Mechanical Analysis and Structural Optimization of Air Hammer Drill Teeth Based on ANSYS /LS_DYNA

Han Wu, Kai Wang*, Zhengyu Feng,Yang Zou

Department of Mechanical and Electrical Engineering, Chengdu University of Technology, Chengdu 610059, China

*e-mail: 1926604417@qq.com

Abstract. Air drilling is a prevailing technology of oil and gas energy industry in today’s world, it can solve problems when drilling in complex layer that can not be done by conventional drilling way. At the same time, some failures of dill bit teeth in air hammer drilling like teeth falling, breaking and severe abrasion seriously affect the drilling efficiency. Thus this paper intended to investigate rock breaking criteria and damage constitutive model, establish a finite element simulation model of single tooth rock breaking and use the impact of dynamic finite element software ANSYS/LS-DYNA to analysis characteristics of rock crushing under confining pressure, which includes fragmentation process, drilling tooth impact and the crush volume of rock broken. The study found that the tapered tooth has the highest efficiency in rock breaking under the same conditions and with edge teeth at 25° angle that increases the rock crushing volume significantly. In addition, the configuration of tooth surface was examined, which showed that the pattern of “spherical teeth in the middle and tapered teeth in the peripheral” has highest rock breaking efficiency.

Keywords: Air drilling; rock breaking criteria; tapered tooth

1. Introduction

In the last few years, air hammer drilling method is widely used in both surface and underground mining (Bu et al., 2009; Luo et al., 2016), owning to its several advantages, including higher penetration rates in drilling hard rock, protecting the reservoir, production of straighter holes (Yin et al., 2013), effective treatment of severe well leaking, and lower costs.

However, with the use of air hammer bit drilling in Tarim and Puguang , some technique and equipment problems have been exposed. For instance, the performance of domestic produced air hammer is unstable. Except that, drill stucking occurs frequently. Besides, drill bit is prematurely broken. The last but not least, the drill bit is too early abrased, which causes the equipment damage and higher maintenance cost.

So far, domestic and foreign scholars have done the following research about the air percussion drilling technology: G. Han (Han, Bruno & Dusseault, 2006) established a simulation model of the drilling and studied the rock breaking mechanism of the hammer bit drilling; Xu (Xu et al., 2017.) studied that the structure of percussion-rotary bit effect on service life and rock breaking performance) The curves of resultant force varying with time, the relation curves of average resultant force and specific energy varying with structure parameters were gotten. Zhang (Zhang, Yan & Chen, 2013) studied the stress of single cutter tooth at different installation angle and drilling speed. Obtained the best installation angle and working speed, and provide guidance for the distribution and installation of the teeth on the tooth surface. Zeng (Zeng et al., 2014) studied the failure analysis and structural optimization of air hammer bit. Considering the horizontal stress of formation rock and the pressure condition of overlaying strata， established the full-size interactive model of piston-bit-rock.

At present, the major problems in the air drilling include(Zhu, Luo & Jia, 2012; Fan, Huang & Gao, 2011):

(1)Most studies did not consider the changes of rock mechanical properties under dynamic load or the numerical simulation analysis which was merely based on the assumed performance parameters. The analysis results could not exactly reflect the actual working condition

(2)Most of the researches focused on the relationship between drilling parameters and rock-breaking energy efficiency, and there were only limited studies on the performance parameters of drill teeth.

Therefore, based on the study of rock performance parameters, this paper has achieved the optimal design of air hammer drill teeth by studying the interaction between the teeth of the drill bit and the rock.

2. Rock breaking analysis

It is of great theoretical significance, engineering value and economic benefit to study the strength theory of geotechnical materials under complex stress. At present, strength theory is divided into two categories: one is linear strength theory, such as Tresca criterion, mo hr-coulomb criterion and double-shear strength criterion; the other is non-linear strength theory, such as Lade criterion, SMP (spatially mobilized plane) criterion and D-P(Drucker-Prager) criterion. D-p criterion has been widely used in numerical analysis of geotechnical materials (Li, 2017). Therefore, This paper uses the D-P criterion. And the criterion stipulates that tensile stress is positive and the yield function is:

$$f = \alpha I_1 + \left(J_2\right)^{1/2} - K \tag{1}$$

Where α and K are the material parameters; I_1 and J_2 are the first invariant and the second invariant of stress deflection, respectively.

