1 SOIL NAIL WALLS

The soil nail wall is an effective technique to construct an 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.

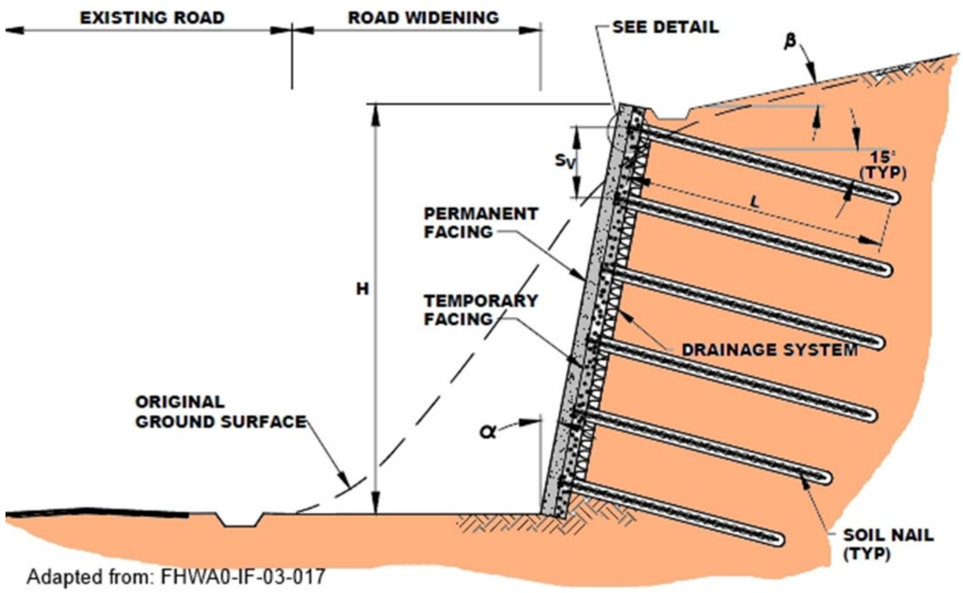

Figure 1 – Schematic Soil Nail Wall

1.1. 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 (2015)*
- *Memos to Designers 5-19, Earth Retaining Systems Communication*
- *Geotechnical Manual, Foundation Reports for Earth Retaining Systems*
- *Bridge Design Aids 3-9, Soil Nail Wall Facing Design*
- *Structure Technical Policy 11.23 Design Criteria for Soil Nail Wall Facing*

1.2. 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 cause 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 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

2 Geotechnical Design Practice

The geotechnical tasks for the design of soil nail walls include:

1. Work with other project development team (PDT) members to evaluate and select the appropriate wall type
2. Evaluate of available information
3. Perform subsurface exploration
4. Perform design and analysis
5. Issue the geotechnical report
6. Assist in developing and reviewing the PS&E package

7. Provide construction support

The following are main task to be carried out during geotechnical design.

3 Project Initiation

During project initiation, the need for a wall will be identified by the District. Upon request, the geotechnical designer should perform preliminary assessment of the site and issue a preliminary geotechnical report that provides an evaluation of feasible wall types and a recommended wall type.

During Type Selection process, communicate and discuss with District Project Engineer and structure designer to select the preferred wall type. Constructability, constraints, and cost should be discussed and evaluated to arrive at the preferred option.

4 Literature Review

Refer to *Geotechnical Investigations* for guidelines on performing literature searches and evaluate available information for applicability to the soil nail wall design. Obtain and evaluate the general plans and cross sections of proposed walls from District or Structure Design (SD).

5 Geotechnical Investigation

Geotechnical investigation for soil nail wall design should obtain enough information for design, including:

- Soil and rock stratigraphy
- Soil and rock engineering properties, including unit weight, shear strength, orientation and spacing of bedding, and estimated nominal pullout resistance
- Groundwater elevation
- Information that may assist in deducing and 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

To plan for and carry out geotechnical investigation, including laboratory test, refer to the applicable modules in the Geotechnical Manual and:

- *FHWA Geotechnical Engineering Circular (GEC) No. 7 Soil Nail Walls*
- *FHWA Geotechnical Engineering Circular (GEC) No. 5 Geotechnical Site Characterization*
- *NCHRP Web-Only Document 258 Manual on Subsurface Investigations (2019)*

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, if feasible, 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 during construction.

6 DESIGN AND ANALYSIS

To perform geotechnical design and analysis 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 design and analysis of the soil nails and structural components of the wall face.

Before using *Snail*, read the *Snail User Guide* and practice 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 the representative cross sections.

