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Hadi Nourizadeh
University of Southern Queensland

Ali Mirzaghorbanali
University of Southern Queensland

Kevin McDougall
University of Southern Queensland

Naj Aziz
University of Wollongong

Mehdi Serati
University of Queensland

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AXIAL BEHAVIOUR OF ROCK BOLTS–PART (B) NUMERICAL STUDY

Hadi Nourizadeh[1], Ali Mirzaghorbanali[1], Kevin McDougall[1], Naj Aziz[2] and Mehdi Serati[3]

ABSTRACT: Axial load behaviour of rock bolts was studied using FLAC commercial software in a two-dimensional framework. The numerical model was calibrated using experimental pull out data. Effects of confinement stresses and rock bolt surface roughness on the axial load behaviour were investigated incorporating the calibrated numerical code. Results indicated that the pull out resistance increases with an increase in confinement stresses and surface roughness.

INTRODUCTION

Fully-encapsulated rock bolts are embedded in the borehole using either resin or cementitious grout. This increase the overall stiffness by generating resistances against axial and shear forces. Sliding blocky rocks or movement of bedding planes induce stress in the grout. The induced stresses are then transferred to the reinforcing element, thus, creating interaction between the bolt and surrounding medium. Eventually, this process produces tensile forces in the bolt, preventing further movement of separated blocks and bedding planes.

LITERATURE REVIEW

In fully grouted rock bolts, failure may occur in various modes including rock-grout interface, grout-bolt interface, rock bolt and surface plate. Nemcik et al. (2014) reported that the most common failure mode is the bolt-grout interface. Relaxation in the confinement stress reduces rock bolt anchorage capacity, particularly at the rock-grout interface. Hyett et al. (1992) carried out split-pipe tests using PVC, aluminium and steel pipes to investigate the effects of confinement stress on the bond capacity of grouted cable bolts. They concluded that the axial bearing capacity of cable bolts increases with an increase in confinement stress. In addition, they reported that the failure mechanisms changed as the confinement stress increased. In another study, Hyett et al. (1995) performed several pull-out tests on encapsulated cable bolts incorporating the modified Hoek cell to simulate confinement stresses. It was noted that confining stress affects the ultimate bearing capacity of encapsulated cable bolts. Blanco Martin et al. (2011) carried out a series of pull-out tests to examine the influence of several factors such as confining stress and the bolt's surface profile. The results revealed that confining stress possesses noticeable effects on the anchoring capacity. It was observed that the radial fractures are more pronounced in low values of confining stress. In another study, Nie et al. (2019) reported that the highest bond and residual strength are achieved with high confining stress.

Hawkes and Evans (1951) carried out pull-out tests showing the distribution of shear (bond) stress along the bolt. They concluded that the load distribution follows an exponential function and the peak takes place before any decoupling occurs. Farmer (1975) conducted theoretical and experimental research on the shear stress distribution along resin encapsulated reinforcement elements and concluded that the mobilised shear resistance is an influential factor in the bond resistance. Li and Stillborg (1999) developed an analytical model for fully encapsulated rock bolts by assuming the peak shear stressoccurring a short distance from the loading point, diminishing exponentially to the free end (Figure 1). According to the piecewise function proposed by Li and Stillborg (1999), the shear stress distribution is divided into four sections along fully-grouted rock bolts. These sections include entirely decoupled (A), partially decoupled with a constant bond strength (B), partially decoupled with linearly increasing bond strength (C) and compatible deformation with no decoupling (D) (Figure 2). The proposed model includes some assumptions which may limit the model practicality. Developing a reliable mathematical model to simulate rock bolt bond-stress behaviour is a cumbersome task due to problem complexities. Several tri-linear bond-slip models were presented to simulate the interfacial

[1] *School of Civil Engineering and Surveying, University of Southern Queensland, email:* hadi.norizadeh@usq.edu.au
[2] *School of Civil, Mining and Environmental Engineering, University of Wollongong, email:* naj@uow.edu.au
[3] *School of Civil Engineering, University of Queensland, email:* mehdi.serari@uq.edu.au

