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DEFORMABILITY ANALYSIS OF NAILED SOIL SLOPES

Analisis de la Deformabilidad de Estructuras de Suelo Cosido

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Abstract

Soil nailing is a reinforcement technique that consists of installing, within a soil mass, semi-rigid elements which are capable of resisting traction and shear loads.
This paper aims at evaluating the influence of slope geometry and construction procedures on stress-strain behavior of nailed excavations. Different slope inclinations and modeling procedures for simulating nails are considered. A parametric study was carried out using a computer program based on finite differences, considering geotechnical parameters from a typical residual soil from southeast Brazil.
The results indicate that a small change of slope inclination from 90 to 80 degrees corresponds to an average reduction of 70% of horizontal displacements at the top of excavation. In flatter slopes, this effect is less pronounced.
Construction of nailed soil slopes, with the nail end tied to the concrete face, provides a 35% reduction of horizontal displacement at the top of vertical excavations.

Resumen

El cosido del terreno es una técnica de refuerzo que consiste en instalar en el suelo, elementos semi-rígidos capaces de resistir a esfuerzos de tracción y de corte.
Este artículo estudia la influencia de la geometría del talud y del método constructivo en el comportamiento tensión-deformación. Inclinaciones distintas del talud y dos procedimientos de modelización han sido testadas. El estudio paramétrico se llevó a cabo con el programa FLAC. Todos los análisis han considerado parámetros de suelos residuales brasileños. Los resultados han indicado que una pequeña variación de inclinación del talud, de 90 hasta 80 grados, implica en una reducción media de 70% en los desplazamientos horizontales del topo de la excavación. Taludes más planos presentan un beneficio más pequeño. La construcción de muros cosidos con extremidad de la inclusión fija en la pantalla, ocasiona una reducción de 35% en el desplazamiento horizontal del topo de las excavaciones verticales

1 INTRODUCTION

Soil nailing is a quite effective reinforcement technique for improving stability of natural and excavated slopes. The slope stabilization process consists of inserting semi-rigid passive elements, capable of resisting to traction and shear loads. These elements are positioned in a nearly horizontal direction within the soil mass. With this configuration, traction, bending moments and shear loads may be resisted by the reinforced soil mass, reducing overall displacements.

This paper intends to present and an analysis of the stress-strain response of nailed soil slopes. The study focuses on the influence of slope inclination (β), and nail fixing process on slope surface (free or fixed nails).

The analyses were performed with a computer program commercially available (FLAC).

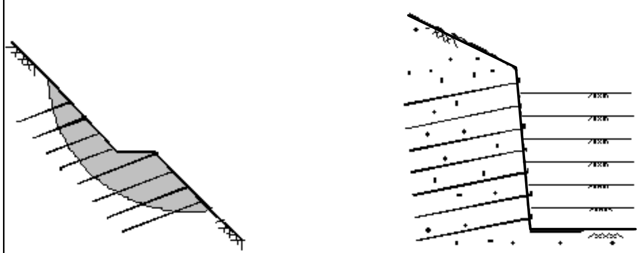
2 SOIL NAILING TECHNIQUE

The progressive stress relief, due to successive excavation stages or to potential failure conditions, induces lateral displacements in the soil mass. As a consequence, internal forces are generated and transferred to the soil-reinforcement system.

In natural slopes (Figure 1a), nails may be introduced in a descending or ascending construction sequence, according to the contractor's convenience. A shotcrete layer, with no structural function, is then placed on slope surface as a protective cover. In excavated slopes (Figure 1b), soil-nailing technique is accomplished in 3 successive stages. First, the excavation is carried out in increments, which may vary from 0,5m to 2,5m in height, depending on the soil properties. Second, the nails are inserted and positioned. Finally, the slope surface is protected by shotcrete.

The thickness of the shotcrete layer may vary from 60mm and 100mm. In gentle slopes (inclination angle less than 45^{o}), it is possible to adopt a surface vegetation cover (Pinto and Silveira, 2001).

