Clump models: an improvement in the rock cutting modeling by DEM?

Nicolas Gonze
UMONS - University of Mons, Mons, Belgium

Jean-Pierre Tshibangu
UMONS - University of Mons, Mons, Belgium

ABSTRACT: The improvement of PCD cutting tools requires a better understanding of rock cutting mechanism. For the moment, the study of this mechanism is based on laboratory tests and numerical modeling. For the numerical aspect, distinct element method seems to be more efficient than finite element method by taking into account the granular aspect of the rock. A new methodology in DEM modeling, the clump logic, tends to give the best results to model the rock mechanical behavior. As this type of model was never used for the rock cutting modeling, the aim of this work is to study the improvement of rock cutting modeling by the use of clump logic. The most important aspect of the study is to verify the destruction mechanism of the rock, ductile or brittle, depending on the depth of cut and to compare this mechanism with laboratory observations made on the Rock Strength Device.

1 INTRODUCTION AND METHODOLOGY OF WORK

The need of improving PCD drilling tools requires a better understanding of rock cutting mechanism. In this context, different methods as laboratory tests, field results and numerical modeling are used to study the rock-tool interaction.

In the rock cutting modeling, the distinct element method is increasingly used. This is because this type of modeling takes into account the granular aspect of the rock, which allows a better modeling of the development of cracks and fractures in small samples of rock.

This DEM modeling, often used with PFC2D software, was generally used in rocks mechanics to model mechanical characterization tests (Potyondy & Cundall 2004) or to study the rock mass stability (Jing & Hudson 2002). Several models were worked out to obtain the best representation of rock behavior. One of this models, the Clump model proposed by Cho et al. (2007), tends to give the best results to model the behavior of rock material.

As this methodology was never been used before, this work aims to study if the clump models have a benefit impact on the rock cutting modeling. The study is divided into three parts:

1. Choice of two rock materials, study of their mechanical properties and cutting tests with the Rock Strength Device (Adachi et al. 1996 and Dagrain 2006) ;
2. Calibration of the models (with and without clumps) on the basis of laboratory tests;

3. Modeling cutting tests to compare the results of the two types of models with the results obtained with the RSD (Rock Strength Device).

2 ROCK MATERIALS SELECTED

The two rocks used in this study are Vosges sandstone and Moca limestone. These rocks were selected because their mechanical parameters (shown in Table 1) are suitable for PCD tools (Figure 1).

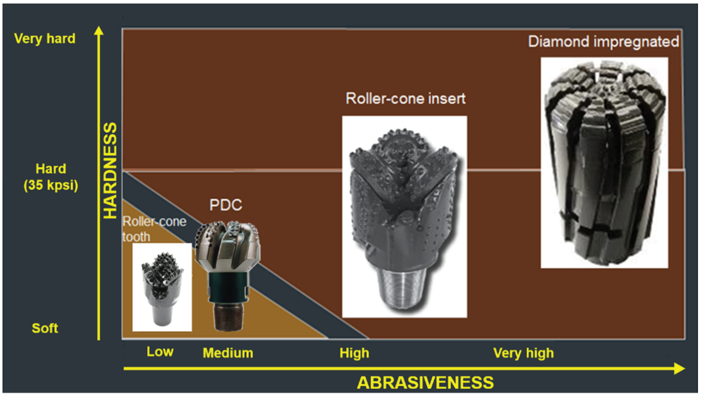

Figure 1. Range of use of the various drilling tools based on properties of rock materials (modified from Da Silva, 2015)

Table 1 presents the most important properties needed to calibrate the model. Some of these parameters are taken from the database of the Mining Department of the University of Mons.

Table 1. Main properties of the two rocks modeled.

Properties		Vosges Sandstone	Moca Limestone
Grain size	[mm]	From 0.2 to 0.6	From 0.3 to 1
UCS	[MPa]	56.5	44.0
Tensile strength	[MPa]	2.4	4.5
Young’s modulus	[Mpa]	9.93	17.9
Poisson’s ratio	[-]	0.25	0.33
FPMs abrasiveness	[-]	43	0.03

3 CLUMP MODELS IN DISTINCT ELEMENT METHOD

As mentioned by different authors (Jensen et al. 1999 and Thomas & Bray 1999), the representation of rock grains by circular particles as normally in DEM is not adequate to model the rock properties like dilation and friction that influence rock cutting modeling.

To solve this problem, Cho et al. (2007) propose to use the clump logic in rock modeling. Clump logic consists in grouping several particles that form a single rigid body with irregular shape. There are two methods to form clumped particles. The first solution is to group an undefined number of circular particles while limiting the clump grain size. In the second one, a group of particles with a predefined shape replaces a percentage of the circular particles. This second method keeps the same particle size than defined in the model.

As it has been shown that the particle size has an influence on rock cutting modeling, the second methodology was used to permit the control of grain size and to obtain the same grain size distribution than in the real rock.

