RESEARCH ARTICLE

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Mechanism of Penetration Rate Improvement in Hot Dry Rock Under the Coupling of Impact Load and Confining Pressure Release

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Abstract

Deep geothermal resources are environmentally friendly and represent a highly competitive form of clean energy. However, low rock-breaking energy combined with high rock strength results in a low rate of penetration (ROP), which significantly restricts the efficient utilization of geothermal resources. Previous studies have shown that rock failure is primarily caused by shear stress. Therefore, this paper aims to enhance the shear stress level by increasing the impact load and releasing the confining pressure, thereby improving the ROP. Specifically, the rock-breaking efficiency under the coupling of impact load and confining pressure releasing is analyzed to reveal the influence of confining pressure releasing on shear stress. Furthermore, a rock-breaking model is established, and an impact load generator is employed to validate the proposed model, enabling the evaluation of rock-breaking efficiency under the coupled action of impact load and confining pressure releasing. The results indicate that the ratio of shear stress to I_1 dominates the rock-breaking process. When this ratio is low, the rock tends to remain in a compressed state, the hydrostatic pressure effect is enhanced, the shear stress effect is relatively weakened, and the rock-breaking efficiency decreases. The coupling of impact load with confining pressure releasing can achieve effective rock breaking under relatively low weight-on-bit conditions in deep wells, thereby providing theoretical support for improving rock-breaking efficiency in hot dry rock geothermal development.

Keywords: percussion drilling, rock breaking efficiency, rate of penetration, confining pressure releasing, impact load.

1 Introduction

Deep geothermal resource is rich, green and environmentally friendly, which is a highly competitive clean energy [1, 2]. However, the main problems faced by geothermal drilling are the high confining pressure, compressive strength and temperature, about 150-300°C, and under the combined effect of high temperature and confining pressure, the strength of hot dry rock is higher, resulting in rate of penetration of about 1m/h.

The interaction between the drill bit and the rock is

Submitted: 17 September 2025
Accepted: 22 January 2026
Published: 26 January 2026

Vol. 2, **No.** 1, 2026.
10.62762/RS.2025.804345

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Citation
Yang, Y., Huang, F., & Kang, S. (2026). Mechanism of Penetration Rate Improvement in Hot Dry Rock Under the Coupling of Impact Load and Confining Pressure Release. *Reservoir Science*, 2(1), 52–64.

a pair of "spear" and "shield" relationship. Therefore, to increase the drilling speed, either strengthen the "spear" or weaken the "shield", from the perspective of strengthening the "spear", the study demonstrates that if a dynamic load is applied above the drill bit, the penetration rate could be efficiently improved [5, 8, 13]. However, the research on the impact rock breaking efficiency mainly focuses on the impact load amplitude and frequency [22], without considering its shape change [3, 10, 19].

The process of rock breaking through percussive drilling involves the transmission of stress waves to the rock [14, 23], it has been found that an impact load of a specific shape can use a certain proportion of its own impact energy for rock breaking [18, 24], and it is demonstrated that the impact energy utilization ratio is about 80% when the impact load is rectangular or sinusoidal shape [6, 9], which indicates that the energy ratio used to breaking rock is decided by the shape of the impact load, while the impact load contains three parts, the magnitude, frequency and shape [15, 17], the magnitude and frequency represent the amount of the impact energy per unit. Therefore, if the impact load or frequency is simply increased without considering the impact load shape on the rock breaking energy utilization rate, the purpose of impact rock breaking may not be achieved [10, 20].

From the perspective of weakening the "shield", if the confining pressure can be released by removing the horizontal in-situ stress, the purpose of reducing the rock strength can be achieved [11]. During drilling, the bottom of the well is subjected to the coupling of hydrostatic pressure, formation pressure and in-situ stress [12, 21], and if the rock to be broken could be separated from the surrounding rocks, so that the rock to be broken is no longer affected by the in-situ stress, and then the rock strength is reduced.

However, the research on improving ROP focuses more on downhole impact tools [7, 16, 23], while there are relatively few studies on increasing the ROP by reducing rock strength [4]. The failure of rock is caused by the shear stress, and the combination of impact load and removing the horizontal in-situ stress could directly improve the shear stress level, achieve the purpose of improving the rock breaking efficiency.

Therefore, in this study, inspired by the above investigations, recognizing that impact load shape, frequency, and load magnitude are the parameters influencing rate of penetration. The objective is to analyze the rock breaking efficiency under coupling of impact load and confining pressure releasing, reveal the influence of confining pressure releasing on the shear stress distribution and strength of the rock; finally, by establishing rock breaking model, evaluating the effect of hot dry rock breaking efficiency under the coupling of impact load and confining pressure releasing, providing theoretical support for the research on hot dry rock breaking efficiency improving.

2 Methodology

2.1 Stress distribution analysis under the impact load

As shown in Figure 1, the bottom hole stress state during drilling is influenced by a combination of factors, including formation pressure, weight on bit, wellbore fluid pressure, in-situ stresses, and the rotary and impact forces from the drill bit. Formation pressure p_h and wellbore fluid pressure p_p are the pressure acting on the well bottom, and pp used to balance the formation pressure and prevent blowouts, generally, p_p is slightly lower than p_h to avoid excessive pressure on the formation, which could lead to wellbore instability or collapse. The horizontal stresses at the bottom of the well are divided into maximum σ_H and minimum σ_h stresses. These stresses are critical in determining how the rock will fracture or fail under drilling conditions, as shown in Figure 1(a), WOB acts on the bottom of the well through the drill bit, the bottom rock breaking through the impact σ_z and rotation of the drill bit; shear stress at the well bottom are generated due to the rotational movement of the drill bit.

Therefore, as shown in Figure 2, the bottom hole stress state is a complex interaction of normal, solid, and shear forces, σ_x is the normal stresses in the x-direction, σ_y is the normal stresses in the y-direction, σ_z is the vertical stress at the bottom, τ_{xy} is the shear stress generated by the drill. Understanding stress distributions at the bottom hole is essential for achieving optimal drilling performance due to the influences of drilling parameters, such as impact load, and confining pressure on the rock breaking efficiency.