In terms of principal stress:

$$I_1 = \sigma_1 + \sigma_2 + \sigma_3 \tag{2}$$

$$J_2 = \frac{1}{6}\left[\left(\sigma_1 - \sigma_2\right)^2 + \left(\sigma_2 - \sigma_3\right)^2 + \left(\sigma_3 - \sigma_1\right)^2\right] \tag{3}$$

Damage variable

In this paper, plastic strain is used as the principle for judging rock fragmentation, that is

$$\varepsilon \le \overline{\varepsilon}_{1y} \tag{4}$$

Where $\overline{\varepsilon}_{1y}$ is the equivalent plastic strain when the rock completely fails and ε is the equivalent plastic strain of the rock. Therefore, the damage variable D(Zhu &Liu, 2017) is introduced.

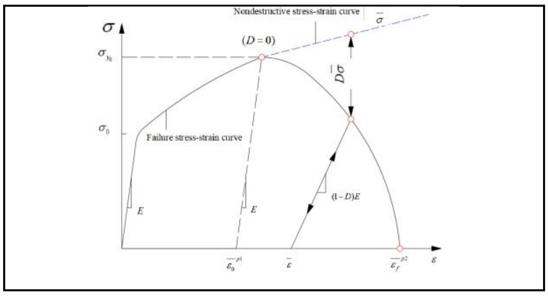


Fig.1 Stress-strain relationship of rock fragmentation process.

3. Damage constitutive model

Rock is a in homogeneous material with a large number of randomly distributed pores, voids and other defects. Therefore, in order to exactly reflect characteristics of rocks at the bottom rocks of the well, the following assumptions are made:

1)The average elastic modulus of the non-damaged rock micro-element is E, which has linear elastic properties before failure.

2)Rock failure criterion is expressed by three principal stress components, namely $f\left(\sigma_1,\sigma_2,\sigma_3\right)=0$

3)The intensity characteristic obeys the statistical law and Weibull distribution：

$$\phi\left(f\left(\sigma_1,\sigma_2,\sigma_3\right)\right)=\frac{m}{f_0}f^{m-1}\left(\sigma_1,\sigma_2,\sigma_3\right)e^{-\left(\frac{f\left(\sigma_1,\sigma_2,\sigma_3\right)}{f_0}\right)^m} \tag{5}$$

Then the rock damage constitutive model equation is established based on Drucker-Prager failure criterion and Weibull distribution(Wang et. al., 2018).

$$\sigma_1=\sigma_{1y}\frac{\varepsilon_1}{\varepsilon_{1y}} \quad \left(\varepsilon<\varepsilon_{1y}\right) \tag{6}$$

$$\sigma_1=E\varepsilon_1\exp\left[-\left[\frac{f}{f_0}\right]^m\right]+2\mu\sigma_3 \quad \left(\varepsilon\geq\varepsilon_{1y}\right) \tag{7}$$

The equation of the brittleness parameter m is

$$m=\frac{-f_p}{E\varepsilon_{1p}\dfrac{\alpha_0\left(\sigma_{1p}+2\sigma_3\right)+\sqrt{3}\left(\sigma_{1p}-\sigma_3\right)/3}{\sigma_{1p}-2\mu\sigma_3}\ln\dfrac{\sigma_{1p}-2\mu\sigma_3}{E\varepsilon_{1p}}} \tag{8}$$

The equation of the intensity parameter f_0 is

$$f_0=\left[\frac{F_p{}^m}{-\ln\dfrac{\sigma_{1p}-2\mu\sigma_3}{E\varepsilon_{1p}}}\right]^{\frac{1}{m}} \tag{9}$$

4. Rock breaking finite element analysis of single tooth

Establishing rock breaking finite element simulation model of single tooth

Ingersoll-Rand QL air hammer bit QL01S ball type was selected as prototype, as shown in Fig. 2. The rock was meshed based on mapping method and the mesh of drill tooth was manually refined to increase the accuracy of the solution.

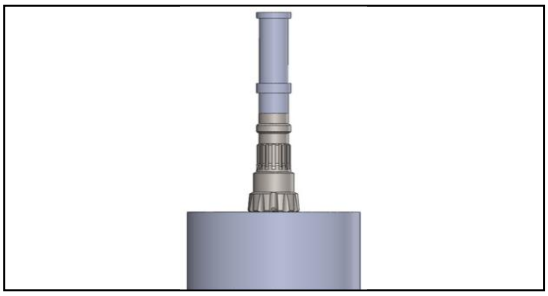


Fig.2 Air hammer drilling system model.

