Simulation of Single Cutter Experiments in Evaporite Through Discrete Element Method

C. Carrapatoso; S. A. B. Fontoura; I. M. R. Martinez & N. Inoue

ATHENA – Computational Geomechanics Group, GTEP – Group of Technology in Petroleum Engineering
PUC-Rio – Pontifical Catholic University of Rio de Janeiro, Brazil

A. Lourenço & D. Curry
Baker Hughes Inc., Houston, USA

ABSTRACT:

The discovery of large oil reservoirs under salt layers is motivating the study of drilling optimization of wells in many basins, notably in Brazil and West Africa. The aim of this paper is to present the laboratory experiments carried out to cut evaporite samples in the so-called single cutter configuration. These tests are meant to generate results to improve the understanding of the mechanics of drill bit – rock interaction. The paper also describes the use of a numerical tool based upon the discrete element method to model the experiments.

The laboratory experiments consist in obtaining the forces acting upon a cutter during its penetration and cutting of a groove in a sample of evaporite. These forces are transformed into mechanical specific energy, MSE. The tests were carried out under different depths of cut and back-rake angles. The results indicate that MSE decreases with the increase of depth of cut until a certain limit when it stabilizes. The experiments also indicate that changing cutter inclination changes the cutting forces and mechanisms, and the paper explores these findings. Triaxial confining tests were carried out in cylindrical samples of the same evaporite used in the cutting experiments. The results of these tests were used to create a virtual rock to be treated by the discrete element method. This is an important step in the workflow and is also described in the paper. Finally, the laboratory experimental results are compared with the results produced by numerical simulation. Both 2D and 3D modeling of the single cutter experiments were carried out under atmospheric conditions and satisfactory results were obtained, revealing the importance of the developed methodology in understanding rock cutting mechanisms.

1 INTRODUCTION

Distinct element method is a numerical technique developed to model problems of interaction between circular particles and has been explored in this work to model rock behavior. This study aims to modeling numerically the cutting action (drilling) of evaporites by a single polycrystalline diamond cutter using the aforementioned technique through the software PFC$^{3D}$ and PFC$^{2D}$. The modeling work is considered an important step to understand the interaction between the drill bit and the rock and consequently optimize rate of penetration while drilling for oil and gas.

Single cutter laboratory experiments are used to simulate drilling action and assist drill bits cutter design and testing by measuring forces acting on the cutter and drilling efficiency. A single polycrystalline diamond cutter (PDC) cuts a groove as a sample of rock rotates at certain angular velocity against it. Several passes over the same groove (single track) occur as drilling progresses. These experiments can be simulated through numerical methods to analyze the effects of changing relevant conditions affecting drilling efficiency. Mechanical Specific Energy (MSE) is commonly used to evaluate cutting efficiency and is defined as the amount of work required for removing a unit volume of rock. This parameter is used as reference to identify what needs to be changed to improve the drilling.

The numerical models developed in this study assume that the cutting is carried out using a perfectly sharped PDC cutter and the cutter surface does not wear off during the test. Therefore, the mechanical specific energy obtained from the simulations considers only the energy used to cut the rock without taking into account the energy dissipation associated with friction between the cutter surface and the rock.
This paper presents the calibration procedure that was implemented to properly simulate the evaporite rock mechanical behavior numerically, including changes to the contact model to create the softening behavior of the observed biaxial / triaxial stress-strain curve. In addition, a set of simulations was carried out with different cutter geometrical conditions in order to study the cutting process. Two-dimensional and three-dimensional simulations were performed under atmospheric conditions. Both depth of cut (DOC) and cutter back-rake angle were changed during the simulations and their influence on the mechanical specific energy was analyzed.

The experimental work, i.e., single cutter experiments as well as triaxial load experiments were carried out at Baker Hughes laboratories. High strain rate triaxial compression tests were performed on samples of the same material used for the single cutter tests to assess the material mechanical behavior (constitutive equation). This information was used to independently calibrate rock behavior (compressive tests) and later compare MSE results obtained experimentally with those predicted numerically.

