INTERNATIONAL SYPMOSIUM ON LANDSLIDES - ISL '2004, 2004, Rio de Janeiro.
Landslides: Evaluation and Stabilization. Netherlands: A.A. Balkema, 2004. v. 2, p. 1671-1676.

Considerations on the soil nailing technique for stabilizing excavated slopes

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ABSTRACT: The construction procedure for soil nailing induces lateral displacements in the soil mass. As a consequence, internal forces are generated and transferred to the soil-reinforcement system. The efficiency of this stabilization technique depends on the development of an interaction mechanism between each nail and the surrounding soil. This paper aims at evaluating the influence of nail's geometry and excavation depth on the stress-strain behavior of vertical nailed excavations. A parametric study has been carried out for a typical slope in gneissic residual soils. The results show the strong influence of design geometry and excavation height on the horizontal displacements of nailed soils. However, the displacements may be considered as negligible when $L/H \geq 0.6$ and $S_v/L < 25\%$. For relatively small height excavations ($H \leq 5m$), the upper limit of the S_v/L ratio can be increased to 50%.

1. INTRODUCTION

Soil nailing is an efficient technique for reinforcement of natural or excavated soil slopes when stability conditions are considered unsatisfactory. Nailing is done through inclusions of semi-rigid passive elements (nails), which are resistant to tension, shear and bending loads. These elements are usually set up by inserting steel bars in pre-drilled holes, which are subsequently filled by cement mortar (Clouterre, 1991).

The reinforcement elements are positioned in a nearly horizontal direction within the soil mass. Progressive unloading of soil mass, caused by staged excavation, generates lateral displacements in the outward direction and induces the internal forces in the nails. Their function is, therefore, to minimize these displacements by adding internal resistant forces.

The current design practice is based on Limit Equilibrium concepts for assessing safety factors and also for required forces that provide or improve equilibrium (Gässler & Gudehus, 1981; Shen et al, 1981; Schlosser, 1982; Bridle, 1989; Elias & Juran, 1990). As a result, stresses and strains within the reinforced mass cannot be predicted.

This paper presents a parametric analysis of a staged excavation in residual soil slopes reinforced with nails. The present study focuses on the influence of nail length and nail spacing on the stress-strain response of the reinforced soil. Geotechnical parameters typical from gneissic soil in Rio de Janeiro have been considered in this study.

Previous studies by the authors have evaluated the effects of nail inclination (Gerscovich et al, 2002), slope inclination and nail fixing procedure on the surface wall (Lima et al, 2003a) and the thickness of the wall (Lima et al, 2003b).

The results have indicated a strong influence of slope geometry on horizontal displacements and, consequently, on axial forces along the nail. The most unfavorable condition corresponds to vertical slopes (Lima et al, 2003a). A slight decrease of the excavation slope angle, from 90^o to 80^o, resulted in a significant improvement of soil nailing response and is therefore recommended for geotechnical design.

The procedure for fixing the nail's end to the slope surface is relevant to soil displacements only if excavation is vertical. However, the mobilized internal forces, which are transmitted to each nail line, show different patterns depending on the displacement compatibility.

Hao & Azzam (2001) have performed numerical analyses of nailed excavations for evaluating the influence of nail parameters such as length and dip angle. For a surface wall of 100mm, the nails at the excavation top should be longer than the ones at the base. They also noted that the nail's inclination should not exceed 15°. Similar conclusions have also been reported by Gerscovich et al (2002).

2. NUMERICAL ANALYSES

The geometry is shown in Figure 1. Depending on the excavation depth (H = 5m or 10m), the lower boundary distance to the base of excavation varied from 46m to 51m. FLAC signal convention attribute positive values of horizontal displacement if the element moves towards the soil mass as also shown in Figure 1.

