Discrete element modelling of rock-cutting experiments under confining pressure

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Due to the necessity to exploit deeper petroleum reservoirs and to uncertainty about the oil price, the oil and gas industry needs to optimize all process costs, and in particular, drilling costs. This requires a better understanding of rock cutting mechanisms in a confined environment, as encountered in deep drilling conditions. In this paper, we focus on the specific cutting mechanism exhibited by polycrystalline diamond compact (PDC) drill-bits. To study the effect of the confining pressure on the rock-cutting mechanism, we use the discrete element method powered by PFC2D software from Itasca. We firstly develop a new approach to calibrate the discrete element model. Unlike the usual method based on considering the mechanical behaviour of the rock under uniaxial conditions, our method considers the behaviour during triaxial compressive tests. We present the results of our numerical simulations of rock-cutting tests with different configurations of confining pressure and cutting depth. We highlight significant differences, in terms of cutting mechanisms and forces acting on the PDC cutter, between results obtained under confining pressure and results gathered in ambient conditions. Finally, we compare the numerical simulation outputs with some laboratory results from the literature, and show a good correlation between the two methods.

INTRODUCTION

The oil and gas industry needs to exploit increasingly deep oil reservoirs that are difficult to access. With the current low oil price, it is essential to optimize the whole process of production to limit costs and, in particular, the expensive drilling operations which are a major contributor to overall expenditures. The optimization of drilling operations requires a good understanding of the rock-cutting mechanisms during drilling. The cutting mechanisms have generally been well studied in ambient conditions, but the effect of the confining pressure in deep drilling conditions is still not well understood.

In this research, we focus more specifically on the cutting mechanisms of polycrystalline diamond compact (PDC) drill-bits. The choice of PDC bits featuring multiple PDC cutters on the bit face is justified by their increasing use in drilling operations due to their superior mechanical properties.

The study of the PDC rock-cutting mechanism is based on both laboratory and on numerical modelling. When considering cutting under confining pressure, numerical modelling is the most cost-efficient method, since laboratory tests under these conditions need specific and expensive facilities. Moreover, numerical modelling allows easy and quick testing of many cutting parameters, despite the fact that reproducing the natural properties of the materials is still an issue.

Among all the numerical modelling methods, the most used in modelling rock cutting are the finite element method (Jaime *et al*., 2015; Zhou and Lin, 2013) and the discrete element method (Carrapatoso, Inoue, and Curry, 2014; Huang, Lecampion, and Detournay, 2013). Due to its capacity to take into account the granular aspect of the rock and to model the propagation of fractures, we chose the DEM method.

In this study, after a calibration procedure based on triaxial tests, we propose to study the effect of mud pressure on the cutting forces and cutting mechanisms. For this purpose, we used the PFC2D DEM software from Itasca Consulting Group (2008).

METHODOLOGY

To study the cutting mechanisms, we divided our investigation into two parts:

1. Calibration of the numerical model to correlate the behaviour of the rock tested in the laboratory with the model. As the cutting mechanism is studied under confining pressure, we modified the calibration procedure given by Potyondy and Cundall (2004) in order to take into account the influence of confinement
2. A modelling phase, studying the effect of mud pressure on the cutting mechanism

We used the Vosges Sandstone as reference rock because it is commonly used to study rock-cutting mechanisms. Moreover, this particular material has already been extensively studied in the Mining Department of the University of Mons.

DISCRETE ELEMENT METHOD

DEM modelling in general

The discrete/distinct element method is a discontinuous numerical method initially developed by Cundall (1971) for the study of fractured rock masses (distinct method), subsequently adapted for the study of the behaviour of soils and small-scale rock materials (discrete method) .

DEM has two important features. Firstly, DEM treats the rock sample as a bonded assembly of rigid or deformable discrete blocks or particles (called balls in 2D). Secondly, elements of the model are connected at their contact points. The contact points between each element need to be identified and continuously updated during the entire deformation/motion process. Each contact is characterized by a set of micro-properties to create bonds between particles that govern the grain behaviour. When the applied stress exceeds a certain value, depending on the micro-properties, the bond between two particles fails and a micro-crack is generated.

One of the most interesting features of the DEM is that there is no need for any special numerical treatment or process for fragmentation tracking.

