Examples of unfavorable or difficult geotechnical conditions for soil nail earth retention are dry, poorly graded cohesionless soils, soils with excessive moisture / wet pockets, and soils containing cobbles, and boulders.

Dry cohesionless soils tend to ravel when exposed and "run" from behind the shotcrete when proceeding to the next excavation level. This causes the shotcrete to become unsupported and the supporting nail at the face experiences tensile stresses and greater bending stresses.

Soils containing wet pockets tend to slough and create face stability problems. In addition, groundwater seeping to the exposed excavation face may cause difficulties for shotcrete adhesion.

Cobbles and boulders present a challenge to the excavation process and/or excavator. Cobbles and boulders encountered at the excavation face must be removed by the excavator. Removing the obstacle (cobble or boulder) can jeopardize the previously placed shotcrete or cause the soil behind the obstacle to loosen and ravel. This causes the shotcrete to become unsupported, or can result in large shotcrete quantity overruns by filling the void created.

All before-mentioned unfavorable geotechnical conditions exist in Colorado mountain regions. A soil nail earth retention system utilizing grout columns can be constructed in these geotechnical conditions to provide a safe and redundant method of earth retention. Rotary percussion drilling systems utilized for grout column and soil nail installation also maintain an efficient and predictive construction schedule.

CONSTRUCTION SEQUENCE

The typical construction sequence of soil nail earth retention incorporating grout columns consists of five steps. The construction sequence is described further and shown schematically in Figure 1.

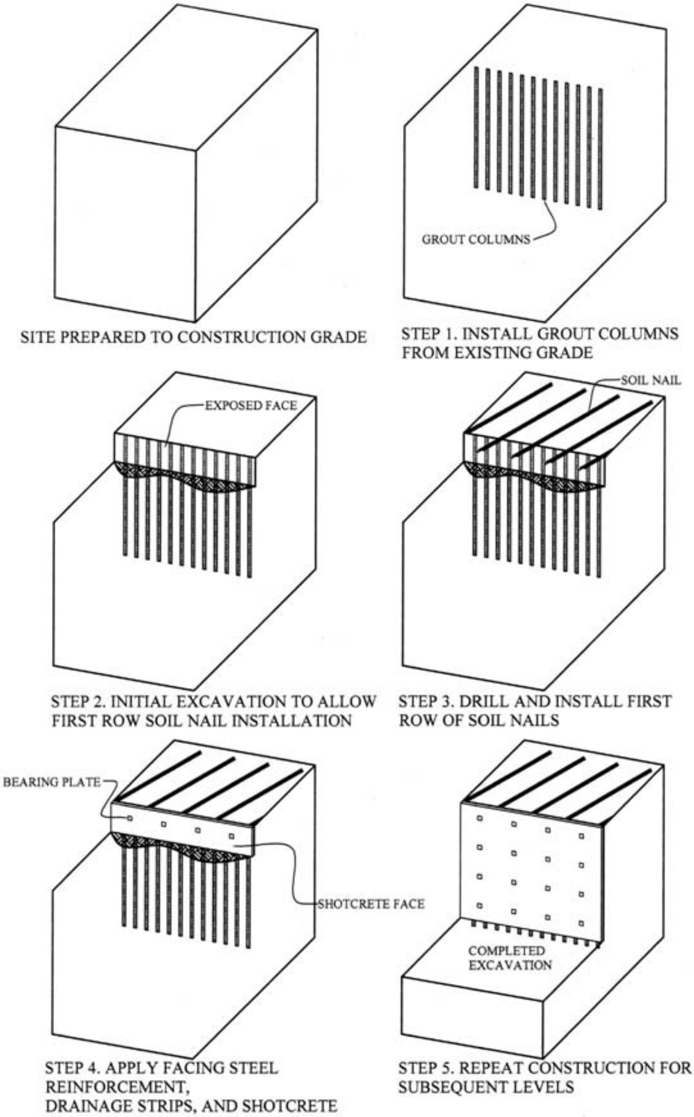

FIG. 1. Soil Nail Earth Retention Incorporating Grout Columns Construction Sequence

Step 1. Install Grout Columns

Grout columns are installed at the beginning of earth retention construction along the perimeter of proposed excavation immediately behind the face of earth retention. The grout columns are typically 152 mm (6 in) in diameter and are spaced 0.61 m (2 ft) on center.

