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Design and instrumentation aspects of a 40m high nailed slope

Aspects de projet et instrumentation d'un talus cloué de 40m d'hauteur

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ABSTRACT
This paper presents details of a monitoring program on a 40m-high nailed excavation in gneissic residual soil. Stability studies and stress-strain analysis of the nailed mass were fundamental for defining the most efficient and economical solution in terms of nails and excavation geometries. The nails are made of steel bars 25mm in diameter, placed in drill holes with variable lengths (15 to 24m), with vertical and in horizontal spacing of 2m. Instrumentation included inclinometer and tell-tales for monitoring horizontal displacements of the soil mass. Strain gauges were also placed on the steel bars for obtaining tension and bending along the nails. Design concepts and construction details are briefly described, together with details of the monitoring program and preliminary results.

RÉSUMÉ
Cet article présente les détailles du projet et monitorage d'une excavation de 40m d'hauteur en sol résiduel de gneiss. Les études de stabilité et les analyses de contrainte-déformation du massif cloué ont été essentielles pour la définition de la solution la plus efficace et économique en fonction des géométries des clous et de l'excavation. Les clous sont des barres en acier avec 25mm de diamètre, installés dans des trous forés avec longueur variable (15 a 24m) et 2m de espacement vertical et horizontal. L'instrumentation corresponds à des inclinomètres et tell-tales pour la mesure des déplacements horizontaux du massif. Des jauges électriques ont été collées sur les barres en acier pour l'obtention des contraintes le long des clous. Les prémisses de projet et les détailles d'exécution sont présentées, ainsi que les característiques du programme de monitorage et les résultats préliminaires.

1 INTRODUCTION

The basic concept of soil nailing consists of strengthening the existing soil mass by installing closely spaced steel bars (nails) into a slope, as excavation proceeds. This creates a reinforced section and restrains its displacements. The design mechanism consists of transferring the resisting tensile forces generated in the nails into the soil mass through the interface friction. The nails act like passive reinforcement elements, as the mass deforms during construction. Nails work predominantly in tension although may also develop bending or shear. The effect of nail reinforcement is to improve stability due to increasing confinement. Hence, the soil shear strength increases and the driving forces are reduced along a potential failure surface in nailed masses.

A shotcrete facing with no structural function is usually required. The shotcrete is typically reinforced by a welded wire mesh. The steel nail bars are typically installed into nearly horizontal drill holes with regular spacing. A small inclination, of 10 to 20 degrees, may be given to these drill holes to facilitate grouting. Nail lengths may vary, being typically 50 to 100% of the wall height. Low cost and rapid construction are the main factors contributing to the fast development of the nailing technique in Brazil and worldwide. Adaptability to irregular topography and soil heterogeneity are also factors favouring a soil nailing solution. Comprehensive reviews on soil nailing have been reported by Elias and Juran (1990), Clouterre (1991), GEO (1996), and Ortigao and Sayao (2004).

Although nailing applications and studies have been mostly applied to homogeneous soils, the technique also adapts well to gneissic residual soils, which are inherently heterogeneous. Many aspects on the behaviour of nailed masses still need to be studied. Topics like soil-nail interaction mechanisms; pullout behaviour, stress distribution and construction details are still open to discussion. A comprehensive investigation on soil nailing is being carried out at PUC-Rio. Numerical studies on nailed excavations have been presented elsewhere (Lima et al, 2003a and 2003b). This paper presents details on design concepts, construction procedures and monitoring program on a 40m-high excavated nailed slope in gneissic residual soil.

2 SITE DESCRIPTION

The excavation herein described was required as preparation for the construction of a 8-storey high-rise building in an expensive waterfront area in the city of Niteroi, Rio de Janeiro State, Brazil. The geometry of the nailed excavation is illustrated in Fig.1. The height of the main nailed wall is about 40m in length. Due to the U-shape of the excavation, lateral nailing was also required.

The geological conditions at the construction site are not simple, with a thick layer of residual soil from gneissic rock. Heterogeneous conditions, with unfavourably dipping foliation, faults and quartzite layers, were visible during excavation. The water level was not detected in the boreholes. Saturation degree is typically about 50 to 70% and the soil is red (at the top) to light yellow (at the bottom) in colour. The material may be described as low plastic sandy silt, with Atterberg limits of LL = 45 and LP = 28.

