Soil Nail Walls

This module presents Caltrans practice for the geotechnical investigation, design, and reporting for soil nail walls. The soil nail wall is an effective earth retaining system (ERS) that requires top-down excavation. In a soil nail wall system, soil nails function as passive reinforcing elements that are installed and grouted in sub-horizontal drilled holes to form a composite mass.

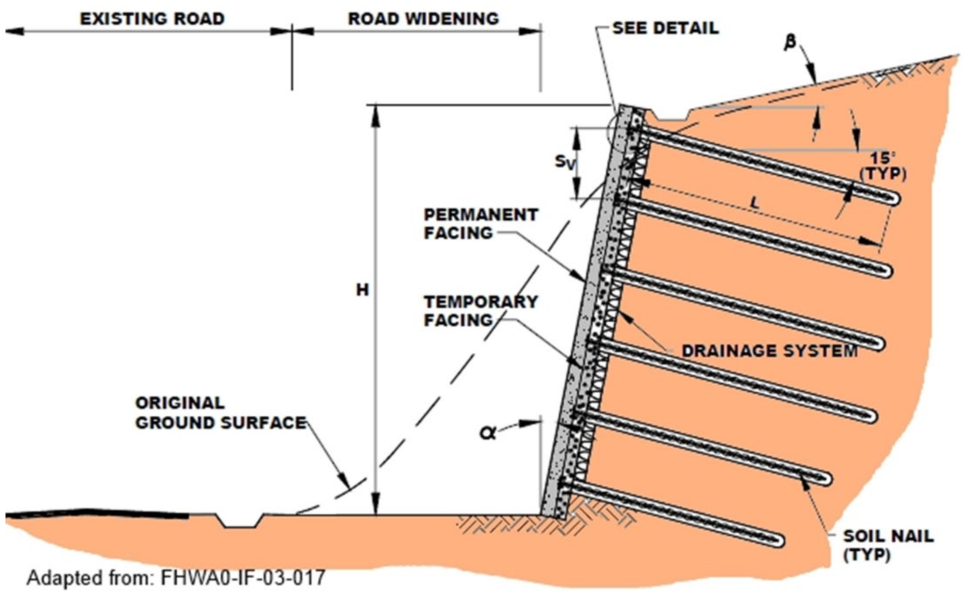

Figure 1: Schematic Soil Nail Wall

Requirements and Guidelines

In addition to this module, refer to the following documents for the requirements and guidelines of geotechnical investigation, design, and reporting of Soil Nail Walls:

- *FHWA Geotechnical Engineering Circular (GEC) No. 7 Soil Nail Walls*
- *Memos to Designers 5-19, Earth Retaining Systems Communication*
- *Bridge Design Aids 3-9, Soil Nail Wall Facing Design*
- *Structure Technical Policy 11.23 Design Criteria for Soil Nail Wall Facing*
- Geotechnical Manual
  - Seismic Design of ERS
  - Overall Stability Modeling of ERS
  - Foundation Reports for Earth Retaining Systems

Advantages and Characteristics of Soil Nail Walls

The advantages of soil nail walls include:

- Less right of way needed than competing systems, such as ground anchors
- Less disruptive to traffic and less environmental impact
- Relatively fast construction
- Cost effective at remote sites and sites with difficult access
- Effective in landslide repair above the landslide scarp
- Relatively flexible and can accommodate relatively large total and differential movements
- Perform well under seismic loading
- Have more redundancy than ground anchors because of the larger number of reinforcing elements per unit area; a passive system with relatively lower tensile stress sustained by the reinforcing elements; and have an established construction quality assurance program
- More economical than conventional earth retaining systems taller than 15 feet
- Typically, are equivalent or more cost-effective than ground anchor walls

Soil nail walls are not feasible when there are:

- Stringent requirements that limit the wall movement during construction, (e.g., the proposed wall is adjacent to and below a critical structure, such as a bridge abutment)
- Utilities behind the wall and within the soil nails reinforced zone
- Difficulty to obtain permanent easements

Favorable subsurface conditions for soil nail wall construction include:

- Excavated face can stand unsupported and stable until the facing is structurally complete
- Stiff cohesive soil or soil with sufficient apparent cohesion; weathered rock with favorable bedding planes; and well-graded and well-compacted backfill
- Drilled-holes can remain open and stable without casing until the nails are installed and the drilled-hole is grouted
- The toe of wall is above the groundwater table

Unfavorable subsurface conditions for soil nail wall construction include:

- Poorly graded loose sand; soft highly plastic clay; organic soil; collapsible soil; expansive soil; cobbles and boulders; weathered rock with unfavorable bedding planes
- Groundwater table is above the toe of wall
- Corrosive soil and groundwater

Investigation

Refer to the *Geotechnical Investigations* module for general instructions on performing the planning-phase site investigation (e.g., literature review, site visit) and the design-phase site investigation (e.g., site visit, selection of investigative methods, locations, and depths).

