Tunnelling and Underground Space Technology 79 (2018) 210–223

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Experimental investigation of hard rock fragmentation using a conical pick on true triaxial test apparatus

Shaofeng Wang[a,b], Xibing Li[a], Kun Du[a,*], Shanyong Wang[b]

[a] School of Resources and Safety Engineering, Central South University, Changsha 410083, PR China
[b] ARC Centre of Excellence for Geotechnical Science and Engineering, The University of Newcastle, Callaghan, NSW 2308, Australia

ARTICLE INFO

Keywords:
Hard rock fragmentation
Conicalpick
Peak cutting force
Insertion depth
Cuttability-improved approach

ABSTRACT

This study aims to determine the influences of confining stresses and cutting parameters on hard rock fragmentation using a conical pick. Using a true triaxial testing apparatus, single/double pick forces and static/coupled static-dynamic pick forces were applied to granite rock specimens to break them confined by biaxial, uniaxial and no lateral stress conditions. The corresponding cuttabilities were estimated and compared by the peak pick force, insertion depth and disturbance duration at rock failure and the associated failure patterns. The results showed that excavation-induced unloading and cracking, which can change the biaxial confining stress conditions into the uniaxial and decrease uniaxial confining stress level, respectively, can significantly improve the hard rock cuttability. The experimental, theoretical and regressive results indicated that the hard rock cuttability initially decreases and then increases as the level of uniaxial confining stress increased. A moderate uniaxial confining stress instead improves the rock cuttability, but a high stress level may induce rock burst triggered by conical pick penetration. Therefore, only the hard rocks under stress-free and low uniaxial confining stress conditions can be easily fragmented with high safety and efficiency, as a complete splitting failure occurs. In addition, the hard rock cuttability can be also improved by the dynamic pick disturbance and the artificial defects such as excavation-induced fractures, pre-slits and boreholes in rock mass.

1. Introduction

Mechanized excavation is a widely used approach in mining and tunneling engineering due to continuous and safe operation, high construction quality and low excavation damage (Bilgin et al., 2013; Wang et al., 2016a,b, 2017). Roadheaders and longwall shearers using rotary cutting of conical picks have been satisfactorily used to excavate soft to medium hardness ore-rock, such as coal, bauxite, and salt minerals, and continue to be promoted by the industrial development (Ergin and Acaroglu, 2007; Peng, 2008; Wang et al., 2016c). Nevertheless, these mining machines are unsuitable for breaking extremely hard ore-rock at present, in which the hard ore-rock under high geostress instead become a primary existing situation in deep underground. The reason for this is that the mining processes are prone to wear-out failure of cutter tool, low operation stability of machine and heavy dust production, resulting from low cuttability of hard rock having high strength, hardness, wear resistance and intactness and high geostress confinement (Ergin and Acaroglu, 2007; Yang et al., 2015; Dewangan and Chattopadhyaya, 2016a; Li et al., 2017a). Deep underground mining in hard ore-rock is a consequent trend with the consumption and depletion of shallow mineral resources. Field observations indicated that pre-existing rock fractures induced by excavation unloading disturbance of high geostress can improve rock cuttability (Kaiser, 2006; Yin et al., 2014b; Li et al., 2013, 2017b). Li et al. (2013) found that the pick consumption and dust production significantly reduced during excavation in an unloading-induced fractured zones under high geostress condition in hard phosphate ore-rock using roadheader, compared to a single-face excavation. Therefore, it is necessary to understand the cuttability of deep hard rock to promote the suitability of mechanized excavation approaches in upcoming deep underground mining.

Rock cuttability is an integrated behavior that reflects the interactions between cutters and rock and is influenced by rock characteristics, cutter performances and stress conditions. Conical picks, which belong to point-attack picks with advantages of greater penetration depth, lower energy expenditure and longer life span, have been widely used for roadheader excavation and longwall shearer mining (Peng, 2008; Dewangan et al., 2015; Dewangan and Chattopadhyaya, 2016b; Nahak et al., 2017). The parameters of conical picks determine the fragmentation abilities of roadheader and shearer, which is significantly influenced by rock characteristics and stress conditions (Li et al., 2017a).

