 \cdot 5 + 115 \cdot 10) \cdot 10}{2} = 3{,}431 \text{ lbs/ft.}$$

After replacing F_2 with $F_{2\_\min}$ in the GLE model, the equivalent friction angle (ϕ_{equ}) to achieve *FoS* value of 1.0 for 2nd layer is 40 degrees (See Figure AII-10).

The required force (F_3) to achieve *FoS* value of 1.0 for 3rd layer from GLE analyses is as follows (See Figure AII-11):

F_2 = 7,600 lbs/ft.

The lateral earth pressure coefficient, K_{a3} for 3rd layer is calculated as follows:

$$K_{a3} = \frac{2F_3}{(2\gamma_1 h_1 + 2\gamma_2 h_2 + \gamma_3 h_3) h_3} = \frac{2 \cdot 7{,}600}{(2 \cdot 120 \cdot 5 + 2 \cdot 115 \cdot 10 + 125 \cdot 10) \cdot 10} = 0.320$$

The values of K_a determined using GLE are summarized in Table AII-6.

Table AII-6: Summary of K_a determined using GLE - Profile No. 2, δ = 15 degrees

Layer No.	Soil	Layer Thickness (feet)	Unit Weight (pcf)	Soil Strength Parameters		Applied Force, F_i (lbs/ft)	K_a
				Effective Friction Angle, ϕ' (deg.)	Effective Cohesion (psf)		
1	Sand	5	120	32	0	680	0.453
2	c'-ϕ'	10	115	41	0	3,431	0.292
3	Sand	10	125	34	0	7,600	0.320

