

# Evaluation of Limit Equilibrium Analysis Methods for Design of Soil Nail Walls

September 2017



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16. Abstract This document presents a parametric study that demonstrates the broad applicability of the soil nail wall load and resistance factor design (LRFD) and analysis procedure that is detailed in Geotechnical Engineering Circular No. 7 (GEC 7), <i>Soil Nail Walls Reference Manual</i> (FHWA-NHI-14-007), to various soil nail wall design heights, soil parameters, and different commercially available software programs. The parametric study uses a framework for the design of soil nail walls that considers the factors of safety used in the allowable stress design (ASD) analysis method while integrating LRFD design principles as demonstrated in GEC 7. The study starts by analyzing a soil nail structure using an ASD-based limit equilibrium (LE) slope stability program at a defined minimum target factor of safety. From the LE results, the nominal tensile, pullout, and facing loads of each soil nail are extracted. The extracted data are then checked using the LRFD platform using the procedures, and the load and resistance factors, presented in GEC 7.			
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# SI\* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
<b>LENGTH</b>				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
<b>AREA</b>				
in <sup>2</sup>	square inches	645.2	square millimeters	mm <sup>2</sup>
ft <sup>2</sup>	square feet	0.093	square meters	m <sup>2</sup>
yd <sup>2</sup>	square yard	0.836	square meters	m <sup>2</sup>
ac	acres	0.405	hectares	ha
mi <sup>2</sup>	square miles	2.59	square kilometers	km <sup>2</sup>
<b>VOLUME</b>				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft <sup>3</sup>	cubic feet	0.028	cubic meters	m <sup>3</sup>
yd <sup>3</sup>	cubic yards	0.765	cubic meters	m <sup>3</sup>
NOTE: volumes greater than 1000 L shall be shown in m <sup>3</sup>				
<b>MASS</b>				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
<b>TEMPERATURE (exact degrees)</b>				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
<b>ILLUMINATION</b>				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m <sup>2</sup>	cd/m <sup>2</sup>
<b>FORCE and PRESSURE or STRESS</b>				
lbf	poundforce	4.45	newtons	N
lbf/in <sup>2</sup>	poundforce per square inch	6.89	kilopascals	kPa

## APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
<b>LENGTH</b>				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
<b>AREA</b>				
mm <sup>2</sup>	square millimeters	0.0016	square inches	in <sup>2</sup>
m <sup>2</sup>	square meters	10.764	square feet	ft <sup>2</sup>
m <sup>2</sup>	square meters	1.195	square yards	yd <sup>2</sup>
ha	hectares	2.47	acres	ac
km <sup>2</sup>	square kilometers	0.386	square miles	mi <sup>2</sup>
<b>VOLUME</b>				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m <sup>3</sup>	cubic meters	35.314	cubic feet	ft <sup>3</sup>
m <sup>3</sup>	cubic meters	1.307	cubic yards	yd <sup>3</sup>
<b>MASS</b>				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
<b>TEMPERATURE (exact degrees)</b>				
°C	Celsius	1.8C+32	Fahrenheit	°F
<b>ILLUMINATION</b>				
lx	lux	0.0929	foot-candles	fc
cd/m <sup>2</sup>	candela/m <sup>2</sup>	0.2919	foot-Lamberts	fl
<b>FORCE and PRESSURE or STRESS</b>				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in <sup>2</sup>

\*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.  
(Revised March 2003)

## EXECUTIVE SUMMARY

Transportation structures and substructures are currently designed using a load and resistance factor design (LRFD) platform. Soil nail walls, a type of substructure commonly used in transportation works, have traditionally been designed using limit equilibrium (LE) slope stability software and an allowable stress design (ASD) platform. In limit equilibrium slope stability analyses, the soil is both a load (i.e., weight of the soil) and a resistance (i.e., soil shear strength is a function of the normal load, or soil weight). This makes applying LRFD principles to limit equilibrium analysis difficult, and an LRFD limit equilibrium slope stability procedure does not exist. Therefore, ASD-based LE procedures for analysis of soil nail walls is required. To complete an LRFD-based design from the ASD LE results, the nominal loads from the analysis first must be identified for each soil nail. Next, appropriate load and resistance factors must be applied to each nail and potential failure mode. Then, the capacity to demand ratio (CDR) for each nail and potential failure mode can be calculated. The initial design should be revised, if necessary, to achieve a  $CDR \geq 1.0$  for each nail and potential failure mode.

The Federal Highway Administration (FHWA) *Soil Nail Walls Reference Manual* (Geotechnical Engineering Circular No. 7 [GEC 7]) (Lazarte et al. 2015) provides detailed guidance and procedures on how to execute LRFD-compliant designs using results from ASD LE analyses. A detailed design example, using analysis results from the soil nail analysis program (SNAP-2), is presented in Appendix C of GEC 7. Subsequent to publication, the applicability and validity of procedures presented in GEC 7 to analysis results from other (except SNAP-2) soil nail wall analysis programs have been questioned.

The parametric study, reported within, evaluated the use of three very different commercially available LE soil nail software programs to develop LRFD-compliant designs. The Snail, Slide, and SNAP-2 programs were used to analyze a wide variety of soil nail structures, and the results from each were used to perform LRFD checks, following GEC 7 procedures. The purpose of this study was to confirm that GEC 7 LRFD platform-based design guidance and procedures, including recommended resistance factors, could be applied to a variety of software program results, with resulting designs that are consistent with past ASD-based designs and industry-standard factors of safety.

Thirteen different wall scenarios were investigated using each of the three soil nail analysis programs. The LRFD design framework presented in GEC 7 was demonstrated to work with three very different ASD LE soil nail stability software programs. All three programs provided LRFD-compliant designs when they used the appropriate factors of safety for the various modes of failure in the ASD analysis.

The broad applicability of the soil nail wall analysis and design procedures detailed in GEC 7 was clearly demonstrated by this study. Therefore, it is concluded that designers and engineers can confidently use GEC 7 guidance and procedures with the analysis results from the ASD LE soil nail program of their choice for LRFD-based soil nail wall designs.

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## 1 Background

This report documents a parametric study performed to evaluate the breadth of applicability of the guidance and procedures presented in the 2015 updated Federal Highway Administration (FHWA) Geotechnical Engineering Circular No. 7 (GEC 7) (Lazarte et al. 2015) for load and resistance factor design (LRFD)-based design of soil nail walls.

GEC 7 is an LRFD platform-based design method for soil nail walls. Load factors used within GEC 7 are consistent with the American Association of State Highway and Transportation Officials (AASHTO 2014) *LRFD Bridge Design Specifications*. Recommended soil nail wall resistance factors that were calibrated to past allowable stress design (ASD) platform-based designs are provided in GEC 7. Applicability of the GEC 7 design procedures and of recommended resistance factors was demonstrated within GEC 7 with an appended design example. That design example used the SNAP-2 computer program to analyze a soil nail structure using ASD platform-based limit equilibrium (LE) analyses. Nominal load values were identified in the analysis results and were used to perform an LRFD platform-based design (or design verification) of the example soil nail wall structure.

The purpose of this parametric analysis was to extend the verification of the GEC 7 guidance and procedures to various soil nail wall design heights, soil parameters, and commercially available software programs beyond the single example presented in Appendix C of GEC 7. Three soil nail computer programs were used to analyze thirteen different soil nail wall design cases.

It was anticipated that this parametric study would demonstrate that GEC 7 (LRFD platform-based) procedures produce designs that are equivalent to, or slightly more conservative than, previous ASD platform-based designs. The parametric designs incorporate the following:

- ASD-based LE slope stability analyses to locate critical slip surface geometries and to quantify nominal soil nail loads
- Load factors following AASHTO (2014) and GEC 7
- Resistance factors as listed in GEC 7

## **2 Purpose**

The purpose of this study was to demonstrate the broad applicability of the soil nail wall LRFD design and analysis procedure (detailed in GEC 7) to various soil nail wall designs heights, soil parameters, and different commercially available software programs beyond the single example presented in Appendix C of GEC 7. The procedure starts with the analysis of a soil nail structure using an ASD-based LE slope stability program with a defined minimum target factor of safety (FS). Next, the nominal tensile, pullout, and facing loads of each soil nail are extracted from the stability analysis. This information enables an LRFD check, or *design*, to be performed using the load and resistance factors presented in GEC 7. The factored resistance must be equal to or greater than the factored load, often referred to as a capacity to demand ratio (CDR), to meet LRFD requirements. The nails are adjusted if needed to achieve CDR values that are equal to or greater than 1.0.

## **3 Scope**

A variety of design parameters were investigated using three different commercially available soil nail design software programs (i.e., SNAP-2, SNAIL, and SLIDE) to demonstrate that limit equilibrium software can provide LRFD-compliant designs when following GEC 7.

Each of the software programs is discussed in detail in Section 6, Software Descriptions. Thirteen different wall scenarios were investigated and are described in Table 1. Thirteen groups of three cases were completed, for a total of thirty-nine parametric analyses.