According to the maximum shear stress strength theory, the Mohr-Coulomb criterion and other failure criteria, shear stress is the key factor causing rock breaking. The failure of rock should be the shear stress exceeding the shear strength, and all the criteria emphasize the shear stress in rock failure. Shear failure is mainly determined by the difference in

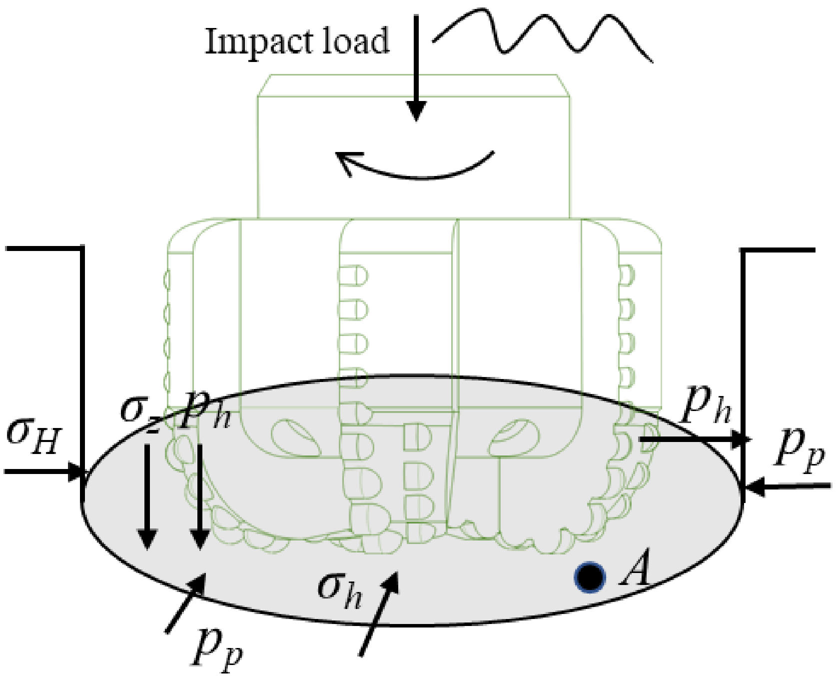

Figure 1. Stress distribution on down the hole wellbore when drilling (p_h is formation pressure, p_p is drill fluid pressure, σ_H is the maximum horizontal in situ stress; σ_h is the minimum horizontal in situ stress, σ_z is the vertical stress from impact load, τ_{xy} is the shear stress from the torque of the drill bit).

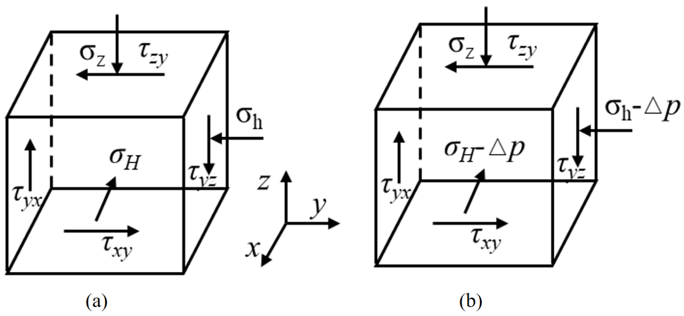

Figure 2. stress distribution when drilling at the wellbore bottom hole before and after confining pressure releasing (p_h is formation pressure, σ_H is the maximum horizontal in situ stress; σ_h is the minimum horizontal in situ stress, σ_z is the vertical stress from impact load, τ_{xy} is the shear stress, Δp is the amount of the confining pressure releasing).

two-dimensional stress: the larger the difference, the more significantly the shear stress level inside the rock will increase, promoting the failure of the rock.

Therefore, in order to improve the rock breaking efficiency, percussive drilling usually relies on stress wave propagation and local stress concentration, which could increase the shear stress. Assuming that the impact load σ_1 acts in the z-axis direction, then the σ_1 expression is in equation 1:

$$\sigma_1 = \sigma_1^0 + \sigma_{\text{impact}} f(t) \tag{1}$$

where σ_1^0 is the initial principal stress; σ_{impact} is the magnitude of the impact load; and $f(t)$ is the time function of the impact load.

2.2 Stress variation analysis under the confining pressure releasing

Increasing the impact load will directly increase the deviator stress component, while reducing in-situ stress will release the confining pressure, which will also increase the deviator stress component and reduce the shear strength of the rock. Assuming that the impact load σ_1 acts in the z-axis direction keeps unchanged, then the σ_2 and σ_3 expression are in equation 2 and 3:

$$\sigma_2 = \sigma_2^0 - \Delta p \tag{2}$$

$$\sigma_3 = \sigma_3^0 - \Delta p \tag{3}$$

where σ_2^0, σ_3^0 are the initial principal stress respectively; Δp is the amount of the confining pressure.

2.3 Shear stress variation under the coupling of confining pressure releasing and impact load

The rock breaking is related to the shear stress level; the higher the shear stress, the easier it is for the rock to break. The change in shear stress level directly affects the failure of rocks. If the impact load can be combined with the reduction of in situ stress, percussive drilling leads to local stress concentration, which could increase the shear stress. Reducing the in situ stress will release the confining pressure; the combination of the two can not only increase the shear stress inside the rock but also effectively weaken the strength of the rock, thereby achieving the purpose of improving the efficiency of hot dry rock breaking. The expression of shear stress is shown in equation (4), and the shear stress under impact load and confining pressure reduction is given in equation (5). According to the Drucker–Prager criterion, if $f > 0$, it indicates that the rock has failed; the larger the f, the easier it is for the rock to break.

$$\tau = 0.71\left[(\sigma_1(t) - \sigma_2^0 + \Delta p)^2 + (\sigma_2^0 - \sigma_3^0)^2 + (\sigma_1(t) - \sigma_3^0 + \Delta p)^2\right]^{0.5} \tag{4}$$

$$\frac{d\tau}{dt} = \frac{1}{2\tau}\left(\sigma_1^0 + \sigma_{\text{impact}} f(t) - \sigma_2^0 + \Delta p\right)\sigma_{\text{impact}}\frac{df(t)}{dt} \tag{5}$$

$$f(t) = \sin(\pi t/T) \tag{6}$$

$$f = \alpha I_1 + \frac{\tau}{\sqrt{3}} - k = 0 \tag{7}$$

where τ is the shear stress, $d\tau/dt$ is the rate of change of the shear stress, $f(t)$ is the impact load function, α and k are material parameters that depend on the internal friction angle and cohesion of the rock, and I_1 is the first invariant of the stress tensor.

In order to explore the influence of different load conditions on rock mechanical behavior, we compare the shear stress, shear stress change rate, and f of rocks under no impact load and no stress reduction, and under the coupling effect of impact load and stress reduction. This reveals that rocks are more likely to reach a higher shear stress level to achieve efficient rock breaking.

As shown in Figure 3, considering the conditions of no impact load and no confining pressure stress releasing, the shear stress change of the rock is basically in a static and stable state, the Drucker-Prager f value is also keeps stable. However, when the rock is only subjected to impact loads, the shear stress of the rock change significantly. Compared with the impact load acting only, when coupling of stress releasing and impact load, in this case, the shear stress is indeed significantly increased, and the rock is more likely to break.

In summary, the coupling of impact load and stress releasing significantly influence the shear stress level of the rock, resulting in an increasing of the shear stress and f, indicating that under this condition, the rock is more likely to reach a high shear stress level and increase the risk of break.

