# Design and Construction of Soil Nailing System

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# INTRODUCTION

This paper summarizes (1) the fundamentals of design of the in-situ soil nailing system, (2) the global stability of the soil nailing system based on the mechanism of deep-seated slope failure, (3) an approximate solution of the displacements at the top of the wall based on the finite element principle, and finally (4) provisions associated with field construction of the soil nailing walls, including the specifications of materials and construction, and the performance monitoring.

The contents of the paper are based on the technical papers that the writer has published, the research that the writer is currently conducting, and the construction and research documents provided by various government agencies and private consulting and construction companies.

# LIMITING EQUILIBRIUM FORMULATION

An extensive study of the soil nailing system (Figure 1) including the design and analysis methods has been conducted by the writer (Bang, 1980, Shen et al. 1981a, 1981b, 1981c, 1982. Kim, 1990. Erickson, 1992. Kroetch, 1992). The design approach is based on the assumption that the failure surface can be represented by a parabolic curve passing through the toe of the wall. This assumption has been derived from the results of a finite element study of in-situ reinforced soil (Shen 1982). A classical method of equilibrium analysis is then used to evaluate the stability of the soil nailing system by considering the contribution of the nails to the overall stability. The tensile forces developed in the reinforcing nails are divided into tangential and normal components along the assumed failure plane. The maximum tensile force in each reinforcing nail is calculated and compared with the tensile resistance of the nails to identify the possibility of nail yielding. The overall minimum factor of safety is then obtained by considering a series of failure surfaces.

The formulation includes random ground surface geometry, variable nail length, multiple layered soil profile, various loading conditions, and inclined shotcrete facing. The factor of safety is calculated by comparing the components of total resisting force and total driving force along the direction of the driving force.

Figure 2 shows the assumed potential failure surface and geometric parameters associated with it. The point at which the parabola intersects the ground surface is determined by the value of "A". In this formulation, it is assumed that the soil layers are horizontal and the nails are inclined at the same angle.

Figure 3 shows a typical free body diagram considered in the formulation. The equilibrium equations of element 1 (reinforced zone) yield

$$N_2=(W_1-S_1)\cos\alpha_3-(N_1+k_hW_1)\sin\alpha_3 \qquad (1)$$

$$S_2=(W_1-S_1)\sin\alpha_3+(N_1+k_hW_2)\cos\alpha_3 \qquad (2)$$

where

| | | |
|---|---|---|
| $W_1$ | = | Weight of element 1 |
| $S_1$ | = | Tangential force between elements 1 and 2 |
| $\alpha_3$ | = | Inclination angle of $S_2$ |
| $k_h$ | = | Horizontal body force coefficient |

The equilibrium equations of element 2 (unreinforced zone) produce

$$N_3 = (W_2+S_1)\cos\alpha_5+(N_1-k_hW_2)\sin\alpha_5 \qquad (3)$$

$$S_3 = (W_2+S_1)\sin\alpha_5-(N_1-k_hW_2)\cos\alpha_5 \quad (4)$$

where

$W_2$ = Weight of element 2

$\alpha_5$ = Inclination angle of $S_3$

It is noted that the elements 1 and 2 may have different factors of safety due to different inclination angles of the potential failure surfaces at the base of each element. To overcome this discrepancy, the following steps have been taken to estimate the overall factor of safety.

First, the total driving force, $S_D$, is obtained by adding the individual element driving forces vectorially, considering the directions of the forces.

$$S_D = \sqrt{S_{DX}^2 + S_{DY}^2} \quad (5)$$

$$\tan\alpha_D = S_{DY}/S_{DX} \quad (6)$$

where

$S_{DX}$ = $S_2\cos\alpha_3+S_3\cos\alpha_5$

$S_{DY}$ = $S_2\sin\alpha_3+S_3\sin\alpha_5$.

Next, the total resisting force, $S_R$, is calculated.

$$S_R = \sqrt{S_{RX}^2 + S_{RY}^2} \quad (7)$$

$$\tan\alpha_R = S_{RY}/S_{RX} \quad (8)$$

where

| | | |
|---|---|---|
| $S_{RX}$ | = | $(c_1'L_3+T_T+N_2'\tan\phi_1')\cos\alpha_3+(c_2'L_2'+N_3\tan\phi_2')\cos\alpha_5$ |
| $S_{RY}$ | = | $(c_1'L_3+T_T+N_2'\tan\phi_1')\sin\alpha_3+(c_2'L_2'+N_3\tan\phi_2')\sin\alpha_5$ |
| $c_i'$ | = | developed cohesion for element i = $c_i/FS_c$ |
| $FS_c$ | = | factor of safety with respect to cohesion |
| $\phi_i'$ | = | developed friction angle for element i |
| | = | $\tan^{-1}(\tan\phi_i/FS_\phi)$ |
| $FS_\phi$ | = | factor of safety with respect to friction |
| $N_2'$ | = | $N_2+T_N$ |
| $T_N$ | = | $\Sigma T_i\cos(90°-\alpha_3-\theta)$ |
| $\Sigma T_i$ | = | resultant of nail axial forces beyond the failure surface |
| $T_T$ | = | $\Sigma T_i\sin(90°-\alpha_3-\theta)$ |
| $L_2$ | = | length of the entire failure arc. |

