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Simulation of rock fragmentation by TBM disc cutter using the hybrid finite-discrete element method

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Summary

The tunnel boring machine (TBM) disc cutter chipping process was studied using a numerical model implementing the finite discrete element method (FDEM) in two-dimensional (2D) space. Disc cutters were simulated as indenters penetrating a rock to a prescribed depth, and the fracture patterns for different cutter spacings were examined. The results displayed fracture patterns typical for disc cutting and the modelling process provided important considerations required to model a TBM disc cutter using 2D FDEM.

Introduction

The rock fracture pattern created by the TBM disc cutter chipping process is described by Rostami & Ozdemir (1993). First, a crushed rock zone develops underneath the disc cutter being rolled on the rock surface to create a cut. Then, tensile cracks initiate from the crushing zone through a transition zone and propagate away from it. As multiple disc cutters roll along the rock, chips form through cracks connecting between these cuts. In order for this chipping process to be at its most efficient, the amount of energy applied on the rock per volume of cut rock must be minimized using the cutter spacing (Rostami & Ozdemir, 1993).

The combined finite discrete element method (FDEM) was used to observe both the development of the crushing zone and the tensile crack pattern typically seen by TBM disc cutters within intact rock. A model was developed simulating a linear cutting machine test for disc cutters was developed in 2D. The cutting forces and the chipped rock area were recorded during the simulation to obtain the specific energy of the cutting process. The simulation results highlighted important considerations required in modelling the disc cutting process using FDEM.

Theory and/or Method

FDEM is able to simulate rock fracture propagation and material interaction using basic geomechanical properties (Mahabadi et al., 2012). With these two modelling processes, FDEM can reproduce the crushing of particles while transmitting force. This is advantageous in simulating the crushing zone underneath a TBM disc cutter. This is also important since the crushing action and the load transfer between the disc cutter and the rock should be considered in modelling the disc cutter chipping process (Geng, Wei, & Ren, 2017). A 2D model of the linear cutting machine test was developed consisting of an idealized disc cutter tip and a rectangular rock sample. Disc cutters were implemented as flat-tipped rigid bodies with a 15 mm wide contact width and a velocity constraint simulating a point on the rolling edge of a disc cutter. Its velocity was determined based on the linear cutter speed, the cutter radius, and the disc penetration. The cutters were also spaced for a given penetration depth. The rock was discretized using a 2D Delaunay triangulated mesh using a nominal element size of 4mm. The rock constrained with pins on the bottom and rollers on the sides (Figure 1).

