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Simulation of Rock Drilling Process using Smoothed-Particle Hydrodynamics Method

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ABSTRACT. Drilling operation in other planets and discovery of their available resources, as well as exploiting oil and gas fields of earth planet have focused the attention of the researchers on finding some ways to reduce drilling time and cost. In this regard, the use of optimized and well-designed drilling tools, especially drilling bits, seems to be very essential. Concerning this issue, a proper and reliable estimation of the rock cutting process using diamond bits could be efficient in this process. On the other hand, the simulation and modeling of the cutting process is a complex issue for which various methods have been proposed. In this paper, concerning the special conditions of rock cutting, the drilling process mechanical analysis was done through smoothed-particle hydrodynamics (SPH) and LS-DYNA was used for analysis purpose. Finally, the results of using this method were investigated. Furthermore, the effect of different rake angles was also investigated. Concerning the hydrodynamic behavior of smoothed particles and the appropriate velocity of meshing and analysis, as well as the heterogeneities of materials such as rock in this code, this method could be considered as suitable for drilling analysis.

Keywords: Rock drilling; Smoothed-particle Hydrodynamics (SPH); Finite element; Granite.

INTRODUCTION

There are several ways to identify the earth stones using specific physical principles; mechanical force or so-called machining is one of the most important methods in this case.[1] Drilling operation consists of several physical processes that in sum lead to rock drilling and crushing. Proper perception of the machining condition of cutting tools and rock is very important as these tools are associated with certain conditions such as unpredictable conditions of other planets or drilling under high-pressure and temperature in oil and gas reservoirs. Reduction in the rate of penetration (ROP) in drilling has been specified by many experts and taken as one of the most important threatening factors in drilling in oil and gas industry.[1] There is a high demand for improving the drilling technology such that increasing ROP and tools lifelong is highly dependent on proper perception of rock drilling process. As far as the observation of rock fragmentation in experimental tests is usually costly, some analytical method such as mechanistic[2] and elasticity[3] are under investigations. Numerical simulations for clarification of tool-rock interaction is a proper and cheap method also. Various numerical models such as finite difference method, finite element method, discrete element method and boundary element method have been utilized by researchers to model the interaction between rock and tools.

Kou et al. performed the rock cutting process through analysis of two-dimensional plane strain process, which is a sample of finite element method code.[4] In their method, rock was considered as an inhomogeneous material despite other simulation methods that considered it as a homogenous material. This model considerably forecast the damage due to cutting and

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crushing and the damage site. They considered steel as tool and modeled it as an almost isotropic homogenous material and considered the rake angle as zero. They performed rock destruction in shearing mechanism through two-dimensional REPA code and believed it to have a main problem. The problem was that the deterioration of element, their analysis of the initial element and after big strains is not properly done.[4] Cho et al. studied the rock destruction process using finite element code in 3D-AUTODYN.[5] This simulation was performed for examination of the size of drilled rock that was accessible in wearing option. They considered steel 4340 material for tools with 3D-AUTODYN materials and ignored the tool wearing. The rocks and stones that they considered were Korean granite, limestone and tuff. They showed that in this method the volume reduced from stone can be calculated in experimental test.[5, 6] Huang and Detournay studied the relation between stone and tools using 2D discrete element method and studied the crushing mechanism.[7] They considered the tool as rigid and stone with semi-elastic behavior and used 2D PFC code for analysis. They conclude that rock fragments could be simulated through discrete element method.[7] Tan et al. used discontinuous displacement to simulate the tool-rock interaction.[8] They considered the tool as rigid and elasticity module of 26.5 Gpa and Poison coefficient of 0.38 for the piecework. Their results showed that the rakes are constituted from several mechanisms including tensile or shearing stress or a combination of them. Yet, the rake separation was not considered in their study.[8] Pradeep et al. simulated rock cutting process using finite-element and LS-DYNA methods and evaluated a spectrum of incline angle, shearing depth and velocity.[9] They used nonlinear explicit finite element code for piecework and tool and considered tetrahedron element for tool and piecework. Furthermore, they selected limestone and sandstone of MAT-105 material model and considered RIGID-20 for tool. In this study, the element machining and separation occurred properly; however, the shape of chips and the effect of tool on piecework were considerably different from practical rock machining. The simulations that are based on networking method usually have some deficiencies in creation and propagation of cracks in fracture simulation complex process and impose some problems for the users. Therefore, the researchers are recently seeking new simulation methods that are not based on networking of pieces for applying stress and its effects which has led to a new method which is known as smoothed-particle hydrodynamics (SPH).[10] This method was first proposed in 1997 by Glingold and Monagan in solving nonsymmetric phenomenon in 3D open space astrophysical hydrodynamic.[10] In the represented system by particles, the mass is usually assumed to be fixed with properties of the material with regular motion to maintain the invariability and reduce the diffusion of computations of various properties of materials. The equation governing the system evolution could be developed in such a way to exactly preserve a large number of relations, motions and energy.