The excavation perimeter is determined at the construction site and marked on the ground. Accurate location of the grout columns relative to the proposed construction is critical to ensure construction of the earth retention system does not impede the proposed construction.

After the grout column layout is accomplished, the grout columns are drilled. Typically, rotary percussion drilling systems as shown in Figure 2 are utilized in the geotechnical conditions described earlier. The grout columns are drilled from existing grade to a predetermined depth below the bottom of the proposed excavation, typically 0.31 m (1 ft) below the proposed bottom of excavation.

FIG. 2. Drilling Grout Columns for Soil Nail Earth Retention

Once the desired depth is obtained, a high strength steel bar with a tremie tube attached is inserted. On-site-prepared high strength grout is pumped into the drill hole from the bottom to the top. The grout typically has a water/cement ratio ranging from 0.4 to 0.5 and exhibits a minimum 28-day unconfined compressive strength of 28 MPa (4,000 lb/in^2). It is desirable to install all grout columns around the excavation perimeter before excavation occurs.

Step 2. Initial Excavation

The depth of the initial excavation lift is typically 1.5 m (5 ft) and extends below the elevation where the first row of nails will be installed. The initial excavation exposes the previously placed grout columns as shown in Figure 3.

FIG. 3. Initial Excavation and Exposed Grout Columns

At times, the initial excavation extends deeper, 2.2 m to 2.4 m (7 ft to 8 ft); however, shotcrete will be placed to cover the upper 1.5 m (5 ft). For example, the deeper initial excavation is utilized where soil nail installation would interfere with a shallow utility. The grout columns allow a deeper cantilever section to the top row of soil nails, permitting the soil nails to pass under the shallow utility without interference.

Step 3. Drill and Install First Row of Soil Nails

After excavation exposes the initial lift, soil nail drilling and installation commences. As with the grout columns, rotary percussion drilling systems are typically utilized in the geotechnical conditions encountered in the Colorado mountain regions to install soil nails. The drill holes for soil nails are drilled to a specified length, diameter, inclination, and horizontal spacing.

Once the specified depth of the drill hole is obtained, a high strength steel bar, 520 MPa (75 kips/in^2), with tremie tube and centralizers attached is inserted into the drill hole. High strength grout, prepared on-site, is pumped into the drill hole from the bottom to the top. The grout is commonly placed under low pressure 1 MPa (150 lb/in^2). Figure 4 shows installation of the top row of soil nails.

FIG. 4. Installation of the Top Row of Soil Nails

Step 4. Apply Facing Steel Reinforcement, Drainage Strips, and Shotcrete

The application of facing steel reinforcement and shotcrete transfers the earth loads applied from the existing exposed face to the previously installed soil nails. In addition, geocomposite drainage strips are attached to the exposed excavation face, between nails, to collect and direct any current or future groundwater. The steel reinforcement typically consists of welded wire mesh located in the middle of the shotcrete thickness. Vertical and horizontal reinforcement bars are located at each nail.

After attaching steel reinforcement to the exposed face, shotcrete is applied to a pre-selected thickness. The shotcrete typically has a 28-day compressive strength of 28 MPa (4,000 lb/in^2) and a 3-day compressive strength of 14 MPa (2,000 lb/in^2). While the shotcrete is still "wet", a steel bearing plate is placed over the nail head and lightly pressed into the shotcrete. A hex nut is then attached to the end of the steel bar to secure the bearing plate to the nail (See Figure 5 for Soil Nail Cross Section).

