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Soil nailing at the tunnel face in difficult conditions: A case study

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ABSTRACT

In presence of difficult conditions in tunnelling, an adequate stabilization of the excavation boundary and face is required to ensure a safe progress of the construction. The stabilization of the tunnel face can be improved by fibreglass soil nailing, offering properties optimal to the purpose and versatility in use. This paper reports a tunnelling experience where difficult conditions, induced by poor mechanical properties of the rock mass and relevant pore water pressures, were faced adopting innovative soil nailing techniques. Some details about the site geological conditions allow to recognize the causes of the difficult conditions which drove towards specific choices about the features of soil nails, acting on both aspects of mechanical reinforcement and drainage. The soil nail mechanical contribution to the tunnel face stabilization is taken into account at the design stage by an equivalent increase of effective cohesion in the improved ground mass. The tunnel face stability is then assessed by analytical approach. The performance and the specific advantages of the innovative technique are discussed also on the basis of results from on site testing.

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1. Introduction

Tunnelling in difficult geological conditions represents a thrust to the development of innovative techniques, or to the improvement of existing ones, devised to allow for an efficient tunnel excavation whereby ensuring the stability. Many equipments and technical provisions have been first introduced to face difficult conditions met in particular tunnel projects and have been later adopted in other similar situations, often after specific improvements (Mair, 2008; Singh and Goel, 2006).

A soft ground medium often leads to difficult conditions in tunnelling, due to its poor mechanical properties and great water bearing capacity. The stress release induced by the excavation causes weakening and possible localized failure at the face and at the roof. In the case of tunnelling at shallow depth, this effect can progress quickly and lead to surface large subsidence or even collapse.

The techniques for the stabilization of the tunnel face are aimed at providing a sufficient support or strength at the heading, to avoid failure and to limit the ground movements and the surface subsidence, that would affect existing buildings, infrastructures, buried pipelines, etc. (Attewell et al., 1986; Guglielmetti et al., 2007; ITA-AITES, 2007). The stabilization can be achieved according to two principles: (i) by equilibrating the pressure of the ground mass which would fail as the stress is released or (ii) by improving the ground conditions at the tunnel heading, that is by increasing the ground mass mechanical strength.

The first case (i) applies for instance to the mechanized EPB shield tunnelling, where a balancing action is exerted by a pressurized fluid against the tunnel face so as to equilibrate the ground pressure and the possible pore water pressures. While this system ensures a continuous support to the face and the control of water flow, the fluid pressure has to be calibrated, depending on the tunnel size and depth and on the site conditions, to avoid both the collapse and the blow out of the soil mass at the face (Anagnostou and Kovari 1996; Li et al., 2009).

In the second case (ii) one can count all the techniques of reinforcement and injection and, more generally, of soil treatment (columns in jet-grouting, grouted and anchored bolts, nailing, soil freezing, etc.). The occurrence of high pore water pressures generally requires specific drainage systems. These reinforcement provisions can be designed with reference to the radial directions in the tunnel cross section, to confine the ground mass and limit the convergence (Carranza-Torres, 2009; Bobet and Einstein, 2011), or ahead of the excavation to support the tunnel face. All the techniques involving the tunnel face, in particular the system of umbrella arch and forepoling, help in limiting the pre-convergence and the volume loss, that are greatly responsible for ground mass

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movements and surface subsidence (Hoek et al., 2008; Aksoy and Onargan, 2010).

Many factors contribute towards the choice of the most appropriate method for tunnelling and face stabilization, primarily the tunnel depth and the related level of initial stress, the ground mass nature and the site conditions. However, the variability of these conditions during the tunnel construction may place the versatility as first requirement for the systems of reinforcement and support.

The soil nailing is one of the techniques often used for the temporary stabilization of the tunnel face in soft ground. It consists of inserting in the soil mass a pattern of bars, driven or grouted inside drilled boreholes, across potential slip surfaces. The soil nailing differs considerably from the ground anchoring. Ground anchorages are installed at a lower density, they are founded outside any potential slip surface and are prestressed against a major structure to distribute the retaining force over the ground face. Conversely, soil nails remain unstressed until the soil deformation mobilizes, within the bar, resisting tensile forces that are transferred to the ground through friction along the interface. These forces build up progressively and strictly depend on the soil/nail relative deformability and on the mechanical interaction along the interface. The slow progression of this mechanical action could represent a limitation of the nailing technique, which may be unsuitable whenever a strict control on ground movements is required.

This technique was first introduced for the reinforcement of natural and artificial slopes (Juran and Elias, 1991; Schlosser, 1982), and was later extended to other geotechnical applications (Mair and Taylor, 1997), being accepted as an efficient and economical method for ground improvement and stabilization. In tunnelling engineering the main advantage is represented by its versatility in use: length and number of nails, as well as their pattern (location and orientation), can be easily modified during the progress of excavation depending on the changing site conditions.

