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Selection of Geometrical Parameters for Discrete Element Modeling of Rock Cutting

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***Abstract*—Rock cutting is modeled using discrete element modeling in which the cutter is defined by solid walls, while a rock sample is approximated as a packing of bonded spherical particles following certain interaction laws. This paper presents analysis of the numerical effects on the cutting force destroying the rock that are due to the elements size and configuration of the model. The content includes the computation results along with recommendations on selection of the numerical model parameters of a sample to obtain required accuracy of modeling.**

***Index Terms*—discrete element method, rock cutting, discrete element size**

I. INTRODUCTION

The understanding the mechanics of rock cutting and the development of an adequate model of the process are crucially important for many industrial applications such as wellbore drilling, mining and building of tunnels, etc. When drilling wells for various purposes, bits with polycrystalline diamond cutters (PDC) are widely applied. The tool requires proper estimation of the forces affecting the bit's cutters. The information is essential for designing various schemes of cutter placement on the bit body as well as for designing new and improved cutter shapes.

The application of experimental methods for studying rock cutting is limited by their high cost and complexity. Therefore, it is necessary to develop new mathematical models and algorithms to replace such experimental studies and use experimental data for verification of the models developed. The Discrete Element Method (DEM)is a tool that enables rock cutting to be analyzed at the local level by paying attention to details.

The main concepts of DEM in application to porous media are presented in [1]. The issues of particle interaction mechanics are described in [2], [3]. The general observation of the method can be found in [4]. The fast development of computational technologies has made it possible to model more complex systems that include millions of particles. Therefore, DEM is a popular and effective technique for solving various engineering problems in the mechanics of granular materials and rocks.

The DEM was used for the modeling of rock deformation processes since the end of the nineties [5], [6]. The modeling parameters are selected from the correlation between the results of numerical modeling and experimental data from the main tests that determine the mechanical features of rocks (such as the uniaxial and triaxial compression tests and the Brazilian test to determine tensile strength).

Developing the approaches presented in [6], in [7] the author proposed the rock cutting algorithm for a single cutter that utilizes DEM via Particle Flow Code (PFC) software (Fig. 1). The main objective of such modeling is estimating the reaction forces affecting the cutter's surface under various cutting conditions.

Drilling a certain part of rock mass is affected not only by the cutters, but also by the stresses from the surrounding rock and by the pressure of the drilling fluid. To model such conditions an algorithm to describe the confining pressure acting on the sample and presented as a set of boundary conditions must be applied.

II. ROCK CUTTING: KEY STAGES OF DEM MODELING

The following are the key stages of modeling a rock cutting process with a single cutter in the PFC3D package.

In the first stage, a discrete sample is generated. For each of the sample's microparameters such as particle elasticity modules, friction coefficient and bonding forces, the calibration is performed using a triaxial compression test. The microparameters are selected in such a way that the elasticity module and maximum compressive strength correspond to the experimental data obtained from real samples [6], [8]. To further strengthen the sample a certain amount of 'indestructible bonds' between the particles should be created and their amount serves as an additional calibration parameter.

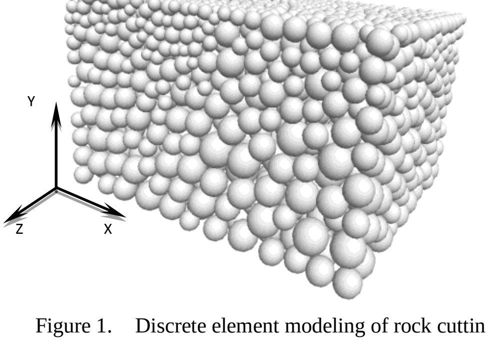

Figure 1. Discrete element modeling of rock cutting.

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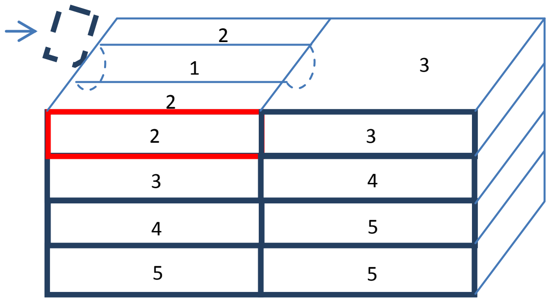

Figure 2. Breaking a discrete sample into layers.

After the calibration and the determination of the microparameters, a sample is created for rock cutting modeling. The sample must contain a number of layers with particles of various sizes. The contact zone around the cutter must contain small particles, the size of which are determined by the cutter's geometry; those particles that are farther from the cutter can be bigger to reduce the required computation time. Similar approach is presented in [9].

Fig. 2 is an example of such a multilayered sample. The crucial condition is to guarantee that the layer with the minimum particle radius in the cutting area is surrounded by layers where the particle radius exceeds the minimum one no more than 2 times. Otherwise, sample generation results in the smaller particles penetrating into the neighboring layers and diffusing the layer boundaries.