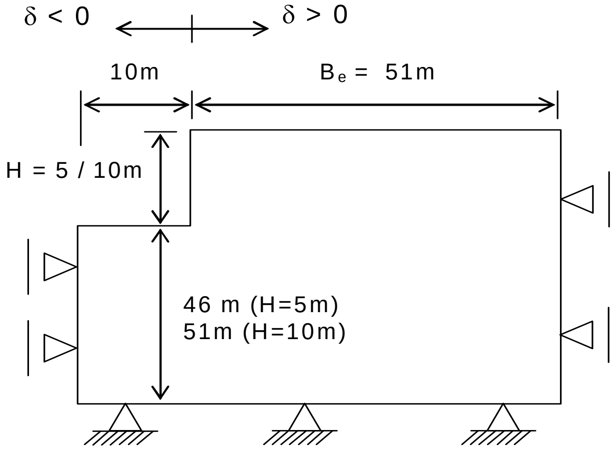


Figure 1. Geometric Parameters and FLAC definitions.

The geotechnical parameters are presented in Table 1. Shear strength and compressibility parameters for the young gneissic residual soil were obtained from laboratory tests, performed with saturated and unsaturated samples. The deformability parameters were obtained in conventional triaxial tests, with saturated samples (Aleixo, 1998). These parameters are primarily influenced by sampling operations, stress level, stress history and stress path, which may cause considerable differences between laboratory and field values. In the present study, the Young modulus was computed as the secant line (E_{50}) corresponding to 50% of the maximum shearing stress. To account for the differences between field and laboratory responses, E_{50} was multiplied by a factor of 5 (Sandroni, 1973; Sieira, 1998; Sayão et al, 1999).

Table 1. Geotechnical parameters.

Parameter	*Value*
Young Modulus E	72 MPa
Poisson's ratio ν	0.15
Unit weight γ	18 kN/m^3
Effective cohesion c'	20 kPa
Effective friction angle ϕ'	20°
Dilatancy angle ψ	0°
Coefficient of lateral stress at rest k_o	0.55

Limit equilibrium analyses were performed with WINSTABL program (Purdue University, 2000), without considering any soil reinforcement.

Global factors of safety (FS) were computed with Bishop Simplified method, assuming circular failure surfaces. In both analyses, soil cohesion (c') was reduced to 20kPa. This reduction aimed at simulating an unfavorable strength condition that could occur as a result of water infiltration within the soil mass due to intense rainfall. The results (Table 2) pointed out the need for stabilization measures.

Table 2. Global Safety Factors.

Excavation height (H)	Safety factor (FS)
5m	1.12
10m	0.69

The stress-strain parametric analyses were performed with the finite difference method computer program, FLAC (Itasca, 1996).

Considerations on FLAC program, for simulating the stress-strain behavior of nailed excavations in soil, were reported elsewhere (Lima et al, 2003b). The studies demonstrated that FLAC may be an useful tool, provided geomechanical parameters are adequately prescribed. Besides, the boundary conditions (geometry and restraints) are shown to be very significant. Values of B_e/H (Figure 1) lower than 4 may result in different values of horizontal displacements, depending on the vertical restraint condition imposed by the lateral boundary.

An Elastic- Perfectly Plastic model, associated to Mohr-Coulomb failure criterion, was used to predict the soil behavior.

Nail simulation was accomplished through a one-dimensional structural element, presenting resistance only to tension. These elements were placed in the soil mesh with an inclination of 10° in pre-drilled holes with 100mm diameter. Nails were free to move at the face of excavation, independently of the shotcrete facing wall. This nail end condition results in larger horizontal displacement (Lima et al, 2003a).

The shotcrete wall behavior was modeled by beams structural elements, with resistance to bending moments.

Table 3 resumes shotcrete wall parameters and nail´s geometric and mechanical parameters.

The influence of horizontal (S_h) and vertical (S_v) spacing between nails, besides the nail length (L), were evaluated by a parametric study of a vertical excavation of 5m and 10m high. In both cases, the relationship between S_h and S_v was kept constant and equal to 1.

The height of each excavation stage was also varied between 1 and 4m. The different analyzed geometric conditions are resumed in Table 4. The number of nails varied depending on the different vertical spacing.

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

Table 3. Nail and shotcrete parameters.

Material	*Parameter*	*Value*
Nail	Nail diameter ϕ_{hole}	100 mm
	Steel bar diameter ϕ_{steel}	25 mm
	Yielding stress σ_{steel}	500 MPa
	Young modulus E_{steel}	205 GPa
	Shear modulus G_{cement}	9 GPa
	Pull-out resistance q_s	150 kPa
Shotcrete layer	Young modulus $E_{shotcrete}$	24 GPa

Table 4. Geometric parameters.