Geotechnical investigation for soil nail wall design should obtain:

- Soil and rock stratigraphy
- Soil and rock engineering properties, including unit weight, shear strength, orientation and spacing of bedding.
- Design Groundwater
- Information that may assist in evaluating potential construction issues, such as difficulties of excavating the wall face and drilling the holes should also be retrieved as much as practically possible.

Designing and constructing a soil nail wall along a highway often require excavating the lower portion of a native slope that extends far above the highway. Access to the steep slope behind the wall layout line to perform geotechnical investigation can be challenging and often impracticable. An alternative option is to perform subsurface exploration in front of the proposed wall by means of trench excavation, geotechnical and geological mapping, and horizontal drilling.

Perform at least one horizontal boring into the slope that is to be excavated and drilled for soil nail wall construction to obtain soil and rock specimens and evaluate the cave-in potential of drilled holes.

Analysis and Design

To perform geotechnical analysis and design of soil nail walls use *Snail*, which is a soil nail wall design and analysis software developed, owned, and maintained by Caltrans. *Snail* implements the design methodologies of *FHWA GEC No. 7*, and includes features for the analysis and design of the soil nails and structural components of the wall face.

Before using *Snail*, read the *Snail User Guide* and practice using the *example files*. Select representative and critical cross sections by reviewing the layout and elevation views of the soil nail wall. Consider applicable excavation heights, geometry, soil and rock profiles, subsurface conditions, and design efficiency when selecting representative cross sections.

The procedures and issues discussed in this module and *FHWA GEC No. 7* only cover internal and external (sliding and overturning) stability of soil nails. Global stability of the soil nail wall system is not addressed in this module or *FHWA GEC No. 7*. Perform global stability analyses in accordance with the *Overall Stability of ERS* module and *Seismic Design of ERS* module.

Typical Design Configuration and Parameters

The following are recommended parameters to start the soil nail wall design.

- Drilled-hole Diameter: 6 inches; increase to 8 inches or larger if necessary, however, drilled-hole diameters greater than 6 inches is rare in soil nail wall construction.

  The drilled-hole diameter entered in the Snail input is only used for calculation and must not be presented in the geotechnical report or the contract plans. According to Caltrans contracting practice, selection of drilled-hole diameter is the contractor's responsibility, and the contractor must demonstrate the selected drilled-hole diameter and associated drilling and grouting methods can provide required nominal pullout resistance, Q_b, via verification and proof tests. To implement this contracting practice, Snail output only shows nominal pullout resistance, Q_b, calculated from the drilled-hole diameter and nominal bond strength. Hence, the Snail output can be included as an attachment to the geotechnical report.

- Soil Nail Length: At least 15 feet and typically 0.7 to 1.0 times designed excavation height, increase as necessary. To facilitate ease of construction and inspection, use a uniform nail length throughout a cross section.

- Soil Nail Inclination: 10° to 15° from horizontal.

  According to the Construction Industry Research and Information Association, (*CIRIA) C637 Soil Nailing - Best Practice Guidance*, a soil nail installed at 15° below the horizontal has an efficiency of 64% of the nail installed at the optimum angle (35° above horizontal). However, it has nearly twice the length in the resistant zone and more than four times the average overburden. Therefore, a soil nail inclined slightly downwards is more effective. As a soil nail inclines steeper than 15° the efficiency decreases rapidly without any increase in pullout length or significant increase in overburden. Therefore, the optimum soil nail inclination angle should be between 10° and 15°.

  Nail inclination angles less than 10° should be avoided to prevent voids in the grout and an extended "bird's beak" at the nail head. Voids can reduce the pullout resistance of soil nails.

- Wall Face Batter: 1(H):12(V) or any batter angle to account for lateral displacement of the wall face during construction. As a passive reinforcing system, soil nails are expected to be strained during construction. A soil nail wall face that rotates outward from vertical may appear unstable even though the wall is still sound and stable.

