APPENDIX A – SOIL NAIL DESIGN COMPARISON

The reports FHWA-IF-03-017 (Lazarte et. al., 2003) and FHWA-SA-96-069R (Byrne et al., 1998), hereafter referred to as [REF1] and [REF2], respectively, contain specific recommendations pertaining to the analysis and design of soil nail walls with a reinforced concrete facing (shotcrete and cast-in-place concrete). The comparison was limited to those sections of each manual providing specific design recommendations that influence or otherwise direct the efforts of engineers engaged in the prescriptive practice of designing and analyzing soil nail walls. Likewise opinions or corrections to the manuals are beyond the scope of the comparison. The design items considered are listed in Table 1 and include external, internal and facing calculations. Where convenient, equations are sometimes shown in Table 1 as a means to illustrate the similarity or difference of the recommendations in the respective manuals; however, the reader is referred to the appropriate report for a complete list of the variables, their definitions and specific discussions on the guidance or limitations of the listed equations. Based on the review of the design methods, a discussion of the main differences between the two manuals is provided.

ACTIVE EARTH LOAD FOR INTERNAL STABILITY AND FACING DESIGN

For estimating the “internal” active earth load resisted by the nails, [REF1] recommends using the slope stability software, SNAIL (CALTRANS, undated). SNAIL is capable of estimating the available nail resistance intersecting a given slip surface based on the controlling condition of grout-soil pullout, facing punching shear or nail tensile yield. The analysis determines the internal “maximum average nail load” that provides a factor of safety of 1.0 (active failure condition). Once the “maximum average nail load” has been determined, the active earth load occurring at the back of the shotcrete is empirically derived using an equation, based on earth pressure measurements at the shotcrete-soil interface done on walls in Germany and France using total stress cells (Clouterre, 1993). The maximum average active earth load applied to the head of the nails may vary from approximately 60% to 100% of the “maximum average nail load” depending on nail spacing.

In contrast, [REF2] applies the full coulomb active earth loading uniformly behind the shotcrete facing. In complex terrain or layered soils, a slope stability analyses can be conducted to determine the magnitude of an external load against the facing. The external load that provides a factor of safety of 1.0 (active condition) is then distributed uniformly along the back of the shotcrete. [REF2] does not rely on any particular software package to complete these calculations.

OVERALL (GLOBAL) STABILITY

Both manuals emphasize the use of global stability analysis to design soil nail walls. [REF1] relies heavily on the software program SNAIL to determine both active earth pressure loading applied to the wall facing (Factor of Safety equal to 1.0) and a search for the critical slip surface producing a minimum factor of safety for a given nail layout (spacing, orientation and lengths). [REF2] has a design procedure that reduces the lengths of the nails towards at the middle and lower elevations in the wall to account for “top down” loading of the soil nails. [REF2] is concerned that after construction of a soil nail wall the nails in the upper part of the wall are more heavily loaded than the middle to lower nails. This is the necessary result of the staged, top-down nature of soil nail wall construction. In order to adjust the engineering calculations to account for this condition, [REF2] has a procedure to reduce the lengths of the nails in the middle to lower portion of the soil nail walls thereby reducing their contribution to slope stability. This procedure is not demonstrated in [REF1].

EXTERNAL STABILITY ANALYSES

Both methods use earth pressure type equations to estimate the factors of safety for external modes of failure (bearing capacity, etc.). However [REF1] considers bearing capacity and sliding, while [REF2] considers bearing capacity and eccentricity of the soil reaction (overturning). Also the pseudo-static seismic coefficient is much larger using [REF2] than [REF1].