Total excavation height (H)	5m (m)	10m (m)
Horizontal spacing (S_h) Vertical spacing (S_v) (S_h= S_v)	1.0 (5 nails) 1.5 (3 nails) 2.0 (3 nails) 3.0 (2 nails) 4.0 (1 nail)	1.0 (10 nails) 1.5 (7 nails) 2.0 (5 nails)
Nail length (L)	3.0 3.5 4.0 6.0 12.0	3.0 6.0 12.0
Excavation stage height ($H_{escav.}$)	1.0m 1.5m 2.0m 3.0m 4.0m	

2.1 RESULTS

Figure 3 shows the computed horizontal displacement profiles for the different geometric conditions of 5m-deep excavation. Table 5 resumes the magnitude of the horizontal displacements at the top and bottom of the face of excavation, besides the maximum value, computed as a percentage of excavation height.

The results indicate that, independent of nail length (L) and relationship between vertical spacing and nail length (S_v/L), the horizontal displacements are always positive. This behavior is unusual since it suggests a pattern of soil movement contrary to the direction of stress relief. The clockwise movement of the wall may be attributed to the combination of 2 factors: i) influence of the boundary conditions; ii) stiffness of the wall, coupled to the stiffness of the soil-nail mass, which may lead to a rigid body behavior.

When the distance between the slope surface and left boundary is reduced to values smaller than H, the resulting displacement profile is opposite to the one shown in Figure 3; i.e. the largest horizontal displacement occurs at the top of the wall towards the excavated region. The larger the width of the base of the excavation the lesser are the constraints imposed to the horizontal displacements and, therefore, the larger upward movements are observed at the base of the excavation. Besides, the relatively high stiffness of the reinforced soil mass contributes to a monolith behavior of the soil-nail material.

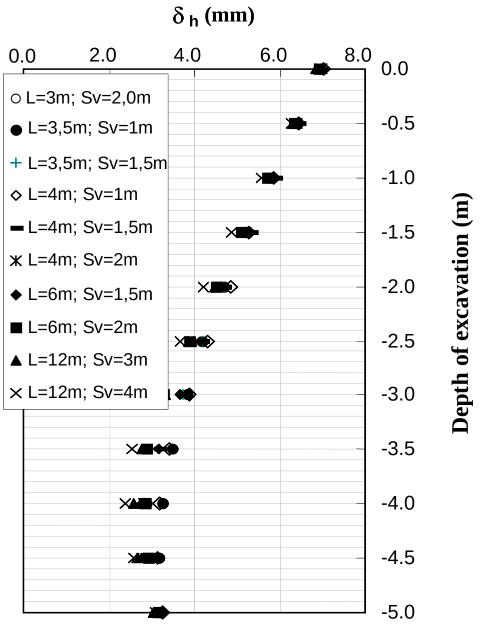


Figure 3. Horizontal displacement for H= 5m.

Table 5. Displacements at the face of excavation (H=5m).

L (m)	L/H	Sv/L (%)	δ_t (mm)	δ_b (mm)	δ_{max} (%H)
3.0	0.6	50	6.98	3.25	0.14
3.5	0.7	29	6.96	3.23	
3.5		43	6.97	3.19	
4	0.8	25	7.00	3.26	
4		38	6.97	3.18	
4		50	7.01	3.25	
6	1.2	25	7.02	3.20	
6		33	7.04	3.26	
12	2.4	25	6.96	3.14	
12		33	7.03	3.19	

Notes: δ = horizontal displacements (t = top; b = base; max = maximum)

Moreover, no significant differences are observed on the computed horizontal displacements. An average horizontal displacement profile, with values of δ_t 6.99mm and δ_b 3.21mm could be used independently of nail length and nail mesh refinement. The maximum displacement is 0.14%H and occurs within the lower third height. The negligible influence of nail's geometric parameters is a result of the combination of favorable conditions. This result is in accordance with previous studies (Gerscovich et al., 2002). The stress-strain behavior of relatively small height excavations (H ≤ 5m) is not dependent on nail geometry, providing L/H ≥ 0.7 and $S_v/L \leq 50\%$. For excavations of greater deep the upper limit of the relationship S_v/L is reduced to 25%.

