Liquid CO\textsubscript{2} Phase Change Fracturing and Vibration Monitoring in Roadbed Slope Excavation

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Abstract. In order to analyze the vibration impact of carbon dioxide fracturing tube blasting red sandstone, combined with the engineering conditions and surrounding environment of Anqing High-tech Zone, the rock-breaking blasting plan is carefully designed. The fracturing tube is arranged in two rows, the first row has 23 holes with a spacing of 1.5m, and the second batch of holes has 22 holes, which are arranged in a quincunx pattern with a distance of 1.3m between the front and rear rows. And design the corresponding vibration signal monitoring test to study the crack propagation caused by blasting, the attenuation law of vibration and its frequency spectrum distribution. The results show that after blasting, there is a relatively smooth crack in the plane area of the fracture zone 7m away from the critical surface. The width of the crack is between 20-40cm. The vibration velocity of the measuring point decays rapidly with the increase of the vibration source distance, and the vibration velocity decay curves in the X and Y directions are basically the same. Spectrum analysis shows that the main frequency band of each sub-velocity is generally below 100Hz, and the main vibration frequencies in the X and Y directions are concentrated in 30–60Hz. The main vibration frequency band of the rock-breaking blasting vibration signal has little correlation with the direction and propagation distance of the vibration signal. And compared with the analysis of emulsion explosives, it is found that the particle vibration speed caused by the emulsion explosive rock-breaking blasting is much greater than that of the liquid CO\textsubscript{2} fracturing tube rock-breaking blasting, indicating that the use of liquid carbon dioxide to break the rock can effectively reduce the vibration generated by blasting.

1. Introduction

Rock mass excavation is often required in the construction of most projects. The main methods of excavation are mechanical crushing, blasting, and cutting. Among them, explosive blasting is commonly used in blasting, and the inherent danger of drug blasting will have a certain impact on the surrounding environment. Therefore, many scientists have begun to explore new technologies that can be used to replace traditional explosives in rock mass excavation work to improve the safety of the excavation.
process. Among them, the carbon dioxide fracturing tube technology was first developed by the British company CARDOX in the 1950s and has been rapidly developed in the following decades. It was introduced to my country in the 1990s and was first used in the coal industry, and gradually used in the rock excavation neighborhood. Guo Zhixing[1] conducted ground experiments with CO₂ blasting cylinders in Pingdingshan No. 7 Mine, and the rock breaking effect was good, indicating that the CO₂ rock breaking process will not produce sparks and is safer. Tang Kaifu[2] carried out the CO₂ rock breaking technology test in the background of Guangzhou Tianhe Park Station. The data measured by the instrument was within the safety range required by the specification, and there was no over-standard situation. Even at a distance of 3.5m near the breaking point, the vibration speed did not exceed the safe value. The research of Liu Zheng[3] shows that carbon dioxide blasting is suitable for projects with surrounding structures. Tests show that the vibration wave produced has little impact on the surroundings (smaller vibration waves), and does not disturb the surrounding original structures and mountains. Li Qiyue[4] Taking a subway foundation pit excavation project in Changsha as the background, using liquid CO₂ phase change rock breaking technology instead of traditional explosive blasting for rock breaking excavation, and analyzing and monitoring its rock breaking effect and safety, it is concluded that Liquid CO₂ phase change rock fragmentation technology can replace traditional explosive blasting methods in terms of rock fragmentation effect, meet the requirements of blasting safety regulations in terms of safety, and can be promoted and used in excavation projects similar to hard rock masses. Li Xibing[5] conducted field tests and vibration monitoring of CO₂ rock breaking and forming wells. The study showed that in a semi-infinite rock mass, the CO₂ rock breaking area can be divided into crushing zone and fracture zone. The diameter of the crushing zone is 3~ of the pipe diameter. 4 times, the diameter of the fracture zone is 10~15 times the diameter of the pipe; CO₂ rock breaking technology overcomes the shortcomings of traditional explosive blasting and is an efficient stepped rock breaking method. Liu Guanghui[6] carried out carbon dioxide fracturing experiments and showed that: compared with explosives, carbon dioxide fracturing has better blasting effect, less vibration, higher safety, larger fragmentation of broken rock mass, and a 50% reduction in dust and gun smoke. Harmful gas is generated, and the safety is high. On the basis of effective vibration data obtained from field test and monitoring, Zhang Xuyang[7] conducted research on carbon dioxide rock-breaking phase change fracturing technology, static rock breaking technology, hollow-hole vibration damping technology and multi-stage wedge-shaped trough based. The construction technology of “hole + reserved optical explosion layer” was studied, and the influence of the continuous interval arrangement of auxiliary eyes and the detonation method on the vibration velocity was analyzed through numerical simulation in the longitudinal direction. Chen Guan[8] showed that the main vibration frequency band of the liquid CO₂ phase change rock-breaking vibration signal has little correlation with the direction and propagation distance of the vibration signal, and it is basically located in the 0~4Hz sub-band. However, the percentage of energy distribution corresponding to the main vibration frequency gradually decreases as the propagation distance increases. The percentage of frequency energy distribution in different directions at the same measuring point is different in the 0-100 Hz frequency band, but it is basically the same in other frequency domains. Wang Haizhu[13] found that the initiation pressure of CO₂ fracturing is lower than that of conventional fluid fracturing. The fracture network formed in the rock is more complicated, and the fractures are connected to each other. They usually crack along the cement with low strength, and rarely penetrate the cement, the particles, the cracked part is relatively rough. Xing Huang[14] conducted three verification experiments with different radial distances between the fracturing tube and the test point on the test system, and in each experiment, four PVDF sensors (as four test points) were arranged to the axial distance of the initiation point is different, and the pressure distribution is tested to get the axial length of the fracturing tube when the radial distance between the fracturing tube and the test point is not too large (≤345mm). The inside is roughly evenly distributed, but when the axial length of the fracturing tube is relatively large (≈895mm), the results between different test points are scattered to a certain extent. Guozhong Hu[15] conducted a test study on the permeability enhancement of cross-measure boreholes using liquid CO₂ phase-transition blasting (LCPTB). Through a numerical simulation of LCPTB, the fracture propagation in the coal seam after
blasting was analysed. The results indicate a significant increase in the permeability of the coal seam and the efficiency of gas drainage following LCPTB. The amount of gas extracted from the blast holes was 1.8–8 times greater than that extracted from boreholes without LCPTB. The practical spacing between boreholes was deemed to be 2.5–3m.

