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Analysis profile of the fully grouted rock bolt in jointed rock using analytical and numerical methods

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ABSTRACT

The purpose of this study was to investigate the effect of bolt profile on load transfer mechanism of fully grouted bolts in jointed rocks using analytical and numerical methods. Based on the analytical method with development of methods, a new model is presented. To validate the analytical model, five different profiles modeled by ANSYS software. The profile of rock bolts T_3 and T_4 with load transfer capacity, respectively 180 and 195 kN in the jointed rocks was selected as the optimum profiles. Finally, the selected profiles were examined in Tabas Coal Mine. FLAC analysis indicates that patterns 6+7 with 2NO flexi bolt 4 m better than other patterns within the faulted zone.

1. Introduction

Steel bolts are an essential part of roadway support in coal mining roadways. The effectiveness of bolt reinforcement is a well known and well researched subject; however, little has been done in optimizing the bolt profile that directly contributes to the load transfer between the bolt and the surrounding grout. To improve bolt load transfer through the steel rebar design, it is essential to research the details of the bolt profile shape and configuration. Analytical studies, laboratory tests and numerical modeling provide the tools that enable a better understanding of the rebar profile role in increasing the shear resistance during the working life of bolts [1]. 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 [2]. The short encapsulation pullout tests of rock bolt indicate significant variance of shear resistance for various bolt profile spacing, angle, shape and size [3,4]. Empirical studies can match the graphs of physical tests, however these methods cannot describe the exact reasoning why such behavior occurs [5]. Numerical modeling techniques are much better as they can mimic the physical tests in great detail, however, these methods depend on an accurate knowledge of the physical properties that must be incorporated or added into the model. The power of the numerical model rests on its ability to compare several models and to establish the optimum solution to the problem. The laboratory testing has its challenges as fabrication of minute differences in bolt profile in the workshop is difficult. Nevertheless the laboratory tests are important to calibrate all the empirical work and the numerical models. At present mathematical description of the bolt profile and its behavior during the bolt pull out test is under development to provide better understanding of the physical process that influences the shear strength of the loaded bolt [6,7]. The in situ pullout tests are commonly used to examine the shear capacity of rock bolts. Only a few researchers have conducted laboratory tests to study various bolt profile parameters and their influence on the bolt anchorage [8–10]. A typical steel bolt profile configuration is shown in Fig. 1 [11]. This study develops a new analytical method to evaluate the effect of bolt profile on load transfer mechanism of fully grouted bolts in jointed rocks. The new analytical method validation was carried out by ANSYS software and finally, the profiles of selected bolts from analytical and numerical methods were used for stability analysis in Tabas Coal Mine.

2. Load transfer capacity

In a fully grouted rock bolt, the load transfer mechanism depends on the shear stress continued on the bolt to grout and grout to rock interfaces. Peak shear stress capability of the interfaces and the rate of shear stress generated determine the reaction

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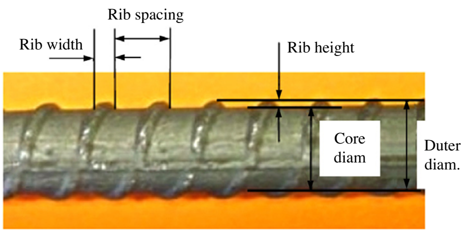

Fig. 1. Steel bolt rib profile configuration [11].

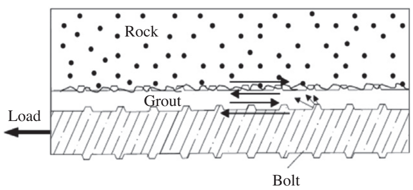

Fig. 2. Mechanism of load transfer [11].

of the bolt to the strata behavior. Load transfer is determined by measuring the peak shear stress capacity and system stiffness. Fig. 2 shows the forces associated with load transfer [6,12].

