ROCK FRACTURING MECHANISMS BY PERCUSSIVE DRILLING

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Abstract

Understanding the mechanisms of force transfer from the hammer to the rock and the subsequent fracturing of the rock is crucial, given that drilling represents one of the most expensive technological aspects of rock disintegration. The process begins with the drilling bit's buttons imprinting on the rock surface, which generates a primary wave (p-wave). The shape of the p-wave's front is directly influenced by the shape of the buttons. As the p-wave propagates, it induces tensile failure between the rock particles, leading to the formation of radial fractures. These radial tensile fractures define small rock prisms that remain attached to the main rock body. The subsequent rotation of the drilling bit results in the disintegration of these prisms. The number and length of the fractures induced are key determinants of the overall efficiency of the drilling process. By gaining a comprehensive understanding of these dynamics, improvements in drilling efficiency can be achieved, reducing costs and enhancing the effectiveness of rock disintegration operations.

Keywords: rock drilling; mining; tunneling; fractures; blasting;

1 INTRODUCTION

Drilling and blasting remain the predominant methods of rock disintegration in the mining industry, where drilling is a time-consuming and cost-intensive process. Drilling necessitates specialized equipment tailored to specific conditions. The efficiency and associated costs of drilling are determined by the rock fracturing process, which is influenced by the design and application of the tools used for drilling.

Percussive, rotary, and rock boring methods have been the subject of numerous research studies and are recognized as major factors in the mining industry. Rock fracturing is a key focus in mining, both generally and specifically in drilling, as it determines drilling efficiency, speed, and the required time for completion. [1-3]

Drilling represents the initial stage of rock disintegration prior to blasting and can serve as a valuable source of information about the rock being drilled. Numerous studies have attempted to utilize data from drilling performance as a means to determine the characteristics of the rocks. These efforts aim to analyze the interaction between drilling equipment and rock formations, leveraging the insights gained to better understand the physical and mechanical properties of the rock. This approach not only helps in optimizing drilling operations by adjusting techniques and tools based on rock characteristics but also contributes to more efficient and effective planning and execution of subsequent blasting processes. [4-6]

2 ROCK FRACTURING MECHANISMS BY PERCUSSIVE DRILLING

Today, two types of percussive drilling are commonly used: percussive drilling and rotary-percussive drilling. Percussive drilling operates through the use of jackhammers, where an air-driven piston moves the drill bit back and forth. After the drill bit impacts the rock, it retracts and rotates to a specific angle before the next impact, creating a circular-shaped drill hole. Rotary-percussive drilling, on the other hand, is employed with drilling rigs, where the drill bit experiences hammer action at its end while the drill rod rotates.

The mechanics of rock fracturing will be explained using the rotary-percussive drilling method, as illustrated in Figure 1. In this process, the drill bit contacts the rock at the bottom of the drill hole, with force applied from the other end. The bit, equipped with a number of wolfram carbide buttons, exerts a pressure load on the rock upon impact. Throughout this process, the entire set of drilling rods rotates at a predetermined number of revolutions per minute.

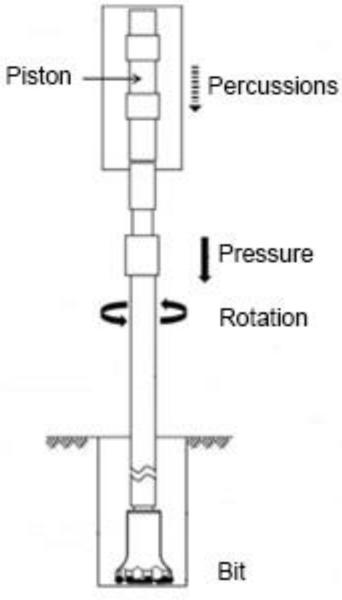

Figure 1 Rotary-percussive drilling

The hammer generates a pressure wave that travels through the pipe down to the drill bit, where the bit's steel body transfers the pressure wave to the wolfram carbide buttons. These buttons, subjected to constant pressure, imprint into the rock.

The percussion of the piston on the shank adapter creates a pressure load within it, which correlates with the intensity of the percussion force and the contact area between the piston and the shank adapter.

$$\sigma_c = \frac{F_u}{S}$$

Where:

σ_c – induced pressure load,
F_u – Percussive force,
S – Area of contact between piston and shank adapter.