Figure 4 shows the results of 10m-deep excavation and Table 6 resumes the magnitude of the horizontal displacements.

The horizontal displacement profiles showed a trend of inclination towards the excavated region, with maximum displacement occurring approximately at the mid height of the excavation. In these cases the constraints imposed by the left vertical boundary are minor since its distance to the face of the excavation is equal to H.

Previous studies (Lima et al, 2003a) carried out with different slope inclinations (60^o to 90^o), have indicated a significantly reduction on the magnitude of horizontal displacement when the slope angle of the excavation was reduced from 90^o to 80^o. Besides, the vertical slopes showed a reasonably vertical movement towards the excavated region, and the maximum displacement, around 0.2%H, occurred at the top of the excavation.

The main differences between the present study and the previous one may be mainly associated to nail geometry (75mm diameter, 6m length), excavation geometry (width of the base of excavation equal to 0.6H) and soil deformability parameter (Young modulus equal to 45MPa). In the present analysis, the lesser influence of the constraints, coupled to the higher stiffness of the reinforced soil mass resulted in a complete different stress-strain behavior.

All cases with $S_v/L < 25\%$ provided similar horizontal displacement profiles. The simulations with $S_v/L \geq 25\%$ resulted in maximum horizontal displacements equal to 0.69%H (S_v/L=25%) and 1.45%H (S_v/L=33%). These values are much greater than the threshold suggested in the literature by Clouterre (1991) and Schlosser et al (1992). The authors monitored different soil slopes, reinforced with nails, and verified that the maximum horizontal and vertical displacements occur at the top of the excavation, and have similar magnitudes, within the range 0.1%H to 0.3%H.

The simulation with 6m long nails (S_v/L=33%) did not fulfill the requirements of both nail length and density (L/H ≥ 0.7 and $S_v/L \leq 25\%$), that might ensure a stable condition. In this case, the stress-strain levels induced a continuous plastic zone, which extended out of the reinforced region, as shown in Figure 5a. This condition characterizes a potential slope failure. Numerical instability was observed when S_v/L exceeded 33%.

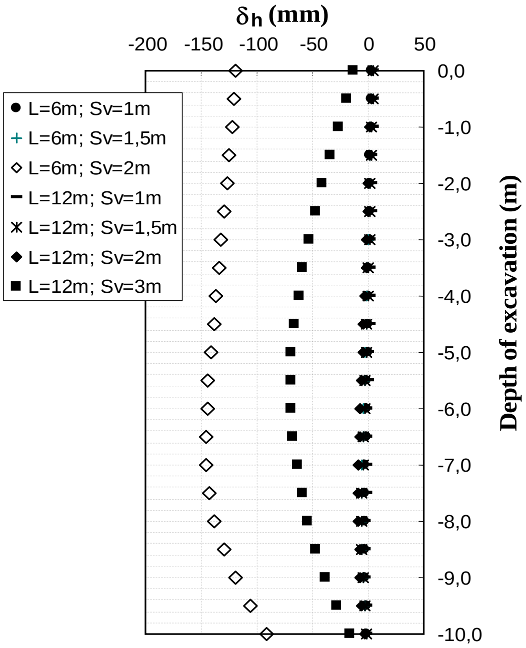


Figure 4. Horizontal displacements for H= 10m.

Table 6. Displacements at excavation face (H=10m).

