DISCRETE ELEMENT SIMULATION OF ROCK CUTTING WITH EVALUATION OF TOOL WEAR

Jerzy Rojek[1], Carlos Labra[2], Eugenio Oñate[2]

[1]*Institute of Fundamental Technological Research, Polish Academy of Sciences, Warsaw, Poland*

[2]*International Center for Numerical Methods in Engineering (CIMNE), Barcelona, Spain*

This paper presents numerical modelling and simulation of rock cutting processes. The rock is modelled using spherical discrete elements. Estimation of tool wear has been included into the numerical model. The discrete element model has been calibrated by simulation of the UCS and Brazilian tests. Rock cutting with a single point attack pick of a roadheader has been studied experimentally and numerically. A good qualitative and quantitative agreement of numerical results with experimental measurements has been found out.

INTRODUCTION

Variety of rock-cutting technologies is used in civil as well as in mining engineering. Design of cutting tools and setting parameters of cutting operations requires knowledge about the cutting process and its parameters. Cutting forces and tool wear are important factors characterizing a cutting process. Experimental studies of cutting processes are expensive and require a lot of tests to check different tool designs and their performance for different process parameters. Theoretical evaluation of the cutting force is not an easy task. Simple analytical models, like those developed by Evans [2] or by Nishimatsu [5], can provide a very approximate estimation of cutting forces only. Numerical methods based on the continuum models, like finite element methods, have serious problems in modelling discontinuities of the material occuring during rock cutting [4]. The discrete element method is commonly regarded as a suitable tool to model cutting processes. Due to large computational effort discrete element of rock cutting modelling is often limited to 2D case [3]. Two-dimensional models, however, cannot predict all the components of cutting forces. Here a three-dimensional model is presented. The discrete element model of rock cutting is extended on the evaluation of tool wear.

BASIC ASSUMPTIONS OF THE ROCK CUTTING MODEL

A numerical model of rock cutting has been developed within the authors' own implementation of the discrete element method [6, 7]. The system consisting of a tool and rock sample is considered in the model. The rock material is represented as a collection of rigid spherical particles interacting among themselves with contact forces. The contact force between two particles $\mathbf{F}$ can be decomposed into normal and tangential components, $\mathbf{F}_n$ and $\mathbf{F}_T$, respectively

$$\mathbf{F} = \mathbf{F}_n + \mathbf{F}_T = F_n \mathbf{n} + \mathbf{F}_T \tag{1}$$

where $\mathbf{n}$ is the unit vector normal to the particle surface at the contact point. The contact forces $\mathbf{F}_n$ and $\mathbf{F}_T$ are obtained using a constitutive model formulated for the contact between two rigid spheres. In the present formulation the elastic perfectly brittle model is used. Initial bonding for the neighbouring particles is assumed. When two particles are bonded the contact forces in both normal and tangential directions are calculated from the linear relationships:

$$F_n = k_n u_n, \quad \|\mathbf{F}_T\| = k_T \|\mathbf{u}_T\| \tag{2}$$

where k_n and k_T are the interface stiffness in the normal and tangential direction, respectively, u_n – normal relative displacement, $\mathbf{u}_T$ – tangential relative displacement. The tensile and shear contact forces are limited by the tensile and shear interface strengths, R_n and R_T, respectively:

$$F_n \le R_n, \quad \|\mathbf{F}_T\| \le R_T \tag{3}$$

Cohesive bonds are broken instantaneously when the interface strength is exceeded either by the tangential contact force or by the tensile contact force. In the absence of cohesion the normal contact force can be compressive only and tangential contact force can be nonzero due to friction. In the present formulation the Coulomb model of friction is used.

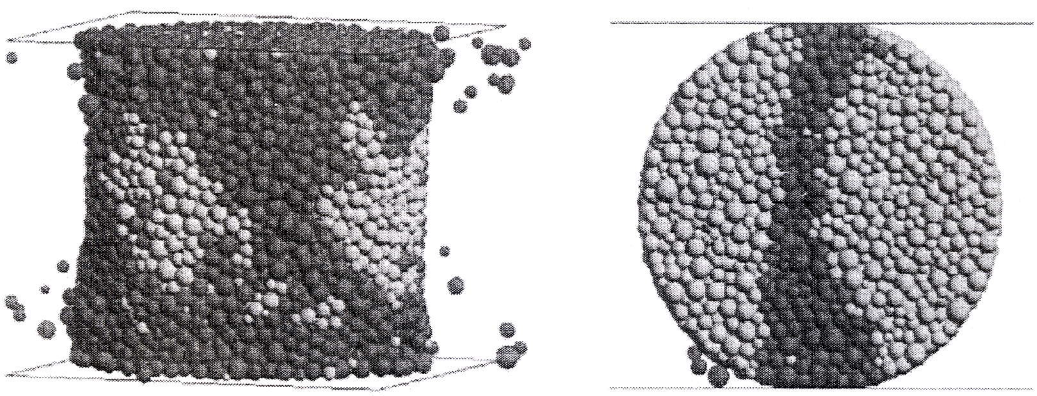
A rock cutting tool is treated as a rigid body with a surface discretized with triangular facets. The tool-rock interaction is modelled assuming Coulomb friction model. The tool-rock contact model is enriched by evaluation of the tool wear. The wear rate $\dot{w}$ is calculated using the Archard formula [1]:

