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Convergence-confinement approach for designing tunnel face reinforcement by horizontal bolting

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ABSTRACT

The ground reinforcement by bolting is a technique in strong development. Bringing a perennial supplement of resistance to the ground, this technique permits to use poor grounds in a sensitive environment. It can be particularly, used for the reinforcement of tunnel faces.

The full numerical simulation of such works remains a heavy and expensive process, notably in terms of geometrical complexity and various scale levels. During the preliminary project stage, it appears necessary to have simplified models, making possible to simply appreciate the effectiveness of the reinforcement.

The existing simplified methods being not well adapted for the optimal conception of these reinforcement systems, a new method based on the convergence confinement approach is proposed and tested in this paper.

1. Introduction

The problem of tunnel head instability, and its proper prevention by an adequate reinforcement, is an important subject in the area of underground works, due to the dramatic consequences of a frontal failure: loss of human lives and equipment, execution delays, ruin of surface structures when the work is carried out at shallow depth. Beyond the question of stability, it is equally important to limit the ground movements ahead of the front. In the case of sensitive materials, excessive displacements – hence strains –, can also undermine significantly the material strength, thereby reducing the stability, and eventually trigger off an early failure, due precisely to the strength reduction.

From the construction standpoint, different techniques of prelining or reinforcement of tunnel heads have been proposed, amongst which use of fully grouted fiberglass bolts presents a few advantages, notably their high longitudinal ultimate strength and the facility of removal during excavation, as well as the facility to adapt locally the reinforcement density to local geotechnical conditions. Such advantages have indeed contributed to the increasing popularity among geotechnical engineers of this fastly emerging technique, as witnessed by its increasing use in tunneling projects at low and high depth. Table 1 shows some well documented cases in France and Italy (Lunardi and Bindi, 2004; Gaudin et al., 1999). On the other hand, their relatively large flexibility results in a slow and progressive force build-up, in such a way that their strength capacity can be fully mobilized only at relatively large strains.

Most of the projects presented in Table 1 have been developed and carried out at high depth. Different collapse mechanisms should also be taken into account: extrusion of the core at high depth and gravitational sliding mechanism at low depth.

The experimental datas on site are rare but are the only ones able to examine the bolt functioning taking into account the digging process, the ground deformation ahead the face and the ground/bolt interaction. Lunardi et al. (1992) has performed experiments on bolts for the tunnel face of the high speed line of Rome–Florence. The results obtained show that the bolt loading is complex, non-monotonic and depends heavily on the quality of the interaction between the soil and the bolt. From the tunnel face to ahead, the load increase gradually to a maximum then an anchorage zone exists with a gradual reduction effort in the bolt. Barla and Barla (2004) relates a monitoring system in terms of longitudinal displacements ahead the tunnel face in an urban tunnel. The comparisons between 2D axisymmetric calculations and measurements give good agreement.

Several authors have studied fiberglass bolts reinforcement for shallow tunnels using 3D small scale models. Calvello and Taylor (1999), Al-Hallak (1999) and Kamata and Mashimo (2003) used laboratory models in centrifuge. They show that extrusion displacements are more reduced if bolts are placed in the peripheral zones of the face and that the optimal length of the dowels is like the double of the distance between the excavation face and the possible sliding surface.

An important detailed analysis has been developed by Yoo and Shin (2003). The author used a small scale model and the finite

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Notations

Ψ	dilatancy angle of soil
$\Delta\sigma_3$	minimum principal stress increment due to reinforcement
ϕ'	friction angle of soil
σ_{max}	maximum admissible stress in a bolt
τ_{max}	maximum shear stress along the soil/bolt interface
A	section of one bolt
c'	natural soil cohesion
c_r	cohesion of the ground in the reinforced zone
D	tunnel diameter
E	Young modulus of the bolts
F_a	axial load in the bolt
n	number of bolts
P_1	equivalent pressure to the bolting system, applied at the tunnel face
P_{face}	pressure applied at the tunnel face
R	tunnel radius
S	surface of the tunnel face
S_l	total lateral surface of a bolt
U_1	maximum axial displacement of the tunnel face
Δ	dimensionless parameter

element method in order to determine the effect of the dowels on the tunnel stability changing ground properties, overburden, tunnel's diameter, density and length of the dowels. The critical bolting density and the critical length over which extrusion displacement and the face ground plasticization are the lowest are defined.