Arbitrarily, three configurations of clumped particles were defined in this study. These three configurations are described in Figure 2 and were used in the following proportions: (a) 30%, (b) 30% and (c) 20%. The remaining 20% are circular elements.

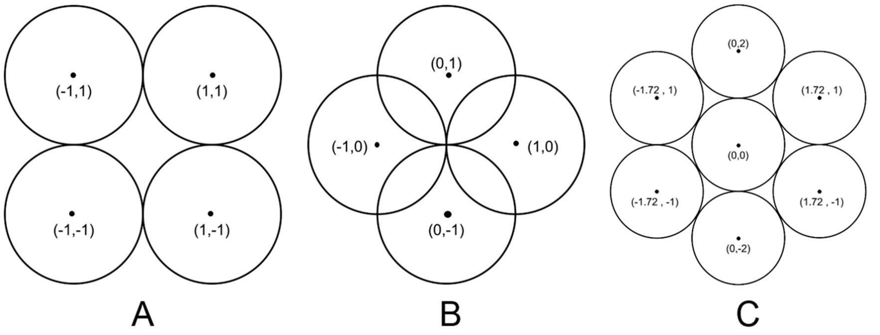

Figure 2. Geometry of different clumps used in this work.

4 RESULTS AND DISCUSSION

4.1 Calibration of the models

The calibration method used in this study to fix micro-parameters of the model is the one proposed by Itasca (2008) and Potyondy & Cundall (2004). This method consists in a uniaxial compressive test that gives the values of compressive strength, Young's modulus and Poisson's ratio. The calibration process consists in the change of micro-properties until the response obtained is similar to laboratory test on rock.

Tables 1 (Moca limestone) and 2 (Vosges sandstone) compare the results of laboratory tests and the results obtained after calibration of the different models.

Table 2. Comparison between Moca limestone's properties measured in the lab and after the calibration.

	σ_c [MPa]	E [GPa]	ν
Real rock	44.0	17.9	0.33
Normal model	44.3	18.2	0.31
Model with clumps	43.1	17.6	0.32

Table 3. Comparison between Vosges sandstone's properties measured in the lab and after the calibration.

	σ_c [MPa]	E [GPa]	ν
Real rock	56.5	9.93	0.25
Normal model	55.4	10.03	0.28
Model with clumps	55.6	10.36	0.33

Figures 3 compares the results of uniaxial compressive test in the lab with the response obtained in the models with and without clumps in the case of the limestone.

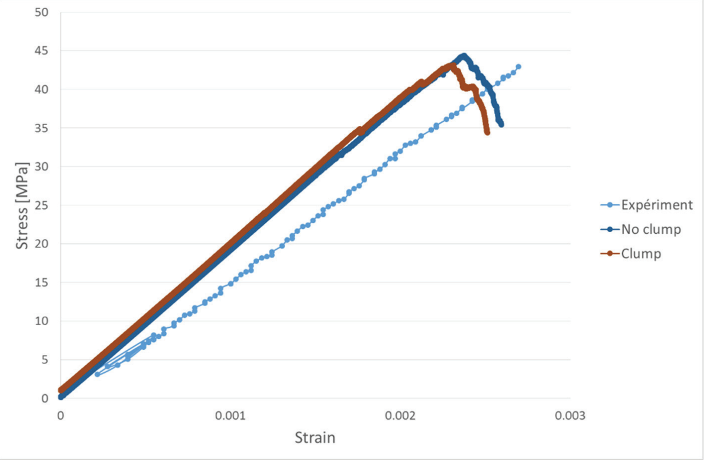

Figure 3. Comparison between the uniaxial tests performed on the numerical models (with and without clump) and that achieved in laboratory on a sample of Moca limestone.

4.2 Rock cutting modeling results and discussion

For the four models studied in this work (two for the Moca limestone and two for the Vosges sandstone) a set of cutting tests were modeled. These models of cutting tests were made for groove depth ranging from 0.2 mm to 2 mm in steps of 0.2 mm.

Comparing the results of cutting forces obtained in these models, we see that the forces computed in a model with clumps are greater than those of a model without clump (Figure 4). Despite of this, it is easy to notice that the computed forces are much lower than what can be measured in the laboratory. As in the case studies without clumped particles, it is clear that the use of two dimensional clumped particles does not override a three-dimensional modeling to enable a more realistic study of cutting forces (Huang et al. 2013).

The same results were obtained in the case of Vosges sandstone where cutting forces are higher by about 30% with the use of clumped particles.