Using this value and Young's elastic modulus of steel we express a strain or relative deformation inside of the adapter:

$$\varepsilon = \frac{\sigma_c}{E}$$

Where:

ε – strain inside of the adapter,
E – Young's elastic modulus.

Percussion of the piston generates pressure wave inside of the rod with intensity expressed as:

$$\sigma_c = V_s^2 \cdot \rho \cdot \varepsilon$$

Where:

σ_c - p-wave intensity in drilling rod (GPa)
V_s - p-wave velocity of steel (km/s)
ρ – steel density (g/cm^3)
ε - strain (m/m)

Upon reaching the drill bit and being conveyed to the buttons, the P-wave is then transmitted further into the rock.

3 ENERGY TRANSFER BETWEEN TWO MATERIALS

When a P-wave travels between two different materials, only a portion of its energy is transferred, except when the materials have the same acoustic impedance. Acoustic impedance determines how a P-wave is transmitted through various materials, and it depends on two factors: the density of the material and the velocity of the P-wave within that material. Acoustic impedance is expressed as follows:

$$Z = \rho \cdot V$$

Where:

ρ – desnity of the material,
V – p-wave velocity of the material.

It is widely recognized that the key to an efficient transfer of strain energy lies in acoustic impedance; if attenuation is disregarded, complete strain energy could be transferred between two materials with the same acoustic impedance. However, a different perspective is offered here:

Assuming a pressure load of 100 MPa inside the drilling rod, which is made of steel with a Young's modulus of 200 GPa, results in a strain of 0.0005 m/m. Consequently, the P-wave induced at the end of the drilling rod has an intensity of:

$$\sigma_c = V_{ps}^2 \cdot \rho \cdot \varepsilon$$

$$\sigma_c = 5.9^2 \ \cdot 7.85 \cdot 0.0005 = 0.137 GPa$$

Where:

σ_c- pressure load in drilling rod (GPa)
V_{ps} - p-wave velocity in steel (5.9km/s)
ρ- steel density (7.85g/cm^3)
ε- strain (0.0005m/m)

If we disregard losses, the P-wave intensity at the contact between the steel bit and the wolfram carbide button will be the same, assuming that steel and wolfram carbide have identical P-wave velocities. Consequently, the P-wave will maintain the same intensity after transmission, meaning no strain energy is lost. However, because wolfram carbide has a density twice as high as steel (15-16 g/cm^3), the resulting strain in the button will be:

$$\varepsilon = \frac{\sigma_c}{V^2 \cdot \rho} = \frac{0.137}{5.9^2 \cdot 16} = 2.46 \times 10^{-4}$$

If drilling occurs in granite with the following properties: Vp (P-wave velocity) = 4.657 km/s; density (ρ) = 2.74 g/cm^3; tensile strength (σt) = 9 MPa; Poisson's ratio (v) = 0.3; and an impact strength ratio (Isr) = 0.9, the wolfram carbide button will not transfer the complete energy to the rock but only a portion that corresponds to the P-wave velocity of the rock being drilled. In granite, the P-wave is induced and has an intensity of:

$$\sigma_{cg} = V_{pg}^2 \cdot \rho_{vk} \cdot \varepsilon_{vk}$$

$$\sigma_{cg} = 4.657^2 \ \cdot 16 \cdot 0.000246 = 0.085 GPa$$

For this intensity of the p-wave strain in granite rock is:

$$\varepsilon_g = \frac{\sigma_{cg}}{V_{pg}^2 \cdot \rho_g} = \frac{0.085}{4.657^2 \cdot 2.74} = 0{,}00143$$

Where:

σ_{cg}- p-wave intensity in granite (GPa)
V_{pg}- p*wave velocity in granite (km/s)
ρ_{vk}- density of wolfram carbide (g/cm^3)
ρ_g – granite density (g/cm^3)
ε_{vk}- strain in wolfram carbide
ε_g – strain in granite