**Table 1 Soil Nail Analysis Cases**

<b>Group</b>	<b>Case Numbers</b>	<b>Analysis Programs</b>	<b>Height (ft)</b>	<b>Soil <math>\phi</math> (deg)</b>	<b>Soil c (psf)</b>	<b>Bond Strength (psi)</b>
A	1, 2, 3	SNAP-2, SNAIL, SLIDE	30	30	0	10
B	4, 5, 6	SNAP-2, SNAIL, SLIDE	30	30	0	20
C	7, 8, 9	SNAP-2, SNAIL, SLIDE	30	38	0	10
D	10, 11, 12	SNAP-2, SNAIL, SLIDE	30	38	0	20
E	13, 14, 15	SNAP-2, SNAIL, SLIDE	50	30	0	10
F	16, 17, 18	SNAP-2, SNAIL, SLIDE	50	30	0	20
G	19, 20, 21	SNAP-2, SNAIL, SLIDE	50	38	0	10
H	22, 23, 24	SNAP-2, SNAIL, SLIDE	50	38	0	20
I1	25, 26, 27	SNAP-2, SNAIL, SLIDE	30	35	0	9
J1	28, 29, 30	SNAP-2, SNAIL, SLIDE	30	38	0	15
K3	31, 32, 33	SNAP-2, SNAIL, SLIDE	30	30	0	28
L4	34, 35, 36	SNAP-2, SNAIL, SLIDE	30	38	0	8
M <sup>5</sup>	37, 38, 39	SNAP-2, SNAIL, SLIDE	25	32	100	14.5

1. Team A Class Exercise
2. Team B Class Exercise
3. Team C Class Exercise
4. Team D Class Exercise
5. GEC 7 Example Problem

## 4 Limit Equilibrium Design Method

The slope stability software programs utilized in this parametric study use a methodology that incorporates LE analysis in the ASD platform for determining global stability. In the LE method, a slip surface is assumed and the mobilized shear strength along the surface is determined. The slip surface shape varies and can consist of a non-circular surface (i.e., planar surface, two-part surface, three-part wedge), circular surface, or log-spiral surface. There are many different LE methods used in global slope stability analysis. LE can be determined for the entire soil mass by solving for a single free body or by discretizing the soil mass into a series of slices and free bodies. In the discretizing method, the slices are treated as unique sliding blocks and the factor of safety of each block is assumed to be equal. Equilibrium must be satisfied for both force and moment conditions.

Single free body methods may consist of infinite slope, log spiral, or Swedish slip circle. Slice methods may consist of ordinary method of slices, Fellenius, Simplified Bishop, Janbu, Janbu corrected, Spencer, Morgenstern and Price, Chen and Morgenstern, Lowe and Karafiath, and U.S. Army Corps of Engineers. The difference in these methods is in how force and moment equilibrium is satisfied.

Slope stability software programs account for uncertainties in the design by applying a factor of safety to the available shear strength of the soil. It can be assumed that a weaker soil is formed when the available shear strength is divided by the FS.

$$\text{Mobilized Shear Strength} = \frac{\text{Available Shear Strength}}{\text{FS}}$$

Equation 1

The FS is the ratio of available shear strength to the mobilized shear strength. The mobilized shear strength is also known as the equilibrium shear strength. The available shear strength typically follows the Mohr Coulomb failure criteria.

$$FS = \frac{\text{Available Shear Strength}}{\text{Mobilized Shear Strength}} \rightarrow \frac{c + \sigma_n \cdot \tan(\phi)}{\tau}$$

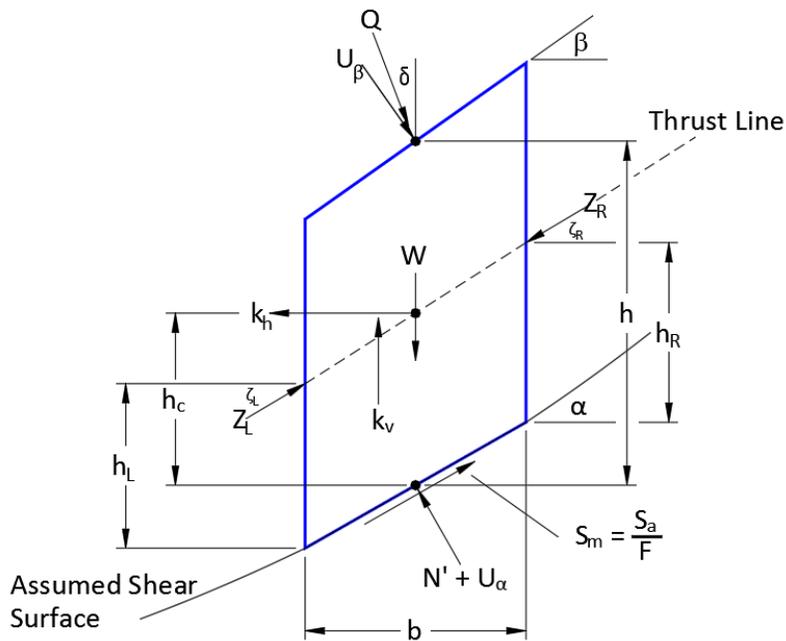
Equation 2

- Where:
- FS = factor of safety (dim)
  - $\tau$  = mobilized shear strength (ksf)
  - c = cohesive strength of soil (ksf)
  - $\sigma_n$  = normal stress (ksf)
  - $\phi$  = internal friction angle of soil (deg)

A FS value that is less than 1.0 correlates to a slope that has exceeded LE, or that has failed. LE is achieved when the available shear strength is equal to or greater than the mobilized shear strength, in other words, when the FS is equal to 1.0. The FS concept can be extended to the moment equilibrium equation as shown in Equation 3.

$$FS = \frac{\Sigma(\text{Resisting Moments})}{\Sigma(\text{Overturning Moment})} \tag{Equation 3}$$

In the slices method, a failure shape is assumed and an overall system of forces integral to each slice is determined as shown in Figure 1.



**Figure 1 Force Diagram of Typical Slice after Abramson 1996**

Where:	$F$	=	factor of safety (dim)
	$S_a$	=	available shear strength (psf)
	$S_m$	=	mobilized shear strength (psf)
	$U_\alpha$	=	pore water force (lbf)
	$U_\beta$	=	surface water force (lbf)
	$W$	=	weight of slice (lbf)
	$N'$	=	effective normal force (lbf)
	$Q$	=	external surcharge (lbf)
	$k_v$	=	vertical seismic coefficient (dim)
	$k_h$	=	horizontal seismic coefficient (dim)
	$Z_L$	=	left interslice force (lbf)
	$Z_R$	=	right interslice force (lbf)
	$\zeta_L$	=	left interslice force angle (deg)
	$\zeta_R$	=	right interslice force angle (deg)
	$h_L$	=	height of left interslice force (ft)
	$h_R$	=	height of right interslice force (ft)
	$\alpha$	=	inclination of slice base (deg)
	$\beta$	=	inclination of slice top (deg)
	$b$	=	slice width (ft)
	$h$	=	slice height (ft)
	$h_c$	=	height to centroid of slice (ft)

Depending on the method that is used, some or all of the interslice forces may be ignored. In the slice shown in Figure 1, a thrust line that connects the interslice forces is shown. This line of thrust is typically assumed or it is determined using a rigorous method of analysis that satisfies complete equilibrium (Abramson 1996). When a method ignores the interslice forces, complete equilibrium is not satisfied.

General assumptions, such as the location and inclination of the interslice force, are made in each slice method to reduce the system of equations to a statically determinant analysis. The system of slice forces can be resolved into horizontal and vertical components or into force components that are tangential (parallel) and perpendicular (normal) to the base of the slice. The forces and moments are then summed. The summed forces and moments are then compared to the mobilized shear strength along the sliding surface.

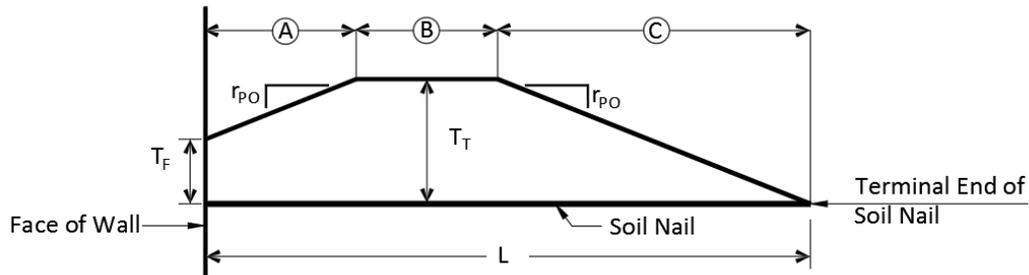
#### 4.1 Introduction of Soil Inclusion to Slope Stability

LE methods can be used to analyze structures that use soil inclusions by including the reinforcement force in the analysis. The analysis is typically an iterative process, where the reinforcement properties are varied until the target factor of safety is achieved. Based on the general equation in slope stability, the reinforcement effects can be *subtracted* from the *mobilized* shear strength equation or *added* to the *available* shear strength equation. These methods are known in the literature as Method A (Active) and Method B (Passive), shown in Equations 4 and 5, respectively.

$$FS = \frac{\text{Available Shear Strength}}{\text{Mobilized Shear Strength} - \text{Reinforcement Strength}} \quad \text{Equation 4}$$

$$FS = \frac{\text{Available Shear Strength} + \text{Reinforcement Strength}}{\text{Mobilized Shear Strength}} \quad \text{Equation 5}$$

The reinforcement force is a function of the soil nail resistance, pullout resistance, and the facing resistance (Figure 2).



**Figure 2 Soil Nail Resistance Envelope**

- Where:
- $T_F$  = facing resistance (kip)
  - $T_T$  = soil nail resistance (kip)
  - $r_{PO}$  = soil nail resistance to pullout (kip/ft)
  - $L$  = soil nail length
  - $A$  = zone where facing resistance controls (dim)
  - $B$  = zone where soil nail controls (dim)
  - $C$  = zone where pullout controls (dim)

If the failure surface intersects in Zone A (see Figure 2), facing resistance controls. If the failure surface intersects in Zone B, the soil nail tensile resistance controls. If the failure surface intersects in Zone C, pullout of the soil nail controls. The reinforcement force in Equation 4 and Equation 5 is equal to the zone where the failure surface intersects the soil nail. Each zone has uncertainties associated with it and the factors of safety are different, and therefore the LRFD resistance factors applied to the respective nominal resistances of each are different.

In Method A, the reinforcement acts to decrease the driving force or driving moment, and the reinforcement forces are input as an allowable force, i.e., divided by the factor of safety for the material (tension, pullout, flexure, shear). As shown in Equation 4, only the soil strength is divided by the factor of safety in the analysis. In Method B, the reinforcement acts to increase the resisting force or resisting moment. The reinforcement forces are required to be input as the nominal force and are then divided by the factor of safety calculated in the slope stability analysis. Because of this, the method assumes that the uncertainty of the soil strength and the inclusion strength are equal. Therefore, Method B does not fit in the framework of the LRFD platform used in this parametric study and this method will not be used.