The procedures and issues discussed in this module and *FHWA GEC No. 7* cover only the 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*. To make the geotechnical analysis complete, global stability analysis of a soil nail wall must be performed.

7 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 diameter greater than 6 inches is rare in soil nail wall construction.

  The drilled-hole diameter entered into 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 *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.
- Horizontal Seismic Coefficient: Follow the *FHWA GEC No. 7* procedure. Use *Caltrans ARS Online* with V_{S30} to determine the Peak Ground Acceleration (PGA) and 1-second response acceleration (S_{D1}). Obtain acceptable wall displacement due to seismic events from the owner of the project or wall, so that the corresponding horizontal seismic coefficient can be determined for the seismic analysis and design of the wall.
- Surcharge: Include live and dead loads, such as traffic and structure loads; consult with Structure Design or District Design.

8 Design Considerations

There are many issues should be considered during the design of a soil nail wall. Some of these issues have been addressed in *FHWA GEC No. 7*. The following are additional issues 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 the set search limits to ensure that the search has yield the most critical surface, and there are no other surfaces outside of the search limits have a lower FoS than the

most critical surface found within the set search limits. When the most critical surface is found lay on the edge of the set 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 happened, 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.

- For global slope stability analysis, use a horizontal seismic coefficient equal to 1/3 PGA.
- 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 the 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.

9 Communication with Structure Designer

Communicate with the structure designer via emails or *geotechnical report (Draft)*, and provide the following information as the first step of 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 the 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 into 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 present in Figure 2.