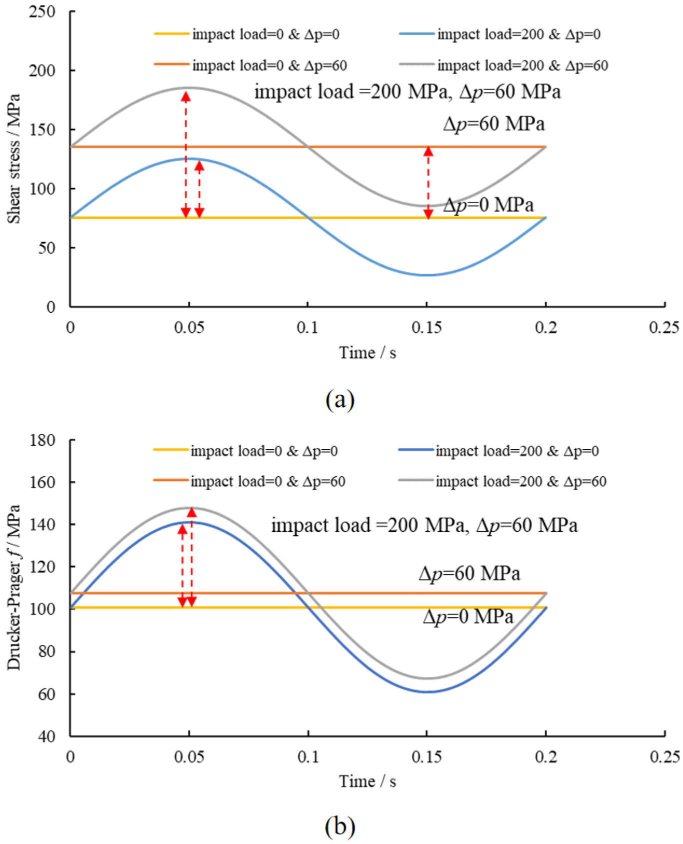

Figure 3. Shear stress and f versus time at the conditions: only under the impact load, confining pressure releasing, coupling effect of impact load and confining pressure releasing, without impact load and confining pressure releasing ($\sigma_1^0 = 150$ MPa, $\sigma_2^0 = 80$ MPa, $\sigma_3^0 = 70$ MPa, $\sigma_{\text{impact}} = 50$ MPa, $\Delta p = 60$ MPa, $k = 12$ MPa, impact load function, here the impact varies as sinusoidal form, see in equation 6).

3 Rock breaking under the coupling of confining pressure releasing and impact load

3.1 Rock breaking model and the boundary conditions

The rock-bit physical model is established as shown in Figure 4(a). The model consists of PDC drill bit and rock and the PDC drill bit with a diameter of 75 mm; The rock has dimensions of 120 mm, 50 mm in height. The rock material is granite, the rock density ρ is 3.1 g/cm^3, Young modulus E is 20 GPa, Poisson ratio μ is 0.33, internal friction angle is 30°. Two main boundary conditions are applied on the bit, one is RPM, and the other is impact load, as shown in Figure 5, the impact load is combined with static load and dynamic load; and the static load varied from 50 to 80 kN, and the amplitude is 10 - 25 kN; the RPM is 120 r/min.

Figure 4(b) shows the stress–strain curve during the

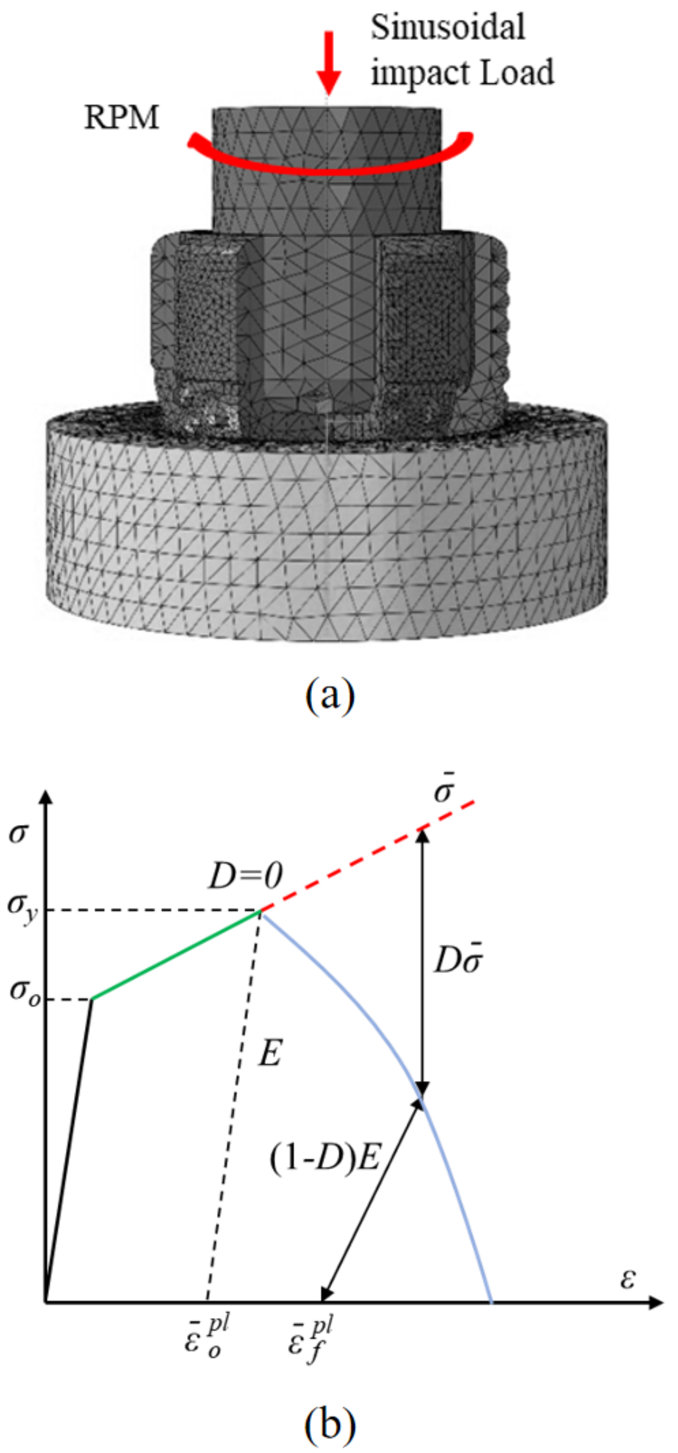

Figure 4. The bit and rock interaction model (WOB is 50–80 kN, drill bit diameter is 78 mm, RPM is 120 r/min, confining pressure reduction $\Delta p = 60$ MPa, rock density $\rho = 3100$ kg/m^3, Young's modulus $E = 20$ GPa, Poisson's ratio $\nu = 0.25$, internal friction angle is 30°, $k = 12$ MPa, $\alpha = 0.23$); Fig. 4b Stress–strain curve in the process of rock damage evolution (the black line is the elasticity stage, green is the plasticity stage, the blue line is the damage stage).