3 DESIGN CONSIDERATIONS

Nails work predominantly in tension, but may also work in bending and/or shear under certain circumstances. Generally, the soil nails significantly increase the apparent cohesion of the soil due to their ability to carry tensile loads.

Several design methods are available for estimating the stability of nailed slopes (Clouterre1991; Schlosser et al. 1992). Limit equilibrium stability studies were complemented with stress-strain analysis of the nailed mass for defining the most efficient and economical solution in terms of excavation and nails geometries (Lima et al., 2003a and 2004). As shown in Fig. 1, the excavation was designed with four stages, with only the lowest two stages being nailed. The stability studies indicated a factor of safety FS = 1.51 for the cross-section shown in Fig. 2 (fixed nails). If free nails were considered, FS would be a little lower (FS = 1.45). The strength parameters required for the stability analysis were obtained experimentally.

In the laboratory, direct shear tests were carried out in 100mm square specimens from block samples. At natural water content, the strength parameters were $c' = 19$ kPa and $\phi' = 33^o$. Lower values were obtained with submerged specimens, simulating heavy rain conditions in the field: $c' = 0$; $\phi' = 32^o$.

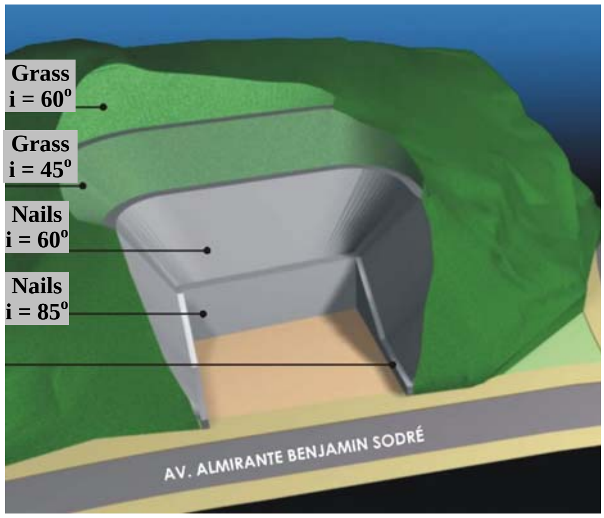

Figure 1 – 3D view of soil nailing design showing excavation stages.

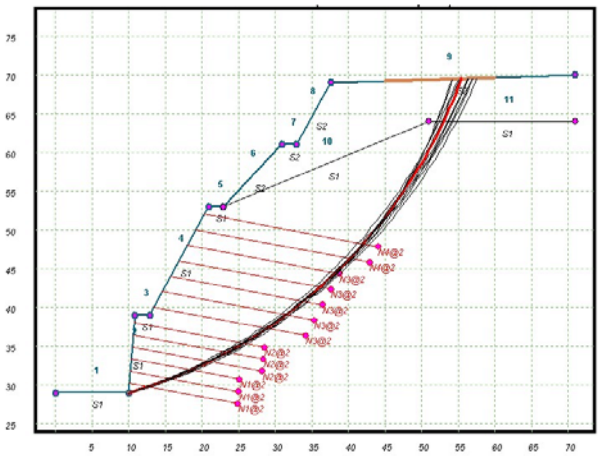

Figure 2 – Potential failure surfaces at end of nailed excavation.

In the field, several nails were instrumented and subjected to pullout tests under different conditions of curing time, grouting procedures and confining stress. The pullout tests were conducted by controlled loading increments in a site next to the excavation front. All tested nails were 4m long and were not used in the final configuration of the nailed structure. An average value for the interface strength q_s may be taken as 200 kPa. Fig. 3 shows a pullout test being carried out. As the excavation progressed rapidly downwards, a test on a nail with 7 days curing time had to be performed on a temporary platform.

Figure 3 - Nail pullout testing on a platform during excavation.

Pullout loads were imposed with a hydraulic jack and monitored with a load cell at the nail head. Strain gauges glued to the steel bar provided information about the load distribution along the nail. Electronic readings were recorded with a data logger and a laptop computer. A dial gauge was used for monitoring the nail extension during the test, with reference to a stable point. Fig. 4 shows a closer view of the test set-up.

Figure 4 - Pullout test set-up.

