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Parametric numerical analyses of soil nailing systems

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ABSTRACT: Parametric finite element studies of a 15m wide 10 m deep excavation supported by a nail system are presented. The purpose of the paper is to investigate the most important factors influencing a soil nailing excavation performed in stages. The key features of a soil nailing system - soil removal, nail placement and face wall installation - have been duely incorporated in the numerical analyses.

1 INTRODUCTION

Classical limit equilibrium methods have been routinely used for analysis and design of soil nailing structures (Schlosser, 1983). This simple approach, similar to slope stability analysis to provide a global safety factor, is adapted to take into consideration the nail internal forces (tension, pullout, shear forces and bending moment) at the failure line.

Another approach, based on local equilibrium of the active zone (Juran et al., 1990), takes into account the progressive failure mechanism of the nails. By considering local equilibrium and nail flexibility, the maximum tension and shear stress on each nail layer are determined. For a practical point of view this approach is limited to conditions of homogeneous soil and simple geometric cases.

Soil stress-strain behavior is not clearly considered on either approach. They do not consider key features of soil nailing systems such as: soil excavation, nail placement and face wall installation. Nevertheless, from a practical point of view the above approaches have shown to be quite useful for design.

Analysis of soil structure interaction in soil nailing is quite complex. Jewell and Pedley (1992) have stated that reinforcement bending stiffness appears only to bring a modest additional improvement to soil stability compared with that due to the nail axial tension. This is a key aspect assessed in this paper.

The objective of this paper is to highlight the most important factors influencing a soil nailing excavation performed in stages. With this purpose finite element analyses have been performed simulating the key aspects of a soil nailing system.

2 FINITE ELEMENT MODELLING

The typical case chosen to be studied here is a 10m deep 15m wide excavation supported by a nailing system. This consists of a 25 mm dia. nail inside a 100 mm dia. grouted hole. A nail-grouting composite bending stiffness was assumed for the nails. These were spaced 2m vertically and 1m horizontally, as shown in Figure 1. A 100 mm thick face wall was also used.

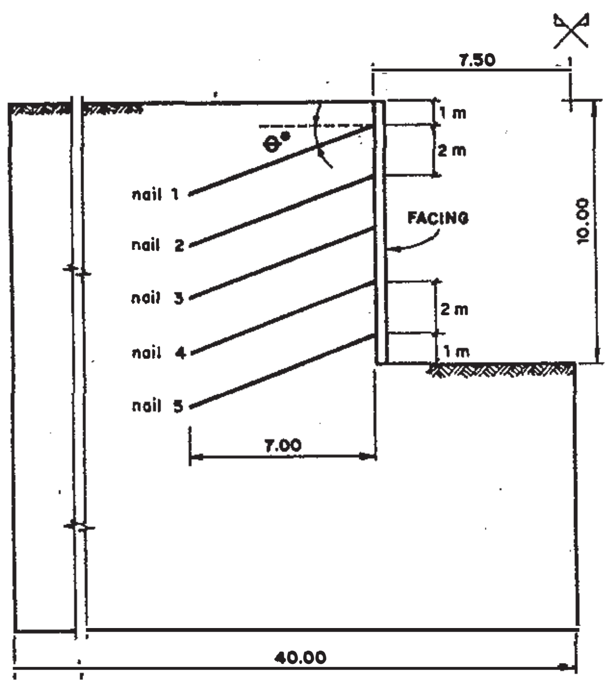

Figure 1. Soil Nailing Excavation

The excavation was performed in 5 steps. Each step of excavation consisted of removal of 2m of soil and installation of the nail (at the mid depth of the corresponding excavation) and the facing wall.

The basic finite element mesh for the horizontal case condition used in the current study has 445 elements, as illustrated in Figure 2. A linear strain quadrilateral finite element has been used for the soil. The no axial tension resistance at the end of the nail was duely modelled using triangular elements. Beam elements with bending and axial stiffness were used for the both nail and face wall.