Set the parameters of the rock materials, as shown in Table 1.

Table.1 related parameters of rock materials.

density（kg/m^3）	Shear modulus（GPa）	cohesion strength（GPa）	Pressure hardening coefficient B	Strain rate coefficient C	Pressure hardening index N	Static uniaxial compression strength (GPa)
2500	14.86	$1.04e^{-2}$	1.65	0.007	0.61	$4.8e^{-2}$
Maximum tensile static pressure	Reference strain rate	Minimum plastic strain before fracture	Standardized maximum intensity	Crushed pressure	Crushed volumetric strain	Standardized maxim intensity
$1.2e^{-3}$GPa	$1e^{-6}$	0.01	7.0	$1.6e^{-4}$GPa	0.001	7.0
Crushed pressure	Crushed volumetric strain	Compaction pressure	Compacted volumetric strain	Damage constant	Pressure constant	Failure strain
$1.6e^{-2}$GPa	0.001	0.8GPa	0.1	D_1=0.04 D_2=1.0	K_1=85GPa K_2=-171 GPa K_3=208 GPa	0.5

Establishing a finite element model for center teeth in the bit, as shown in Fig. 3.

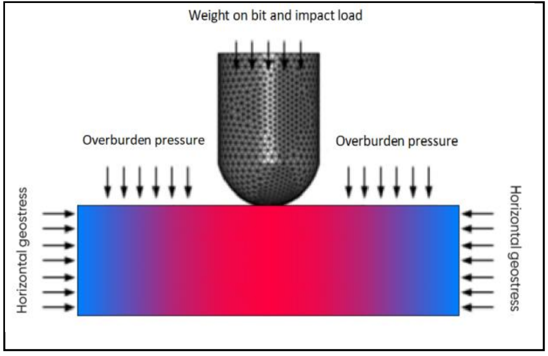


Fig.3 Finite element model for center teeth in the bit.

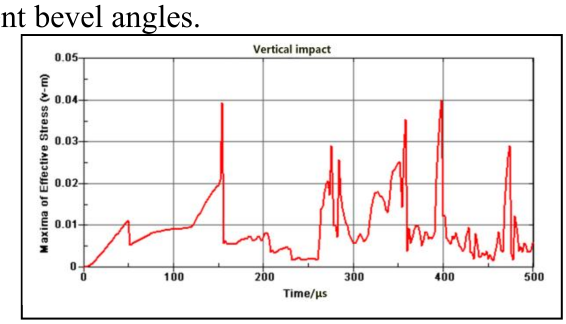
Defining failure criteria:

Failure principal stress $\sigma_{\max}$ as failure criterion, unit failure when $\sigma > \sigma_{\max}$, where σ is maximum principal stress.

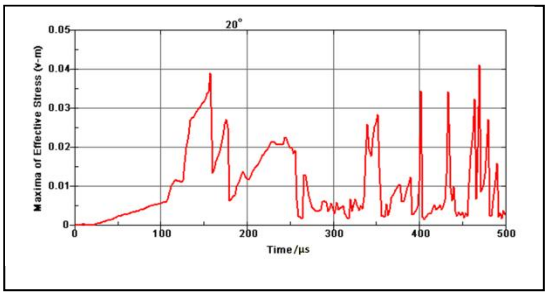
5. Rock breaking analysis of single tooth

Firstly, one-tooth-impact-system model was established and the tooth at different angles were titled to the rock, and then the effect of tooth bevel angle were studied on crush volume, sinking depth and tooth stress.

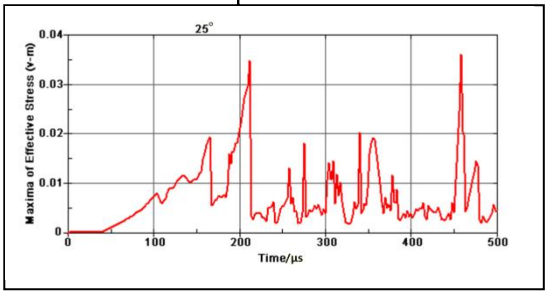
As shown in Fig. 4 a-g, that is the maximum equivalent stress curves of spherical tooth impact rock breaking under different bevel angles.



