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Comparison and discussion on fragmentation behavior of soft rock in multi-indentation tests by a single TBM disc cutter

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ABSTRACT

This paper is to investigate the mechanical responses and failure characteristics of soft rock in multi-indentation tests by a single TBM constant cross section (CCS) disc cutter. Different pre-set penetration depths and totally three cycles of indentation processes were employed in the repeated indentation tests conducted on the cubic cement mortar specimens. The load-penetration depth curve, penetration load, peak-load penetration depth, rock breakage work and compacted zone depth for the three indentation processes were analyzed. The strength and deformation properties and failure behavior of soft rock under different indentation conditions were revealed. The rock breakage behavior after several indentation processes still presents brittle failure characteristic with small pre-set penetration depths, but the specimens with large pre-set penetration depths appear obvious plastic failure mode. Approximately equal leap loads are obtained from both the intact specimen in direct indentation failure test and the weakened specimens after several indentation processes with different pre-set penetration depths, but the peak-load penetration depths for specimens with different pre-set penetration depths are varying. Curves of the cumulative penetration depth and cumulative rock breakage work both reach the corresponding peak values for one certain pre-set penetration depth. Along with this most unfavourable pre-set penetration depth, rock breakage efficiency is the lowest and energy consumption is the highest.

1. Introduction

Penetration depth and cutter spacing are the two key factors affecting the cutting performance of disc cutters mounted on full-face rock tunnel boring machine (TBM). With fixed cutter spacing and shallow penetration depth, crack network induced by cutter indentation process is relatively inefficient in fragmenting the rock surface, thus resulting in rock-bridges between two adjacent cutting grooves, and consequently the rock breakage efficiency is unfavorably limited. Otherwise, in rock disc cutting process with large penetration depth, the rock between two adjacent cutter paths is over-broken with high specific energy consumed, not only uneconomic but also leading to severe cutter breakage due to higher cutter forces (Liu et al., 2002; Ozdemir and Wang, 1979; Roxborough and Phillips, 1975; Snowdon et al., 1982). Therefore, optimum penetration depth selection for specific cutter spacing has long been the worldwide highlight that is extensively investigated by many researchers, aiming at fulfilling high rock breakage efficiency and maintaining reasonable cutter forces simultaneously.

As the theoretical basics of TBM performance optimization, rock breakage mechanism and efficiency improvement in TBM disc cutting process have been widely and deeply studied. A series of physical and numerical indentation tests on rocks with different strengths by indenters with various shapes and sizes have been employed to investigate the fragmentation zone formation and internal crack network propagation inside the rock specimens (Chen and Labuz, 2006; Gong et al., 2005, 2006; Huang et al., 1998; Innaurato et al., 2007; Liu et al., 2002; Ma et al., 2011; Pang and Goldsmith, 1990; Yin et al., 2014; Zhang et al., 2012). Observation of craters, crushed zones and different types of crack networks both weakening rock internal structures and spalling rock chips were carried out. Load-penetration depth curves under different indentation conditions were studied with acoustic emission (AE) parameters, digital image correlation (DIC) results and other real-time monitoring techniques (Chen and Labuz, 2006; Yin et al., 2014; Zhang et al., 2012). The influences of lateral confining stress on crack network propagation, failure mode transition of the rocks and normal force of the indenters were widely investi-

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gated by using laboratory or numerical confined indentation tests (Chen and Labuz, 2006; Huang et al., 1998; Innaurato et al., 2007; Liu et al., 2002; Ma et al., 2011; Yin et al., 2014). Choi and Lee (2015) and Gong et al. (2005, 2006) conducted numerical simulations by using discrete element methods (PFC or UDEC) to reveal the influences of joint spacing and orientation on TBM penetration performance. The rock fragmentation patterns, TBM penetration rate and cutting power were well studied as function of the joint spacing and orientation. Chen and Labuz (2006), Pang and Goldsmith (1990), Yin et al. (2014) and Zhang et al. (2012) studied the crack initiation and propagation and the dominant rock failure mechanisms in indentation process with physical laboratory indentation tests. Their researches mainly focused on the evolution process and mechanism of the rock breakage under different indentation conditions, and the most remarkable achievement is the propagation process and mode of the internal induced crack network in indentation by various tools.