The software programs SNAP-2 and SLIDE each use the Simplified Bishop method, and therefore a circular failure surface is assumed. It should be noted that SLIDE has many different LE options to select from, and the Simplified Bishop method was selected to be used in this parametric study. The software program SNAIL uses a force equilibrium method, and a two-part wedge failure surface is used for the stability analysis.

#### **4.2 Circular Failure Surface – Simplified Bishop Method**

The software program SNAP-2 uses the Simplified Bishop method in conjunction with Method A for the soil nail inclusion. These methods were used in the software program SLIDE to be consistent with SNAP-2. Again, it should be noted that the Simplified Bishop method is not the only method that can be used in the design of earth retaining structures with inclusions.

The Simplified Bishop method uses a circular failure surface and assumes the interslice forces are horizontal and that there are no interslice shear stresses between each slice. This method satisfies vertical force equilibrium and overall moment equilibrium about the center of a circular failure surface. Horizontal force equilibrium is not satisfied.

The overall moment equilibrium of each slice is determined about the center of the circle. The Simplified Bishop method assumes that the FS is equal for each slice. Based on this, and through algebraic manipulation, the solution to the Simplified Bishop equation provided in most slope stability textbooks and design manuals is given by Equation 6 through Equation 11. Note that Equation 6 has been simplified by dividing through by the radius (R). The variables in the equation are given in Figure 1.

$$FS = \frac{\sum_{i=1}^n (c + N'_i \cdot \tan \phi)}{\sum_{i=1}^n (A_1 - A_2 + A_3)} \quad \text{Equation 6}$$

Where:

$$N'_i = \frac{1}{m_\alpha} \left[ \begin{array}{l} -U_\alpha - k_h \cdot W \cdot \sin \alpha + W \cdot (1 - k_v) \cdot \cos \alpha \\ + U_\beta \cdot \cos(\beta - \alpha) + Q \cdot \cos(\delta - \alpha) \end{array} \right] \quad \text{Equation 7}$$

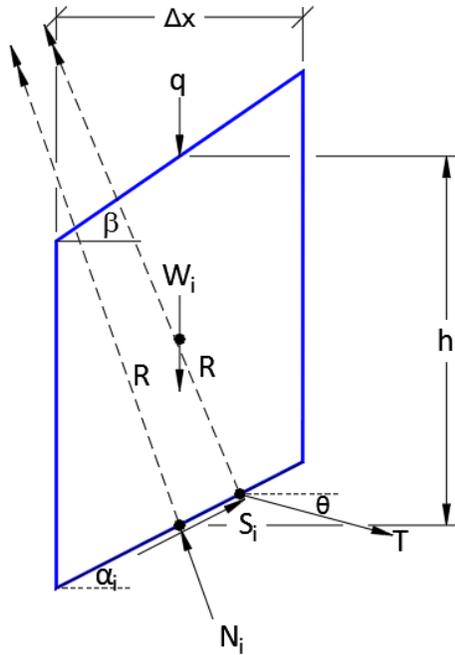
$$A_1 = (W \cdot (1 - k_v) + U_\beta \cdot \cos \beta + Q \cdot \cos \delta) \quad \text{Equation 8}$$

$$A_2 = (U_\beta \cdot \sin \beta + Q \cdot \sin \delta) \cdot \left( \cos \alpha - \frac{h}{R} \right) \quad \text{Equation 9}$$

$$A_3 = (k_h \cdot W) \cdot \left( \cos \alpha - \frac{h}{R} \right) \quad \text{Equation 10}$$

$$m_\alpha = \cos \alpha \left( 1 + \frac{\tan \alpha \cdot \tan \phi}{FS} \right) \quad \text{Equation 11}$$

A detail of the system of forces for a slice in a slope that has no pore water pressures and no seismic forces is illustrated in Figure 3.



**Figure 3 Force Diagram of Typical Slice after Abramson 1996**

In addition, the detail shows the soil nail force T. When this system of forces is used, Equation 6 reduces to Equation 12.

$$FS = \sum_{i=1}^n \frac{1}{m_{\alpha_i}} \frac{[c \cdot \Delta x_i + (W + T \cdot \sin(\theta)) \cdot \tan(\phi_i) + q \cdot \Delta x_i]}{W \cdot \sin(\alpha_i) - T \cdot \sin(\alpha_i + \theta)} \quad \text{Equation 12}$$

- Where:
- i = slice number (dim)
  - n = number of slices (dim)
  - c = cohesion of slice (psf)
  - $\Delta x_i$  = slice width (ft)
  - W = weight of slice (lbf/ft)
  - T = allowable force in soil nail (lbf/ft)
  - $\theta$  = inclination of soil nail from the horizontal (deg)
  - $\phi_i$  = internal friction angle of slice (deg)
  - q = surcharge (psf)
  - $\alpha_i$  = inclination of slice base from horizontal (deg)

Because the FS (note that FS is in the variable  $m_{ai}$ ) is on both sides of the equation, the solution requires iteration. It is important to note that the inclination of the soil nail and the sign used for the angle, i.e., positive clockwise or counterclockwise, determines the sign for the soil nail force in the numerator of the equation. When Method A is used, the capacity of the soil nail is reduced to the allowable tensile capacity prior to input into the program. In other words, the tensile capacity is reduced by the required factor of safety for strength. It should also be noted that because pullout of the soil nail and facing failure are possible failure mechanisms, they are implied in Equation 12. That is, if pullout controls, it is used in place of the soil nail force; likewise, if facing strength controls, it is used in place of the soil nail force. The facing strength and pullout are each reduced by their respective appropriate factor of safety.

#### 4.3 Force Equilibrium – Noncircular surface

For a failure surface that is not a simple shape, such as planar, circular, or log-spiral, force equilibrium is satisfied. The forces may be resolved into vertical and horizontal components or perpendicular and tangential components. The software program SNAIL uses a two-part or three-part wedge with a force equilibrium procedure to determine the factor of safety. Interslice forces are considered, and the inclination of the application of the interslice force is prescribed by the user. The system of forces shown in Figure 1 can be used. The generalized equation for the FS in the force equilibrium method is given in Equation 13.

$$FS = \frac{\Sigma \text{Resisting Forces}}{\Sigma \text{Driving Forces} - \Sigma \text{Reinforcement Forces}} \quad \text{Equation 13}$$

Because the reinforcement acts to decrease the driving force, Equation 13 is equivalent to Method A. As defined in Section 4.1 in this report, the reinforcement forces are the allowable force, i.e., they are divided by the factor of safety for the material (tension, pullout, flexure, shear) before input into the equation. Only the resisting force (i.e., the soil strength) is divided by the stability factor of safety in the analysis. Figure 4 shows the system of forces acting on a two-part wedge failure surface that passes through the toe of a vertical faced structure (with no seismic forces or pore water pressure) when an external load is applied to the surface of the structure

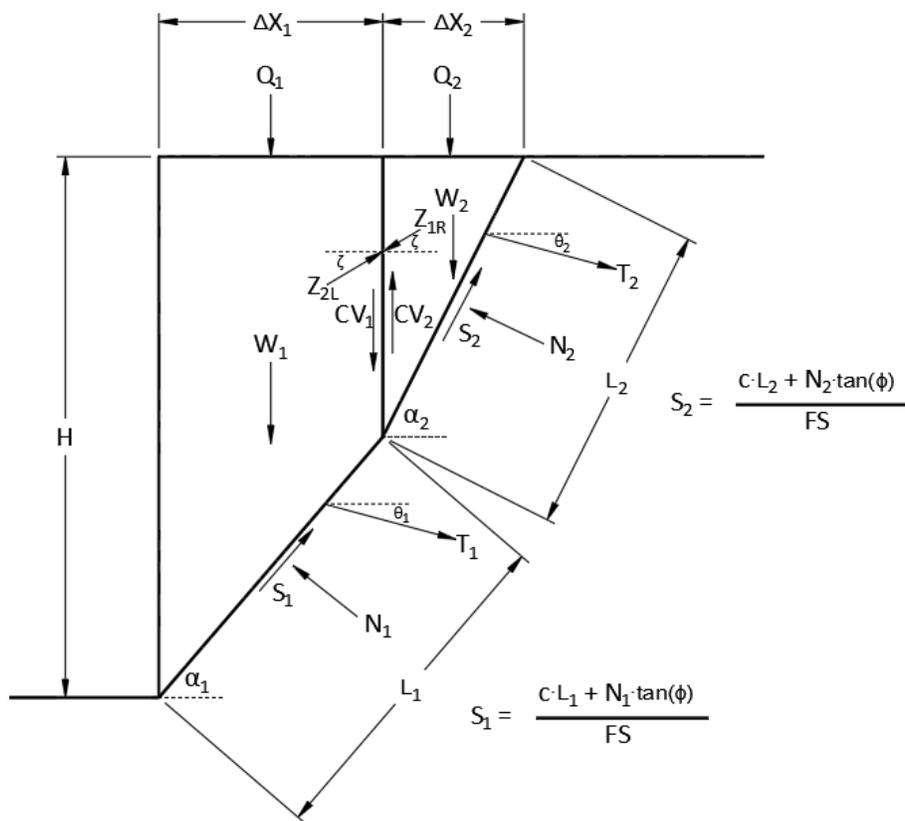


Figure 4 System of Forces for Two-Part Wedge

Where:	$H$	=	height of structure (ft)
	$L_i$	=	length of base of the slice (ft)
	$\alpha_i$	=	angle of base of the slice (deg)
	$\Delta x_i$	=	width of the slice (ft)
	$S_i$	=	mobilized shear on the slice (lbf/ft)
	$N_i$	=	normal force of slice-1 (lbf/ft)
	$W_i$	=	weight of the slice (lbf/ft)
	$Q_i$	=	external surcharge load applied to the slice (lbf/ft)
	$T_i$	=	total resistance force from the soil nail over the slice (lbf/ft)
	$\theta_i$	=	inclination of the soil nails over the slice (deg)
	$CV$	=	interslice shear force due to cohesion (lbf/ft)
	$Z$	=	interslice force acting between the slice (lbf/ft)
	$\zeta$	=	inclination of the interslice force (deg)
	$c$	=	cohesion of slice (psf)
	$\phi$	=	internal friction angle of the slice (deg)

In this force equilibrium analysis method, the interslice forces are not known. The angle at which the interslice forces are applied is assumed by the user. There are several different procedures to determine the assumed forces such as the Lowe and Karafiath, simplified Janbu, and the U.S. Army Corps of Engineers methods. Because the interslice forces are not known, the solution to the equation is iterative and is found through trial and error.