Shin et al. (2008) in a large small scale experimentation show that the umbrella arch permits to increase longitudinal load transfer to an excavated area, reducing consequently deformations and increasing the face stability. Face pipes can be shorter than arch umbrella ones without significant loss of structural benefit. In fact, the part of the pipes far beyond failure zone does not have a significant contribute in ground stabilization. The monitoring of crown pipes behavior shows that the maximum axial forces are observed at 0.5–0.7L from the tunnel face (L is the pipes length).

From the theoretical point of view, studies have been conducted to analyze the stability of the core ahead of the face in shallow tunnels. Leca and Dormieux (1990), Anagnostou and Kovari (1996), Dias et al. (2008) and Mollon et al. (in press) set up calculation methods to evaluate the stability conditions of the core, with particular reference to tunnels excavated with mechanised shields. The main purpose of these studies was to evaluate the pressure that the machines should apply to the excavation face in order to guarantee stability. Using Limit Equilibrium method, Anagnostou and Serafeimidis (2007) have developed a computational method to design tunnel face reinforcement.

Oreste et al. (2004) have studied numerically the effectiveness of deep tunnel face reinforcement. The results of their analyses were also compared with real measures. These authors show that for deep tunnels, horizontal bolting permits to reduce the plastic deformations in the core and the displacements towards the tunnel and guarantee local stability of the face and prevent the detachment of rock blocks.

At the scale of the reinforced soil mass, the contribution of the reinforcement is approximately equivalent to an anisotropic cohesion (De Buhan and Salençon, 1987; De Buhan et al., 2008; Bernaud et al., 1995, 2009; Wong et al., 2000, 2004, 2006).

The detailed simulation of the bolting using a 3D numerical study is extremely heavy (Al-Hallak, 1999; Dias, 1999; Schweiger and Mayer, 2004) due to scale differences, going from centimeters for the bolt diameter to hectometers for the soil mass. Thus, we propose a simplified convergence-confinement approach allowing an easy design of the bolting system.

The three-dimensional study of a tunnel face reinforced by bolting is based on the example of the Toulon tunneling site in France (Dias et al., 2002). The results of the calculation are compared to experimental data and the simulation process is validated. After a critical study of the existing simplified approaches to design the tunnel face reinforcement, we propose a simplified convergence-confinement method, based on a parametrical three-dimensional study.

2. Three-dimensional simulations of the reinforcement of a tunnel face

In the comparative study presented below, the geometrical as well as the geotechnical parameters adopted, based on in situ tests, are those taken for the design of the tunnel construction in Toulon (Dubois et al., 1999; Dias and Kastner, 2005).

The analysis was carried out by means of a three-dimensional numerical tool using an explicit finite differences scheme (FLAC^{3D}). The numerical model considered corresponds to an average representative cross section of the tunnel. Due to the symmetry, only one quarter of the entire domain is considered in the analysis as shown in Fig. 1. In all subsequent numerical calculations, as the

Table 1
Examples of tunnel projects using fiberglass bolts for face reinforcement.

Year	Country	Project	Section (m^2)	Max overburden (m)	Length (m)
1988–1990	Italy	Railway tunnels Roma – Firenze	110	90	7370
1990–91	France	Galaure tunnel	145	80	2680
1991	Italy	San Vitale tunnel	110	150	1300
1993	Italy	Vasto tunnel	80	100	4970
1997	Italy	Rome Metro tunnel (line A)	125	22	120
1996–98	France	Tartaiguille tunnel	180	140	2340
1997–1998	France	Pech Brunet tunnel	155	21	330
1995–99	France	Toulon tunnel	100	35	1200
1999	Italy	Rome outer ring motorway (Appia Antica)	194	18	1130
2000–2009	Italy	Railway line Bologna – Firenze	140	700	73,000