$$\dot{w} = k \frac{p_{\mathrm{n}} v_{\mathrm{T}}}{H} \tag{4}$$

where p_{n} is the contact pressure, v_{T} – the slip velocity, H – the hardness of worn surface, and k – a dimensionless wear parameter.

DETERMINATION OF ROCK MODEL PARAMETERS

A set of micromechanical parameters yielding required macroscopic rock properties has been determined using the methodology developed by Huang [3] based on the combination of the dimensional analysis with numerical simulation of the standard laboratory tests for rocks, unconfined compression test (Fig. 1a) and Brazilian test (Fig. 1b).

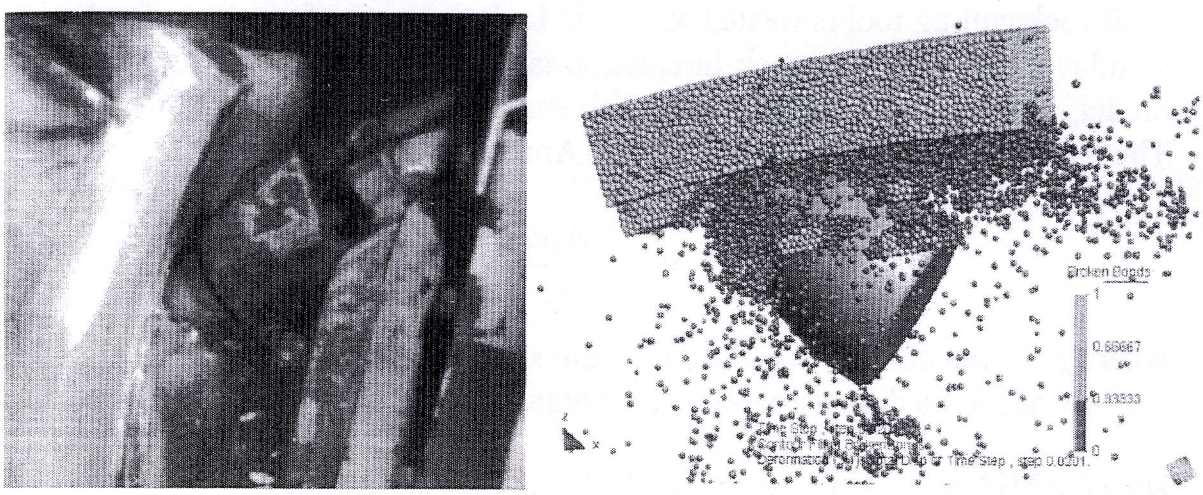


a) b)

Fig 1. Results of numerical simulation of laboratory strength tests: a) unconfined compression test, b) Brazilian test

SIMULATION OF ROCK CUTTING WITH A ROADHEADER PICK

Validation of the rock cutting model has been carried using experimental results obtained in a laboratory test performed in the laboratory of Sandvik Mining and Construction (Fig. 2a). The tests consisted in cutting of a sandstone block



a) b)

Fig 2. Laboratory rock cutting test: a) experiment (courtesy of Sandvik Mining and Construction GmbH, Zeltweg, Austria), b) numerical simulation

with a rotating roadheader pick. Mechanical properties of the rock have been determined experimentally and are the following: Young modulus E = 18690 MPa, Poisson ratio ν = 0.23, compressive strength σ_c = 127 MPa and tensile strength σ_t = 12 MPa.

The test has been analysed using a three dimensional discrete element model. Rock sample has been discretized using 71,200 spherical particles. For the rock considered the following set of micromechanical parameters has been found for the DEM model: contact stiffness in the normal direction $k_n = 5.4\cdot106$ N/m, contact stiffness in the tangential direction $k_T = 2.16\cdot106$ N/m, cohesive bond strengths in the normal and tangential direction, $R_n = R_T = 86$ N. The results of numerical simulation are shown in Fig. 2b. Splitting of chips typical for brittle rock cutting can be seen.

The three components of cutting forces obtained in simulation are plotted in Fig. 3. Numerical forces are compared with experimental average measurements. Quite a good agreement can be observed.