- 1st Soil Nail Row: 2.5 feet from the top of excavated face.

- Soil Nail Spacing: 5 feet for both horizontal and vertical spacing; with columnar layout to facilitate the placement of geocomposite drains.

- Nail Bar Diameter and Grade: Use No. 8 and Grade 75 bar.

- Nominal Bond Strength, q_u: Refer to *FHWA GEC No. 7* (Tables 4.4a, 4.4b, 4.5, and 4.6) for suggested nominal bond strength ranges for different soil, rock, and conditions.

The nominal bond strength entered into the Snail input is only used for calculation. Do not present the nominal bond strength values in the geotechnical report or contract plans. Instead, the nominal pullout resistance, Q_b, which is derived from the nominal bond strength and drilled-hole diameter, should be presented in the geotechnical report and contract plans.

- Surcharge: Include live and dead loads, such as traffic and structure loads; consult with Structure Design or District Design.

Design Considerations

There are many issues to consider when designing a soil nail wall. Some of these issues have been addressed in *FHWA GEC No. 7*. The following are additional issues that should be considered.

- For a soil nail wall with a steep slope above the wall, potential rock fall and mud flow issues should be addressed (see *Rockfall* module).
- In limit equilibrium analysis, the resulting most critical surface must be bracketed by defined search limits to ensure that the search yields the most critical surface, and that no other surfaces outside of the defined search limits have a lower factor of safety (FoS) than the most critical surface found within the defined search limits. When the most critical surface is found near or on the edge of the defined search limits, extend or move the search limits to capture the actual most critical surface.

  When analyzing soil nails with sloping ground above the wall, sometimes the upper point of the most critical surface may persistently lay on the point that defines the upper search limit. As a result, the upper search limit may need to be continually moved further up-slope while the most critical surface cannot be found. When this happens, limit the search to 3 times the excavation height horizontally away from the wall face. The reason for limiting the search to 3 times the excavation height horizontally is that the analysis of soil nails only addresses internal and external stability of the soil nail wall system. A search beyond this limit is considered a global slope stability analysis and should be carried out using a slope stability analysis tool, such as Slide or Slope/W.
- When a soil nail wall is to be constructed under and in front of structures or facilities that may be sensitive or affected by the lateral displacement of the wall or the settlement of the ground above the soil nail wall, numerical analysis using software, such as Plaxis and FLAC, should be performed. This working stress analysis is needed to evaluate the expected lateral displacement and settlement of the ground above the wall, and to analyze possible excavation and construction options to limit the displacement and settlement.

Communication with Structure Designer

Communicate with the Structure Designer via emails to provide the following information during final design iterations.

1. Elevation-view plan sheets with delineation of wall zones
2. Instruction for placement of soil nails, including
   - Nail array pattern – use columnar layout to facilitate the placement of geocomposite drains
   - Maximum horizontal and vertical soil nail spacing
   - Vertical distance of soil nails from the top of the excavated face – 2.5 feet (typical), and the bottom of the wall – 2.5 feet (typical)
   - Horizontal distance from the ends of the wall – 2.5 feet (typical)
   - Minimum spacing between soil nails – 2.5 feet (typical), when adjusting soil nail spacing near the bottom and ends of the wall
   - Minimum clearance between soil nails and utilities or obstructions – 2.5 feet (typical)
   - Maximum allowable horizontal and vertical rotation of soil nails from design orientation – 20° (typical), to provide clearance for utilities or obstructions
3. Schedule of soil nail lengths
4. Inclination of the soil nails measured from horizontal
5. Wall face batter measured from vertical
6. Calculated Factor of Safety for internal and global stability (according to Table 5-1, *FHWA GEC No. 7*)
7. Estimated static lateral displacement, if applicable. If the soil nail wall design satisfies the stability requirements of soil nails, then the lateral displacement may be assumed acceptable.
8. Nominal pullout resistance Q_b of soil nails in force/unit length, which should be shown on the Plans as the value for Q_b.
9. Soil nail bar ASTM designation and grade that arrived at the bar yield strength, the bar diameter entered in Snail, and the required Factor of Safety provided by the Structure Designer.
10. Allowable facing resistance, i.e. unfactored tensile force at soil nail head, ($F_{unfactored}$) used in Snail calculation and T_o (Note: unfactored tensile force at soil nail head should always be greater than T_o; unfactored tensile force at soil nail head = allowable facing resistance from geotechnical ASD calculation).
11. Layout of proof test nails, on the provided elevation-view plan sheets of the wall that are 8 percent of the total number of production soil nails for each wall zone; be aware of the typical location of the geocomposite drains.

