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Soil nailing wall with vertical nails to displacement reduction: Brazilian Practice

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Abstract
Most of the time, geotechnical engineering interventions require solutions that necessarily aim for better use of the available space. Many slope stabilization techniques were developed following that assumption, and one of the most applied procedures in Brazil is the soil nailing reinforcement. These engineering techniques are constantly improving. Consequently, a continuous study of the design and behavior of soil nails is important. The technique of vertical nails reinforcement in soil nailing is recent in the Brazilian scenario. Nowadays, some constructors started to use them near the slope face when stabilizing huge excavations. This paper aims to verify the vertical nails' efficiency in reducing horizontal displacements. We present three numerical modeling analyses using the finite elements method (FEM). The proposed model is a soil nailing of approximately 18m high in a homogeneous subsoil in São Paulo city. Comparing situations with and without vertical nails, as if an inclined face (slope), the results showed that adding those nails could reduce horizontal displacements.

Keywords: soil nailing, vertical nails; shotcrete facing; Finite Elements Method (FEM); horizontal displacements.

Pared de clavado del suelo con clavos verticales para la reducción de los desplazamientos: la práctica Brasileña

Resumen
La mayoría de las veces, las intervenciones de ingeniería geotécnica requieren soluciones que necesariamente apuntan a una mejor utilización del espacio disponible. Muchas técnicas de estabilización de taludes fueron desarrolladas siguiendo esa premisa y uno de los procedimientos más aplicados en Brasil es el refuerzo con clavos del suelo. Como todas esas técnicas de ingeniería están en constante perfeccionamiento, es importante que el diseño y el comportamiento de los clavos de suelo sigan siendo estudiados. La técnica de refuerzo con clavos verticales en el suelo es reciente en el escenario brasileño. Ahora algunos constructores comenzaron a utilizarlos cerca de la cara del talud al estabilizar grandes excavaciones. Este trabajo tiene como objetivo verificar la eficiencia de los clavos verticales en la reducción de los desplazamientos horizontales. Se presentan tres análisis de modelización numérica mediante el método de elementos finitos (MEF). El modelo propuesto es un clavado de suelo de aproximadamente 18 m de altura, en subsuelo homogéneo en la ciudad de São Paulo. Comparando situaciones con y sin clavos verticales, como con una cara inclinada (talud), los resultados mostraron que la adición de esos clavos podría reducir los desplazamientos horizontales.

Palabras clave: clavado de suelos; clavos verticales; revestimiento de hormigón proyectado; Método de Elementos Finitos (MEF); desplazamientos horizontales.

1 Brief History of Soil Nailing in Brazil

In Brazil, the pioneering use of the soil nailing technique was in the 1970s, in a water supply tunnel construction by SABESP (São Paulo water company) and in retaining slopes of the Imigrantes road, in São Paulo [1]. However, it was from Professor Rabcewicz's lecture in 1975 that the technique of soil nailing became usual in the country [2].

The mainly used methods of analysis of soil nailing consider that the ground behind the wall is subdivided into

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two different zones: one active, limited by the slope face and a potentially slippery surface and another passive zone, that contains all the rest of the mass, besides the potential failure. The global stability analysis is usually done considering the stabilizing forces of the nail acting in the active mass. For example, there is another method of calculation that considers the active wedge as a gravity wall (for higher nail densities in the mass) and verifies global stability in that situation. However, all methods usually differ in the shape of the potential failure surfaces, accounted acting forces (slip mass weight, interaction forces between slices) or the method of safety factor calculation.

Soil nailing is currently one of the most used techniques in Brazil for natural or cut slope reinforcements because it is a relatively low-cost technique that presents reasonable speed and easy execution, providing an excellent price-performance ratio in most diverse situations.

In Brazil, global safety factors in geotechnical design are usually adopted, whose necessary magnitude changes according to the application of the retaining in time, whether it is provisional or permanent. However, it is known that there is an international geotechnical tendency of design for partial safety factors (LRFD), considering load and resistance. This paper considers design by global safety factor because the LRFD methodology is not widespread in our Brazilian technical environment yet. Recently, the Brazilian geotechnical committee engaged in preparing the new text of the soil nailing standard. The norm created had as its main objectives to reflect the national experience and propose a text as comprehensive as possible, without imposing specific methods and procedures. The new standard is ABNT NBR 16920-2 [3]. It should be noted that this is the first standard for soil nailing in Brazil.