The use of discrete element method to simulate single cutter tests was reported by some researchers. Lei et al. (2004) simulated rock cutting using DEM to investigate the effects of various parameters on the cutting force. The effect of brittle and ductile failure on drilling efficiency was also investigated through numerical modeling (Block and Jin, 2009; Huang et al., 2012). Mendoza et al. (2011) modeled scratching tests using a three-dimensional distinct element program. They studied the influence of depth of cut on the cutting forces and found that shallow cuts do not always lead to ductile failure as earlier established by Huang and Detournay (2008). Akbari et al. (2011) studied the influence of dynamic loads on the drilling efficiency. They created a cutting environment using a two dimensional distinct element program and applied a vertical velocity that could be constant (representing weight on bit) or oscillatory (representing vibration assisted rotary drilling).

2 MICRO PARAMETERS FOR EVAPORITES

The discrete element method implemented in PFC describes the real rock as a package of particles connected together at their contacts. The properties at the contacts are described by micro parameters. Whenever PFC is used, macro parameters are output data obtained by a calibration process where the inputs are set by micro parameters. The procedure to obtain the proper set of micro parameters for a given virtual rock is an iterative process that ends when the predicted real rock properties (its macro parameters such as Young’s modulus, Poisson’s Ratio, unconfined compressive strength) are equivalent to those obtained at laboratory tests. In this paper the calibration process was carried out using, as reference, the results of unconfined compression test performed in the target evaporite, i.e., halite.

In the discrete element method, the Newton’s second law is applied to each particle, providing its position and velocity. The contact forces are calculated from the relative particle displacements and from the constitutive model used in the contacts.

The magnitude of the normal contact force is calculated as presented in Equation 1 where $k_n$ is the normal stiffness at the contact. $k_n$ is determined from the current contact stiffness model.

$$F_n = k_n \cdot U_n$$

The shear force at the contact is computed in an incremental fashion. When the contact is formed, the total shear contact force is equal to zero. Each subsequent shear displacement increases the shear stress. In this way, to determine the shear strength is necessary to compute the force generated by the translational displacement of the contact and the force generated by the rotation of the particles.

Figures 1 and 2 present the cutting forces from single cutter experiments and the stress-strain curve corresponding to an unconfined compressive test carried out under a strain rate of 10%/min. At the beginning of stress application, the curve displays an inelastic, concave-upward interval and this happens because fissures and pores begin to close (Goodman, 1989). On halite, this interval is large compared to other rocks because rock salt experience greater deformation under loading. Otherwise, this phase is almost inexisten for confined tests, probably because of counteracting confinement forces preventing the development of fissures and pores. The decrease of the tangent module with increasing axial strain is evident, suggesting a softening response.

A calibration process is needed to model the rock in PFC. Laboratory experiments such as triaxial compression test, Brazilian test, direct shear and tension tests (Itasca, 1999) can assist in obtaining the micro parameters. In this paper the triaxial test was selected.

To generate the PFC model for the evaporite rock, using the stress strain curve shown in Figure 2, the linear contact model combined with parallel bond was chosen as a first approximation. After some iteration, a synthetic specimen was modeled in PFC$^{2D}$ and its stress-strain curve was compared with the experimental curve shown in Figure 2.

The synthetic sample stress-strain curve shows an elastic behavior until failure. After the peak, the material has a brittle behavior. The linear model combined with parallel bond has been used in many studies (Kaitkay & Shen, 2004; Akbari et al., 2011; Block et al., 2009; Martinez et al., 2011; Mendoza et al., 2011; Rajabov et al., 2012) to represent the cut-
ting of brittle rocks like marble, sandstone and shale with good results.

![Figure 1. Experimental cutting forces under no confinement](image)

![Figure 2. Laboratory test stress-strain curve and model calibration using linear contact model—PFC^{2D}.](image)

Analyzing Figure 2, it is clear that this contact model does not represent the real experimental curve since the evaporite sample shows a ductile behavior. Other contact models available in PFC^{2D} and PFC^{3D} were applied (like simple ductile model and simple viscoelastic model) without success in obtaining the hardening behavior.

