Vibration Effect Induced by Rock Breaking Technology Based on Dry Ice and Energy-gathered Agent in Trench Excavation

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Abstract. Rock breaking technology based on dry ice and energy-gathered agent has been developed and successfully applied in trench excavation for construction of oil pipeline. The vibration velocity waveform induced by this technology was monitored in site test to determine the attenuation law of vibration velocity with hypocentral distance. The results show that this rock breaking technology is effective method of trench excavation. It does not excessively damage the adjacent rock mass, ensuring the integrity of ditch walls. The vibration velocity induced by this technology is decay with the increase of hypocentral distance. At the hypocentral distance of 10m, the vibration velocity reduces to less than 20mm/s, which meets the requirements of the safety standard of blasting vibration in general buildings engineering. The results of this experiment have an important guiding effect on the field engineering practice and application of rock breaking technology based on dry ice and energy-gathered agent.

Keywords. Rock breaking technology; Dry ice; Energy-gathered agent; Vibration velocity.

1. Introduction
At present, explosive blasting, high energy gas fracturing (HEGF) and supercritical fluid fracturing technology are the typical technologies applied to breaking rock mass, which were used in mining and related engineering. Explosive blasting is a process of energy conversion and rapid expansion of gas volume in a very short time. It has the characteristics of high reaction heat (3-6 MJ/kg), fast reaction speed (within 10-6s) and large amount of gas generation. It is an efficient way to break rock and widely used in mining and urban infrastructure construction [1-3]. However, explosive blasting poses a threat to the ecological environment and the health of workers at different degrees [4-6]. It usually causes intolerable noise, strong earthquake, blasting shock wave and a large number of blasting stones, which are harm to the surrounding environment, buildings, and safety of life [7-9]. Meanwhile, explosive blasting produces toxic and harmful gases and waste residue [10-12], causing harm to the health of animals and plants [12-19].

In the 1980s-90s, carbon dioxide (CO₂) phase transition fracturing technology had been gradually promoting in the field of rock excavation and coal mining. This technology uses liquid CO₂ and
heating agent as medium of rock breaking, which are encapsulated in an airtight container. The heating agent is excited to generate a high temperature above 800 °C within 0.1 s, and liquid CO₂ is instantly gasified, resulting in rapid volume expansion and high pressure [18]. Compared with compressed air, nitrogen and other media, liquid CO₂ is an excellent work medium because it is easy to compress and obtain high density at ambient temperature.

![Structure diagram of CO₂ fracturing tube.](image)

**Figure 1.** Structure diagram of CO₂ fracturing tube.

The CO₂ phase transition fracturing technology was first proposed by Cardox company in the 1950s, and the fracturing of rock was realized by CO₂ fracturing tube [20]. The fracturing apparatus are composed of main tube body, chemical energizer, rapture disc, fill head and discharge head as shown in figure 1. Since the technology was introduced into China in the 1990s, it had been widely studied by many researchers, and used in the field of coalbed methane exploitation to solve the problem of low permeability of coal seams. Fan et al. [21] studied the application of CO₂ phase transition fracturing technology in gas drainage. He et al. [22] established a numerical calculation method for the influence range of permeability of coal seam after CO₂ fracturing. Yan et al. [24] found that the coal fracture after CO₂ fracturing is more complex than that caused by hydraulic fracturing. At present, it hasn't been specifically studied for the mechanism of crack initiation and crack propagation using supercritical CO₂ phase transition fracturing [25-27]. Zhang et al. [28] established the cyclic dynamic model of rock fracture, and pointed out that the rock fracture using CO₂ phase change fracturing technology is result from the stress wave. Goodarzi et al. [29] concluded that the gas pressure has great influence on the crack length than the stress wave.

