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Tunnelling and Underground Space Technology 21 (2006) 46–55

Tunnelling and Underground Space Technology incorporating Trenchless Technology Research

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Numerical modelling of the effects of joint spacing on rock fragmentation by TBM cutters

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Received 3 January 2005; received in revised form 2 June 2005; accepted 9 June 2005
Available online 10 August 2005

Abstract

The influence of joint spacing on tunnel boring machine (TBM) penetration performance has been extensively observed at TBM site. However, the mechanism of rock mass fragmentation as function of the joint spacing has been scarcely studied. In this study, the rock indentation by a single TBM cutter is simulated by using the discrete element method (DEM), and the rock fragmentation process is highlighted. A series of two-dimensional numerical modelling with different joint spacing in a rock mass have been performed to explore the effect of joint spacing on rock fragmentation by a TBM cutter. Results show that the joint spacing can significantly influence the crack initiation and propagation, as well as the fragmentation pattern, and can hence affect the penetration rate of the TBM. Two crack initiation and propagation modes are found to fragment the rock mass due to the variation of joint spacing. The simulation results are analyzed and compared with in situ measurements.

Keywords: TBM cutter; Fragmentation; Joint spacing; Crack; UDEC

1. Introduction

With the significant advances of TBMs concerning the capacities of thrust and torque as well as the development of large diameter rolling cutters, TBM is extensively utilized in rock tunnel excavation and its performance prediction in different rock masses has become an important topic for project planning and choice of tunneling methods. In the past years, many prediction models have been proposed based on the site observations and laboratory tests. Some are single factor models that are only suitable for estimating the performance of TBMs on homogenous and isotropic rocks (e.g., Graham, 1976; Nelson et al., 1985; Hughes, 1986). Some are comprehensive models that are based on laboratory testing and in situ observations. In these models, the significance of joint spacing on TBM performance is emphasized (Bruland, 1998; Cheema, 1999; Barton, 2000). But, there seems to be a lack of complete understanding of the rock cutting process due to the very complex nature of the interaction of TBM cutters and rock masses (Rostami et al., 1996).

Howarth (1981) studied the impact of spacing of a set of joints on TBM performance using rock cutting rig in the laboratory. In his study, the strike of the joint set was parallel to the axis of the tunnel. The spacing varied from 20 to 100 mm and the angle of cutting attack from 30° to 90°. The experimental results showed that the smaller the spacing, the less is the thrust force required to penetrate a fixed depth. Wanner and Aeberli (1979) studied the effects of different kinds of discontinuities on TBM performance. The total area of all joint planes per unit volume of excavated rock was used as

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0886-7798/$ - see front matter
doi:10.1016/j.tust.2005.06.004

a quantitative expression of joints in the rock mass. By field observations, it was found that tight joints and fissures produced by tensile stresses in rock mass did not improve the TBM performance. On the contrary, for joints caused by shear stresses with gauge material, mylonites and fractured rock zones, they lead to an increase of the penetration rate. Laughton et al. (1994) proposed a joint impact index (JII) to evaluate the effect of joints on TBM performance. A length, which was equal to twice bored tunnel diameter, was used as a survey unit cell length. Within the unit cell, eight scanlines perpendicular to the tunnel axis was used to quantify the cell's joint intensity. The total number of joint intercepts was counted for these eight scanlines, and the number of joint intercepts per bored diameter of scanline was reported as an average joint intensity. With the increase of JII, the penetration rate increases. When the JII ranges from 4 to 6, the penetration rate reaches the maximum. As the jointing becomes more extensive, the face itself becomes more unstable, and leads to "blocky condition", resulting in a negative influence on penetration rate. Bruland (1998) divided discontinuities into three types, namely, fissure, joint and single marked joint. Fissures and joints were then classified into four classes. Based on a large number of case histories, a fracturing factor was obtained according to the type and class of discontinuities. With the decrease of the joint spacing, the TBM penetration increases distinctly (Bruland, 1998).

Due to the theoretical difficulties, numerical modelling methods have been used to probe into the mechanism of rock fragmentation. Amongst them, finite element method (FEM), finite difference method (FDM) and discrete element method (DEM) may be the most commonly applied approaches. Cook et al. (1984) employed a linear axisymmetric elastic finite element model to simulate the fracture process in a strong, brittle rock by a circular, flat-bottomed punch. Chiaia (2001) incorporated a lattice model into the FEM program to model the penetration process in heterogeneous material by a hard cutting indenter. It was revealed that the dominant modes of the indentation mechanisms are the plastic crushing and brittle chipping. Based on rock failure process analysis model, Liu et al. (2002) presented a numerical code R-T^{2D} to reproduce the progressive process of rock fragmentation by indenters. The failure process of the rock and the realistic crack pattern were observed. Other simulations of brittle material penetration by high speed hard projectile using FEM and FDM (finite difference method) procedures were also reported (Hanchak et al., 1992; Resnyansky, 2002). Generally speaking, the current numerical efforts mainly concentrate on the modeling of indentation in continua, and modelling of fragmentation in discontinua is limited. The DEM, which was originally developed for quasi-static problems (Cundall, 1971; Jiao et al., 2004), has been applied in rock dynamics recently (Chen and Zhao, 1998; Fan et al., 2004). Gong et al. (2005) employed DEM to investigate the joint orientation effects on rock fragmentation by TBM cutters. The simulated relationship between joint orientation and TBM penetration rate has a good agreement with that from the site observations. This paper presents a sequential study on rock fragmentation by TBM cutters by Gong et al. (2005). The joint spacing effects on indentation of rock mass are highlighted and modeled by using the 2D DEM code UDEC (Universal Distinct Element Code) (Itasca, 1996), and the obtained numerical results are compared with those from the field observations.

2. Discrete element model set-up

As shown in Fig. 1, the dimension of all the computational models is 0.6 m × 0.6 m, and one set of vertical joints is included. The joint spacing varies from 10 to 500 mm. The dip direction of the joint set is assumed to be perpendicular to the cutter loading direction. The cutter is modelled by a normal force applied at mid height of the left boundary through contact thickness of 15 mm. Since it is 2D modeling, the rolling force acting on the cutter cannot be taken into consideration. The upper, lower and right boundaries are regarded as fixed displacement boundaries. The rock blocks between the set of joints are discretized with fine finite difference meshes, namely zones in UDEC. The zone size is 5 mm and the damping value 0.1. In order to compare with the in situ TBM penetration performance in granite rock mass in Singapore later, the rock mass modeled is typical granite distributed in Singapore. The rock material properties and joint properties are summarized

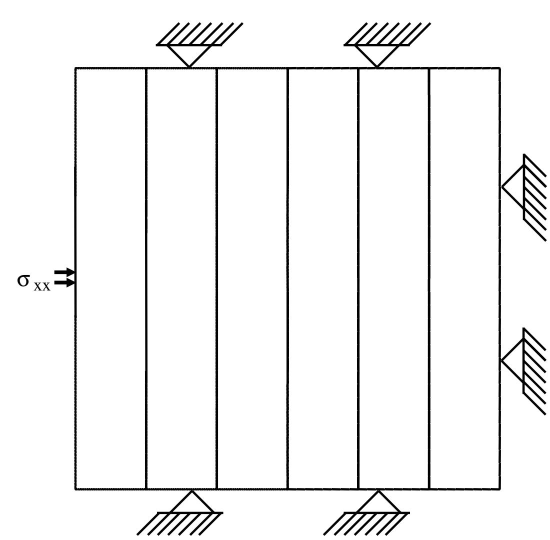

Fig. 1. Numerical simulation model with joint spacing of 100 mm.