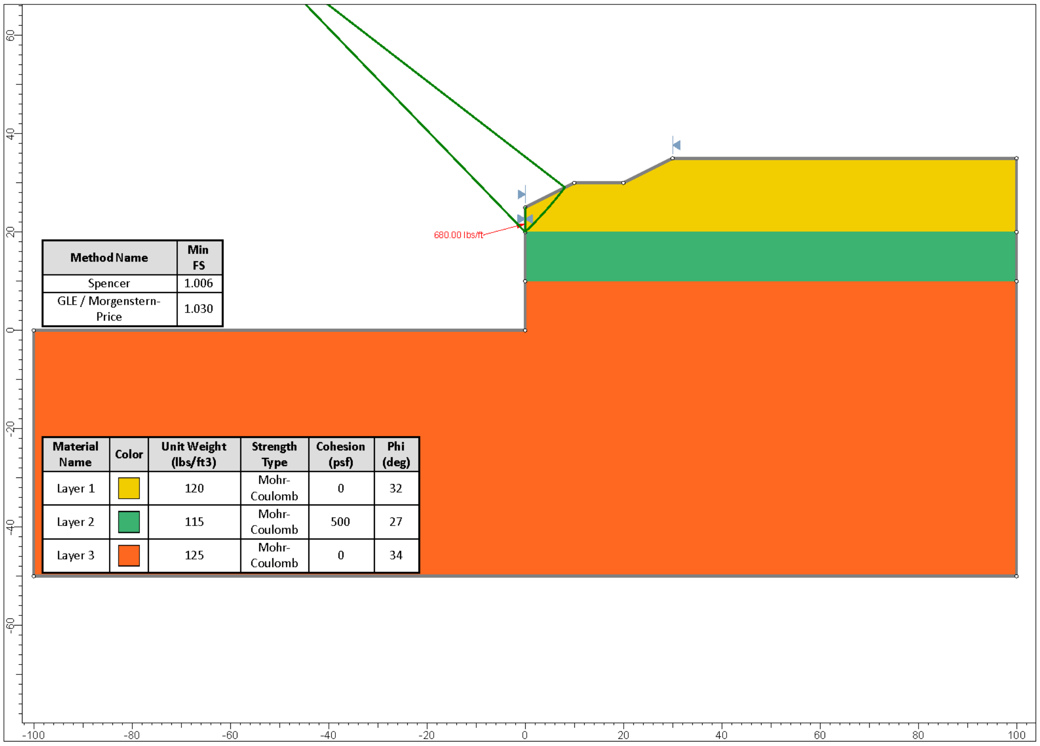

Figure AII-8: GLE Result for Profile No. 2, 1st layer

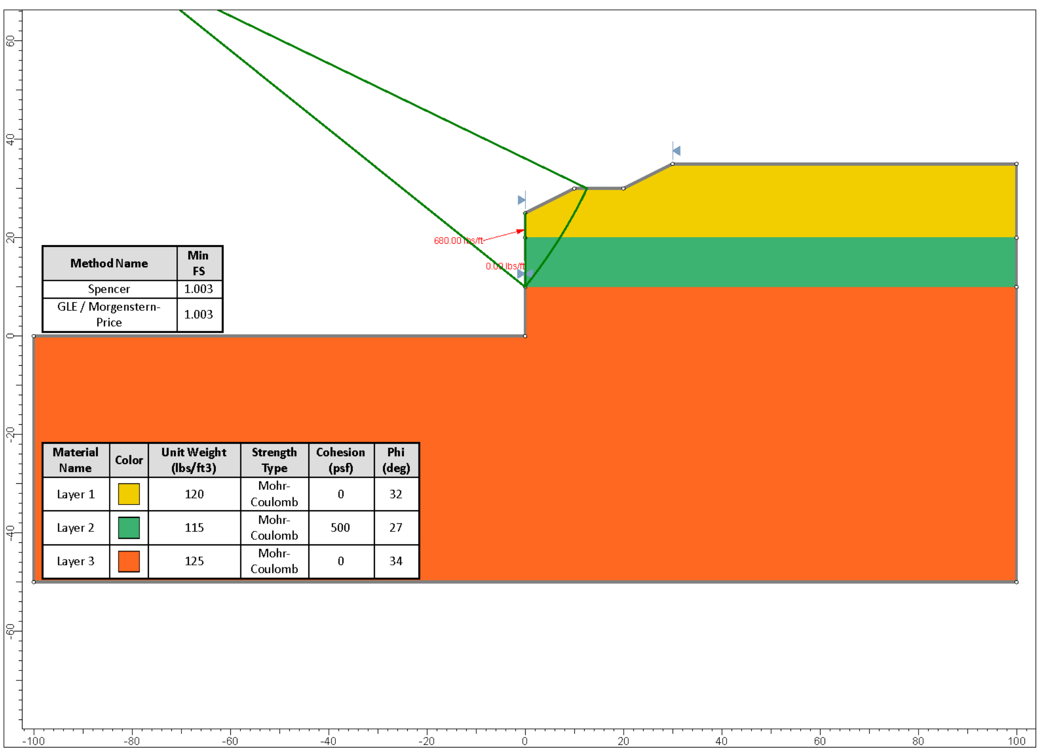

Figure AII-9: GLE Result for Profile No. 2, 2nd layer

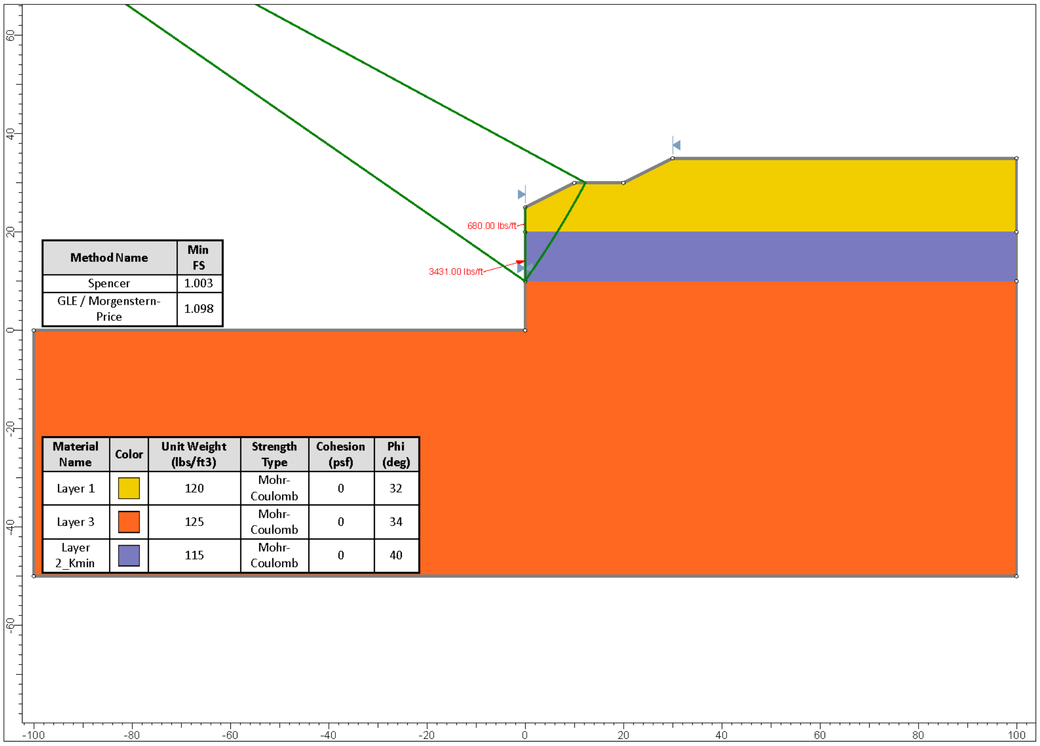

Figure AII-10 GLE Result for Profile No. 2, 2nd layer

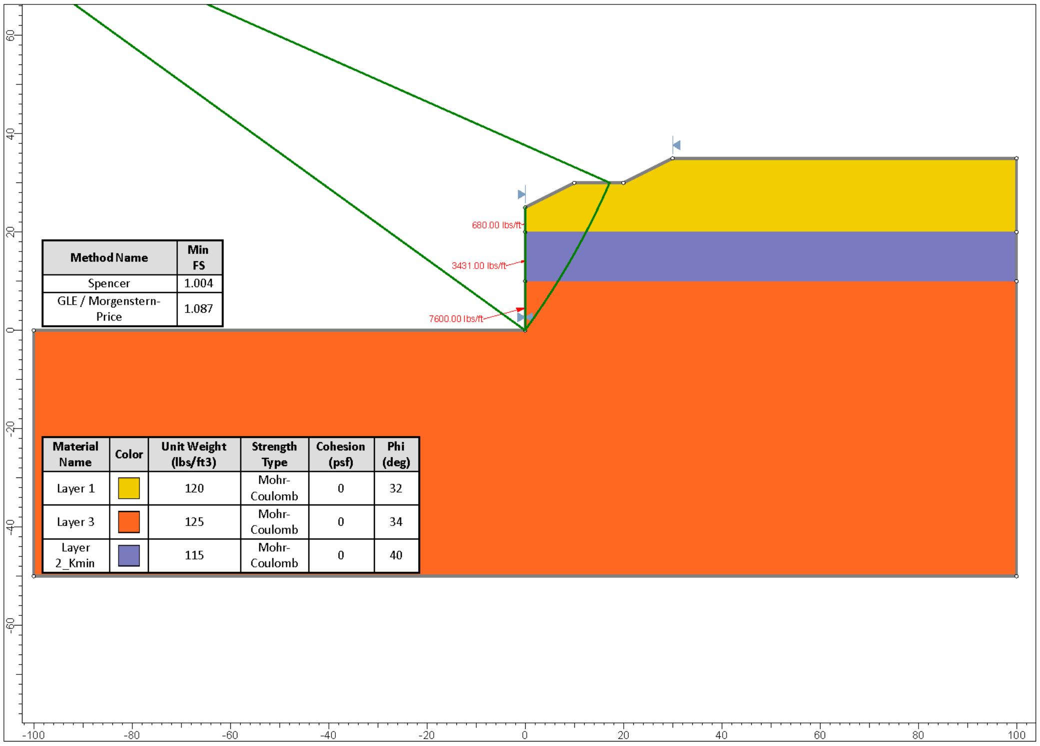

Figure AII-11: GLE Result for Profile No. 2, 3rd layer

Seismic Condition

The model and result of GLE analyses for seismic condition are presented in Figure AII-23 through Figure AII-15. The horizontal acceleration coefficient (kh) is assumed as 0.2. The locations (xi) of applying Forces (Fi) are calculated as follows:

$$x_1 = \frac{h_1}{3} = \frac{5}{3} = 1.67 \text{ ft.}$$

$$x_2 = \frac{h_2\left(\gamma_1 h_1 + \frac{\gamma_2 h_2}{3}\right)}{(2\gamma_1 h_1 + \gamma_2 h_2)} = \frac{10\left(120 \cdot 5 + \frac{115 \cdot 10}{3}\right)}{(2 \cdot 120 \cdot 5 + 115 \cdot 10)} = 4.18 \text{ ft.}$$

$$x_3 = \frac{h_3\left\{(\gamma_1 h_1 + \gamma_2 h_2) + \frac{\gamma_3 h_3}{3}\right\}}{2(\gamma_1 h_1 + \gamma_2 h_2) + \gamma_3 h_3} = \frac{10\left\{(120 \cdot 5 + 115 \cdot 10) + \frac{125 \cdot 10}{3}\right\}}{2(120 \cdot 5 + 115 \cdot 10) + 125 \cdot 10} = 4.56 \text{ ft.}$$

The required force (F_1) to achieve *FoS* value of 1.0 for 1st layer from GLE analyses is obtained as follows (See Figure AII-12):

$$F_1 = 1{,}420 \text{ lbs/ft.}$$

The lateral earth pressure coefficient, K_{a1} for 1st layer is calculated as follows:

$$K_{a1} = \frac{2F_1}{\gamma_1 h_1^2} = \frac{2 \cdot 1{,}420}{120 \cdot 5^2} = 0.947$$

For 2nd layer, the required force (F_2) to achieve *FoS* value of 1.0 from GLE analyses is as follows (See Figure AII-13):

$$F_2 = 2{,}480 \text{ lbs/ft.}$$

The lateral earth pressure coefficient, K_{a2} for 2nd layer is calculated as follows:

$$K_{a2} = \frac{2F_2}{(2\gamma_1 h_1 + \gamma_2 h_2)h_2} = \frac{2 \cdot 2{,}480}{(2 \cdot 120 \cdot 5 + 115 \cdot 10) \cdot 10} = 0.211$$

As 2nd layer is *c'*-*ϕ'* soil, $K_{\min}$ is checked/calculated using the following:

$$K_{\min} = \frac{0.035}{(5 \cdot 0.120 + 10 \cdot 0.115 + 10 \cdot 0.125)/25} = 0.292 \ (\geq 0.25)$$

Therefore, K_{a2} is taken as 0.292 ($K_{a2} < K_{\min}$).