It is worthwhile to mention that drainage systems must not be disregarded or overlooked, when designing or building nailed soil structures.



(a) natural slope (b) man-made slope

Figure 1. Soil nailing applications

Nails are usually made of steel bars, but it is also possible to use micro-piles or synthetic bars with cylindrical or rectangular sections.

After positioning the nails in a nearly horizontal pre-drilled hole, cement mortar is injected. The nail inclination may vary from 5^{o} to 20^{o} for facilitating cement injection. Alternatively, nails may be simply driven into the soil mass.

Nail spacing on slope surface usually follows a regular pattern, depending on the strength characteristics of the soil mass. Spacing from 1m to 2m in both horizontal and vertical directions may be considered as common practice.

The nail end, close to the slope surface, may be embedded within the concrete face (Figure 2), therefore enabling free relative displacements between nails and the surrounding soil. Alternatively, the nail end may be fixed to the shotcrete face (Figure 3).

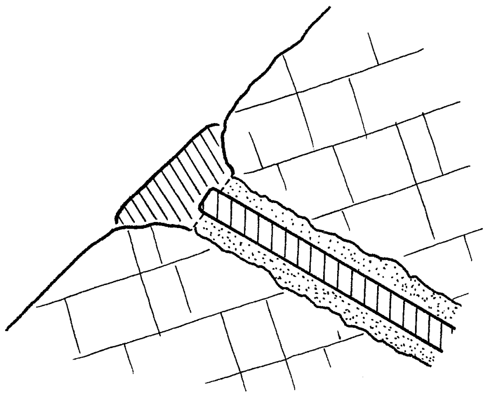


Figure 2. Embedded nail (free condition).

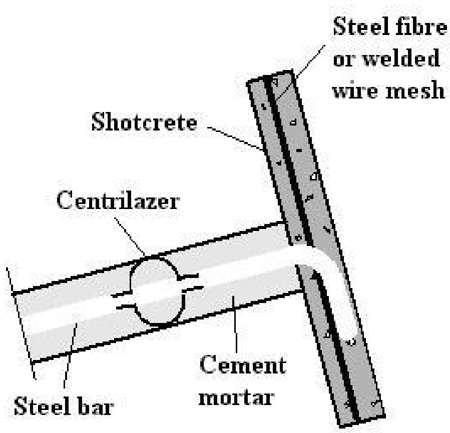


Figure 3. Fixed nail.

In Brazil, soil nailing is usually carried out with steel bars of CA-50 or DYWIDAG type, with diameters ranging from 16mm and 32mm. The steel bars ase inserted in pre-drilled holes of 70mm to 120mm in diameter. The literature reveals that this technique has been adopted in natural and man-made slopes, 5m to 25m high, with inclinations from 50^{o} to 90^{o} (ABMS/ABEF, 1999).

2.1 Soil nailing design

In order to ensure internal and external stability, soil-nailing design requires definition of several geometric parameters for the nails, such as length, installation angle, and horizontal and vertical spacings.

Current design practice uses limit equilibrium methods for assessing safety factors and also for required forces that provide or improve equilibrium. Based on these forces and on pullout resistance, nail geometric parameters are therefore prescribed in the design.

Several limit equilibrium procedures are available in the literature (Shen et al, 1981; Stocker et al, 1979; Schlosser, 1983; Juran et al, 1988; Bridle, 1989; Anthoine, 1990). These methods differ from each other by the shape of failure surface, the computation, nature of the balance forces acting on the potential sliding surfaces. Besides, there is no agreement on nail response to bending.

Limit equilibrium methods assume a rigid and perfectly plastic soil behavior. As a result, they are not able to predict strains and stress redistribution during soil nailing construction stages.

The stress-strain behavior of nailed soil slopes may be predicted by specific computer programs that are capable of simulating construction stages, and which incorporate constitutive models for reproducing different materials (Springer et al, 2001, Gerscovich et al, 2002).