Work with the Structure Designer to arrive at an agreed upon allowable facing resistance, i.e., unfactored tensile force at soil nail head ($F_{unfactored}$), used for both geotechnical and structure design.

Obtain plan sheets from the Structure Designer, and review delineation of wall zones, soil nails and proof test nails layout to ensure the geotechnical design information and recommendations are implemented on the plan sheets.

The following flowcharts present Caltrans design processes of soil nail walls in various conditions according to *BDA 3-9*. The typical conditions that cover most of the soil nail wall design scenarios are presented in Figure 2.

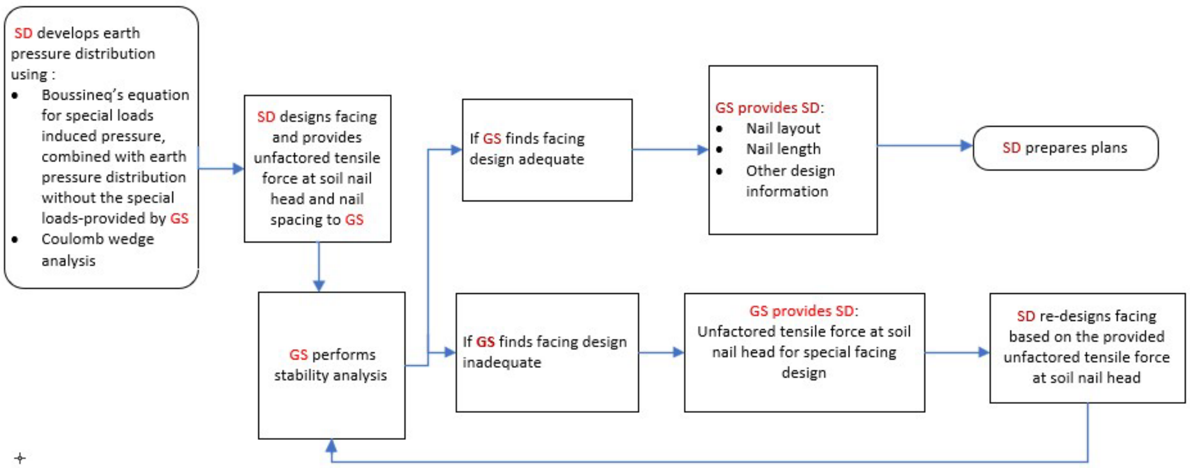

Figure 2: Design Process for Typical Conditions

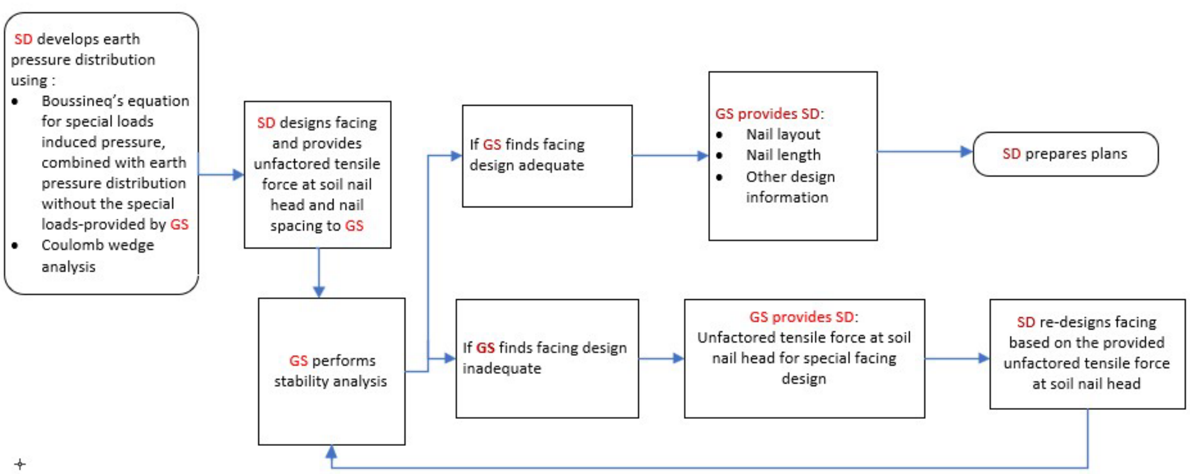

Figure 3: Design Process for Complex Conditions 1

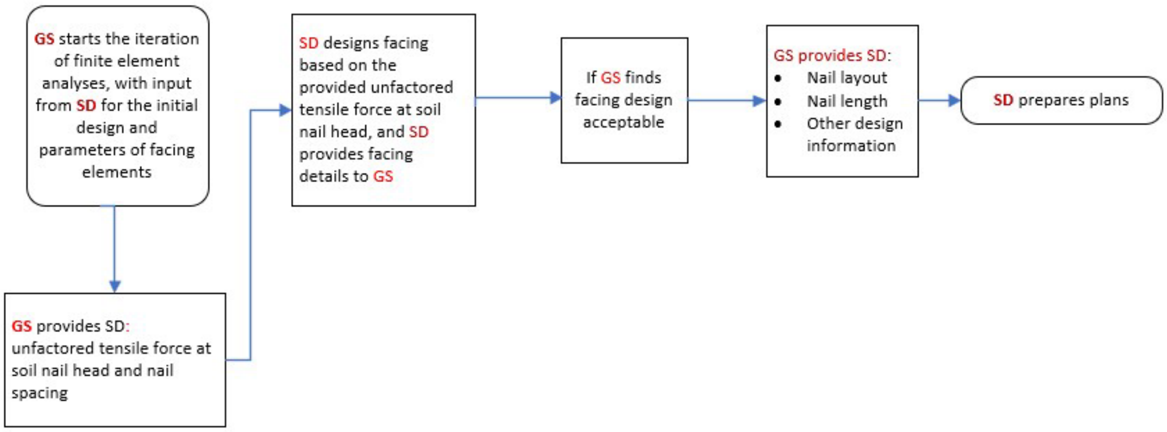

Figure 4: Design Process for Complex Conditions 2

Reporting

Present Soil Nail Wall recommendations in accordance with the *Foundation Reports for Earth Retaining Systems* module.

Include the following in the *Analyses and Design* section of the Preliminary Foundation Report or Foundation Report:

1. Describe the representative cross-sectional geometry and ground line condition. Reference the plan sheets when possible.
2. Description of external loads (e.g., surcharge).
3. Design groundwater elevation.
5. Calculated factor of safety and resistance factor for overall global stability and local slope stability (service and extreme event limit states). Provide the method of analysis.
6. Estimated seismic lateral displacement, if calculated.
7. Effects of Soil Nail construction on adjacent ground and/or existing structures, utilities, both above and below ground. Present related recommendations in the *Recommendations* section.

Include the following in the *Recommendations* section of the Preliminary Foundation Report or Foundation Report:

1. Seismic hazard recommendations required in the following modules, as applicable:
    a. Surface Fault Rupture
    b. Seismic Global Stability (see *Seismic Design for ERS* module)
2. If requested by Bridge Design, provide mitigation recommendations for specific seismic hazards identified in 1.
3. Layout and limits of wall zones, or refer to the Plans that show the wall zones
4. Instruction for placement of soil nails, including
    - Nail array pattern.
    - Maximum vertical distance of the soil nails from the top of the wall, and the bottom of the wall.
    - Maximum horizontal distance from the ends of the wall.
    - Minimum spacing between soil nails when adjusting soil nail spacing near the bottom and ends of the wall.
    - Minimum clearance between soil nails and utilities or obstructions; and the maximum allowable horizontal and vertical rotation of soil nails from design orientation to provide clearance for utilities or obstructions.
5. Inclination of the soil nails measured from horizontal.
6. Wall face batter measured from vertical.
7. Nominal pullout resistance Q_b of soil nails in force/unit length, which should be shown on the Plans as the value for Q_b.
8. Nail bar yield strength, the bar diameter entered in Snail, and the required Factor of Safety provided by the Structure Designer.

9. Layout of proof test nails, on the provided elevation-view sheets of the wall that are 8 percent of the total number of production soil nails.
10. *Soil Nail Design Recommendations* table (see below).
11. *Nominal Pullout Resistance for each Wall Zone* table (see below).

Do not layout the verification test nails on the Plans. The locations of verification test nails in each wall zone are to be determined by the contractor, because it is the contractor who determines which location and direction to start constructing each wall zone.