Generally speaking, fracture of intact rock is mainly caused by the impact effect of stress wave, while rock mass with relatively developed primary fractures is mainly caused by the expansion wedge effect of gas [30]. Because liquid CO₂ rock breaking is a physical process, the vibration caused by liquid CO₂ rock breaking is less than that caused by explosive blasting used the same charge amount. For the energy distribution of a single vibration waveform in different frequency bands, the study found that most of the energy is mainly distributed below 100Hz, and the frequency of the main vibration is generally below 20Hz [31-35]. In addition, the peak velocity of liquid CO₂ rock-breaking vibration is different in different directions. The peak velocity is affected by the direction and types of the fracture [36]. In general, vibration velocities in the vertical direction are higher than the horizontal, and the vibration velocities in the three directions gradually decrease and converge with increasing of distance [37].

Compared with explosive blasting, liquid CO₂ phase transformation process is slower than it, which is completed within milliseconds [23]. Therefore, it is more conducive to the generation and expansion of rock mass fractures, and the vibration damage and noise pollution are less. However, many shortcomings are revealed when this technology was widely used in engineering. Firstly, the high pressure gas was released in the lower end of the liquid storage pipe, and the breaking energy was limited. Secondly, the high pressure vessel was used to transport and filling the liquid CO₂, these processes pose a threat to workers; In addition, many accidental triggering events occurred during the
filling process of the CO₂ cracker, such as pipe burst and fly-pipe accidents. Finally, the conventional CO₂ fracturing technology is limited by policies, as the chemicals used to heat liquid CO₂ is characteristic of explosive properties. Hu et al. [38] developed a new CO₂ fracturing technology, which adopted an intrinsically safe energy accumulating agent to realize the CO₂ phase change. As the energy accumulating agent is only a heating product rather than an explosive product, it improves the security of the CO₂ fracturing technology.

In this paper, the new rock breaking technology based on dry ice and energy-gathered agent (Hereafter, dry ice rock breaking technology) was applied to the excavation of trenches. The characteristics of vibration velocity waveform induced by this rock breaking and the attenuation law of vibration velocity with hypocentral distance were monitored and analysed.

2. Test Site and Test Method

2.1. Test Site
The site is located in Longhui No. 002-H5 Construction Project beside Xiangtangzi River, Wenchong Town, Dazhou City, Sichuan Province, China, as shown in figure 2. The depth of the trench for the construction pipeline is 1.2 m, the width is 0.8 m, and the top is 1.0 m. The lithology is mainly purple mudstone and grayish yellow sandstone. Because the test site is close to residential buildings, explosives blasting cannot be used to rock breaking. In order to improve the efficiency of rock breaking and to diminish the influence of vibration on the adjacent dwellings, dry ice rock breaking technology was carried out in this area. Microseismic monitoring system was used to monitor the vibration in whole process of rock breaking.

![Figure 2. Location of filed test.](image)

2.2. Test Methods and Procedures
Dry ice rock breaking device is composed of dry ice powder cabin, energy accumulating agent tube, heater, gas blocking system, safety relief valve, detonator and accumulator, etc. (see figure 3).
Figure 3. Schematic diagram of dry ice fracturing device.

The dry ice powder cabin used in this study were 600 mm and 400 mm in length, and 100mm in diameter, which could accommodate CO\(_2\) of 1.5 kg and 1 kg, respectively. The energy accumulating agent tube is 400 mm in length, 50 mm in diameter and 0.4 kg in weight. It is a kind of functional material with porous micro nano structure, which has strong adsorption characteristics. This structure is conducive to the combustion exothermic reaction of the energy accumulating agent [38]. The physical and chemical parameters of the energy accumulating agent are shown in table 1.

Table 1. Basic physical and chemical parameters of the CO\(_2\)-EA [38].

| Material | Apparent density (g/mL) | Porosity | Specific surface area (m\(^2\)/g) | Heat of combustion (kJ/g) | Thermal conductivity (W/m k) |
|----------|--------------------------|----------|----------------------------------|----------------------------|-----------------------------|
| CO\(_2\)-EA | 0.12                     | 0.92     | 240                              | 21.33                      | 0.016                        |

As shown in figure 4, the test procedures were divided into drilling, cement sealing, sensor layout, and data collection. As shown in figure 5, a total of two holes were drilled at a 45 angle to the ground, the diameter was Φ110 mm, and the depth was 1.5 m. Dry ice powder cabin were inserted into the hole, and then sealed with quick-drying cement. Vibration sensors were arranged at different distance and different direction. Finally, microseismic data were collected after initiating the detonator.