General Calibration Procedure

An important stage of any study using the DEM is the calibration procedure. This yields the micro-properties to assign to the models in order to generate an assembly displaying macro-properties that are comparable to those of the real material.

Generally, the procedure used to calibrate the model is the same as proposed by Itasca (2008) and Potyondy and Cundall (2004). This calibration method models a uniaxial compression test. The objective is to iteratively adjust the micro-properties until the resulting macro-properties in the uniaxial compressive test model are in good agreement with those measured in the laboratory.

The limitation of this calibration procedure lies in the fact that it only takes into account the behaviour of the rock material in unconfined conditions. In this study, the modelled sample is subjected to confinement and it is therefore essential to be able to take into account the evolution of the material's behaviour with respect to confinement during the initial calibration.

New Calibration Procedure

In order to comply with the deep working conditions already mentioned, we used triaxial tests to reproduce the behaviour of our rock material under confinement.

For the calibration, we slightly modified the Itasca script to adapt the model to the true triaxial cell of the mining department of the University of Mons. The sample tested had a height of 31 mm and a width of 30 mm.

For this new procedure, compressions to a confinement of 20 MPa were carried out in an iterative fashion.

Calibration of the Model

Before beginning the iterative calibration procedure, it is essential to set the particles sizes. A uniform distribution between 0.1 and 0.3 mm for the particle radius is chosen in order to optimally relate to the size of the elements constituting the Vosges Sandstone.

After each step of the iterative procedure, we compared the rock behaviour obtained from a set of micro-properties with the laboratory results presented by Tshibangu and Descamps (2012) on Vosges Sandstone. The curves in Figure 1 compare the laboratory behaviour of Vosges Sandstone at 20 MPa confining stress (blue curve) with the behaviour of the numerical model that we obtained at the end of the calibration procedure (yellow curve).

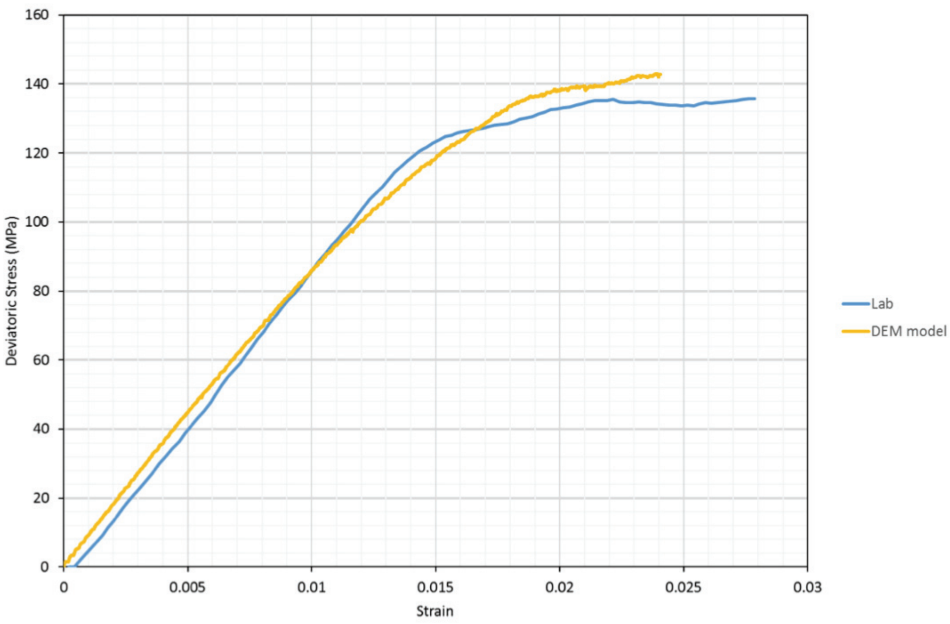

Figure 1. Comparison between laboratory (Tshibangu and Descamps, 2012) and triaxial modelling test at 20 MPa confining stress.

Table I shows the micro-properties of the model after calibration.

Table I. Micro-properties obtained after calibration .