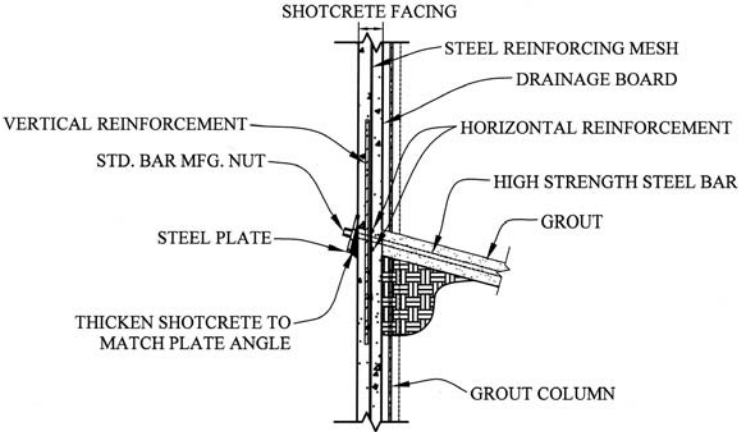

FIG. 5. Soil Nail Cross Section

Step 5. Repeat Construction for Subsequent Levels

Steps 2 through 4 are repeated for the remaining excavation lifts until the bottom of excavation is attained (See Figure 6). The drainage strips extend below each lift and ultimately extend to the bottom of the excavation where they are incorporated into a collection system.

FIG. 6. Drilling Bottom Row of Soil Nails

DESIGN OF GROUT COLUMNS

Grout columns, in general, provide two mechanisms of resistance during excavation. The mechanisms of resistance are in the horizontal and vertical directions. First, the grout columns provide horizontal resistance to the applied earth pressure while excavating from lift to lift. Second, the grout columns provide vertical resistance or additional axial capacity to the soil nail face while excavating from lift to lift. Both mechanisms of resistance, horizontal and vertical, as they relate to the design of grout columns are discussed further.

Horizontal Resistance

The geotechnical conditions encountered in the Colorado mountain regions are typically non-cohesive. These types of soil have a tendency to “flow” while excavation proceeds from lift to lift. Properly spaced grout columns provide horizontal resistance and reduce the potential of “flowing” soils. Basically, grout columns provide the cohesionless soil with an apparent cohesion, allowing the soil to “arch” between the grout columns.

The potential for “flowing” soils must be analyzed to determine the optimum horizontal spacing of the grout columns while providing adequate resistance to the applied earth pressure. This potential can be determined with a procedure shown in (Pearl, Campbell, and Withiam, 1992). See Figure 7.

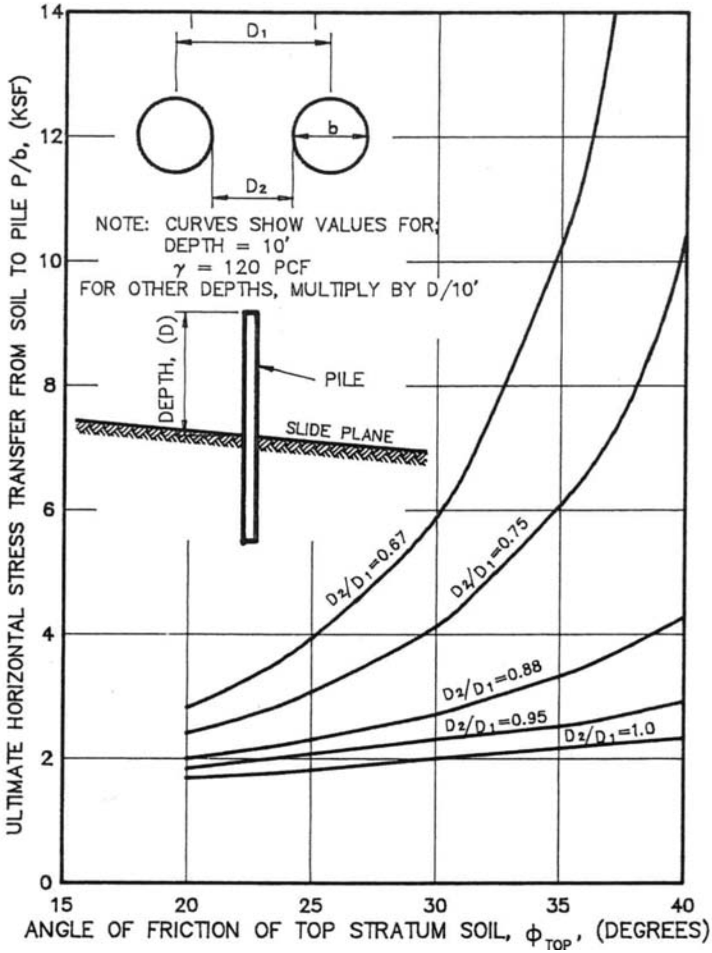

FIG. 7. Ultimate Stress Transfer from Soil to Piles vs. Shear Strength of Soil

Utilizing Figure 7 with $\varphi = 30$ degrees and $\gamma = 19.1$ kN/m^3 (120 lb/ft^3), the Factor of Safety between earth pressure and grout column resistance for various horizontal grout column spacings is shown in Table 1.