3 NUMERICAL ANALYSES

The numerical analyses were performed with FLAC, which is a two-dimensional finite element computer program (Itasca, 1996).

The finite difference mesh was considered with 138 horizontal divisions and 84 vertical divisions, totaling around 11,600 nodes. Boundary conditions were prescribed far enough from the excavation zone, for minimizing boundary effects on computed displacements.

3.1 Geometric Conditions

The conditions simulated in this paper correspond to a long symmetrical excavation 6.0m wide and 10.5m deep. Different slope inclinations (β = 60^o, 70^o 80^o or 90^o) were considered, as schematically shown in Figure 4.

Limit equilibrium analyses (Figure 4) indicated that, independently of slope inclination, a stabilization solution would be required. All computed safety factors (FS) were lower than 1.0, before soil reinforcement was considered.

Excavation was carried out with 7 successive steps, with 1.5m height each.

Nails were placed with an inclination of 10^o. Except for the first nail line, which was located 1,0m deep from the top of excavation, the vertical and horizontal spacing were kept constant and equal to 1,5m.

The nails consisted of 25mm diameter steel bars, 6m length, which were positioned in 75mm diameter pre-drilled holes, fulfilled by cement mortar.

At each excavation step, the nail positioning was simultaneously carried out with placement of a 100mm thick shotcrete layer.

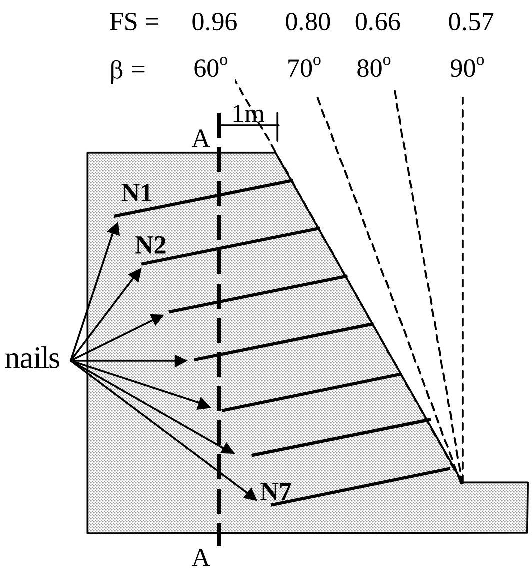


Figure 4. Excavation scheme and safety factors for different slope angles

3.2 Soil Conditions

In the present paper, soil behavior was predicted by an Elastic- Perfectly Plastic model, associated to Mohr-Coulomb failure criterion. Nail simulation was accomplished through a one-dimensional structural element, presenting resistance only to tension. The shotcrete wall behavior was modeled by beams structural elements, with resistance to bending moments.

All parameters adopted in these simulations are presented in Table 1. Shear strength and compressibility parameters attributed to the soil mass corresponded to typical experimental results of Brazilian residual soils (Maccarini, 1980; Aleixo, 1998; Lacerda and Almeida, 1995).

Table 1 Geomechanical parameters

Material	Parameter	Value
Nail	σ_{steel}	500MPa
	E_{stee}	205GPa
	G_{cement}	9GPa
	q_s	150kPa
Shotcrete layer	$E_{shotcrete}$	24GPa
Soil	E_{soil}	45MPa
	ν	0,25
	γ	18,5kN/m^3
	c'	10kPa
	ϕ'	32^o
	ψ	7,5^o
	k_0	0,5

Notes: σ_{steel} = yielding stress, E = Young modulus, G = shear modulus, q_s = pull-out resistance, ν = Poisson's ratio, γ = unit weight, c' = effective cohesion, ϕ' = effective friction angle, ψ = dilatancy angle, k_o = coefficient of lateral stress at rest.

3.3 Nail conditions

FLAC enables two different procedures for fixing nail ends in the finite difference mesh. The extremity of the structural element may be anchored in a specific mesh node (fixed ended nail). In this case, there is complete compatibility between soil and nail displacements at this node, and no stress transfer to the structural element occurs around this point. Alternatively, nails may respond independently of the mesh deformation (free ended nail).