Finally, the global factor of safety is calculated by comparing the component of the total resisting force along the direction of driving force with the magnitude of total driving force, i.e.,

$$FS = \frac{S_R\cos(\alpha_R - \alpha_D)}{S_D} \tag{9}$$

It is assumed that at any given time equal percentage of soil cohesion and friction are mobilized. Therefore, the desired factor of safety is obtained by equating those factors of safety, i.e.,

$$FS_c = FS_\phi = FS \tag{10}$$

Iteration is performed to obtain the factor of safety.

The detailed formulation considers two cases separately; the first case with a failure surface extending beyond the reinforced zone and the second case with a failure surface lying entirely within the reinforced soil zone. Note that the effect of layered soil profile is included in the formulation by considering the discrete geometry of each soil layer and its material properties.

Referring to Figure 3, $\alpha_3$ and $\alpha_5$ are the directions of the tangential forces acting along the bottom of elements 1 and 2, and assumed to be parallel to the corresponding chords. $W_1$ is the weight of reinforced soil zone (element 1). $W_1$ may consist of multiple layers of soil with different unit weights. Thus it is the sum of weights of all layers ($W_i$) within the element 1. In a typical case, it is expressed as

$$W_i = \int_{H_i}^{H_i+1} \tau_{i+1} a \sqrt{y(H+H_s)dy} - \tau_{i+1}\left(H_{i+1}^2 - H_i^2\right)\tan\delta/2 \qquad (11)$$

Similarly, $W_2$ can be calculated from

$$W_i = \int_{H_i}^{H_i+1} \tau_{i+1} a \sqrt{y(H+H_s)dy} - \tau_{i+1}\left(L_T\cos\theta + H'\tan\delta\right)\left(H_{i+1} - H_i\right) \qquad (12)$$

$N_1$ is the resultant of lateral earth pressure developed between the elements 1 and 2. At-rest lateral earth pressure condition has been used to describe this force. In the case of layered soils, $N_1$ is the sum of resultant forces of each layer,

$$N_1 = \sum N_i \qquad (13)$$

where $N_i$= resultant of $i^{th}$ layer.

The developed nail forces can be calculated in two ways. One approach assumes that the unit frictional resistance is directly proportional to the overburden and therefore can be calculated from the normal and tangential stresses acting on the nail. However, due to possible soil arching, especially in dense cohesionless soils, the unit frictional resistance may remain almost the same beyond a certain depth. For this reason, the analysis allows an alternative method of estimating the nail axial force, i.e., by specifying the frictional resistance of the nail obtainable from the field pull-out test.

The formulation also allows two possible descriptions of the nail length variation; linear variation and step variation. In the case of linear variation, only the lengths of uppermost and lowermost nails are specified. When step variation of the nail length is used, the number of nail sets having the same length, the number of nails in each set, and the nail length in each set are specified as part of the input.

## DEEP SEATED SLOPE STABILITY

The factor of safety describes in the previous section is based on the sliding mechanism whose failure plane passes through the toe of the wall. This is a reasonable and correct mechanism for relatively steep walls. However, for relatively flat walls, the failure surface may penetrate below the toe of the wall.

For the purpose of analyzing the stability of the soil nailing system that may include a deep-seated failure surface, circular failure surfaces have been assumed. The minimum factor of safety can then be calculated from the ratio between the resisting moment and the overturning moment about the circle center, considering a series of circles that may or may not cut through the soil nails.

The overturning moment associated with a given failure circle can be approximated from the method described by Lowe (Lowe, 1989). The Lowe's method calculates the minimum factor of safety against overturning for slopes with no reinforcement, no surcharge, and flat ground surface. To approximately estimate the factor of safety against the deep-seated failure of a soil nailing wall that may have surcharge and/or sloping ground surface, the following steps have been taken (Figure 4).