Table 1. Factor of Safety for Various Grout Column Horizontal Spacing

b mm (ft)	D_1 mm (ft)	D_2 mm (ft)	D_2/D_1	P (Ult.) kN/m (kips/ft)	P (Ser.) kN/m (kips/ft)	E_p kN/m (kips/ft)	Factor of Safety
152 (0.50)	457 (1.50)	305 (1.00)	0.67	43.8 (3.00)	21.9 (1.50)	6.13 (0.42)	3.57
152 (0.50)	610 (2.00)	457 (1.50)	0.75	29.2 (2.00)	14.6 (1.00)	8.18 (0.56)	1.79
152 (0.50)	762 (2.50)	610 (2.00)	0.80	26.3 (1.80)	13.2 (0.90)	10.2 (0.70)	1.29
152 (0.50)	914 (3.00)	762 (2.50)	0.83	23.3 (1.60)	11.7 (0.80)	12.3 (0.84)	0.95

Notes:
b = Diameter of grout column
D_1 = Center to center distance of grout column
D_2 = Clear space between grout columns
P (Ult.) = Determined from Figure 7
P (Ser.) = P (Ult.) / 2
E_p = Earth Pressure = $(K_a \gamma H) * D_1$; where H = 2.13 m (7 ft) (Maximum excavation lift height throughout the soil nail wall construction.)
Factor of Safety = P (Ser.) / E_p

The geotechnical conditions encountered in the Colorado mountain regions have similar properties to those used for the calculations in Table 1. It can be seen from Table 1 that as the grout column horizontal spacing increases, the Factor of Safety decreases. Therefore, a 0.61 m (2 ft) center to center spacing of grout columns yields an appropriate Factor of Safety (author's opinion; greater than 1.35 for temporary condition).

It is not surprising that closely spaced grout columns provide higher resistance to the applied earth pressure than grout columns spaced farther apart. The horizontal spacing of grout columns should consider cost and constructability while providing an appropriate Factor of Safety.

In addition to determining the "flowing" potential of soil between the grout columns, the structural capacity for horizontal resistance of the grout columns should be determined. The resisting bending moment from the composite section of circular grout in the drill hole and the high strength steel bar can be calculated. This calculated value is then compared to the bending moment calculated from the applied earth pressure. An appropriate Factor of Safety should exist between these two calculated values (author's opinion; greater than 1.35 for temporary condition).

A cracked section of grout should be considered when determining resisting moment of the composite section. Particular attention should be paid to the water / cement ratio to assure grout quality. Calculations indicate a higher resisting moment can typically be achieved by increasing drill hole diameter rather than increasing the diameter of the high strength steel bar reinforcement.

Calculations and observations indicate that grout columns that are 152 mm (6 in) in diameter and are spaced 0.61 m (2 ft) on center exhibit approximately 22 kN to 44 kN (5 kips to 10 kips) of ultimate horizontal resistance during soil nail earth retention construction for heights up to 2.3 m (7 feet).

Vertical Resistance

Conventional bearing capacity theory is typically utilized to determine the bearing capacity of a reinforced block of ground such as a soil nail earth retention system. Further, charts are often utilized to assess heave potential at the bottom of an excavation and check against basal heave. Literature sources state that as long as soil nail earth retention is not constructed in soft soils, bearing capacity failure mode is not critical for most soil nail projects (FHWA 1996, FHWA 2003).

The authors recognize numerous soil nail earth retention projects are successfully completed throughout the country each year utilizing traditional bearing capacity analysis. However, from observation of construction of several soil nail earth retention projects, the authors believe bearing capacity may have larger importance to the performance (vertical and horizontal displacements) of soil nail earth retention than indicated in the literature.