This article takes the red sandstone blasting on the left side of section K5+440-K5+600 of Yongjin Road in Anqing High-tech Zone as the engineering background. Since this area is a restricted area for civil aviation and military aviation, explosives and other explosives are strictly prohibited; it is also a city in the lower Yangtze River Delta Group construction areas have high environmental protection requirements, so liquid CO\textsubscript{2} fracturing pipes are used to break rocks and blasts to improve construction efficiency. According to this test, a monitoring program is designed to obtain liquid CO\textsubscript{2} phase-change rock-breaking vibration signals, analyze the vibration attenuation and frequency spectrum characteristics of the vibration signals, and provide a theoretical basis for controlling the impact of liquid CO\textsubscript{2} phase-change rock-breaking vibration.

2. Blasting parameter design

2.1. Background of the project

This test is a key component of the PPP project for the comprehensive development of the Shankou area in Anqing High-tech Zone, and the "One Bridge and One Road" (Yongjin Road, Yongjin Road Bridge) project will be constructed first. The total length of the construction project is about 6.8km, the red line width of the road is 60m, and the road is positioned as an urban main road. The construction site is located in Shankou Township, Daguan District, Anqing City. The blasting site was located in the middle weathered sandstone section on the left side of section K5+440-K5+600 of Yongjin Road. The rock is weathered into sand or a small amount of fragments, with pebbles (gritstone or weathered conglomerate) in some parts, and extremely developed fissures. The content of pebbles is 20-40%, and the diameter of pebbles is 3-8cm. The composition is mainly quartzite and flint. The completeness of the rock mass is extremely fractured, the basic quality of the rock is V, and the hardness is soft rock.