1. Calculate the minimum factor of safety (FS) and the overturning moment ($M_O$) from the Lowe's method, assuming no surcharge and flat ground surface.
2. Calculate the resisting moment ($M_R$) of the slope considered in step 1 from
   $M_R = FS \cdot M_O$
3. Estimate the additional overturning moment ($M_{O1}$) due to surcharge and sloping ground to obtain the modified overturning moment ($M_O'$)
   $M_O' = M_O + M_{O1}$
4. Estimate the additional resisting moment ($M_{R_1}$) due to the friction provided by the soil nails located outside the circular failure zone. The modified resisting moment ($M_R'$) then becomes
   $M_R' = M_R + M_{R_1}$
5. The deep-seated global factor of safety (FS') of the soil nailing wall can then be estimated from

$$FS' = \frac{M_R'}{M_O'}$$

The details of the formulation are not included in this paper due to the length of the equations. The calculations of the average shear strength of layered soil system, the friction developed on each nail beyond the assumed failure surface, the stress distribution due to surcharge, and the contribution of the sloping ground surface are essential parts of the formulation. The computer program, NAILM11, includes the calculation of this deep-seated slope stability of the soil nailing wall.

## DISPLACEMENTS AT THE TOP

The detailed analysis of displacements associated with the soil nailing system requires the use of a complete method such as the finite element method. However, the use of the finite element method has not been widespread, mainly because of the difficulties associated with input preparation and output interpretation.

Since the soil nailing system typically produces the largest displacements at the top of the wall, they may be approximated if the following assumptions are made.

1. The deformations remain zero at the bottom of the wall and increase linearly with the vertical distance from the toe.
2. The deformations along the plane that passes through the toe of the wall and is inclined $45^\circ + \frac{\phi}{2}$ to the horizontal remain zero.
3. The behavior of the nail-reinforced soil can be represented by the concept of a unit cell, i.e., the total number of soil nails is numerous.

These assumptions lead to the use of the finite element method of analysis with an isoparametric linear triangular element (Figure 5). The hypotenuse of the triangle coincides with the Coulomb's planar failure surface that passes through the toe. The effect of the soil nails can be included through the use of the unit cell concept, which describes the reinforced soil behavior by an orthotropic material constitutive relationship. Furthermore, only one triangular finite element may be used due to the assumption of linear variations in displacements. Following describes briefly the necessary formulation.

The stiffness matrix of the isoparametric linear triangle finite element is obtained from the basic mechanical and energy principles as:

$$[K] = t_e A_e [B]^T [D][B]$$

where

$t_e$ = thickness of the element

$A_e$ = area of the element

$$[B] = \begin{bmatrix} \frac{\sqrt{N}}{H} & 0 & \frac{-\sqrt{N}}{H} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{H} & 0 & \frac{-1}{H} \\ 0 & \frac{\sqrt{N}}{H} & \frac{1}{H} & \frac{-\sqrt{N}}{H} & \frac{-1}{H} & 0 \end{bmatrix}$$

[D] = 6x6 three dimensional global constitutive matrix of the element

$= [R][C]^{-1}[R]^T$

[R] = 6x6 transformation matrix that rotates the local coordinate system to the global coordinate system

[C] = 6x6 three dimensional local constitutive matrix of the soil-nail unit cell

$$N = \tan^2\left(45 + \frac{\phi}{2}\right)$$

The load vector consists of two terms; i.e., due to the body force and the surcharge. The resulting expression becomes:

$$\{F\} = \left\{0,\ \frac{-\gamma H^2 + 3HT_y}{6\sqrt{N}},\ 0,\ \frac{-\gamma H^2 + 3HT_y}{6\sqrt{N}},\ 0,\ \frac{-\gamma H^2}{6\sqrt{N}}\right\}^T$$

where

H = height of the wall

$\gamma$ = unit weight of the soil

Ty = vertical surcharge applied

Finally the system simultaneous equation is solved for unknown displacements at the nodes, $\{q\}$.

$$[K]\{q\} = \{F\}$$

The detailed formulations of the matrices [D], [R], and [C] are not included in this paper. The resulting matrix [K] and vector {F} are relatively simple so that the displacements at the top of the wall can be found by solving 2x2 simultaneous equations.

By varying the angle $\alpha$ - inclination of the soil nails - one can analyze the other well-known earth reinforcing systems. If the angle $\alpha$ is taken as zero, the solution can analyze the behavior of the Reinforced Earth or geosynthetics. When the angle become $90^\circ$, it represents the behavior of the root piles or the micro-pile reinforcing system.

To illustrate the use of the aforementioned approximate solution of the soil nailing wall deformations at its top, the following parameters have been assumed.

| | |
|---|---|
| Modulus of reinforcement | $= 30 \times 10^6$ psi |
| Modulus of soil | = 2,000 psi |
| Soil Poisson's ratio | = 0.25 |
| Soil friction angle | $= 30^\circ$ |
| Reinforcement spacing | = 4 ft. x 4 ft. |
| Height of the wall | = 10 ft. |
| Soil unit weight | = 100 pcf |
| Vertical surcharge | = 1,200 psf |
| Soil reinforcement angle | $= 0^\circ$ |

Table - 1 shows the results of the analysis with various amounts of nail cross-sectional area (Ar).