However, indentation tests can merely capture crushing failure of the rock underneath the disc cutter, namely the former groove formation process, not the subsequent rock chipping process. As the main deficiency, none evident dynamic rock chipping and spalling phenomena are accurately reflected, thus the rock breakage efficiency in indentation tests cannot be directly related to real disc cutting efficiency in practical TBM tunneling. Now full-scale linear rock cutting tests are widely accepted as the most reliable and accurate approach for TBM performance prediction (Balci, 2009; Copur et al., 2014; Rostami, 1991; Tuncdemir et al., 2008). Selection of the optimum ratio of cutter spacing to penetration depth and the corresponding TBM performance evaluation for given rock type were extensively studied (Cho et al., 2013; Choi et al., 2014; Gertsch et al., 2007; Gong et al., 2015). Meanwhile, many researchers carried out laboratory or numerical linear rock cutting tests to investigate the effects of different rock types and cutting conditions on rock cuttability and cutting efficiency (Abu Bakar et al., 2014; Balci and Tumac, 2012; Cho et al., 2010; Gertsch, 1993, 2000; Rostami, 2013; Tumac and Balci, 2015). Their researches mainly concentrated on the disc cutting forces, rock fragmentation characteristics and rock breakage efficiency optimization in disc cutting process, and the most popular theoretical result is the proposal and acceptance of the specific energy concept (Teale, 1965).

In practical TBM tunneling, to avoid excessive disc cutter cutting forces in hard rock disc cutting, mostly the mechanical properties of the hard rock formations along the tunnel alignment or on the tunnel face are used in the determination of cutter spacing and the corresponding penetration depth (Tóth et al., 2013). Once determined, modification and rearrangement of the cutterhead and cutting tools are both time-consuming and uneconomic. However, practical TBM excavation performance is always severely challenged by the frequent occurrence of soft rock formations and mixed ground conditions (Tóth et al., 2013; Ma et al., 2015; Zhao et al., 2007). For the shallow penetration depth in hard rock disc cutting, crack network can well propagate and rock chips will successfully form with disc cutter cutting force less than the nominal cutter load-bearing value. Whereas disc cutters with same penetration depth rolling onto soft rock surface may lack of necessary penetration depth to fragment and chip the rock, resulting in merely crushed craters without efficient rock breakage. Thus a few times of disc cutting passes are practically required for effective fragmentation and chipping of the soft rock. In multi-pass disc cutting process, soft rock formations under the indentation-rolling effect of TBM disc cutters is repeatedly subjected to the 'compaction, unloading, and re-compaction' process, with the induced changes in rock mechanical and physical properties. For now, the strength and deformation behaviors of the excavated soft rocks, initiation and propagation of the new-induced and pre-existing cracks are not fully investigated, same to the efficiency determination and performance optimization of rock fragmentation process under TBM disc cutters. The above-mentioned theoretical and technical problems are extremely unfavorable for the penetration rate prediction and tool consumption analysis in TBM tunneling. For this reason, comprehensive investigation on the evolution process and rule for soft rock fragmentation behaviors in multi-pass disc cutting process are of conceptually guiding importance for parameter selection of TBM tunneling in complex geological conditions, especially in mixed ground conditions and soft rock formations.

However, the testing machines for multi-pass linear rock cutting tests are only available in quite few institutes. Therefore, researchers may be interested in establishing the correlations between the two types of damaged zones that are either induced by multi-pass disc cutting or multi-indentation. Thus in this study, the RMT-150C electro-hydraulic servo rigidity testing machine is employed for the multi-indentation tests conducted on cubic cement mortar specimens with six pre-set penetration depths by using a small-scale self-manufactured constant cross section (CCS) disc cutter. The penetration load, peak-load penetration depth, rock breakage work and compacted zone depth of each multi-indentation test with different pre-set penetration depths are analyzed to obtain the evolution process and rule of the mechanical and deformation properties of the soft rock in multi-indentation tests by a single TBM disc cutter. The result of this research would contribute to deeper understanding of soft rock mechanical response in multi-indentation process, thus providing theoretical basis and practical guidance for the determination of operation parameters in TBM tunneling.

2. Experimental procedures

The main purpose of this study is mainly focused on the analysis on the strength and deformation properties and fragmentation process of the cement mortar specimens in the multi-indentation tests by a single TBM CCS disc cutter. Thus the testing system generally consists of three main parts: loading system for rock indentation test, self-manufactured CCS disc cutter and cement mortar specimens.

2.1. Loading system for rock indentation test

The loading system employed for indentation tests is the RMT-150C electro-hydraulic servo rigidity testing machine, which is widely applied for the mechanical property tests of rock- and concrete-like materials. The indentation tests are conducted in vertical displacement travel control mode with loading rate of 0.005 mm/s for the simplicity of quasi-static loading. The frame stiffness is about 5000.0 kN/mm, and thus can be roughly regarded as rigidity machine when compared with the relatively low reaction stiffness and elastic modulus of the indented specimens. The vertical load (penetration load) and indentation depth (penetration depth) are automatically recorded and transferred through the sensors mounted on the loading jack during the indentation tests. To reduce the potential risk of sudden splitting failure during loading, the left and right sides of specimens are restricted with rigid pressing plates, which can offer 0.1 MPa initial confining stress, and then fixed as lateral displacement confinements during the multi-indentation tests.

2.2. Self-manufactured CCS disc cutter

For the tested specimens are cement mortar with relatively low strength and stiffness, and the effective loading space of the testing machine is strictly limited, thus the self-manufactured small diam-