Hot dry rock breaking with PDC bit under various of impact loads

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ABSTRACT: Deep dry hot rock geothermal energy is a new type of renewable energy, which is environmental friendly and abundant. The ROP improvement is one of the bottleneck faced in deep hot dry rock drilling. Regarding to the high temperature, strength of hot dry rock, the combination of downhole impact drilling tools and PDC bits has become an effective method to increase the ROP of hot dry rock, and the waveform of the impact load generated by percussive drilling tool is an important factor influencing the ROP of the hot dry rock. Therefore, a 3D polycrystalline diamond compact（PDC）bit-hot dry rock model is established, in order to evaluate the ROP of dry hot rock under the coupling of impact loads. The research results shows that ROP improvement rate of rectangle impact load is the best， which could provide a theoretical basis for the design of rock breaking percussive drilling tool.

Keywords: Hot dry rock, percussion drilling, rock breaking, energy transfer efficiency, impact load.

1 INTRODUCTION

Green, clean and sustainable utilization of hot dry rock geothermal energy, and deep geothermal development are research hotspots and development trends in the world's energy field. As a carbon-neutral energy, geothermal energy will play a role in promoting the realization of carbon emission peak action before 2030, carbon neutrality before 2060, and optimization of industrial and energy structures. Accelerating the development of deep geothermal resources is in line with national major strategic needs.

The essence of drilling is to solve the interaction problem between the drill bit and the rock, as well as to improve the drilling speed through the efficiency increase of rock breakage (Ma et al., 1995; Wu et al., 2014). In deep and ultra-deep wells(Guarin et al., 1949; Whiteley and England, 1985; Wanamaker, 1951; Melamed et al., 2000), the difficulty of drilling speed improvement increases due to the complicated geological conditions, the geological uncertainty and the poor drilling ability (An et al., 2012). The study demonstrated that if a dynamic load was applied above the drill bit, the penetration rate could be efficiently improved (Gray et al., 1962; JIN et al., 2012; Han et al., 2006; Han et al., 2005). Due to the various designs of rotary drilling tools as well as of working conditions, impact loads of various characteristics will be generated during impact (Lundberg and Okrouhlik, 2006; Lundberg, 1982). The various impact loads correspond to various incident stress waves. The various incident stress waves correspond to various energy utilization rates, which in turn affect the rock breaking efficiency (Shan et al., 1995; Zhao et al., 2005; Lundberg, 1973a; Lundberg, 1973b). In addition to the experimental method, the finite element was implemented to simulate the rock breakage process (Reddish et al., 2005; Sazid and Singh, 2013). Compared to testing, the 3D simulation could deal with complicated boundary conditions. As an example, the ROP (rate of penetration) or displacement could be obtained under the specific types of dynamic load. Currently, the conventional rock breakage simulation method is to apply a displacement or velocity boundary condition above the drill bit (Kuang et al., 2015). In contrast, the real drilling process involves the dynamic or static load or coupling of static and dynamic load to be sustained, which is not in accordance with the practical operation. Consequently, the rock breakage simulation was conducted with different types of dynamic load in this paper. Through the rock energy utilization rate analysis with exponential, rectangular and sinusoidal stress wave shapes, it was demonstrated that the impact energy utilization rate could reach to approximately 80% when the load was rectangular or sinusoidal (Li and Gu, 1994; Samuel, 1996). Therefore, it was significantly important to study the rock breakage under the various characteristics of the loads.

In this paper, the breaking efficiencies under four different types of dynamic loads (exponential, rectangular, triangular and sinusoidal) were compared. Simultaneously, the rock breakage efficiencies of the parameters (frequency and amplitude) under the sine waveform load were studied specifically.

2 PERCUSSION DRILLING

Percussion drilling fascinates the oil and gas industries for its potential to provide quicker penetration rates (ROP) than conventional rotary drilling, especially in hard formations such as granite and dolomite. For conventional rotary drilling, the weight on bit (WOB) first forces the drill bit cutters to penetrate into the rock in the direction normal to the bit movement. Thereafter, the cutters shear chips off of the penetrated rock as the bit rotates (Han et al., 2006; Han et al., 2005). Two requirements are essential for a rotary drill to advance through the rock: (1) the WOB must be large enough to press the drill bit cutters into the rock; and (2) the cutters must generate enough localized shear stress to break the rock, a matter related to rotation speed and cutter properties.