As can be seen from the table, the vertical displacement at the top of the wall does not change much between the cases when the wall is not reinforced at all (Ar = 0) and when the wall is reinforced. However, the horizontal displacement decreases by approximately $\frac{1}{4}$ and $\frac{1}{7}$ when the wall is moderately reinforced and heavily reinforced, respectively. These observations are as expected, since the reinforcements are installed horizontally.

| Ar ($in^2$) | Horiz. Disp. at top (inches) | Vert. Disp. at top (inches) |
|---|---|---|
| 0 | -0.4620 | -1.3337 |
| 0.5 | -0.1140 | -1.1328 |
| 1.0 | -0.0650 | -1.1045 |

Table - 1 Displacements at Wall Top

It is noted that the developed method of approximation is only applicable to the soil nailing walls with vertical facing, flat ground surface, and constant surcharge. The formulations, however, can be easily expanded to include conditions other than assumed.

## CONSTRUCTION DETAILS

Following is a brief summary description detailing the material provisions, construction provisions, and performance monitoring associated with the soil nailing system.

### Material Provisions

(1) Soil Nails

Typically, the soil nail consists of either an epoxy coated reinforcing bar or a reinforcing bar encapsulated full length in a grouted corrugated plastic sheath so that all space between the sheath and reinforcing bar is filled. The epoxy coating should have a minimum thickness of 12 mils. Soil nails should have a yield strength of not less than 60 ksi conforming to ASTM A-615. This is also true for reinforcements to be used in facing shotcrete.

Soil nails should not be spliced during the initial manufacturing. Soil nails should be threaded on one end over the length of a minimum of 6 inches. Threading must be continuous spiral and should not be cut into a reinforcing bar. If threads are cut into a reinforcing bar, the next larger bar designation number should be used and receive coarse threading.

Soil nails should be installed in the drilled holes using centralizers. Centralizers should be fabricated from plastic, steel, or material nondetrimental to the soil nails. Wood should not be used. Centralizers should adequately support the soil nail in the center of the drilled hole and be spaced at a maximum of 5 feet on center to center.

The corrugated plastic, if used, should be either polyvinyl chloride (PVC) or high density polyethylene (HDPE). The minimum sheath wall thickness is 40 mils. HDPE shall have a density between 0.94 and 0.96 $g/cm^3$, when measured in accordance with the ASTM designation: D792, A-2.

The sheathing must have sufficient strength to prevent damage during construction operations, be watertight, chemically stable without embrittlement or softening, and nonreactive with concrete.

(2) Anchorage with shotcrete

The nuts, washers, wedges and bearing plates to be encased in concrete need not be galvanized. They must develop the specified ultimate strength, e.g., 39 kips for #6 rebar, 68 kips for #8 rebar, etc.

(3) Grout and shotcrete

Grout must have 7 day compressive strength of 4,000 psi with $\frac{1}{4}$ in. maximum aggregate size. The following shows typical grout design mix.

| Material | Weight (lbs) | Volume ratio |
|---|---|---|
| Type I cement | 940 | 4.78 |
| Building sand | 2,600 | 15.55 |
| water | 433 (52 gal) | 6.94 |
| % entrapped air | 1.5 | 0.41 |
| TOTAL | 3,973 | 27.67 |
| w/c ratio | 0.46 | |

Shotcrete must have 7 day compressive strength of 4,000 psi with $\frac{3}{8}$ in. maximum aggregate size. Typical shotcrete design mix includes

| Material | Weight (lbs) | Volume ratio |
|---|---|---|
| Type I cement | 705 | 3.59 |
| Building sand | 1,991 | 11.91 |
| Sand ($\frac{3}{8}$ in. - #4) | 1,090 | 6.45 |
| water | 300 (36 gal) | 4.81 |
| % entrapped air | 1.5 | 0.41 |
| TOTAL | 4,086 | 27.15 |
| w/c ratio | 0.43 | |

**Construction Provisions**

(1) Drilled Holes

Holes should be within 1 foot of the planned location. Hole length should not be shorter than the planned length. Hole inclination should be plus or minus 3 degrees of the planned inclination.

Holes should be cleaned to remove any material resulting from the drilling operations, or to remove any other material that would impair the strength of the soil nails. The use of water for cleaning holes is not permitted. Foreign materials dislodged or drawn into the hole during soil nail installation should be removed. Casing may be used to stabilize the hole, but should be removed prior to or during the grouting operation.

