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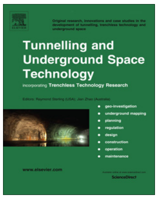

A new analytical solution for the displacement of fully grouted rock bolt in rock joints and experimental and numerical verifications

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ABSTRACT

This study proposes a new analytical solution to predict displacement of a fully grouted rock bolt intersected by single rock joint. The main characteristics of the analytical model, consider the bolt profile and joint movement under pull test condition. The anchorage capacity of fully grouted bolts has been studied for many years; however, the bolt profile and its effect on bolt shear resistance are poorly understood. Investigations of load transfer between the bolt and grout indicate that the bolt profile shape and spacing play an important role in improving the shear strength between the bolt and the surrounding strata. Rock displacement is a sum of elastic part and a jump part due to the presence of joints planes. The performance of the proposed analytical model is validated by experimental method and comparison with numerical modeling. The results showed that there is a promising agreement between analytical and numerical methods. Studies indicate that the displacement rate between the bolt and the rock declines exponentially. Which is dependent on the bolt characteristics such as: rib height, rib spacing, rib width and thickness grout, material and joint properties.

1. Introduction

Rock bolting has advanced rapidly during the past four decades due to understanding of load transfer mechanisms and advances made in the bolt system technology (Cao et al., 2012). A rock bolt consists of a bar inserted in a borehole that is drilled into the surrounding soil or rock mass and anchored to it by means of a fixture. A rock bolt reinforcement system has four principal components (Windsor and Thompson, 1993): the rock or soil, the reinforcing bar, the internal fixture to the borehole wall, and external fixture to the excavation surface. Such a system is very efficient if it is used in one or several of following applications (Chappell, 1989; Fine, 1998).

- Stabilization of blocky rock masses, provided that the far end of the bolt is anchored to a stable zone,
- Rock confinement, contributing to the use of the broken rock bolt to confine the stable rock mass,
- Improvement of the mechanical properties of the rock mass.

In addition, the easy installation and low cost of rock bolts compared to those of other reinforcement elements have contributed to their worldwide success (Stillborg, 1986).

Fully grouted rock bolts are able to support tensile, compressive, shear, and bending loads. The current study focuses on their tensile behavior since it is often encountered and furthermore it allows studying the load transfer mechanism between the rock mass and the reinforcement element. Experiences have revealed that under tensile solicitations failure often takes places by de-bonding at either the bolt–grout interface or the grout–rock interface, depending on the weaker interface. In fact, if a bolted rock mass tries to move, a load is progressively transferred to the rod, and a shear stress develops along the embedded length. As the shear strength of the interface is progressively reached, de-bonding occurs (Blanco et al., 2011). Blumel et al. (1997) was the first to report the influence of profile spacing on load transfer capacity of the bolt. Blumel et al. (1997) carried out numerical simulation of the bolt load transfer characteristics, the main aspect of the analysis being investigation of the difference in the bolt behavior versus the rib geometry and in particular the spacing between the ribs. The numerical simulation was based on using finite element mesh to study the load transfer mechanisms which was aimed to be incorporated in future interface modeling (Blumel et al., 1997). Aziz and Jalalifar (2007) extended the work to include

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modeling of bolt profile configuration under axial and lateral loading conditions. They simulated short encapsulation pull and push tests and compared the results with the laboratory and field tests. Their findings outlined the refined techniques available to conduct sensitivity studies on various bolt rib profiles and their spacing to enable the selection of the optimum bolt profile geometry (Aziz and Jalalifar, 2007).

Cao et al. (2010) presented advanced numerical modeling methods of rock bolt performance in underground mines.

This study showed how the numerical modeling methods could be successfully used to optimize the load transfer between the bolt and the surrounding strata. The study indicated that the standard rock bolt reinforcing elements, which are commonly used in the numerical simulation of the supported underground excavations, cannot be used to optimize the load transfer capabilities of the bolt. A detailed model of the bolt profile must be constructed, loaded to failure, and compared with other profiles to find the optimum bolt profile with maximum load transfer capabilities between the bolt and host strata (Cao et al., 2010). Further studies by Cao et al. (2011) were on the improvement in profile rock bolt. The study of the bolt profile shape manifested how the mathematical equations were derived. These equations are used to calculate the pull-out force needed to fail the grout for different bolt profile configurations. The calculations can be applied to any plane of probable failure within the grout. They presented another procedure to examine grout failure around the bolt for different profile configurations which could be compared with laboratory tests and numerical modeling, providing a better understanding of the bolt–grout interaction with rock reinforcement (Cao et al., 2011). Das and Deb (2011) presented an analytical model for fully grouted rock bolts, considering movements of rock joints. The proposed analytical solution has been applied for evaluating the bolt displacements, axial load, and shear stress along the bolt length when the bolt intersected single and multiple joint planes (Das and Deb, 2011). Aminaipour (2012) studied geometric parameters affecting the load transfer mechanism, showing that the most important parameter is the thickness of the grout.