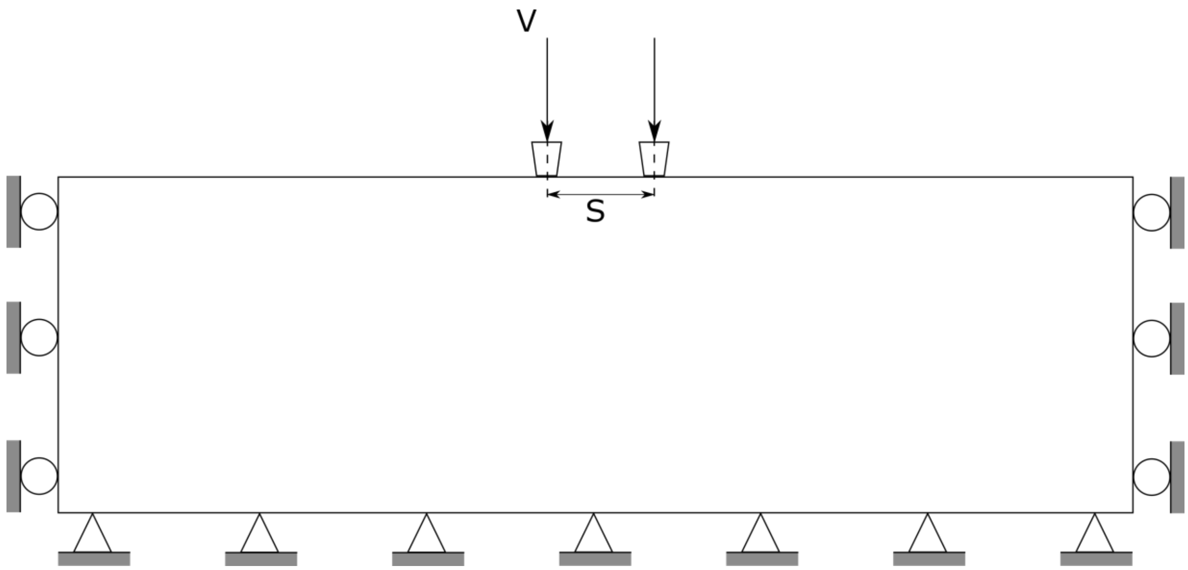

Figure 1. Geometry and constraints of the TBM disc cutters and rock sample. Rigid disc cutters are spaced by S using an s/p ratio and an enforced penetration rate, p. The velocity, V, is set to reproduce the vertical displacement of the cutter with a set penetration and cutter radius.

Material data for Hwangdeung granite was used as reported by Cho et al. (2010) to compare the FDEM model results to linear cutting machine tests. The material strength was calibrated using simulated uniaxial compressive strength (UCS) tests and Brazilian tensile strength (BTS) tests. The only data for fracture parameters provided for the granite was Mode I fracture toughness. However, using this data to estimate the Mode I fracture energy resulted in tensile fractures propagating excessively. Instead, the model was calibrated through successive disc cutter tests until the fracture lengths appeared reasonable under a single-cutter indentation.

Results

Since the contact surfaces of the cutter disc tips were flat, large shear stresses started to appear in the rock adjacent to the tip corners and fracture initiation from stress concentration. The rock immediately underneath the cutters began failing by Mode II fracturing. A cone underneath both cutters developed as a crushing zone and started opening the “median crack”, or the crack typically found at the cutter centreline, as a tensile crack as described by Rostami & Ozdemir (1993). However, most of the other tensile cracks formed to open passageways for the crushing zone rock fragments (Figure 2). These passages formed when the walls containing the crushing zone fractured away and the crushing zone rock fragments were ejected through the sides. After the crushing zone rock fragments were expelled, the cutter was no longer able to transfer load to the rock as it continued the velocity-constrained penetration.

The normal cutter forces and the surface area of displaced rock chips were recorded for each simulation. A mean normal force was calculated for each cutter after the simulation. Specific energy was then calculated as the product of the penetration depth and the normal force applied by both cutters divided by the total chipped area. However, an element size of 4mm was found to be oversized since many elements broke off into singular elements and started wedging between intact connected elements. It is important to note that elements do not undergo failure by themselves and can only fail along the element boundaries. Artificial fracturing started to form as a result of the wedging and the total chipped area in the model was overestimated. In the worst case, approximately 33,000 mm^2 of debris was collected from the model representing 16.5% of the rock sample cross-section. This significantly reduced the specific energy by orders of magnitude compared to the specific energy from linear cutting machine tests reported by Cho et al. (2010). Therefore, the specific energy could not be reasonably determined by these models in their current form.