The choice between both alternatives is particularly important in defining the anchorage condition of nail end on the slope surface, since inside soil mass nail is always free to move. On the slope surface, depending on construction procedure, nail may be tied to shotcrete protective cover by a wire mesh (Figure 3), or free to move (Figure 2).

When fixed end nails are used, the maximum axial nail force occurs close to the slope surface (Cardoso and Gonçalves, 1997; Jewell, 1990). On the other hand, with free ended nails, the maximum axial force moves away from the excavation surface (Juran and Elias, 1990; Plumelle and Schlosser, 1990).

The shear resistance at the soil-nail interface is defined in FLAC program by adhesion and friction components. Definition of these parameters depends on the nail's geometric characteristics and pullout resistance.

2D FLAC program allows indirect simulation of 3D pattern of soil nailing structures; through the division of some nail parameters (elasticity modulus, yielding load, etc) by the horizontal nail spacing.

4 RESULTS

Results presented herein focused the influence of slope inclination and nail installation processes (free or fixed nail) on stress-strain behavior of nailed soil slopes. The development of axial forces along the nail lines, as a result of successive excavation steps, has also been analyzed.

The computed horizontal displacements were compared at a vertical line (section A-A in Figure 4), 1m far from the top of the excavation. This approach was adopted to prevent eventual inconsistencies due to the variable slope inclination and rigidity of the shotcrete layer.

The horizontal displacement profiles, computed as a percentage of the excavation height (%H), are shown in Figure 5. The results indicate a significant influence of the slope inclination and nail anchoring system (free nail *vs* fixed nail). Independent of nail type, there is an increase of the horizontal displacement, as the face becomes steeper.

Maximum displacements at the top of the excavation are only observed in vertical slopes (β=90^o). In gentle slopes, maximum displacement occurs around the lower third of excavation height. No significant differences are observed below the bottom of the excavation,

A slight sloping of the excavation face reduces significantly the magnitude of horizontal displacements. An average reduction of 75% was observed, at the excavation top, when the excavation slope was reduced from 90^o to 80^o.

Except for the vertical excavation, the nail type (free or fixed end) has minor effects on horizontal displacements. The vertical slope, with free-ended nail, provided higher horizontal displacements, and a profile pattern similar to a rigid body movement.