debonding of steel bolting systems (Benmokrane et al., 1995, Ren et al., 2010, Blanco Martín et al., 2011). Benmokrane et al. (1995) proposed a bond-slip model for the interfacial constitutive behaviour of three linear sections (I, II, III) as shown in Figure 3. Ren et al. (2010) represented the full range behaviour of fully grouted rock bolts to define the shear stress and bond-slip relation along the interface, axial load in the bolt and load-displacement relationship by applying the tri-linear bond-slip model. The proposed full-range constitutive model consists of five distinguished stages, namely, elastic, elastic-softening, elastic-softening-debonding, softening-debonding and debonding. Also, closed-form solutions were proposed to calculate the axial load distribution, interfacial shear stress distribution, load-displacement relationship and bond-slip relationship. This model is not straightforward to apply in practice due to its complexity. Blanco Martín et al. (2011) modified Ren's model to predict the full-range mechanical behaviour of rock bolts. In the presented approach, the input parameters are bolt elastic modulus, bolt radius, displacement of the free end and the constitutive law governing the bolt-grout interface. In this model, shear stress is a function of displacement and tangential interfacial stiffness. Ma, et al. (2013) developed a non-linear bond-slip model (Figure 4) by applying the slip function presented by Zhou et al. (2010).

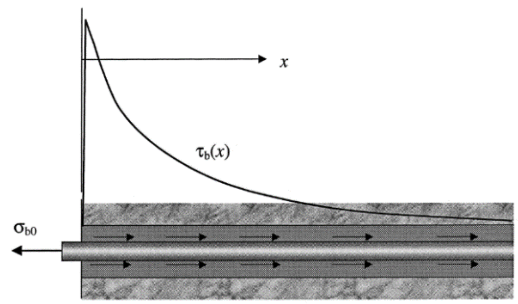

Figure 1: Shear stress along a full-encapsulated bolt subjected to a pull-out load before decoupling occurs (Li and Stillborg, 1999)

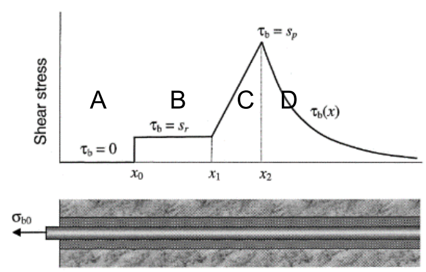

Figure 2: Distribution of shear stress along a full-encapsulated bolt subjected to a pull-out load after decoupling (Li and Stillborg, 1999)

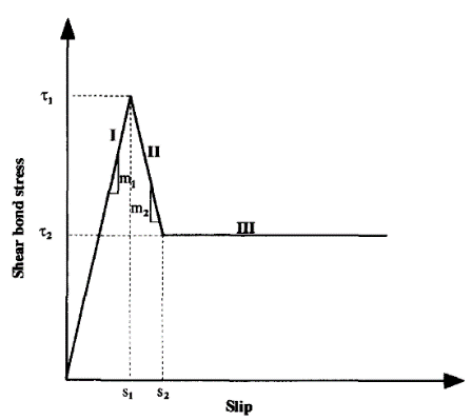

Figure 3: Idealised bond-slip relationship at the bolt-grout interface (Benmokrane, et al., 1995)

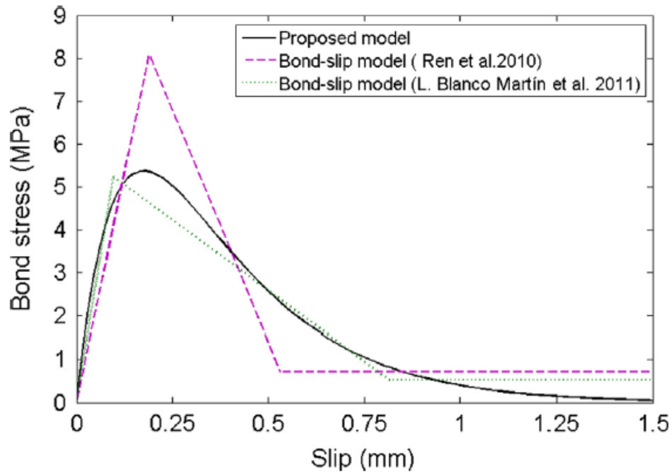

Figure 4: Comparison of the bond-slip models proposed by (Ren et al., 2010), (Blanco Martín et al., 2011) and (Ma et al., 2013)