Table 1. Soil Nail Retaining Wall Design Comparison Summary.
(equations provided for visual comparison – see referenced section in the appropriate design manual for variable identification and additional information)

Design Cate-gories	Analyses Consideration	[REF1] FHWA IF-03-017 Geotechnical Circular No. 7	[REF2] FHWA-SA-96-069R Manual for Design and Construction Monitoring of Soil Nail Wall	Comments
General	UNITS	English, SI	SI	Equations in Summary Table use English Units for Illustration.
	DESIGN METHODOLOGY	ASD	ASD & LRFD	Currently ASD is the preferred methodology
	SHORT AND LONG TERM FACTORS OF SAFETY	See Table 2 below		Same or similar general discussion in both manuals
External Design	GLOBAL STABILITY	Section 5.4.2 Uses slope stability limiting equilibrium calculation with consideration for tensile forces in the nail controlled by either facing, tensile or pullout capacity. Discusses SNAIL and GOLDNAIL as two popular software programs capable of managing the soil shear strength with the multiple potential failure modes of the soil nails. Relies on SNAIL to determine "maximum average nail loading" (see internal design below).	Section 4.3.2 Uses slope stability limiting equilibrium calculation with consideration for tensile forces in the nail controlled by either facing, tensile or pullout capacity. Does not rely on any specific software program.	[REF1] relies on SNAIL software to complete analyses. [REF2] does not rely on any specific software package.
	BEARING	Section 5.4.4	Section 4.2.4 & 4.7.1	Both design manuals

Design Cate-gories	Analyses Consideration	[REF1] FHWA IF-03-017 Geotechnical Circular No. 7	[REF2] FHWA-SA-96-069R Manual for Design and Construction Monitoring of Soil Nail Wall	Comments
	CAPACITY	Check for Basal heave of fine grained soil at base of excavation.	General Bearing Capacity Evaluation and Check for Basal Heave	provide for a separate, earth pressure type, bearing capacity calculation. [REF1] emphasizes basal heave for fine grained soils.
External Design	SLIDING	Section 5.4.3 Conducts separate earth pressure type sliding calculation	Section 4.2.4 The discussion suggests that no separate earth pressure calculation for sliding is necessary as thorough global stability analyses will capture this mode of failure.	Separate earth pressure type sliding calculation is considered in[REF1] but not in [REF2]
	OVERTURNING	Does not promote a separate calculation for overturning.	Section 4.2.4 Check that the eccentric soil reaction is within middle third of foundation	[REF1] does not provide a separate earth pressure type overturning calculation. [REF2] checks whether the eccentric soil reaction is located within the middle third of the foundation.

Design Cate-gories	Analyses Consideration	[REF1] FHWA IF-03-017 Geotechnical Circular No. 7	[REF2] FHWA-SA-96-069R Manual for Design and Construction Monitoring of Soil Nail Wall	Comments
	SEISMIC	Section 5.4.5 Uses pseudo static seismic coefficient applied to global stability analyses. Uses Mononobe-Okabe method for sliding check	Section 4.7, Chapter 5 and Appendix G Uses pseudo static seismic coefficient applied to global stability analyses. The discussion recommends a different coefficient for "internal" slip surfaces than for "external or mixed" slip surfaces. Uses Mononobe-Okabe method for bearing capacity and eccentricity check	For slip surfaces that are "external or mixed" the global stability analyses is the same for both manuals. [REF2] uses a higher pseudo static seismic coefficient for "internal" slip surfaces. Both manuals apply the M-O method for external stability checks; however, each manual checks different modes of external failure.
	SERVICE/ DEFORMATION	Section 5.7 See Figure 86 below	Section 2.8 See Figure 87 below	The estimated vertical and horizontal deformations are identical. The extent of the estimated influence zones behind the wall face is different.

Design Categories	Analyses Consideration	[REF1] FHWA IF-03-017 Geotechnical Circular No. 7	[REF2] FHWA-SA-96-069R Manual for Design and Construction Monitoring of Soil Nail Wall	Comments
Internal Design	MAXIMUM NAIL LOADING (SEE FIGURE 87 BELOW)	Section 5.6.2 Uses Charts or SNAIL Program (FS=1.0) to Estimate "Maximum Average Nail Loading."	Section 2.4.4 & 4.7 Determines coulomb active earth load and applies uniformly to nails with consideration of nail spacing.	The estimate for maximum nail loading is more involved for [REF1] than for [REF2]. [REF1] uses the slope stability program SNAIL, searching for "internal" slip surfaces with consideration for available nail resistances (controlled by facing, tensile yield or pullout) to determine the maximum average nail loading at a FS=1.0 (active state). [REF2] calculates the coulomb active earth load and uniformly distributes the load to the nails with consideration of nail spacing (tributary area).
	GROUT-SOIL PULLOUT	Section 5.5.2 $Q_{.u} := \pi \cdot D_{.h} \cdot L_{.p} \cdot q_{.u}$	Section 4.2.2 $Q_{.u} := \pi \cdot D_{.h} \cdot L_{.p} \cdot q_{.u}$	Same or similar general discussion in both manuals.
	NAIL-GROUT	Section 5.5.1	Section 4.2.2	Same or similar general