With respect to high impact speed and short contact time and based on the law of conservation of momentum, the drill bit in percussion drilling is able to produce a much higher impact force along the direction of bit movement. The drill bit crushes the rock below when the force exceeds the compressive strength and creates fractures, forming a narrow wedge along the outer boundaries where the bit is inserted (Han, Bruno & Dusseault, 2005).

There are two factors that needs to be addressed for effective percussion drilling: (1) accelaration of the drill bit to an impact speed high enough to overcome the rock strength, and (2) cuttings removal and transport. The pulverized rock needs to be removed as quickly as possible so that a fresh rock surface is available for the next impact. If the fragements are not removed before the next impact, most of the percussive energy will dissipate by rock fragment abrasion rather than contributing to penetration deeper into the rock.

3 MATHEMATICAL FORMULATION AND ANALYSIS THE RESULTS AND DISCUSSION

3.1 Load & Penetration Depth Relationship

During the impact process for breaking rocks in drilling, the drill bit creates a concentrated impact load within the rock. The tip of the drill bit is within the rock, forming first a broken crater which eventually turns into a pit hole. The theoretical and experimental results of the penetration depth show that the penetration force is proportional to the nth power of the depth, as shown in equation (1),

$$P = Ky^n \tag{1}$$

where y is the depth of penetration; K is the force-penetration slope; reflecting the difficulty of invading the rock, and the type of rock, strength, size and shape of the tools related to rock breaking. n is in the range of 0.5-2; for wedge or long bar rock tools, the value of n is close to 1, and the conical or cylindrical shape is between 1-2. This is due to the fact that the crushing angle is substantially constant, and the volume of the crushed rock by the wedge-shaped tool is proportional to the square of the depth of penetration and the cone or cylinder. The shape is proportional to the depth to the third power.

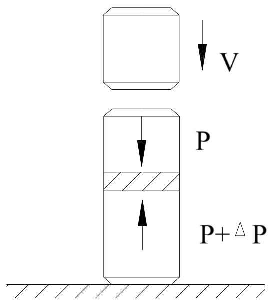

Figure 1. schematic of the impacted stress wave deliever.

3.2 The Force-Displacement Equation

Rock under an impact load will lead to an impact point as the centre of the semi-circular longitudinal wave and shear wave propagate. The shear wave propagation velocity in the rock is half of the longitudinal wave. Whether it is the longitudinal wave or shear wave, after passing to the free interface, it generally has to reflect two vertical and horizontal waves; therefore the waveforms in finite objects are exceptionally complex. In the rock, the tensile strength is much smaller than the compressive strength. Compressed waves are reflected within the free surface into a tensile wave, and these waves are superimposed with a large tensile stress. The opposite direction of the two striking spreads is the main reason for the tearing of the rock, and the shear wave propagation velocity is slow, often before the rock cracks. Consequently, the influence of the shear wave can be neglected in the analysis.

Assuming that the incident wave p (t) is known, the function form of the waveform does not change during propagation, p '(t) represents the reflected wave at the time of chipping, and P is used to denote the penetration force. The relationship between the force and the displacement at the time of a single impact is as given in equation (1).

In the drilling process, the drill bit shape is mostly wedge-shaped, so here n = 1, and both sides of equation (1) are differentiated:

$$\frac{dP}{dt} = K\frac{dy}{dt} = Kv_{ip} \tag{2}$$

Where v_{ip} is the piston impact speed.

From the synthesis of waves, we can obtain:

$$P = 2p(t) - mv_{ip} \tag{3}$$

Finalizing:

$$\frac{dP}{dt} + \frac{K}{m}p = \frac{2K}{m}p(t) \tag{4}$$

Thus, the general form of the chipping equation is given as:

$$P = Ce^{-\frac{K}{m}t} + e^{-\frac{K}{m}t}\int \frac{2K}{m}e^{\frac{K}{m}t}p(t)dt \tag{5}$$

When t=0, P=0.

$$P = \frac{2K}{m}e^{-\frac{K}{m}t}\int e^{\frac{K}{m}t}p(t)dt \tag{6}$$

3.3 Physical Model Definition

The physical model of bit and rock interaction was shown in Figure2. In oil and gas drilling process, the drill bit which connected to the drill string was applied on the formation, the drill bit move forward through the drill collar deliver WOB on the drill bit. PDC drill bit was commonly used in the modern well drilling. Therefore, in this paper, a rock- PDC bit model was used to verify the theoretical analysis.

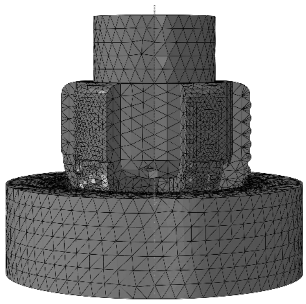

Figure 2. full size PDC –rock physical model of dry hot rock.