When drilling into sandstone with the following characteristics: P-wave velocity (Vp) = 2.146 km/s; density (ρ) = 2.16 g/cm^3; tensile strength (σt) = 4.4 MPa; Poisson's ratio (v) = 0.2; and an strain energy index (Isr) = 0.55, the wolfram carbide button will not transfer the full energy to the rock. Instead, it will only transfer a portion that corresponds to the P-wave velocity of the rock being drilled. In sandstone, the P-wave that is induced has an intensity of:

$$\sigma_{cp} = V_{pp}^2 \cdot \rho_{vk} \cdot \varepsilon_{vk}$$

$$\sigma_{cp} = 2.146^2 \ \cdot 16 \cdot 0.000246 = 0.0181 GPa$$

And corresponding strain in sandstone:

$$\varepsilon_p = \frac{\sigma_{cp}}{V_{pp}^2 \cdot \rho_p} = \frac{0.0181}{2.146^2 \cdot 2.16} = 0{,}00182$$

Where:

σ_{css}- p-wave intensity in sandstone (GPa)
V_{pss}- p*wave velocity in granite (km/s)
ρ_{vk}- density of wolfram carbide (g/cm^3)
ρ_{ss} – sandstone density (g/cm^3)
ε_{vk}- strain in wolfram carbide
ε_{ss} – strain in sandstone

Strain energy between a wolfram carbide (WC) particle will be transferred to the granite particle until the velocity of deformation of WC reaches the velocity of deformation of granite. Attempting to deform the rock faster than this velocity makes it indefinitely stiff, causing the remaining strain energy of WC to be returned in the form of a reflected P-wave.

4 IMPRINTING WC BUTTONS IN ROCK

Before drilling begins, the drill bit, equipped with wolfram carbide (WC) buttons, is imprinted into the rock by applying force at the end of the drilling rod. The WC buttons are spherical, with the shape of a hemisphere.

To calculate the depth of the WC button's imprint in the rock, or to determine the necessary force to make an imprint of a certain depth, Hertz's contact theory is utilized:

$$\delta = \left(\frac{3}{4} \cdot \frac{F}{E^*} \cdot \sqrt[3]{\frac{1}{R}} \right)^{2/3}$$

Where:

δ – displacement (depth of imprint)
F -force
R – WC button radius
E^*- reduced elastic modulus:

$$\frac{1}{\mathrm{E}^*} = \frac{1 - \nu_1^2}{\mathrm{E}_1} + \frac{1 - \nu_2^2}{\mathrm{E}_2}$$

Where:

ν_1, E_1- Poisson’s ratio and Young elastic modulus of material being imprinted, WC in this particular case,
ν_2, E_2- Poisson’s ratio and Young elastic modulus of rock.

5 TENSILE FRACTURE FORMATION AT THE CONTACT BETWEEN THE WC AND THE ROCK

The P-wave induced within the drilling rod reaches the rock where the WC (wolfram carbide) button will be imprinted, resulting in a contact area shaped like a spherical cap, as shown in Figure 2. The shape of this contact influences the spherical shape of the P-wave front. As illustrated in Figure 3, rock particles are displaced to new locations, with displacements of:

$$\Delta R = \varepsilon_R \cdot R$$

during this process, particles are displaced apart. Length of the circular arc is then increased:

$$\Delta L = \varepsilon_L \cdot L$$

The compressive strain in the radial direction is equal to the lateral strain ($\varepsilon_R = \varepsilon_L$). This simplification holds true for all directions, or for each arc formed by intersecting the spherical cap with a plane passing through its center.