2 The vertical nails practice in Brazil

Like many types of reinforcement, the major purpose of vertical nails is to improve the condition and resistance of soil, and contribute to retaining its mass. It reduces minor failures (local stability) during the first excavation stages and reduces horizontal displacements along the face – an inherent consequence of the soil nailing reinforcement.

Depending on how vertical nails are considered, they can also improve the global stability condition, increasing the excavation's overall safety factor.

There is an example of construction where this variant of the classical technique was applied [4]. A soil nailing wall of 8.0 m high was monitored. It was composed of six rows of nails drilled with ϕ75 mm diameter, 8.0 m length with 10º to the horizontal. The vertical elements had the same dimensions as the sub-horizontal ones. They were disposed in four rows: the first is 1.0 m from the face and the others 0.3 m from one another.The author monitored the wall and noted that the vertical elements did not contribute to reducing the acting axial forces in the sub-horizontal nails. However, they facilitate the sequential excavation execution, guaranteeing the local soil stability, and might have reduced the bending forces in the nails by stiffening the face region.

Other solutions have been incorporated into the nailing soil practice to minimize the deformations of the rock mass. Among these solutions is the use of additional vertical and horizontal nails to reduce the displacement of the structure. Vertical nails can be seen in containment for a building basement, with 7.4 m height, executed in 2000 [5]. Insertion of three rows of vertical nails at a distance of 2 m from the wall was also reported [6], with an inclination between 0 and 20º concerning the vertical axis in an excavated trench to control excessive deformations that the excavation was undergoing. The Manual of Geotechnical Services [7] emphasizes the importance of the execution of vertical nails excavation along the alignment of the Reinforced Soil, because it aims to improve the soil and pre- Reinforced Soil.

The experience of using nails with sectorized phases of reinjection into landfill soil, uncontrolled landfill soil, and organic clay was also reported in literature [8].

Using numerical model, it was proved in literature that vertical nails arranged in two levels at the top and the foot of the Reinforced Soil allowed an average gain of 5% in the stability-related factor of safety for the limit equilibrium methods proposed by authors Morgenster and Price, Spencer, Bishop, and Janbu [9]. In the same study, using the Geotudio software, the authors showed that the vertical nails they used mitigated the displacement of the stapled soil face by 20% for the upper half and 10% for the lower half

The Plaxis 2D and Plaxis 3D finite element programs were used to analyze vertical nails [10]. The results showed a significant gain in the horizontal displacement reduction and traction in the sub-horizontal nails. However, it was necessary to use a lot of vertical nails, which may not be economically feasible.

2.1 *Empirical displacements evaluation*

Based on some data from real constructions monitoring, the horizontal and vertical displacements occur at a rate of 1:1 [11]. The typical values observed show that the horizontal strain is about 0.3% for predominantly clayey soils, 0.2% for predominantly sandy soils, and 0.1% for excavations in rock material or similar.

The typical horizontal strains values are used as mentioned inliterature [11,12]. The definition of the potential failure surface is estimated also considering already published works[13,14]. A recent published work [15] observed that vertical and horizontal deformations do not occur equally between displacements, not expected by previous publications [11].

2.2 *Numerical modeling in displacements evaluation*

Nowadays, finite element modeling has been gaining ground against limit equilibrium due to its easy access and use of computer programs. Using numerical tools based on the Finite Element Method (MEF) allows us to analyze not only the safety factors against failure but also the stresses and deformations which occur in the various execution phases. Usually, "Mohr-Coulomb" is used as a model for the behavior of the soil. For the nails and wall, materials of elastic-linear behavior are used in beam or plate elements. Some authors point out that numerical analysis using MEF, unlike conventional methods, allows a more economical project [16,17]. A recent work performed numerical analyzes in the excavation of residual soil and observed a considerable influence of geological faults in horizontal displacements - something that could not have been assessed in the limit equilibrium analyzes [15]. In these analyses, the displacements did not obey the 1: 1 ratio between horizontal and vertical positions, as provided in previous publications cases [11].

For the soil nailing technique, there is an international parameter called horizontal ridge deformation, which is used for stability assessment, as shown in eq. (1):

$$\delta = \frac{d}{H} \qquad (1)$$

Where:
δ - horizontal deformation of the crest (dimensionless)
d - measured deformation at the slope crest (m)
H - excavation height at a given construction stage (m)

The ratio shown in eq. (1) was obtained from the d and H data measured at the main slope plumb lines. The percentage of the deformation along the construction was also calculated. Fig. 1 shows an example of horizontal deformation data of the crest of the nails soil execution of the Hospital da Beneficiência Portuguesa in São Paulo [18].