The SPH relations, complex physical effects are easily organized and therefore used for a wide range of problems. These activities include elastic flow,[11] fluid flows,[12, 13] heat transfer problems,[14] multiphase flows,[15] which are all used to solve these problems. Pramanik et al. simulated rock destruction process using SPH.[16] They utilized elastoplastic model and Draker-Praer performance model for analysis of plastic deformation and applied the Brazilian compressive strength tests on a piece of simulated stone in form of a disk with diameter of 54 m, elastic module of 50 Gpa and Poison coefficient of 0.1. For this simulation, they used 14296 particles with diameter of 0.4 mm. Mardalizada et al. performed rock fracture simulation through FEM coupled to SPH in LS-DYNA software.[17] In this method, they could identify the crack initiation areas. Moreover, they selected finite element nonlinear Lagrange method due to precision and speed in problem solving for their simulation. The reason for selection of this method is that there is usually distortion in the rock behavior, the rock fracture simulation through FEM is usually done without considering the elements that cause severe heterogeneity and this is inevitable. In FEM coupled to SPH technique, by replacing the extremely inhomogeneous elements with SPH using finite element Lagrange method, this problem will be avoided after a certain limit. They performed their simulation on a Pietra Serena Sandstone block and under pure bending test according to ASTM1998 standard, under vertical pressure of two cylinders and verified the results through practical test. Furthermore, they used Karagozian and Concrete (KCC) model and concluded that this model is calibrated with a high precision using operational tests and the numerical results are still expected to be improved by direct identification of materials based on Pietra Serena

Sandstone block under a three-axial test. They concluded that the presented numerical simulations have proved the performance and reliability of KCC material in iteration of bending test.[17]

MATERIALS AND METHODS

Governing Equations

The damage model considered for rock is HJC which is material No. 111 in LS-DYNA model and selected for implementation of this model. This damage model considers the stress and hydrostatic pressure, material destruction and final stress.[18]

$$\sigma^* = [A(1-D) + BP^{*N}](1 + Cln\,\dot{\varepsilon}^*) \tag{1}$$

Where, $\sigma^* = \frac{\sigma}{f_c}$ which is normal stress equation,

$\sigma^* \leq S_{MAX}$,

D is $(0 \leq D \leq 1)$,

$P^* = \frac{P}{f_c}$,

$\dot{\varepsilon}^* = \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}$ is the dimensionless stress, and

$\dot{\varepsilon}_0 = 1\,S^{-1}$ is the rate of reference stress

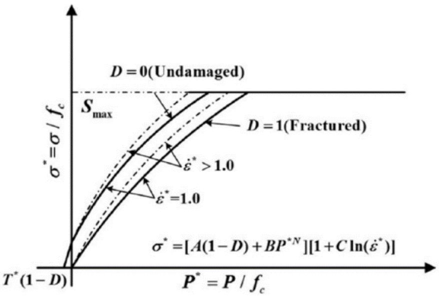

Fig. 1: Equation of yield surface.[18]

$$D = \sum \frac{\Delta\varepsilon_P + \Delta\mu_P}{\varepsilon_P^f + \mu_P^f} = \sum \frac{\Delta\varepsilon_P + \Delta\mu_P}{D_1(P^* + T^*)^{D_2}} \tag{2}$$

Equation 2 is obtained from the sum of the equations of plastic strain and plastic volumetric strain. According to above equation, $\Delta\varepsilon_P$ and $\Delta\mu_P$are plastic strain and plastic volumetric strain and D_1 and D_2 are fixed values. $\varepsilon_P^f + \mu_P^f$ is the plastic strain under P fixed pressure failure. $T^* = \frac{T}{f_c}$ is maximum normal stress under hydrostatic pressure, where T is the maximum stress under hydrostatic pressure to which the material can resist.