As K_{min} controls K_a, a force (F_{2_min}) corresponding to K_{min} is calculated using $K_{min} = K_{a2} = 0.292$ by assuming a linear distribution of the lateral earth pressure for this layer:

$$F_{2\_min} = \frac{K_{a2} \cdot (2\gamma_1 h_1 + \gamma_2 h_2) h_2}{2} = \frac{0.292 \cdot (2 \cdot 120 \cdot 5 + 115 \cdot 10) \cdot 10}{2} = 3{,}431 \text{ lbs/ft.}$$

After replacing F_2 with F_{2_min} in the GLE model, the equivalent friction angle (ϕ_{equ}) to achieve *FoS* value of 1.0 for 2nd layer is 50 degrees (See Figure AII-14).

The required force (F_3) to achieve *FoS* value of 1.0 for 3rd layer from GLE analyses is as follows (See Figure AII-15):

$F_3 = 2{,}500$ lbs/ft.

The lateral earth pressure coefficient, K_{a3} for 3rd layer is calculated as follows:

$$K_{a3} = \frac{2F_3}{(2\gamma_1 h_1 + 2\gamma_2 h_2 + \gamma_3 h_3) h_3} = \frac{2 \cdot 12{,}500}{(2 \cdot 120 \cdot 5 + 2 \cdot 115 \cdot 10 + 125 \cdot 10) \cdot 10} = 0.526$$

The values of K_a determined using GLE are summarized in Table AII-7.

Table AII-7: Summary of K_a determined using GLE - Profile No. 2, Seismic

Layer No.	Soil	Layer Thickness (feet)	Unit Weight (pcf)	Soil Strength Parameters		Applied Force, F_i (lbs/ft)	K_a
				Effective Friction Angle, ϕ' (deg.)	Effective Cohesion (psf)		
1	Sand	5	120	32	0	1,420	0.947
2	c'-ϕ'	10	115	50	0	3,431	0.292
3	Sand	10	125	34	0	12,500	0.526