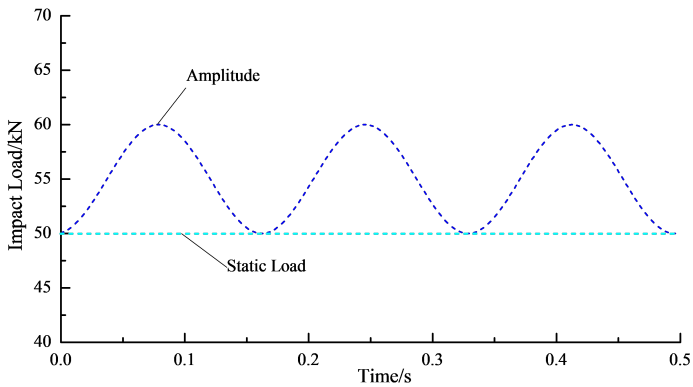

Figure 5. The impact load variation applied on the rock bit (the static load is from 50-80 kN, and the impact load amplitude is from 10-25 kN, the impact load frequency is from 5-14 Hz).

process of rock damage accumulation. It can be seen that the rock breaking behavior under load undergoes three stages: elasticity stage, plasticity stage, and damage stage.

In the elasticity stage, stress is $\sigma = E \times \varepsilon$, meaning the rock responds purely elastically. In the plasticity stage, the governing equation of the rock model is the Drucker–Prager criterion (equation 7), which accounts for the intermediate principal stress and the hydrostatic pressure effect.

In the damage stage, D is used to describe the extent of damage in the rock: when $D = 0$, the rock is undamaged; when $D = 1$, the rock is completely damaged. When the equivalent plastic strain reaches a critical value ε_0, the rock begins to experience damage. At this stage, the effective stress decreases to $(1-D)\times\sigma$ (blue line), indicating that the accumulated damage reduces the rock strength. In the complete damage stage, when the equivalent plastic strain ε_p reaches a critical value, D becomes 1, meaning the rock has completely failed, and the stress approaches zero. The corresponding elements in the mesh of the model are considered removed in the simulation.

The analysis of rock breaking, as seen in equation 8, shows that the ratio $\gamma = \tau/I_1$ can provide a basis for determining rock breaking, because τ reflects the shear stress state of rocks, while I_1 reflects the compression of rock by confining pressure. A higher ratio usually indicates that the rock is easier to break, while a lower ratio indicates that the rock requires a larger shear stress to break. When γ is large, it means that shear stress plays a dominant role in the rock breaking; when γ is small, the confining pressure plays a greater role in the rock breaking.

Moreover, when investigating the rock breaking efficiency, the rock breaking efficiency is proposed as

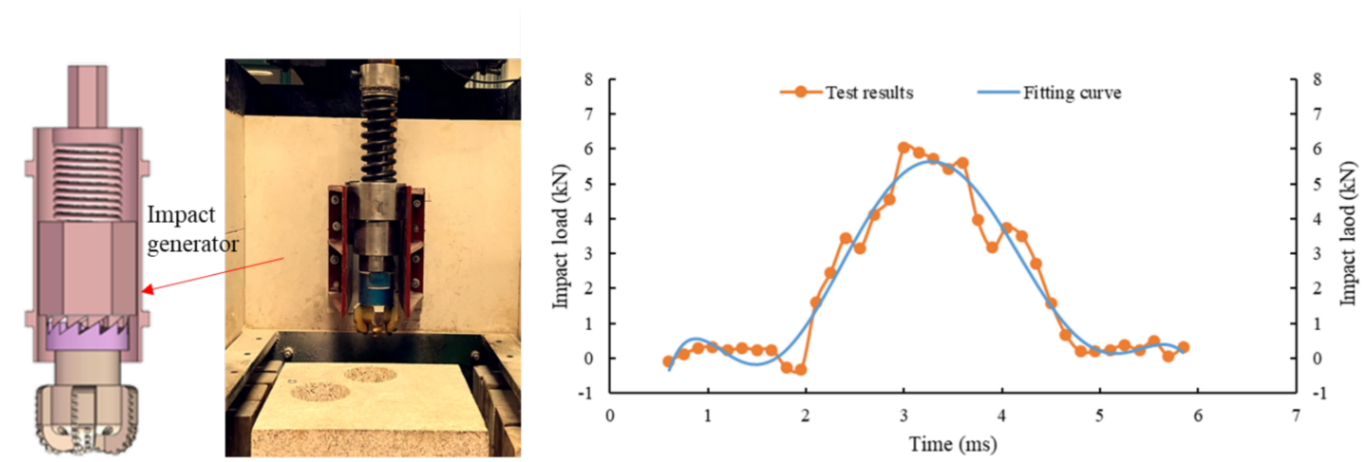

Figure 6. (a) The impact load generator device (when the hammer moves upward, the spring energy is compressed, when it moves downward, the spring energy are released to let the hammer hit the anvil to generate impact load); (b) the load characteristic out-putted of the impact load generator (theoretical impact load characteristics change in a sinusoidal form).

in equation (9). It can be inferred from the equation that the rock breaking efficiency is defined as the increase rate of the rate of penetration under impact load relative to that under static load.

$$\gamma = \frac{\tau}{\sqrt{3I_1}} \tag{8}$$

$$\eta = \frac{v_d}{v_s} - 1 \tag{9}$$

where v_d is the rate of penetration under impact load, and v_s is the ROP under the static load.

3.2 Testing validation of the rock breaking model

In order to verify the rock breaking model, the impact load generation device shown in Figure 6(a) is used to generate impact loads. The device can adjust the impact load amplitude and load vibration frequency by replacing the spring. Figure 6(b) shows the theoretical impact load characteristics and test impact load characteristics generated by the device. It can be seen that the theoretical impact load characteristics change in sinusoidal form, and the test impact load is close to sinusoidal shape.

Figure 7 is the comparison of simulation and test results. It can be seen that the simulated test results and the validation test results have the same trend of rate of penetration with the impact load amplitude. When the impact load amplitude is 0, that is, when the load is a static load, both the simulation and the validation test results show that the ROP is lower than the rock breaking efficiency under impact load, at the same time, it can be seen that the simulation test results are significantly higher than the validation test results, which is resulting from the assumption that the rock cuttings are cleared in time during the simulated process, while in the validation test, the rock cuttings cannot be cleared in time, resulting in repeated breakage of the rock, thus making the test results lower than the simulated test results. Through the analysis and comparison of two sets of experimental and simulation results, it can be seen that the model can effectively predict the rock breaking effect under the impact load.