Design Cate-gories	Analyses Consideration	[REF1] FHWA IF-03-017 Geotechnical Circular No. 7	[REF2] FHWA-SA-96-069R Manual for Design and Construction Monitoring of Soil Nail Wall	Comments
	PULLOUT	Recommends use of deformed or threaded bar.	Promotes use of deformed bars to provide mechanical interlock. Not typically a design concern for soil nails	discussion in both manuals.
	NAIL TENSILE	Section 5.5.4 $R_{.T} := A_{.t} \cdot f_{.y}$	Section 4.2.2 $T_{.NN} := A_{.b} \cdot F_{.y}$	Same or similar general discussion in both manuals
	NAIL BENDING	Section 5.5.1 The influence of nail shear and bending on stability is conservatively ignored.	Section 2.4.7 Design does not use nail bending resistance.	Same or similar general discussion in both manuals

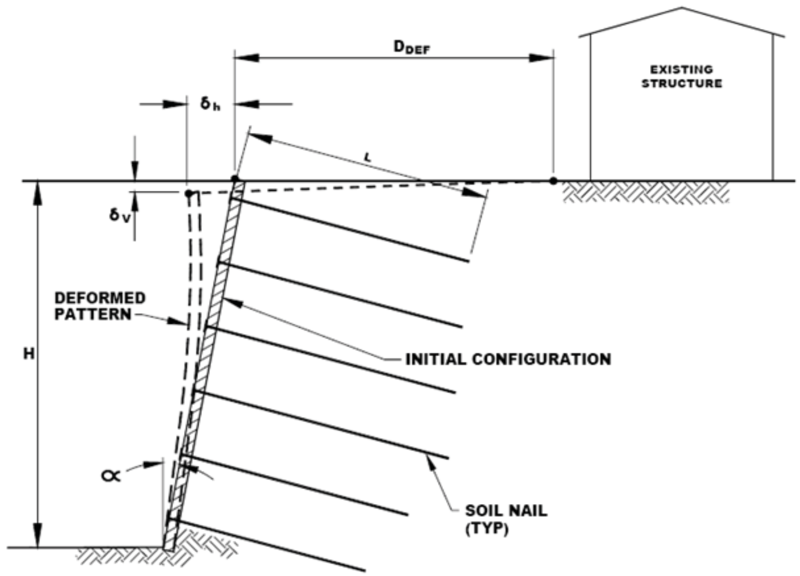
Design Cate-gories	Analyses Consideration	[REF1] FHWA IF-03-017 Geotechnical Circular No. 7	[REF2] FHWA-SA-96-069R Manual for Design and Construction Monitoring of Soil Nail Wall	Comments
Wall Facing Design	FACE LOADING	Section 5.6.2 Uses Charts or SNAIL Program (FS=1.0) to Estimate Maximum Nail Loading. Face loading varies from approximately 60% of maximum nail loading for closely spaced nails to full maximum nail loading (FS=1.0).	Section 2.4.5 & Section 4.7.1 $t_{.F} := \frac{2 \cdot F_{.F} \cdot P_{.a} \cdot S_{.h} \cdot S_{.v}}{H}$ where $F_{.F} := 0.5$ $P_a =$ Coulomb Active Earth Load	[REF1] uses SNAIL software to conduct a global stability analysis, interacting with available nail resistances (whether pullout, facing or tensile control) to determine the maximum average nail load. Depending on nail spacing this load may be reduced using an empirical formula to arrive at the applied earth load at the nail head. [REF2] applies the full coulomb active earth load distributed uniformly behind the facing.