All nails were made of corrosion-protected steel bars, 25mm in diameter. The bars were inserted in 75mm boreholes and then cement-grouted. Ribbed bars were used to increase bar-cement adhesion. Thirteen rows of nails with variable length (24 to 15m) and inclination of 10 degrees to the horizontal were adopted.

4 MONITORING DETAILS

Five rows of nails were instrumented in two central vertical sections. Instrumentation included strain gauges glued onto 10 bars for verifying the tension and bending distributions along the nails. The strain gauges were protected against mechanical and electrical damages during transportation and installation of the nails. The gauge positions along the nails in one vertical section are indicated in Fig. 5 (Lima, 2005). Horizontal movements of the nailed soil mass were monitored with tell-tales and inclinometers.

In a central vertical section, twenty tell-tales were installed in 5 different elevations close to instrumented nails. Along each elevation, the tell-tales were positioned at 1.5, 7.0, 14.0 e 28.0m. The deepest one (position 28.0m) was anchored in stable soil (beyond a potential failure surface) for reference.

Two vertical inclinometer boreholes, 28 and 15m deep, were drilled in the central region of the nailed mass, as shown in Fig. 5. Inclinometer readings were taken twice a week during construction. All electronic readings were recorded with a data logger and a laptop computer. Horizontal displacements (Δh) obtained from tell-tales compared fairly well with Δh obtained from inclinometer readings.

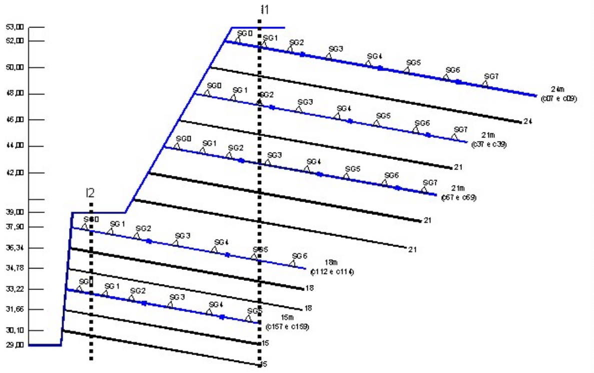

Figure 5 – Cross-section of excavation with instrumented nails.

5 CONSTRUCTION DETAILS

The typical construction sequence of the soil nailing began with the excavation of a shallow cut, about 2m deep. Nails were installed in predrilled sub-horizontal holes (about 10 degrees to the horizontal). Plastic centralisers were positioned at 2m intervals along the bars. The holes were then injected with cement grout and shotcrete was then applied to the excavation face. This sequence was repeated until subgrade was reached.

Grouting was carried out starting from the low end of the drilled hole. Most nails had grouting tubes provided with manchette valves for grout re-injection after a few hours. This procedure proved to increase q_s in about 20 to 50% (Pitta et al. 2003; Springer 2005). The grout was prepared with a water-cement ratio of 0.50. The shotcrete facing was about 18 cm thick, with a double mesh of steel wire. A fixed condition was provided to the nail head with a bolt and plate system built in the shotcrete face.

The first excavation stages required detailed planning for the access to the top of the slope of construction equipment, such as driller, earth-working machine and grout-injection pump. As shown in Fig.1, the top two stages of the slope had their faces only protected by grass, with no reinforcement. The nails were installed only in the third and fourth excavation stages. A 2m uniform spacing between nails was adopted both in vertical and in horizontal directions. Fig. 6 shows a front view of the site at the installation of the second row of nails. These upper nails were 24m long, for reaching the active soil zone beyond the potential failure surface. Fig. 7 is a picture of the nailed excavation at end of construction. As the excavation progressed, nails were made progressively shorter. At the bottom, the nails were only 15m long.

Subsurface drainage is normally considered an important element for controlling the stability of concrete faced nailed masses, particularly in low permeability soil conditions. In the work herein presented, drainage was provided by weep outlet holes and deep perforated pipes. All drains were 75mm diameter PVC pipes with 2m spacing in both horizontal and vertical directions. Outlet holes were made of short pipes, about 30 cm long, with coarse granular material wrapped in filter fabric at the inner end. Perforated pipes were about 10m long, also wrapped in filter fabric for clogging protection. This configuration follows the recommendations by Kenney et al. (1977).

Figure 6 – First stages of nailed excavation.

Figure 7 – Last stages of 40m high nailed excavation.