To solve this problem, a modification was made on the linear model combined with parallel bond. The parallel bond contact stiffness was modified in each cycle, assigning decreasing contact stiffness as a function of disc overlap. This technique converts the linear model available on PFC in a different model with nonlinear behavior, standing as a new methodology to obtain a representative contact model of rocks with nonlinear stress-strain behavior.

### 2.1 Methodology of Micro Parameters Calibration

The proposed methodology is composed of 3 steps that summarize the validation of the new model.

First, it is necessary to understand how the evaporite sample stiffness changes during the triaxial / uniaxial test. In PFC, the relation between the stiffness and the elastic modulus at a single contact bond is found as in Equation 2, where $k_n$ is the tangent stiffness at the contact, $t$ is sample thickness and $R$ is the particle radius.

$$k_n = k_s = 2E_c \left( \frac{t}{2R} \right)$$  \hspace{1cm} (2)

It is possible to find a relationship between tangent modulus and sample strain from the experimental stress-strain curve. Figure 3 illustrates this relationship for a 2 MPa confined test. Assuming that the value of the laboratory sample tangent modulus is roughly the same of the contact modulus, this last parameter can replace the sample tangent modulus in the relation shown in Figure 3. This relation represents the tangent modulus variation of each point in the curve according to the sample axial strain. It is important to note that this procedure is done for each specific stress-strain curve. In the case of halite, Equation 3 shows this relationship for a confined test of 2 MPa, where $E_c$ (in GPa) is the contact elastic modulus and $\varepsilon$ is the axial strain of the laboratory sample (triaxial / uniaxial test).

$$E_c = 2.28 \cdot \varepsilon^{(0.233)}$$  \hspace{1cm} (3)

Knowing that contact elastic modulus is equivalent to twice the contact stiffness multiplied by stiffness on PFC^{2D}, and is equivalent to four times the contact stiffness multiplied by particle radius on PFC^{3D} (Equation 1), it is possible to rewrite Equation 3 as Equation 4 and 5. The particle ratio is kept constant and with equivalent values on all numerical simulations.

$$k_n = 4.56 \cdot \varepsilon^{(-0.233)} \cdot t \quad \text{(PFC^{2D})} \hspace{1cm} (4)$$

$$k_n = 9.12 \cdot \varepsilon^{(-0.233)} \cdot R \quad \text{(PFC^{3D})} \hspace{1cm} (5)$$

The second step consists in using the relationship shown in Equations 4 and 5 to modify the linear contact model. In order to do this, it was necessary to create a code that calls this function at each simulation cycle. Thus, the contact stiffness will always be a function of the synthetic sample axial strain obtained in the previous step of the test. The stiffness at the contact decreases with the axial strain and hence the triaxial /biaxial test is continuously simu-
lated in order to check if the numerical curve is close to the experimental one.

The use of macro parameters (sample strain, for example) as an input for calibration is not the conventional way to work with PFC because the particle size and the packing arrangement affect the model behavior. Also, it is not possible to use Equations 4 and 5 in single cutter simulation because an axial sample strain is not observed. Having said that, a retro-analysis of the calibration was performed. Some contacts were monitored during simulation to observe how micro parameters were changing (balls’ overlap and contact’s normal stiffness). It is worth mentioning that an additional code was written in order to monitor the contacts since PFC is unable to automatically identify them. Figure 4 presents the relationship found between contact stiffness and balls’ overlap for a single contact during a triaxial simulation. Equation 6 presents the final relationship between contact stiffness and balls’ overlap used to represent numerically the nonlinear behavior of the evaporite rock.

At this point, the simulation of the triaxial / biaxial test is repeated using Equation 6 at each simulation cycle. A new stress-strain curve is found that correlates well with the laboratory test curve. Figures 5 and 6 present the final calibration (PFC^2D and PFC^3D) and volumetric strain obtained in the three-dimensional modeling. Table 1 shows the micro parameters found after calibration procedure. These data and Equation 6 were used to simulate the evaporite behavior during the single cutter modeling.