Significant efforts have been undertaken to understand cutting

---

* Corresponding author.
E-mail addresses: wsfcumt@163.com (S. Wang), dukuncsu@csu.edu.cn (K. Du).

https://doi.org/10.1016/j.tust.2018.05.006
Received 18 January 2018; Received in revised form 7 May 2018; Accepted 10 May 2018

behaviors of point-attack picks using experimental, theoretical and numerical investigations. Experimental studies were conducted to obtain specific cutting parameters of conical picks such as the cutter force, specific energy, fragment production, fractured surface roughness and fragment features influenced by rock properties and cutting parameters (Bilgin et al., 2006, 2013; Balci and Bilgin, 2007; Bao et al., 2011; Yang et al., 2015; Kang et al., 2016; Liu et al., 2017; Copur et al., 2017; Yasar and Yilmaz, 2017). Bilgin et al. (2006) undertook laboratory full-scale linear cutting tests to investigate the performances of conical picks on 22 different rock specimens varying from the soft to the hard under different cut depth and cutter spacing values. They found that the cutter force and specific energy values are positively correlated with rock properties especially expressed by uniaxial compressive strength and Brazilian tensile strength. Dewangan et al. (2015) and Dewangan and Chattopadhyaya (2016a,b) investigated the wear mechanisms of conical picks in coal cutting. Kang et al. (2016) made a new linear cutting machine and investigated the influences of specimen strength (low, moderate and medium), cutting depth and cutting spacing on the cutting force of conical pick. Copur et al. (2017) studied the influences of cutting parameters (single-, double- and triple-spiral cutting patterns, cutting depth and cutting speed) and rock properties (from soft to hard) on the cutting performances of conical picks (normal, cutting and side forces, specific energy, yield and fractured surface coarseness index) using a full-scale linear cutting apparatus. Several theoretical models were proposed to estimate the maximum and mean cutting forces of conical pick (Evans, 1984; Roxborough and Liu, 1995; Goktan, 1997; Goktan and Gunes, 2005; Bao et al., 2011). Obtained from these models, the cutting forces are correlated with rock properties, cutting depth, the geometric factors of conical pick and the friction coefficient between cutter and rock. In addition, a number of numerical simulations using the finite element and discrete element methods were undertaken to simulate rock cutting of conical picks to trace the complex process in more detail and reduce costs (Liu et al., 2014; Su and Akcin, 2011; Rojek et al., 2011). These studies provided valuable information to shed light on the rock cutting mechanism using conical pick. However, they did not consider the influence of geostress confinement, which can be ignored in shallow excavations but is a common, growing and serious factor in deep mines and tunnels (Li et al., 2017a).

The influence of confining stress on cutting performances of other types of cutting tools such as wedge-shaped cutter and disc cutter has been investigated and found that a modest level of lateral stress could close the cracks and decrease the tensile stress around the cutting groove, and then increase the cutting difficulty (Pomeroy, 1958; Gehring, 1995; Bilgin et al., 2000; Innaurato et al., 2007, 2011). Nevertheless, other studies undertook field observations, laboratory tests and numerical simulations and found that confining stress has both beneficial and adverse influences on rock cutting using tunnel boring machine (TBM) cutters (Ma et al., 2011, 2016; Yin et al., 2014a,b; Liu et al., 2016a,b). Confining stress can facilitate rock fragmentation if it is high enough to induce rock pre-cracking near the excavation face; otherwise, it hinders rock cutting. The aforementioned studies focused on the cutting abilities of wedge-shaped pick and TBM disc cutter influenced by confining stress, but did not involve the conical pick. Unlike these cutting tools, a conical pick performs as a sliding indenter to crush and then fragment the rock, which is fundamentally three-dimensional and difficult to be simplified into a two-dimensional case (Bao et al., 2011). Moreover, the influence of confining stress on rock fragmentation does not occur as a single event, as determined by indentation tests of TBM cutters. In addition, the load types and the stress-redistribution factors induced by excavations and pre-existing defects have not been considered in previous studies.