$$D_1(P^* + T^*)^{D_2} \geq EFM \tag{3}$$

$$\text{P} = K\mu \tag{4}$$

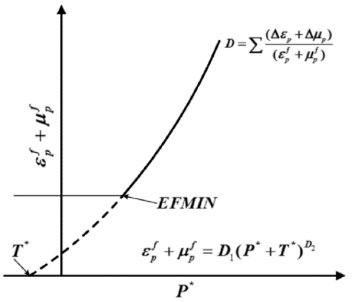

Fig. 2: Damage of HJC model.[18]

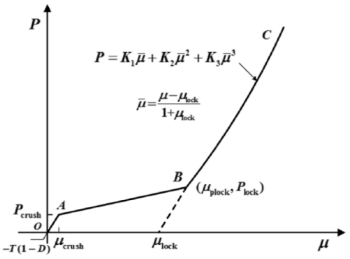

Fig. 3: Equation of State.[18]

Fig. 2 represents HJC damage model and Fig. 3 represents HJC equation of state which is divided into three phases of linear elastic, plastic and density phase. The first area is related to linear elastic phase where $(0 \leq \mu \leq \mu_{crush})$, P is hydrostatic pressure and $K = \frac{P_{crush}}{\mu_{crush}}$.

The second area which is known as transient area is in fact plastic phase where $(\mu_{crush} \leq \mu \leq \mu_{lock})$. In this area, the pores in the material are compressed and deformed as plastic.

$$P = \text{P}_{crush} + K_{lock}(\mu - \mu_{crush})\;(loading) \tag{5}$$

In above equation, $K_{lock} = \frac{(P_{lock} - P_{crush})}{(\mu_{lock} - \mu_{crush})}$ is established.

$$P = \text{P}_{crush} + K_{lock}(\mu_0 - \mu_{crush}) + [(1-F)K + FK_{lock}]\,(\mu - \mu_0)(unloading) \tag{6}$$

For Equation (6), it is possible to consider $F = \frac{(\mu_0 - \mu_{crush})}{(\mu_{lock} - \mu_{crush})}$. μ_0 is volumetric stress before loading.

The third area in HJC equation of state is known as density area. In this area μ ≥ μ_{crush} and the pores inside the material is do condensed. In this stage, the fracture has been completely done.

Generally, the loadings and discharges are proposed in form of Equation 7.

$$\text{P} = K_1\bar{\mu} + K_2\bar{\mu}^2 + K_3\bar{\mu}^3 \tag{7}$$

$$\text{P} = K_1\bar{\mu}\;(unloading) \tag{8}$$

Where $\bar{\mu} = \frac{(\mu - \mu_{lock})}{(1+\mu_{lock})}$ is established. $\bar{\mu}$ is the modified volumetric strain and K1, K2 and K3 are fixed values. $\bar{\mu}$ is introduced to prevent the material softening condition after entrance to density area (third area).

It is noteworthy that HJC damage model is considered for stone and in the mentioned simulation, the cutting tool is considered as a rigid object.

SPH

Guo-Xing Zhang[19] used SPH method in LS-DYNA software to simulate a steel bullet with a diameter of 25 mm diameter hitting a cylindrical block with a diameter of 400 mm and a thickness of 100 mm. They used HJC material model to simulate the stone and verified their results through a practical test. They used HJC damage model to describe the deformation and nonlinear fracture properties of rock and metal materials. They concluded that modeling through SPH method is more accurate than the finite element method. This present work intends to simulate the stone cutting process by compressed polycrystalline diamond which is done through SPH. Moreover, it is intended here to examine the rock destruction during simulation using HJC damage equation and compare the results with experimental test to verify this simulation.