3.3 Comparison of rock breaking efficiency under the coupling of confining pressure releasing and impact load

In rock breaking processes, increasing weight on bit(WOB) is considered a direct method to enhance the rate of penetration [22]. However, as the well depth increases, applying higher weight on bit requires heavier drill collar. Consequently, the increase in drill string weight unavoidably leads to drill string fatigue damage, moreover, it is hard to improve the weight on bit in deep wells. Therefore, percussive drilling should couple the confining pressure releasing, which could achieve the rock breaking efficiency under high weight on bit conditions.

Figure 8 shows the changes in rock breaking efficiency under impact load and confining pressure release conditions. It can be seen that under the condition of confining pressure release of 30 MPa, the increase in impact load has a relatively gentle effect on the rock breaking efficiency. Under the condition of confining pressure release of 60 MPa, the change trend of rock breaking efficiency is more significant, especially

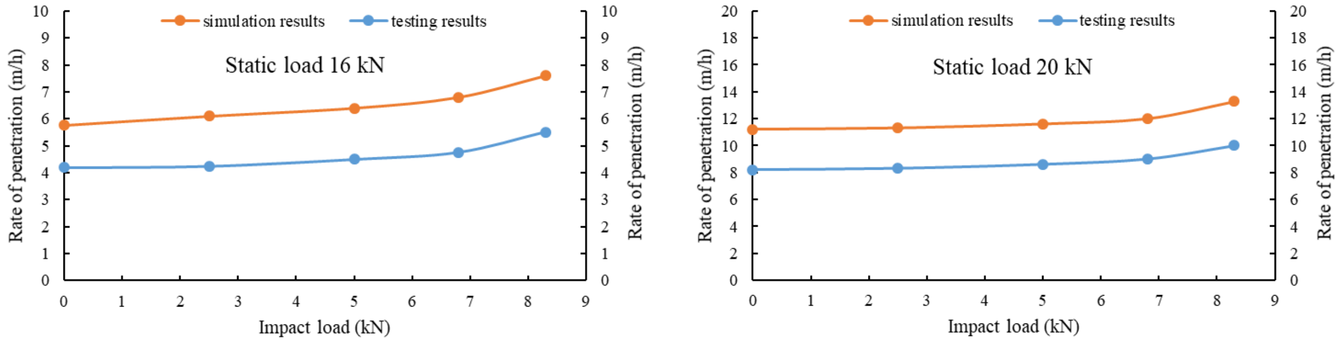

Figure 7. The simulation results and test results under sinusoidal impact load (the static load is 16 and 20 kN respectively, the amplitude is from 0 8.5 kN, RPM is 60r/min, frequency is 20 Hz).

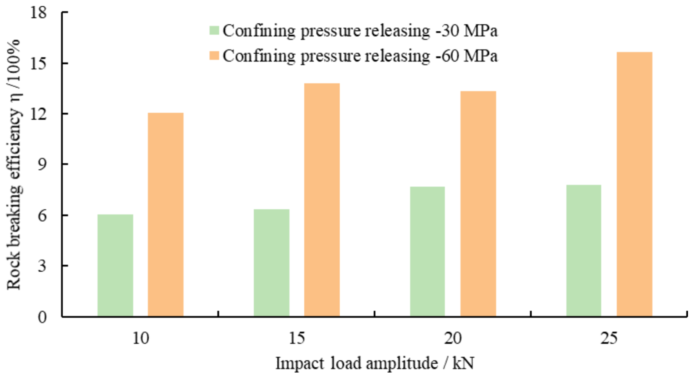

Figure 8. The rock breaking efficiency η under coupling of impact load and confining pressure releasing (the static load is 50 kN, the impact load amplitude is from 10- 25 kN, impact load frequency is 6 Hz, the confining pressure releasing Δp is 30, 60 MPa respectively, RPM is 120 r/min).

under higher impact loads (such as 20 kN and 25 kN), the increase in rock breaking efficiency is more obvious, which indicates that higher confining pressure release (60 MPa) helps improve drilling efficiency, especially under higher impact loads. The result shows that the coupling of impact load and confining pressure release on rock breaking is more significant. Lower confining pressure can effectively increase rate of the penetration, especially under higher impact load, the increase in penetration rate is more obvious.

Figure 9(a) shows the stress distribution during the rock breaking process when the confining pressure releasing is 30 MPa, the contact area between the drill bit and the rock shows stress concentration, which may involve local shear stress accumulation, according to the shear stress DP criterion, during the rock breaking process, rock fracture usually occurs when the shear stress exceeds a certain critical value. It can be seen that the high stress area is concentrated in the section where the drill bit contacts the rock, suggesting that the shear stress may exceed the critical value there, thereby promoting the occurrence of the rock breaking process.

Figure 9(b) shows the stress distribution when the confining pressure releasing is 60 MPa. Compared with Figure 9(b), the stress distribution in Figure 9(b) has changed significantly, and the stress in some areas has changed from low values to high values. This change may be due to the accumulation of shear stress during the rock breaking, which leads to a decrease in the strength of the local area of the rock, when the shear stress reaches the critical shear strength of the rock, the rock will break.

By combining the impact load and confining pressure releasing, we can deeply understand the interaction between the drill bit and the rock, especially in the stress concentration area, the relationship between the accumulation of shear stress and rock fracture is clearer, which can effectively improve rock breaking efficiency.

4 Results and discussion

4.1 Rock breaking efficiency of impact load under confining pressures releasing condition

Through the discussion of rock breaking efficiency under coupling of impact load and confining pressure releasing, the influence of impact load on the rock breaking efficiency is going to be discussed in this section, with reference to Figure 5, the impact load is time-dependent, which is applied as sinusoidal shape and impact frequency is 6 Hz. The static load varies from 50 80 kN, and the amplitude is 10 25 kN; once the impact load is applied on the drill bit, rock breakage occurred following the stress exceeding the rock strength, as determined by the failure criteria, the failed mesh would be removed, subsequently, the

