Development of a 3D discrete element method approach to study the evolution of rock cutting mechanism in high-depth conditions: application to Vosges Sandstone.

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ABSTRACT: While wells reach deeper and deeper targets, understanding the cutting mechanism under confinement is not yet fully mastered. Among the numerical methods used to study this problem, the Discrete Element Method has already shown promising results, but the evolution of rock behavior with confinement is not always considered. This work proposes a calibration method based on UCS and triaxial tests to represent the evolution of rock behavior with confinement. This calibration procedure is implemented on Vosges Sandstone. The rock model failure envelope is built based on further triaxial tests and agrees with the experimental one. Secondly, linear cutting tests under confinement were implemented on the calibrated model. The results are compared to experimental ones. Their good agreement allows the validation of the proposed approach.

Keywords: DEM, model calibration, rock cutting, confinement, PDC.

1 INTRODUCTION

Understanding the destruction mechanisms in a confined environment due to high depths conditions is essential for optimizing deep drilling, not only for the gas and oil industry but also in the context of deep geothermal energy recovery or CO_2 storage. With PDC drill bits accounting for 90% of the distance drilled annually, understanding the cutting mechanism is essential. The current state of the art shows that this mechanism is well understood in atmospheric conditions (Rostamsowlat, 2017), but the impact of high depths conditions (confinement, temperature, and pore pressure) is not yet fully mastered.

Different approaches are used to study this topic (experimental, numerical, and study of drilling logs); among them, numerical methods such as the Discrete Element Method (DEM) have demonstrated encouraging results (Carrapatoso et al., 2015; Helmons, 2017). Unfortunately, numerical models sometimes show a lack of representativeness concerning the evolution of the behavior of rock materials with confinement. Therefore, they are unable to reproduce the evolution of the mechanism and typically give cutting forces that differ from the ones measured in laboratories.

This work proposes a method of calibration and simulation of cutting tests with DEM that allows getting as close as possible to experimental data to validate the numerical modeling and deepen the understanding of the cutting mechanism. The method has been applied to Vosges Sandstone.

2 SYNTHETIC ROCK MODEL CALIBRATION

2.1 Vosges Sandstone behavior

The mechanical behavior of Vosges Sandstone has been widely studied through the years, and the literature referring to this rock is very broad (Descamps, 2007; Couture & Bésuelle, 2019). Indeed, this rock, whose characteristics are comparable to oil and gas reservoir rocks, is generally used as a reference. Although numerous references dealing with Vosges Sandstone are available in the literature, this section mainly refers to the work of Descamps (2007). Descamps performed compression tests under confinement on triaxial and polyaxial (true-triaxial) devices. Results of polyaxial tests performed up to 90 MPa of confinement are presented in Figure 1. For low confinement values ranging from 0 to 10 MPa, the Voges Sandstone presents a brittle behavior with a residual strength. From the confinement of 20 MPa, the rock shows a ductile behavior with perfect plasticity and hardening at higher confining pressure. These tests allow determining the failure envelope of Vosges Sandstone in the Mohr plane (Figure 2 (b)).

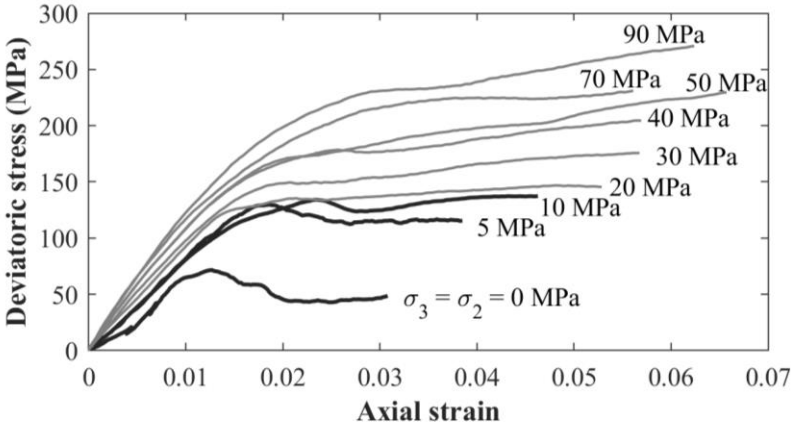

Figure 1. Stress-strain curves of the Vosges sandstone under conventional triaxial compression conditions. Data from Descamps (2007).

2.2 Calibration procedure

Any modeling project with Discrete Element Method codes starts with a first calibration step. During this step, selecting a constitutive model and calibrating its micro-properties is necessary to obtain a representative behavior of the studied material. The Bonded Particle Model (Potyondy & Cundall, 2004) has been used. This constitutive model has already been widely used in modeling related to rock mechanics problems.

