Borehole parameter optimization for supercritical carbon dioxide phase-transition fracturing

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Abstract. In recent years, supercritical carbon dioxide phase-transition fracturing (SCDPTF) has extensively been used in rock engineering as an environmentally friendly rock breaking technology. It is important to improve the energy efficiency and rock breaking effect by examining the SCDPTF borehole parameters. In this study, SCDPTF was first analyzed by numerical simulations. Based on the numerical simulation results, field tests were subsequently performed to determine the optimal borehole parameters. The results indicate that the rock mass around the borehole under the carbon dioxide phase-transition fracturing load can be divided into a crushing zone, a cracking zone, and a vibration zone. The radius of the crushing zone was ~0.297 m and that of the cracking zone was ~1.399 m, respectively. The optimal minimum burden line was 1.8 m, and the optimal borehole spacing was 2.5 m, respectively. The abovementioned results could provide effective guidance for the parameter design of SCDPTF.

1. Introduction

With the development of underground space technology, the requirements for construction safety and environmental protection have gradually increased. More stringent requirements for the environmental impact control have been put forward on the blasting vibration, dust, and noise in special areas. Supercritical carbon dioxide phase-transition fracturing (SCDPTF) is an environmentally friendly rock breaking technology, which has many advantages such as non-explosive spark, non-toxic gases, low ground vibration, and high security. In the 1950s, SCDPTF was first proposed by a British company called CARDOX, and was primarily used in coal mines [1]. By the 1980s, the technology was extensively used in developed countries, such as Germany, France, and the USA [2]. In recent years, it has widely been adopted in China’s infrastructure construction. Many studies focused on analyzing the mechanisms and application of SCDPTF. Huo et al. [3] successfully applied SCDPTF in a coal mine to increase permeability of coal seams. Xie et al. [4] illustrated the applicability of SCDPTF in the pile-well excavation by field testing and vibration monitoring. Zhan [5] analyzed the influence of different factors on the fracturing effect of SCDPTF. Sun et al. [6] developed a controllable supercritical carbon dioxide gas explosion device. Zhou et al. [7] studied the pressure response of a supercritical carbon dioxide blasting system by laboratory experiments and proposed an explosive energy calculation method.

Although SCDPTF has been successfully applied in rock excavation engineering, theoretical research on this technology lags behind its applications. Because the borehole parameter design theory of SCDPTF has not yet been established, the SCDPTF application relies strongly on the existing
experience. In this study, the numerical model was formulated to study the effective fracturing capability of SCDPTF. Furthermore, based on the numerical simulations, field tests were performed to determine the optimal borehole parameters. The results provide an experimental basis for the parametric design of SCDPTF.

2. Review of supercritical carbon dioxide phase-transition fracturing

2.1. Structure of the carbon dioxide fracturing pipe

As shown in Figure 1, the carbon dioxide phase-transition fracturing device comprises a filling head, a heating pipe, a storage pipe, a shearing sheet, a release head, and two gaskets. The filling head has a built-in carbon dioxide injection valve. The heating pipe is made of special chemical materials to provide enough energy for the carbon dioxide phase transition. The liquid storage pipe is used for storing liquid carbon dioxide. The shear strength of the shearing sheet determines directly the supercritical carbon dioxide release pressure, and consequently influences the fracturing effect. The two gaskets are then used to prevent the leakage of carbon dioxide. The release head with the guide holes is the channel for gas release. During fracturing, the high-pressure gaseous carbon dioxide is released via the guide holes [8].

2.2. Mechanism analysis of supercritical carbon dioxide phase-transition fracturing technology

The phase diagram of the carbon dioxide is shown in Figure 2. When pressure is >7.38 MPa, and the temperature is >31.4°C, carbon dioxide will be transformed to the supercritical state [9]. Supercritical carbon dioxide shares some properties with its gas phase and other with its liquid phase. Its density is close to the liquid phase, and its diffusion coefficient is close to the gas phase, exhibiting strong diffusion and low viscosity. When performing the SCDPTF in a rock mass, liquid carbon dioxide is first poured into the liquid storage pipe, and then the filled-in fracturing pipe is inserted into a pre-drilled hole. Subsequently, the heating pipe is electrified to produce a large amount of heat, and the liquid carbon dioxide will convert into the supercritical state. According to the ideal gas state equation, the internal pressure in the storage pipe is continuously rising as the temperature increases, and when the pressure exceeds the maximum shear strength of the shearing sheet, the shearing sheet will break, and the supercritical carbon dioxide will convert to high-pressure gaseous carbon dioxide, freed through the release head. The high-pressure gas instantly generates a stress wave with enormous energy, crushing the rock mass around the borehole, and generating cracks. After the high-pressure gas enters the cracks, the cracks continue to expand under the gas-wedge load.
3. Numerical simulation of supercritical carbon dioxide phase-transition fracturing

3.1. TNT equivalent calculation

The TNT-equivalent method is widely used to calculate the total energy of SCDPTF, $E_g$, [10]:

$$E_g = \frac{PV}{K - 1} - \frac{1}{K - 1} [1 - \left( \frac{P_2}{P_1} \right)^{K-1}]$$

where $P_1$ is the absolute pressure in the liquid storage pipe, $P_2$ is the standard atmospheric pressure, $V$ is the volume of the liquid storage pipe, and $K$ is the adiabatic index of carbon dioxide.