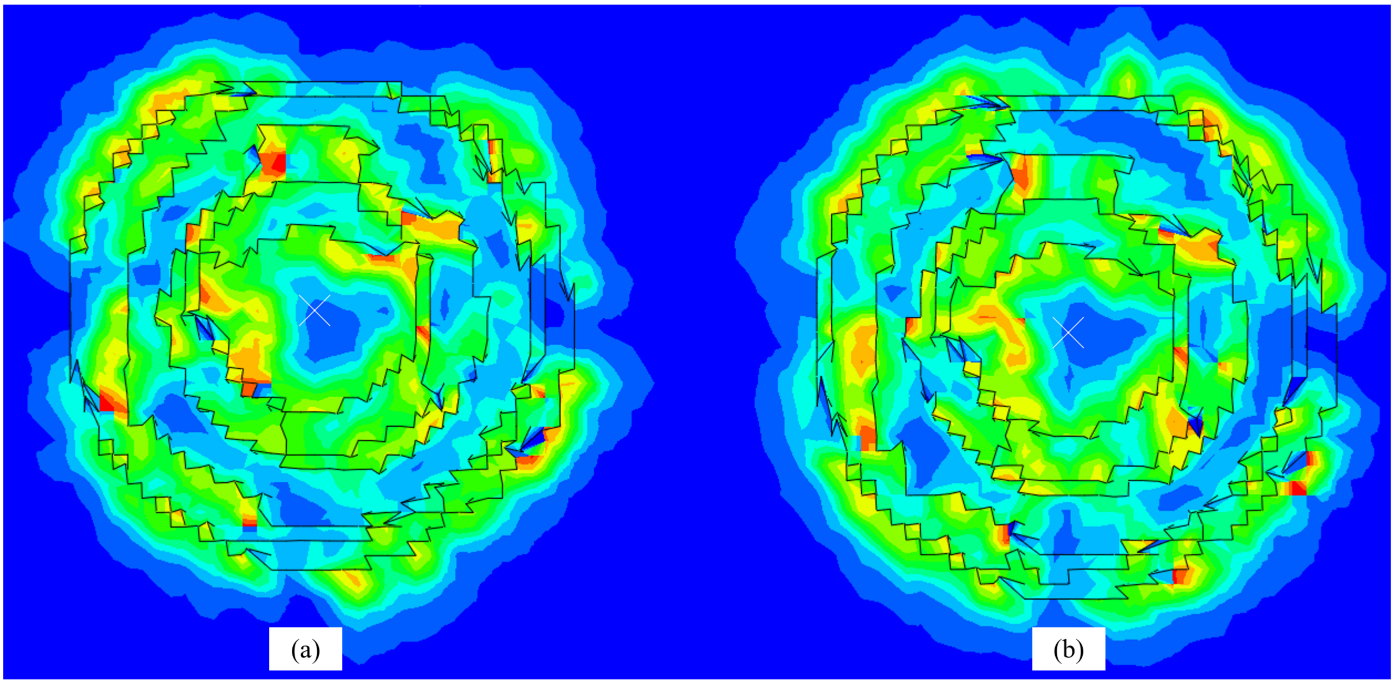

Figure 9. Stress distribution of hot dry rock breaking under coupling of impact load and confining pressure releasing (the static load is 50 kN, the impact load amplitude is from 10- 25 kN, impact load frequency is 6 Hz, confining pressure releasing Δp is 30, 60 MPa respectively, RPM is 120 r/min).

impact load repeats the rock breaking process.

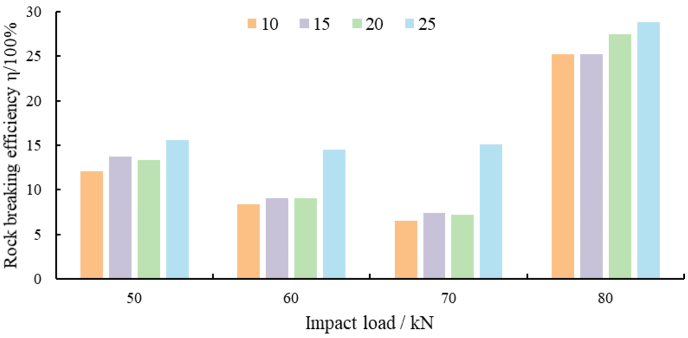

Figure 10. The rock breaking efficiency η under different impact load (the static load is from 50 kN to 80 kN, the impact load amplitude is from 10 kN to 25 kN, confining pressure releasing Δp is 60 MPa, impact load frequency is 6 Hz, RPM is 120 r/min).

Figure 10 shows the effect of static load and load amplitude on rock breaking efficiency, it can be seen that the rock breaking efficiency gradually increases with the increase of static load, especially under higher static load conditions (80 kN), the rock breaking efficiency is particularly improved, under these high static load conditions, the rock breaking efficiency increases significantly with the increase of load amplitude, especially when the load amplitude is 25 kN, the rock breaking efficiency reaches the maximum, while under the condition of lower static load (50 kN), increasing the load amplitude has a significant effect on improving the rock breaking efficiency.

When the static load is 50 kN, the average hydrostatic pressure I_1 on the rock is small, as shown in equation 8, the impact load makes the shear stress component dominant, according to the Drucker-Prager criterion, the failure is mainly controlled by the shear stress, if the shear stress is large enough, the rock is easy to break, therefore, the rock breaking efficiency is relative high. While when the static load increases to 60 kN and 70 kN, the average hydrostatic pressure I_1 increases, causing the rock to tend to be in a compressed state, in this case, although the impact load is still applied, the hydrostatic pressure effect is enhanced and the shear stress effect is relatively weakened, the strength of the rock is increased, and the rock breaking efficiency is reduced. When the static load increases to 80 kN, the rock breaking efficiency is significantly improved, which because under high static load conditions, the contribution of the impact load increases, and the shear stress of the rock reaches a critical state, resulting in rock breaking.

In summary, by reasonably adjusting the load amplitude, the shear stress can be effectively increased, and the rock breaking efficiency can be improved. This provides important guidance for the rock breaking operations, especially under lower static load conditions, by increasing the load amplitude to improve drilling efficiency.

4.2 Rock breaking efficiency of impact frequency under coupling of impact load and confining pressure releasing

Figure 11 is the rock breaking efficiency under various frequencies, it can be obtained that under low impact loads (10 and 15 kN), the rock breaking efficiency is generally low, according to the Drucker-Prager criterion, the shear stress generated by the lower impact load is not enough to reach the critical shear strength of the rock, the rock is still in the elastic deformation stage, and the rock breaking efficiency is low. In this condition, increasing the impact frequency has a limited effect on improving the rock breaking efficiency.

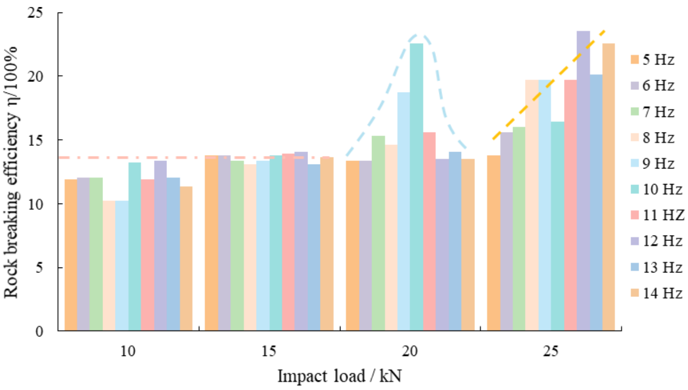

Figure 11. The rock breaking efficiency η at various frequencies (the static load is 50 kN, the impact load amplitude is from 10 kN to 25 kN, confining pressure releasing Δp is 60 MPa, impact load frequency is from 5 to 14 Hz, RPM is 120 r/min).