This study experimentally investigated hard rock fragmentation using a conical pick on an innovative true triaxial testing apparatus that can apply high biaxial or uniaxial confining stresses and variform axial pick forces to multi-size granite rock specimens. The cuttability indices such as peak force, insertion depth and disturbance duration and the failure patterns were measured and compared in the tests to estimate the influences of conical pick performances (loading velocity, load type and installation interval) and stress conditions (biaxial stress, uniaxial stress and stress-free conditions) on granite rock fragmentation.

2. Experiment method

2.1. Test apparatus

This study was performed on an innovative testing apparatus using the TRW-300 electro-hydraulic servo system for true triaxial coupled static and dynamic loading tests. The apparatus consisted of *X*, *Y* and *Z*-direction loading units, dynamic disturbance unit, external digital controller, hydraulic pump controller, control software for true triaxial static loading and dynamic disturbance, camera, and video surveillance, as shown in Fig. 1. The static loading capacities of the apparatus were 0–2000, 0–2000, and 0–3000 kN in *X*-, *Y*- and *Z*-directions, respectively. The dynamic disturbance allowed 0–500 kN amplitudes and 0–70 Hz frequencies (Du et al., 2016).

2.2. Experiment conditions

Rock fragmentation is a complicated process with the interaction between rock and cutter influenced by rock characteristics, cutter performances and geostress conditions (Li et al., 2017a). Therefore, this study mainly investigated the influences of rock characteristics, loading parameters of conical pick and confining stress conditions on the hard rock fragmentation on granite specimens.

2.2.1. Rock specimens

The rock material used in tests was extracted from homogeneous matrix blocks of granite. A series of cylindrical granite specimens with sizes of Φ50 × 100 mm and Φ50 × 25 mm were prepared to determine the conventional physical and mechanical parameters of the rock material, including its density, Young's moduli, Poisson's ratios, tensile strengths, cohesions, friction angles, uniaxial compressive strength (UCS), and conventional triaxial compressive strengths under 30 MPa (TCS-30) and 60 MPa (TCS-60) confining stresses. There were five specimens for each conventional test, and the average values of tested results were listed in Table 1. Then, the piecewise linear and non-linear peak strength curves were regressed from the experimental peak strength values under the different confining stresses based on Mohr-Coulomb and Hoek-Brown strength criteria expressed as linear Eq. (1) and non-linear Eqs. (2) and (3), respectively (Hoek et al., 2002; Brady and Brown, 2006; Zhang and Zhao, 2014a; Wang et al., 2018). The measured strength values and regressive strength curves were plotted in Fig. 2, and the corresponding regressive coefficients were shown in Table 1. The strength grades of the granite used for rock fragmentation tests were very strong according to these strength parameters, and the granite belongs to a stiff and brittle material. As shown in Fig. 2, the failure envelope curves regressed by piecewise linear criterion using Eq. (1) and modified non-linear criterion using Eq. (2) can reflect the full strength characteristics of granite from tensile to compressive stress conditions. However, the failure envelope curve regressed by original non-linear criterion using Eq. (3) can only reflect the strength characteristics of tested rock under compression tests and is unsuitable for determining tensile failure.

$$\sigma_1 = \frac{1+\sin\varphi}{1-\sin\varphi}\sigma_3 + \frac{2C\cos\varphi}{1-\sin\varphi} \tag{1}$$

$$\sigma_1 = \sigma_3 + \sigma_c\left[m\frac{\sigma_3}{\sigma_c} + s\right]^a \tag{2}$$

$$\sigma_1 = \sigma_3 + \sigma_c\left[m\frac{\sigma_3}{\sigma_c} + 1\right]^{0.5} \tag{3}$$