![Figure 3. Experiment stress-strain curve and its derive curve – 2MPa of confinement](image)

![Figure 4. Contact stiffness versus ball’s overlap, U, of a single contact – triaxial simulation](image)

\[ k_n = -8E09 \cdot U^{(-0.181)} \]  

(6)

![Figure 5. Laboratory triaxial test and model calibration using nonlinear contact model – PFC^2D and PFC^3D](image)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Value</th>
<th>PFC^2D</th>
<th>PFC^3D</th>
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<td>Ball stiffness ratio (GPa)</td>
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<td>Ball friction coefficient</td>
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<td>(\tau_c), std. dev.</td>
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3 SINGLE CUTTER MODEL

This part of the paper describes the modeling of the single cutter experiment and uses the parameters found in the calibration procedure to represent the salt rock. The model geometry is defined by a cutter that moves along the length of a synthetic rock with a fixed velocity. Depth of cut (DOC) can be changed or kept constant during simulations. In the two-dimensional simulation, the cutter is represented as a sharp edged pair of walls, and the particles are represented as discs. In the three-dimensional scenario, the cutter is composed of a set of faces that form a cylinder and particles are represented as spheres.

Figure 7 shows the simulation set implemented in PFC\textsuperscript{2D} and PFC\textsuperscript{3D}.

4 VALIDATION OF THE CUTTING MODEL

Initially, a two-dimensional rock cut model was developed using the same features of the single cutter experiments. The objective was to reproduce the experimental results as close as possible. The numerical cutter had constant horizontal velocity of 1m/s and vertical velocity of 0.060 m/s. To reduce the simulation time, these velocities are higher than those applied in the actual experiments (horizontal velocity = 0.44m/s and vertical velocity = 0.0008m/s). It is believed that the lower cutter velocities in the experiments may have been responsible for the observed MSE values stabilizing at higher depths of cut than those predicted by the simulations. Figures 8 and 9 show the calculated forces and mechanical specific energy respectively.

Figure 8 shows that the profile of both vertical and horizontal forces is in good agreement with experiments. However, the order of magnitude is substantially higher than the observed in the experimental curve (847 N) and it is also higher when compared to results obtained for Carthage marble (Kaitkay e Shen, 2004). One possible explanation is that halite experiences greater deformation before it fails and this probably leads to higher cutting forces. In addition, the modeling is carried out on a two-dimensional environment and forces generated are not of the same magnitude as those generated by a three-dimensional cutter.

Figure 9 exhibits the comparison between calculated and measured MSE as a function of the depth of cut (DOC). Note that for computation reasons, simulations were performed at smaller depth of cuts, but the calculated curve exhibits similar shape as the experimental curve. However, its final value is higher than the experimental one. The final calculated specific energy was 125 MPa against 92 MPa in the experiments.
The cutting model considered a specimen with 5 cm of length and the test is run until 2.5 cm of length is reached. This is smaller than in the experiments, where the cutter reaches 2 m of total displacement through grooves produced on the sample. Because of that, the rate of penetration is higher in the simulations aiming at reaching the same order of magnitude as of the experiments. Despite of differences between simulated and real cutter geometry, the specific energy profile was similar to observed during experiments. The specific energy tends to initially decrease with DOC until it stabilizes at a certain value. Another observation is that a larger displacement is needed for the specific energy to stabilize. In order to make reliable comparisons between modeling and experimental results, a single value of specific energy was used as reference: the end value in the curve after it stabilizes.

A discrepancy between the reference calculated and experimental values of specific energy were observed (Figure 9). Two possible explanations are given here: the contact model does not properly represent halite or the particles that remain ahead of the cutter during simulation are leading to higher specific energy estimations. The last assumption is more likely to be the reason because in a numerical simulation carried out under atmospheric conditions, see Figure 10 – (a), a lot of particles (that simulates the crushed material) accumulate in front of the cutter, creating extra forces against the cutter movement. Its influence on the generated mechanical work must be investigated in order to adjust it for reproducing real experimental conditions. In confined experiments, cuttings remain in front of the cutter during test as ribbon like structures before detaching. However, cuttings are ejected away under atmospheric conditions due to the release of elastic energy (Ledgerwood III, 2009). In order to solve this problem and obtain better numerical results, a change was made into the PFC\textsuperscript{2D} rock cutting code. Particles ahead of the cutter are deleted using a particle positioning criterion. It works as all particles with broken bonds disappear from the cutter’s face at a certain position. Figure 10 (b) shows a cutting view using this modification and Figures 11 and 12 show the simulation results.