When the impact load increases to 20 kN, the rock breaking efficiency is significantly improved, the rock breaking efficiency reaches the maximum when the impact frequency is 10 Hz, the shear stress generated by the impact load increases, when the impact load is 25 kN, the rock breaking efficiency is further improved, and the shear stress has increased significantly, and the rock breaking is no longer restricted by insufficient shear stress.

In conclusion, the increase in impact frequency causes more impact loads to act on the rock, thereby accelerating the rock breaking process, under low impact load, the increase in impact frequency has slight influence on improving rock breaking efficiency, which because the impact energy is not enough to make the shear stress reach the critical shear strength of the rock. When the impact load increases, the effect of the impact frequency gradually increases, especially under high impact loads of 20 kN and 25 kN, the rock breaking efficiency is significantly improved. The increase in frequency increases the impact energy applied per unit time, thereby more effectively concentrating the shear stress and promoting rock breaking, under higher impact loads (such as 20 kN and 25 kN), the shear stress generated by the impact load is sufficient to break the rock, and the increase in impact frequency further enhances this effect, thereby improving the rock breaking efficiency.

4.3 Discussions on the rock breaking efficiency of the impact load and impact frequency

Through the above analysis, it is found that under low impact load conditions (10 kN), increasing the impact frequency has limited effect on improving the rock breaking efficiency because the shear stress is not enough to reach the critical of rock breaking. While under high impact load (such as 20 kN and 25 kN), the rock breaking efficiency is significantly improved, the increase in impact frequency accelerates the rock breaking process by increasing the shear stress accumulation. According to the Drucker-Prager criterion, the impact load and impact frequency promote rock breaking by increasing the shear stress effect, and optimizing the combination of impact load and frequency can significantly improve the rock breaking efficiency.

The rock breaking is related to the shear stress level, according the equation 8, the higher the shear stress, the easier it is for rocks to break, and the change in shear stress level directly affects the failure of rocks, when the impact load combined with the confining pressure releasing, it can not only increase the shear stress inside the rock, but also effectively weaken the rock strength, thereby achieving the purpose of improving the efficiency of hot dry rock breaking. Figure 12(a) is the rock breaking efficiency under different impact load amplitude when the confining pressure Δp is 60 MPa, with increasing of the impact amplitude, the rock breaking efficiency increases, moreover, it can be seen clearly that when the static load is over 70 kN, the rock breaking efficiency is much higher than other static load conditions. It is noteworthy that the rock breaking efficiency is higher than that of 60 and 70 kN.

Figure 12(b) is the rock breaking efficiency under different impact load when the confining pressure Δp is 60 MPa, it can be seen that with increasing of the impact load, the rock breaking efficiency decreases firstly and then increases lastly, existing a minimum impact load, and the rock breaking efficiency has almost same trend when the impact load amplitude is

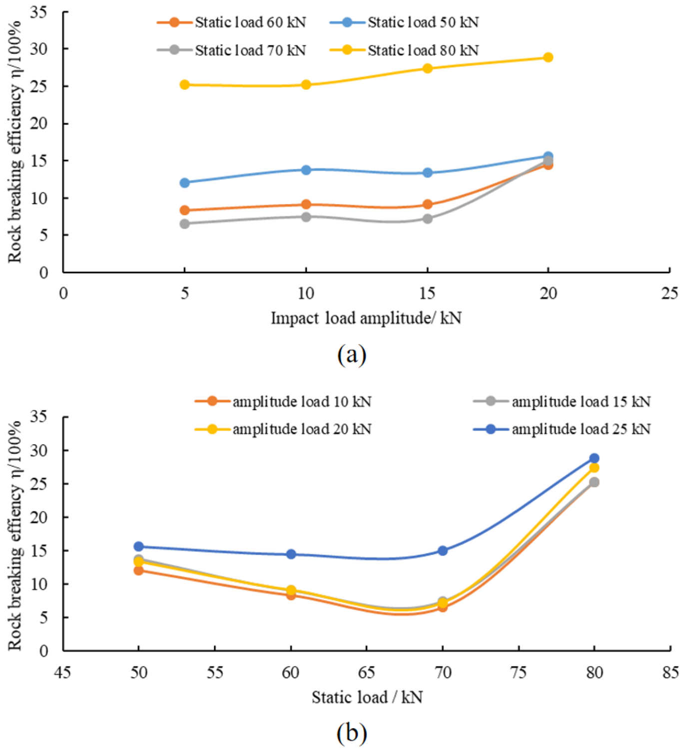

Figure 12. Rock breaking efficiency at various impact load amplitudes (the static load is from 50 to 80 kN, the impact load amplitude is from 10 kN to 25 kN, confining pressure releasing Δp is 60 MPa, impact load frequency is 6 Hz, RPM is 120 r/min).

10, 15 and 20 kN respectively, when the static load is from 50-80 kN, in addition, the rock breaking efficiency is much higher at the impact load amplitude is 15 kN, when the static load is from 50-80 kN.

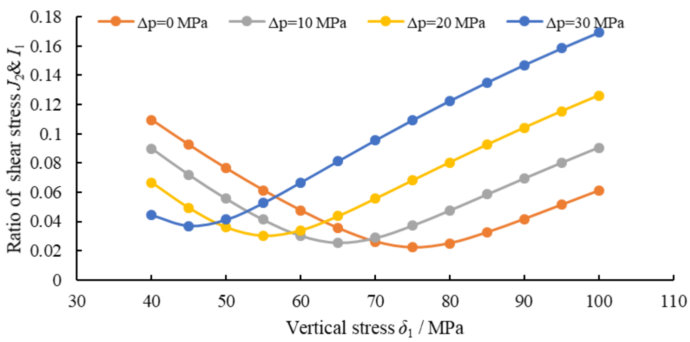

Figure 13. Ratio of shear stress and I_1 γ versus impact load (σ_1 is from 60 to100 MPa, σ_2^0 is 80MPa, σ_3^0 is 70 MPa, Δp is form 0 to 30MPa).

Figure 13 shows the ratio γ of the shear stress to I_1. It can be seen that with the increase of the vertical load (i.e., impact load), γ shows the same trend as shown in Figure 13(b), which indicates that when γ is large, the shear stress plays a dominant role in the rock breaking process; when γ is small, the confining pressure plays a greater role in the rock breaking.

Therefore, when the static load increases from 50 kN to 70 kN, the average of σ_1, σ_2, and σ_3 increases, causing the rock to tend to be in a compressed state. In this case, although the impact load is still applied, the hydrostatic pressure effect is enhanced and the shear stress effect is relatively weakened. The yield stress of the rock is increased, and thus the rock breaking efficiency is reduced.