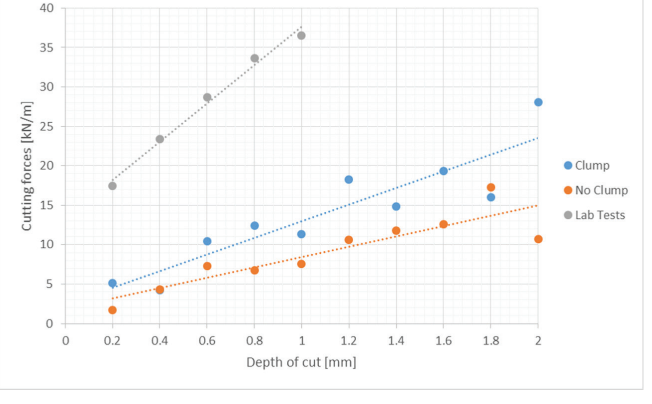

Figure 4. Comparison between cutting forces measured in the laboratory and the cutting forces obtained in the different models (case of Moca limestone).

Regarding the main subject of this study considering the impact of clumped particles in rock cutting modeling, several observations have been highlighted.

The visual comparison of different cutting models with or without clumped particles indicate that both mechanisms of destruction, ductile and brittle, are encountered in each of the models. The transition from one mechanism to the other occurs at a cutting depth of about 1.2 mm for Moca limestone and 0.8 or 1.0 mm for the Vosges sandstone. The transition from one mode to the other is viewable by the formation of rock chips in the case of brittle destruction.

Despite this similarity in the ductile to brittle transition, there is an important difference in the size of formed chips. Indeed, the chips formed in a model without clumped particles are sometimes up to 3 to 5 times larger than those formed in the models with clumped particles. These chips then can sometimes reach two centimeters length. Figure 5 corresponds to a cutting test at 1.4 mm depth of cut. The chips are circled in red to highlight the difference in size between the chips formed in two different models.

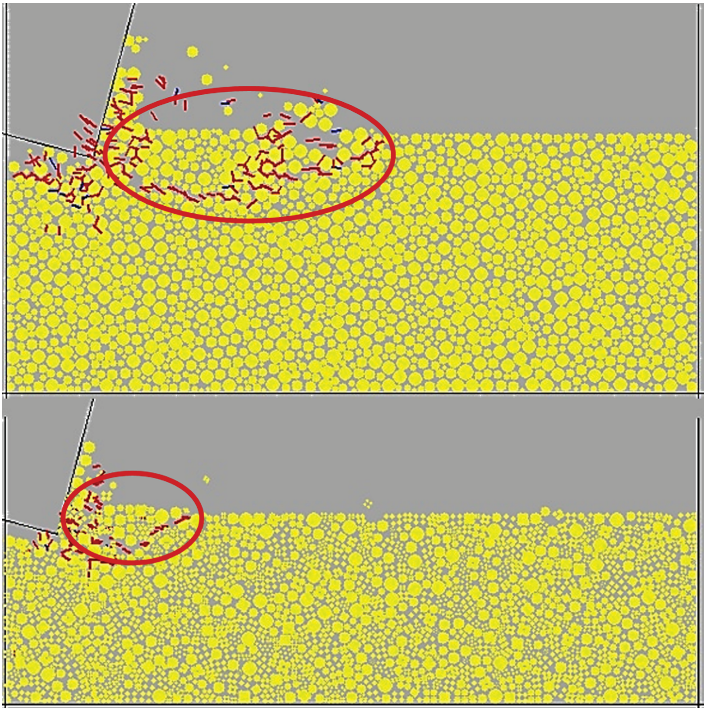

Figure 5: Illustration of the difference in size between a chip formed in a model without clumped particles (top) and a chip obtained in a model with clumped particles (bottom). In both case, the cut material is Moca limestone samples with 40 mm length.

The formation of these large chips also induces a much greater depth of groove than the theoretical depth of cut that can range from single to double. The chips obtained in the clump models seem to be more in agreement with laboratory observations on the Rock Strength Device.

The second main observation done during this study is the propagation of cracks under the cutting surface. As demonstrated by Tan et al. (2009) DEM models can also model the fracture propagated under the cutting surface with a good agreement with the lab observations.

In both models tested, macrocracks tend to develop under the cutting surface. The difference being that in the case of the normal model, these cracks may sometimes be more than one centimeter while in clump models, the crack will propagate only a few millimeters below the cutting surface.

5 CONCLUSIONS AND OUTLOOK

The aim of this study was whether the utilization of clumped particles could afford to bring improvement in the modeling of cutting rocks. According to our first results, the use of clump models seems to make DEM models more in agreement with laboratory tests to match with the method of destruction observed in the laboratory.

Indeed, the chips formed in the models as well as the crack propagation seem more realistic in the case of clump models. The clumps used in this study are relatively simple and it could be imagined to carry out work introducing greater diversity in the form of these clumps. We could also vary the proportion of the different clumps to study the impact of this change.

It appears, however, that to get an accurate idea of the method of destruction and cutting forces it is necessary to move to 3D modeling.

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