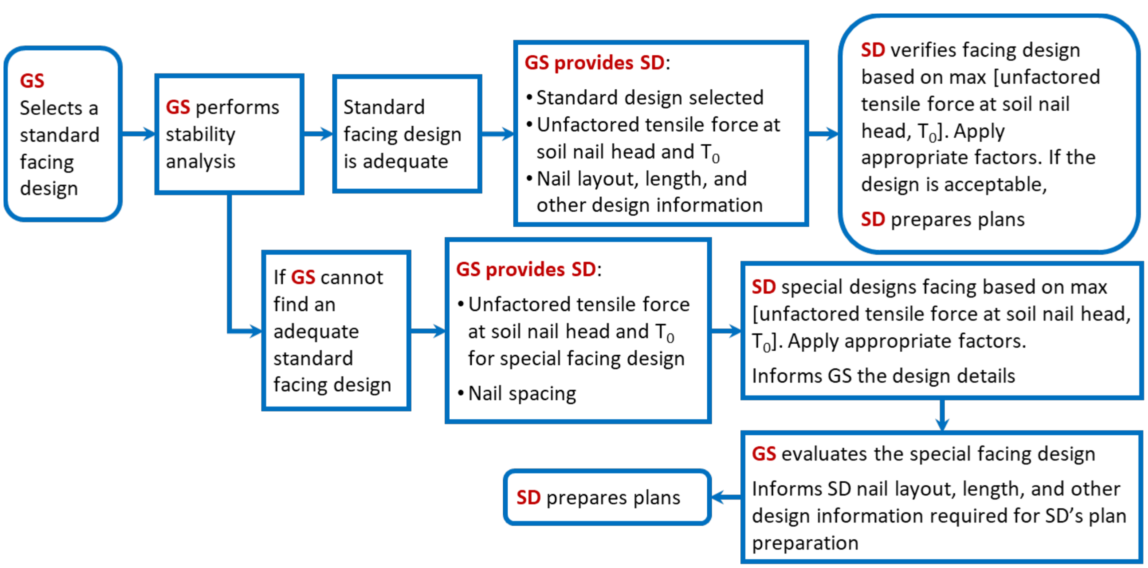

Figure 2 – Design Process for Typical Conditions

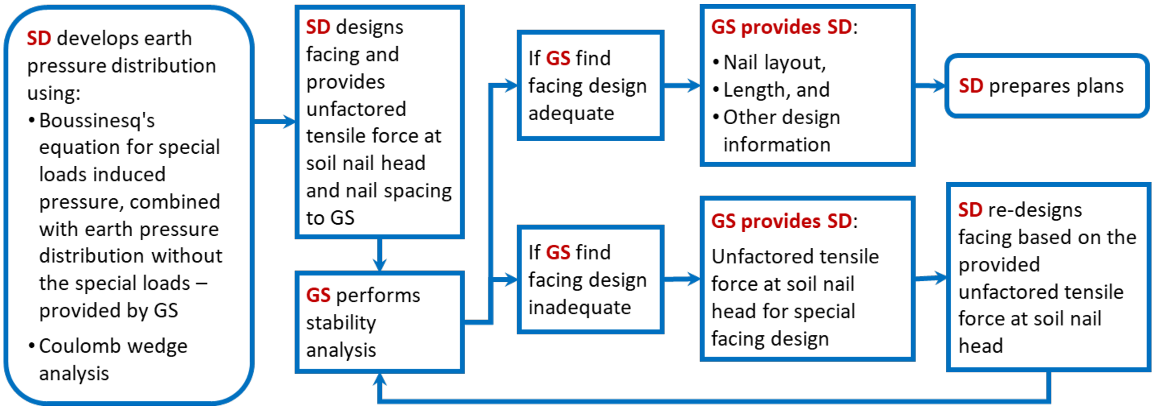

Figure 3 – Design Process for Complex Conditions 1

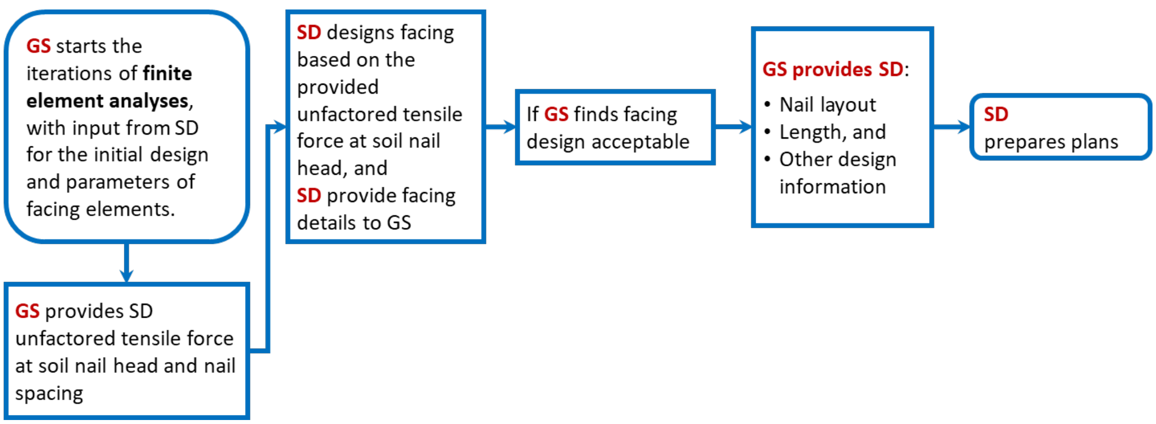

Figure 4 – Design Process for Complex Conditions 2

10 Reporting

Produce geotechnical reports per *Foundation Reports for Earth Retaining Systems* and the requirements herein.

The *Geotechnical Recommendations* section conveys design information to the structure designer, whereas the *Notes for Specifications* conveys information and instruction to the Specifications Engineers for the edits and compilation of Special Provisions.

Provide the following information in the *Geotechnical Recommendations* and *Notes for Specifications* sections of the Foundation Report.

11 GEOTECHNICAL RECOMMENDATIONS

1. Description or schematic design cross sections showing the structure elements, loads, and interpreted subsurface profiles with soil types and layers. For each soil layer, include interpreted soil total unit weights, shear strength parameters, and groundwater conditions
2. Layout and limits of wall zones, or refer to the Plans that show the wall zones
3. Instruction for placement of soil nails, including
   - nail array pattern
   - the maximum horizontal and vertical soil nail spacing
   - the maximum vertical distance of the soil nails from the top of the wall, and the bottom of the wall
   - the maximum horizontal distance from the ends of the wall
   - the minimum spacing between soil nails when adjusting soil nail spacing near the bottom and ends of the wall
   - The 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
4. Schedule of soil nail lengths – recommended
5. Inclination of the soil nails measured from horizontal
6. Wall face batter measured from vertical
7. Calculated Factor of Safety for internal and global stability
8. Estimated lateral displacement, if calculated
9. 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
10. Nail bar yield strength, the bar diameter entered into Snail, and the required Factor of Safety provided by the structure designer
11. Required allowable facing resistance, i.e. unfactored tensile force at soil nail head, ($F_{unfactored}$) used to satisfy geotechnical design requirements and To. (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). The structure designer must ensure that structural facing design meets or exceeds $F_{unfactored}$.
12. 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

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.

Following examples show the recommended design information in the geotechnical report.

