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Analysis of soil nailing system

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ABSTRACT: An expanded formulation for the design of soil nailing system based on two-dimensional plane strain limiting equilibrium is presented. It considers parameters, including the soil type, depth of excavation, geometry of the nails, spacing of the nails, variation of the ground surface, layered soil profile, inclined panel facing wall, and various loading conditions. An analytical parametric study to identify the effects of several pertinent parameters on the overall factor of safety has also been conducted and the results are summarily presented.

1 INTRODUCTION

An in-situ lateral earth support system, known as the soil nailing system, has been widely used in recent years and summarized by Mitchell (1987). In this technique, the native soil adjacent to the slope or excavation is strengthened by a series of grouted anchors so that it can remain stable at depths which would normally require the installation of a lateral support system. Figure 1 shows a typical cross section of the soil nailing system.

An extensive study of the soil nailing system including the design and analysis methods has been conducted by the writers (Shen et al. 1981a, 1981b, 1981c, 1982). 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 finite element study of in-situ reinforced soil (Shen et al. 1981a). Centrifuge model study has also been performed to validate this assumption (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 overall stability. The tensile forces developed in the reinforcing nails are divided into tangential and normal components along the 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 panel facing wall. The factor of safety is calculated by comparing the components of total resisting force and total driving force along the direction of driving force. Fundamentals of the analytical formulation are briefly explained and effects of several parameters on the overall stability of the soil nailing system are discussed in this paper.

2 LIMIT ANALYSIS FORMULATION

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 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

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

$$S_2=(W_1-S_1)\sin\alpha_3+(N_1+k_hW_1)\cos\alpha_3 \quad (2)$$

where

W_1=Weight of element 1
S_1=Tangential force between elements 1 and 2
α_3=Inclination angle of S_2
k_h=Horizontal body force coeff.

The equilibrium equations of element 2 (unreinforced zone) produce

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

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

where

W_2=Weight of element 2
α_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.

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

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

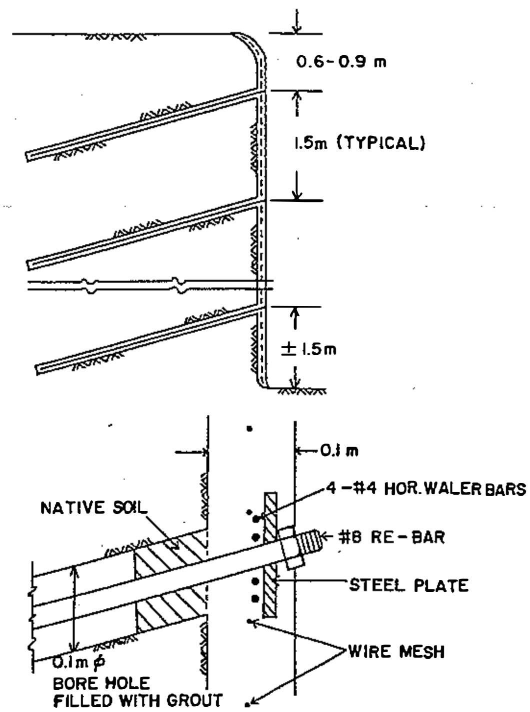

Figure 1. Typical cross section

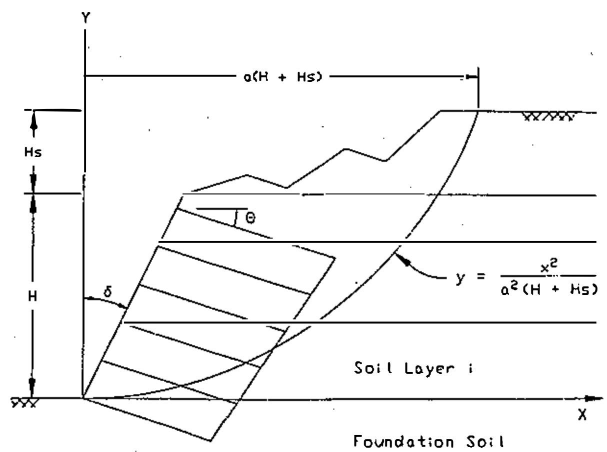

Figure 2. Assumed failure surface

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
ϕ_i'=developed friction angle for element i $=\tan^{-1}(\tan\phi_i/FS_\phi)$
FS_ϕ=factor of safety with respect to friction

$N_2' = N_2 + T_N$
$T_N = \Sigma T_i \cos(90° - \alpha_3 - \Theta)$
ΣT_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.,

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

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

$$FS_C = FS_\phi = FS. \qquad (10)$$

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, α_3 and α_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

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

Similarly, W_2 can be calculated from

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

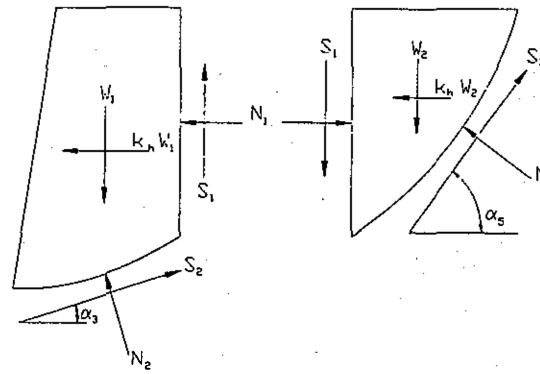

Figure 3. Free body diagram

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,

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

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 allows two possible descriptions of 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 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.

