

Research Article

Study of the Interaction Model of PDC Cutters with Rock

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Abstract: The existing PDC cutters with rock interaction models does not match the actual drilling condition, because WOB can't be loaded on their equipment, the influence of the cutting velocity on the force of cutters doesn't be considered. A drilling experiment was carried out in the experimental device in which cutters can be loaded WOB. The relationship of cutting area, cutting speed, back dip angle of PDC cutter and rock performance with the force of PDC cutter were considered. The multiple nonlinear regression analysis were done on the basis of the experimental data, a new cutter-rock interaction model was established. The cutter area is the principal component influencing the force of cutters though the cluster analysis and principal component analysis. It is a logarithmic relationship between cutting velocity and the force of cutter, the theory of particle dynamics confirms this relationship.

Keywords: Back rake angle, force of cutter, interaction model, PDC bit, rock drill-ability

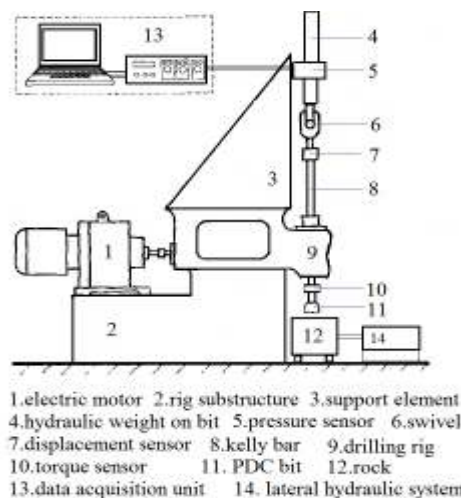
INTRODUCTION

The interaction model of PDC cutters with rock is very important to forecast the ROP of the bit. Deyong and Wang (2005) and Ma and Wang (2006) established some PDC cutter rock interaction models on the cutting rock experiment using lathe, but their models have some problems. Their equipment can't WOB loaded on the bit. Their model don't consider the influence of the cutting velocity on the force of cutters. To solve these problems, a new drilling experiment was carried out, using a drilling machine which can loaded WOB on the bit, under different WOB, cutting velocity, rock and back rake angle of PDC cutter.

MATERIALS AND METHODS

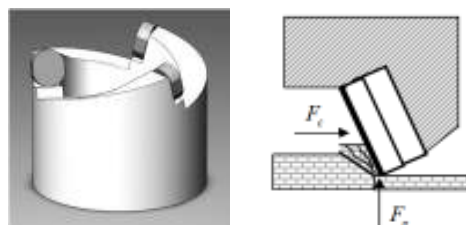
Equipment and methods of drilling experiment: The No. XY-2B drilling machine consists of electric motor, kelly bar, PDC bit, hydraulic system, sensors, data acquisition unit etc. in China University of Petroleum, shown in Fig. 1a. Hydraulic pressure loaded on the bit is 3, 4, 5, 6, 7 KN, respectively. The cutting velocity of PDC cutter is 0.05, 0.28, 0.66 and 1.18 m/sec, respectively. There are 15 kinds of PDC bit which consists of three cutters, shown in Fig. 1b. The cutter's diameters are 13, 16, 19 mm and their back rake angle are 5, 10, 15, 20 and 25°, respectively.

Tangential force F_c is in the direction of the cutter velocity. Normal force F_n is in the normal to the rock surface, shown in Fig. 1c. The pressure sensors are used to measure the normal force of the PDC cutter. A



1.electric motor 2.rig substructure 3.support element
 4.hydraulic weight on bit 5.pressure sensor 6.swivel
 7.displacement sensor 8.kelly bar 9.drilling rig
 10.torque sensor 11. PDC bit 12.rock
 13.data acquisition unit 14. lateral hydraulic system

(a) No. XY-2B drilling machine



(b) A bit

(c) A model of cutting rock

Fig. 1: Equipment of text

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Table 1: Rock parameter

Kinds of rock	Rock drill-ability K_d	Indentation hardness/MPa	Compressing strength/MPa	Tensile strength/MPa
Shale	5.0	944.5	67.34	5.58
Marble	5.7	1118.4	84.79	6.21
Granite	6.4	1490.8	94.18	7.02
Limestone	7.0	1785.4	103.54	7.87

Table 2: Contribution rate and eigenvalues of variables

	Tangential force	Cutting area	Rock drill-ability	Back rake angle	Cutting velocity
Eigenvalues	5.443	2.380	0.845	0.813	0.612
Contribution rate	54.399	22.901	8.567	8.124	6.009
	Normal force	Cutting area	Rock drill-ability	Back rake angle	Cutting velocity
Eigenvalues	5.192	2.470	0.878	0.827	0.632
Contribution rate	51.924	24.704	8.778	8.269	6.325

torque sensor is used to measure the tangential force of the PDC cutter. The averages of rock drill-ability, indentation hardness, compressing strength, tensile strength are shown in Table 1.