The interaction between the components in the rock bolting systems subjected to a tensile force is complicated. Therefore the conventional approaches may not be capable of studying this behaviour in details. On the other hand, computer simulations are powerful tools dealing with complexity in Engineering problems. Rao Karanam and Dasyapu (2005) conducted extensive experimental pull-out and push-out tests to investigate fully grouted rock bolt performance with variations in the bolts diameter and length and water to cement ratio. According to the collected experimental data, detailed numerical analysis using the ALGOR computational package was carried out to analyse displacement, stress and strain distribution along the interface. Ghadimi et al. (2014) developed a three-dimensional numerical code based on finite element method to investigate the behaviour of rock bolts in jointed rocks and to validate the proposed analytical solutions. Nemcik, et al., (2014) developed a numerical model for fully grouted rock bolts loaded in tension by applying a non-linear bond-slip relationship using FLAC software. Nie, et al. (2014) established several rock bolt models by assigning elastic and linear strain-hardening behaviour. Chen, et al. (2018) proposed a numerical model using the commercial code of FLAC2D to determine the maximum induced confinement stress in pull-out tests of different cable bolts. Results indicated that modified cable bolts produce more confinement stress within the rock samples, making them suitable for high *in situ* stress conditions. Nie, et al. (2019) used two-dimensional Discontinuous Deformation Analysis to investigate rock bolt behaviour under various conditions. The bond-slip curves obtained from the numerical models follow trends that can be translated to the tri-linear bond-slip model. Parametric studies showed that the ultimate bond strength and residual strength increase as confining stress increases. Yu, et al. (2019) evaluated the behaviour of fully grouted rock bolts by conducting experimental and numerical analysis. The numerical models simulated the failure process under various embedment length and indicated that microcracks occur initially at the loading end expanding toward the free end as the axial load increases. Moreover, the influence of critical embedment length and the friction coefficient on the residual axial stress were analysed. Che, et al., (2020) investigated the behaviour of ribbed bolts installed in soft rocks from micro-scale to macro-scale using the discontinuous element method. The influence of embedment length and confining stress on the ultimate load as well as failure mode were analysed.

As far as can be determined, there are limited numerical simulations investigating the effects of confinement stress and surface roughness on axial load behaviour of fully grouted rock bolts, which are the subject of this paper. This is a companion paper, which complements the part (A) paper, discussing experimental results.

SIMULATION OF ROCK BOLT AXIAL BEHAVIOUR IN FLAC

FLAC software was developed by the ITASCA Consulting Group, Inc. based on explicit finite difference concepts and represents several structural reinforcing elements such as rock bolts and cable bolts (Itasca, 2000). FLAC 2D is a robust two-dimension simulation software to assess the mechanical behaviour of rock bolts. In FLAC, rock bolts are modelled based on the pile element, comprising axial and bending behaviour. The pile element is connected to the grid in the normal and shear directions by spring coupling concepts. The reinforcement element is divided into several segments with the length of L connected at nodal points. The segments are assumed to behave linearly elastic, yielding in the axial direction once the tensile or compressive stress reaches the user-defined tensile or compressive strengths. The shear behaviour of the bolt/grid (grout) interface is defined by the spring-slider system at the nodal points. This behaviour is described by the coupling spring shear stiffness (cs_sstiff) in the software once the nodal points move relative to the grid (Equation. 1) (Figure 5a).

$$\frac{F_s}{L} = cs_{sstiff}(u_p - u_m) \quad (1)$$

where, F_s is shear force developing in the shear coupling spring; L is the contributing length of the bolt element; cs_{sstiff} is the coupling spring shear stiffness; u_p is the axial displacement of the bolt and u_m is the axial displacement of the grid (grout or rock).

The maximum induced shear force due to pull-out load along the bolt-grid is determined by the interface's cohesive strength and frictional resistance along the interface. The following equation determines the maximum shear force (Figure 5b):

$$\frac{F_s^{max}}{L} = cs_{scoh} + \sigma_c' \times \tan(cs_{sfric}) \times P \quad (2)$$

where cs_{scoh} is the cohesive strength of the coupling shear spring, σ_c' is the mean effective confining stress normal to the bolt element, cs_{sfric} is the friction angle of coupling shear spring and P is the perimeter of the bolt. User-defined tables, $cs\_sctable$ and $cs\_sftable$, are available in FLAC to prescribe the softening behaviour, which is a function of shear displacement for shear coupling spring cohesion and friction angle properties. The tables mentioned above defines a number of tables relating cohesion and friction angle of shear coupling spring to relative shear displacement.

The anchorage capacity and load transfer mechanism in fully grouted rock bolts are affected by the mechanical properties of grouts, bar specifications and *in-situ* conditions. In this study, the results of pull-out experiments (part (A)) were employed to numerically study the fully grouted rock bolt axial load transfer mechanisms subject to confinement stresses. Within the literature, it is proposed that short encapsulation can be employed to experimentally study the debonding mechanisms. This is aimed to ensure uniform distribution of shear stress along the bolt-grout interface (Blanco Martín et al., 2011, Benmokrane et al., 1995, Tepfers, 1979). For this reason, only 100 mm of the bolt was encapsulated using Stratabinder HS, a cementitious grout produced by Minova Australia. The pull-out test was conducted by setting the servo-controlled MTS 100 kN tensile machine at the strain rate of 1mm per minute, and over the tests, the load-displacement interaction was monitored on integrated computer software connected to the machine. The obtained load-displacement relationships from the pull-out tests are converted to bond-displacement using the following equation:

$$\tau = \frac{P}{\pi d_b L} \quad (3)$$

where, P is the subjected pull load, d_b is the bolt diameter and L is the embedment length. This conversion is valid until the embedment length (L) is short enough, and the shear stress is uniformly distributed along the entire bolt