The soil has been modeled as an elasto-plastic Mohr-Coulomb drained material, a reasonable hypothesis for unsaturated tropical soils, as far as the studies here are concerned. Analyses have been performed for total stress conditions, thus assuming that the water level is well below the bottom of the excavation, a common situation for tropical soils. Both the nail and the face were modelled as linear elastic materials. A recent version of the well tested CRISP program (Britto and Gunn, 1987) has been employed here.

The nails were spaced 2m in vertical and 1m in horizontal directions. The 3-D condition was transformed into a 2-D condition by means of an equivalent stiffness for the plane strain nail. Typical material parameters used for the studies performed here are shown in Table 1.

Table 1 - Material Parameters adopted in FE analyses

Parameters adopted	Values
soil cohesion, c	15 kPa
soil friction angle, ϕ,	30°
soil unit weight, γ,	20 kN/m^3
soil elastic modulus, E_s	10 MN/m^2
soil Poisson's ratio ν	0.3
soil K_o (total stress)	0.5
nail stiffness EI$^{(1)}$	6.4 kNm^2/m
wall face stiffness EI	6.4 kNm^2/m

Note: (1) for 2-D condition

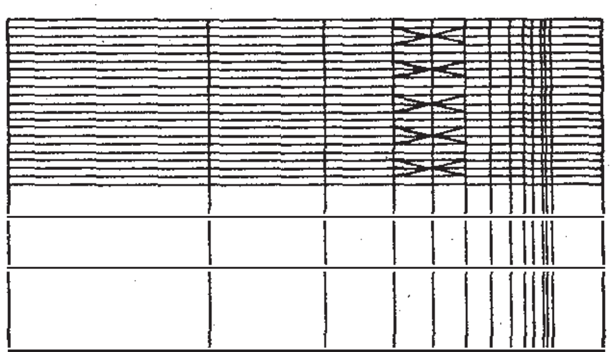

Figure 2. Finite Element Mesh

3 NUMERICAL ANALYSES

3.1 *Numerical analysis for the basic situation*

Initial results are shown for the basic situation, i. with parameters as given in Table 1 plus n inclination equal to 20° and nail length equal to 7 Figure 3 shows the face horizontal displacements, versus depth at the end of construction. It is observ that δ_{hmax} occurs at about 7.5 m depth and that 1 variation of δ_h with depth is not smoth, owing to 1 coupled influence of the face and nail stiffness.

Results of the axial force and bending mom along the nails for this condition are shown in Fig 4. With the exception of the lowest nail level, tension on reinforcement increase with dep Bending moments also vary with depth but in complex way.

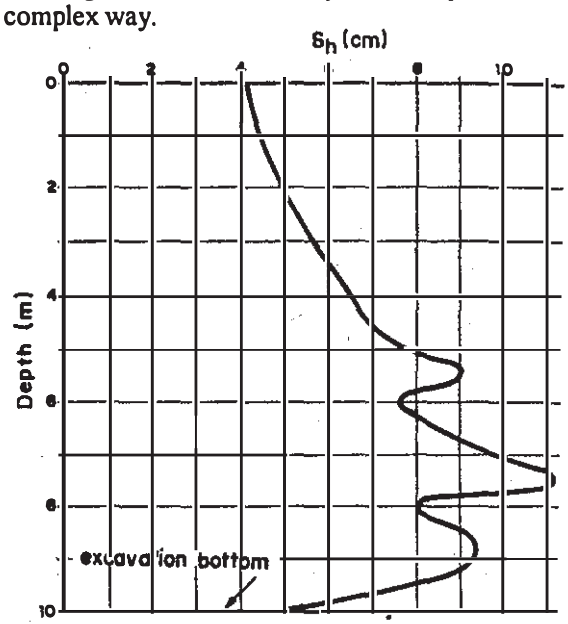

Figure 3. Face horizontal displacements versus de (basic situation)

3.2 *Nail influence*

Parametric studies have been performed for following situations:

- nail stiffness ranging from 0 to 100 EI;
- nail inclination θ ranging from 0° to 30°
- nail length ranging from 4 to 10m;

In Figure 5 yielding regions for the excavation no nails is compared with the excavation with fle nails or EI = 0, modelled by using a no ben stiffness truss element, all for nail inclination equ 20° and nail length equal to 7m. It is observed the nails are quite effective in reducing soil yiel The influence of nail stiffness is analysed in Fig for nail stiffness equal to EI and 10EI. These re illustrate clearly that the greater the bending stiffness the smaller is the soil yielding.