Parameter	Value
Minimum ball radius (mm)	0.1
Ball size ratio	3
Contact modulus (GPa)	6.5
Ball stiffness ratio	3
Ball friction coefficient	1
Parallel bond modulus (GPa)	6.5
Parallel bond stiffness ratio	3
Parallel bond normal strength, mean (MPa)	50
Parallel bond normal strength, std. dev. (MPa)	35
Parallel bond shear strength, mean (MPa)	50
Parallel bond shear strength, std. dev. (MPa)	35

As shown by different authors (Potyondy and Cundall, 2004; Cho, Martin, and Sego, 2007), the tensile strength is generally overestimated with PFC models. The tensile strength obtained with our calibration by the Brazilian test is about 7.2 MPa, which is considerably larger than the 2.8 MPa measured in the laboratory.

ROCK-CUTTING SIMULATION UNDER MUD PRESSURE

After the calibration of the model, we proceeded to the construction and parameterization of our cutting model. To do this, we used an existing PFC2D script to generate a sample and adjust the various parameters of the cutting test.

After numeric generation of a sample 0.8 cm high and 3 cm long with random assembly of particles, a perfectly sharp PDC cutter, considered as a rigid body, was set at the left end of the sample. The drilling mud is not represented as such in the model, but is assimilated to a membrane structure that lies on top of the rock sample. This membrane applies load normally to the rock material. The membrane is not rigid but evolves during cutting process, and it always stays in contact with rock material as it breaks. We also observed that the membrane affects only the rock sample and there is no interaction with the cutter.

Cutting parameters are reported in Table II, after Kaitkay and Lei (2005).

Table II. Cutting parameters used for the rock-cutting modelling

Cutting parameter	Value
Rake angle	15°
Depth of cut	1 and 2 mm
Velocity	1 m/s
Mud pressure	1–40 MPa

During the cutting simulations, we monitored vertical and horizontal forces acting on the PDC cutter. Due to the plane strain state considered by PFC2D, the whole model has a unit thickness of 1 m. Therefore, in order to compare the forces calculated by the model and the laboratory measurements provided by other researchers, we divided the forces calculated by the model by 100 in order to address a 1 cm wide cutter.

RESULTS AND DISCUSSION

Before studying the impact of mud pressure on the cutting mechanism, we attempted to validate the calibration phase.

To do this, we conducted laboratory cutting tests on a rock strength device (Richard *et al.*, 2012) and ran our numerical cutting model in ambient conditions. This ensures that the calculated forces in ambient conditions are comparable to those observed in the laboratory.

Because of the plane strain state considered in the 2D model, the modelling results were compared to those from a slab test (Figure 2). Owing to this plane strain state, DEM models have a third hidden dimension of unit thickness, generally 1 m. Consequently, each particle is not modelled as a single disk but as a cylinder with a length of 1 m. The modelled PDC cutter is also 1 m long. The rock sample and the PDC cutter have therefore the same width.

This geometrical feature illustrated in Figure 2 is similar to that encountered in slab tests presented by Dagrain, Detournay, and Richard (2001). The peculiarity of this test is that the rock sample is prepared in such a way that the width of the cutting surface is equal to the width of the rectangular PDC cutter used.

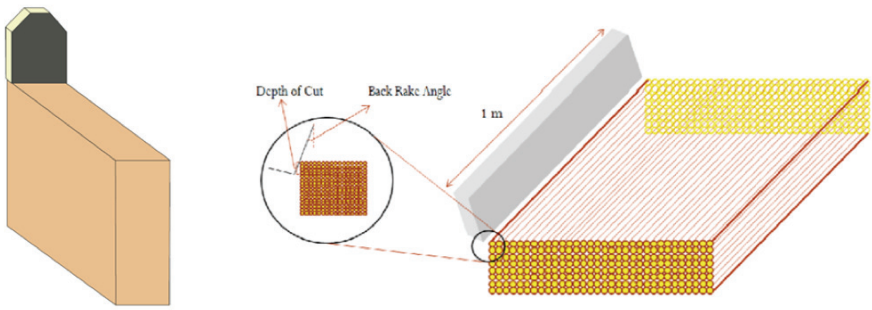

Figure 2. Comparison between a schematic representation of a slab test on the left (Dagrain, Detournay, and Richard, 2001) and a '3D' view of the 2D DEM model on the right (Joodi et al., 2012).