Design Cate-gories	Analyses Consideration	[REF1] FHWA IF-03-017 Geotechnical Circular No. 7	[REF2] FHWA-SA-96-069R Manual for Design and Construction Monitoring of Soil Nail Wall	Comments
Wall Facing Design	FLEXURAL STRENGTH (EQUATIONS SHOWN REPRESENT VERTICAL DIRECTION)	Section 5.6.3 $R_{.FF} := 3.8 \cdot C_{.F} \cdot (a_{.vn} + a_{.vm}) \cdot \frac{S_{.h} \cdot h}{S_{.v}} \cdot f_{.y}$	Section 4.5.2 & Appendix F $T_{.FN} := C_{.F} \cdot (m_{.v\_pos} + m_{.v\_neg}) \cdot \left(\frac{8 \cdot S_{.h}}{S_{.v}} \right)$ where: $m := \frac{A_{.s} \cdot F_{.y}}{b} \cdot \left(d - \frac{A_{.s} \cdot F_{.y}}{1.7 \cdot f_{.c} \cdot b} \right)$	Equations are different; however, they result in similar nominal flexure resistance
	PUNCHING SHEAR STRENGTH – BEARING PLATE	Section 5.6.4 $R_{.FP} := C_{.P} \cdot V_{.F}$ where: $V_{.F}(kip) := 0.58 \sqrt{f_{.c}(psi)} \cdot \pi \cdot D_{.c}(ft) \cdot h_{.c}(ft)$	Section 4.5.3 & Appendix F $T_{.FP} := \frac{V_{.N}}{1 - \left[\frac{C_{.S} \cdot (A_{.c} - A_{.gc})}{S_{.v} \cdot S_{.h} - A_{.gc}} \right]}$ where: $V_{.N} := 4 \sqrt{f_{.c} \cdot psi} \cdot \pi \cdot D_{.c} \cdot h_{.pl}$	Results are identical for nominal punching shear resistance
	HEADED STUD CONNECTION	Section 5.6.5 $R_{.HT} := N_{.H} \cdot A_{.SH} \cdot f_{.y}$	Section 4.5.3 (b), Section 4.5.4 & Appendix F Punching Shear calculated the same as for bearing plate. Only the perimeter area is different where D_C is based on the stud spacing. Check for Stud Tensile Capacity $T_{.FN} := 4 \cdot A_{.HS} \cdot F_{.u}$	For tension check the capacity is based on yield strength [REF1] and ultimate strength for [REF2]. The maximum compression force exerted on the concrete behind the head of the studs is evaluated differently.
	STEEL REINFORCEMENT CHECKS	Section 5.6.3 & Appendix D Reinforcement Ratio (min and max) Minimum Cover Appropriate Development & Splices	Section 4.7 Waler Reinforcement Minimum Reinforcement Ratios Minimum Cover	Same or similar result using either manual

Design Cate-gories	Analyses Consideration	[REF1] FHWA IF-03-017 Geotechnical Circular No. 7	[REF2] FHWA-SA-96-069R Manual for Design and Construction Monitoring of Soil Nail Wall	Comments
		Waler Bars	Reinforcement Development and Splices	
Other	UPPER/LOWER CANTILEVER CHECK	Not a Separate Design Step	Section 4.7 Check for Flexure and One Way Shear at Cantilever	[REF1] does not check upper cantilever for shear or flexure.
Other	SPECIAL DESIGN CONSIDERATIONS	Section 5.11, 5.12 & Chapter 6 Drainage Frost External Loads Strut Nails Tiered Walls Composite (Hybrid) Structures Varying Nail Inclinations Varying Nail Orientations Varying Nail Lengths	Section 4.10 Heterogeneous Soil Profiles Surcharge Loading Bridge Abutments Tiered Walls Composite (Hybrid) Wall Types Variable Nail Lengths Variable Nail Inclinations Variable Nail Orientations Ground Water Seepage Water Table Close to Base of Wall Infinite Slope Condition Performance Under Seismic Loading Frost Protection Expansive Soils Residual Soils Structures with Externally Loaded Wall Facing Strut Nails for Facing Support End of Wall Transitions CIP Concrete Form Connection to Shotcrete Facing	

Table 2. Factors of Safety Comparison for [REF1] and [REF2].