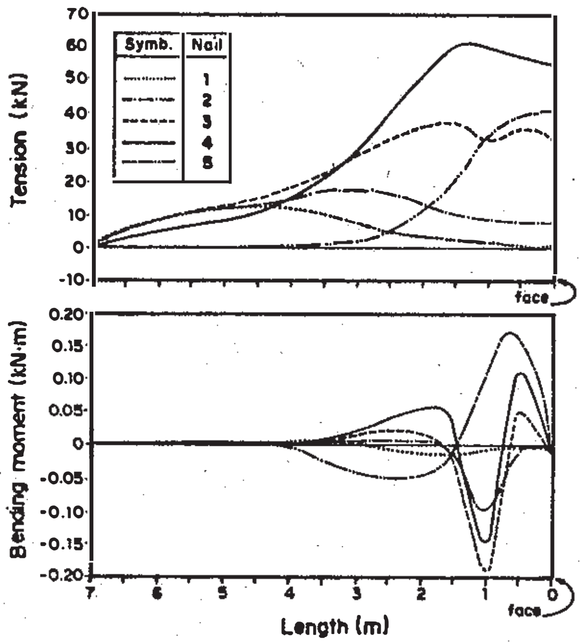

Figure 4. Axial force and bending moment along

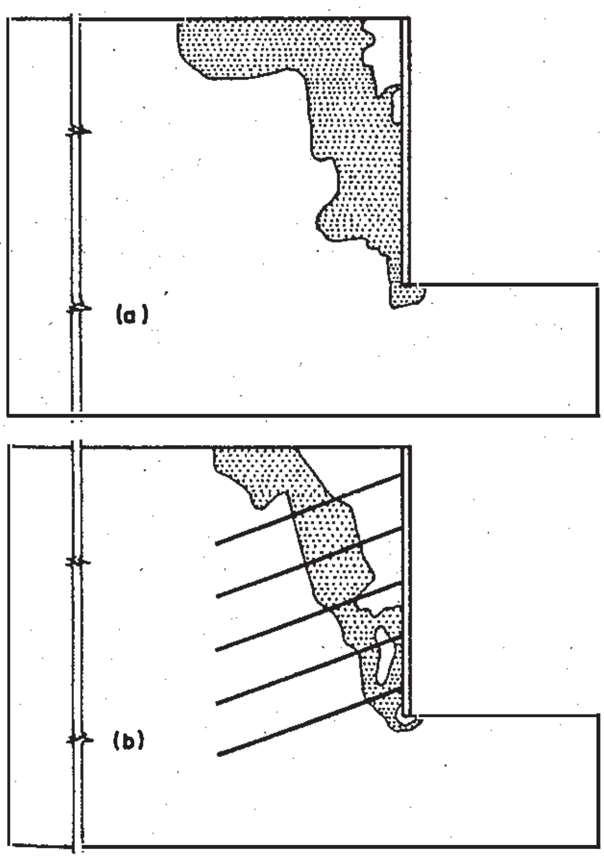

Figure 5. Yielding regions for (a) no nails; (b) flexible nails, EI = 0.

Yielding regions for horizontal nails (zero inclination) are shown in Figure 7. Comparision between Figures 6 and 7 shows that nail inclinations close to the horizontal are more effective in controlling soil yielding, although, for a practical point of view commonly used inclinations are between 10° and 20°.