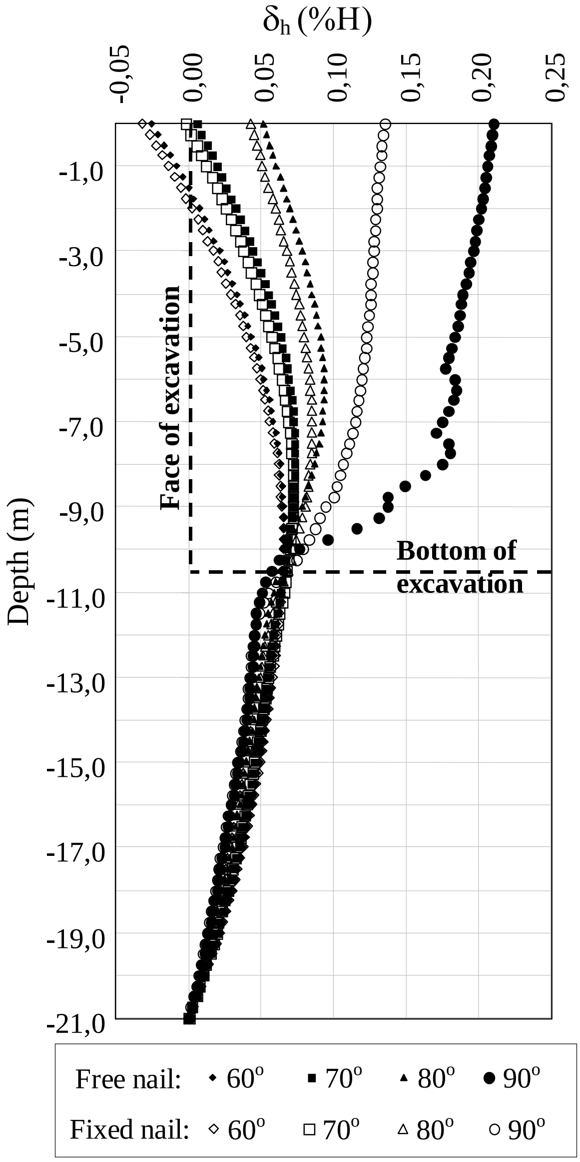


Figure 5. Horizontal displacement profiles

The results indicate that, independent of the nail type, nails closer to the surface are less mobilized. This is noted despite higher horizontal displacements occurring in this region, in vertical slopes. It is also observed that the maximum axial force increases with the slope inclination. Moreover, the depth of the most mobilized nail line varies with nail type (free or fixed end). With free-ended nails, a maximum axial nail mobilization occurs at 9m depth (nail line 06). With fixed-ended nail, the largest axial force position varied with excavation inclination, and occurred at a lower depth, between 7.5m and 9m depth (nail line 05).

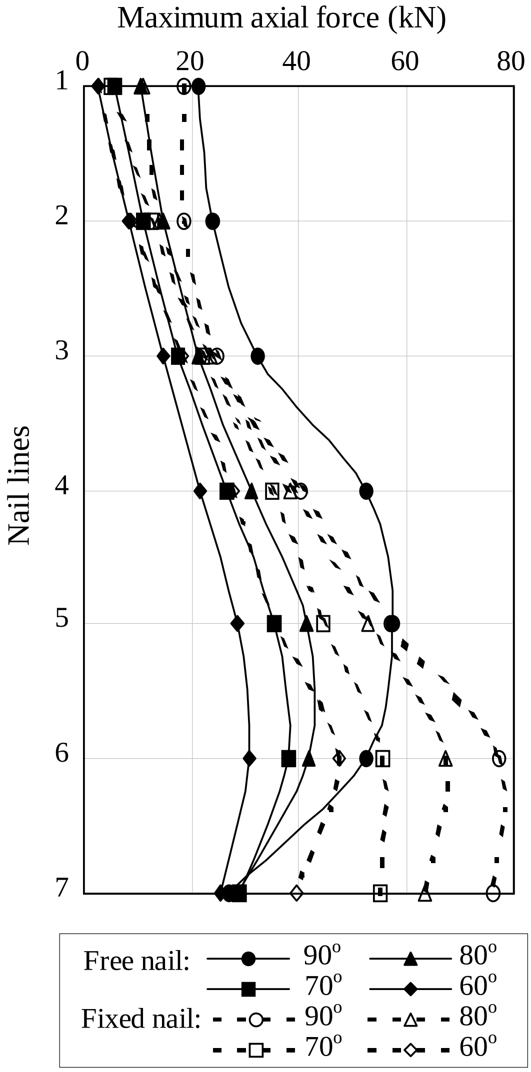


Figure 6. Maximum axial force on nail lines.

It is worthwhile to notice that, in all cases, the maximum axial force is about 33% of the corresponding yielding force.

5 CONCLUSIONS

This paper presents the results of numerical analyses of nailed soil slopes, with FLAC program. Different slope inclinations and tying alternatives for fixing nail end at slope surface have been evaluated. All analyses have considered soil parameters based on experimental results of Brazilian residual soils.

The results have indicated a strong influence of slope geometry on horizontal displacements and, consequently, on axial forces along nail length.

Vertical slopes provided the most unfavorable conditions. A slight sloping of excavation, from 90° to 80°, resulted in a significant improvement of soil nailing response, and, therefore, should be recommended in geotechnical design.

The tying process of nail end at to slope surface, is relevant on soil displacements only if excavation is performed vertically. However, the mobilized internal forces, transmitted to each nail line, show different patterns depending on displacement compatibility.

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