## 5 ASD Platform-Based Analyses and LRFD Platform-Based Design

The software programs used in this parametric study, to design the soil nail structure, use the ASD platform. The ASD slope stability results are used to quantify nominal tendon tensile loads, nominal pullout loads, and nominal facing loads. The CDR for tendon tension, nail pullout, and facing design are then quantified using these computed nominal loads and the load factors and resistance factors presented in GEC 7. The factors of safety the slope analysis given in GEC 7 are shown in Table 2. Note that in GEC 7 it is specified that the FS for temporary applications are equal to the permanent application. The user should verify in the software program which FS is used in the temporary application and the permanent application.

**Table 2 ASD Factors of Safety (GEC 7 Table 5.1)**

Location	Variable	Value
Factor of Safety for Yield	$FS_T$	1.80
Factor of Safety for Pullout	$FS_{PO}$	2.00
Factor of Safety for Facing Flexure (Permanent)	$FS_{FF}$	1.50
Factor of Safety for Facing Flexure (Temporary)	$FS_{FF\_T}$	1.50
Factor of Safety for Punching Shear (Permanent)	$FS_{FP}$	1.50
Factor of Safety for Punching Shear (Temporary)	$FS_{FP\_T}$	1.50
Factor of Safety for Headed-Stud (Permanent)	$FS_{FH}$	2.00
Factor of Safety for Headed-Stud (Temporary)	$FS_{FH\_T}$	1.50

The general equation that is used in the LRFD framework is given in GEC 7 Equation 5.4 and is reproduced here in Equation 14.

$$\phi \cdot R_n \geq \sum_{i=1}^N \gamma_i \cdot \eta_i \cdot Q_i$$

Equation 14

Where:	$R_n$	=	nominal resistance of the structural component at a given limit state
	$\phi$	=	resistance factor related to $R_n$
	$\gamma_i$	=	load factor related to $Q_i$
	$\eta_i$	=	load-modification factor relating to ductility, redundancy, or operational classification (equal to 1.0 for soil nail walls)
	$Q_i$	=	generic load
	$i$	=	various loads/effects in the limit state
	$N$	=	total number of loads/effects in the limit state

Equation 14, establishes that the LRFD framework accounts for uncertainties in design through the use of load factors and resistance factors and that these factors are unique to each component. This is in contrast to ASD, which uses one FS that is applied to all the loads in the system. This is the fundamental reason that Method B (see Equation 5) in slope stability analysis should not be used when using the procedures described in this parametric analysis.

In the LRFD platform, the factored resistance is required to be greater than or equal to the factored load as dictated by the inequality sign in Equation 14. Based on this, the ratio of the factored load to the factored resistance (CDR) is required to be greater than one. The CDR is used to quantify the ratio of the factored resistance to the factored load as shown in Equation 15.

$$CDR = \frac{\phi \cdot R_n}{\sum_{i=1}^N \gamma_i \cdot \eta_i \cdot Q_i}$$

Equation 15

When examining individual components of a soil nail wall, this equation simplifies to Equation 16.

$$CDR = \frac{\phi \cdot R}{\gamma \cdot Q}$$

Equation 16

In the framework of the LRFD for a soil nail structure, the nominal resistances ( $R_n$ ) include the yield strength of soil nails, the pullout resistance of soil nails, and resistance of the facing components. The load factors and their combinations are given in AASHTO (2014) Section 3 and are summarized in GEC 7. Currently, resistance factors for soil nail structures are not provided in AASHTO (2014). GEC 7 defines resistance factors for the soil nail structure in Table C.2, which is reproduced in this report in Table 3. For each of the CDR calculations, the load factor is typically set equal to the maximum vertical earth pressure factor of 1.35, as given in AASHTO (2014) Section 3 and as discussed in GEC 7.

**Table 3 LRFD Resistance Factor (after GEC 7 Table C.2)**

<b>Strength Limit State</b>	<b>Symbol</b>	<b>Resistance Factor</b>
Overall Stability	$\phi_{OS}$	0.65
Nail Pullout	$\phi_{PO}$	0.65
Nail Tension	$\phi_T$	0.75
Facing Flexure	$\phi_{FF}$	0.90
Facing Punching Shear	$\phi_{FP}$	0.90
Facing Headed Stud Tensile	$\phi_{FH}$	0.70

## **6 Software Descriptions**

Three commercially available software programs (i.e., SNAP-2, SNAIL, and SLIDE) were used in the parametric analysis. The parametric analysis was performed on simple soil nail structures. In each of the cases, the structures were designed assuming a vertical wall facing, horizontal back-slope, no external surcharge, uniform size and length soil nails, and one in situ soil type.

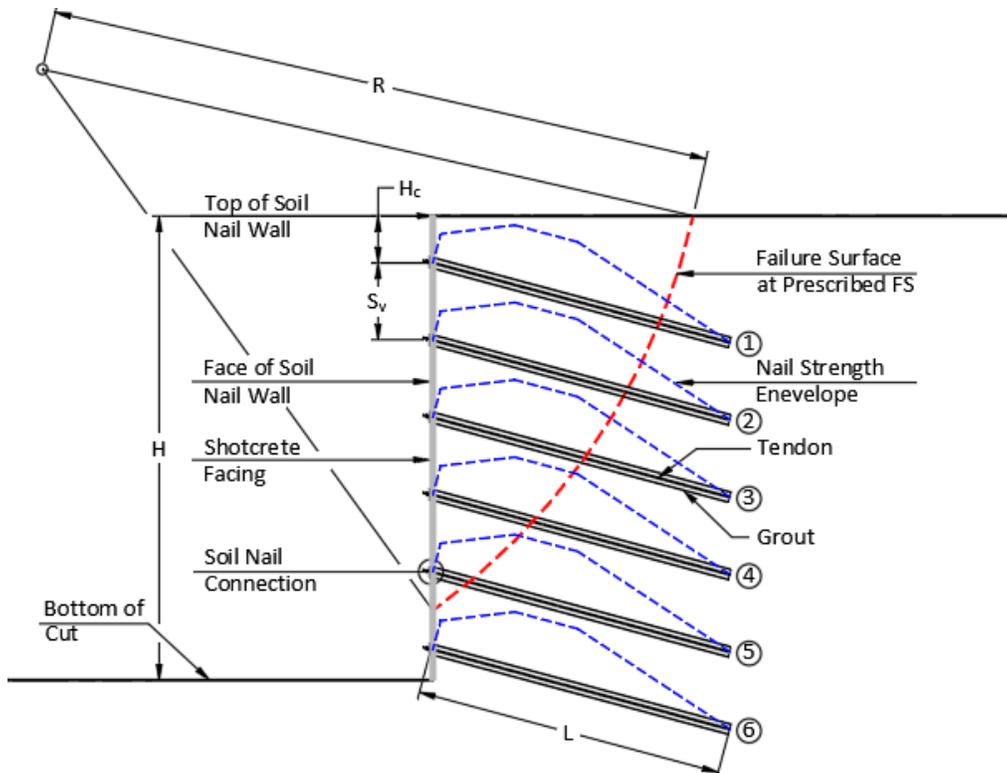
Each software program used in the parametric analysis is briefly discussed in this section. For a more detailed description, the reader is encouraged to view the respective websites of each of the vendors. The user manuals are given in the hyperlinks below:

- SNAP-2 - <https://www.fhwa.dot.gov/engineering/geotech/software/snap2/snap2.pdf>
- SNAIL - [http://www.dot.ca.gov/hq/esc/geotech/software/snail/Snail\\_User\\_Guide.pdf](http://www.dot.ca.gov/hq/esc/geotech/software/snail/Snail_User_Guide.pdf)
- SLIDE - [https://www.rocscience.com/downloads/slide/Slide\\_TutorialManual.pdf](https://www.rocscience.com/downloads/slide/Slide_TutorialManual.pdf)

## 6.1 SNAP-2

SNAP-2 is a software program for designing soil nail earth retaining structures. This includes the design of all of the soil nail system components, including the soil nail, facing (temporary and permanent), external stability, and global stability. The design method in SNAP-2 was developed in general accordance with the FHWA guidelines presented in GEC 7; however, it uses an ASD platform. SNAP-2 can be downloaded from the FHWA website (<https://www.fhwa.dot.gov/engineering/geotech/software.cfm>). The user interface is unique to this program and differs from other Windows-based software. For example, SNAP-2 does not have standard file manipulation tools and toolbars. The user manual explains how to manage the files.

The internal stability analysis in SNAP-2 evaluates maximum nail loading along the length of each nail using methods outlined in GEC 7. SNAP-2 uses the Simplified Bishop method and Method A, which was described in Section 4.2. The program uses the nail head strength determined from the facing analysis, the nail tendon strength entered by the user, the grout-ground pullout strength entered by the user, and the factors of safety entered by the user to generate a nail support diagram for each nail as shown in Figure 5.



**Figure 5 SNAP-2 Failure Surface Detail**

As described in Section 4.2, the nail support diagram for each nail is used in the global stability analysis. For each slip circle evaluated, the program determines the nail loads at the locations where the slip circle intersects each nail. These loads are applied to their respective slices in the global FS calculations for each slip circle. A typical trial slip circle in SNAP-2 is also shown in Figure 5.

SNAP-2 analyzes and reports the FS at each stage of the construction installation procedure. This is unique to this program. In other soil nail software programs, the user is required to perform individual analysis on each stage of the construction installation procedure to determine the stability of the structure.