2.3 Slope facing inclination

According to literature, the near the foot of the excavation, the more upright the slope, the greater the horizontal deformation and vertical stresses acting within the mass [2]. Fig. 2 illustrates one case with both face conditions (vertical and inclined). For facing slopes of less than 60 degrees with the horizontal, it is suggested that only a vegetal covering of the face could be adopted to prevent erosion and small localized failures [19]. In other cases, the face must be protected with another type of coating, such as shotcrete.

Therefore, vertical slopes have maximum vertical displacement magnitudes and a greater difference between the shifts at the top and central region of the excavation when compared with the inclined face. Using a numerical computational tool, the influence of the face inclination and the orientation of the nail on the overall stability of the structure was investigated [20]. The safety factor was also higher in inclined cases compared to vertical ones.

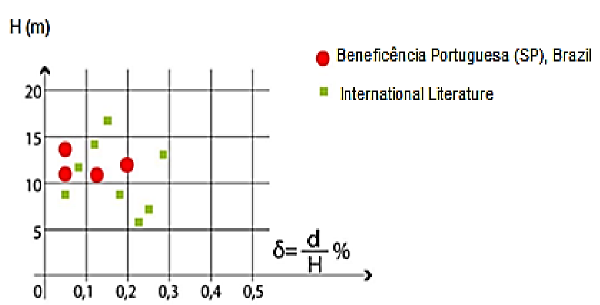

Figure 1. Horizontal strain data analysis
Source:[18]

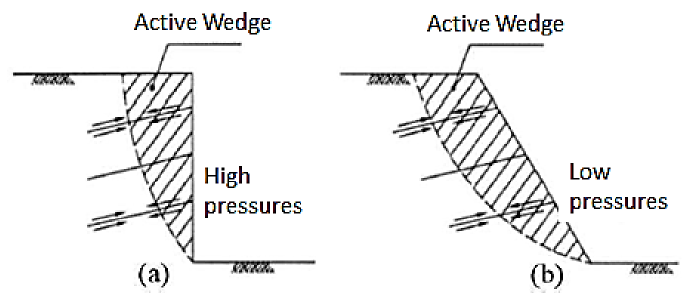

Figure 2. Influence of slope face inclination.
Source:[2]

Table 1.
Adopted soil parameters

Soil Type	E (kPa)	Cohesion (kN/m²)	Friction Angle (º)	Specific Weight (kN/m³)	Poisson Coefficient
Sandy Silt	6500	15	30	17,5	0,3

Source: The authors

3 Materials and Methods

3.1 Soil mass and nailing wall characterization

The geotechnical parameters of the soil were adopted conceptually, based on an N $_{SPT}$ value of 13 strokes in sandy silt soil and the correlations with resistance parameters proposed in literature [21]. Friction angle adopted homogeneous underground in the whole massif. The geotechnical parameters used are shown in Table 1.

The soil nailing has a height of 17.5 meters (Fig. 3). Three different situations were compared, presented graphically in Fig. 4.

I. conventional, without the use of vertical nails (Case I);
II. using three lines of vertical nails (Case II);
III. with an inclination of the excavation face, without vertical nails (Case III).

In the modeling, the RS2 software, which performs analysis by finite element method in two dimensions, was used in the flat state of deformations.

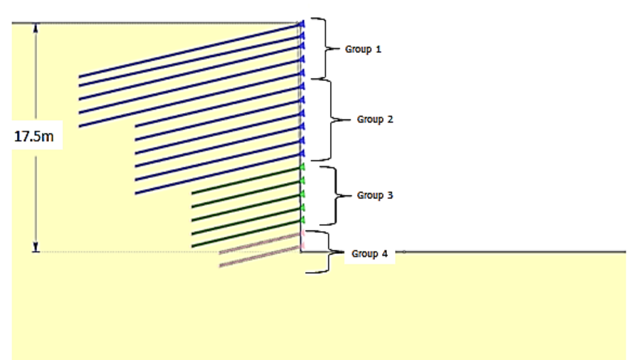

Figure 3. Sub-horizontal nails configuration and specifications
Source: The authors

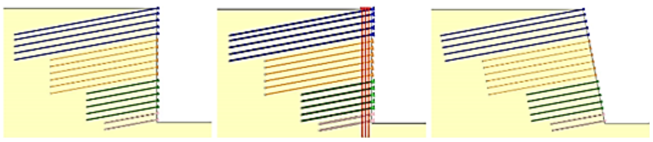

Figure 4. Schemes of the analyzed situations
Source: The authors

Table 2.
Soil nail informations

Group	Nail length (m)	Nail spacing (m)	Nail inclination (º)	Steel bar	Stell diameter (cm)
1	23,7	1,0	10	2□20	12,5
2	17,7	1,0	10	2□20	12,5
3	11,7	1,0	10	1□25	12,5
4	8,7	1,0	10	2□16	12,5

Source: The authors

Table 2 shows the main characteristics of the groups. It is very common to design clamps with the same properties, but to optimize the design costs, we adopted clamps with different lengths.