The Fig. 2 sample includes 4 layers. While modeling the particle radius, the length and width of the layer varied in layer 2. Table I shows the variation. Additionally, in the cutting area under the cutter, the layer 1 with the minimum particle radius equal to 75 % of the minimum particle radius in layer 2 is created. Layer 3 comprises particles with the minimum radius of 1.3 mm and is 8-mm-thick. Layer 4 has the minimum particle radius of 1.6 mm and the thickness of 10 mm. Layer 5 comprises a radius and thickness of 2.0 mm and 13 mm, respectively.

Next, the confining pressure is applied to the generated sample. In general, to model the pressure acting on a boundary comprising discrete elements, determine which elements form the boundary surface and set a force to be applied to each such element. To model the confining pressure in PFC3D for big deformations that change the boundaries of a sample, a combined algorithm developed by authors earlier is applied. The details of the algorithm and general modeling process are described in [10].

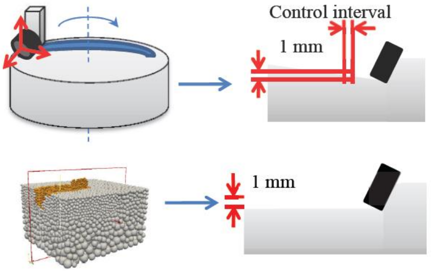

Figure 3. Control interval of cutting in experiment (top) and modeling (bottom).

After the confining pressure is applied, the horizontal cutting of a stress-balanced sample with a single cutter is modeled at a given velocity. In this case, unlike the experiment of cutting a cylinder along its surface with a given penetration depth, the cutting of a parallelepiped is modeled along one of its sides with a constant cutting depth (the 2D sections of the cutting geometry can be observed in Fig. 3).

Therefore, to provide a correct comparison with the experiment, the data from a relatively small time period within which the depth of cut in the experiment is almost constant is employed. Moreover, a virgin sample is modeled; in the experiment, though, a damaged rock is cut beginning from the second cutter revolution. That is why the data gathered during the first cutter revolution must be applied.

III. DISCRETE SAMPLE: VARIATION OF PARAMETERS IN CUTTING MODELING

A rock sample 82x30x56 mm in size was modeled. The cutter velocity was 1 m/s and the confining pressure was 20 MPa. In the modeling, a discrete model of the sample meeting the deformation and strength characteristics of Carthage limestone [7] was used.

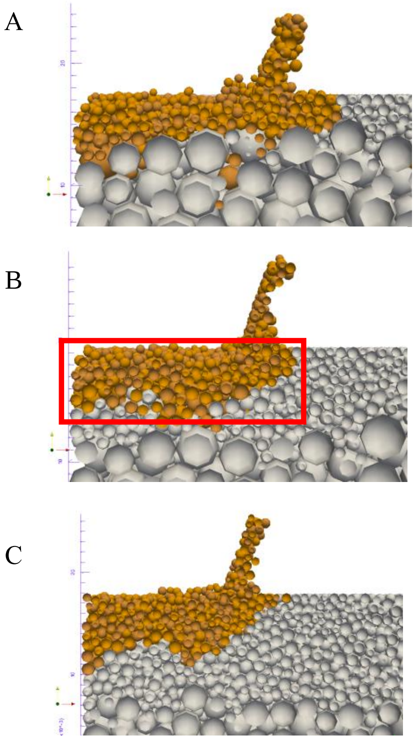

Figure 4. Destruction zones in z-section under a cutter with the upper layer thickness of 4mm (A), 8 mm (B) and 12 mm (C).

To determine the necessary thickness of the upper layer, the destruction zone in the sample was studied, i.e. the zone where the particles lost all bonds with any other particles. The zone was visualized in the midsection of the sample in the vicinity of the cutter (Fig. 4). For the modeling parameters (given above), the zone depth was calculated as 6 mm. The orange color marks the particles with no bonds. To test if the destruction zone thickness does not depend on the size of the model's upper layer, cutting modeling was performed for the layers with 4 mm, 8 mm and 12 mm thickness. The modeling demonstrated that if the upper layer thickness increases to more than 6 mm, the destruction zone thickness remains the same (Fig. 4). If the destruction zone thickness is bigger than thickness of the upper layer (case A), the particles lose their bonds even in the lower layers. Therefore the upper layer thickness was set to 8 mm to include the entire destruction zone.