(2) Grout

Grout should be injected at the lower end of the drilled hole and completed in a continuous operation. The grout should be placed after the insertion of the nail. The grout may be pumped through grout tubes or drill rods. Typically soil nails that are not to be tested are grouted full length. The unbonded length of the test soil nails should not be initially grouted. When grouting the test soil nails, packers or other appropriate devices should be used to insure that the bonded portion of the soil nail conforms the details shown on the plans.

After placing the grout for the test soil nails, they should remain undisturbed until the grout has reached a strength sufficient to provide anchorage during testing operations. Test soil nails should be grouted to the shotcrete facing after the testing has been completed.

(3) Securing Soil Nails

Each soil nail should be secured at the face of the shotcrete with an anchorage system. The steel plate portion of the anchorage system should be seated flush with the shotcrete surface and the nuts should be hand-tightened before the set of the shotcrete. The nuts should be secured wrench tight (at least 100 ft-lbs torque) after the shotcrete has set for a minimum of 24 hours. Figure 6 shows an example of soil nail and shotcrete facing connection used by the Hart Crowser, Inc. (Baska 1992).

(4) Soil Nail Proof Testing

Pullout test should be performed on test soil nails in all lifts. Testing should be performed against a temporary bearing yoke which bears directly on the shotcrete face.

Temporary bearing pads should be kept a minimum of 6 inches clear from the blockout for the test soil nail.

Applied test loads should be determined with either a calibrated pressure gage or a load cell. Movements of the end of the soil nail, relative to an independent fixed reference point, should be measured and recorded to the nearest 0.001 inch at each increment of load during the entire load tests.

A pullout test consists of loading the test soil nail to the maximum test load or failure point, whichever occurs first. Failure point should be defined as the point where increases in the movement of the test soil nail continues without increases in the load or when the soil nail has displaced 2 inches. The failure load corresponding to the failure point should be recorded as part of the test data.

The pullout test should be conducted by measuring the test load applied to the test soil nail and the movement of the test soil nail end during incremental loadings of 12.5%, 25%, 37.5%, 50%, 62.5%, 75%, 87.5%, 100% and 125% of the maximum load.

Each increment of load should be applied in less than one minute and held for at least one minute but not more than 2 minutes (preferably with less than 0.04 inches of movement).

A successful test would be the one which held the maximum test load without noticeable creep and exhibited a linear or near linear relationship between the load and the deformation over the entire test range. Noticeable creep is defined as a rate of movement of approximately 0.08 inch per log cycle of time in minutes.

The soil nail should be unloaded only after completion of the test. Test soil nails that have been pullout tested should be cut back to the front face of the shotcrete. Test soil nails should be grouted to the face of the shotcrete after testing in the lift has been completed.

(5) Excavation

The excavation should proceed downward from the top in a horizontal lift sequence. A lift should not be excavated until the nail installation and shotcrete placement for the preceding lift are completed. After a lift is excavated, the cut surface should be cleaned of all loose materials, mud and other foreign materials that could prevent or reduces shotcrete bond. A stabilizing berm of soil may be left in place at the face of the excavation lift for removal and trimming to final excavation line after installation and full length grouting of the nails.

If any temporary open cuts above nailed slope is necessary, slope protection measures should be provided as necessary to prevent sloughing and erosion of open cut slopes. Typically visqueen, shotcrete, or other appropriate coverage are used.

(6) Shotcreting

The initial shotcreting should be placed within 24 hours of any horizontal excavation lift or portion of a lift. The second shotcrete layer should be placed as soon as is practical after full length grouting of the nails.

Excavation for subsequent excavation lifts should not be accomplished until the shotcrete of the preceding lift has reached 25% of its required minimum strength. Shotcrete should cover all steel bars by at least 1.5 inches.

**Performance Monitoring**

As a minimum, several vertical and horizontal monitoring locations should be selected. At each location, one monitoring point at the top of the wall, and two points at 10 and 20 feet behind the top of the wall should be installed. The measuring system should have an accuracy of at least 0.01 ft. All reference points on the existing ground surface should be installed and read prior to construction. They should be read prior to and during critical stages of construction. The frequency of measurements depends on the results of previous read-up and the rate of construction. However, measurements should be taken about 3 times per week throughout the construction. More frequent reading may be required at critical times during construction or if significant movement is indicated.

If more detailed measurements are necessary, slope indicators and extensiometers may be installed. They can measure the horizontal displacements relative to its tip with high accuracy.