RESULTS AND DISCUSSION

Cluster analysis: The similar variables were classified into a class using system clustering method, shown in Fig. 2. Cutting area is clustered early with cutting depth, contact arc and cutter diameters. Then, they are clustered with the force of cutters. Cutting area can comprehensively reflect the effect of cutter shape on the force of cutters, so we only consider cutting area in the interaction model of PDC cutters with rock. Rock drill-ability is clustered early with indentation hardness, compressing strength and tensile strength. Then, they are clustered with the force of cutters. Rock drill-ability can comprehensively reflect rock breaking efficiency, so we only consider rock drill-ability in the model.

Principal component analysis: The main factors were found using principal component analysis, shown on the Table 2. The sum of tangential force's contribution rate and cutting area's contribution rate is over 76%. It is the same to normal force. So cutter area is the principal component influencing the force of cutters.

Regression analysis:

Relationship between cutting area and the force of cutter: When the back rack angle, cutting velocity and rock drill-ability is a constant, the force of cutters increases linearly with the cutting area shown in the Fig. 3. Because cutter area is the principal component influencing the force of cutters, the relationship between the force and cutting area can be expressed as a linearly function:

$$\begin{cases} F_n = a_1 A + b_1 \\ F_c = a_2 A + b_2 \end{cases} \quad (1)$$

a_1, a_2, b_1, b_2 are factors

Relationship between rock drill-ability and the force of cutter: When the back rack angle, cutting velocity and cutting area is a constant, the force of cutter

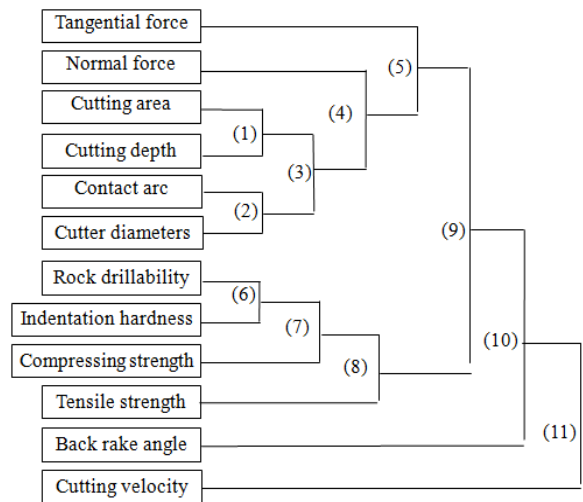


Fig. 2: Cluster diagram

increases linearly with rock drill-ability K_d , shown in the Fig. 4.

Relationship between back rake angle and the force of cutter: When rock drill-ability, cutting velocity and cutting area is a constant, it is a quadratic relationship between back rake angle and the force of cutter, shown in the Fig. 5. When the back rake angle of cutter is over 10° , the normal force F_n , tangential force F_c increases with the back rake angle of cutter.

Relationship between cutting velocity and the force of cutter: When rock drill-ability, back rake angle and cutting area is a constant, the normal force F_n , tangential force F_c increases with the cutting velocity. It is a logarithmic relationship between cutting velocity and the force of cutter, shown in the Fig. 6.

Some authors Fairhurst (1955), Gray *et al.* (1962) and Roxborough and Pedroncelli (1982) ignored the effect of cutting velocity on the normal force and tangential force using forward rake cutter. Because their experiment's condition did not match drilling filed, their theory is not right. Other authors Dagrain and Tshibangu (2002) and Pelfrene *et al.* (2011) pointed out that the normal force and tangential force increases with the cutting velocity using backward rake cutter.