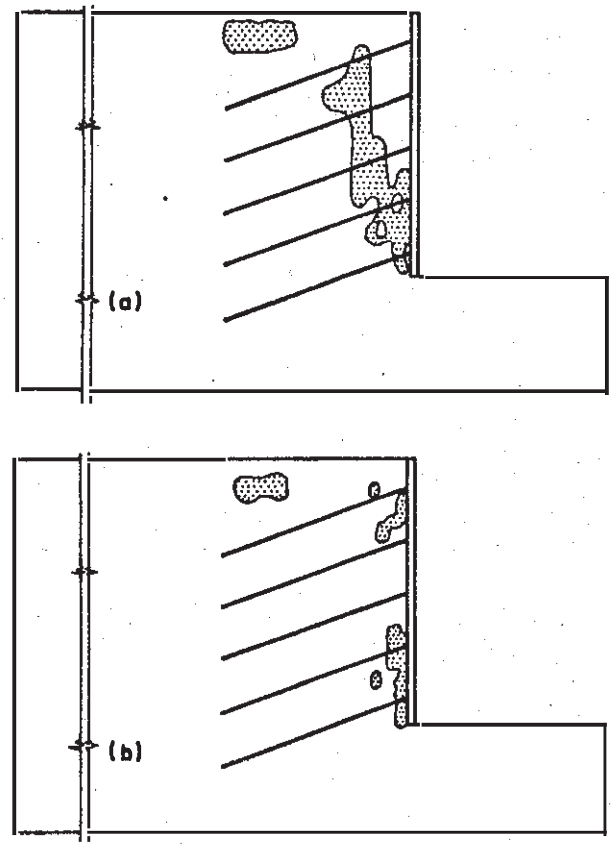

Figure 6. Yielding regions for (a) nail stiffness equal to EI. (b) nail stiffness equal to 10EI

Figure 8 shows the influence of the nail stiffness and inclination on the normalized values of maximum horizontal face displacement, δ_{hmax}, and on the summation of the nail maximum axial force, ΣT_{max}, and maximum bending moments, ΣM_{max},. As expected, horizontal displacements reduce with the in crease in nail stiffness and reduction of nail inclination. Maximum lateral face displacement, δ_{hmax}, for all case studies ranged from 0.9 % to 1.4 % of the excavation depth. It has been observed that the face movements were not much influenced by nail bending stiffness and inclination. Nail tension and bending moment increase with nail stiffness. Bending moment also in creased with nail inclination. Nail tension had hardly any variation with nail inclination varying from 0^0 to 20^0. However there is significative variation of nail tension when inclination varies from 20^0 to 30^0.

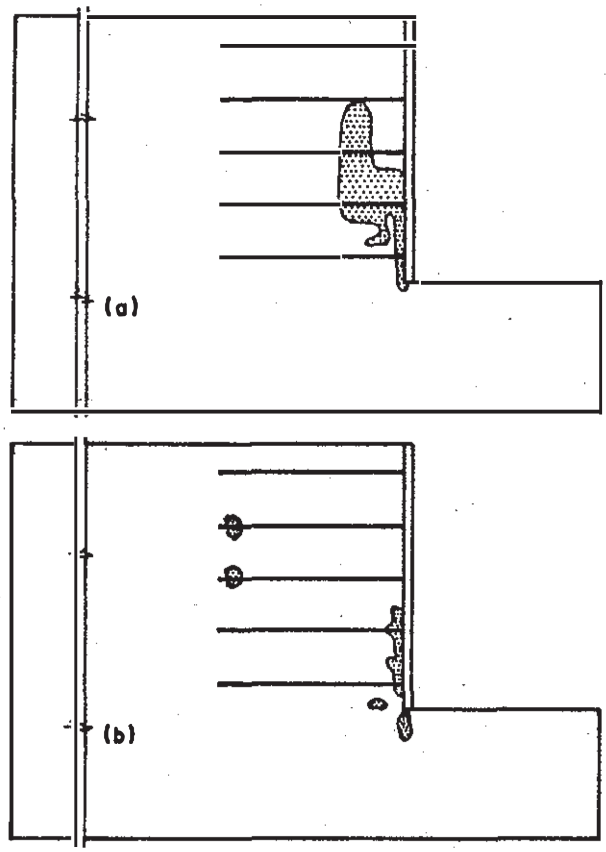

Figure 7. Yielding regions for horizontal nail inclination: (a) nail stiffness equal to EI and (b) 10EI

The relative importance of the bending moments on nail internal stresses may be related to the index I_m, defined by

$$I_m = (6/e)\,\Sigma M_{max} / \Sigma T_{max} \quad (1)$$

where e is the thickness of the 2-D equivalent nail. Calculated I_m values for different nails bending stiffness and inclination are shown in Figure 9.