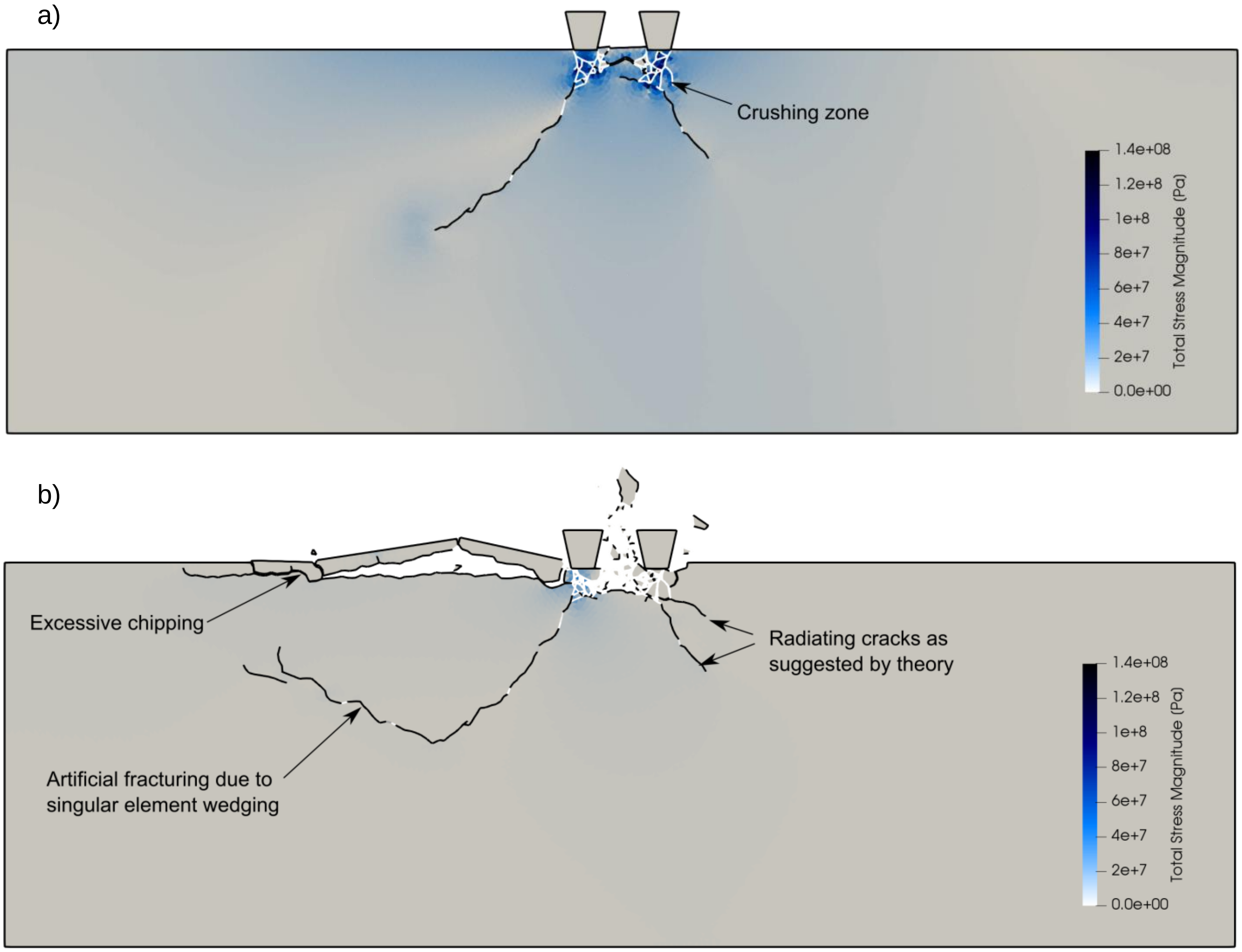

Figure 2. (a) Fractured model with s/p = 12 and 4 mm penetration before crushing zone is expelled. The model extents and Mode I fracturing is shown in black. Mode II fracturing and Mixed Mode I-II is shown in white. The total stress magnitude is shown in blue. (b) Fractured model after the crushing zone is expelled.

Development of a crushing zone is important in capturing realistic fracturing of the disc cutting process. A crushed powder develops underneath the moving disc cutter and transfers the load to the rock creating tensile cracks. However, the stress distribution within this zone is very complex (Geng et al., 2017). Although this crushing zone appeared in the simulation, the rock elements underneath the cutter tips were too large and needed to be further refined. However, the refinement of the elements is limited by the processing time desired and must be considered when selecting the element size. The element size should be chosen to allow a sufficient number of elements to make contact with the cutter tip width and should be less than the desired penetration depth.

The cutter geometry can also be improved at the contact surface. Since the development of high shear stresses on the cutter corners leads to fracturing, the crushing zone particles are more likely to be expelled away from the cutter too early in the simulation. This prevents the cutter from transferring load to the rock. A smaller flat contact surface with a slight taper on the corners may simulate a more realistic disc cutter. It may also help prevent crushing zone material from being discharged too quickly.

Conclusions

The TBM disc cutter chipping process was simulated using FDEM. The crushing zone and the median crack created through disc cutting (Rostami & Ozdemir, 1993) were observed. Although the results were affected by artificial fracturing through singular element wedging, much of the crushing zone behaviour and the radiating cracks were captured by the model. Mode II fractures dominated the crushing zone and Mode I fractures were typically observed in radial cracks. The crushing zone was able to transfer load from the cutter until the rock supporting the sides failed. Crushing zone material was ejected afterwards due to the high stress.

Artificial fracturing due to the element size produced an excessive amount of chipping debris. The model can be improved to reduce artificial fracturing by capturing the crushing zone behaviour using smaller elements around the cutter tips. The size of the element must balance the need for small particles and the computation power available. The cutter tip can also be refined with a slight taper to reduce the amount of particles being expelled too quickly.

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