Figure 9. Comparisons between single cutter test and PFC\textsuperscript{2D} rock cut modeling – atmospheric conditions

Figure 10. (a) Cutting view; (b) Cutting view with particle removal from cutter’s face.

Figure 11 exhibits the cutting forces for the simulation considering crushed material (particles ahead of the cutter) removal. It can be seen that the forces are significantly smaller than those presented in Figure 8. The removal of particles ahead of the cutter led to an average 22\% reduction in calculated forces. Figure 12 compares the calculated specific energy without particles removal (red curve) and for the case with partial removal of particles ahead of the cutter (blue curve). Specific energy stabilized during simulation in the value of 96.35 MPa that represents a much better agreement with the 92 MPa from experiments.

Figure 11. Forces of the PFC\textsuperscript{2D} rock cut modeling with particle removal from cutter’s face.

Based on Figure 12, it is clear that specific energy decreases with the removal of crushed material in front of the cutter once any additional matter is re-worked and wastes mechanical energy that otherwise would go into cutting rock.
5 INFLUENCE OF BACK RAKE ANGLE ON ROCK CUTTING

PFC\textsuperscript{2D} and PFC\textsuperscript{3D} rock cutting algorithms were used to analyze the influence of cutter’s back-rake angle on rock cutting efficiency. The modeling were carried out under atmospheric conditions, using a depth of cut of 0.8 mm and varying back-rake angle from 5° to 30°. The cutter had constant horizontal velocity of 3m/s for 3D-simulations and of 1m/s for 2D simulations. As commented previously, higher velocities are used for modeling than those applied in the actual experiments (horizontal velocity = 0.44m/s) in order to reduce the simulation time. It is important to emphasize that a new contact model was created to better represent salt behavior numerically.

Figure 14 and 15 display the cutting forces for two simulations using back-rake angles of 5° and of 30° at PFC\textsuperscript{2D} and PFC\textsuperscript{3D}, respectively. The average tangential forces are of 59 kN and 89 kN for the two-dimensional simulations and 134.08 kN and 190.87 kN for PFC\textsuperscript{3D}, respectively.

The area of the cutter in contact with the material (groove area) increases with the increase of back-rake angle. Because of this fact, the cutter has to push more material resulting in higher forces observed on simulations with higher back-rake angles. Figure 14 illustrates the phenomenon. The reason for the increase of forces at higher back-rake angles is the increased degree of difficulty to remove cuttings from cutter front at large back-rake angles. Similar behavior was reported by Kaitkay and Shen (2004).

Figure 16 present the effect of back-rake angle on MSE for two-dimensional (green points) and three-dimensional (black points) simulations. The specific energy increases with the cutter inclination. Modeling on PFC\textsuperscript{2D} shows that mechanical specific energy has almost equivalent values when using back-rake angles of 20° and 25°. MSE continues to increase at higher angles as it happened at lower angle ranges (5°, 10° and 15°). Experiments were carried out using a back-rake angle of 20° under atmospheric condition and result is shown in Figure 16 and the reference MSE value of 92 MPa was measured. Three-dimensional modeling yielded better results than the two-dimensional approach. Table 2 shows the comparison.
since the values are closer to the unconfined compressive strength of salt (22 MPa).

Figure 15. Increased contact area and cutting forces when the back rake angle increases – PFC3D.

Unfortunately no similar works involving DEM applied to simulating cutting in evaporite could be found in the literature. In spite of that a few works on other types of rocks are highlighted here. Rajabob et al. (2012) performed single cutter tests on Carthage marble, changing back-rake angle from 5° to 40°. They observed that the mechanical specific energy may double its value when the back-rake increases. Ghoshouni and Richard (2008) while performing scratch tests on some brittle rocks also observed an increase on specific energy with increasing back-rake angle.