The detailed mathematical formulation associated with this soil nailing design can be found in reference (Bang et al. 1992).

3 PARAMETRIC STUDY

The effects of nail properties - spacing, length, and inclination angle - and the effects of panel facing wall inclination angle and layered soil profile on the global stability are briefly discussed below. The results are based on nail frictional resistance being proportional to the overburden (designated as R=OB in the figures) and being specified by the pull-out resistance (designated by the values of R in the figures). Table 1 shows the variations of geometric and material parameters used in the study

Table 1. Geometric and material parameters used.

Height of the wall:	50 ft.
Facing wall incl. angle:	0-40° (0)
Diameter of bore hole:	4 in.
Diameter of nails:	1 in.
Spacing of nails:	2-7 ft. (5)
Length of nails:	20-60 ft. (40)
Yield strength of nails:	30-80 ksi (30)
Inclination angle of the nails:	0-40° (15)
Soil unit weight:	100-125 pcf (100)
Soil friction angle:	5-40° (30)
Soil cohesion:	0.5-2 ksf (1)
Slope of backfill surface:	0°

* Numbers in parentheses are the standard values used in the study.

The factor of safety decreases dramatically as the horizontal spacing of nails increases (Figure 4). When the nail length is 20 ft., which is relatively small compared with the height of panel facing wall (50 ft.), the factors of safety are much lower than those calculated for longer nails and the effect of nail spacing is less significant. This is primarily because the contribution of shorter nails to the overall stability is relatively small. However, due to the yielding of the nails the factor of safety becomes

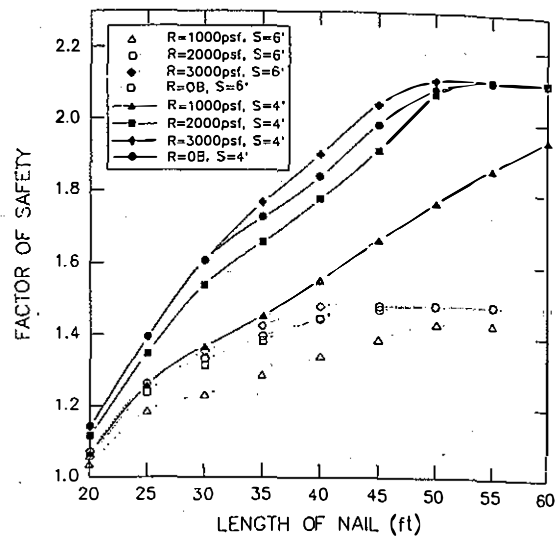

Figure 4. Effect of nail length

more or less constant with further increases in nail length. When the nails are short, slippage is the dominant failure mechanism, while breakage becomes more dominant when the nails get longer.

Decreasing the nail spacing is equivalent to increasing the contact area between the nails and the surrounding soil. This causes a direct increase in developed nail tensile force. Figure 5 shows the effect of nail spacing on the overall factor of safety with different nail lengths and frictional resistances. As the nail length increases from 20 ft. to 60 ft., the factors of safety increase accordingly. The curves become flatter as the spacing of the nails increases and eventually converge to the factors of safety obtained without nails. This is because the contribution of nail tensile forces to the global stability becomes smaller as the nail spacing increases. Note that the value of frictional resistance (R) has very little influence on the factor of safety as the nail spacing increases.

The effect of nail inclination angle is shown in Figure 6. It is interesting to note that the highest factor of safety occurs at a nail inclination angle of approximately 5 to 20 degrees. This finding confirms the previous result of the optimum nail inclination angle obtained by the writers that was based on simple analytical calculations