The work presented here extended the analytical model fully grouted rock bolt based on bolt profile and movement joint. The analytical model was validated by experimental method. Finally, comparisons between the analytical model, and numerical modeling are presented and the results are discussed.

2. Analytical approach

A bolt installed in a deformable rock mass is subjected to an axial loading and it provides resistance to the movement of rock mass through shear stresses which is developed axially in the bolt–grout interfaces (Das and Deb, 2011). All theoretical models are capable of determining the load transfer mechanism with one fracture, regardless of their bolt profile. Thus, in order to successfully determine only a small part of the bolt–grout and rock joint is modeled as shown in Fig. 1. The new analytical model that is presented here, is the extension of Farmer (1975), Li and Stillborg (1999), Cao et al. (2011) and Das and Deb (2011).

In Fig. 1, $b\sin\theta$ is the rib height (mm), c the rib spacing (mm), θ the rib slope (degree), a the profile width (mm), m the grout width (mm), L the failure plane (mm), L_j the length of the bolt to at bolt intersect and the joint plane from the excavation face (mm), L the length of the bolt, $\int\sigma_n dh$ the normal forces in the grout–rock interface (KN) and $\int\tau dh$ the shear forces in bolt–grout interfaces (KN).

2.1. Model description and assumptions

2.1.1. Stress distribution in infinite elastic media

Derived mathematical equations enable calculations of the stress tensor at any point within the grout encapsulating the loaded steel bolt, making the assessment of the bolt profile and its influence on the shear strength possible. Boussinesq is derived from fundamental solutions in various loads on infinite or semi-infinite elastic media. Loading an infinite strip on the surface of a semi-infinite mass as shown in Fig. 2; anywhere, the stress tensor within the media can be calculated as a function of the load, position and material properties. For a uniform normal load as shown in Fig. 2, the stress tensor can be calculated using the Boussinesq equations while for the uniform shear load, the stress distribution can also be calculated via Cerutti's equations(Poulos and Davis, 1974).

Applying the principle of superposition, the total stress σ_z at $A(X, Z)$ point resulting from a strip load distributed over a $B = 2b$ width can be written as:

$$\sigma_z = p[\alpha + \sin\alpha\cos(\alpha + 2\delta)]/\pi \tag{1}$$

Therefore σ_x, σ_y can be calculated.

$$\sigma_x = p[\alpha - \sin\alpha\cos(\alpha + 2\delta)]/\pi \tag{2}$$

$$\sigma_y = 2p\nu\alpha/\pi \tag{3}$$

where ϑ is Poisson's ratio and p the strip load per unit area.

Shear stresses are as follows:

$$\tau_{xz} = p[\sin\alpha\sin(\alpha + 2\delta)]/\pi \tag{4}$$

It can be derived that:

$$\frac{\sigma_x + \sigma_z}{2} = \frac{\alpha}{\pi}p \tag{5}$$

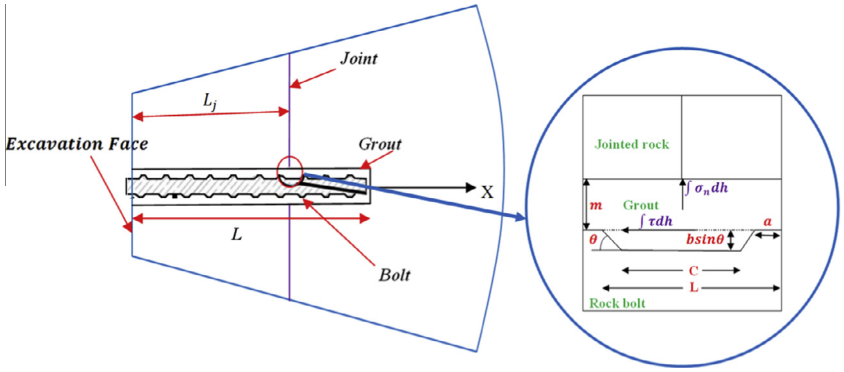

Fig. 1. Stress component along a fully grouted bolt (the proposed research model).