Preliminary results from the monitoring program are presented in Fig. 8. A strain-gauged nail (Fig. 9) reveals a non-uniform load distribution along the bar. The central region of the 24m long nail, with larger tensile loads, corresponds to the probable position of a potential shear zone in the nailed soil. The load decreases to near zero at the inner end of the nail (position 24m). Fig. 8 suggests that the front end (position 0) has a positive load of up to 20 kN, due to the nail's fixed-end condition at the shotcrete face wall.

The 40m excavation herein described was completed in about 7 months, from January to July, 2004. Monitoring of the nailed mass went on for many months after construction was completed.

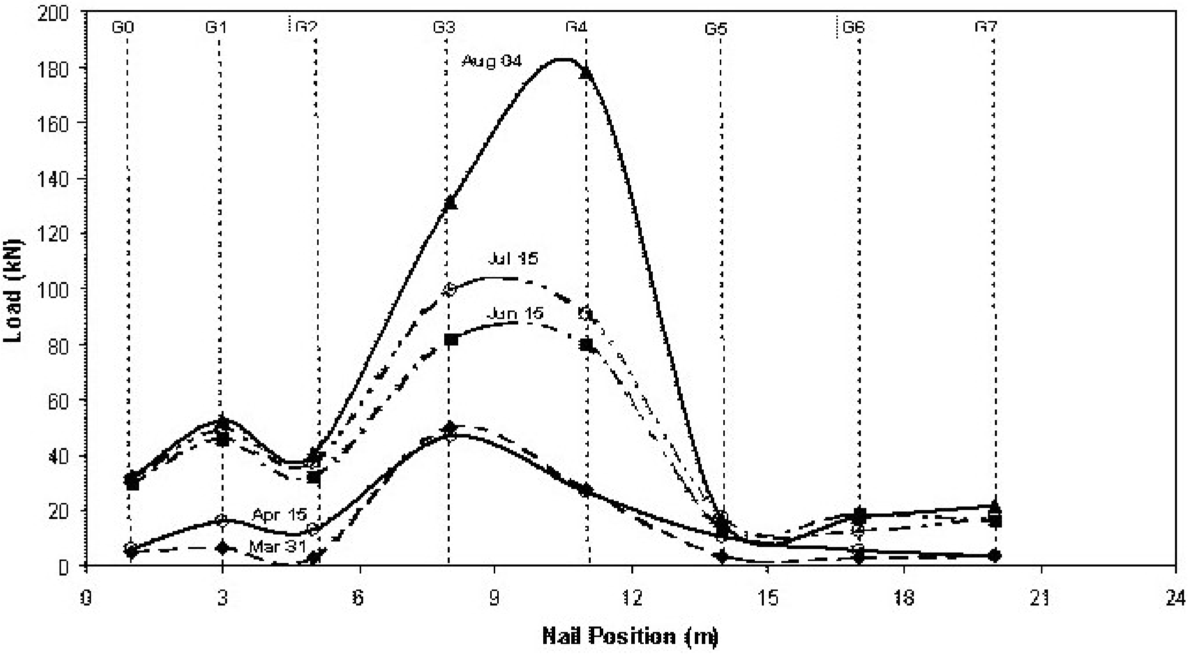

Figure 8 – Load monitoring along one nail during excavation.

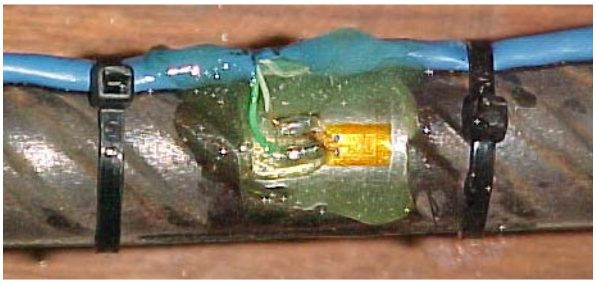

Figure 9 – Nail bar with a protected strain gauge and a grouting tube.

6 CONCLUSIONS

This paper presents details of the design and construction of a 40m nailing excavation in gneissic residual soil. Instrumentation included strain gauges glued to the steel bars, inclinometer and tell-tails. Results of the monitoring program indicate a non-uniform load distribution along the nails. Moreover, horizontal displacements recorded with tell-tales agreed reasonably well with those obtained from inclinometer readings

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