The Process Simulation

In this paper, concerning the experimental test of Zhen Chenge et al.,[20] Granite was selected to simulate the implementation of rock machining model and it was assumed that the cutting process has been done without any greaser and cooling material. In this simulation, the rake angles of 10, 20 and 30 degrees were studied. For this modeling, the workpiece was considered fixed and the tool as moveable which exactly matches the experimental test by Zhen Chenge et al.[20] The rock material was granite, the tool was compressed polycrystalline diamond and the used method was FEM. The analysis was 3D which was implemented in room temperature. In this simulation, concerning the experimental test, the cutting depth is considered as 0.3, 0.6, 0.9, 1.2 and 1.5 mm. Each drilling bit includes several cutting tools placed in regular layouts. The angle and the location of each cutter is selected precisely proportionate to the bit situation in respect to the target rock. In this paper, in order to simplify the simulation operation and reduce the time of computations in software, a cube of 15×15×19.5 mm was considered which is sufficient for full engagement of a cutter and rock. In bits, the cutters are placed in such a way that the empty spaces cover each other. Therefore, consideration of a cutter for simulation and the symmetry of the general structure of bit will not impose any problem in accuracy of the simulation response. The modeling of the piecework and the tool has been done in the software. In this method, the density of the particles changes with variation in the distance between them. In this simulation, the density of particles is considered as 0.25 per millimeter for rock element which was selected through investigation of distances from 0.01 to 0.5 mm due to excessive increase of analysis time. Therefore, this distance is enough for observation of the results and the energy transmission from one particle to another can be easily observed. Due to formulation properties as of SPH code, there is no need to increase the density of particles in machining areas using remeshing method in each step of analysis. As far as the deformation of tool is less than stone and rock, FEM code and tetrahedral element with density of 0.3 mm as tool have been used in this analysis. Concerning the difference between the used codes between tool and piecework, the automatic nodes to surface has been considered for the tool to piecework contact. The tool has been located at the edge of piecework and 1.2 second has been considered as the time step against rotational velocity. The drilling bit and the manner of its location during drilling operation inside the earth layers have been modeled based on the practical sample, and they are schematically shown in Fig 4.

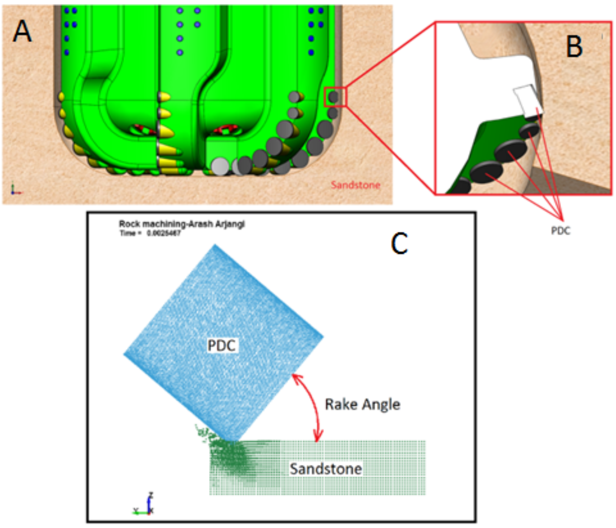

Fig. 4: A) Drill bits in sandstone layer, B) Cut section of drill bits and diamond insert location, C) Finite element and hydrodynamic particle plan design for drilling simulation.

RESULTS AND DISCUSSION

Concerning what is mentioned so far, the simulation process of rock machining has been done using compressed polycrystalline diamond with SPH and the stone was easily separated from the piecework. The advantages of this method include the precise examination of the variations of piecework and even the rock fracture process and the capability of simulation of machining process without any need to fragment the meshing or perform remeshing for solving the problem. Cutting force is very important at investigating many parameters such as diametrical error in workpiece.[21]

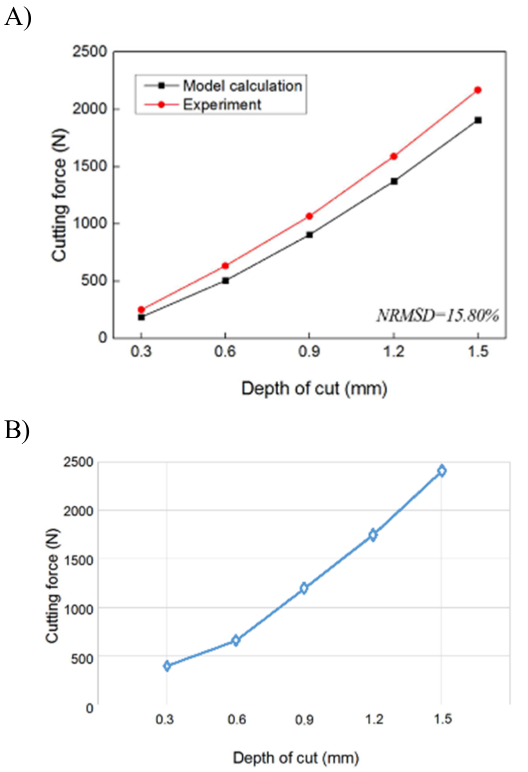

Fig. 5: Using the test method of cutting depth in SPH method; A) Experimental testing research,[20] B) Analysis with LS-DYNA.