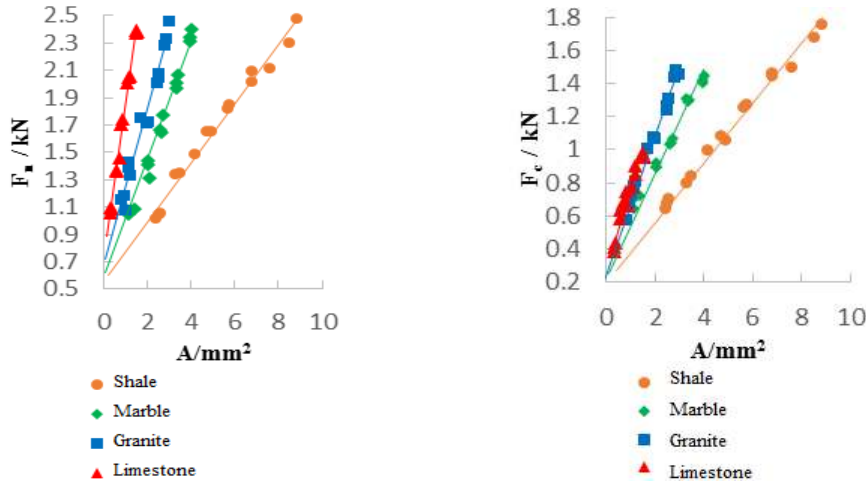


Fig. 3: Relationship between the cutting area A and normal force F_n , tangential force F_c (back rake angle is 15° , cutting velocity is 0.28 m/sec)

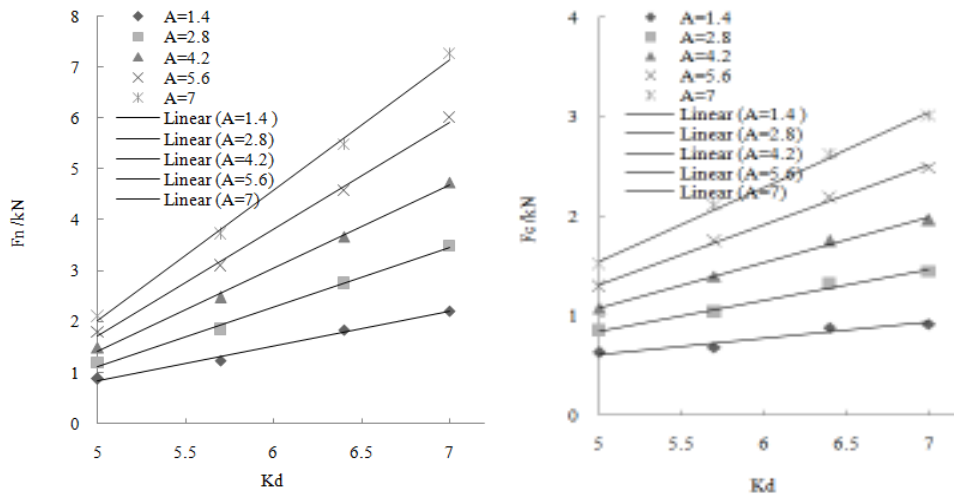


Fig. 4: Relationship between the rock drillability and normal force F_n , tangential force F_c (back rake angle is 15° , cutting velocity is 0.28 m/sec)

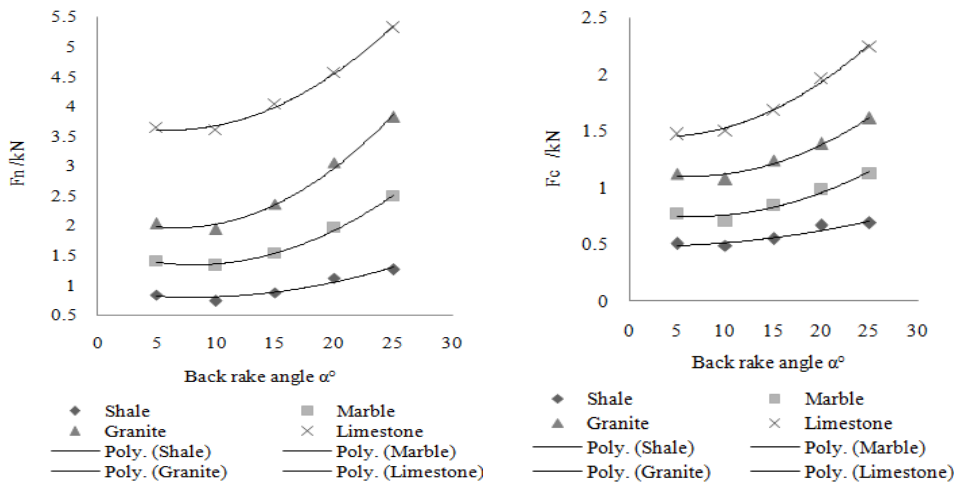


Fig. 5: Relationship between the back rake angle α and normal force F_n , tangential force F_c (cutting area is 2.8 mm^2 , cutting velocity is 0.28 m/sec)