Figure 3 compares the results obtained in the laboratory with those from the numerical model. We can see that the cutting forces calculated in DEM models are in agreement with the forces measured on the rock strength device.

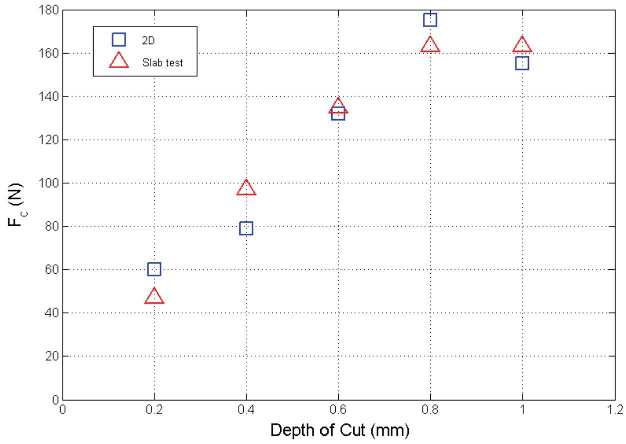

Figure 3. Comparison between the evolution of the cutting forces measured in laboratory (slab test) and those obtained after calibration in ambient conditions (2D).

Following the calibration phase, we modelled the effect of the confinement pressure imparted by the drilling mud on the cutting mechanism, focusing on:

- The destruction mechanism
- The cutting forces.

Effect of Mud Pressure on the Rock-Cutting Mechanism

In ambient conditions, the cutting mechanism depends on the depth of cut. The cutting mode is described as 'ductile' or 'fragile', following the classification of Detournay and Defourny (1992), depending on whether the grains are pulled off or chips are formed (Figure 4). Depending on the properties of the rock and the cutting parameters, a critical cutting depth is generally observed, which marks the limit between the ductile (or frictional) mode associated with a shallow cut and the brittle mode with greater depth of cut.

Figures 4B and 4D respectively illustrate the numerical approach of the ductile and brittle mode observed with our model.