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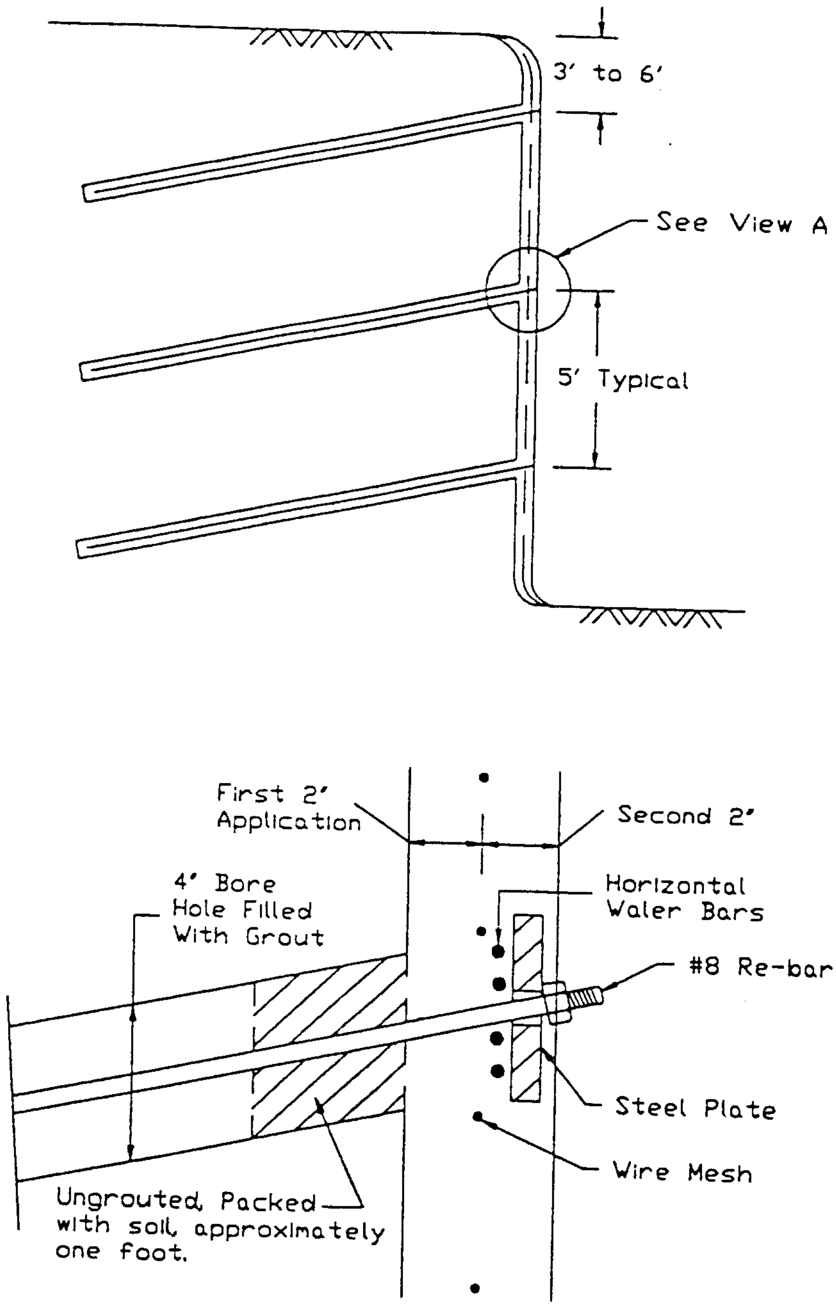