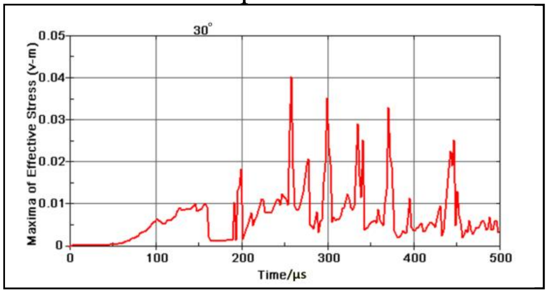
a)Curves of time history of the maximum equivalent stress for the tooth at 0° angle.



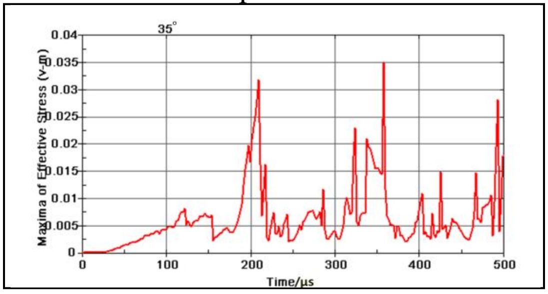
b)Curves of time history of the maximum equivalent stress for the tooth at 20° angle.



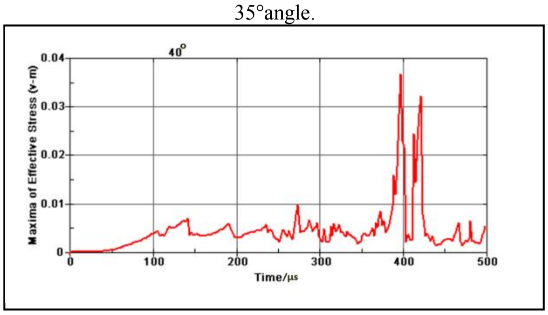
c) Curves of time history of the maximum equivalent stress for the tooth at 25° angle.



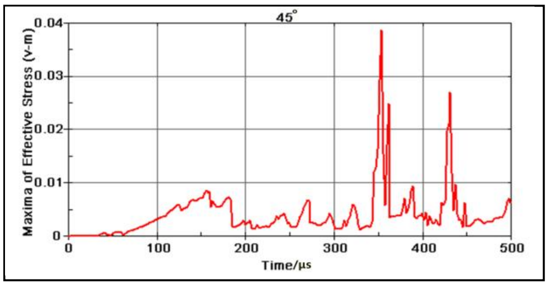
d) Curves of time history of the maximum equivalent stress for the tooth at 30° angle.



e) Curves of time history of the maximum equivalent stress for the tooth at 35°angle.



f) Curves of time history of the maximum equivalent stress for the tooth at 40°angle.



g) Curves of time history of the maximum equivalent stress for the tooth at 45°angle.

Fig.4 a)-g) Curves of time history of the maximum equivalent stress for the tooth different bevel angle.

According to Fig. 4 a)-g), it can be concluded that, at first, the rock undergoes plastic deformation under the action of drilling pressure at the initial stage of the impact, and the maximum equivalent stress of the seven models fluctuates little. With the impact load increases instantaneously, the stress in the contact area between the rock and the tooth tip is highly concentrated, and the rock undergoes compress-elastic deformation and be condensed to a dense core. When the impact load reaches the maximum, the piston drill bit generates stress waves that can make large amplitude in short time, the fragile part first begin to break and then become full break)With the progress of rock damage, the surface cracks and internal cracks of the rock intersect with each other, and the rock begins to rupture and form a fracture pit. And some conclusions can be drawn as follows:

(1) The maximum equivalent stress curve of the inclined teeth fluctuates greatly, and the stress peaks of the vertical center teeth appear earlier than the inclined side teeth.

(2) At different inclination angles, the peak value of the stress wave and the peak occurrence time are different. And the maximum peak occurrence times are: 20°>25°>40°>45°>35°>0°>30°, and the corresponding maximum equivalent stresses are: 45°>20°>0°>35°>30°> 40°>25°. Therefore, in the same case, the edge teeth at 25° angle have the smallest maximum equivalent stress, and the edge teeth at 45° angle have the largest maximum equivalent stress.