The Validation of Simulation

In 2018, Cheng et al.[20] experimentally studied the rock cutting force and the damage surfaces created in rock cutting test. They considered some items such as cutting depth, machining angle and the shape of machining. The test was performed on three samples of Granite stone, Marble and Sandstone. The samples were fixed on the milling machine in form of cubic pieces and the linear machining process was simulated by horizontal automatic movement of the machine table. Concerning the cutting depth, the machine table had vertically degree of freedom and a holder was designed for fixing the tool in different angles. The researchers used a known cutter diamond, known as PDC cutter of diameter 19 and height of 13 as the main cutter for the test. This cutter was one of the most common cutters used in oil drilling industry (Fig. 4). The test procedure was such that after fixing the piecework, they changed the holder to intended angles and iterated this test repeatedly and recorded the force applied by dynamometer to the end of test. Results of SPH simulation are shown in Figs. 5-7 in comparison with the experimental test by Cheng et al.[20]

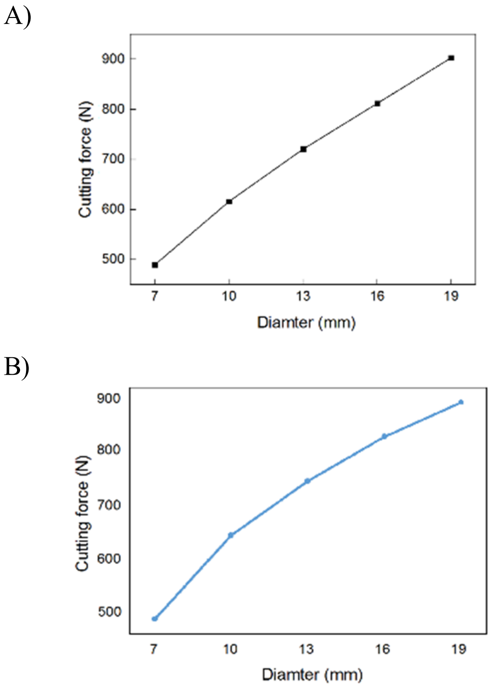

Fig. 6: Using the test method of cutting diameter in SPH method A) Experimental testing research,[20] B) Analysis with LS-DYNA.

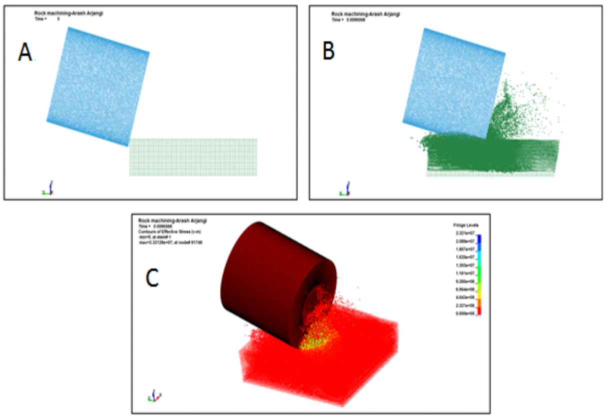

Fig. 7: Cutting by SPH method; A) moment of contact with the work piece, B) penetration of grate into the granite, C) stresses and position of cracks propagation.

It can be inferred from the figures that the forces and cutting energy can be easily identified in this method can be even used for crack development and propagation. The speed of analysis and meshing in this method is higher than other methods including FEM. It is no longer any need to further fragment the meshes to avoid negative volume or to perform remeshing.

CONCLUSION

The results of software output and the behavior of SPH and the comparison of the obtained results indicate the efficiency of this code for stone machining and cutting process. The forces and machining energy could be easily identified in this method and used for crack development and propagation. The analysis and meshing in this method are very speedy and quick. Furthermore, there is no need to fragment the meshes or to perform remeshing to avoid creation of negative volume which facilitates the analysis and achievement of the intended result. Concerning the verifications, this method could be used for calculation, prediction and optimization of drilling bits in oil industry and tunnel boring machines while saving the laboratorial costs. It is noteworthy that the rate of calculations in this method is lower than FEM.

Indices

σ Equivalent stress
f_c Static uniaxial compressive strength
A Normal cohesive strength
B Normal pressure stiffness coefficient
N Hardening pressure
S_{max} Maximum normal pressure
C Strain rate coefficient
D Destruction variation
P Normal pressure stiffness coefficient
$\dot{\varepsilon}$ Hardening pressure
K Elastic bulk module
P_{crush} Bulk pressure
μ_{crush} Bulk strain
P_{lock} Bulk pressure in uniaxial compressive stress test
μ_{lock} Bulk strain in uniaxial compressive stress test
μ_0 Bulk strain before loading

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