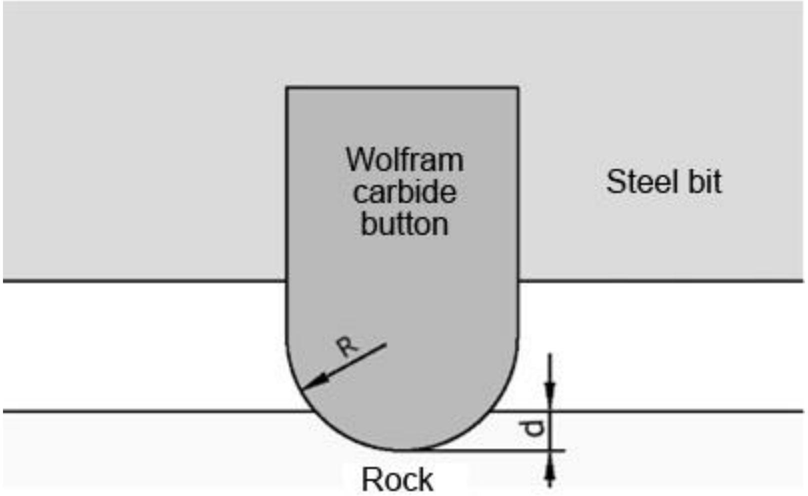

Figure 2 WC button imprint into the rock

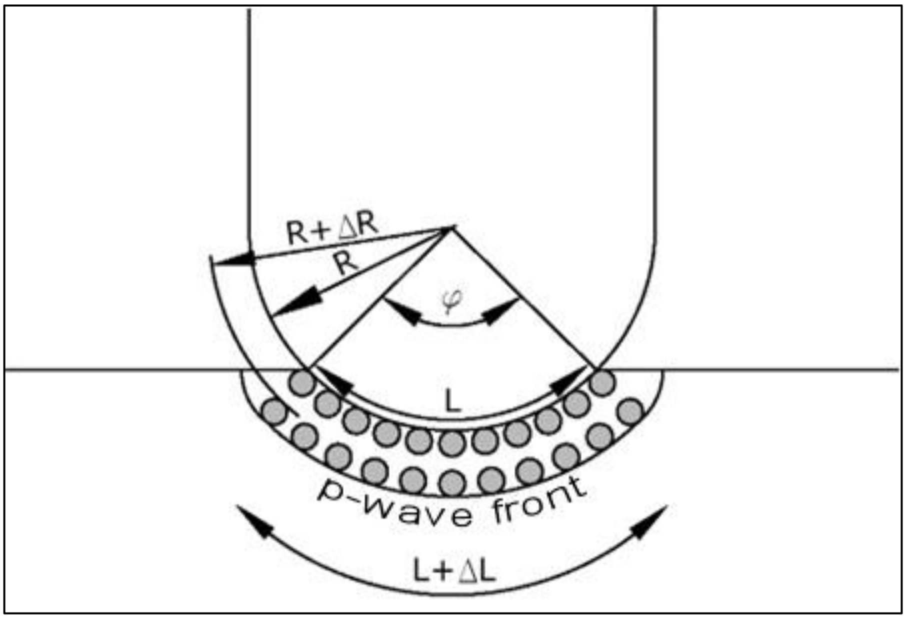

Figure 3 Position of rock particles before and after inducing the p-wave

Given that the tensile strength of rock is 8 to 10 times lower than its compressive strength, it is evident that compressive strain in the radial direction will induce radial tensile fractures. This is because the tensile strain, normal to the direction of the radial fractures, exceeds the rock's tensile strength. The number of radial tensile fractures along the arc of the spherical cap is:

$$n = \frac{e_L}{e_t}$$

Where:

$$e_t = \frac{\sigma_t}{E}$$

Where:

e_t- tensile strain
σ_t- tensile strength
E – elastic modulus of rock

Since the entire area of the spherical cap is under a tensile load in all directions, a network of interconnected radial tension fractures is formed. By dividing the spherical cap into a set of hexagons (as shown in Figure 4), each hexagon will have an inscribed circle diameter that corresponds to the distance between two tensile fractures. After the P-wave passes, the rock in front of the WC (wolfram carbide) buttons will be divided into a set of hexagonal prisms, which remain connected to the main rock by their base. Due to the rotation of the drill bit and the friction between the WC and the rock, each of these prisms will break off due to the tension, resulting in rock disintegration as depicted in Figure 5.