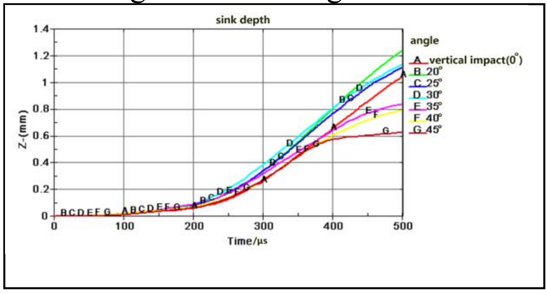


Fig.5 Curves of time history of the sinking depth at different inclined teeth angle.

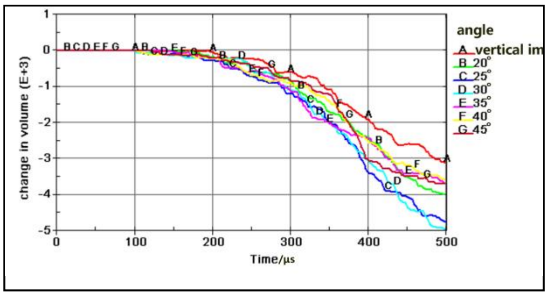


Fig.6 Curves of time history of crush volume at different inclined teeth angle.

Fig. 5 and Fig. 6 show that the curves of time about sinking depth and crushing volume in different inclined teeth angles. As can be seen from Fig. 5 and Fig. 6, under the same drilling parameters, the order of depth of the drill bit intrusion into the rock that in one cycle is 20°>30°>25°>0°>35°>40°>45°, and the order of crush volume is 30°>25°>35°>20°>40°>45°>0°. Therefore, knows that the edge tooth at 25° angle tooth has the highest efficiency.

Since the shape of the drill bit directly affects the rock breaking efficiency, in order to research which tooth shape has the highest efficiency and study the effect of the tooth profile on the crater volume and the sinking depth under the same parameters, a single tooth impact finite element analysis model of the spherical tooth, tapered tooth and bullet tooth is established, as show in Fig. 7.

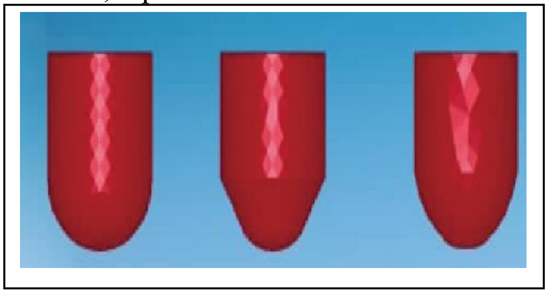


Fig.7 Shapes of three kinds of bit teeth.

Fig.8 shows the curves of time history of the crater volume influenced by different tooth shapes. It can be obtained that the tapered tooth has the largest crater volume and the spherical tooth has the smallest crater volume.

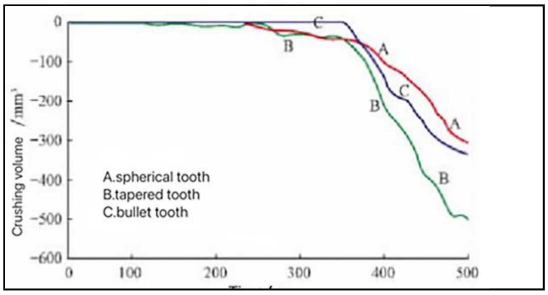


Fig.8 Curves of time history of the crater volume influenced by different tooth shapes.

As shows in Fig. 9, tapered tooth has the largest sinking depth and bullet tooth has the least sinking depth.

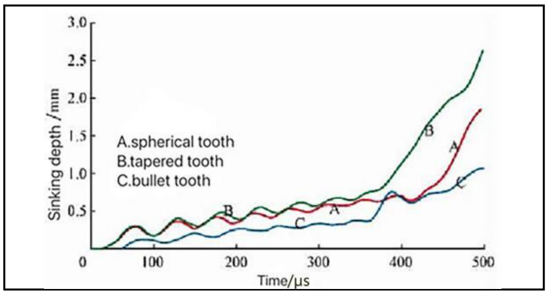


Fig.9 Curves of time history of the sinking depth of different tooth shapes.

