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Physical and numerical studies of rock fragmentation subject to wedge cutter indentation in the mixed ground

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ABSTRACT

To study the effects of the mixed ground conditions on the cutter force and failure pattern during the tunnel boring machine (TBM) excavation, rock cutting tests under wedge cutter are conducted both in the physical experiments and the bonded particle model (BPM) numerical simulations. The results of simulation are generally comparable with those of experiments under single cutter. It demonstrates that the softer bottom material causes more disperse stress distribution which leads to wider AE accumulated area and more rapid displacement change in the indentation direction. Further simulations are conducted under double cutters. Crack may propagate deeper into the specimen due to the weaker bottom material. When the inclination of the material interface changes, the failure pattern of the specimen becomes highly asymmetric and the forces of the two cutters are not equal any more. Frequent change of ground conditions causes high asymmetric cutter force distribution, frequent changing cutter force as well as high eccentric moments on the cutter head.

1. Introduction

Nowadays tunnel boring machine (TBM) is widely used in rock tunnel excavation. A better prediction of the TBM performance will reduce the construction time and cost (Zhao et al., 2007). Among many factors that influence the TBM performance, rock mass properties and the layout of the disc cutters are the dominant. Complex geological factors, such as faulted zone, mixed face and joint conditions, may lead to serious problems (Gong and Zhao, 2007; Huo et al., 2011). To better understand the cutting processes under TBM cutters and fragmentation mechanism for rock mass, many rock cutting tests have been conducted. Yin et al. (2016) studied the influences of joint spacing using full-scale linear cutting tests. Gertsch et al. (2007) measured the normal, rolling, and side forces for a series of full-scale cutting tests. Innaurato et al. (2006) studied the rock breaking and chipping behavior on a rock specimen under high stress confinement. Snowdon et al. (1982) performed rock cutting on different rock types to measure cutter forces and specific energies. However, the microscopic mechanism of rock fragmentation is often not well understood due to the limited measurement in physical tests (Li et al., 2016). Numerical modeling methods give more direct observations compared to physical tests thus it is widely used to study the mechanism of rock fragmentation. A lot of numerical researches have been conducted to study the fracture process in rock cutting. Cook et al. (1984) used finite element method (FEM) to study the rock fragmentation process induced by flat-bottomed punch. Gong et al. (2005, 2006) used universal distinct element code (UDEC) to study the influence of joint spacing and orientation on rock fragmentation by TBM cutters. Tan et al. (1998) used displacement discontinuity method (DDM) to simulate crack development by indentation tools. Zhai et al. (2016, 2017) and Zhou et al. (2015) applied the general particle dynamics (GPD), a meshless numerical method, to study the fracture process in rock cutting. The pre-existing flaws and intermittent joints were found to have significant effects on the crack initiation and coalescence thus affect the performance of TBM cutters. Oñate and Rojek (2004) combined the bonded particle model (BPM) with FEM to simulate the rock cutting process. Moon and Oh (2012) used the BPM to study the efficiency of TBM performance under different cutting spacing/penetration ratios. Su and Akcin (2011) used the BPM in Three-Dimensions to measure the cutter forces during rock cutting. Li et al. (2016) used the BPM to study fragmentation mechanisms under different wedge cutters. Among the common used numerical methods, the bonded particle model (BPM) seems a realistic way to reproduce cracking behavior. The BPM, as a discrete element model, allows separate bodies to be attached or apart. It is capable to reproduce rock mass that is heterogeneous in nature (Cundall and Strack, 1979; Potyondy and Cundall, 2004; Rostami, 2013). Huang (1999) investigated the scale laws for the 2D assembly and found that the micro bond strength ratio controls the failure mode, i.e., a larger shear bond strength to normal bond strength ratio indicates more brittle failure mode. Huang et al. (2012) and Huang and Detournay (2013)

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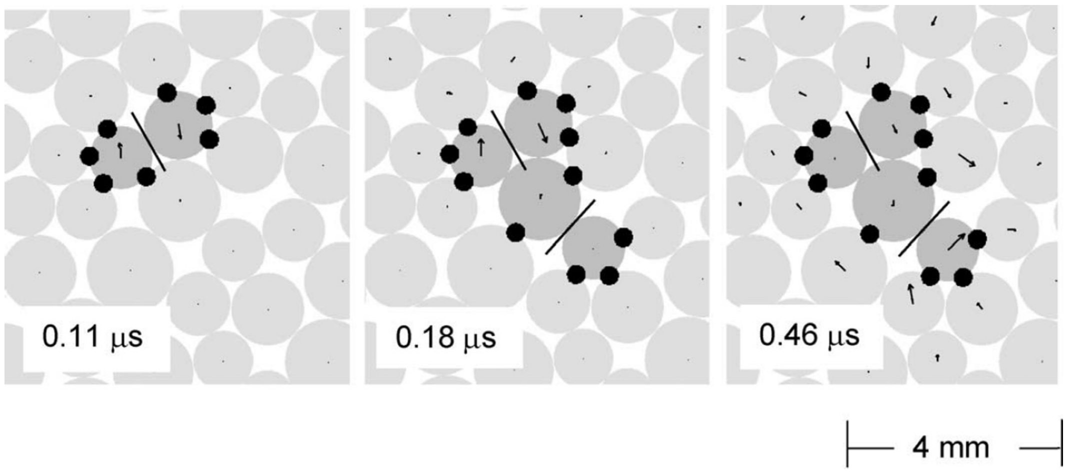