The tools used in the laboratory tests of rock cutting have special tips made of copper, a soft material which is easily worn. This allowed us to obtain visible wear effects after few cuts (Fig. 4a). Evaluation of wear was included in the analysis. Evolution of the tool wear predicted by the analysis is shown in Fig. 4b. It can be seen that the wear pattern obtained in simulation agrees very well with the worn area observed in the tools used in laboratory tests.

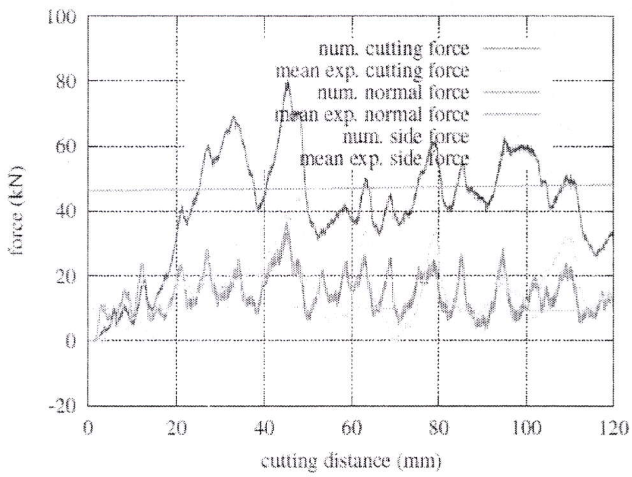
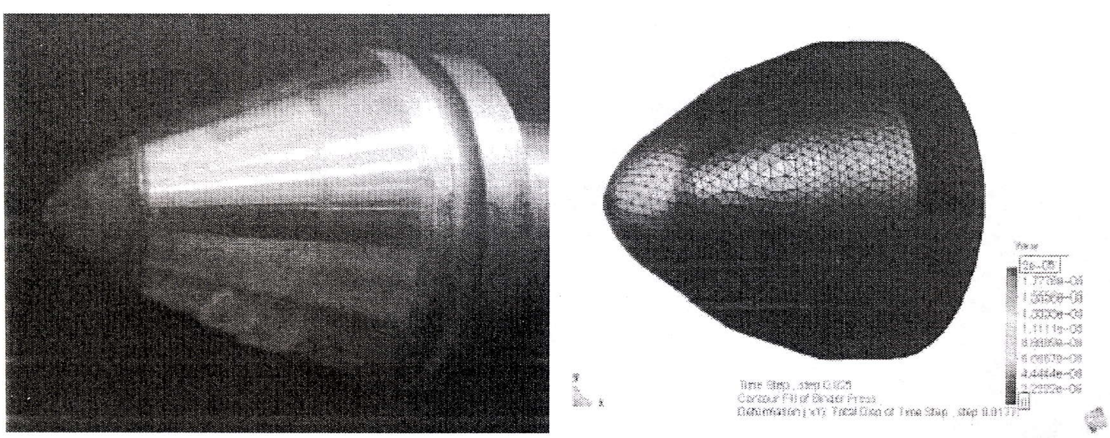


Fig 3. Rock cutting forces – comparison of numerical results with experimental average values



a) b)

Fig 4. Wear pattern on the tool surface: a) laboratory test, b) simulation

CONCLUSION

The three-dimensional discrete element model of rock cutting is capable to represent correctly complexity of a rock cutting process. A good qualitative and quantitative agreement of numerical results with experimental measurements has been found out in the validation of the model developed in the present work. The model developed can be employed in the design of rock cutting tools and processes.

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REFERENCES

1. J.F. Archard, Contact and rubbing of flat surfaces, *J. Appl. Phys.*, **24**, 981–988, 1953
2. I. Evans, The force required for pointed attack picks, *Int. J. Min. Engng.*, **2**, 63–71, 1965.
3. H. Huang, *Discrete Element Modeling of Tool-Rock Interaction*, PhD Thesis. University of Minnesota, 1999.
4. J. Jonak, J. Podgórski, Mathematical model and results of rock cutting modelling, *Journal of Mining Science*, **37**, 615–618, 2001.
5. Y. Nishimatsu, The mechanics of rock cutting, *Int. J. Rock Mech. Mining Sci.*, **9**, 261–270, 1972.
6. E. Oñate, J. Rojek, Combination of discrete element and finite element methods for dynamic analysis of geomechanics problems, *Comput. Meth. Appl. Mech. Eng.*, **193**, 3087–3128, 2004.
7. J. Rojek, E. Oñate, F. Zarate, J. Miquel, Modelling of rock, soil and granular materials using spherical elements, *Proc. of the 2nd European Conference on Computational Mechanics ECCM-2001*, Cracow, Poland, 26-29 June 2001.