Analysis of figures 8 and 9 leads to the conclusion:

(1) For stiffer nails the increase of nail inclination means lower nail tension and higher nail bending moment, the opposite behavior occurs for low stiffness nails;
(2) The higher the nail inclination, the greater is the bending stiffness influence in internal stresses;
(3) The relative importance of bending moments on nails internal stresses increase with bending stiffness and inclination.

Analyses have also shown that increasing the nail length from 4 to 10m, resulted in a 11 % decrease on maximum lateral face displacement of, δ_{hmax}, and a 15 % increase on the summation of maximum nails bending moments, ΣM_{max}. These analyses have also shown a negligible variation on nails tension, ΣT_{max} variation were less than 1 %.

3.3 *Influence of facing stiffness*

Parametric studies have been performed for the following values of wall stiffness: EI, EI/20 and EI = 0, and nail stiffiness equal to $64kN/m^2$.

The influence of the facing stiffness on the maximum horizontal face displacement and on nails internal efforts is shown in Figure 10. The face horizontal movements were not greatly influenced by facing characteristics. Facing stiffness influenced the

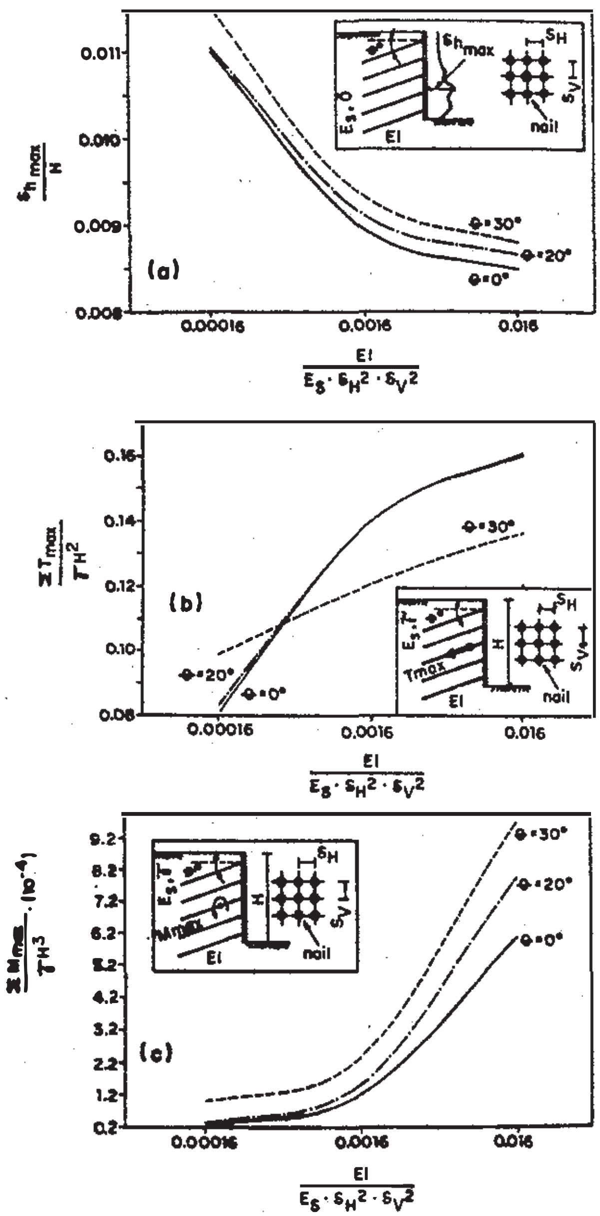

Figure 8. Influence of the nail stiffness and inclination on: (a) face horizontal displacement; and on the summation of nails maximum (b) axial force and (c) bending moments.