6. Influence of different tooth configurations on crush volume

In Section 3, we could get that tapered tooth has the largest sinking depth and the largest crater volume. However, the high efficiency of the single tooth could not prove that all the teeth have high efficiency. Therefore, we chose spherical and tapered teeth for the tooth configurations, and obtain a new bit solid model. By studying the new bit solid model, we could obtain the influence of different tooth configurations on the sinking depth and the crater volume.

Establishing different tooth configurations, as show in Table 2.

Table.2 tooth configurations.

Bit tooth surface structure	Central tooth	Other tooth
1	Spherical tooth	Spherical tooth
2	Spherical tooth	Tapered tooth
3	Tapered tooth	Tapered tooth
4	Tapered tooth	Spherical tooth

7. Conclusions

In this paper, the effects of the edge tooth inclination on the crush volume and sinking depth of rock breaking were studied through establishing a dynamic constitutive model of rock based on the theory of rock plastic mechanics and a finite element analysis of single tooth rock breaking . And some conclusions could be drawn as follows:

(1)The maximum equivalent stress curve of the inclined tooth fluctuates greatly, and the stress peaks of the vertical middle teeth appear earlier than the inclined side teeth.

(2)In the same case, the edge teeth at 25° angle have the smallest maximum equivalent stress, and the edge teeth at 45° angle have the biggest maximum equivalent stress. Therefore, the edge teeth at 25° angle is the optimum value.

(3)Through the studying the curves of time history that the sinking depth and the crater volume in different tooth shapes, it can be found that the tapered teeth have the highest rock breaking efficiency. Moreover, the sinking depth of the drill teeth is not continuous, but is increased step by step.

(4)Through the study of the different tooth configurations, it can be found that the middle teeth of air hammer bit in spherical teeth and the other teeth in tapered teeth can have the highest rock breaking efficiency.

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References

[1] Bu, C.G., Qu, Y.G., Cheng, Z.Q., Liu, B.L., 2009. Numerical simulation of impact on pneumatic DTH hammer percussive drilling. J. Earth Sci. China 5 (20), 868-878.

[2] Y Luo, J Peng, L Li, J He, X Gan, K Yin, Z Zhao. Development of a specially designed drill bit for down-the-hole air hammer to reduce dust production in the drilling process. Journal of Cleaner Production 112 (2016) 1040-1048.

[3] Q Yin, J. Peng., B Kun., H He., Y Kui , G. Xin. Study on dust control performance of a hammer drill bit. Int. J. Min. Reclamat. Environ. 2013, 27 (6), 393-406.

[4] Han G, Bruno M S, Dusseault M B. 3D Simulation of rock breakage with air hammers in gas-well drilling: proceedings of the 2006 SPE Gas Symposium, Calgary, Oklahoma, May 15-17, 2006[C].

[5] H. Xu, Y. Zheng, H. Zhao, S. Xu. Effect of structure of percussion-rotary bit on its service life and rock breaking performance. Journal of HeFei University of Technology. 2017, 40 (12).

[6] Y. Zhang, B. Yan, E Chen, X Liu. Dynamic analysis of coal rock in cutting machine picking based on ANSYS/LS DYNA. Journal of Machine Design, 2013, 30 (2): 74-77.

[7] Q. Zeng , Z. Huang, X. Zeng, M. Wang, W. Yin, Y. Zhou. Failure analysis and structural optimization of air hammer bit. China Petroleum Machinery. 2014, 42 (2).

[8] X. Zhu, H. Luo, Y. Jia. Numerical analysis of air hammer bit drilling based on rock fatigue model. Chinese Journal of Rock Mechanics and engineering. 2012, 31 (4): 754-761.

[9] Y. Fan, Z. Huang, D. Gao. Research on rock breaking mechanism of geophysical prospecting hammer bit. Petroleum drilling techniques. 2011, 39 (3): 110-113.

[10] H, Li. Constitutive Models with Elasto-plastic Damages for Rock-like Materials Subjected to High Confining Pressures and High Strain Rates [D]. TianJin: TianJin University, PH. D. Dissertation, 2017.

[11] X, Zhu, W. Liu. The rock breaking and ROP rising mechanism for single-tooth high-frequency torsional impact cutting. ACTA PETROLEI SINICA. 2017, 38 (5): 570-580.

[12] J. Wang, Y. Li, W. Song, W. Xu. Analysis of damage evolution characteristics of rock mass with different joint dip angle. Journal of Harbin Institute of Technology. 2018.