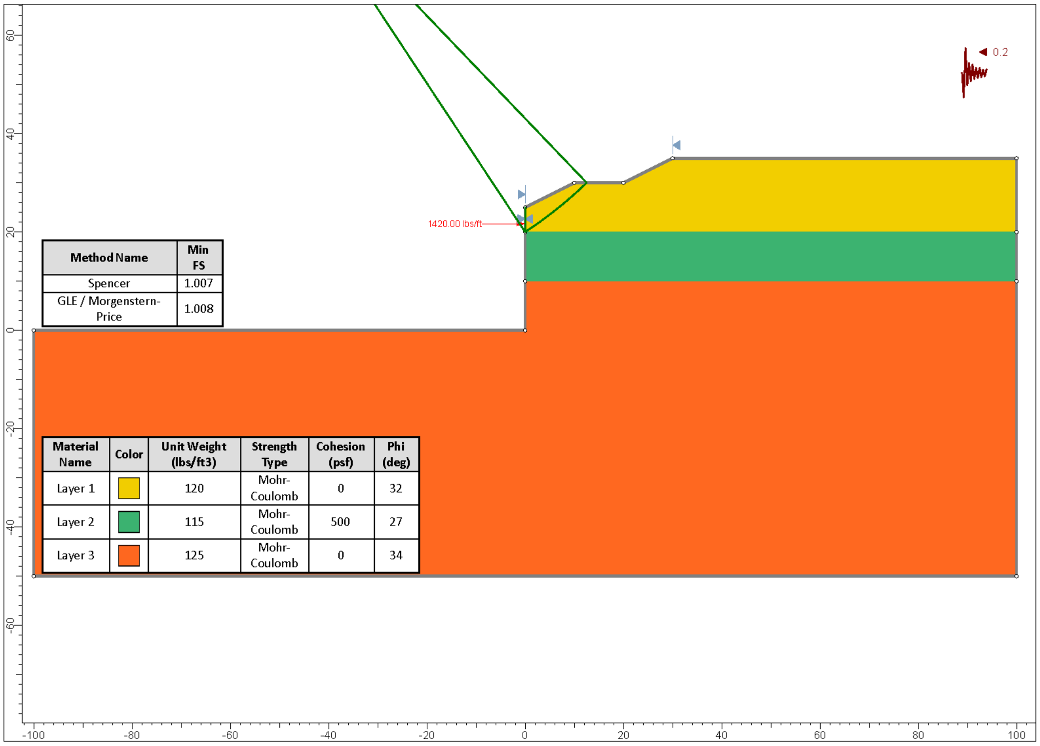

Figure AII-12: GLE Result for Profile No. 2, 1st layer

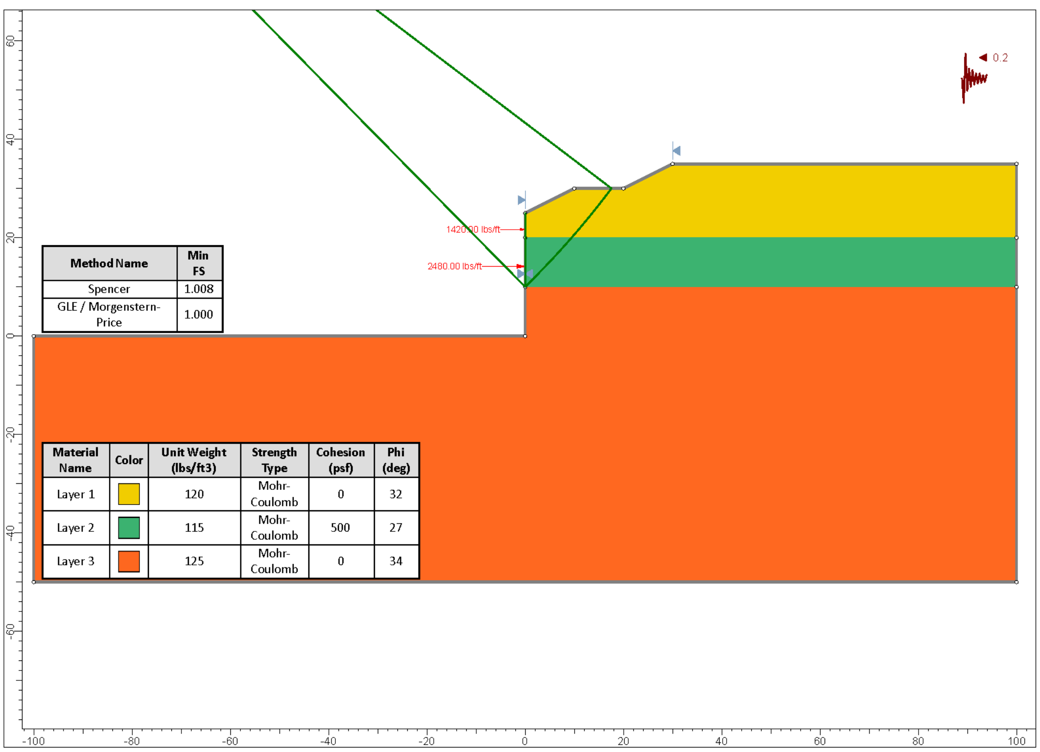

Figure AII-13: GLE Result for Profile No. 2, 2nd layer

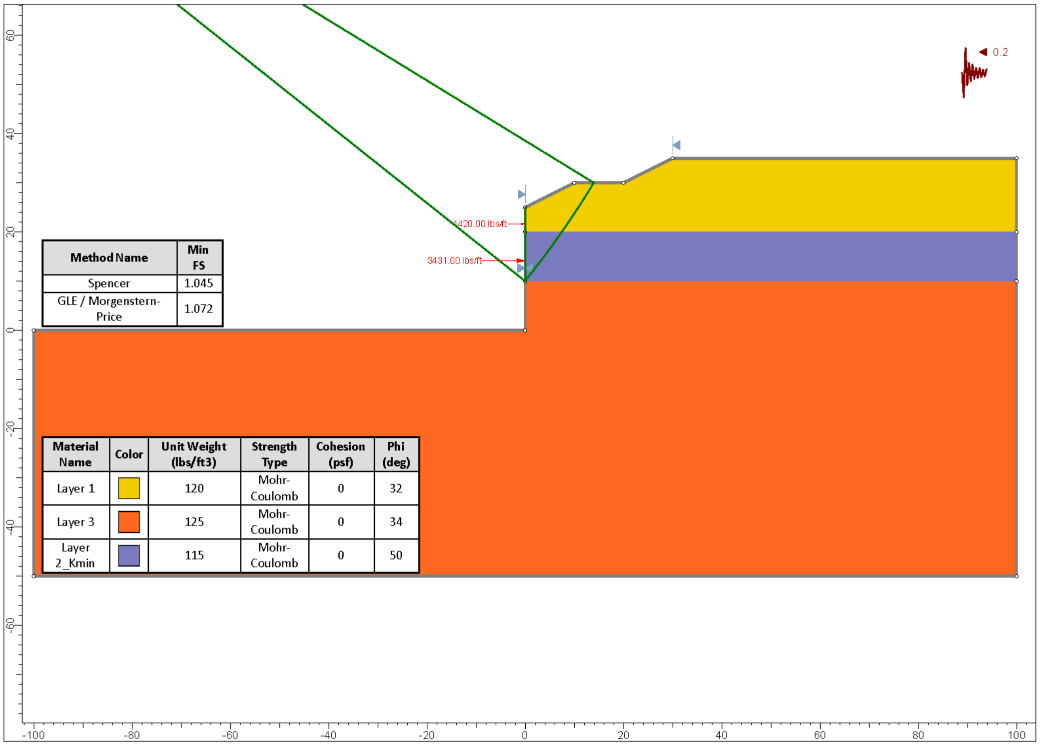

Figure AII-14: GLE Result for Profile No. 2, 2nd layer

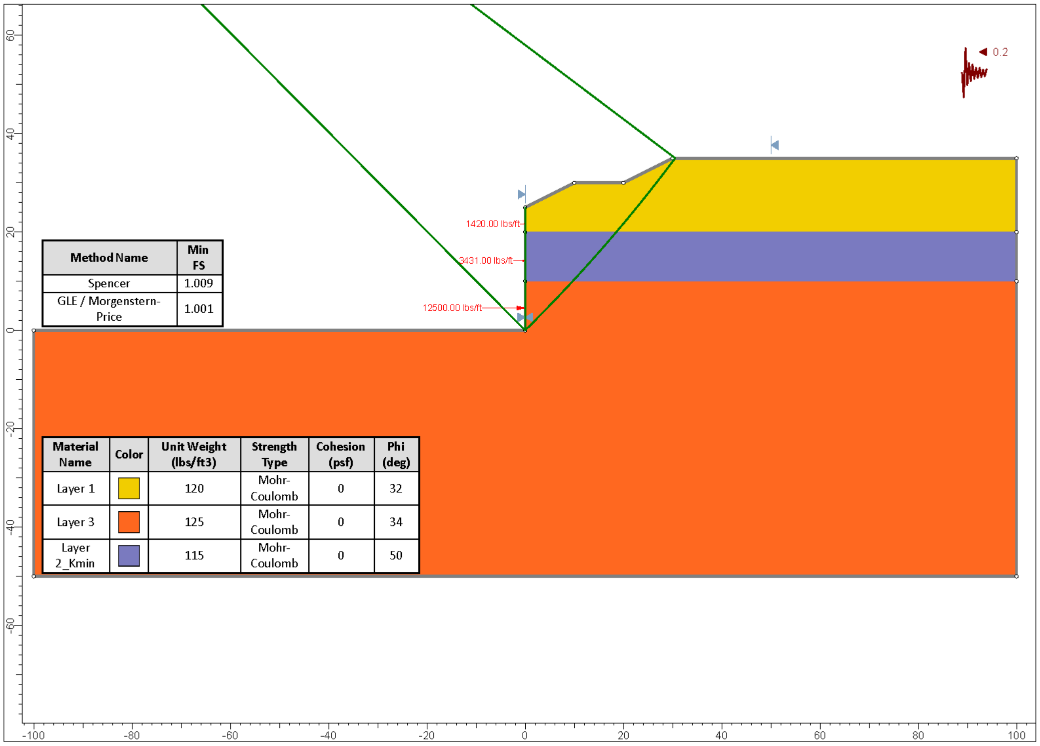

Figure AII-15: GLE Result for Profile No. 2, 3rd layer

Profile No. 3

The soil parameters of Profile No. 3 used for the example analyses are presented in Table AII-8.

Table AII-8: Soil Parameters - Profile No. 3

Layer No.	Soil	Layer Thickness (feet)	Unit Weight (pcf)	Soil Strength Parameters		Long-Term Strength Parameter	
				Effective Friction Angle, ϕ' (deg.)	Undrained Shear Strength (psf)	Effective Friction Angle, ϕ' (deg.)	Effective Cohesion (psf)
1	Sand	5	120	32	0	32	0
2	Clay	10	115	0	S_u = 700	32	0
3	Sand	10	125	34	0	34	0

The model and result of GLE analysis for the proposed are presented in Figure AII-16 through Figure AII-20. The locations (x_i) of applying Forces (F_i) are calculated as follows:

$$x_1 = \frac{h_1}{3} = \frac{5}{3} = 1.67 \text{ ft.}$$

$$x_2 = \frac{h_2\left(\gamma_1 h_1 + \frac{\gamma_2 h_2}{3}\right)}{(2\gamma_1 h_1 + \gamma_2 h_2)} = \frac{10\left(120 \cdot 5 + \frac{115 \cdot 10}{3}\right)}{(2 \cdot 120 \cdot 5 + 115 \cdot 10)} = 4.18 \text{ ft.}$$

$$x_3 = \frac{h_3\left\{(\gamma_1 h_1 + \gamma_2 h_2) + \frac{\gamma_3 h_3}{3}\right\}}{2(\gamma_1 h_1 + \gamma_2 h_2) + \gamma_3 h_3} = \frac{10\left\{(120 \cdot 5 + 115 \cdot 10) + \frac{125 \cdot 10}{3}\right\}}{2(120 \cdot 5 + 115 \cdot 10) + 125 \cdot 10} = 4.56 \text{ ft.}$$

The required force (F_1) to achieve *FoS* value of 1.0 for 1st layer from GLE analyses is obtained as follows (**Error! Reference source not found.**16):

$$F_1 = 750 \text{ lbs/ft.}$$

The lateral earth pressure coefficient, K_{a1} for 1st layer is calculated as follows:

$$K_{a1} = \frac{2F_1}{\gamma_1 h_1^2} = \frac{2 \cdot 750}{120 \cdot 5^2} = 0.5$$

For 2nd layer, the required force (F_2) to achieve *FoS* value of 1.0 from GLE analyses is as follows (See FigureAII-17):

F_2 = 2,400 lbs/ft.