3.2 *Numerical modeling*

The finite element mesh consists of triangular elements with three nodes. A total of 8589 elements and 4392 nodes were employed.

Excavation phases were modeled to allow a more realistic simulation of the displacement evolution. In a real nailed soil, the sequential excavation phases of the massif allow a gradual development of deformations and the consequent activation of the upper (passive) nails already executed.

The executive sequence adopted in the modeling followed:

(1) Excavation corresponding to three levels of nails with activation of the wall in the section;
(2) Activation of the sub-horizontal nail lines of the excavated section;
(3) Excavation corresponding to the three levels of subsequent nails and activation of the wall;
(4) Return to the item (2) of the sequence and continue steps (2) to (4) until the end of the 17.5m excavation and complete execution of the nailed soil.

In case II of analysis, with vertical nails, the first intervention in the model consisted of executing the three nail lines to then proceed with the executive sequence listed above, from (1) to (4).

As previously mentioned, the facing was activated simultaneously with the phases of excavation. In the following phase, the nails were activated. Both the nails and the wall were modeled with the "Liner" (bar/plate).

The constitutive model chosen for the soil was linear-elastic, perfectly plastic with plasticization criteria according to Mohr-Coulomb. It is generally used as a first approximation of the behavior of the soil [22]. N shall be considered a relative sliding wall in the soil-soil interface and no-cramp. The nail material was also modeled with elastic-linear behavior, governed by failure criteria consistent with the material's tensile and compression strengths.

The material properties of the wall and nails are shown in Fig. 5. The upper nails, with lengths of 23.7m and 17.7m, were modeled as Liner 2. The nails with a length of 11.7m and 8.7m were modeles as Liner 3 and Liner 4, respectively. While the vertical nails adopted Liner 5 and the wall Liner 1.

Liner Name	Color	Type	Young's Modulus (kPa)	Poisson's Ratio	Material Type	Peak Compressive Strength (kPa)	Res. Compressive Strength (kPa)	Peak Tensile Strength (kPa)
Liner 1		Standard Beam	2.8e+007	0.25	Plastic	35000	35000	35000
Liner 2		Standard Beam	1.3608e+007	0.2	Plastic	20124.2	20124.2	20124.2
Liner 3		Standard Beam	1.1109e+007	0.2	Plastic	16428.6	16428.6	16428.6
Liner 4		Standard Beam	8.232e+006	0.2	Plastic	12173.9	12173.9	12173.9
Liner 5		Standard Beam	8.232e+006	0.2	Plastic	12173.9	12173.9	12173.9

Figure 5a. Structure parameters used in the model
Source: The authors

Liner Name	Color	Res. Tensile Strength (kPa)	Thickness (m)	Area (m2)	Moment Of Inertia (m4)	Pre-Tensioning Force (kN)	Beam Element Formulation	Stage Properties?
Liner 1		35000	0.12				Timoshenko	No
Liner 2		20124.2		0.00785398	4.90874e-006		Timoshenko	No
Liner 3		16428.6		0.00785398	4.90874e-006		Timoshenko	No
Liner 4		12173.9		0.00785398	4.90874e-006		Timoshenko	No
Liner 5		12173.9		0.00785398	4.90874e-006		Timoshenko	No

Figure 5b. Structure parameters used in the model(continued)
Source: The authors

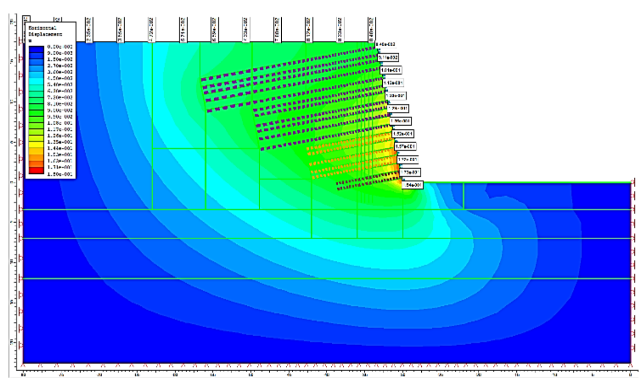

Figure 6. Horizontal displacements in excavation with 3 vertical nail lines
Source: The authors.