The 3D physical model was built with the ABAQUS. The rock properties were: density ρ of 3100kg/m^3, Young modulus E of 20GPa, Poisson ratio μ of 0.33, internal friction of 30°, hot dry rock temperature is 150°C, and the four different shapes of impact loads was applied on the drill bit, which are exponentially, sine, rectangle and triangle impact load.

The main constitutive models of rock model were the Mohr-Coulomb and the Drucker-Prager criteria, whereas the D-P criterion was from the M-C criterion (Abo-Elnor et al., 2003; Abo-Elnor et al., 2004).

$$\alpha I_1 + \sqrt{J_2} - K = 0 \tag{7}$$

where, α, K (flowstress ratio) are the constant parameters related to the angle of friction φ (M-C) and c is cohension, β is angle of friction (D-P), δ_c is compression yield stress.

4 COMPARISON OF DIFFERENT WAVE-SHAPED IMPACT LOAD

In order to obtain the influence of the shape loaded above the bit on the ROP, WOB varied as sine, rectangle, triangle and exponent shape were applied on the bit, and the static load is 50kN, the amplitude of dynamic load are 10, 20, 30 and 40kN respectively, RPM is 104r/min, and frequency is 10Hz, hot dry rock temperature is 150°C.

Figure 3(left) shows the penetration depth of sine, triangle, rectangle and exponent wave shaped loads. It can be seen that with the increasing of the impact load, the ROP increased as well; when the impact load is 0, that is, under the static load, the penetration depth are same; however, when dynamic load were applied on the bit, the penetration depth is higher than that under static load, it is indicated that drilling performance is excellent under the combination of static and dynamic load.

In addition, generally, ROP under sine and rectangle shows similar performance, and better than that of exponent and triangle load apparently, and the higher impact load, the difference of drilling performance is more obvious. At the same time, penetration depth under exponent and triangle shows similar tendency, however, the penetration depth is lower than that of sine and rectangle significantly.

Figure 3(right) shows that the penetration depth and rock breaking volume is rectangle > sine > exponent > triangle, which is highly in agreement with the theoretically results (Yang, Y.et al, 2019). The shapes of sine and rectangle load corresponded to a high efficient drilling performance. Therefore, this research provide fundamental guidance for down the hole drilling tool design.

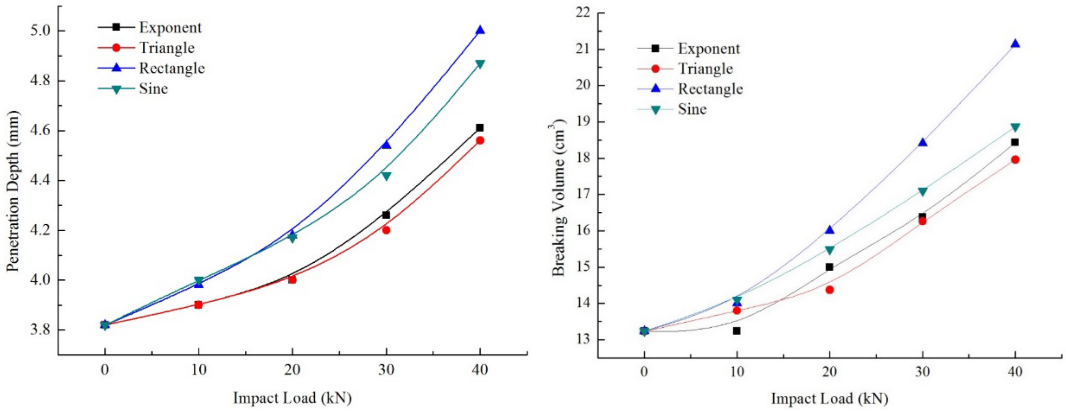

Figure 3. comparison of penetration depth & rock breaking volume under impact load.

5 CONCLUSION

A 3D simulation of dry hot rock breakage was conducted to investigate the various impact waveforms and the corresponding rock breakage efficiencies. The results of the study demonstrated that different incident stress wave corresponded to a certain dynamic load shape. It is indicated that load shapes of the sine, triangle, exponent and rectangle shaped matched to the wave shape of incident stress. Theoretically analysis shows that the energy transfer efficiency of sine and rectangle load shows the similar performance, and the result is highly in agreement with the simulation results. Therefore, the impact drilling too can be designed to generate a certain shape of load, for example, sine or rectangle.

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