Liquid CO₂ Phase-Transition Rock Fracturing: A Novel Technology for Safe Rock Excavation

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Abstract: In order to determine the applicability of liquid CO₂ phase-transition fracturing technology in rock mass excavations, the principles of CO₂ phase-transition fracturing were analyzed, and field tests of liquid CO₂ phase-transition fracturing were performed. An “Unmanned Aerial Vehicle (UAV) camera shooting + Microstructure Image Processing System (MIPS) analyzing” method was used to acquire the rock mass characteristics. Further, the Hilbert–Huang Transform (HHT) energy analysis principle was adopted to analyze the characteristics of fracturing vibration waves. The experimental results showed that during the process of fracturing, there were both dynamic actions of rock breakage due to excitation stress wave impacts, and quasi-static actions of rock breakage caused by gasification expansion wedges. In semi-infinite spaces, rock-breakage zones can mainly be divided into crushing zones, fracture zones, and vibration zones. At the same time, under ideal fracturing effects and large volumes, the fracturing granularity will be in accordance with the fractal laws. For example, the larger the fractal dimensions, the higher the proportion of small fragments, and vice versa. Moreover, the vibration waves of the liquid CO₂ phase-transition fracturing have short durations, fast attenuation, and fewer high-frequency components. The dominant frequency band of energy will range between 0 and 20 Hz. The liquid CO₂ phase-transition fracturing technology has been observed to overcome the shortcomings of traditional explosive blasting methods and can be applied to a variety of rock types. It is a safe and efficient method for rock-breaking excavations; therefore, the above technology effectively provides a new method for the follow-up of similar engineering practices.

Keywords: liquid carbon dioxide; phase-transition; rock mass excavation; fragmentation distribution; HHT

1. Introduction

At the present time, the excavations of rock masses under general conditions are still mainly dependent on explosive blasting methods; however, due to the high safety risks and severe environmental impacts of explosive blasting, the management, and control of such explosives have become much stricter [1]. This has resulted in the reduced application feasibility of explosive blasting methods. Particularly, in many special environments, such as the implementation of excavations in densely populated areas or buildings, vibration-sensitive areas, and so on, conventional blasting methods cannot be safely applied [2]. As a result, safe and reliable non-blasting excavation methods have attracted increasing attention and have begun to be applied in rock excavation projects. Since the 1970s, researchers have carried out many relevant studies regarding non-blasting excavation methods [3,4]. These methods can be mainly divided into three categories: Mechanical excavations, physical and chemical rock-breaking processes, and rock-breaking processes.
using electrical equipment [4]. The most commonly used mechanical excavation methods involve hydraulic breakers and road-headers, which have the advantages of high safety performance results, strong environmental protection, and simple operations; therefore, mechanical excavation methods are considered to be suitable for the excavations of some types of soft rock masses; however, mechanical wear and tear are unavoidable [5,6]. Further, it has been found that the above equipment cannot be applied in a large-scale project due to low work efficiency and slow construction progress. When electrical equipment excavation methods are used, it has been observed that there is less rock breakage; however, the effects of electrical equipment methods are only significant for hard rock masses, and the economic costs are high [5–7]. Physical and chemical work methods often utilize static cracking agents or metal burning agents [8,9]. The use of such agents involves both physical and chemical reactions and presents certain potential environmental and safety hazards. Liquid CO\textsubscript{2} phase-transition fracturing technology is a new type of “physical and chemical” technology for rock mass excavations which falls into the category of physical blasting technology. This newly introduced technology has been found to have the ability to overcome the shortcomings of non-blasting excavation methods and traditional explosive blasting methods, and it has been observed that the energy utilization rates tend to be noticeably improved [10]. Moreover, the method’s applications require no open fires, and are characterized by high safety, small vibrations, and low dust [11]; therefore, the potential of damages occurring to surrounding buildings, rock masses, and environments is greatly reduced. Due to these positive features of liquid CO\textsubscript{2} phase-transition fracturing technology, it can be widely used in rock mass excavations.