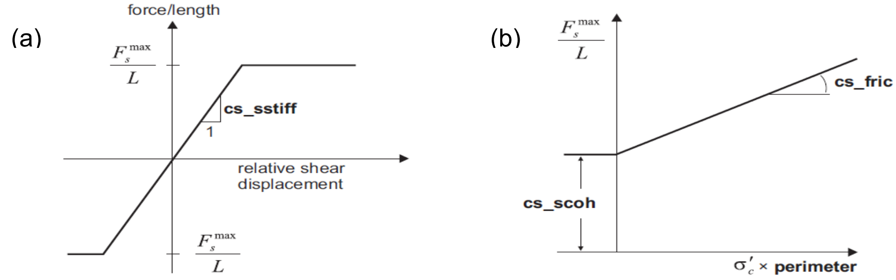

Figure 5: a) Shear force against displacement b)Shear strength criterion in FLAC (Itasca, 2000)

NUMERICAL MODELLING

Finite element method using FLAC2D was applied with the primary aim of examining the load and displacement developed along the encapsulated bolts. The secondary objective is to examine the effects of confining stress and friction angle on the axial behaviour of fully grouted rock bolts. In order to verify the capability of FLAC2D in simulating the behaviour of fully grouted rock bolt in pulling out conditions, the model was compared and validated with the results of pull-out experiments. After calibration, confining stress ranging from 0 to 7.5 MPa, and bolt-grout interface friction angle ranging between 30-45 degrees were applied. Normal displacement at the top was constrained to simulate testing conditions. Nevertheless, the bolt was free of movement along the vertical axis.

The relevant properties used in the model are the cross-sectional area of 2.44 E-4 m^2, Elastic modulus of 200E9 Pa, 5.65E-2 in perimeter, cs_scoh of 4.5E5 N/m and cs_sstiff of 6.89E9 N/m/m. Rock properties were assigned a bulk modulus of 5.00E9 Pa, shear modulus of 3.2 E9 Pa and density of 2000 Kg/m^3. In the simulation process, it was assumed that the confining stresses acting on the bolts are isotropic.

Figure 6 illustrates a comparison between the load-displacement curve of the numerical simulation and that of experimental data with a grout curing time of 28 days and water to grout ratio of 36%. The numerical simulation agrees well with the experimental data, capturing the elastic region, peak value and residual conditions. Axial load distribution along the bolt is illustrated in Figure 7. It is noted that the bolt axial load gradually decreases from the loading-end to the free-end. The numerical study also demonstrates that the bond strength increases with confining stress. According to the simulation (Figure 8), the ultimate pulling force increases from 43.55 kN to 48.44 kN when 2.5 MPa confinement stress is exerted to the lateral boundaries. However, the incremental impact of confinement decreases after reaching 5 MPa, as the ultimate pull-out load reaches 55.6 kN when the confinement stress is 7.5 MPa (i.e. lower increment compared to the previous case). Frictional strength also indicates a jump when confining stress increases in the model. Figure 9 depicts the effect of the friction angle (i.e. bolt surface roughness) on the anchorage capacity. As shown, increasing the friction angle from 30 to 45-degree causes the ultimate anchorage capacity to increase from 46.2 kN to 50.6 kN.