Failure Mode	Resisting Component	Minimum Factor of Safety					
		[REF1]			[REF2]		
		Static Loads			Static Loads		
		Temporary Structure	Permanent Structure	Seismic Loads	Temporary Structure	Permanent Structure	Seismic Loads
External	Global Stability (long-term)	1.35	1.5	1.1		1.35 (1.50)	1.01 (1.13)
	Global Stability (construction staging)	1.2-1.3		NA		1.20 (1.35)	NA
	Sliding	1.3	1.5	1.1		NA	NA
	Eccentricity Check for Overturning, e					?±B/6	?±B/6
	Bearing Capacity	2.5	3.0	2.3		2.5	1.88
Intern al	Pullout Resistance	2.0		1.5		2	1.5
	Nail Bar Tensile Strength	1.8		1.35		1.8	1.35
Facing Strength	Flexure	1.35	1.5	1.1		1.5	1.12
	Punching Shear	1.35	1.5	1.1		1.5	1.12
	Stud Tensile (A307 Bolt)	1.8	2.0	1.5		2	1.5
	Stud Tensile (A325 Bolt)	1.5	1.7	1.3		1.7	1.27



Empirical data show that for soil nail walls with typical L/H between 0.7 and 1.0, negligible surcharge loading, and typical global factors of safety (FS_G) values of 1.5, the maximum long-term horizontal and vertical wall displacements at the top of the wall, δ_h and δ_v, respectively, can be estimated as follows:

$$\delta_h = \left(\frac{\delta_h}{H}\right)_i \times H$$

where:

$(\delta_h/H)_I$ = a ratio dependant on the soil conditions "i" indicated in the table below; and
H = wall height.

The size of the zone of influence where noticeable ground deformation may take place, is defined by a horizontal distance behind the soil nail wall (D_{DEF}) and can be estimated with the following expression:

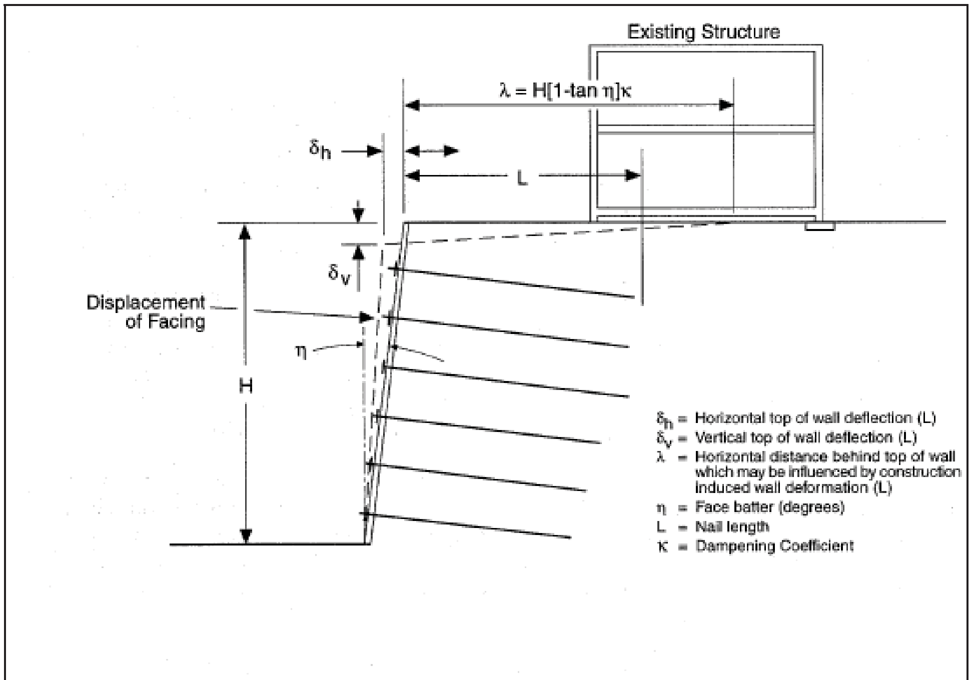
$$\frac{D_{DEF}}{H} = C\,(1 - \tan\alpha)$$

where α: is the wall batter angle; and C coefficient

Values of $(\delta_h/H)_i$ and C as Functions of Soil Conditions.