2.2. Maintaining the Integrity of the Specifications

According to different blasting media, different geology and different objects, it is necessary to design suitable blasting parameters, such as: drilling diameter, spacing, depth, fracturing tube type selection and diameter, filling pressure length, etc. to design, determine the initial fracturing hole After the network parameters, the cracking test is performed. The vibration speed of key targets is monitored through trial cracking, the effectiveness of flying stone protection measures is evaluated, and the hole mesh parameters are adjusted until the effect meets the design requirements. Use disposable fracturing pipe (pipe diameter 90-120mm, length 1-1.5m, liquid CO\textsubscript{2} aeration volume 4-6kg) for deep-buried loosening phase change fracturing construction. The specific hole mesh parameters designed for the cracked pipe are as follows:

1. Step height: L=3.5~15m (adjust and determine according to the actual situation on site);
2. Drilling depth: h=3.5~15m, slightly smaller than the step height;
3. Aperture: d=100~130mm
4. Hole distance: a=1.5~2.0m; (should be optimized according to the actual fracturing effect)
5. Resistance line: W=1.5~2.2m (should be adjusted according to the actual fracturing effect);
6. Number of rows: b=1~2; (To ensure safety, try to adopt a single-row hole design)
7. Number of single-row holes: N=5~15.
8. Drilling method: Use vertical holes as much as possible, which makes drilling operations easier and convenient for pipe installation.
9. The number of pipes installed in a single hole: the drilling depth is 3.5-5 meters, and a single hole should be equipped with 1 fracturing pipe with a length of 1 meter or 1.2 meters; the drilling depth is 5-8 meters, and a single hole should be equipped with 2 m fracturing pipe; the drilling depth is 8-15
meters, and a single hole should be equipped with 3 fracturing pipes of 1 m long; the specific number of single-hole pipes should be optimized and adjusted according to the actual fracturing effect and safety protection conditions.

(10) Packing depth: After the fracturing pipe is drilled and filled, the upper packing depth shall not be less than 2h/3. The packing material can be made of small angular gravel and quick-drying cement. The detonation can be carried out after the packing material reaches early strength. Considering the blasting power and hole depth, this project adopts the MZL220-89/1000 carbon dioxide phase change fracturing device, and the fracturing tube wall thickness is 2mm. Use a down-the-hole drill for drilling, the blasthole depth is 4m, a carbon dioxide fracturing tube is used for blasting, and a special blasting line is laid on the ground. Arrange two rows of blastholes, one row of 6 holes near the airside surface, and the other row of 5 holes. The specific blasting plan is listed in Table 1.

| Sorting | Number of holes per circle | Hole depth | Hole charge | Sequence of initiation |
|---------|---------------------------|------------|-------------|------------------------|
| 1       | 6                         | 4          | 1 fracturing tubes | 1                      |
| 2       | 5                         | 4          | 1 fracturing tubes | 1                      |
| total   | 11                        |            | 11 fracturing tubes |                        |

The monitoring instrument adopts the TC-4850 blasting vibrometer produced by Chengdu Zhongke Measurement and Control Co., Ltd., equipped with X, Y, and Z three-dimensional integrated speed sensors. The horizontal X direction of the sensor is the axial direction, the horizontal Y direction is the radial direction, and the Z is the vertical direction, which is perpendicular to the horizontal plane. The purpose of this experiment is mainly to monitor the blasting vibration data at the surface during the blasting process of the red sandstone empty surface. The layout plan of the measuring points for the blasting monitoring is: 5 measuring points are selected vertically along the center of the blasthole connection line, and measuring points A, B, C, D, E and F are arranged in sequence, of which point A is 4.7 from the center of the blasthole connection line m, a sensor is arranged every 3m in the future. Due to the soft rock and soil at the monitoring site, in order to accurately collect the monitoring data, a special steel plate platform is used to fix the sensor. The steel plate platform is 10*10 long and wide, and welded with 10cm long steel bar plugs. The specific layout is shown in Figure 1.