VIEW A

Figure - 1 Soil Nailing System

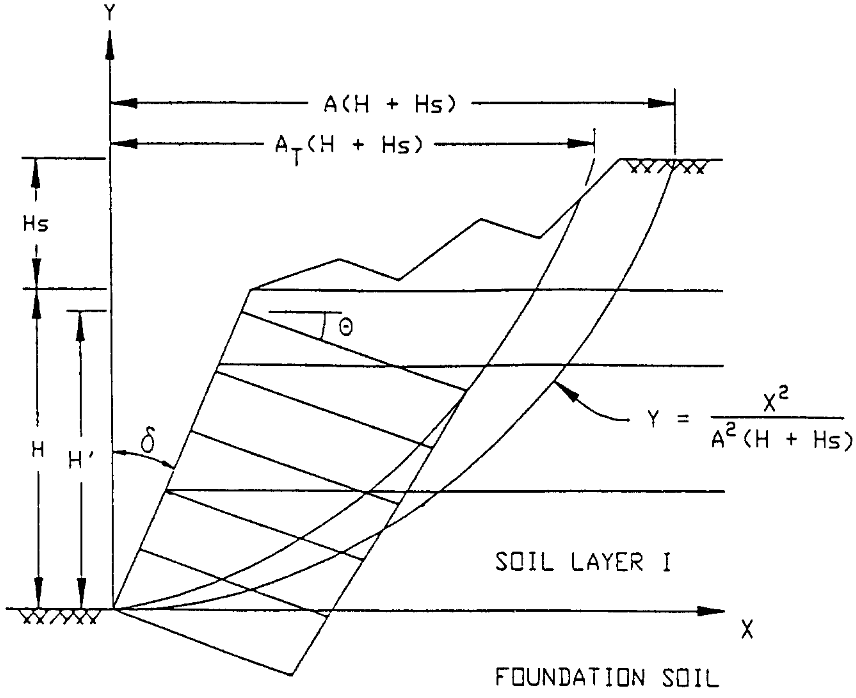


Figure - 2 Assumed Potential Failure Surface

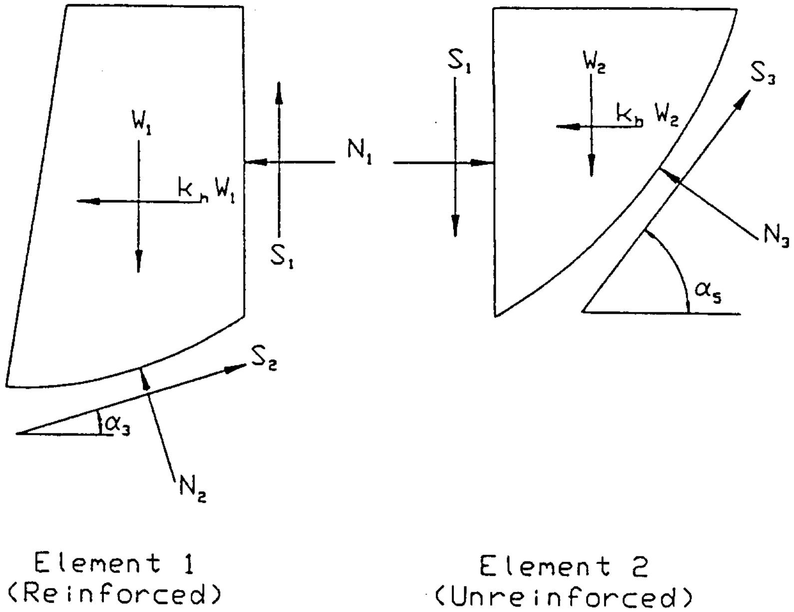


Figure - 3 Free Body Diagram

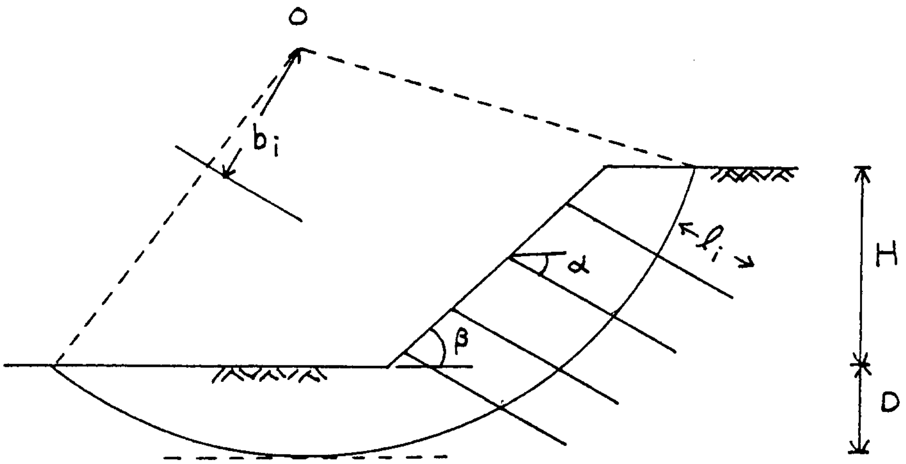