The lateral earth pressure coefficient, K_{a2} for 2nd layer is calculated as follows:

$$K_{a2} = \frac{2F_2}{(2\gamma_1 h_1 + \gamma_2 h_2)h_2} = \frac{2 \cdot 2{,}400}{(2 \cdot 120 \cdot 5 + 115 \cdot 10) \cdot 10} = 0.204$$

As 2nd layer is *c'-f'* soil, $K_{\min}$ is calculated using the following:

$$K_{\min} = \frac{0.035}{(5 \cdot 0.120 + 10 \cdot 0.115 + 10 \cdot 0.125)/25} = 0.292\ (\geq 0.25)$$

Therefore, K_{a2} is taken as 0.292 ($K_{a2} < K_{\min}$).

As K_{min} controls K_a, a force (F_{2_min}) corresponding to K_{min} is calculated using $K_{min} = K_{a2} =$ 0.292 by assuming a linear distribution of the lateral earth pressure for this layer:

$$F_{2\_\min} = \frac{K_{a2} \cdot (2\gamma_1 h_1 + \gamma_2 h_2)h_2}{2} = \frac{0.292 \cdot (2 \cdot 120 \cdot 5 + 115 \cdot 10) \cdot 10}{2} = 3{,}431 \text{ lbs/ft.}$$

After replacing F_2 with $F_{2\_\min}$ in the GLE model, the equivalent friction angle (ϕ_{equ}) to achieve *FoS* value of 1.0 for 2nd layer is 41 degrees (See Figure AII-18).

It is assumed for this example (Profile No. 3) that the long-term (effective) friction angle (ϕ') for 2nd Layer is equal to 32 degrees. Since the drained friction angle is less than the equivalent friction angle ($\phi' < \phi_{equ}$), the friction angle of 2nd layer is replaced with the long-term (effective) friction angle (32 degrees) in the GLE model. After re-running the GLE analysis with the friction angle of 32 degrees for 2nd layer, the required force (F_2) to achieve *FoS* value of 1.0 is (See Figure AII-19):

F_2 = 5,050 lbs/ft.

The lateral earth pressure coefficient, K_{a2} for 2nd layer is calculated as follows:

$$K_{a2} = \frac{2F_2}{(2\gamma_1 h_1 + \gamma_2 h_2)h_2} = \frac{2 \cdot 5{,}050}{(2 \cdot 120 \cdot 5 + 115 \cdot 10) \cdot 10} = 0.430$$

The required force (F_3) to achieve *FoS* value of 1.0 for 3rd layer from GLE analyses is as follows (See Figure AII-20):

F_3 = 8,500 lbs/ft.

The lateral earth pressure coefficient, K_{a3} for 3rd layer is calculated as follows:

$$K_{a3} = \frac{2F_3}{(2\gamma_1 h_1 + 2\gamma_2 h_2 + \gamma_3 h_3)h_3} = \frac{2\cdot 8{,}500}{(2\cdot 120\cdot 5 + 2\cdot 115\cdot 10 + 125\cdot 10)\cdot 10} = 0.358$$

The values of K_a determined using GLE are summarized in Table AII-9.

Table AII-9: Summary of K_a determined using GLE - Profile No. 3

Layer No.	Soil	Layer Thickness (feet)	Unit Weight (pcf)	Soil Strength Parameters		Applied Force, F_i (lbs/ft)	K_a
				Effective Friction Angle, ϕ' (deg.)	Effective Cohesion (psf)		
1	Sand	5	120	32	0	750	0.5
2	Clay	10	115	32	0	5,050	0.430
3	Sand	10	125	34	0	8,500	0.358