Figure 4. Schematic diagram of the test.
2.3. Vibration Monitoring System and Layout Method

KJ522 microseismic monitoring system was used to monitor the vibration wave. This study focuses on the vibration attenuation law induced by dry ice rock breaking technology within 15 meters. The vibration sensor layout network was shown in figure 5. A total of 8 vibration sensors were arranged. S5 sensor was closest to H1 (1.05m) and S4 was closest to H2 (1m). S1, S6, S7 and S8 were installed along the left side of the rural road. S8 was the farthest from H1 and H2. A mixture of gypsum powder was used to fix the sensor, and the test was carried out after the gypsum hardened.

3. Test Results and Analysis

(a) H1 excited, H2 reserved  
(b) H1 and H2 all excited

Figure 6. Schematic diagram of crack effect of single row of grooves.
Figure 7. Schematic diagram of H1 vibration waveform.

Figure 8. Schematic diagram of H2 vibration waveform.

Figure 9. Vibration velocity attenuation diagram.
H1 and H2 were excited successively, and the result of rock breaking was shown in figure 6. Rock mass within trench was severely damaged by dry ice rock breaking technology, while side wall of trench remains integrity. It has achieved the desired purpose. The events of fly-pipe punching and fly-stone were not occurred. Compared with pick-axe machine, dry ice rock breaking technology exhibited higher construction efficiency in trench excavation. This result indicates that dry ice rock breaking technology is an effective method for trench excavation.

Figure 7 and figure 8 show the vibration waveform induced by two rock-breaking events. The amplitude of waveform velocity decrease with the increase of hypocentral distance. The first arrival time of different waveforms is obvious different.

Figure 9 shows the attenuation statistics of the vibration velocity induced by two rock breaking events with the hypocentral distance. The sensor S5 was the closest (1m) to the position of H1, and the maximum vibration velocity was 494.530 mm/s; the sensor S4 was the closest (1m) to the position of H2, and the maximum vibration velocity was 271.601 mm/s. The vibration velocity induced by dry ice rock breaking is attenuated with increasing of distance, and it conforms to the attenuation of power function, and the fitting accuracy is 0.99. Therefore, the vibration velocity of any seismic source distance can be predicted by the power function. According to figure 8, the vibration attenuation induced by dry ice rock breaking can also be divided into three regions, namely, the rapid reduction area (0~3m), the slow reduction area (3~10m) and the stable area (>10m).

4. Analysis and Discussion

The size of the dry ice fracturing cylinder in the H1 and H2 drilling holes used in this time is Φ100*600 mm and Φ100*400 mm respectively, and the fracture pressure obtained through the laboratory test is 60MPa. The energy calculation of CO₂ phase transformation cracking in the application of coal seam gas [39, 40], gas extraction [41], and exploration source are all calculated by the following equations [42]:

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

As in equation (1), \( E_g \) is the burst energy of gas, kJ; \( P \) is the absolute pressure of gas in the container, MPa; \( V \) is the volume of the container, m³; \( K \) is the adiabatic index of the gas, 1.295. It can be obtained that blasting energies of the 60 mm and 40 mm tubes are 793.402 kJ and 508.952 kJ, respectively.

The approximate TNT equivalent of dry ice rock breaking device can be calculated by using equation (2):

\[ W_{TNT} = \frac{E_g}{Q_{TNT}} \] (2)

As in equation (2), \( Q_{TNT} \) is 1 kg TNT explosion energy, 4250 kJ/kg. After calculation, the TNT equivalent of 60mm tube is 179.674g, and that of 40mm tube is 119.754g.