### 6.1.1 SNAP-2 Input

Input parameters in SNAP-2 are organized into a series of tabs, sub-tabs, radio buttons, and sliders. Hovering over the tab, radio button, or slider activates a banner that appears in the status bar describing or defining the item. Automatic dimensional checks for some of the inputs are performed by the program and warn the user of a possible input violation. A yellow triangle is displayed in the item if the design check is not satisfied, and a blue orb is displayed if the design check is satisfied. The data boxes in each of the forms can be active or inactive. Active dialog boxes require user input. Inactive dialog boxes are calculated values and do not allow for user input. Active dialogue boxes have white text, while inactive boxes have grey text.

SNAP-2 requires the user to define the following input by selecting the main tab. When the main tab is selected, sub-tabs may appear that require user input. In SNAP-2, the material strength parameters are determined internal to the program and are factored from the ultimate strength to the allowable strength when required. The main tabs include the following:

1. Slope – Defines the geometry of the problem
2. Soils – Defines the location of the soils and their properties
3. Water – Defines the location of ground water
4. Nails – Defines the soil nail type and size and factors of safety
5. Facings – Defines the reinforcing and concrete configuration
  - a. Temporary facing
  - b. Permanent facing
6. Supports
  - a. Wall – Sets the construction sequence wall face configuration
  - b. Nails – Defines length and displays calculated forces
  - c. Slope – Defines front slope and back slope
7. Surcharge – Defines surcharge with construction sequence
8. Seismic – Defines seismic parameters

In SNAP-2 under the Nails tab, the user inputs the nail tendon size (Bar No.), outside diameter of the bar ( $D_{out}$ ), steel yield strength ( $F_y$ ), factor of safety on the tendon tensile strength ( $FoS_y$ ), drill hole diameter ( $D$ ), and factor of safety on pullout ( $FoS_p$ ). The minimum recommended  $FS_T$  varies by the grade of the nail tendon and by loading type, i.e., static or seismic. Minimum recommended  $FoS_y$  values are presented in Table 5.1 of GEC 7 under  $FS_T$ . Similarly, the minimum recommended  $FoS_p$  values vary depending on loading type and are also presented in Table 5.1 of GEC 7.

The symbols and nomenclature for variables vary between GEC 7 and SNAIL. A summary of the factor of safety variables is presented in Table 4 (also see Table C.1 of GEC 7).

**Table 4 SNAP-2 and GEC 7 Nomenclature**

Limit State	Condition	GEC 7 Symbol	SNAP-2 Symbol
Overall Stability	Internal	$FS_{os}$	FS
Strength – Geotechnical	Pullout Resistance	$FS_{PO}$	$FoS_p$
Strength – Structural	Tendon Tensile Strength	$FS_T$	$FoS_y$
Strength – Facing	Flexural	$FS_{FF}$	TF FoS
Strength – Facing	Punching Shear	$FS_{FP}$	TR FoS
Strength – Facing	Steel Stud	$FS_{FH}$	HT-FoS

### 6.1.2 SNAP-2 Analysis

The input parameters are used in SNAP-2 for the limit equilibrium analyses. In SNAP-2, stability analyses are performed for both the construction sequence steps and for the final wall structure. The nominal strengths of the tendons that can be mobilized and used in the analyses are limited by (i) the product of the tendon cross section area and the steel yield strength reduced by the factor of safety on tendon tensile strength ( $FoS_y$ ); (ii) the product of pullout bond strength, circumference of drill hole, and distance to end of the nail reduced by the factor of safety on pullout ( $FoS_p$ ); or (iii) the nail head capacity (i.e., punching shear) reduced by the factor of safety for punching shear ( $FoS_{FP}$ ). An overall minimum slope stability factor of safety (FS) is computed for the given geometry, soil properties, loading, soil nail pattern, and construction sequence stage.

Design of the soil structure is modified by the user until the minimum factor of safety of overall stability (FS) is met or exceeded for the final and construction sequence step geometries. Once the design is finalized, the SNAP-2 output provides the nominal nail forces (T-Force) and failure mode, which are used to perform LRFD platform-based design computations.

### **6.1.3 SNAP-2 Output**

The stability of the structure is calculated by the program as the input is entered and when the user changes any input. This means that any manipulation of a file input is retained without activating a “save as” command or a “calculate” command. Output in SNAP-2 is accessed by selecting the main tabs. The following main tabs and sub-tabs provide output:

1. Supports
  - a. Checks – Provides sliding, bearing, and global FS
  - b. Vars – Provides details of most calculated values
2. Bishop – Provides global FS for each construction sequence
3. Report – Sends a report to a web browser

The output for temporary facing as well as permanent facing can be displayed. The user must define which output is to be displayed in the Supports tab and the Wall sub-tab. The user then selects either the Permanent Facing or Temporary Facing under the Wall form. The information that is output in the Checks and Vars tabs is associated with the facing that has been selected.

To output the calculated forces of the soil nail, the user selects the main tab Supports, the sub-tab Nails, and then inside the Nails form the number under the heading “Nail List”. When this is selected, it opens the form shown in Figure 6.

Nail List					
	$C_{dH}$ , ft	Failure	$L_{fail}$ , ft	$T_{Force}$ , kip	T-Forces
1	3.00	Pullout from Med. Dense Sand	14.66	15.8	...[4]...
2	8.00	Pullout from Med. Dense Sand	12.40	21.4	...[4]...
3	13.00	Tendon Failure	9.34	25.1	...[4]...
4	18.00	Tendon Failure	5.30	25.1	...[4]...
5	23.00	-	0.00	0.0	...[4]...

**Figure 6 SNAP-2 Report Output of Nail Forces**

This form displays the nominal nail force ( $T_{Force}$ ) for each nail, the distance from the face to the failure surface ( $L_{fail}$ ), and failure mode (Failure). The failure mode defines whether the nominal load is the tensile load in the tendon or the pullout load. The nominal nail force is related to the construction sequence that is selected in the main tab Bishop. The nail resistance envelope can be displayed by selecting the number in the tab under the heading “T-Force” in the Nail List form.

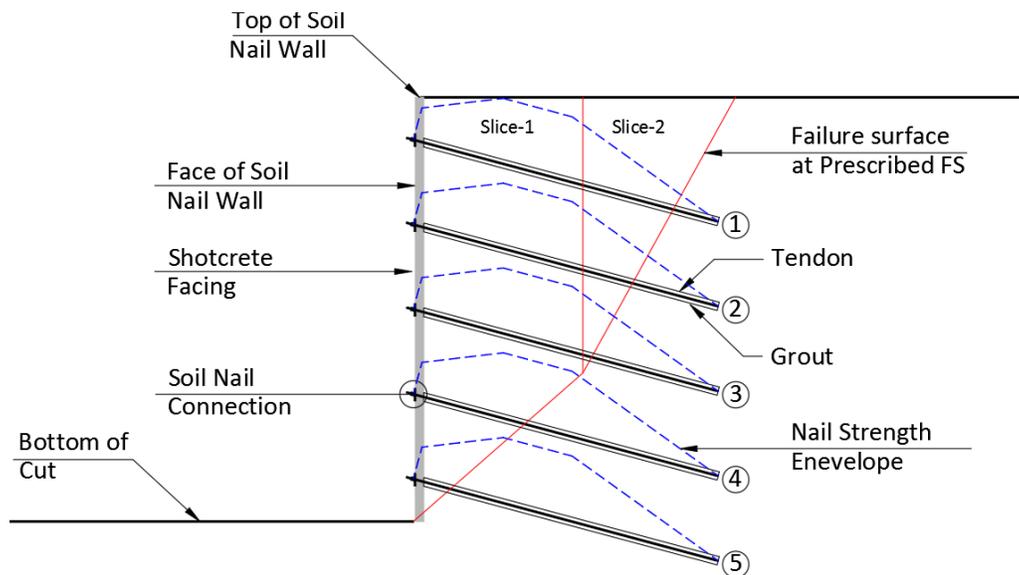
#### 6.1.4 SNAP-2 Post-Processing Capacity to Demand Ratio

The nominal loads computed in the ASD, limit equilibrium analyses are then used to check the LRFD CDR using Equation 16. The maximum nominal tendon tension and pullout for each nail is used to compute the respective CDR. A load factor and a resistance factor, following GEC 7, are applied to compute the CDRs, per Equation 16. The respective CDRs are determined manually using a spreadsheet and the procedures outlined in GEC 7. The soil nail wall design should be adjusted if any CDR is less than 1.0, and the new design should be re-analyzed and the CDRs recomputed until all CDRs are equal to or greater than 1.0.

## 6.2 SNAIL

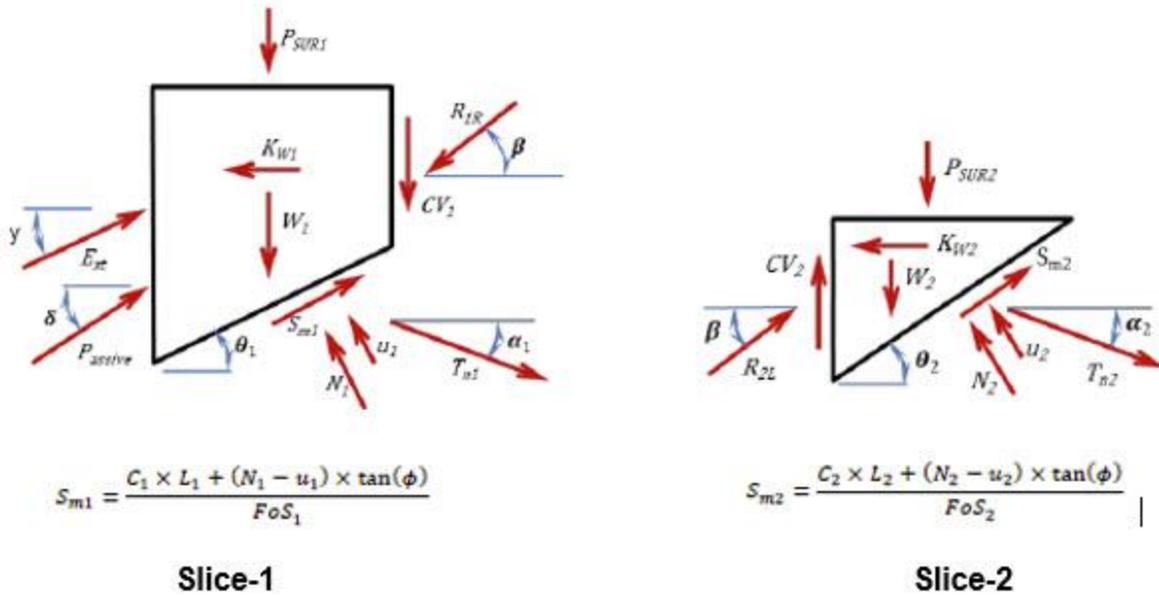
SNAIL is a soil nail design and analysis program developed by the California Department of Transportation (Caltrans). The software is maintained by the Office of Geotechnical Services, Division of Engineering Services, at Caltrans ([http://www.dot.ca.gov/hq/esc/geotech/software/geo\\_software.html](http://www.dot.ca.gov/hq/esc/geotech/software/geo_software.html)). The software performs stability analysis of soil nail walls including the facing. Version 2.0.3 was used in this analysis. The user interface is similar to other Windows-based software with standard file manipulation tools, toolbars, and structure.