![Figure 1: Layout of measuring points (unit: cm)](image)

3. Blasting effect analysis
Monitoring at the moment of initiation, the sandstone within 5m of the fracture area was fractured, and the rock mass was lifted and then landed. There were large fractures on the top surface and critical
surface of the drilling platform. There is a relatively smooth crack at 7m from the interface with a width of 20-40cm. On the outside of both ends of the fracture zone, there are also cracks 3-5cm wide. On the side of the critical surface of the fracturing zone, there are multiple cracks after initiation. The largest crack is at 3-5m and the crack reaches 10-30cm. Then the crack gradually extends to both ends, and the width of the crack becomes smaller and smaller. In terms of location depth, it is mainly in the blasting area of the fracturing tube, and the area 4-7m from the hole position is also the area with the best fracturing effect. In the fracturing area above 4m, the fracturing cracks are denser, indicating that the fracturing effect is better, and the energy is also released to the side with space.

![Figure 2: On-site liquid CO₂ cracking effect diagram](image)

![Figure 3: On-site crack growth picture](image)
4. The law of blasting vibration propagation

In order to study the vibration propagation law of the red sandstone carbon dioxide fracturing tube blasting on the surface, the law of the three-dimensional component of the vibration velocity at the surface measurement point caused by the blasting is analyzed, as shown in Figure 5.

The research of King Kong\cite{9} found that the particle vibration velocity decays rapidly with the vibration source distance. When the vibration source is 5m away, the vibration velocity drops below 2.5cm/s, which is much smaller than explosive blasting and has a small influence range. The Regulations require the vibration speed of general buildings\cite{11}. The vibration velocities in the three directions at the measuring point 4.7m away from the vibration source in this test are all less than 0.8cm/s, indicating that the impact of carbon dioxide fracturing tube blasting on the surrounding environment is very small, and it is difficult to cause damage to existing buildings harm. It can be seen from the situation of CO2 rock breaking on site that the noise generated when carbon dioxide is breaking rock is not large.

Through the analysis of Figure 5, comparing the vibration velocity in the three directions, it is found that the vibration velocity in the Z direction > the vibration velocity in the X direction > the vibration velocity in the Y direction. Comparing the attenuation of the vibration velocity in the three directions,
it can be obtained that the vibration attenuation curve of the vibration velocity in the X direction and the vibration velocity in the Z direction at the three measuring points of 4.7m, 7.7m, and 10.7m are roughly the same, while the vibration velocity attenuation in the Y direction is less obvious. The vibration velocities in the three directions at the two measuring points of 13.7m and 16.7m decay slowly, but the vibration velocity is lower than 0.3cm/s at smaller values.

5. Analysis of seismic wave spectrum characteristics
Firstly, the data obtained from measuring point C is used as the analysis object to obtain the frequency spectrum characteristics of the red sandstone blasting by carbon dioxide fracturing tube in all directions. The spectrum characteristic curve of the three-way vibration velocity of a typical blasting section is shown in Figure 6.

![Figure 6](image)

**Figure 6** Spectrogram of three-way vibration velocity at D measuring point
From the Fourier spectrum of the measurement point D, we can see that the frequency spectrum of the three-directional vibration velocity of the carbon dioxide burst tube blasting has similar frequency bands, and it can be found that the main frequency band of each sub-velocity is below 100 Hz. The dominant frequencies in the X direction and Y direction are mainly distributed between 30 and 60 Hz, relatively concentrated; the dominant frequency distribution in the Z direction is slightly less obvious.

In order to study the change of the vibration frequency of liquid rock breaking blasting with distance, taking the Y vibration velocity of liquid carbon dioxide rock breaking blasting as an example, the vibration frequency spectrum changes at different positions are analyzed, as shown in Figure 7.

![Figure 7](image)

(1) 4.7m from the connecting line of the blast hole
Figure 7 Variation of vibration velocity spectrum of liquid carbon dioxide rock breaking blasting with distance

From the figure, we can see that with the gradual increase of the distance, when the main frequency of the rock-breaking blasting vibration signal is less than 7.7m from the blast hole line, the main vibration frequency has undergone a process of change from 60Hz to 30Hz. When the distance is greater than 7.7m, the frequency distribution of the main vibration is not obvious and there is no trend of change. It shows that the main vibration frequency band of the liquid CO2 rock fragmentation blasting vibration signal has a small correlation with the direction and propagation distance of the vibration signal, and it is basically located at 25Hz-100Hz.
6. Analysis of Blasting Vibration Contrast Emulsion Explosive Analysis of seismic wave spectrum characteristics