Figure 4 - Deep Seated Slope Stability

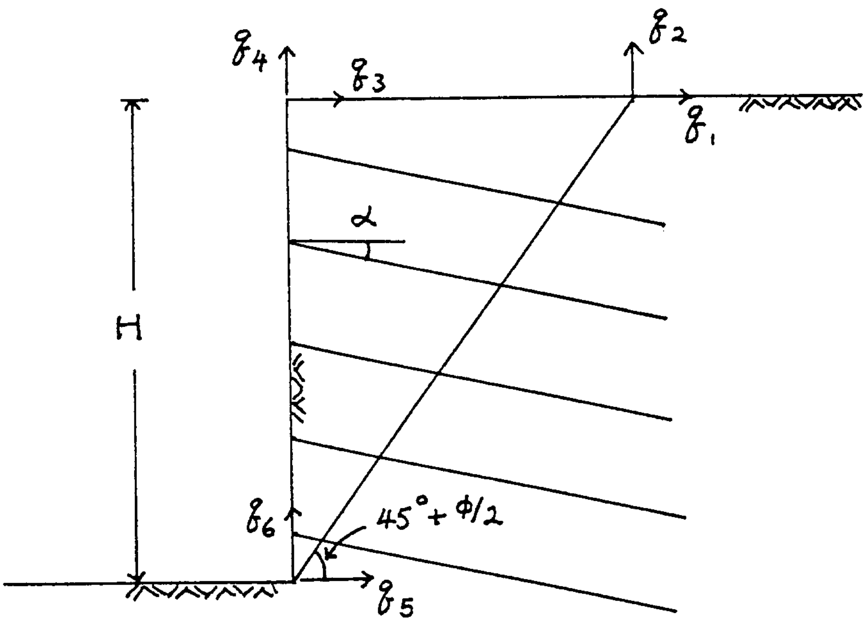


Figure - 5 Finite Element Approximation

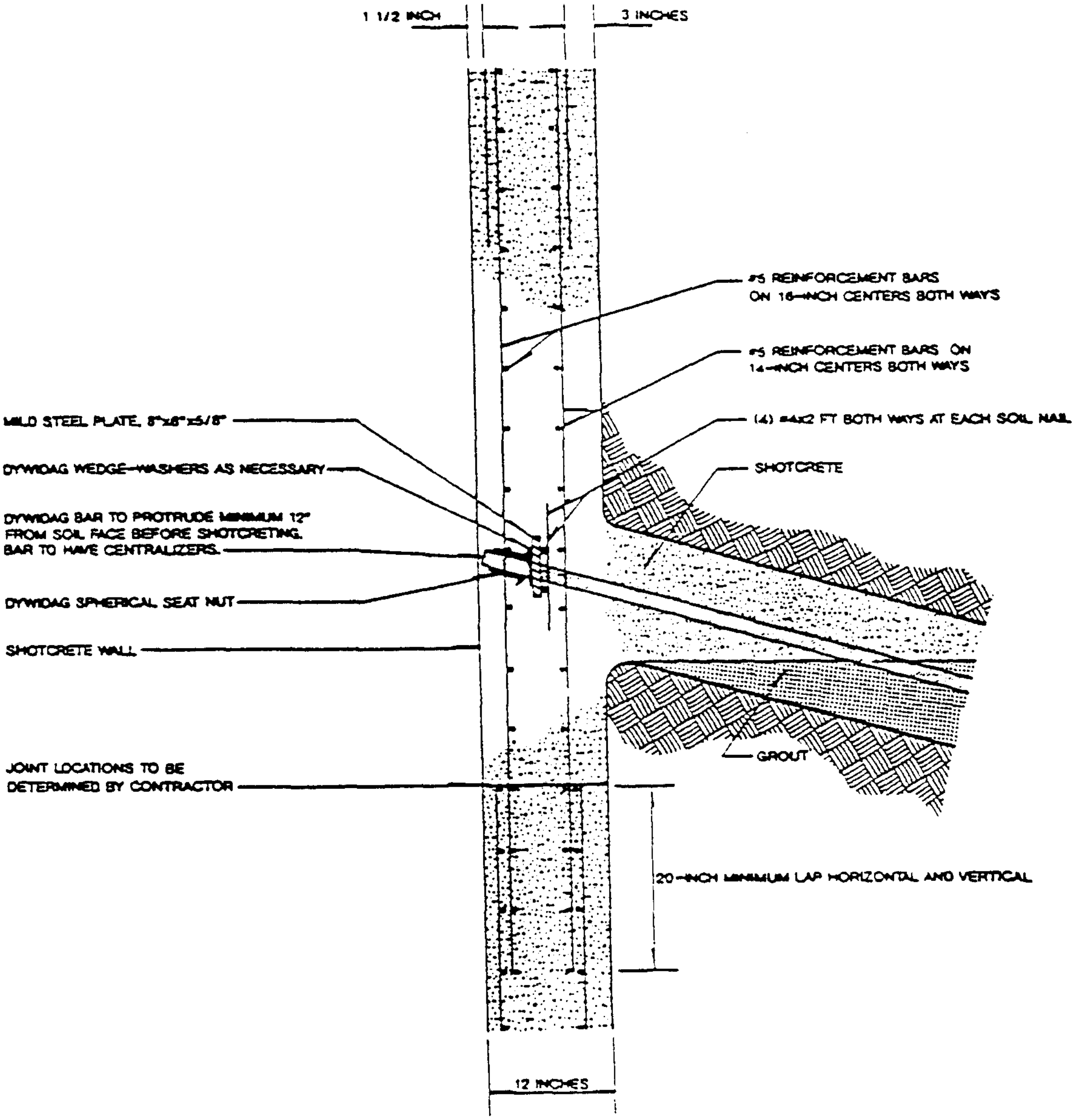


Figure 6 - Nail and Shotcrete Facing Connection