SNAIL uses a force limit equilibrium analysis format. The software program uses a bi-linear (two-part) failure surface that passes through the toe of the wall. In addition, the program generates a tri-linear (three-part) failure surface that passes under the toe of the wall and that daylights in front of the wall. Only two-part wedge analysis, as shown in Figure 7, is discussed in this document.



**Figure 7 SNAIL Two-Part Wedge Detail**

Each slice develops interslice forces in the analysis, as shown in Figure 8.



**Figure 8 SNAIL Force Diagram (SNAIL)**

Because the interslice forces are not known, the FS is calculated through iteration. The following steps are used within SNAIL to calculate the FS. The interslice force angle can be prescribed by the user in the Search Option: Advanced Search Options.

1. Calculate the initial normal force of each slice with no interslice forces.
2. Calculate the initial FS with the normal forces calculated in step 1 with no interslice forces.
3. Update the interslice force with the FS calculated in step 2.
4. Update the normal forces with the calculated forces and the FS calculated in steps 2 and 3.
5. Update the FS with normal forces and interslice force calculated in previous steps.
6. Calculate the tolerance.
7. Iterate until the tolerance calculated in step 6 is less than the default tolerance.

### 6.2.1 SNAIL Input

Input parameters in SNAIL are organized into a series of icons or toolbar commands. Each of the inputs, when activated, opens a form that prompts the user for the required input. SNAIL requires the user to define the following input:

1. Project Information – Standard project information input
2. Geometry
  - a. Layout – Input for wall location and configuration
  - b. Ground surface – Input definition for ground surface at top and toe of wall
  - c. Soil layers – Defines the number of soil layers
  - d. Ground water – Defines location of ground water
3. Soil Nails – Defines soil nail and facing configuration
  - a. Diameter of drill hole
  - b. Maximum vertical spacing
  - c. Number of soil nail rows
  - d. Uniformity/Vary
  - e. Length
  - f. Inclination
  - g. Distance to first nail from top of structure
  - h. Vertical spacing
  - i. Horizontal spacing
  - j. Bar diameter
  - k. Yield strength

4. Soil Properties – Defines properties of soil layer
  - a. Description
  - b. Unit weight
  - c. Friction angle
  - d. Cohesion
  - e. Bond strength
5. Loads – Defines location of loads
  - a. Seismic
  - b. External
  - c. Surcharges
6. Factor of Safety
  - a. Pullout (distal end)
  - b. Pullout (proximal end)
  - c. Yield
7. Search Options
  - a. Limits
  - b. Advance options (interslice inclination)

SNAIL allows for up to seven different soil layers. The soil layers are all input in a two-point straight line relationship. Therefore, complex soil profiles are not allowed. The ground water profile is input in a series of straight line relationships. A maximum of eighteen points can be used.

SNAIL also allows the user to design and analyze the facing. The facing design is used in determining the controlling facing resistance and is a function of flexure, punching shear, or stud tensile shear. Stud tensile shear is only applicable in a permanent facing design. The facing design follows the method outlined in GEC 7.

The symbols and nomenclature for variables vary between GEC 7 and SNAIL. A summary of the factor of safety variables is presented in Table 5 (also see Table C.1 of GEC 7). The SNAIL factors of safety are defined in the Factor of Safety form and the Facing Analysis form or Facing Design form. The factors of safety defined in the forms are used to determine the ASD allowable resistance for each limit state.

**Table 5. SNAIL and GEC 7 Nomenclature**

<b>Limit State</b>	<b>Condition</b>	<b>GEC 7 Symbol</b>	<b>SNAIL Symbol</b>
Overall Stability	Internal	FS <sub>os</sub>	FoS
Strength – Geotechnical	Pullout Resistance	FS <sub>PO</sub>	* Note
Strength – Structural	Tendon Tensile Strength	FS <sub>T</sub>	* Note
Strength – Facing	Flexural	FS <sub>FF</sub>	* Note
Strength – Facing	Punching Shear	FS <sub>FP</sub>	* Note
Strength – Facing	Steel Stud	FS <sub>FH</sub>	* Note

\* SNAIL does not provide variables for the factors of safety. The tendon and pullout FS are defined under the FS toolbar tab on the main form. The facing FS are defined in the facing form.

SNAIL uses a linear search pattern at the ground surface located at the top of the wall. The search boundary is defined by the user. The user defines the search pattern starting and ending point. The search is then divided into ten equal parts for a total of eleven search points. There is not an input value enabling the user to prescribe the number of search points. Therefore, the user may be required to perform multiple analyses to verify that the most critical failure surface has been captured in the defined search boundary.

### **6.2.2 SNAIL Analysis**

The input parameters are used in SNAIL for force limit equilibrium analyses. The nominal strengths of the tendons that can be mobilized and used in the analyses are limited by (i) the product of the tendon cross section area and the steel yield strength reduced by the factor of safety on tendon tensile strength; (ii) the product of pullout bond strength, circumference of drill hole, and distance to end of the nail reduced by the factor of safety on pullout; or (iii) the nail head capacity (i.e., punching shear) reduced by the factor of safety for punching shear. An overall minimum slope stability factor of safety (FoS) is computed for the given geometry, soil properties, loading, soil nail pattern, and the defined search criteria.

Design of the soil structure is modified until the required minimum factor of safety of overall stability (FoS) is met or exceeded. Once the design is finalized, the SNAIL report output provides the nominal nail forces (T-Force) and failure mode for the minimum calculated FoS. These values can be used to perform LRFD platform-based design computations.

### **6.2.3 SNAIL Output**

Output in SNAIL can be generated in a text report or can be displayed graphically. Once force equilibrium is solved, the user can select the graphical input icon. When this is selected, the FoS for each prescribed analysis are displayed in a spreadsheet table. The user can select any of the cells in the spreadsheet to activate the graphical solution of the analysis, which is then displayed to the right of the spreadsheet. The nail forces required to perform the LRFD check can be found in the report mode of SNAIL for the ten most critical failure surfaces. An example of a portion of a report is provided in Figure 9.

Search Point	Minimum Factor of Safety	Distance of Wall From Toe feet	Failure Planes				Reinforcement		
			Lower		Upper		Level	Stress ksi	Controlling Resistance Failure Mode
			Angle degrees	Length feet	Angle degrees	Length feet			
1	1.64	3.00	65.77	6.58	89.29	24.00	1	41.7	Bar Yield
							2	41.7	Bar Yield
							3	41.7	Bar Yield
							4	41.7	Bar Yield
							5	41.7	Bar Yield
							6	41.7	Bar Yield
** 2	1.47	7.70	65.20	16.52	87.06	15.02	1	41.7	Bar Yield
							2	41.7	Bar Yield
							3	41.7	Bar Yield
							4	41.7	Bar Yield
							5	41.7	Bar Yield
							6	41.7	Bar Yield
3	1.54	12.40	58.20	21.18	84.10	12.06	1	37.2	Pullout
							2	38.3	Pullout
							3	41.7	Bar Yield
							4	41.7	Bar Yield
							5	41.7	Bar Yield
							6	41.7	Bar Yield

**Figure 9 SNAIL Report Output Example**

This report example demonstrates how the results are presented. The report is for three of the most critical failure surfaces. Search Point 2 is identified as being the critical search point (as identified by the double asterisk) that produced the minimum factor of safety of 1.47. In the far right-hand column, the controlling resistance failure mode is listed for each nail. The column to the left of the far-right column displays the stress associated with the controlling resistance failure mode. The stress is converted to force and is used in the post-processing.

#### 6.2.4 SNAIL Post-Processing Capacity to Demand Ratio

The nominal loads computed in the ASD, force limit equilibrium analyses are then used to check the LRFD CDR using Equation 16. The maximum nominal tendon tension and pullout for each nail is used to compute respective CDRs. A load factor and a resistance factor, following GEC 7, are applied to compute the CDRs, per Equation 16. The respective CDRs are determined manually using a spreadsheet and the procedures outlined in GEC 7. The soil nail wall design should be adjusted if any CDR is less than 1.0, and the new design should be re-analyzed and the CDRs recomputed until all are equal to or greater than 1.0.

## **6.3 SLIDE**

The computer program SLIDE is comprehensive slope stability analysis software that can perform finite element groundwater seepage analysis, rapid drawdown, sensitivity and probabilistic analysis, and support design. The software is developed, maintained, and distributed by Rocscience Incorporated, located in Toronto, Ontario, Canada (<https://www.rocscience.com/rocscience/products/slide>). The software can analyze retaining structures with inclusions using nine different methods, including Simplified Bishop, Corps of Engineers #1, Corps of Engineers #2, Morgenstern-Price, Janbu Simplified, Janbu Corrected, Low-Karafiath, Ordinary/Fellenius, and Spencer. The design methods that are to be used in the design or analysis are determined by the user. Software version 6.039 was used in this parametric study.