In order to perform bearing capacity analysis, at least one geometric parameter (such as the length to which the bearing load is applied) has to be determined. Typically, the length of soil nail located in the reinforced block of ground is utilized as the bearing length. It is usual for the length of soil nail to be approximately equal to the completed exposed height. In this case, sufficient length will exist to distribute the load resulting in a greater value than the Factor of Safety determined in regard to bearing capacity. When bearing capacity analysis is performed for soil nail earth retention systems, the final or completed condition is typically utilized to check bearing capacity.

From observation of construction and analysis of field data, the authors believe the most critical bearing load is only applied to the front portion of the wall during excavation, approximately one-sixth or less of the reinforcement length. In addition, the authors believe a triangular bearing load distribution (loaded side of the triangle at the face) occurs in lieu of a rectangular distribution. Further research and monitoring are needed to verify the previous statements.

During construction of a typical soil nail system, material is removed from under the previously completed lift. This directly affects the bearing resistance of the system and is, in the authors' opinion, the most critical stage of construction for soil nail walls. The temporary excavated condition below the previously installed lift presents a greater risk of bearing failure than the final or completed soil nail condition. Further, if three or more rows of soil nails exist above a temporary exposed excavation, an additional vertical load is imposed on the bearing stratum.

The use of grout columns in soil nail earth retention provides vertical resistance during excavation and increases the bearing capacity Factor of Safety. The grout columns perform similar to a deep foundation system as the vertical load is transferred from the excavated lift to deeper, more competent soil. The grout columns vertically support the upper portions of the soil nail system and allow construction of the lower soil nail system. Figure 8 illustrates the vertical forces applied to the bearing stratum during soil nail construction without and with grout columns.

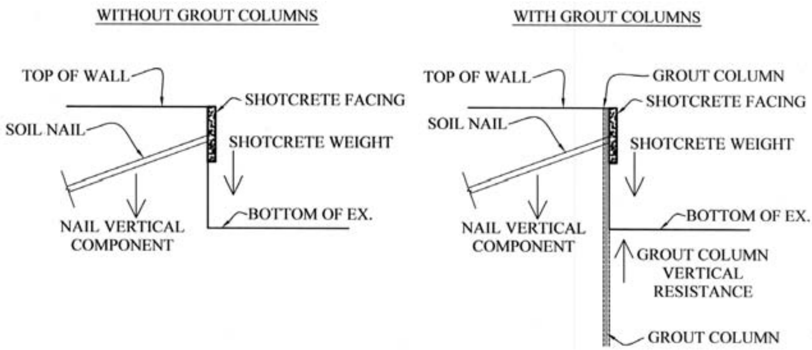

FIG. 8. Vertical Forces With and Without Grout Columns during Soil Nail Construction

As shown in Figure 8, the primary contributors to vertical load at the face of soil nail wall are the shotcrete weight and the vertical component of the soil nail due to its orientation. For typical soil nail earth retention, the shotcrete weight is resisted by the shear friction between the earth and shotcrete or the adhesion of shotcrete to the earth. The soil nail vertical component is resisted by bending stiffness of the soil nail and the interaction between the soil nail and the supporting underlying soil. As soil nail construction proceeds, the vertical load increases, inducing higher loads at the bottom of the excavation.

The use of grout columns located immediately behind the shotcrete face provides resistance to both the shotcrete weight and the soil nail vertical component. Skin friction of the grout columns below the temporary construction benches provides resistance to the imposed vertical loads.

BENEFITS OF GROUT COLUMNS IN EARTH RETENTION

Deeper First Cut to Start Under Utilities

Real estate is at a premium in many Colorado mountain towns. Consequently, developers need to utilize as much of a site as possible to ensure financial feasibility of the project. This often means the proposed structure is just a few feet away from an existing street where most underground utilities are located. Grout columns may allow the first row of soil nails to be installed deeper below existing grade, thus avoiding most utilities. Avoiding existing utilities can aid in obtaining easements and increasing productivity as individual soil nails will not have to be adjusted to ensure an existing utility is avoided.