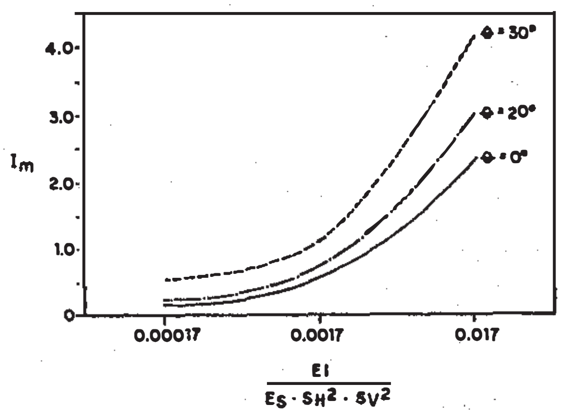

Figure 9. Relative importance of the bending moments on nail internal stresses for different nail stiffness and inclination

nails bending moments but did not significantly effect the nail tension forces. Analyses have also shown that facing stiffness helps control soil yielding near the face.

4. STABILITY ANALYSIS

Limit equilibrium analyses have yielded a factor of safcty $F_s = 0.67$ for the excavation without nailing.

Limit equilibrium analyses for the nailed excavation were carried out as shown in Figure 11 using the equation

$$F_s = \tan\phi / \tan\phi_{mob} = c / c_{mob} \qquad (1)$$

where c_{mob} and ϕ_{mob} are the mobilized cohesion and friction angle, respectively, thus calculations had to be performed iteratively. The Σ T_{max}, determined from the FE analyses (for nail stiffness equal to EI) were used in the calculations. Bending moments were not incorporated into these analyses. Limit equilibrium analyses for the nailed excavation have yielded F_s equal to 1.50, 1.22 and 1.12, for inclination equal to zero, 20° and 30°, respectively.

5. CONCLUSIONS

Finite element studies of a 15m wide 10m deep excavation supported by a nailing system performed in stages have been presented here. The main objective of these analyses was to highlight the most important factors influencing a soil nailing excavation.

Parametric analyses have shown the importance of the nails on the soil mass stability. Analyses of the nail stiffness have shown the important role of the bending stiffness in controlling the soil yielding.

High stiffness nails and inclinations close to the horizontal are more effective in controlling the soil