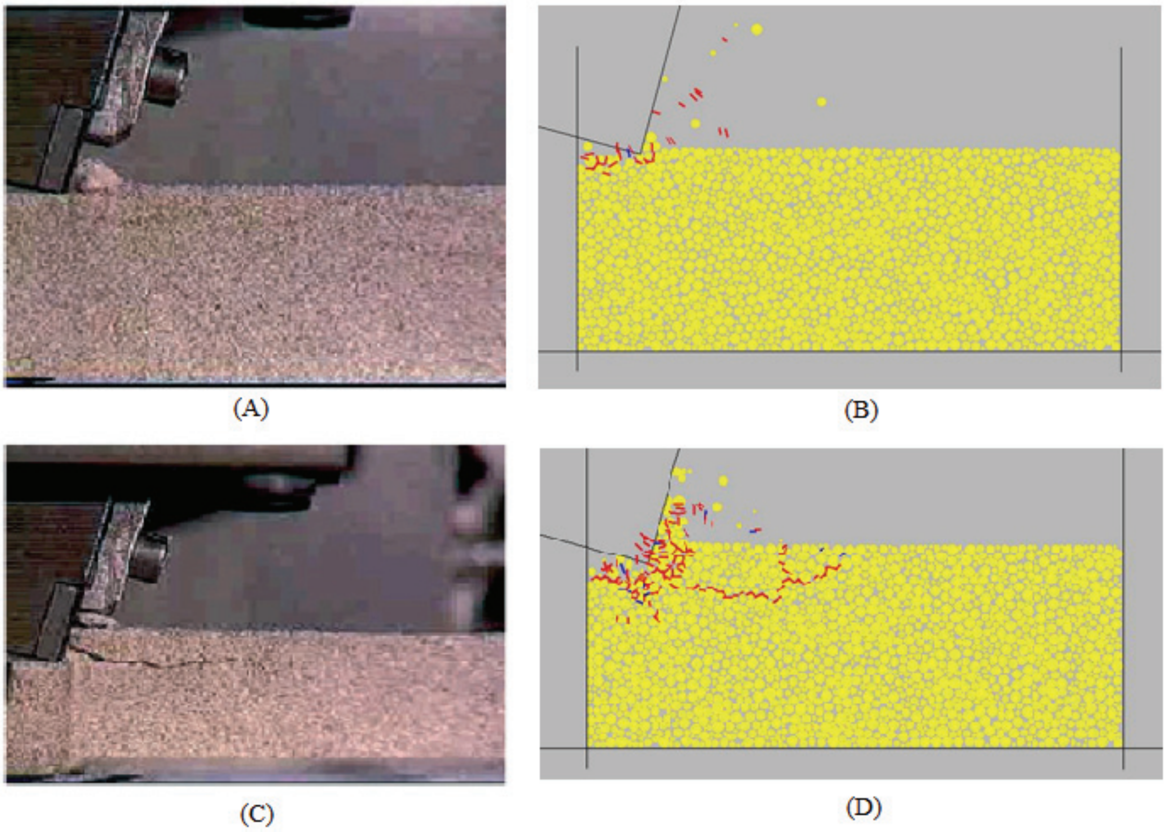

Figure 4. On the left: (A and C; Richard, 1999*), difference between ductile and brittle cutting mechanisms obtained in the laboratory. On the right (B and D), similar cutting mechanisms observed with our DEM model.*

Once a confinement pressure was applied to the surface of the sample in the numerical model, we observed that the cutting mode is of ductile type whatever the depth of cut. Indeed, due to the confinement pressure, the rock is crushed at the passage of the cutter. Moreover, all the detached material is compressed on the face of the cutter. A long ribbon is then formed (Figure 5).

The observations made by numerical modelling are in good agreement with those of Kaitkay and Lei (2005). Indeed, they have experimentally shown that cutting mechanism in a confining environment produces ribbons. The ribbons formed due to the application of mud pressure are not continuous but consist of crushed material recompacted due to the mud pressure.

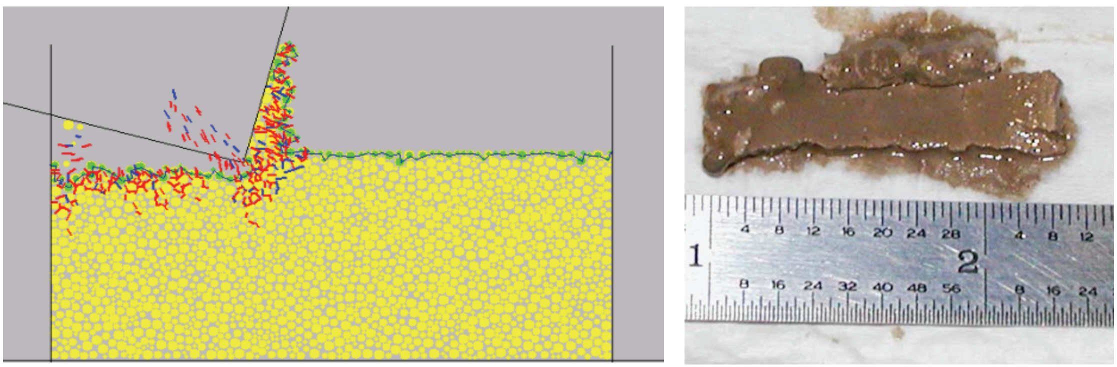

Figure 5. Formation of ribbon in DEM modelling (left) and ribbon observed by Kaitkay and Lei (2005*) in laboratory tests.*

Impact of Mud Pressure on Cutting Forces

We also observed that the mud pressure has a significant effect on the measured cutting forces. From a qualitative point of view, in ambient conditions, the ductile mode cutting forces vary slightly around an average value. In confined conditions, two sequences stand out. In the first, the forces increase during the formation of the ribbon of rock. Subsequently, the forces reach a steady state, with a slight increase during the tests. Kaitkay and Lei (2005) observed the same evolution during their laboratory tests (Figure 6).