The calibration procedure has been built based on two compressive tests, a uniaxial one and one under confinement. Based on a first set of micro-properties, uniaxial compressive tests are simulated iteratively by modifying the micro-properties until a uniaxial behavior comparable to the one observed experimentally is obtained. Once this first phase is completed, the set of micro-properties is tested in a triaxial test with the confinement of 20 MPa (transition between brittle and ductile behavior in Descamps (2007)). This test aims to verify that the set is suitable for reproducing the rock post-failure behavior while reaching a comparable confined compressive strength to the one measured in laboratory testing. The micro-properties are validated if the results obtained during the triaxial test are conclusive. Otherwise, it is necessary to adapt micro-properties and restart the uniaxial step.

2.3 Calibration results and validation

More than 80 iterations were necessary to obtain satisfactory results with a maximum of 10% variation in compressive strength and Young's modulus. The stress-strain curves of the final calibration step are presented in Figure 2 (a), while the micro properties are given in Table 1.

Table 1. Parallel bond's micro-properties to create synthetic Vosges Sandstone model.

Micro-properties	Values
Minimum ball radius (mm)	0.1
Ball size ratio	3
Contact modulus (GPa)	4
Ball stiffness ratio	3
Ball friction coefficient	4
Parallel bond modulus (GPa)	16
Parallel bond stiffness ratio	4
Parallel bond tensile strength (MPa)	25 ± 70
Parallel bond shear strength (MPa)	130 ± 60

To validate the calibration procedure, confined compressive tests were simulated with confinement ranging from 5 to 70 MPa to determine the failure envelope of the synthetic rock model and compare it to the one proposed by Descamps (2007). Figure 2 (b) presents the failure envelope of the synthetic rock model in the Mohr plane. The general shape of this envelope is close to Descamps' one built from experimental tests. Besides the evolution of mechanical properties, verifying the evolution of the behavior with confinement is essential. For this purpose, Figure 2 (c) to (e) presents the stress-strain curves recorded numerically for three different values of confinement (5, 30, and 70 MPa) and compares them to the experimental ones. These curves highlight the good agreement between the numerical and experimental behavior of the Vosges Sandstone.

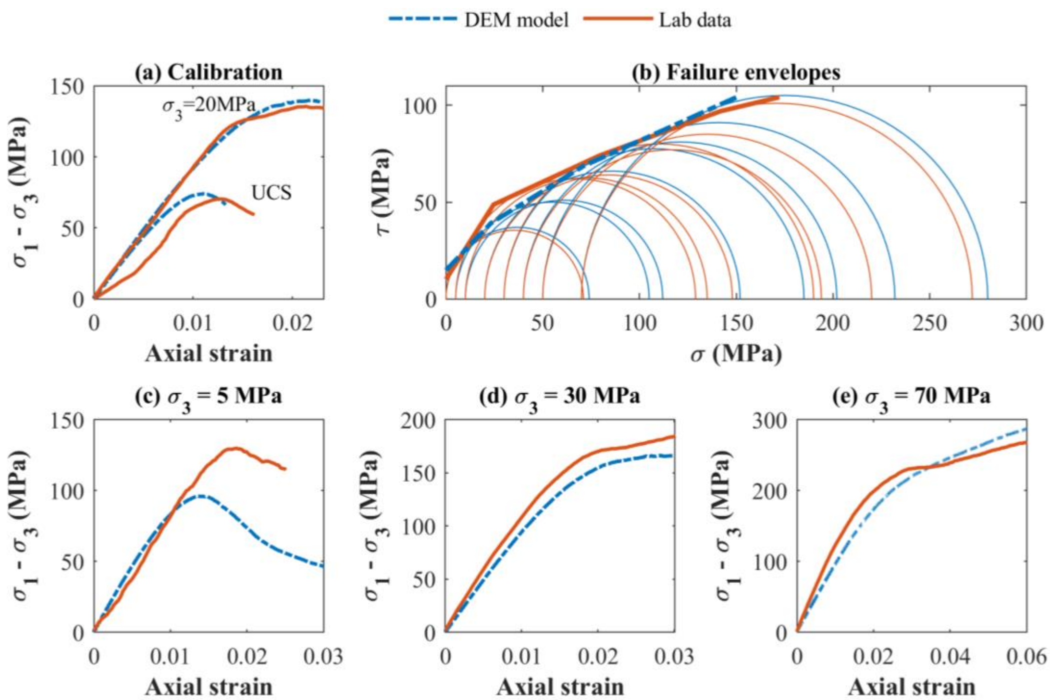

Figure 2. Results of the calibration procedure. (a) Stress-strain curves at the end of the calibration procedure for UCS and test a 20 MPa of confinement. (b) Comparison between laboratory et numerical failure envelopes. (c) Validation of synthetic rock model at 5 MPa of confinement. (d) Validation of synthetic rock model at 30 MPa of confinement. (e) Validation of synthetic rock model at 70 MPa of confinement.