Figure 16. Effect of back-rake angle: results for halite at atmospheric conditions in 2D and 3D models

Table 2. Comparison between experimental single cutter test and numerical modeling

<table>
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<tr>
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<th>Experiment</th>
<th>Modeling 2D</th>
<th>Modeling 3D</th>
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<th>Error 2D (%)</th>
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<td>98</td>
<td>96.04</td>
<td>4.4</td>
<td>6.5</td>
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6 EFFECT OF DEPTH OF CUT

The effect of DOC on rock cutting efficiency is discussed in this section. Analogously to the previous section, simulations were carried out under atmospheric conditions, but now using a constant back-rake angle of 20°, the same as in the single cutter experiments.

Figure 17 shows the horizontal force for the three-dimensional modeling. Simulations were performed at DOC of 0.3 and 0.8 mm. Results show an increase of cutting forces with the increase in DOC. Figures 18 and 19 show the average forces for all simulations with different DOC for the two and three-dimensional modeling. The average horizontal forces increased linearly with DOC that is in agreement with results of similar studies on Carthage marble presented by Mendoza et al. (2011). Richard et al. (1998) demonstrated that cutting forces are proportional to the cross sectional area of the cut geometry for shallow depths of cut which is coherent with the observed linear trend between cutting forces and DOC. The authors stress that this relationship is expected when cutting happens in ductile regime.

Figure 17. Cutting forces – depths of cut of 0.3 mm and of 0.8 mm

Figure 18. Average cutting forces versus depth of cut – PFC2D.
Figure 20 shows the calculated mechanical specific energy for two and three-dimensional modeling using different DOC. In spite of that, DOC was constant during a particular simulation. Results reveal a decrease of specific energy with the increase of DOC. Similar results were found by Rajabov et al. (2012) on experiments carried out on Torrey Buff sandstone with DOC up to 0.8 mm. Jianyong (2012) also found analogous results while working with Carthage marble. Figure 20 shows that specific energy decreases until the depth of cut of 1.4 mm to further stabilize around a value of 77 MPa.

For every rock type, there is a DOC range where drilling is optimum. This range varies depending on bit type and bit wear off characteristics.

It is important to emphasize that some results produced in this study are indicative of the specific behavior of the studied target rock: halite. Finally, acknowledging all model assumptions, Figure 20 suggests that the efficient drilling for modeling occurs for DOC greater than 0.8 mm.

7 CONCLUSIONS

A Discrete Element Modeling methodology on evaporite drilling was proposed that involved setting micro properties of spherical discrete elements and the establishment of relationship between contact stiffness and ball’s overlap for the same discrete element set. A new method to calibrate the parameters affecting the mechanical behavior of a virtual material in order to reproduce realistic compressive mechanical behavior of halite samples based on the triaxial test data was also presented. The model was tested against single cutter experimental data and drilling efficiency analysis was performed based on the effects of different cutter back-rake angles and depths of cut.

The calibration process was challenging given the fact PFC does not have contact models readily available for the target scenario. A complementary code was developed based on a linear model combined with parallel bond technique. A new artifice was employed and the parallel bond contact stiffness was changed in each simulation cycle, assigning decreasing contact stiffness as a function of balls overlap. This artifice converted the linear model available on PFC in a different model with nonlinear behavior. As a result, a new stress-strain curve was found that correlated well with the lab test curve.

A relevant aspect concerning the physics of rock cutting was implemented in the model leading to better agreement between calculated and experimental drilling mechanical specific energy. Particles ahead of the cutter were deleted using a particle position criterion for 2D-simulations.

A second set of modeling was performed to understand the impact of changing back-rake angle on the mechanical specific energy. The increase in back-rake angle increases the specific energy and cutting efficiency improves when low back-rake angles are used since the values approximate with the unconfined compressive strength of salt (22 MPa).

Furthermore, the study on the effect of depth of cut on specific energy revealed that specific energy decreases with the increase of depth of cut until a particular point from where specific energy stabilizes. Initial results from the frictionless model suggest that for halite drilling using a sharp PDC bit, DOC higher than 0.8 mm and up to 1.6 mm were considered optimum.

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