TABLE I. DISCRETE SAMPLE PARAMETERS FOR CUTTING MODELING

Sample size	0.082 x 0.039 x 0.056 [m]
Minimum particle diameter	*0.3 [mm] – 1 [mm]*
r_{max}/ r_{min}ratio	1.6
Confining pressure	20e6 [Pa]
Cutter thickness	0.008 [m]
Cutter diameter	0.016 [m]
Chamfer	0.000406 [m]
Depth of penetration	0.001 [m]
Cutting velocity	1 [m/s]

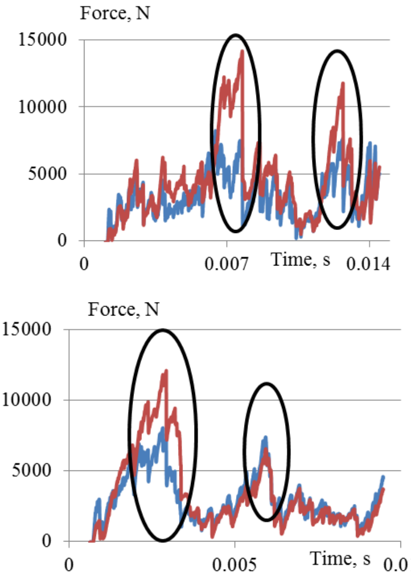

Figure 5. Vertical (red) and horizontal (blue) forces affecting cutter’s surfaces for a sample with the particle radius of 0.5 (upper) and 0.375 (lower) mm.

In DEM modeling, bigger particles must be utilized to reduce computation time. On the other hand the smaller the particles utilized, the more adequately the modeling reflects the behavior of a real porous medium. Moreover, the complex geometry of the cutter with a chamfer is crucial for selecting an optimal minimum particle size. To determine the optimum size, cutting modeling was performed with particles with minimum radius of 0.3, 0.375, 0.5, 0.6, 0.7 and 1.0 mm. The cutting of first 16 mm of the sample was modelled. Fig. 5 shows the vertical and horizontal components of force acting on the cutter’s surfaces for the minimum particle radius of 0.5 and 0.375 mm. The obtained data contains the peaks, of which the amplitude is reduced in conjunction with the particle radius.

One possible explanation of the peaks can be a particle getting onto the cutter’s edge, increasing dramatically the interaction force between the particle and the cutter. This force in turn contributes to the joint force affecting the cutter. It also explains why these peaks decrease with the particle size.

TABLE II. RELATIVE MEAN-SQUARE DEVIATION OF MODELING RESULTS.

Min. particle radius [mm]	Δ, %	MSE, %	Num. of particles	Time, hours
1.0	86.98	36.16	3754	12
0.7	72.65	26.39	6679	24
0.6	66.28	15.79	9337	44
0.5	53.87	8.47	14632	55
0.375	48.64	-2.5	36053	180
0.3	39.88	1.45	43163	306

When processing the modeling results, it was found that the mean-square deviation from the data’s average value is also reduced with the particle size. The values of the relative mean-square deviation are calculated using the formula (1):

$$\Delta = \sqrt{\sum \frac{(x-\bar{x})^2}{n\bar{x}^2}} \cdot 100\% \qquad (1)$$

where $\bar{x}$ denotes the arithmetic average value and n is the number of points(Table II, Δ).

The number of particles and computation time was increased with decreasing particle radius almost exponentially (Table II).

For comparing with experiment the results of the modeling of cutting the rock sample 82x30x56 mm with a cutter velocity of 1 m/s and a confining pressure 20 MPa are provided. A discrete model of the sample corresponds to the deformation and strength characteristics of Carthage limestone [7]. The output parameters of the modeling are the force acting on the cutter and mechanical-specific energy (MSE). MSE is the amount of work required to cut a unit volume of rock. Fig. 6 shows the comparison between mechanical-specific energy measured in experiment and estimated from modeling.

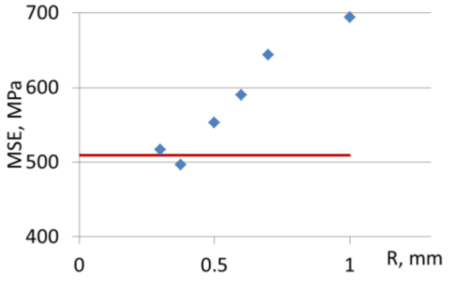

Figure 6. Mechanical-specific energy (MSE): experiment (red line) and modeling results (blue markers).

As the minimal particle size in cutting area decreases, the average value of MSE gets closer to the experimental value (Table II, MSE). If the radius of the particle is smaller than the cutter chamfer (0.4 mm), the difference between modeling and experimental results is stable and does not exceed 5%.

IV. CONCLUSION

This paper analyses the effects of typical discrete element sizes and discrete sample configuration on the results of DEM of cutting modeling. The study shows that:

- To optimize the computation time and preserve the correctness of the modeling, a layered sample must be employed with smaller particles in the cutting area and with bigger particles at a particular distance from it;
- The thickness of the top layer with the smallest particles must exceed the thickness of the destruction zone;
- The particle size in the bottom layers must not be more than two times larger than the particle size in the upper layers;
- Reducing the minimum particle size in the upper layer decreases the peaks in the modeling data as well as their mean-square deviation;
- Computation time was increased with decreasing particle radius almost exponentially;
- The error in mechanical-specific energy estimated from modeling when the minimal radius of the particle is smaller than the cutter chamfer (0.4 mm)is less than 5%.

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