Fig. 1. Evolution of an AE event composed of two shear micro cracks. The contacts surrounding the source are indicated by small black circles. From Hazzard and Young (2002). Times given are from the time of the first bond breakage.

studied the transition from a ductile to a brittle failure mode with the increasing cutting depth, the decreasing material characteristic length and decreasing confining pressure. Helmons et al. (2016a, 2016b) and Helmons (2017) coupled the DEM with the Smoothed Particle approach to study the pore fluid pressure effect in the cutting process on saturated rock. It was found with increasing hydrostatic pressure, the failure mode changed from micro-tensile dominated to micro-shear dominated. Rojek et al. (2011) used DEM to model cutting processes with a roadheader pick and got good agreements with experiment measurements.

Generally, analytical models for TBM performance are established based on a single infinite ground condition, i.e., Lawn and Swain, 1975; Evans, 1965; Peng et al., 1989; Paul and Sikarski, 1965. Some prediction models based on data obtained from lab tests also lacks a consideration for mixed ground condition (Roxborough and Phillips, 1975; Rostami et al., 1994), even though having considered the joint effects (Benjumea and Sikarskie, 1969; Sanio, 1985; Howarth and Roxborough, 1982). When TBM tunneled through the mixed ground, great difficulties occurred such as high cutter wear, flat cutters and instable tunnel face (Zhao et al., 2007). A few researches have been conducted to study the effects of the mixed ground conditions. Yang et al. (2016) used a theoretical approach to analyze cutting forces and damage zone under mixed ground conditions. Liu et al. (2015) used numerical manifold method (NNM) to study rock fragmentation process under double cutters in mixed ground. In the present study, physical tests and numerical method using the bonded particle model (BPM) are conducted to study the effect of mixed ground conditions in the cutting process. The cutter forces, failure pattern and acoustic emission events (AE) are carefully analyzed.

2. AE simulation in the BPM and modeling of the mixed ground

2.1. Bonded particle model and AE simulation

As many previous studies have introduced the principle of bonded particle model (BPM) (Potyondy and Cundall, 2004), the present study will only give a brief description of it. As a discrete element model (DEM), the BPM contains two main types of models namely "contact bond model" and "parallel bond model". In the contact bond model, particles are joined by a point of glue and contacts cannot transfer moment. While in the parallel bond model particles are joined by an area of glue and contacts can resist moment induced by particle rotation. Thus the parallel bond model can represent a cement-like substance, such as rock. Zhang and Wong (2012) extended the comparisons to the cracking characteristics of specimens that contain flaws, such as the crack initiation position, crack initiation angle, overall cracking pattern and macroscopic specimen strength, which are obtained from physical tests. Many researches demonstrate that the BPM has the capability to realistically simulate the cracking processes in rock-like material (Zhang et al., 2015; Zhang and Wong, 2012, 2013a). However there are still some important issues concerning with the DEM. The difference between the size and shape of the elements with real grains leads to cross effects with the micro parameters on the macroscopic behavior. A size effect exists as the fracture roughness of the material depends on the radius of the discrete elements (Potyondy and Cundall, 2004; Donzé et al., 2009). In the present study, the parallel bond model conducted by a commercial software Particle Flow Code (Itasca, 2004) is used to simulate the cracking processes in gypsum subject to wedge cutters.

In the BPM, when the local stresses exceed the bond strength, a bond breakage occurs and a single micro crack forms. Bond breakages occurring in close time and space are considered to be within the same acoustic emissions (AE) event. For a single AE event, the duration of the event is defined as twice the time for a shear wave to propagate one particle diameter length. A new bond breakage that falls adjacent the existing bond breakage contained in the AE event is considered within this AE event if it is still active, i.e., the current bond breakage time is within the AE event duration since the first bond breakage. An example is shown in Fig. 1. During the calculations, moment tensors are calculated every step and the maximum moment tensor is recorded for every AE event. More details about simulating AE events in the BPM, readers can refer to Hazzard and Young (2000, 2002), Zhang et al. (2017) and Zhang and Zhang (2017a).

2.2. Scenarios of the mixed ground

There are three types of materials in the present study, namely hard material, medium material and soft material. "H", "M" and "S" indicate hard material, medium material and soft material, respectively. In the BPM, the uniaxial compressive test is generally employed to calibrate the macro properties of rock, such as Young's modulus, Poisson's ratio and uniaxial compressive strength (UCS). Their macro properties