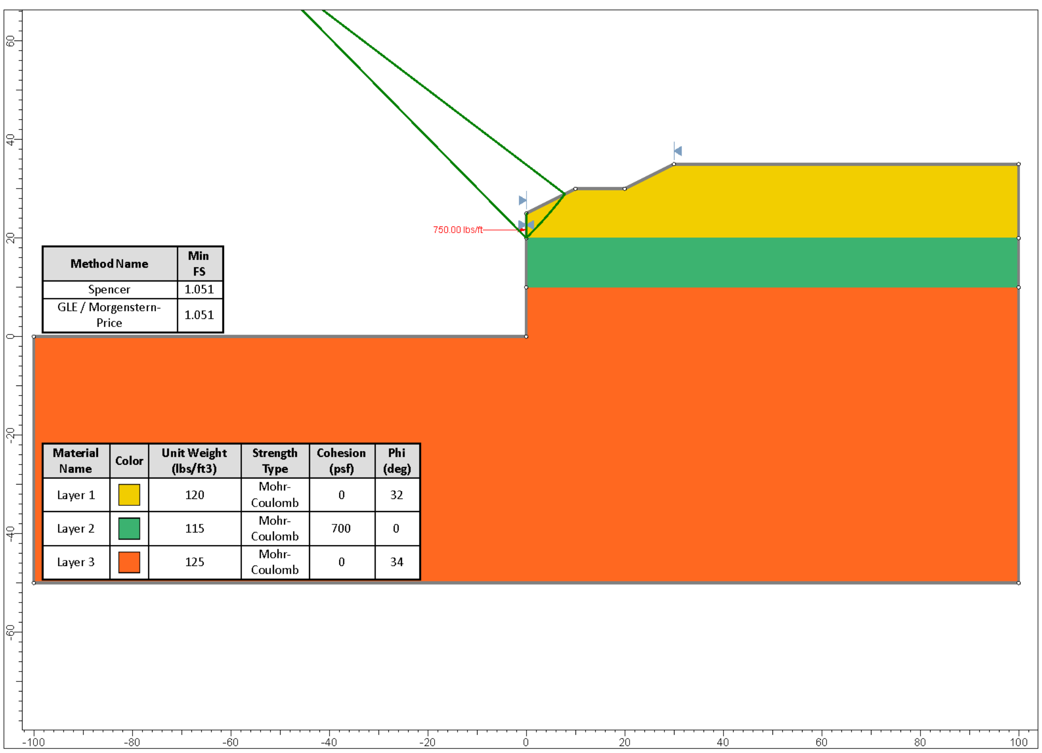

Figure AII-16: GLE Result for Profile No. 3, 1st layer

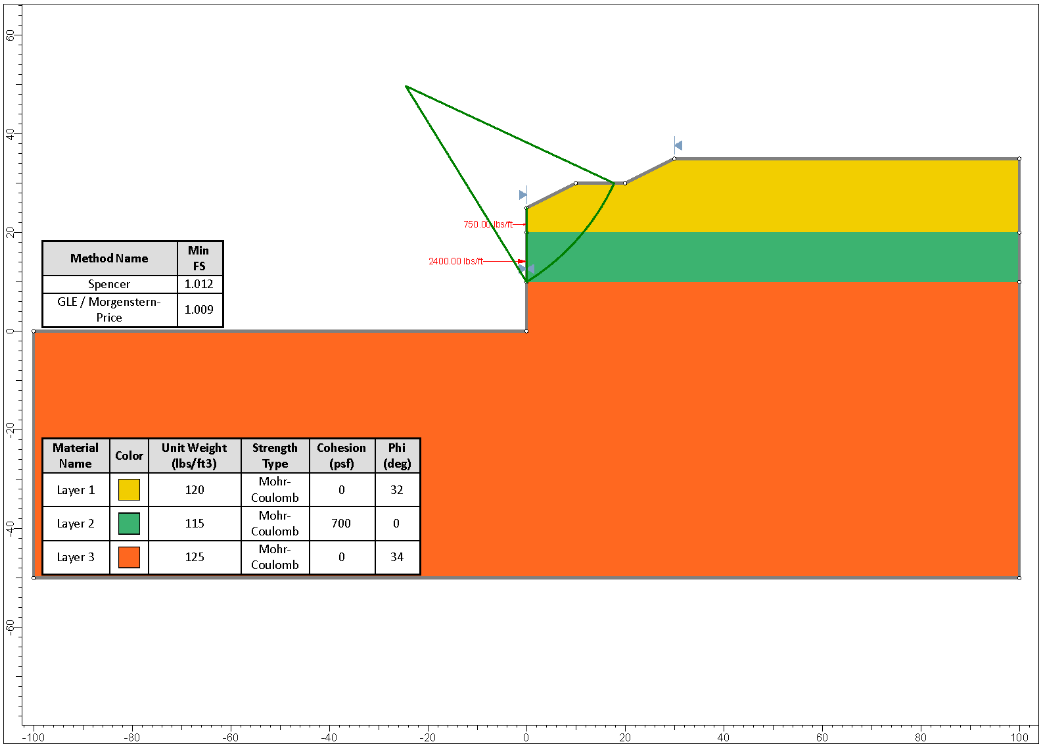

Figure AII-17: GLE Result for Profile No. 3, 2nd layer

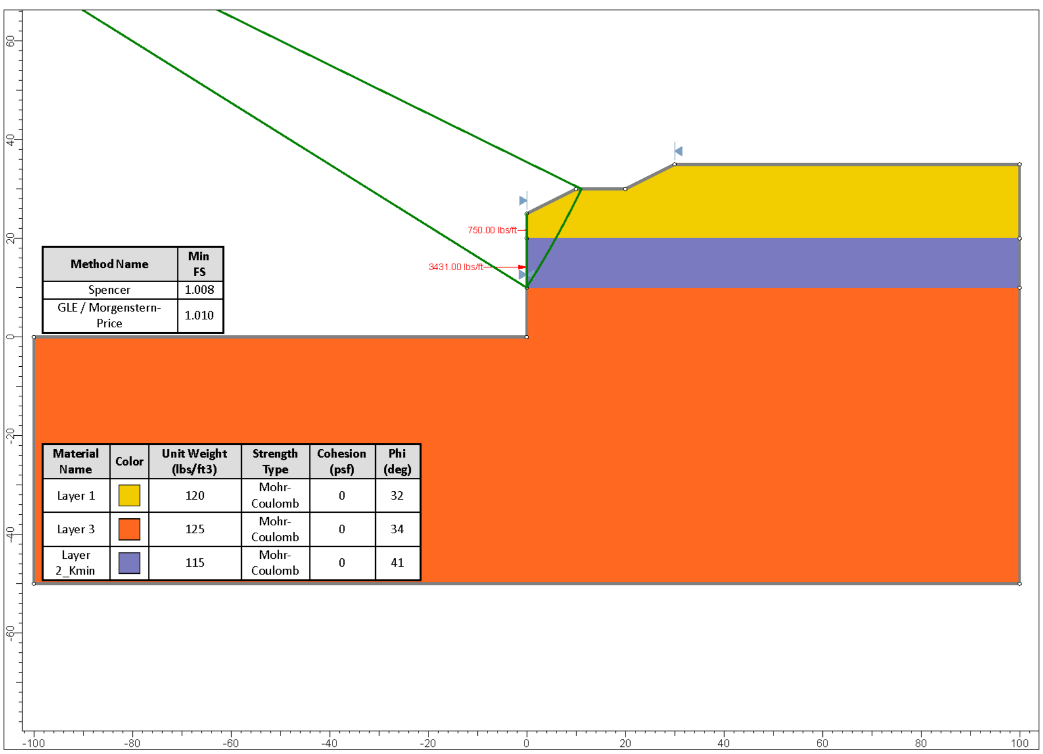

Figure AII-18: GLE Result for Profile No. 3, 2nd layer

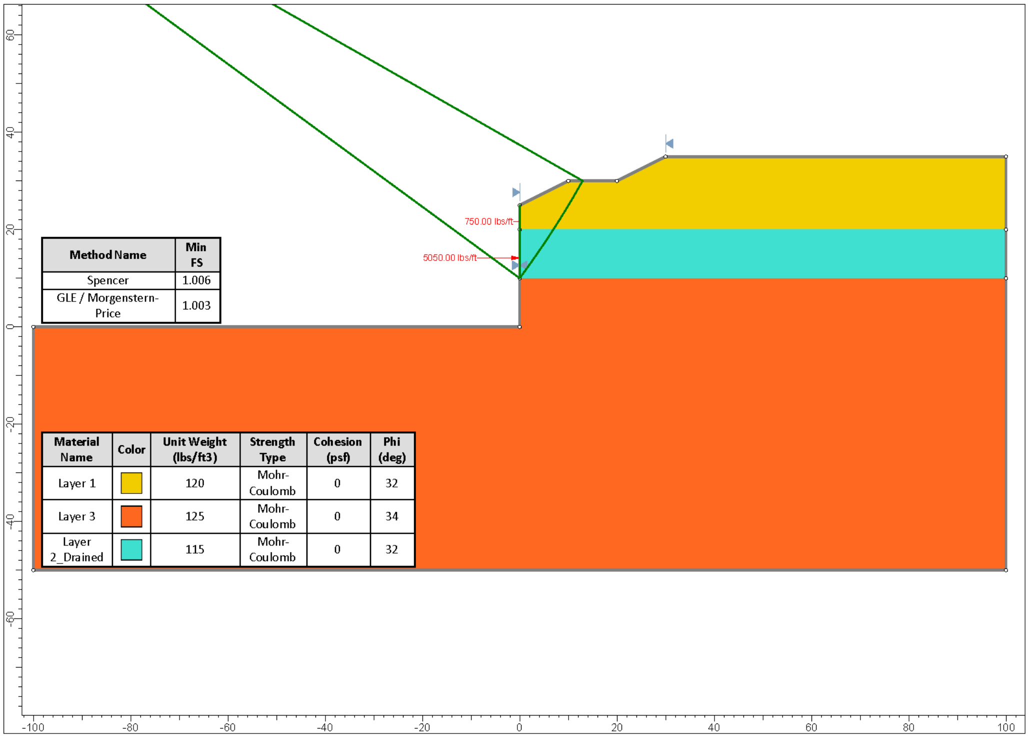

Figure AII-19: GLE Result for Profile No. 3, 2nd layer

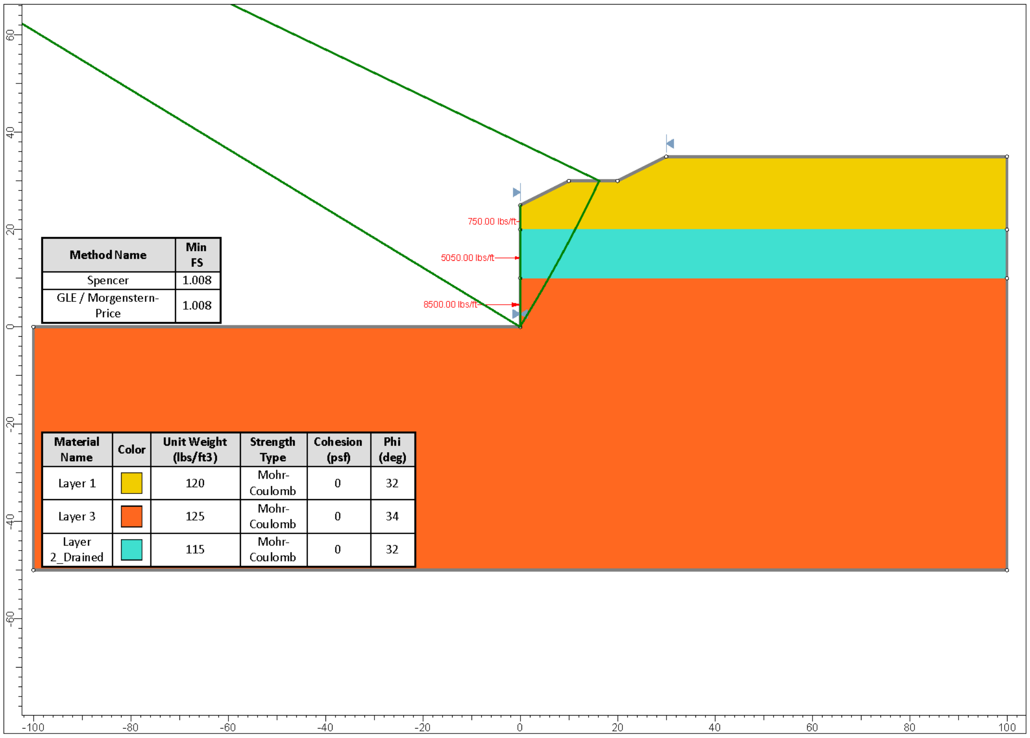

Figure AII-20: GLE Result for Profile No. 3, 3rd layer

Profile No. 4

The soil parameters of Profile No. 4 used for the example analyses are presented in Table AII-10.

Table AII-10: Soil Parameters - Profile No. 4

Layer No.	Soil	Layer Thickness (feet)	Unit Weight (pcf)	Soil Strength Parameters	
				Effective Friction Angle, ϕ' (deg.)	Effective Cohesion (psf)
1	Sand	5	120	32	0
2	Sand	10	115	31	0
3	Sand	10	125	34	0

The model and result of GLE analysis for the proposed method are presented in Figure AII-21 through Figure AII-23. The locations (x_i) of applying Forces (F_i) are calculated as follows:

$$x_1 = \frac{h_1}{3} = \frac{5}{3} = 1.67 \text{ ft.}$$

$$x_2 = \frac{h_2\left(\gamma_1 h_1 + \frac{\gamma_2 h_2}{3}\right)}{(2\gamma_1 h_1 + \gamma_2 h_2)} = \frac{10\left(120 \cdot 5 + \frac{115 \cdot 10}{3}\right)}{(2 \cdot 120 \cdot 5 + 115 \cdot 10)} = 4.18 \text{ ft.}$$

$$x_3 = \frac{h_3\left\{(\gamma_1 h_1 + \gamma_2 h_2) + \frac{\gamma_3 h_3}{3}\right\}}{2(\gamma_1 h_1 + \gamma_2 h_2) + \gamma_3 h_3} = \frac{10\left\{(120 \cdot 5 + 115 \cdot 10) + \frac{125 \cdot 10}{3}\right\}}{2(120 \cdot 5 + 115 \cdot 10) + 125 \cdot 10} = 4.56 \text{ ft.}$$