As reinforcing elements, fibreglass pipes are adopted since the nineties in all the applications where their characteristics could represent an advantage (Ortigao, 1996). They offer high tensile strength, low unit weight, high resistance to corrosion and they can be easily removed by cutting. The latter property is particularly relevant whenever the removal of the already nailing stabilized ground mass has to take place, such as during the tunnel face advance.

The effectiveness of the reinforcement depends on the nature and condition of the soil being reinforced and on the characteristics of the nailing system (nail density, length, stiffness, strength, bond capacity), as it has been highlighted by field experience (Mair, 2008; Wong et al., 1999), laboratory centrifuge testing (Kamata and Mashimo, 2003; Juneja et al., 2010) and parametric numerical analyses (Ng and Lee, 2002; Yoo and Shin, 2003).

Over the years, the improvements have concerned the materials for injections (Karol, 2003; Kim et al., 2009; Zenti, 2006), the bar production processes and the equipments for nail application (Cheng et al., 2009; Zenti et al., 2012), and the testing techniques to assess the quality of injections and the bond capacity (e.g. Chu and Yin, 2005).

At the same time, analytical and computational procedures have been worked out to help in understanding the contribution of the reinforcing elements to the stability, with reference to the tunnel cross section and face, for deep and shallow tunnels (Anagnostou and Serafeimidis, 2007; Oreste and Dias, 2012; Wong et al., 2000).

The combined experimental, theoretical and computational findings have driven to the definition of possible criteria to assist the design process. Although shortcomings might limit the applicability of the various approaches proposed in literature, it is a fact that nowadays the reinforcing mechanical action provided by the nail system can be taken into account at the design stage (e.g. Lunardi, 2008).

In this paper, an innovative soil nailing technique is presented and its effectiveness in contributing to ensure the safety during excavation is discussed on the basis of a soft ground tunnelling experience in Italy, where it was extensively adopted, in combination with heavy support, to face particularly difficult conditions.

Some aspects are addressed about the features of the new technique and its performance, which was also investigated in the past by pull out tests in soil and rock masses of various nature and conditions and by comparison with the performance of conventional nails (Zenti et al., 2008). In the paper, details are also given about the design approach adopted to evaluate the reinforcing action and the calculation of the safety factor in presence of improved ground conditions.

2. Tunnel face reinforcement in difficult conditions

2.1. Characteristics of the innovative reinforcements

In order to face particularly difficult conditions, in water bearing rock masses having poor mechanical properties, two innovative solutions for soil nailing are introduced, named PERGround® by Elas Geotecnica S.r.l. (Milan, Italy): the one having the sole function of mechanical reinforcement (type f2) and the other combining the reinforcing function with a drainage action (type f1).

The main innovative feature of these soil nailing solutions is the presence of an expandable geotextile sheath which wraps the fibreglass reinforcing pipe for the whole of its length and is sealed at the head and at the tip.

The first solution (type f2) is shown in Fig. 1a. Once the nail is inserted in a previously drilled borehole, a low shrinkage cement-based grout is injected through a small tube between the pipe and the sheath, so that the sheath inflates till the gap in the borehole is closed. The fibreglass pipe has 60 and 40 mm as respectively external and internal diameters and can be cut to the design length. Fig. 1 shows 20 m long nails; also greater lengths have been used, to date up to 24 m.

The fibreglass pipe also presents an innovation: the external surface has a corrugated shape, obtained in the production process by a phase of preforming before the polymerization, that improves the bonding adherence between the pipe and the surrounding grout. While for standard fibreglass pipes the adherence is improved by etching a spiral groove along the pipe surface and consequently cutting part of the external glass fibres, in this case the fibre longitudinal continuity is maintained, thus ensuring higher tensile strength of the pipe. Pull out laboratory tests were carried out on standard and corrugated pipes, embedded in cement grout for a length of 30 cm, after 24 and 48 h of setting. The details of the testing equipment are described in Zenti et al., 2012. The results show that the corrugated pipes offer higher resistance in all the tested cases, reaching a pull out force equal to twice the value reached by standard pipes. The reason of this result lies in the different mechanical interaction between the pipe and the grout, which is highlighted by the fracture pattern observed after pull out: while in the case of standard pipe the fractured zone is localized around the pipe surface and the cylindrical block of grout seems unaffected, with the corrugated pipe the fractures extend in the surrounding grout. The particular corrugated surface allows the pipe to activate compression stresses within the grout, thereby providing a better pull out performance than standard pipes (Zenti et al., 2012).

The other innovative solution for soil nailing (type f1) is an improvement of the previous, it is made of a coaxial connection between a type f2 element, 10 m long, and a drain of equal length (Fig. 1b). The drain is a micro-slotted HDPE pipe protected by a non-woven fabric geotextile. The water collected from the deepest

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