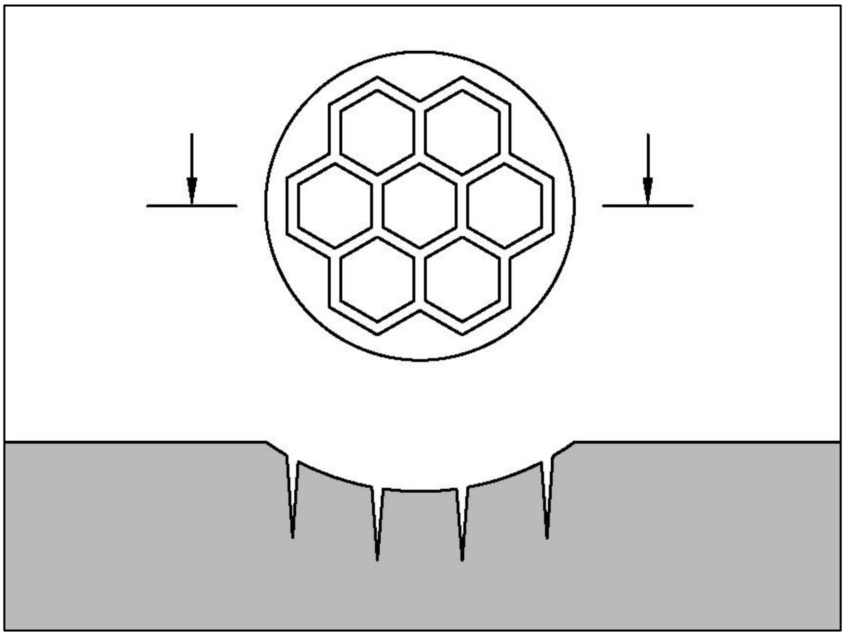

Figure 4 Fracture network in rock below the WC button

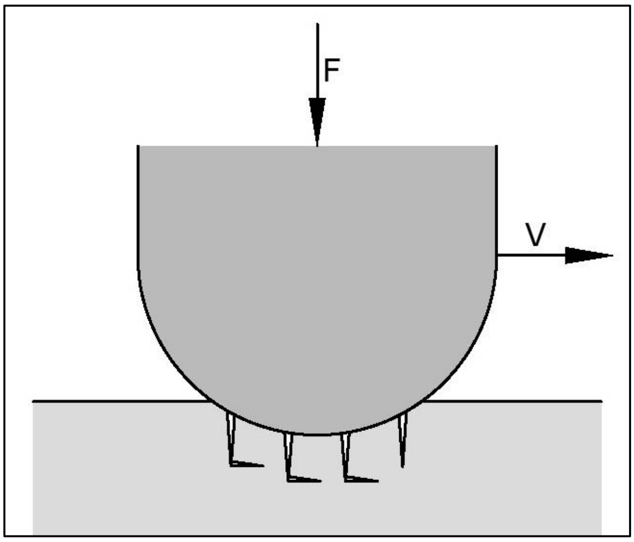

Figure 5 Rock disintegration by subsequent drill bit rotation

6 CONCLUSION

The force applied by the hammer to the drilling rods is transmitted to the drill bit and the tungsten carbide (WC) button, which then act on the rock surface. This interaction generates a pressure wave, leading to the formation of fractures at the points where the buttons press into the rock surface. Concurrently, the constant rotation of the drilling tools results in the disintegration of the rock in a secondary phase. The imprint of the WC button on the rock determines the shape of the primary wave (p-wave) front within the rock, facilitating the development of radial tensile fractures. This process is crucial for estimating the efficiency of the drilling operation by allowing the calculation of the number and length of fractures produced by the bit's action. Understanding the transfer of energy from the hammer to the buttons, along with the effects of the button's shape and placement, opens avenues for enhancing the overall energy efficiency of the drilling process as well as optimizing its duration. This deeper insight into the energy dynamics and mechanical interactions at play offers significant potential for improving drilling performance and outcomes.

7 REFERENCES

[1] Zhang, Z. (2016). Rock Drilling and Boring. , 155-175. https://doi.org/10.1016/B978-0-12-802688-5.00007-5.

[2] Wagner, H. (2019). Deep Mining: A Rock Engineering Challenge. *Rock Mechanics and Rock Engineering*, 52, 1417-1446. https://doi.org/10.1007/s00603-019-01799-4.

[3] Vogt, D.. (2016). A review of rock cutting for underground mining: past, present, and future. *Journal of the Southern African Institute of Mining and Metallurgy*, *116*(11), 1011-1026. https://dx.doi.org/10.17159/2411-9717/2016/v116n11a3

[4] Park, J., & Kim, K. (2020). Use of drilling performance to improve rock-breakage efficiencies: A part of mine-to-mill optimization studies in a hard-rock mine. *International Journal of Mining Science and Technology*, *30*(2), 179-188.

[5] Zhang, W., Li, C., Jin, J., Qu, X., & Fan, S. (2021). A new monitoring-while-drilling method of large diameter drilling in underground coal mine and their application. *Measurement*, *173*, 108840.

[6] Hatherly, P., Leung, R., Scheding, S., & Robinson, D. (2015). Drill monitoring results reveal geological conditions in blasthole drilling. *International Journal of Rock Mechanics and Mining Sciences*, *78*, 144-154.