Table X: Soil Nail Design Recommendations

Excavation Height (ft)	Min. Nail Length (ft)	Max. Vertical Nail Spacing (ft)	Max. Horizontal Nail Spacing (ft)	Nail Bar		Nominal Pullout Resistance Q_b (lbf/ft)	Unfactored Tensile Force = Factored (Allowable) Facing Resistance at Soil Nail Head (kips)	
				Yield Strength (ksi)	Diameter (inch)		Static	Seismic

Note: The unfactored tensile force at soil nail head should always be greater than T_o; unfactored tensile force at soil nail head = allowable facing resistance from geotechnical ASD calculation). The Structure Designer must ensure that structural facing design meets or exceeds $F_{unfactored}$.

Table Y: Nominal Pullout Resistance for each Wall Zone

Wall Zone	Nominal Pullout Resistance Q_b (lbf/ft)

Note: Wall Zones should be delineated on the Plans with Wall Elevation View.

Geotechnical Tasks during Construction

Pre-Construction Meeting

Contact the Resident Engineer (RE) and Structure Representative to attend pre-construction meeting with or without the Contractor. Be prepared to discuss and answer questions related to the design and construction of the soil nail walls, including Standard Specifications and Special Provisions Sections 19 and 46.

Shop Drawing Review

Before construction, Shop Drawings will be submitted by the contractor for review, as described in Sections 19-3.01C(4) and 46-1.01C(2) of *Standard Specifications*. Review the following items in the Shop Drawings and provide comments to the Structure Representative. Do not direct the means and methods of construction as these are the responsibility of the contractor.

Under Section 19 Earthwork:

- Soil parameters used for stability analysis,
- Stability analysis of proposed excavation lifts, and
- Proposed *stability test* locations.

Under Section 46 Ground Anchor and Soil Nail Wall:

Refer to the Contract Plans while reviewing the proposed test nail details in the Shop Drawings, including:

- Proposed drilled-hole diameter,
- Estimated nominal bond strength,
- Converted nominal pullout resistance,
- Verification and proof test details,
- Quantity of test nails, and
- Soil nail bar grade and diameter.

Test Nail Results Review and Archive

Request the Structure Representative to forward all soil nail test data, irrespective of whether the test nails passed or failed. Reviewing and collecting test nail data is the only means to evaluate the estimate of pullout resistance during design, and to calibrate for future design.

When a soil nail wall is completed, the contractor needs to send an email with the soil nail test results as a tabulated spreadsheet to the Engineer and Geotechnical.Data@dot.ca.gov (Section 46-1.01C(3) of *Standard Specifications*). Obtain the test results from Geotechnical.Data@dot.ca.gov and archive the test results in GeoDOG.

Typical Construction Issues

Site conditions, diligence of the design deliberation, and competency of the contractor dictate whether construction difficulties or issues will arise during construction. Typical issues encountered during soil nail wall construction include:

- Sloughing of excavated face due to dry sandy materials
- Desiccation, weathering, and instability of the excavated face due to prolonged exposure after excavation
- Creeping and continual movement of the wall face due to high plasticity clay
- Difficult drilling through cobbles and boulders
- Caving of drilled holes
- Excessive groundwater seepage and poor control of surface water and groundwater
- Construction mistakes, poor workmanship, and incorrect installation
- The original grade (OG) line as shown on the Plans does not match and is above the top of the excavated face at the site
- Failed verification and proof tests

Work closely with the Structure Representative and be prepared to promptly answer calls and address Request for Information (RFI) to resolve construction issues in a timely manner.

Technical Notes

This section provides addition design insights to be considered during design of soil nail walls.

Corrosion Protection of Soil Nails

The long-term stability of a soil nail wall or slope primarily depends on the corrosion protection of the soil nails that protect the structural integrity of the soil nail bars.

The grout surrounding the soil nails should not be relied on as a water barrier as the grout column will develop cracks under tensile stress. To develop pullout resistance, which is the inherent function of soil nails; the grout, as a medium between the soil/grout interface and soil nail bar, will sustain tensile stress and ultimately develop cracks to transfer the stress. Subsequently, surrounding water and moisture will infiltrate through these cracks and reach the soil nail bars.

The following three-volume articles published by *Belgian Building Research Institute* provide excellent and comprehensive detailed pullout test data, physical measurement and photos of the exhumed ground anchors, grout columns, and developed cracks. Even though these articles are solely for ground anchors, the mechanisms of grout/ground and grout/tendon are the same for both ground anchors and soil nails, and applicable to soil nails.