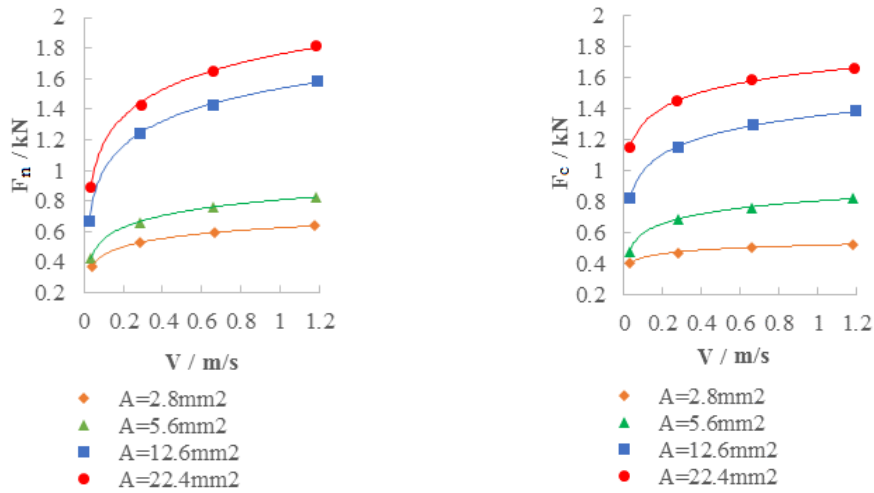


Fig. 6: Relationship between cutting velocity V and normal force F_n , tangential force F_c (back rake angle is 15° , shale)

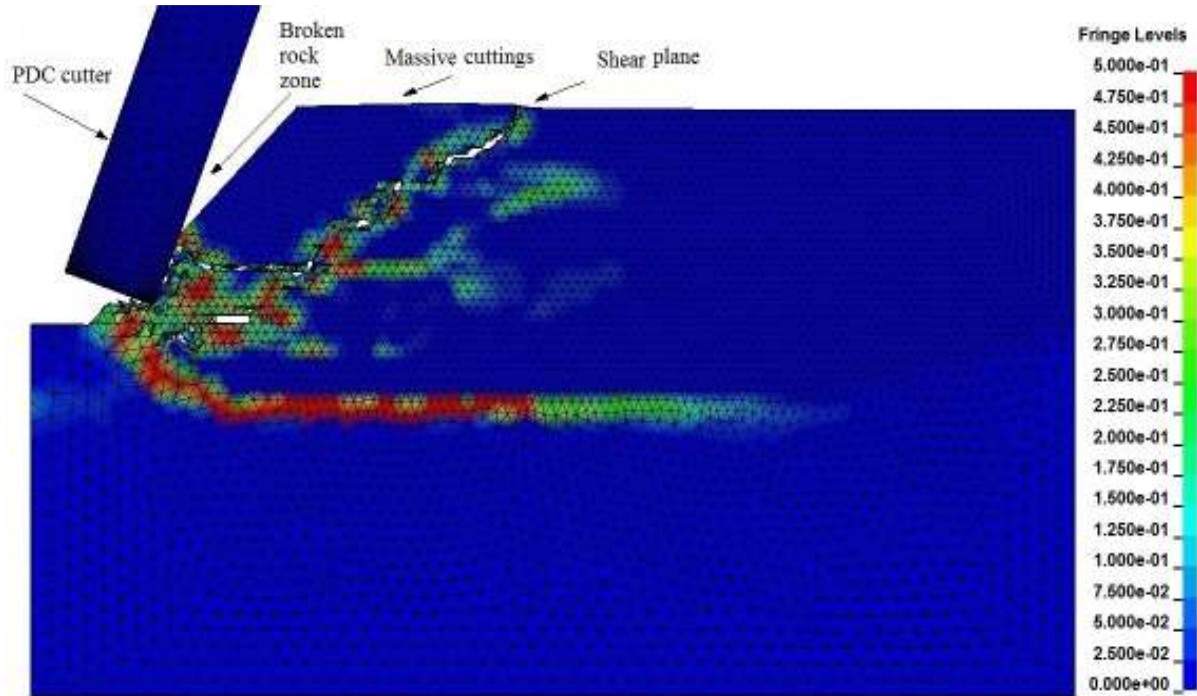


Fig. 7: Numerical simulation of cutting rock

In order to explain this logarithmic relationship, a finite element stress analysis was done for dynamic cutting rock, using LS-DYNA finite element computer program, shown in Fig. 7. Massive cuttings will be cut down from the rock along the shear plane. The rock powder of broken rock zone can't move forward neither backward under the effect of squeezing, confined within the cutter and massive cuttings.