3 CUTTING MODELS CONSTRUCTION

3.1 Conceptual and numerical models

Figure 3 (a) presents the conceptual model considered to build the numerical cutting model. Although in practice, the cutting process in drilling is a 3D process where the cutter is in a simultaneous circular and vertical motion, on a small scale, the movement of the cutter can be assimilated into a linear movement at constant horizontal speed and constant depth of cut (vertical velocity is null). The rock is normally subjected to a tri-dimensional state of stress where the upper surface is subjected to mud pressure (P_m) and the lateral surfaces to horizontal in-situ stresses (P_c). However, as Sellami et al. (1990) have shown, the role of lateral stress on the cutting mechanism is negligible when drilling under confinement. Therefore, the stresses applied to the lateral faces of the models were such that $P_m=P_c$. Figure 3 (b) presents the general rock cutting model geometry in 3D. The rock sample is represented as a rectangular parallelepiped with dimensions H, L, and W. While the length L and height H of the specimen were constant and respectively fixed at 25 mm and 8 mm for all simulations, the width W was a function of the depth of cut. To limit the calculation time, the refine function of PFC3D was used to create different particle size distributions in the model by increasing the particle radius in areas that are not affected by the displacement of the PDC cutter. Three zones were defined to progressively increase the particles size with depth. The particles in the upper zone have the size defined during the calibration stage. The distribution is multiplied by 1.5 in the central zone and 2 in the lower one. Circular sharp cutters with a diameter of 13 mm were used in this study. Back and side rake angles were set for all simulations to 15° and 0°. Cutter velocity (V_c) was fixed to 1m/s, and the confinement was applied via the 'shinning-lamp' algorithm (Schöpfer et al., 2017).

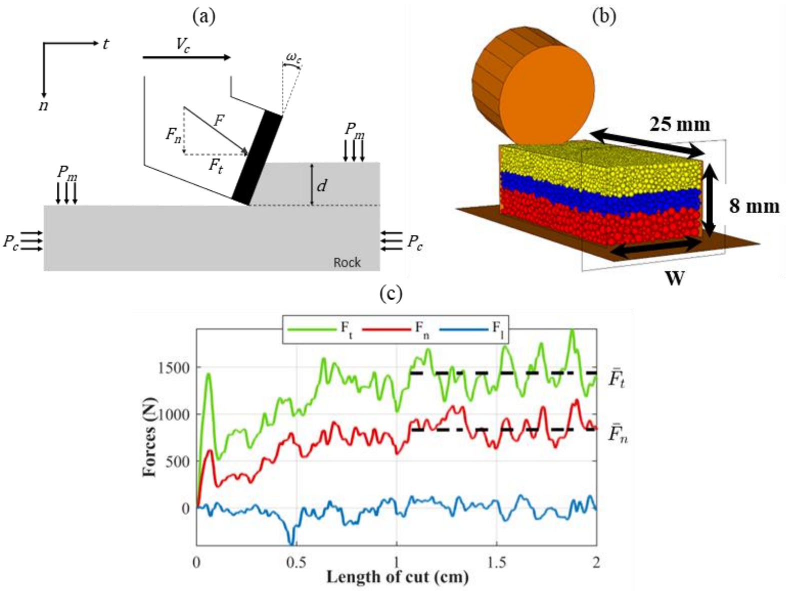

Figure 3. Model of rock cutting and output data. (a) Conceptual model. (b) 3D numerical model. (c) Cutting forces registered during the simulation of rock cutting.

3.2 Output data

During simulations, total forces acting on the cutter in the three principal directions were recorded: the tangential cutting force F_t (in the direction of motion), the vertical (thrust) force F_n, and the lateral force F_l (perpendicular to the direction of motion). They are respectively represented in green, red, and blue in Figure 3 (c). This work mainly focuses on the tangential cutting force F_t. Specific Energy E is used to compare simulations with different depths of cut. Usually, E is defined as the ratio between the average tangential cutting forces F_t and the active surface of the cutter A_c (Detournay & Defourny, 1992).