Sadovsky formula is an empirical formula based on a large number of measured data and the principle of similarity law, through studying the blasting seismic effect of concentrated charge [43-47].

\[ v = K \left(\frac{\sqrt{Q}}{R}\right)^\alpha \] (3)

As in equation (3), \( V \) is the particle vibration velocity, cm·s⁻¹; \( K \) is the parameters related to blasting site conditions; \( Q \) is volume of tube, kg; \( R \) is the distance between the measuring point and the center of the charge, m; \( \alpha \) is the coefficient related to geological conditions. According to equation (3), the calculating formula of dose is
\[ Q = R^\frac{3}{a} (\frac{v}{K})^3 \] (4)

Table 2. Relationship between $K$ value and $a$ value.

| Lithology       | $K$        | $a$   |
|-----------------|------------|-------|
| Hard rock       | 50~150     | 1.3~1.5 |
| Medium hard rock| 150~250    | 1.5~1.8 |
| Soft rock       | 250~350    | 1.8~2.0 |

According to the engineering report, the strength of highly weathered sandstone was about 20 MPa. Table 2 shows the relationship between $K$ value and $a$ value. The estimated dose range of 60mm tube was 173.244g ~ 236.157 g, and that of 40 mm tube was 94.179 ~ 129.681 g.

According to the calculation results, the TNT equivalent of 60 mm tube is 179.674 g, and that of 40 mm cracked pipe is 119.754 g, which is obviously within the charge range of vibration energy. It indicates that it is reasonable to use equation (1) to calculate the energy of dry ice tube. The effect on the building can be judged by estimating the vibration velocity of the dose.

Dry ice rock breaking technology is mainly through the rapid combustion of the energy accumulating agent under the excitation of instantaneous high voltage, releasing a large amount of heat to promote the rapid gasification of CO$_2$, so as to form a transient high pressure in the closed space to break the tube. The high-pressure CO$_2$ gas could rush from the tube rupture will impact on the borehole wall and generate stress waves. The stress state or dynamic stress field formed by stress wave disappears quickly due to the impact of the initial time is short. The range of cracks formed at the beginning of reaction is small. When CO$_2$ gas penetrates into impact cracks and primary cracks, it will produce an effect similar to an air wedge under static pressure, which will make the cracks continue to extend forward and cause rock fracture until the energy of high-pressure gas is exhausted.

In addition, the peak frequency of vibration induced by dry ice powder pneumatic rock breaking is mainly distributed in 0-50 Hz, which is similar to the peak frequency distribution of explosive blasting vibration. According to the vibration safety standard, the low frequency of the main frequency will cause more serious damage to the surrounding buildings. As the distance increases, the low frequency of dry ice rock breaking vibration decreases faster than the high frequency of that. When the distance far way 10m, the vibration wave velocity drops to less than 20mm/s, and the low frequency vibration wave attenuates more rapidly. Therefore, the vibration damage of buildings with a distance of more than 10m caused by dry ice rock breaking meets the safety allowable standards of blasting vibration. Compared with traditional blasting, dry ice rock breaking technology is a safer method of rock breaking.

5. Conclusion
(1) Dry ice rock breaking technology can be well applied to trench excavation, the cracking depth is about 1m, and it will only deepen the depth of the bottom groove, and protect the side. Compared with the pick machine, dry ice fracturing is more efficient and the noise is less;
(2) The vibration velocity induced by dry ice rock breaking technology will drop to less than 20mm/s the distance far way 10m. It is lower than the vibration velocity requirement of general buildings in the safety allowable standards of blasting vibration. Therefore, it is a more safe and reliable rock breaking technology.
(3) The TNT equivalent of cracking energy is applicable to Sadovsky formula, and this formula can be used to predict the wave velocity in field engineering, so as to carry out on-site safety assessment.
(4) The vibration velocity induced by dry ice rock breaking is conform to the attenuation of power function. The vibration attenuation induced by dry ice rock breaking can also be divided into three
regions, including the rapid reduction area (0–3m), the slow reduction area (3–10m) and the stable area (>10m).

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