In our opinion, broken rock zone is a kind of granular materials. We invoked a dynamic mechanism studied in the field of granular materials. Hartley and Behringer (2003) have shown experimentally that

increasing the shearing rate of a granular material, confined within the annular space of a rotor and a stator, increases the normal stress in the granular network. It is due to the increasing difficulty to reorganize the grain network as the shearing rate increases. According to this theory, the rock strength of broken rock zone depends on the cutting velocity.

Multiple nonlinear regression analysis: A multiple nonlinear regression analysis were done on the basis of the experimental data, we got a interaction model of PDC cutters with rock:

Table 3: Experimental data and calculated value of the force of cutters

Kinds of rock	Back rake angle/°	Cutting velocity m/sec	Cutting area/mm ²	Normal force F _n /kN		Tangential force F _c /kN	
				Experimental data	Calculated value	Experimental data	Calculated value
Shale	10	0.28	7.396	0.9854	0.9862	0.5958	0.5943
	15	0.66	9.842	1.3383	1.3379	0.9354	0.9348
	20	1.18	11.531	1.6806	1.6811	1.1989	1.1979
Marble	10	0.28	4.472	1.0325	1.0329	0.3883	0.3888
	15	0.66	6.213	1.3148	1.3142	0.8978	0.8982
	20	1.18	7.582	2.0135	2.0142	1.2171	1.2167
Granite	10	0.28	4.794	1.3287	1.3292	0.8008	0.8013
	15	0.66	7.448	2.0783	2.0779	1.2383	1.2375
	20	1.18	7.842	2.3375	2.3368	1.4647	1.4636
Limestone	10	0.28	3.755	1.6599	1.6586	0.8435	0.8445
	15	0.66	2.636	1.7455	1.7449	0.6651	0.6662
	20	1.18	3.936	2.4243	2.4236	1.2576	1.2568

$$\begin{cases} F_n = a_1 A + b_1 \\ a_1 = (0.03\alpha^2 - 0.07\alpha + 11.84)(2.31K_d - 8.87)(0.43 \ln V + 0.81) \\ b_1 = (0.19\alpha^2 - 5.34\alpha + 321.83)(1.10K_d - 3.38)(0.04 \ln V + 0.08) \end{cases} \quad (2)$$

$$\begin{cases} F_c = a_2 A + b_2 \\ a_2 = (0.01\alpha^2 - 1.29\alpha + 11.23)(2.12K_d - 7.83)(0.44 \ln V + 0.82) \\ b_2 = (0.01\alpha^2 + 0.03\alpha + 96.39)(0.31K_d - 0.60)(0.04 \ln V + 0.07) \end{cases} \quad (3)$$

Calculated values of the force are similar to the experimental data, shown in the Table 3. This model give an accurate description of the relationship between cutting area and the force of cutter.

CONCLUSION

- The cluster analysis and principal component analysis were done on the basis of the experimental data, cutter area is the principal component influencing the force of cutters.
- It is found that our experimental data match the drilling filed data, using a drilling machine which can load WOB.
- When rock drill-ability, back rake angle and cutting area is a constant, it is a logarithmic relationship between cutting velocity and the force of cutter.
- When the back rack angle, cutting velocity and rock drill-ability is a constant, the force of cutters increases linearly with the cutting area.
- When rock drill-ability, cutting velocity and cutting area is a constant, it is a quadratic relationship between back rake angle and the force of cutter.

NOMENCLATURE

PDC = Polycrystalline Diamond Compact
 ROP = Rate of Penetration (m/h)

WOB = Weight-on-Bit (tonnes)
 F_c = Tangential force (kN)
 F_n = Normal force (kN)
 α = Back-rake angle (°)
 V = Cutting velocity (m/sec)
 A = Cutting area (mm²)
 K_d = Rock drill-ability

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