In order to further study the characteristics of rock-breaking vibration of liquid CO2, the maximum value of the vibration velocity vector of the red sandstone particles measured by the instrument at five measuring points A, B, C, D, and E is selected, and obtain the relationship diagram of the vibration velocity of the particle with the distance of the explosion source, as shown in Figure 6. According to Tao Ming’s research, the phase change energy \( E_g \) (approximate blasting energy) of liquid CO\(_2\) can be expressed as:

\[
E_g = \frac{\rho V}{k-1} \left[ 1 - 0.1013 \frac{k-1}{kp} \right]
\]

Where: \( V \) is the volume of the liquid storage tube, m\(^3\); \( p \) is the absolute pressure of the gas in the liquid storage tube after expansion, Pa; \( k \) is the adiabatic coefficient, which is 1.295\(^{[12]}\). The MZL220-89/1000 disposable liquid CO\(_2\) fracturing tube used in this test has a liquid storage tube volume of 3.26L, and the pressure acting on the rock at the moment of gas expansion is 220 MPa. Substitute the above formula to calculate a single fracturing. The energy released by fracturing the rock blasting is about 2430.93kJ, which corresponds to about 3009kJ of 1kg emulsion explosive. It can be seen that the energy released by a single MZL220-89/1000 disposable liquid CO\(_2\) fracturing tube is about 0.81kg of the energy released by the rock emulsion explosive. A total of 11 fracturing tubes were used in this test, which is equivalent to the energy released by the blasting of 8.91kg of rock emulsion explosive.

According to Sadowski’s empirical formula \( V = K \times \left( \frac{Q^m}{R} \right)^2 \), the particle vibration velocity of the rock emulsion explosive at the corresponding side point can be calculated. Where: \( V \) is the vibration velocity of the particle; \( Q \) blasting charge; \( R \) is the distance from the particle to the blasting source; \( m \) is the charge coefficient, which is 1/3; \( K \) is the correlation coefficient of geology, terrain and blasting conditions, which is 150; \( \alpha \) As the attenuation coefficient, take 1.5. The calculated vibration velocity data of the particle is plotted as the relationship between the vibration velocity of the particle and the distance from the explosion source, as shown in Figure 9.

![Figure 8](attachment:figure_8.png)

**Figure 8** Variation curve of particle vibration velocity with blasting source distance caused by CO\(_2\) fractured rock
Comparing the analysis of Figures 6 and 7, it can be found that the particle vibration velocity caused by the emulsion explosive rock breaking blasting is much greater than the liquid CO2 fracturing tube rock breaking blasting. The particle vibration velocity of emulsion explosive at measuring point E, which is 16.7m away from the blasting source, is 6.56cm/s calculated by the empirical formula, while the actual vibration produced by liquid carbon dioxide blasting is 0.212cm/s. It shows that using liquid carbon dioxide to break the rock can effectively reduce the vibration effect caused by blasting.

7. conclusions

(1) Large cracks exist on the top surface and critical surface of the drilling platform after blasting. In the plane area of the fracturing zone, there is a relatively smooth crack at a distance of 7m from the critical surface, with a crack width between 20-40cm.

(2) Within the range of 4.7m to 16.7m on the surface, the vertical component of the vibration velocity at each measurement point on the surface is the largest. The vibration speed in the X direction and the Z direction will decay faster as the distance increases, and the decay speed in the Y direction is relatively gentle due to the smaller vibration speed. The vibration velocity in the three directions does not exceed 0.8cm/s, which has little impact on the surrounding environment. Compared with the analysis of emulsion explosives, it is found that the particle vibration velocity caused by the emulsion explosive rock breaking blasting is much greater than that of the liquid CO2 fracturing tube rock breaking blasting, indicating that liquid Carbon dioxide rock breaking can effectively reduce the vibration caused by blasting.

(3) The main frequency band of each sub-velocity of red sandstone carbon dioxide fracturing tube blasting is generally below 100 Hz, and the main vibration frequencies in the X and Y directions are concentrated in 30-60 Hz. The main vibration frequency band of the liquid CO2 rock fragmentation blasting vibration signal has little correlation with the direction and propagation distance of the vibration signal.

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