4 Results and discussion

In Figs. 6, 7 the results of the analysis are presented in the RS² software for cases without vertical nails, with vertical nails and considering the vertical face, respectively.

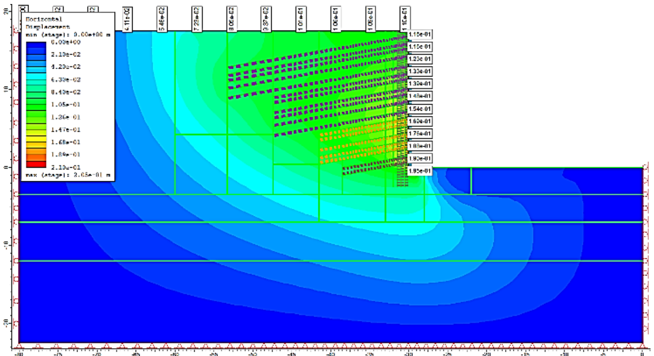

Figure 7. Horizontal displacements with an inclined face; no vertical nails
Source: The authors

In the hypothesis of a vertical wall without the nails, the maximum horizontal displacement was 197mm. After the inclusion of the 3 vertical nails, the maximum horizontal displacement practically did not change, being equal to 195 mm. Considering an inclined wall (without vertical nails), the maximum horizontal displacement was 176mm.

We noticed that regardless of the maximum value, for the analyzed reinforcement, the vertical nails caused a reduction in the horizontal displacements along practically the entire wall. However, the inclined wall was more effective in this reduction.

Fig. 8 shows a graph of the variation in the facing horizontal displacements measured with the depth from the crest of the slope after all stages of excavation had been performed.

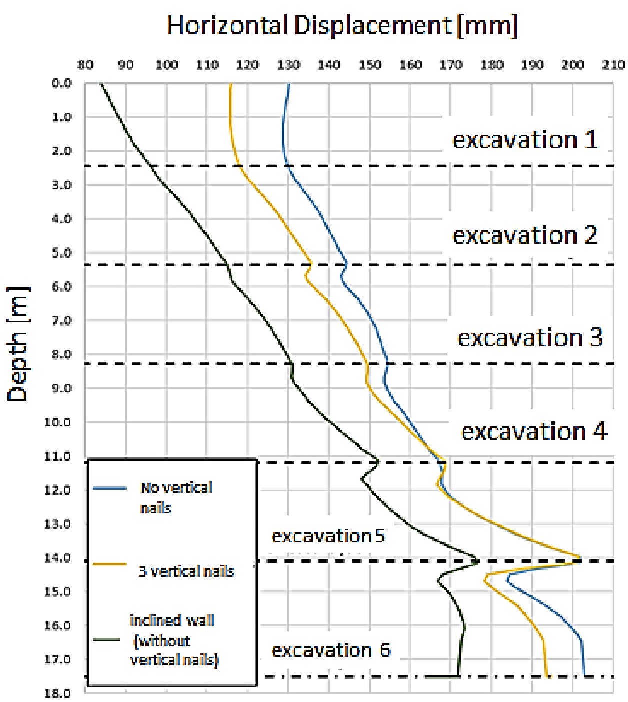

Figure 8. Horizontal displacements in three situations: with and without vertical nails and with inclined slope face
Source: The authors

5 Conclusions

Soil Nailing is a good solution for the reinforcement of earthy masses aiming at the retaining of natural or cutting slopes, due to its low cost, equipment availability, speed and ease of execution, besides the necessary materials which are commonly and hugely used in engineering nowadays.

With the scenarios presented in this paper, we sought to deduce from numerical modeling with the observation that vertical nails influence the reduction of displacements along with the reinforcement - confirming the first hypothesis. However, the maximum displacement has not been reduced due to the presence of these nails.

Also, it was found that the face inclination brings a significant gain in the reduction of horizontal displacements and can be an alternative when designing the project. The choice for the reduction alternative via vertical nails or inclination of the wall will depend on the magnitude of the necessary reduction and the economic question regarding the project, since tilting the face is probably a less costly choice than the execution of some vertical nail lines.

Verifying the efficiency of using vertical nails is not very common in scientific research. Even so, it was shown that numerical modeling is a viable option not only to assess displacements but also to serve as a tool to project the number of vertical nails needed - given the purpose of reducing displacements.

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