The required force (F_1) to achieve *FoS* value of 1.0 for 1st layer from GLE analyses is obtained as follows (See Figure AII-21):

F_1 = 750 lbs/ft.

The lateral earth pressure coefficient, K_{a1} for 1st layer is calculated as follows:

$$K_{a1} = \frac{2F_1}{\gamma_1 h_1^2} = \frac{2 \cdot 750}{120 \cdot 5^2} = 0.5$$

For 2nd layer, the required force (F_2) to achieve *FoS* value of 1.0 from GLE analyses is as follows (See Figure 22):

F_2 = 5,300 lbs/ft.

The lateral earth pressure coefficient, K_{a2} for 2nd layer is calculated as follows:

$$K_{a2} = \frac{2F_2}{(2\gamma_1 h_1 + \gamma_2 h_2)h_2} = \frac{2 \cdot 5{,}300}{(2 \cdot 120 \cdot 5 + 115 \cdot 10) \cdot 10} = 0.451$$

The required force (F_3) to achieve *FoS* value of 1.0 for 3rd layer from GLE analyses is as follows (See Figure AII-23):

F_3 = 8,500 lbs/ft.

The lateral earth pressure coefficient, K_{a3} for 3rd layer is calculated as follows:

$$K_{a3} = \frac{2F_3}{(2\gamma_1 h_1 + 2\gamma_2 h_2 + \gamma_3 h_3)h_3} = \frac{2 \cdot 8{,}500}{(2 \cdot 120 \cdot 5 + 2 \cdot 115 \cdot 10 + 125 \cdot 10) \cdot 10} = 0.358$$

The values of K_a determined using GLE are summarized in Table AII-11.

Table AII-11: Summary of K_a determined using GLE - Profile No. 4

Layer No.	Soil	Layer Thickness (feet)	Unit Weight (pcf)	Soil Strength Parameters		Applied Force, F_i (lbs/ft)	K_a
				Effective Friction Angle, ϕ' (deg.)	Effective Cohesion (psf)		
1	Sand	5	120	32	0	750	0.5
2	Sand	10	115	31	0	5,300	0.451
3	Sand	10	125	34	0	8,500	0.358