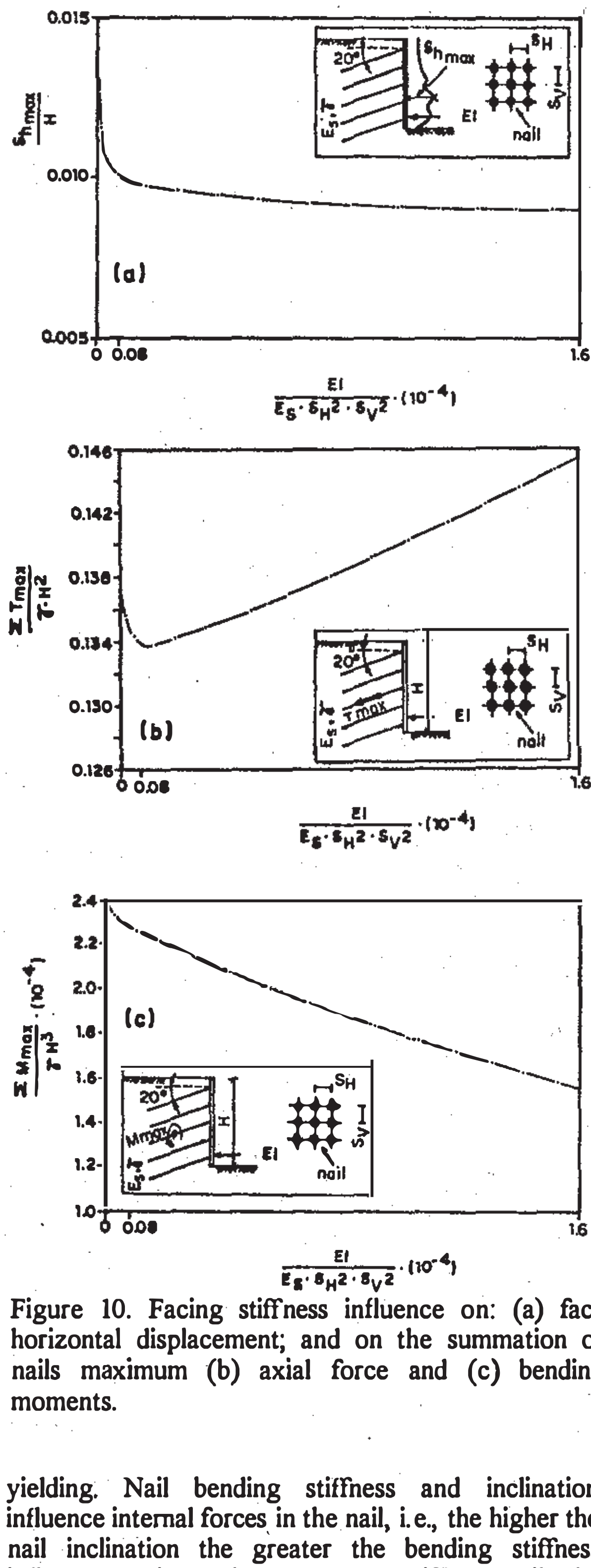

Figure 10. Facing stiffness influence on: (a) face horizontal displacement; and on the summation of nails maximum (b) axial force and (c) bending moments.

yielding. Nail bending stiffness and inclination influence internal forces in the nail, i.e., the higher the nail inclination the greater the bending stiffness influence on internal stresses. For stiffener nails the increase of nail inclination means lower nail tension and higher nail bending moments, the opposite behavior ocouns for low stiffness nails. The relative importance of bending moments on nails internal stresses increase with bending stiffness and inclination.

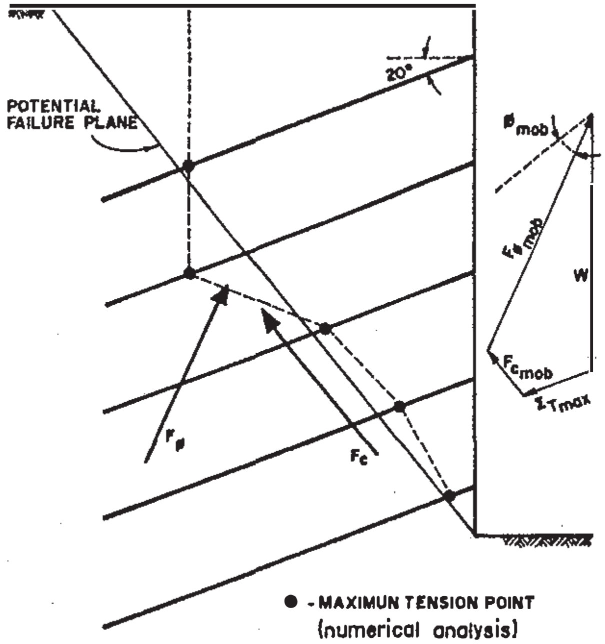

Figure 11. Factor safety determination

Parametric analyses also show that: (1) facing helps in controlling soil yielding near the face; (2) facing stiffness influences the nail bending moments, but it has no significant effect on nail tension forces; (3) the maximum lateral displacement, δ_{hmax}, of the face for all case studies were 0.9 % to 1.4 % of the excavation depth; (4) the face horizontal movements were not greatly influenced by facing characteristics, nails bending stiffness and inclination; (5) the nail length variation does not lead to a significant influence on results.

REFERENCES

Britto, A.M. & Gunn, M.J. 1987. Critical state soil mechanics via finite elements. *Ellis-Horwood Chichester.*

Jewell, R. A. & Pedley, M.J. 1992. Analysis for soil reinforcement with bending stiffness. *Journal of Geotechnical Engineering, ASCE.* 118(10): 1505-1528.

Juran, I., Baudrand, G., Farrag K. & Elias V. 1990. Kinematical limit analysis for design of soil-nailed structures. *Journal of Geotechnical Engineering, ASCE.* 116(1) : 54-72.

Schlosser, F. 1983. Analogies et differences dans le comportement et calcul des ouvrages de soutement en terre armée et par clouage du sol. *Annales de L'Institut Technique de Batiment et des Travaux Publiques.* 148: 26-38.

Shen, C. K., Bang, S. & Hermann, L.R. 1981. Ground movement analysis of an earth support system. *Journal of Geotechnical Engineering, ASCE.* 107(12).