Example 1

General Design Information:

1. Excavation height is the vertical distance from the original grade behind the wall to the bottom of excavation for the wall.
2. Use columnar nail layout pattern.
3. Set soil nail inclination angle at 15 degrees from horizontal.
4. Set wall batter at 1(H):12(V).
5. Place the first row of soil nails no more than 2.5 feet below the original grade behind the wall for nail spacing of 5 feet. Place the first row of soil nails no more than 2.0 feet below the original grade behind the wall for nail spacing of 4 feet.
6. Place the bottom row of soil nails no more than 2.5 feet above the bottom of excavation of the wall.
7. For structural wall facing design, use the unfactored tensile force at soil nail head facing resistance provided in the following table

Table 1: Section Specific Design Information

Design Excavation Height (ft)	Min. Nail Length (ft)	Max. Vertical Nail Spacing (ft)	Max. Horizontal Nail Spacing (ft)	Nail Bar		Min. Unfactored Tensile Force at Soil Nail Head (kips)	
				Yield Strength (ksi)	Diameter (inch)	Static	Seismic
Up to 10	15	5	5	75	1.0	27	34
10 to 16	18	5	5	75	1.0	27	34

Table 2 – Nominal Pullout Resistance for Wall Zones

Wall Zone	Station (M Line)	Nominal Pullout Resistance Q_b (lbf/ft)
1	634+12.09 to 635+57.04	2720
2	638+37.28 to 639+82.69	2720

Example 2

General Design Information:

1. Excavation height is the vertical distance from the original grade behind the wall to the bottom of excavation for the wall.
2. Use columnar nail layout pattern.
3. Set soil nail inclination angle at 15 degree from horizontal.
4. Set wall batter at 1(H):12(V).

5. Place the first row of soil nails no more than 2.5 feet below the original grade behind the wall for nail spacing of 5 feet. Place the first row of soil nails no more than 2.0 feet below the original grade behind the wall for nail spacing of 4 feet.
6. Place the bottom row of soil nails no more than 2.5 feet above the bottom of excavation of the wall.
7. For structural wall facing design, use the unfactored tensile force at soil nail head provided in the following table.

Table 3: Section Specific Design Information

Wall Zone	Station ("B" Line)	Max. 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 at Soil Nail Head (kips)	
						Yield Strength (ksi)	Diameter (inch)		Static	Seismic
1	2093+75 to 2109+00	8.5	15	5	5	75	1.0	2,720	30	38
	2109+00 to 2121+00	11.7	20	5	5	75	1.0	2,720	30	38
2	2121+00 to 2127+50	34.5	35	5	5	75	1.0	3,200	30	38
	2127+50 to 2127+96	34.4	30	5	5	75	1.0	3,200	30	38
3	2127+96 to 2129+50	30.5	25	4	4	75	1.0	3,200	30	38
	2129+50 to 2130+50	26.6	20	4	4	75	1.0	3,200	30	38
4	2130+50 to 2134+73	23.1	15	4	4	75	1.0	3,200	30	38

12 NOTES FOR SPECIFICATIONS

Follow the instructions provided in the Geotechnical Notes for Specifications module in the Geotechnical Manual for the information and recommendations should be provided in this section.

Send the Soil Nail Verification Test nSSP (section 46-3), available on the NSSP for Geotechnical Design intranet page, to the Specification Engineer so it can be included in the contract Special Provisions of the project. This nSSP implements the maximum pullout load of 3 × Estimated Nominal Pullout Resistance (Test Load), with the goal of pulling the verification test nails to failure. The objective is to obtain actual nominal pullout resistance of soil nails in the soil/rock conditions at the site and with the construction methods provided.

14 Geotechnical Review for Final Structure PS&E (Expedite Notice)

According to *Structure Design Expedite Notice* process, a Geotechnical Review must take place after the issuance of Draft Structure PS&E and before the start of Final Structure PS&E (Expedite Notice) process.

During Geotechnical Review, review and verify that draft Plans and Special Provisions have implemented the recommendations of the Foundation Report. Geotechnical reports are part of the contract. Any inconsistency between the geotechnical reports, Plans, and Special Provisions can cause serious problems during construction.

15 Geotechnical Tasks during Construction

16 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.

17 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.

18 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 need 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.

19 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-plastic clay
- Difficult drilling through cobbles and boulders
- Caving in of the 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.

20 Technical Notes

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

21 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, 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*

22 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 there is 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 that based on directly measured strength or performance probability density functions is rarely available, if it is not non-existence.

Hence, almost all the nominal strengths 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.

23 Nominal Strength and Pullout Resistance of Soil Nails

In soil nail construction, 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.

24 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 need 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 the particular soils and rocks. Some may consider these values as the average values compiled from collected data, which is naturally the case when presenting summary 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 strength and associated design parameters of these soils and rocks. Only after we compared 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 in 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, 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.