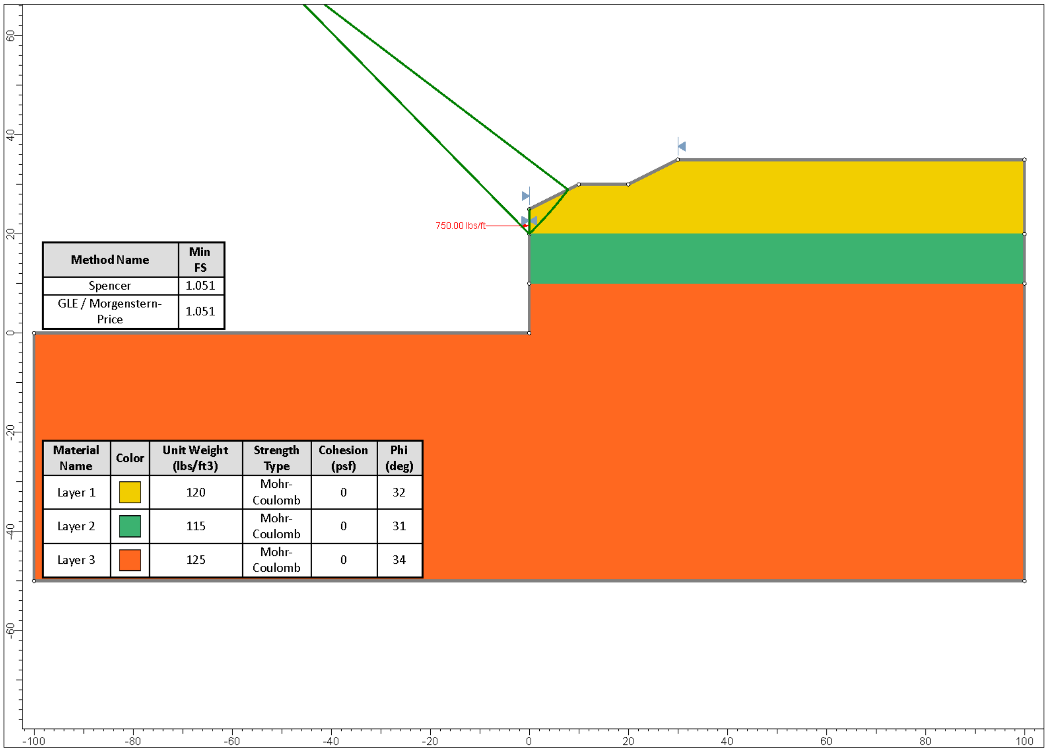

Figure AII-21: GLE Result for Profile No. 4, 1st layer

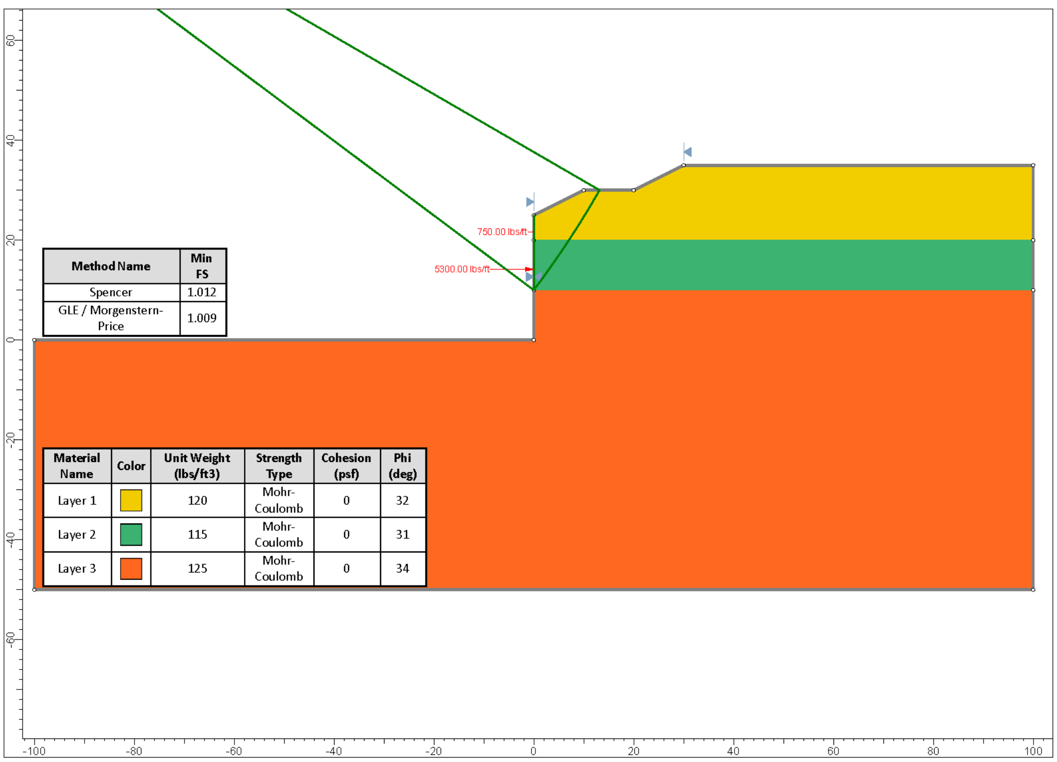

Figure AII-22: GLE Result for Profile No. 4, 2nd layer

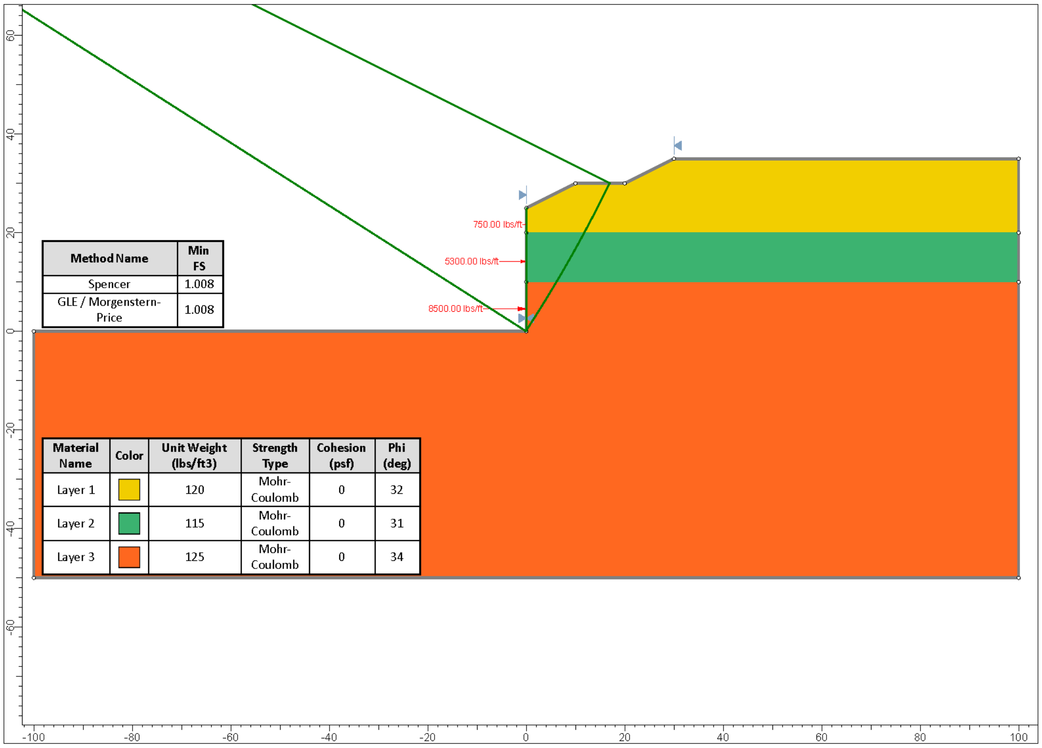

Figure AII-23: GLE Result for Profile No. 4, 3rd layer