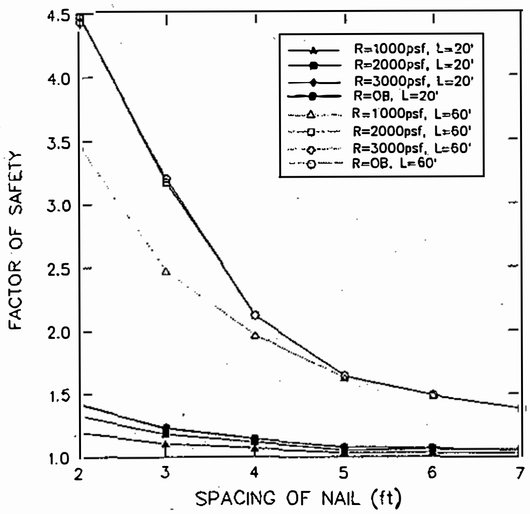

Figure 5. Effect of nail spacing

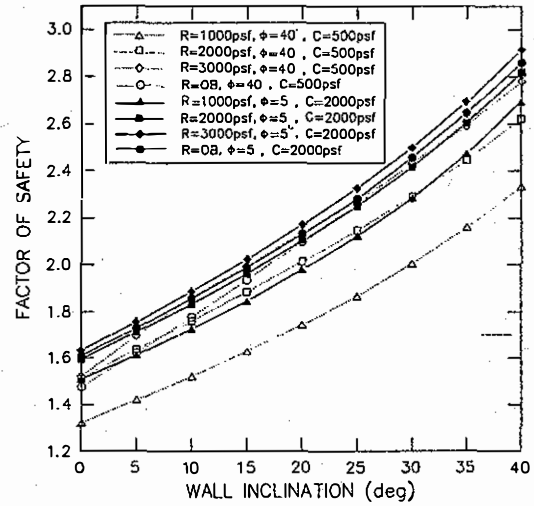

Figure 7. Effect of wall inclination

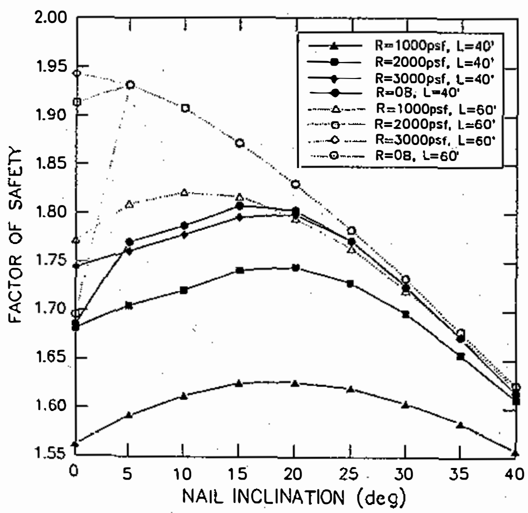

Figure 6. Effect of nail inclination

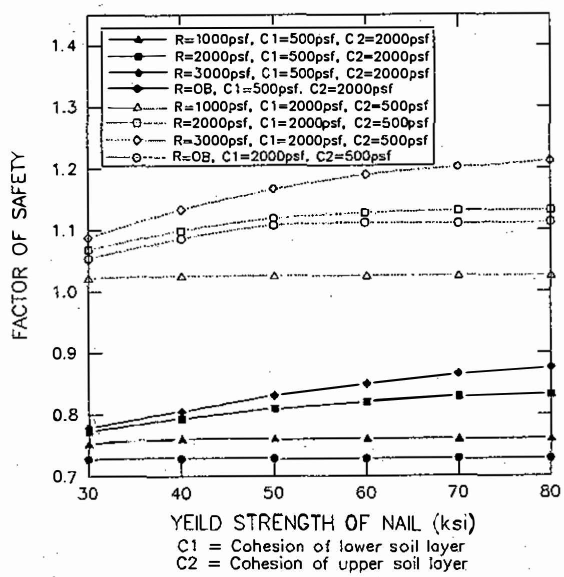

Figure 8. Effect of layered soil

(Bang et al.1980). Note also that for shorter nail lengths, the optimum inclination angle is higher than that of the longer nails.

Increasing the inclination angle of the panel facing wall corresponds to increasing the effective nail length of a given nail and to decreasing the driving forces. Therefore increasing the inclination angle results in increasing the factor of safety. As the panel facing wall inclination angle increases from 0 to 40 degrees, the factor of safety increases almost linearly - by nearly 85 percent, regardless of the soil strength parameters and the frictional resistance values (Figure 7).

The nails located near the bottom of the excavation have longer effective nail lengths beyond the probable failure surface, resulting in larger developed tensile forces within them. This indicates that the stability of soil nailing wall is primarily influenced by the shear strength of soil near the bottom of excavation rather than that near the top (Figure 8).

4 CONCLUSIONS

This paper presents a limiting equilibrium formulation for the design of a soil nailing system. It includes most of the pertinent design parameters that are thought to govern the behavior of soil nailing system and is intended to estimate the overall stability of the system against sliding.

A parametric study to identify the effects of several design parameters on the overall stability has been carried out and the following observations have been made:

1) The nail spacing and length have profound effects on global stability.
2) There is an optimum nail inclination angle, approximately 5 to 20 degrees to the horizontal.
3) The factor of safety is approximately linearly proportional to the inclination angle of the panel facing wall.
4) When the soil is layered, the stability of the soil nailing system is primarily influenced by the soil properties located near the bottom.

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