- *Proceedings International Symposium – Ground Anchors, Limelette test field results, May 14, 2008, volume 1, volume 2, volume 3*

Nominal Strength

Nominal strength can be best defined as: the capacity of a structure or component to resist the effects of loads, as determined by computations using specified material strengths (such as yield strength, f_y, or ultimate strength, f_u) and dimensions and formulas derived from accepted principles of structural mechanics or by field tests or laboratory tests of scaled models, allowing for modeling effects and differences between laboratory and field conditions.

Nominal strength of a batch of construction material, such as steel and concrete, is a strength value derived from testing to failure of specimens sampled from that batch. Even though the reported nominal strength values are typically the nearest rounded-down customary value from the minimum tested strength values, the reported nominal strength is still inherently correlated to the probability density function of the material. For example, the strength distribution of an ASTM A36 steel production batch should be mostly greater than the nominal yield strength of 36,000 psi; i.e. near 100% probability that the ASTM A36 steel has a yield strength of greater than 36,000 psi, the nominal strength.

There is a much more clearly defined material strength value that is based on statistical concept, the characteristic strength. The characteristic strength is defined as: the strength of the material below which not more than 5% of the test results are expected to fall. Sometimes, the characteristic strength is selected as the nominal strength of a material.

In any event, test-to-failure data is needed to establish the strength probability density function of a construction material or construction components. Establishing a strength probability density function for construction materials and construction components is a major and necessary step to truly implementing LRFD, and to assigning Factor of Safety under ASD. Without the strength probability density function based on test-to-failure data, the design practice can rely only on theory and combined with observed performance of prior construction.

Among geotechnical construction components, very few, if any, have an established and direct probability density function. This is because it is physically, financially, and contractually very difficult to test to failure a geotechnical component, such as a driven pile, let alone to test to failure a batch of these components. Therefore, the nominal strength of geotechnical construction components based on directly measured strength or performance probability density functions is rarely available.

Hence, almost all nominal strength values used for geotechnical construction components are established based on theory, inferred from basic soil and rock properties, and combined with observed performance. Very few of these nominal strength values have been verified by test to failure.

Nominal Strength and Pullout Resistance of Soil Nails

In soil nail construction, a statistically significant amount of sacrificial soil nails are required to be tested to and pass the nominal pullout resistance in order to satisfy the acceptance criteria. The implemented test regime provides relatively higher confidence for constructed soil nails than that for other geotechnical components.

However, tests that stop short of reaching failure cannot be used to establish the strength probability density function that can verify the reasonableness of the selected nominal pullout resistance.

Improvement in Interpreting Nominal Strength from Subsurface Exploration

The discussion in the previous section has not addressed the issue of how to interpret nominal pullout resistance based on field and laboratory tests during design. Currently, the often-quoted references on this subject are the tables (Tables 4.4a, 4.4b, 4.5, and 4.6) from *FHWA GEC No. 7*. However, the information presented in these tables needs to be updated and improved.

First of all, there is a need for clarification and agreement on where the presented strength values reside in terms of the probability density function of particular soils and rocks. Some may consider these values as the average values compiled from collected data, which is naturally the case when presenting summaries of findings. However, during construction, the values selected for design, mostly referenced from these tables, are the construction acceptance criteria – the absolute lower bound according to typical construction contract language and the de facto nominal strength values. Understanding this potential disconnect is needed when referencing these values.

Then, clearly defined nominal strength with respect to the probability density function needs to be established and agreed upon. Meanwhile, we need a concerted effort to continually accumulate engineering properties of soils and rocks from laboratory and in-situ tests and interpreted nominal pullout strengths and associated design parameters of these soils and rocks. Only after we compare the interpreted nominal strengths with the nominal strengths obtained from soil nail pullout tests and other tests during construction, can we calibrate our practice. The first step taken by Caltrans is implementing the requirement of emailing all the pullout test results as a tabulated spreadsheet by the contractor to the Engineer and Geotechnical.Data@dot.ca.gov after completion of a wall construction.

This above discussion offers a general direction needed to prepare for the gradual implementation of LRFD for soil nails. It can take years, and probably decades, and requires gradual improvement to our geotechnical investigation practice for soil nail design.

Current soil nail design practices all apply various assumptions to simplify a complex composite system to comprehensible models so that workable design procedures can be implemented. Be diligent and aware of these assumptions, and be involved throughout the design, contract development, and construction phases to continually improve on the understanding of soil nail design and construction.