SLIDE is a slope stability program that allows for the analysis of earth retaining structures with inclusions. SLIDE is an analysis program and not a design program, so the inclusion strength parameters must be input by the user. Therefore, the user must have an understanding of how the design method selected for analysis determines the factor of safety in order to determine how the inclusion strength parameters should be input into the program. The Simplified Bishop method and Method A were used in this study, so the tensile, plate (facing strength), and pullout capacity needed to be input at the allowable loads.

### **6.3.1 SLIDE Input**

User input in Slide utilizes a CAD graphical interface. This interface allows the user to easily draw and edit the boundary conditions on the screen using a mouse or keyboard input. The user inputs are selected using the graphical toolbar icons. The following user input is required to define a retaining structure with inclusions in SLIDE:

1. Project Information
2. Geometry
  - a. Layout
  - b. Ground surface
  - c. Soil layers
  - d. Ground water
3. Soil Properties
  - a. Description
  - b. Unit weight
  - c. Friction angle
  - d. Cohesion
  - e. Bond strength
4. Loads
  - a. Seismic
  - b. External
  - c. Surcharges
5. Search Options
  - a. Method
  - b. Search options
  - c. Grid
  - d. Limits
6. Support
  - a. Pattern
  - b. Properties
    - i. Type
    - ii. Spacing
    - iii. Tensile capacity
    - iv. Plate capacity
    - v. Pullout bond strength

The Support properties for the tensile capacity, plate capacity, and the pullout bond strength are input by the user using the allowable load values. Therefore, these values must be determined by the user prior to input. Unlike SNAP-2 and SNAIL, SLIDE does not perform any design analysis other than overall stability.

The symbols and nomenclature for variables vary between GEC 7 and SLIDE. A summary of the factor of safety variables is presented in Table 6 (also see Table C.1 of GEC 7).

**Table 6 SLIDE and GEC 7 Nomenclature**

<b>Limit State</b>	<b>Condition</b>	<b>GEC 7 Symbol</b>	<b>SLIDE Symbol</b>
Overall Stability	Internal	FS <sub>OS</sub>	FS
Strength – Geotechnical	Pullout Resistance	FS <sub>PO</sub>	* Note
Strength – Structural	Tendon Tensile Strength	FS <sub>T</sub>	* Note
Strength – Facing	Flexural	FS <sub>FF</sub>	* Note
Strength – Facing	Punching Shear	FS <sub>FP</sub>	* Note
Strength – Facing	Steel Bolt	FS <sub>FH</sub>	* Note

\* SLIDE does not check the factors of safety for any element besides overall stability.

### 6.3.2 SLIDE Analysis

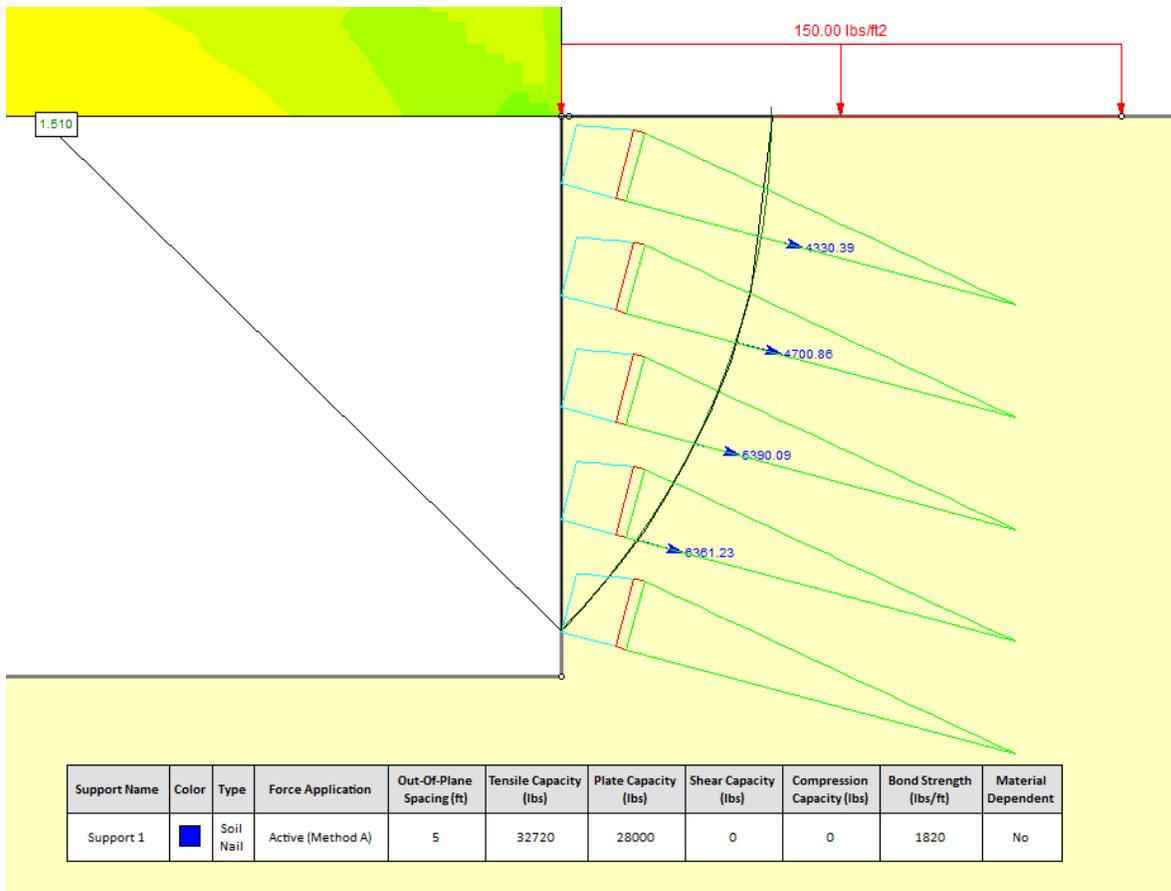
The input parameters are used in SLIDE for force limit equilibrium analyses using the user-selected Simplified Bishop method and Method A. The nominal strength of the tendons that can be mobilized and used in the analyses is limited by (i) the product of the tendon cross section area and the steel yield strength reduced by the factor of safety on tendon tensile strength; (ii) the product of pullout bond strength, circumference of drill hole, and distance to end of the nail reduced by the factor of safety on pullout; or (iii) the plate capacity (i.e., punching shear) reduced by the factor of safety for punching shear. An overall slope stability factor of safety is computed for the given geometry, soil properties, loading, soil nail pattern, and the defined search criteria.

Design of the soil structure is modified until the minimum factor of safety of overall stability (FS) is met or exceeded. Once the design is finalized, the SLIDE Interpreter post-processing module is selected to display the output. The output provides the nominal nail forces (T-Force), defined as the mobilized support force, at the location of failure surface for the minimum calculated FS. These values can be used to perform LRFD platform-based design computations.

### **6.3.3 SLIDE Output**

The user solves the slope stability by invoking the “compute” command icon located in the toolbar. The output in SLIDE is provided in a separate post-processing module called Interpreter. When this toolbar icon is activated by the user, a window opens that shows the solved slope stability problem and displays the failure surface that generated the lowest factor of safety. The user can select any failure surface that was solved by the program by performing a query. The “query” command is located in the toolbar. The support forces (i.e., soil nail or inclusion forces) for the failure surface that generated the lowest factor of safety can be displayed by selecting the “show slices” icon in the toolbar. In addition, Mobilized Support Forces must be selected in the display options in order to show the support force that is mobilized at the interface of the failure surface. The support envelope can be displayed by selecting the “show support forces” icon in the toolbar. The material properties can be displayed in table form by selecting the appropriate icon in the toolbar. If the “query” command was initiated by the user, it will not show the associated support forces. If the user wants to know the support forces for the “query,” then a separate analysis using a single defined failure surface will have to be initiated by the user.

The nominal loads that are used in post-processing are the mobilized support forces. These values do not show the controlling resistance mode of failure in the same manner as SNAP-2 and SNAIL. Instead, the user determines the resistance mode of failure by comparing the values to the allowable values input into the program and the intersection location of the failure surface on the support load envelope. If the support force is equal to the nominal support tensile force, then tensile resistance is the controlling failure mode. If the force is less than the nominal support tensile force, then pullout controls. For example, a generic structure that has been solved in SLIDE is shown in Figure 10.



**Figure 10 SLIDE Interpreter Structure Output Example**

In this example, the failure surface that produced a FS equal to 1.51 is shown. One soil nail type, as shown in the support properties table, is defined with an allowable tensile capacity of 32,720 lbf, allowable plate capacity 28,000 lbf, and allowable bond strength of 1,820 lbf/ft, and a force application using Method A has been specified. The soil nail force envelope along with the mobilized support forces are shown at the location of the soil nails. The support forces are given in lbf/ft and need to be increased by the out-of-plane spacing of the soil nail before a comparison is made to the allowable support forces.

Based on the location of the failure surface in relationship to the soil nail failure envelope, it can be determined that pullout is the controlling support force for the upper four soil nails and that the bottom soil nail is not included in the analysis (i.e., the soil nail does not show a mobilized support force). These support forces are what the user will extract to be used in the post-processing.

#### **6.3.4 SLIDE Post-Processing Capacity to Demand Ratio**

The nominal loads computed in the ASD, limit equilibrium analyses are then used to check the LRFD CDR using Equation 15. The maximum nominal tendon tension and pullout for each nail is used to compute the respective CDR. A load factor and a resistance factor, following GEC 7, are applied to compute the CDRs, per Equation 15. The respective CDRs are determined manually using a spreadsheet and the procedures outlined in GEC 7. The soil nail wall design should be adjusted if any CDR is less than 1.0, and the design should be re-analyzed and CDRs recomputed until all are equal to or greater than 1.0.

## **7 Parametric Study Results**

The following tables list the CDR results of the parametric analysis. The CDR values are directly related to the parameters of each of the cases. It was not the intent of the study to design structures that had a CDR greater than 1.00 for each component. The intent of the study was to show that if the recommended factors of safety for ASD design, as outlined in GEC 7, are used with commercially available limit equilibrium software, the results will generally satisfy the LRFD design requirements in GEC 7. This was demonstrated by determining the equivalent CDR in the LRFD format from the ASD limit equilibrium analysis. Equation 16 in this report and GEC 7 were used to determine the CDR for each failure mode.