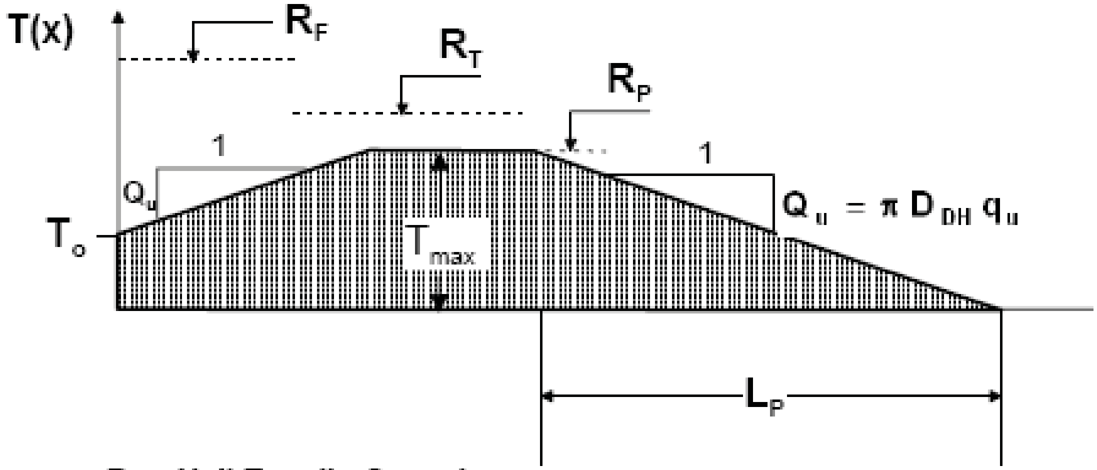
Variable	Weathered Rock and Stiff Soil	Sandy Soil	Fine-Grained Soil
δ_h/H and δ_v/H	1/1,000	1/500	1/333
C	1.25	0.8	0.7

Figure 86. Schematic. Estimating the Deformation and Extent of Influence. [REF1].



Type of Soil	Weathered Rocks Stiff Soils	Sandy Soils	Clayey Soils
δ_h and δ_v coefficient κ	H / 1000 0.8	2 H / 1000 1.25	3 H / 1000 1.5

Figure 87. Schematic. Deformation Estimate at Top of Wall and Extent of Influence. [REF2]



R_T = Nail Tensile Capacity
R_F = Facing Capacity
R_P = Pullout Capacity

Q_u, q_u = Ultimate load transfer rate and bond strength

$T_O \sim 0.6\text{-}1.0\ T_{max}$

1) $R_P < R_T < R_F$ (pullout controls, shown in example above)
2) $R_T < R_P < R_F$ (tensile failure controls)
3) $R_F < R_P$ or R_T (facing failure may control depending on T_o/T_{max})

Figure 88. Schematic. Illustration of Distributed Nail Tensile Loads (T_o, T_{max}, etc.) and the Limiting Nail Capacities (Tensile, Facing, & Pullout). [REF1]