While when the static load increases to 80 kN, the rock breaking efficiency is significantly improved. This is because under high static load conditions, although the average of σ_1, σ_2, and σ_3 increases, the contribution of the impact load increases, the shear stress J_2 increases as well, and the stress state of the rock reaches a critical state, resulting in high rock breaking efficiency.

Figure 14 is The rock breaking efficiency under different of impact load amplitudes and impact frequencies, which indicates that with the increase of impact load frequency, the rock breaking efficiency keeps almost stable with limited improvement, when the impact load amplitude is 10 and 15 kN respectively, which indicates that at lower impact frequencies, the impact energy has a slight effect on rock breaking, and the shear stress accumulation is not significant enough.

With the increase of impact frequency, the rock breaking efficiency begins to increase significantly, especially when the impact amplitude is 20 kN and 25 kN, the rock breaking efficiency shows a clear upward trend, at 10 Hz and 11 Hz, the rock breaking efficiency reaches its peak, especially when the impact amplitude is 20 kN and 25 kN, the efficiency increases significantly.

When the impact frequency continues to increase (12 Hz to 15 Hz), the rock breaking efficiency begins to decrease, especially at higher impact amplitudes (20 kN and 25 kN), the rock breaking efficiency shows a downward trend, which indicates that at higher frequencies, excessive impact energy may lead to plastic deformation of the rock, which in turn reduces the rock breaking efficiency.

In the case of low impact frequency, resulting in a slower increase in shear stress on rock, and the impact load is not applied frequently enough, the shear stress accumulates slowly, while there is not enough dynamic shear stress to reach the critical shear strength, resulting in low rock breaking efficiency. When the frequency of the impact load increases, and the number of impact load applied to the rock per unit time increases, which allows the shear stress on the

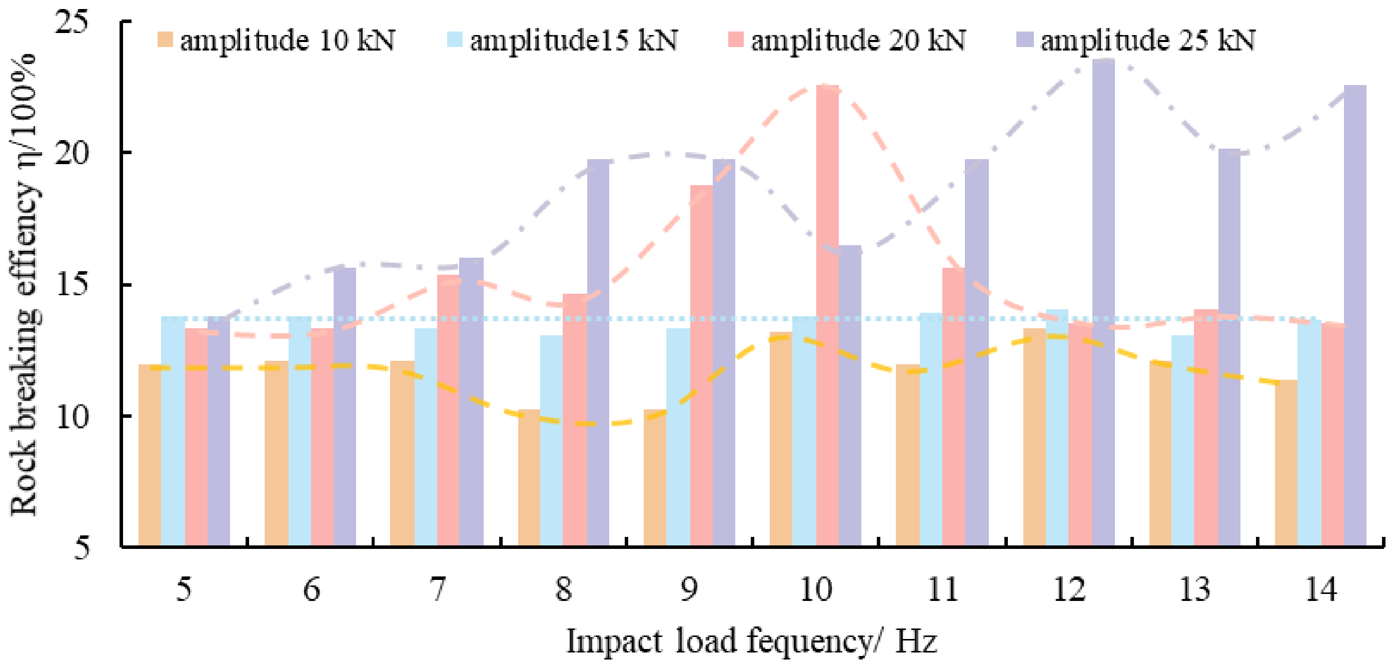

Figure 14. The rock breaking efficiency under different impact load amplitudes and impact frequencies (the static load is 50 kN, the dynamic load is from10 kN to 25 kN, confining pressure releasing Δp is 60 MPa respectively, impact load frequency is from 5 to 14 Hz, RPM is 120 r/min).

rock to accumulate in a shorter time, enhancing the concentration of shear stress, making it easier to exceed the critical shear strength, therefore, the rock breaking efficiency is significantly improved.

In conclusion, according to the DP criterion, at high frequencies, excessive concentration of shear stress may lead to stress redistribution in local areas, failing to effectively break through the critical shear strength of the rock. Therefore, although the impact load amplitude is large, too high a frequency will make the rock fracture unstable, which will reduce the rock breaking efficiency.

5 Conclusions

The rock breaking efficiency is discussed under the coupling of the impact load and confining pressure releasing, the failure of rock is caused by the shear stress exceeding the rock strength, which is mainly determined by the shear stress level, and the coupling of impact load and confining pressure releasing will increase the shear stress and resulting in rock breaking efficiency improving. The ratio of the shear stress and I_1 dominants the rock breaking, when the γ is small, the rock to tend to be in a compressed state, in this case, although the impact load is still applied, the hydrostatic pressure effect is enhanced and the shear stress effect is relatively weakened, the yield stress of the rock is increased, and the rock breaking efficiency is reduced.

In deep wells, applying higher weight on bit will unavoidably leads to drill string fatigue damage, and it is hard to improve the weight on bit in deep wells. Therefore, percussive drilling should couple the confining pressure releasing, which could achieve the rock breaking efficiency under relative low weight on bit conditions.

Data Availability Statement

Data will be made available on request.

Funding

This work was supported in part by the Natural Science Basic Research Plan of Shaanxi Province of China under Grant 2024JC-YBQN-0474; in part by the Natural Science Special Project of Shaanxi Provincial Education Department of China under Grant 24JK0723; and in part by the Young Talent Fund of Association for Science and Technology in Yan’an under Grant YAU202506703.

Conflicts of Interest

The authors declare no conflicts of interest.

AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable.

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