SNAP-2 results of the parametric study are listed in Table 7.

**Table 7 SNAP-2 Parametric Results**

<b>Case Number</b>	<b>Global CDR</b>	<b>Nail Tension CDR*</b>	<b>Nail Pullout CDR*</b>	<b>Temp. Facing Flexure CDR</b>	<b>Temp. Facing Punching CDR</b>	<b>Perm. Facing Flexure CDR</b>	<b>Perm. Facing Punching CDR</b>	<b>Perm. Facing Stud CDR</b>
1	1.16	1.26	1.01	1.45	1.67	1.38	1.31	1.91
4	1.00	1.65	1.01	1.22	1.36	1.71	1.10	1.05
7	1.37	3.58	1.00	2.17	2.05	3.05	1.95	1.74
10	0.98	1.00	1.49	2.18	2.94	4.38	2.81	2.69
13	0.97	2.16	1.01	1.41	1.46	1.76	1.18	1.87
16	0.98	2.52	1.03	1.57	1.79	2.24	1.45	1.52
19	0.98	3.71	1.00	1.34	1.63	1.81	1.52	1.60
22	0.98	1.60	1.02	1.71	1.36	2.68	2.26	2.37
25	0.90	2.82	1.01	5.30	1.88	4.38	1.66	3.87
28	0.74	1.17	1.02	5.30	1.88	4.38	1.66	3.87
31	0.80	1.50	1.01	4.05	1.44	3.34	1.23	1.31
34	0.66	2.13	1.00	4.98	1.76	4.11	1.50	1.62
37	0.98	1.24	0.87	1.35	1.64	2.24	1.44	1.38

\*The CDRs for Tension and Pullout are for Nail #3.

For cases 1, 4, 7, 10, 13, 16, 19, and 22, the design was modified (i.e., nail strength and length) as required to provide a global factor of safety of 1.5. For these cases, the CDRs were all above 1. As noted in GEC 7, the various recommended resistance factors were quantified by back-calibrating to current practice and rounding up to the nearest 0.05 value. This rounding up can introduce a slight conservatism in LRFD results versus ASD results. When CDRs are slightly below the minimum of 1.0, the designer may adjust and re-analyze the soil nail wall and/or accept a CDR that rounds up to 1.0. The remaining cases were specific designs that were not modified to provide a global factor of safety of 1.5. The global factor of safety in each case was less than 1.5. Therefore, we would expect the global CDR for these cases to be less than 1. However, the nail tensile strength, pullout strength, and face punching shear were selected in these problems based on the recommended factors of safety for each mode of failure. The resulting CDRs are above 1.0.

SNAIL results of the parametric study are listed in Table 8.

**Table 8 SNAIL Parametric Results**

<b>Case Number</b>	<b>Global CDR</b>	<b>Nail Tension CDR*</b>	<b>Nail Pullout CDR*</b>	<b>Temp. Facing Flexure CDR</b>	<b>Temp. Facing Punching CDR</b>	<b>Perm. Facing Flexure CDR</b>	<b>Perm. Facing Punching CDR</b>	<b>Perm. Facing Stud CDR</b>
2	0.99	1.20	0.96	1.21	1.18	1.49	1.41	2.06
5	0.96	1.00	1.25	1.22	1.36	1.71	1.10	1.05
8	0.98	2.41	0.96	1.24	1.16	1.74	1.11	1.07
11	0.99	1.38	0.96	1.11	1.50	2.24	1.43	1.37
14	1.01	2.72	0.96	1.36	1.41	1.70	1.14	1.81
17	1.01	4.39	0.96	1.30	1.48	1.77	1.19	1.25
20	0.98	3.18	0.96	1.27	1.54	1.71	1.44	1.51
23	1.03	5.71	0.94	1.27	1.55	1.71	1.45	1.51
26	0.59	1.96	0.97	5.53	1.96	4.57	1.73	4.04
29	0.72	1.59	0.96	5.29	1.88	4.37	1.66	3.87
32	0.69	1.67	0.96	5.53	1.45	3.35	1.24	1.32
35	0.55	2.33	0.96	4.69	1.65	3.87	1.41	1.52
38	0.90	1.5	0.96	1.35	1.64	2.24	1.43	1.37

\* The CDRs for Tension and Pullout are for Nail #3.

For cases 2, 5, 8, 11, 14, 17, 20, and 23, the design was modified (i.e., nail strength and length) as required to provide a global factor of safety of 1.5. For these cases, the CDRs were all above 1. The remaining cases were specific designs that were not modified to provide a global factor of safety of 1.5. The global factor of safety in each case was less than 1.5. Therefore, we would expect the global CDR for these cases to be less than 1. However, the nail tensile strength, pullout strength, and face punching shear were selected in these problems based on the recommended factors of safety for each mode of failure. The resulting CDRs are above 1.0.

SLIDE results of the parametric study are listed in Table 9.

**Table 9 SLIDE Parametric Results**

<b>Case Number</b>	<b>Global CDR</b>	<b>Nail Tension CDR*</b>	<b>Nail Pullout CDR*</b>	<b>Temp. Facing Flexure CDR</b>	<b>Temp. Facing Punching CDR</b>	<b>Perm. Facing Flexure CDR</b>	<b>Perm. Facing Punching CDR</b>	<b>Perm. Facing Stud CDR</b>
3	0.97	1.31	0.96	1.33	1.53	1.27	1.20	1.75
6	0.97	1.00	1.08	1.23	1.25	1.35	1.79	1.30
9	0.98	1.21	0.96	1.27	1.41	1.79	1.11	1.71
12	0.98	2.34	0.96	1.19	1.20	1.79	1.15	1.10
15	0.98	1.37	0.96	1.34	1.58	1.67	1.12	1.77
18	0.98	13.52	0.93	1.30	1.48	1.77	1.20	1.25
21	0.98	3.13	0.96	1.35	1.65	1.83	1.53	1.61
24	1.01	7.13	1.86	1.27	1.33	1.71	1.45	1.51
27	0.56	1.59	0.96	5.91	2.17	3.23	2.74	4.46
30	0.65	1.00	1.25	5.30	1.88	4.38	1.66	3.87
33	0.67	1.00	1.19	5.52	1.44	3.35	1.23	1.31
36	0.55	1.82	0.96	5.19	1.83	4.29	1.57	1.69
39	0.83	1.06	0.96	1.35	1.64	2.24	1.44	1.37

\* The CDRs for Tension and Pullout are for Nail #3.

For cases 3, 6, 9, 12, 15, 18, 21, and 24, the design was modified (i.e., nail strength and length) as required to provide a global factor of safety of 1.5. For these cases, the CDRs were all above 1. The remaining cases were specific designs that were not modified to provide a global factor of safety of 1.5. The global factor of safety in each case was less than 1.5. Therefore, we would expect the global CDR for these cases to be less than 1. However, the nail tensile strength, pullout strength, and face punching shear were selected in these problems based on the recommended factors of safety for each mode of failure. The resulting CDRs are above 1.0.

The global CDR results for Groups I through M (Table 1) from SNAP-2 (cases 25, 28, 31, 34, and 37), SNAIL (cases 26, 29, 32, 35, and 38), and SLIDE (cases 27, 30, 33, 36, and 39) can be compared to each other. The computed global FS values, which are used to compute the global CDR values, for these analyses are summarized in Table 10.

**Table 10 Global FS Results for Groups I through M**

<b>Group</b>	<b>SNAP-2 Case Number</b>	<b>SNAIL Case Number</b>	<b>SLIDE Case Number</b>	<b>SNAP-2 Global FS</b>	<b>SNAIL Global FS</b>	<b>SLIDE Global FS</b>	<b>Difference SNAP-2 to SNAIL</b>	<b>Difference SNAP-2 to SLIDE</b>
I	25	26	27	1.39	0.91	0.87	53%	60%
J	28	29	30	1.14	1.11	1.00	3%	14%
K	31	32	33	1.23	1.06	1.04	16%	18%
L	34	35	36	1.02	0.84	0.84	21%	21%
M	37	38	39	1.50	1.38	1.27	9%	18%

Differences between program slope stability results are normal and are attributable to the use of different slope stability analysis theories or methods, variations in how reinforcement is incorporated into the stability safety factor computation, differences in program search routines, assumptions used within programs, use of significant digits, etc.

The SNAP-2 and SLIDE programs both use the Simplified Bishop theory and the Method A FS computation method. Therefore, the anticipated difference between these two programs is about 3% to 5%. SNAIL uses a different analysis method, and therefore a greater difference, up to about 7% to 10%, may be anticipated.

The percent differences in computed FS values for the respective groups of analyses are also listed in Table 10. Comparing the values from SNAP-2 to those from SNAIL, one finds significantly more than a 7% to 10% difference for three of the five groups. Similarly, comparing the values from SNAP-2 to those from SLIDE, one finds significantly more than a 3% to 5% difference for all five groups. A comparison of SNAIL and SLIDE values shows good agreement, with differences between 0% and 11% (where about 7% to 10% maximum was anticipated).

These comparisons show a small difference between SNAIL and SLIDE results, and are within the range typically expected. However, significant differences between SLIDE and SNAP-2 results were found for all five groups, and significant differences between SNAIL and SNAP-2 results were found in three of five groups. An investigation of the differences in analysis results between these three computer programs was not within the scope of this study. However, based upon the results of this work, it is recommended that further study be performed to investigate differences in analysis results from various soil nail wall computer programs.

## 8 Conclusions

The broad applicability of the soil nail wall analysis and design procedures detailed in GEC 7 was clearly demonstrated by this study. The LRFD design framework presented in GEC 7 was demonstrated to work with three very different LE software programs. All three programs provided LRFD-compliant designs when they used the appropriate factors of safety for the various modes of failure in the ASD analysis.

It is concluded that designers and engineers can confidently use GEC 7 guidance and procedures with the analysis results from the ASD LE soil nail program of their choice for LRFD-based soil nail wall designs.

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