4 RESULTS AND COMPARISON TO EXPERIMENTAL TESTS

Linear cutting simulations have been performed for depth of cut from 0.5 to 2.5 mm and confinement from 0 MPa to 40 MPa. The first interest was the evolution of the magnitude of mean cutting forces with confinement. Regarding the magnitude of the cutting force, Figure 4 compares the measured average forces obtained numerically under different confinement conditions with results published in the literature (Kaitkay & Lei, 2005; Majidi et al., 2011; Amri et al., 2016). The cutting forces are standardized based on UCS, as experimental conditions and tested materials are not always the same. The standardized cutting force (SCF) values are very interesting to compare. Indeed, the SCF values are close for tests carried out under comparable confinement. The SCF values show that the forces obtained numerically are consistent with experimental measurements. Although this is not a formal proof of the exact validity of the measured forces, it shows consistency with experimental values.

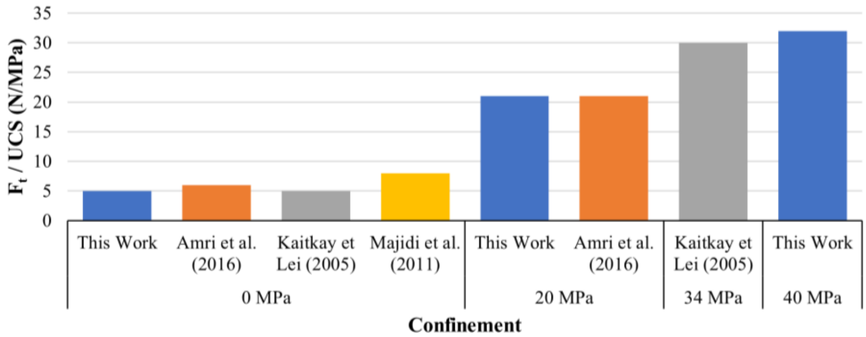

Figure 4. Comparison of tangential cutting force between simulations and various lab tests in the literature (Kaitkay & Lei, 2005; Majidi et al., 2011; Amri et al., 2016).

The second point of interest is the evolution of the Specific Energy according to the depth of cut. The graphs in Figure 5 show the existence of an optimum for each confinement. This optimal depth of cut is not unique but evolves with increasing confinement. These results agree with those generally found in the literature (Akbari et al., 2011; Rajabov et al., 2012).

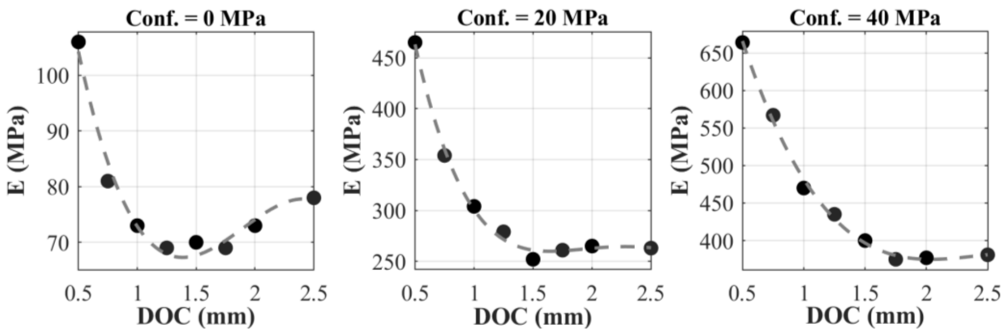

Figure 5. Curve fitting of the evolution of Specific Energy with DOC at different confinement values.

5 CONCLUSIONS AND OUTLOOKS

This work aimed to propose a methodology to improve the study of the cutting mechanism under confinement by the Discrete Element Method.

The first step concerned the calibration of the numerical model. This phase is critical when implementing the Discrete Element Method. The main focus was calibrating the synthetic rock model to reproduce the Vosges Sandstone behavior evolution with confinement. While traditional calibration methods are generally based on uniaxial or triaxial tests, the protocol implemented in this work combines both tests. The results show that an appropriate choice of the confinement value for the triaxial test allows to reproduce quite accurately the rock behavior.

The second step involved cutting simulations to determine cutting forces and energies. The objective was to compare the numerically measured forces with experimentally measured ones under similar conditions. Contrary to numerical research generally published in the literature in which the simulated cutting forces are very different from the ones measured in the laboratory, the model developed in this work is able to simulate forces magnitudes that are in good agreement with experiments. Furthermore, it can correctly represent the evolution of the Specific Energy with depth of cut for a given confinement.

The methodology developed during this work and the results provide opportunities for future research, such as the validation of the methodology and results with other rock materials, the consideration of the hydro-mechanical coupling, and the application of the work methodology to other destruction mechanisms.

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