To quantify the load of SCDPTF, the TNT equivalent of the liquid carbon dioxide can be calculated by the following equation:

$$W_{\text{TNT}} = \frac{E_g}{Q_{\text{TNT}}}$$

where $W_{\text{TNT}}$ is the TNT equivalent of the liquid carbon dioxide, and $Q_{\text{TNT}}$ is the explosive energy of 1 kg of TNT equal to 4250 kJ/kg.

In the field tests, the ZL-73 carbon dioxide phase-transition fracturing pipe was used, which is shown in Figure 3. The storage pipe volume was 2.07 L, and the maximum shear strength of the shearing sheet was 270 MPa. From Equations (1) and (2), the total energy released by a single ZL-73 carbon dioxide phase-transition fracturing pipe is 1580.45 kJ, and the TNT equivalent of the liquid carbon dioxide is 0.372 kg.

3.2. Calculation model and material parameters

LS-DYNA is a finite element software extensively used in blast engineering, which effectively solves explosion impact and dynamic load problems. Therefore, it was chosen to analyze the capacity of the ZL-73 carbon dioxide phase-transition fracturing pipe. The numerical model comprises a cubic rock mass with a side length of 8 m, and a borehole with a radius of 5 cm and a depth of 3 m, as shown in Figure 4. The TNT is set at the bottom of the borehole, and the reminder of the borehole is blocked...
with stemming materials. A multi-material Euler solver was used for the TNT because of its proven efficiency in eliminating the problem of small-time steps and inaccuracy resulting from large deformation of Lagrange meshes. Moreover, to ensure the accuracy of the simulation results all boundary planes had no reflection, except for the upper boundary plane \([11]\).

**Figure 4.** Numerical model of SCDPTF.

The plastic kinematic model was used for the rock mass \([12]\) whose relevant physical and mechanical parameters are listed in Table 1.

| Density \((\text{g/cm}^3)\) | Elastic modulus \((\text{GPa})\) | Poisson’s ratio \((-\)) | UCS \((\text{MPa})\) | Tensile strength \((\text{MPa})\) |
|---------------------|------------------|-----------------|---------------|------------------|
| 2.714               | 44.134           | 0.213           | 202.676       | 16.137           |

The Jones–Wilkins–Lee (JWL) equation of state, which can accurately predict the performance of high explosives, was used to describe TNT \([13]\):

\[
P = A \left(1 - \frac{\omega}{R_1V}\right) e^{-\frac{R_2V}{R_1V}} + B \left(1 - \frac{\omega}{R_1V}\right) e^{-\frac{R_2V}{R_1V}} + \frac{\omega E_0}{V}
\]

where \(P\) is the explosion pressure; \(A, B, R_1, R_2\) and \(\omega\) are the JWL coefficients; \(V\) is the relative volume; and \(E_0\) is the initial specific energy. The values of the parameters are listed in Table 2.

**Table 2.** Parameters of JWL state equation

| A \((\text{GPa})\) | B \((\text{GPa})\) | R1  | R2  | \(\omega\) | \(V\) | E0 \((\text{GPa})\) |
|----------------|-----------------|-----|-----|----------|------|------------------|
| 371.2          | 3.231           | 4.15| 0.95| 0.3      | 1.0  | 7.0              |

3.3. **Analysis of numerical simulation results**

The von Mises effective stress can summarize the stresses in the rock mass during SCDPTF. To explore the change of the von Mises effective stress, several stress figures corresponding to the representative time steps are shown in Figure 5.
Figure 5. von Mises effective stress clouds at different time steps.

Figure 5 shows the process of stress wave propagation in the rock mass subjected to the carbon dioxide phase-transition fracturing. The influence extent reached the peak at time 1499.8 μs, when the pressure in the borehole vicinity was much larger than the compressive strength of the rock mass. Moreover, the initial guiding cracks were generated by the compressive stress, and a crushing zone formed. Under the high-pressure gas-wedge load, radial cracks continued to expand, thus forming a cracking zone. As the stress wave kept spreading outside the cracking zone, it caused rock mass elastic vibrations; thus, this area is referred to as the vibration zone.