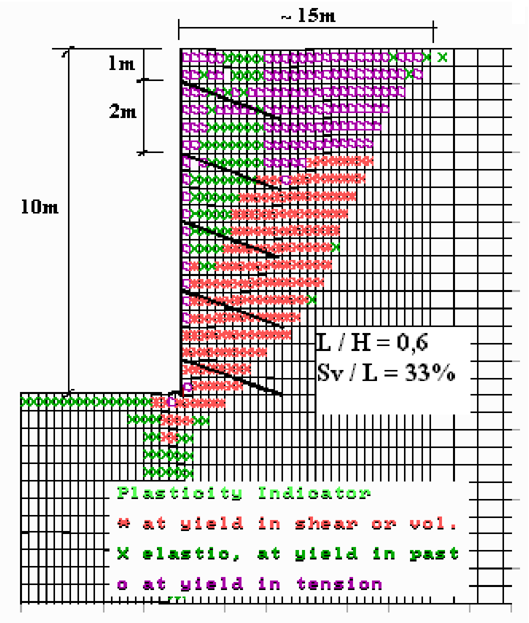
L (m)	L/H	S_v/L (%)	δ_t (mm)	δ_b (mm)	δ_{max} (%H)
6	0.6	17	3.36	-1.15	0.04
6		25	2.75	-1.85	0.06
6		33	-119.7	-91.3	1.45
12	1.2	8	5.02	-0.85	0.04
12		13	4.44	-1.56	0.06
12		17	3.20	-3.08	0.09
12		25	-13.20	-16.78	0.69

Notes: δ = horizontal displacements (t = top; b = base; max = maximum)

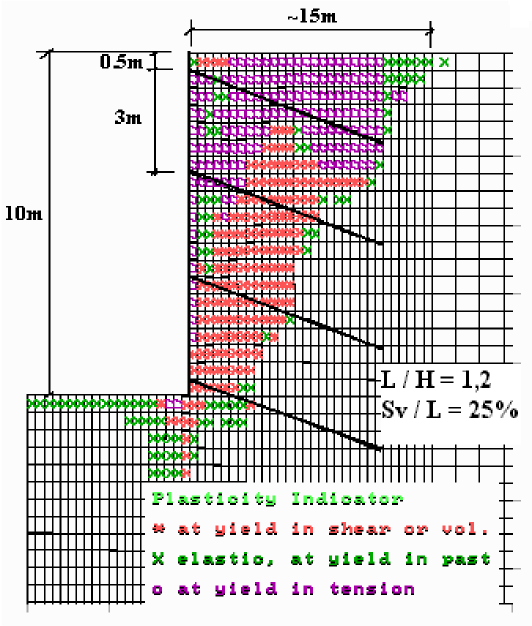
It is worthwhile to note in Figure 4 that a significant increment of horizontal displacement occurs when the relationship between S_v/L increases from 17% (Sv = 2m) to 25% (Sv=3m).

In both cases, the criteria L/H > 0.7 and $S_v/L \leq 25\%$, (L=12m; L/H = 1.2) are satisfied, but the maximum displacement exceeds the upper limit of

0.3%H recommended by Clouterre (1991) and Schlosser et al (1992). Figure 5b shows that, a continuous plastic state is generated, but the reinforced system is still contributing to the global stability.



(a) L= 6m



(b) L = 12m

Figure 5. Plasticity indicators (H=10m).

3. FINAL REMARKS

The studies herein presented aimed at investigating the stress-strain response of a vertical excavation reinforced with nails. Different alternatives of nail length and vertical spacing were evaluated. The analyses have considered residual soil parameters of a Brazilian soil.

The results have confirmed the strong influence of geometric design parameters and excavation height on horizontal displacement. However, provided that $L/H \geq 0.6$ and $S_v/L < 25\%$ the displacements are negligible. For relatively small height excavations ($H \leq 5$m) the upper limit of the relationship S_v/L can be increased to 50%.

The horizontal displacement profiles indicated different inclinations, depending on nail density and excavation height. In all cases the maximum displacement occurred bellow the mid-height of excavation, which is in disagreement with other results available in the literature. This divergence was mainly attributed to the proximity of boundary conditions imposed at the vertical line near the base of excavation. Greater distances impose a smaller restriction on the vertical displacements and, therefore, allow a clockwise movement of the face of excavation. This effect is amplified with the increase of stiffness of the soil-nail material. Judgment must be therefore exercised while trying to model the stress-strain behavior of soil nailed excavations using numerical tools.

ACKNOWLEDGMENTS

The authors acknowledge the assistance of Ms. Fernanda Springer (PUC-Rio) and the financial support of Brazilian research agencies CAPES and CNPq.

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