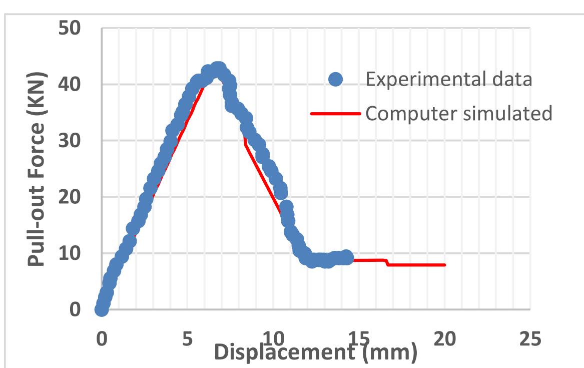

Figure 6: Comparison between numerical model and experimental data

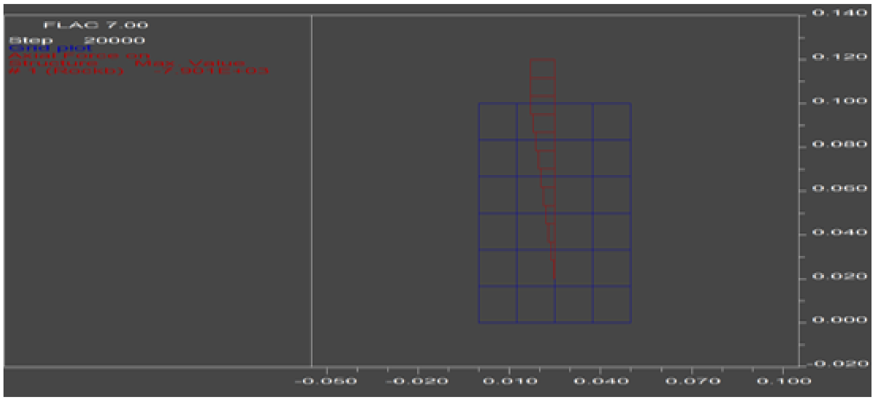

Figure 7: Axial load distribution along the bolt

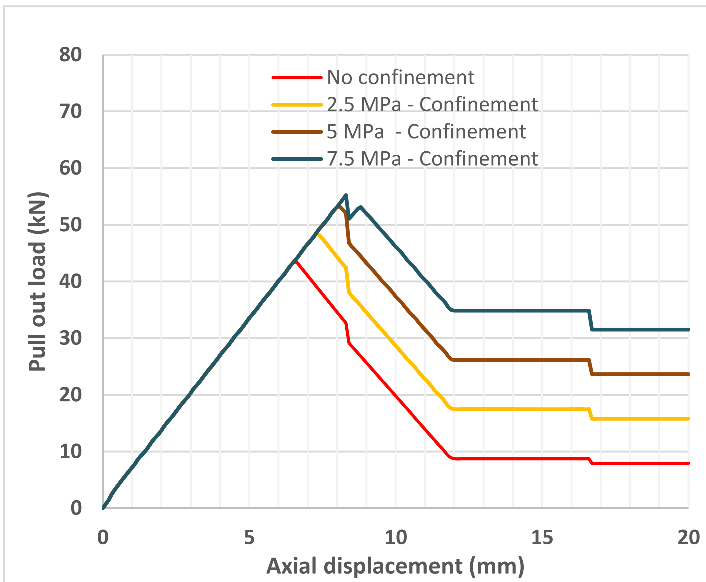

Figure 8: Effects of confinement on the bolt axial behaviour

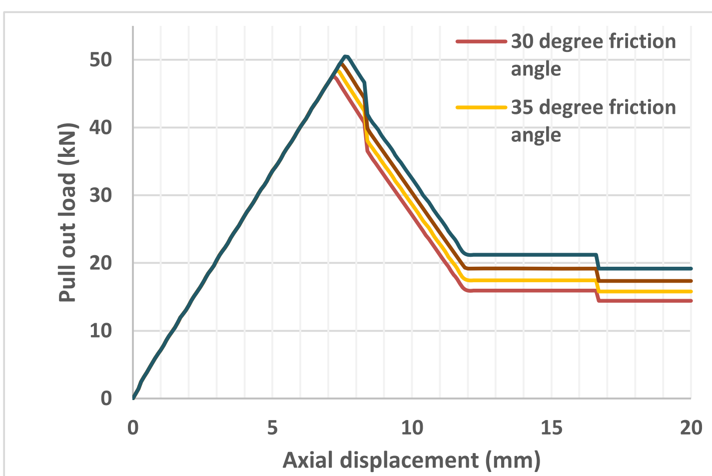

Figure 9: Effects of surface roughness on bolt axial behaviour

CONCLUSIONS

In this study, FLAC 2D was incorporated to evaluate the effects of confining stress and bolt surface roughness on axial load behaviour of grouted rock bolts. The following main conclusions are drawn from this investigation:

- The numerical model is in close agrement with the experimental data, thus, indicating the capabilities of FLAC 2D in simulating rock bolt axial behaviour.
- The numerical models also showed that the confinement and surface roughness influence the bonding resistance of fully grouted rock bolts subject to axial loading. According to the simulations, the ultimate bearing capacity and residual strength increase with an increase in confining stress and friction angle.
- This study was carried out under the assumption of isotropic confinement conditions. In the field, horizontal stresses may differ from each other. Therefore, it is suggested to carry out further research studies by considering anisotropic confinement conditions.

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