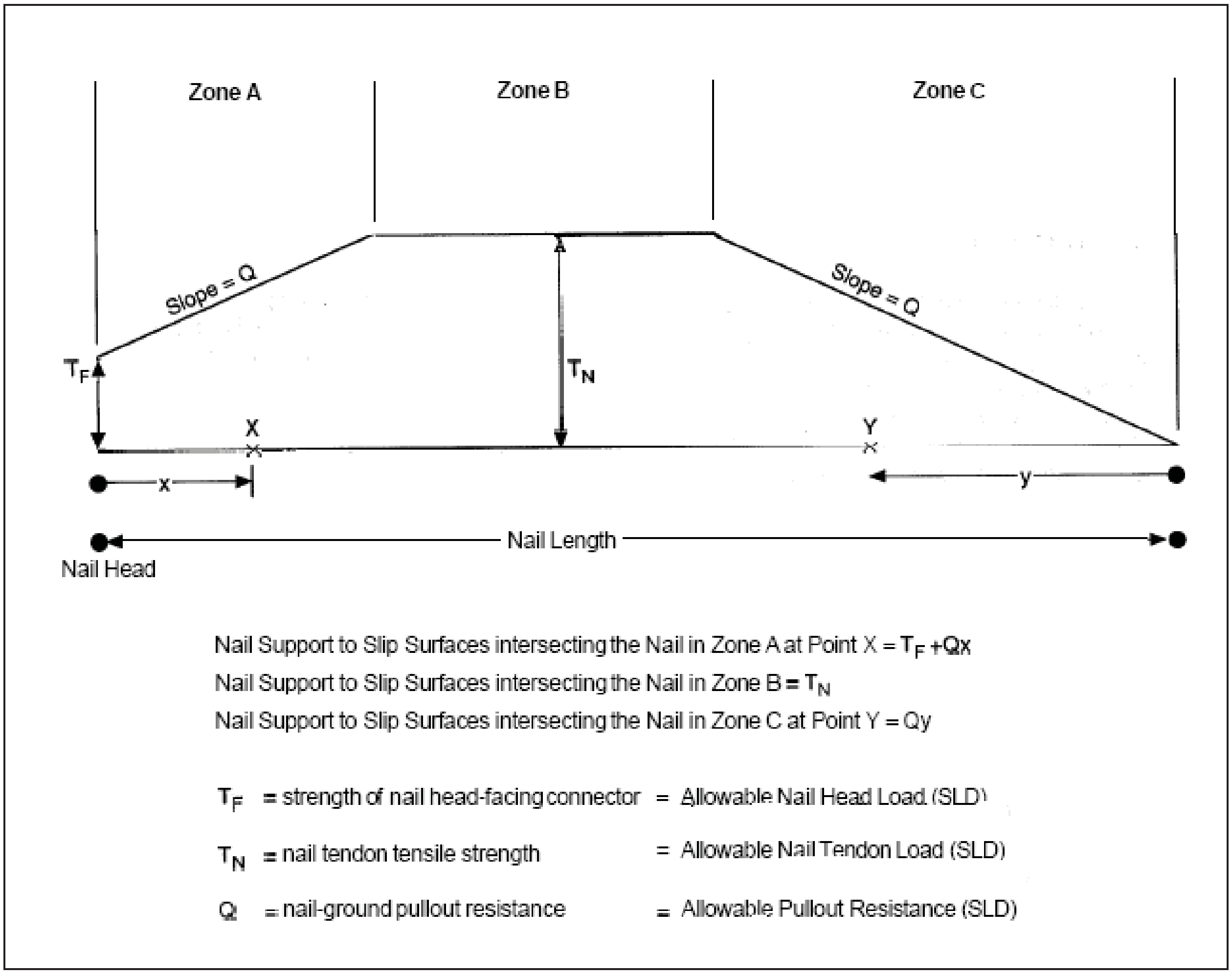


Figure 89. Schematic. Illustration showing the Distributed Nail Capacities. [REF2]

APPENDIX A REFERENCES

Lazarte, C.A., Elias, V., Espinoza, R.D. and Sabatini, P.J. (2003). "Geotechnical Circular No. 7 – Soil Nail Walls," Report No. FHWA IF-02-017, Federal Highway Administration, Washington, D.C.

Byrne, R.J., Cotton, D., Porterfield, J., Wolschlag, C. and Ueblacker, G. (1998). "Manual for Design and Construction Monitoring of Soil Nail Wall," Report No. FHWA SA-96-069R, Federal Highway Administration, Washington D.C.

CALTRANS (Undated). "Manual of Instructions for SNAILZ, Version 3.10," California Department of Transportation, Engineering Service Center, Division of Materials and Foundations, Office of Roadway Geotechnical Engineering, Sacramento, California.

Clouterre (1993). "Recommendations CLOUTERRE 1991 – Soil Nailing Recommendations 1991," English Translation, Presses de l'Ecole Nationale des Ponts et Chaussées, Paris, France.