To obtain the accurate damage extent of the rock mass, the stresses in eight mesh elements were analyzed, as shown in Figure 6. The horizontal distance from the center of the borehole to each element was 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, and 1.6 m, respectively. The peak von Mises effective stresses at time 1499.8 μs in the eight elements were fitted with a line, which is shown in Figure 7. The relationship between the peak von Mises effective stress and distance can be expressed as follows:

\[
\sigma = 424.41 \exp\left(-\frac{x}{0.39}\right) + 4.25
\]

(4)

where \(\sigma\) is the peak von Mises effective stress, and \(x\) is the distance between the borehole center and the selected element.

From Figure 7, we can conclude that the peak von Mises effective stress shows exponential attenuation with the distance. Substituting the compressive and tensile strength of the rock mass into the attenuation formula [14], we can obtain the crushing zone radius of 0.297 m and that of the cracking zone as 1.399 m.
4. Field tests

4.1. Experimental methodology
The minimum burden line length and the borehole spacing are the two important parameters that influence the rock breaking behavior during blasting. Two field tests were conducted to investigate the influence of the minimum burden line length and the borehole spacing on the rock breaking behavior. The relevant parameters of the ZL-73 carbon dioxide fracturing pipe used in the field tests were consistent with the numerical simulations. Considering that there are certain joint cracks distributed in the test rock mass, and the non-penetrating structural plane can continue expanding forward under the driving force of high-pressure gaseous carbon dioxide, the minimum burden line and the borehole spacing selected in the field tests were larger than the numerical simulation results. In the first test, three boreholes were arranged with the minimum resistance line length of 1.5, 1.8, and 2.1 m, respectively, and spaced by 3.0 m, as shown in Figure 8. In the second test, four boreholes with the borehole spacing of 2.2, 2.5, and 2.8 m, and depth of 3.0 m were arranged, as shown in Figure 9. The radius of all boreholes was 5 cm. Figure 10 shows the schematic of the carbon dioxide fracturing pipe installation.

Figure 7. Variation of peak von Mises effective stress with distance from borehole center.

Figure 8. Borehole layout in the first test.

Figure 9. Borehole layout in the second test.
4.2. Analysis of results

After the first fracturing, there are many cracks around the borehole; it can be seen that the cracks generated by SCDPTF are mainly radial cracks extending toward the free surface, but a few microcracks developed in the other directions, as shown in Figure 11. The results demonstrate that the free surface has a crucial effect on the development of cracks. The average crack length was ~1.423 m, and the two main cracks directly penetrated the free surface forming a triangular cracking zone seen in Figure 11 (a). As shown Figure 11 (b), the average crack length was ~1.810 m, and the volume of the cracking zone was larger than that of the minimum burden line of 1.5 m. In Figure 11 (c), the average crack length was ~1.3125 m, and the cracking zone failed to extend to the free surface, indicating that the minimum burden line was too large to achieve effective rock breaking. We can conclude that the borehole with the minimum burden line of 1.8 m had the best cracking effect.

Figure 10. Schematic of the carbon dioxide fracturing pipe installation.

In the second test, the number and length of cracks were used to evaluate the rock breaking effect of different borehole spacing, and the test results are shown in Table 3. When the hole spacing was 2.8 m, the number of the cracks was minimal, and the average length the shortest. Although the number of cracks was not much different compared to the case of hole spacing of 2.2 m, the average crack length in the area with a hole spacing of 2.5 m was the longest. Therefore, it can be judged that the rock breaking effect in this area with a hole spacing of 2.5 m was the best. When the borehole spacing was too short, the crack penetration occurred early; thus, the energy utilization of high-pressure carbon dioxide was lower, and the rock breaking area smaller. In the area with the 2.8 m borehole spacing, there were only four cracks, and they did not penetrate and formed two independent fracture areas, i.e., the distance between the boreholes was too large to achieve a satisfying rock breaking effect. In general, when the borehole spacing is 2.5 m, the rock breaking effect was the best.

Figure 11. Crack distribution of SCDPTF.
Table 3. Number and length of cracks

| Borehole number | Borehole spacing (m) | Number of cracks | Average crack length (m) |
|-----------------|----------------------|------------------|--------------------------|
| 4-5             | 2.2                  | 8                | 0.78                     |
| 5-6             | 2.5                  | 7                | 0.95                     |
| 6-7             | 2.8                  | 4                | 0.52                     |

5. Conclusions
This paper combined numerical analysis and field tests to investigate the optimal borehole parameters of SCDPDF. The following conclusions have been made:
(1) The total energy released by a single ZL-73 carbon dioxide fracturing pipe is 0.372 kg of TNT equivalent.
(2) The rock mass around the borehole is divided into a crushing zone, a cracking zone, and a vibration zone under SCDPTF. The radii of the crushing and the cracking zone are 0.297 and 1.399 m, respectively.
(3) In the field tests, the optimal minimum burden line length and the optimal borehole spacing are 1.8 and 2.5 m, respectively.

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