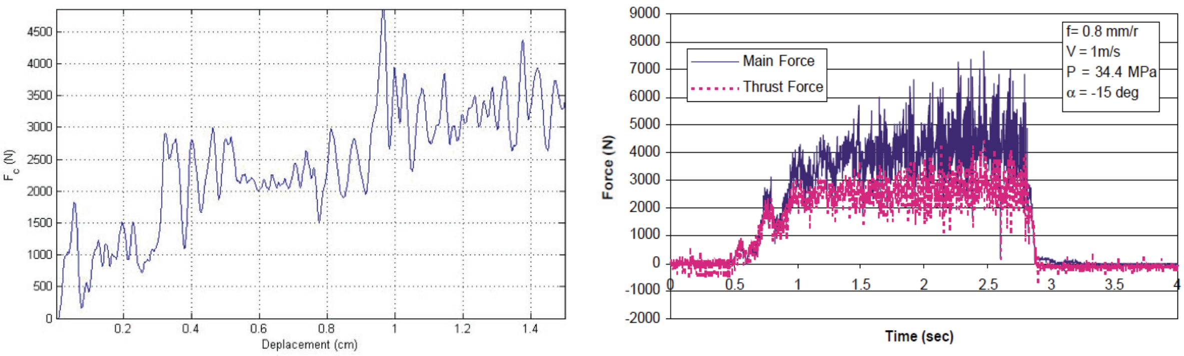

Figure 6. Evolution of the cutting forces during a test at 34.4 MPa mud pressure. On the left, forces calculated numerically, and on the right, forces measured by Kaitkay and Lei (2005).

Based on multiple numerical models run at different confining pressures, we observed that the mud pressure has a significant effect on the cutting forces. Figure 7 shows the significant increase in the cutting forces with the application of mud pressure. These results were obtained from a cutting model at a depth of cut of 2 mm.

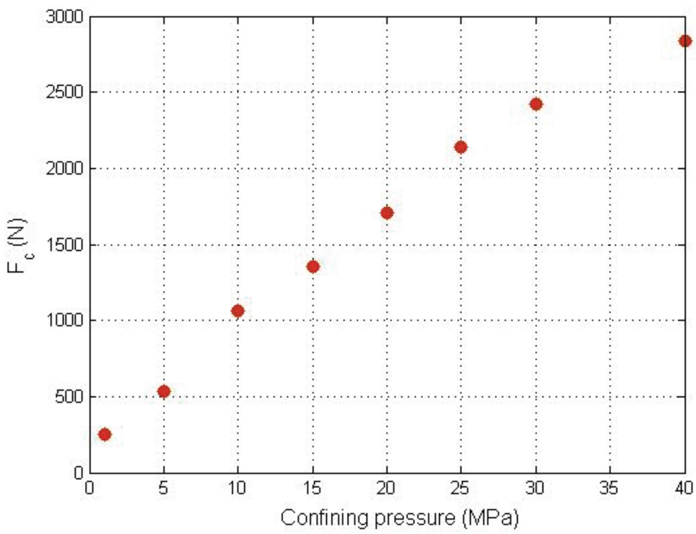

Figure 7. Evolution of the average cutting forces with confining pressure obtained with DEM cutting model.

CONCLUSIONS AND OUTLOOK

Understanding of cutting mechanisms of rocks is important for the optimization of drilling operations to limit development costs. Generally, these mechanisms are well understood in ambient conditions, but to optimize drilling operations a better understanding of the destruction mechanisms in the confined environment resulting from mud pressure is required.

In the case of the increasingly used PDC drilling tools, the cutting mechanism exhibited has been studied extensively in ambient conditions but less under deep drilling conditions. It is therefore necessary to obtain a better understanding of this phenomenon in order to develop a constitutive law of rock cutting in deep drilling conditions.

To study the effect of mud pressure on the cutting mechanism, we used the PFC discrete element code. After calibration of the model based on triaxial tests, we demonstrated the change of cutting mechanism induced by mud pressure.

The cutting mechanism can be described as ductile, with formation of a ribbon consisting of agglomerated cut material, compressed by the mud pressure on the cutter face.

In term of the forces acting on the PDC cutter, two stages are observed: a first transitional stage during which the forces increase, and a second stage in which the forces plateau, indicating a steady state.

The results obtained by 2D DEM modelling are in good agreement with laboratory observations. However, it is necessary to extend the study to 3D modelling in order to handle additional parameters such as the side rake or the standard circular geometry of PDC cutters. 3D modelling would also allow the study of the removal of the ribbon from the cutter face.

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