3. Stress distributions in infinite elastic media

Derived mathematical equations enable the calculations of the stress tensor at any point within the grout encapsulating the loaded steel bolt. Such detail can make assessment of the bolt profile and its influence on the shear strength possible. Boussinesq derived the fundamental solutions for various loads on infinite or semi-infinite elastic media. While loading an infinite strip on the surface of a semi-infinite mass, the stress tensor anywhere within the media can be calculated as a function of the load, position and material properties (Fig. 3). For a uniform normal load as shown in Fig. 3, 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 [13].

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

$$\sigma_z = p[\alpha + \sin\alpha \cdot \cos(\alpha + 2\delta)]/\pi \quad (1)$$

Therefore σ_x, σ_y can be calculated.

$$\sigma_x = p[\alpha - \sin\alpha \cdot \cos(\alpha + 2\delta)]/\pi \quad (2)$$

$$\sigma_y = 2p\nu\alpha/\pi \quad (3)$$

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

Shear stresses are as follows:

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

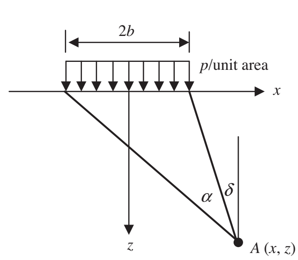

Fig. 3. Calculated stress tensor at any position given by x and z coordinates within the semi-infinite elastic medium loaded by a uniformly distributed load (p) [13].

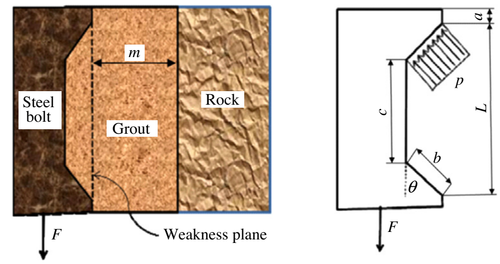

Fig. 4. Single spacing between two bolt profiles showing geometry [7].

It can be derived that:

$$\frac{\sigma_x + \sigma_z}{2} = \frac{\alpha}{\pi}p \quad (5)$$

$$\frac{\sigma_x - \sigma_z}{2} = -\frac{\sin\alpha \cdot \cos(\alpha + 2\delta)}{\pi}p \quad (6)$$

4. Normal and shear stress on a failure plane

To draw a link between the load transfer system and the bolt profile configuration, a single spacing between two bolt ribs are examined (Fig. 4) [7].

In Fig. 4, F is the axial bolt pull out force, kN; c the rib spacing, mm; $b\sin\theta$ the rib height, mm; θ the rib slope, °; α the profile width, mm; m the grout width, mm; and L the failure plane, mm.

To investigate where the grout failure will occur, several potential planes of failure can be trailed. As an example a plane of failure that spans between the two rib tops is considered. The Mohr–Coulomb criterion of failure was used to calculate the maximum pull out force needed for the assumed plane of failure. The equations to calculate the bolt pull out force are derived after linking the bolt geometry (Fig. 4), the sum of integrated normal and shear stresses along the failure plane. For static equilibrium, the sum of forces parallel to the bolt axis is zero:

$$\sum F_y = 0 \rightarrow p = \frac{F}{b\sin\theta} \quad (7)$$

where P is the normal load on bolt boundary at the profile inclination b [7].

5. Stress distributions in the grout

To apply Bossiness's stress transformation equations in calculating the normal and shear stress along the studied plane of failure, the coordinate system must be rotated to match the geometry (Fig. 5). The distance PQ represents the failure plane and the angle θ is the rib slope. Point A is any point on the plane of failure while variable h is the distance from Point P. Under normal conditions the grout elastic properties are similar to the

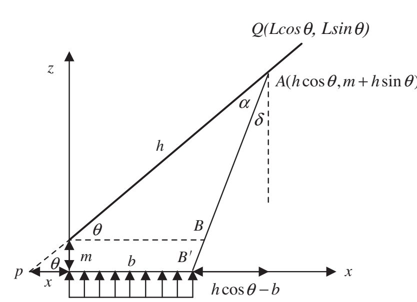

Fig. 5. Rotated axis of the loading diagram with the assumed plane of failure.