Liquid CO\textsubscript{2} phase-transition fracturing technology was first proposed by Cardox Co. (United Kingdom) [12,13]. It was first mainly used in the fracturing, permeability enhancement, and mining of low-permeability and high-gas coal seams, in order to reduce the risks of coal dust and gas explosions [1,14]. With the development of liquid CO\textsubscript{2} fracturing technology and its proven enhancements of energy release processes, the applications of the technology were extended to ore mining and concrete cracking projects [15]. At the present time, researchers generally believe that CO\textsubscript{2} fracturing is a process of physical change. The energy that is released by the expansion of gases during physical explosions is mainly related to the gas pressure levels, container volumes, and the physical properties of the medium within the containers [16]. Singh SP, Zhou Xihua et al. [17,18] conducted studies of the fracturing mechanism of CO\textsubscript{2} fracturing in coal seams. The results showed that the PCF (Penetrating Cone Fracture) principle could be used to analyze the high-pressure CO\textsubscript{2} fracturing performances. In other words, it was found that tension stress fields were formed when high pressure was applied at the bottom of boreholes. Meanwhile, annular fractures were formed due to the stress concentrations in rock masses, which had then tended to develop toward the free surfaces. Finally, conical fractures had formed in the rock, which had achieved the purpose of fracturing the rock masses [14,17,19,20].

In recent years, the technology has been gradually popularized in developed countries, and is now widely used in cement, electric power, and other industries, such as pipeline blockage removal, caking removal, ice breaking, and so on [17,21]; however, there are still a series of problems: 1, Its engineering practices and scientific research have mainly focused on gas-type coal mining; 2, there are few application studies in surface rock excavation; 3, research on the impact of cracking effect is lack; 4, there is little research on the impact of adjacent buildings.

Therefore, in the current study, based on the analysis of the principle of liquid CO\textsubscript{2} phase-transition fracturing, field tests and vibration monitoring were carried out in a foundation pit excavation project located in Fangshan District, Beijing, China. The fracturing effects, granular distributions, particle velocities, and vibration energy levels following fracturing excavations were scientifically analyzed. The feasibility of liquid CO\textsubscript{2} phase-transition fracturing technology in the foundation pit excavations had been successfully demonstrated in this study, which will potentially facilitate its popularization and future applications.
2. Liquid CO₂ Phase-Transition Rock Fracturing

2.1. CO₂ Phase-Transition Fracturing Device

In the present study, the CO₂ fracturing device was mainly composed of a riser, firing head, heater, fracturing tube, constant pressure shear sheet, and energy releaser [22]. The physical structure is shown in Figure 1. The riser is used for putting the fracturing pipe into the borehole. The firing head serves as a valve for filling and sealing liquid CO₂ in the tube. The fracturing tube is used for filling liquid carbon dioxide (CO₂) of 0.5–2 kg depending on the application purpose. Further, the heater is sealed in the tube for heating, which is turning liquid CO₂ into supercritical carbon dioxide (SC-CO₂) rapidly. The constant pressure shear sheet has controlled the fracturing pressure varying from 60 to 270 Mpa depending on rock mass mechanical properties. The energy releaser on the end of the tube blows out high-pressure SC-CO₂ breaking the rock mass.

![Figure 1](image.jpg)

**Figure 1.** (1) Riser; (2) firing head; (3) heater; (4) fracturing tube; (5) constant pressure shear sheet; (6) energy releaser. The structure of CO₂ blasting device [1,13,23]. (a) Photograph of CO₂-Frac. (b) Sketch of CO₂-Frac system.

2.2. Principle of the CO₂ Phase-Transition Fracturing

The core of CO₂ phase-transition fracturing technology is the liquid–gas conversion of CO₂. It is essentially a typical physical blasting technology. During the fracturing operations, liquid CO₂ is injected into the tube using special filling equipment, and the gas pressure is maintained at between 8 and 10 MPa. The heater has been made to generate large amounts of heat, and the liquid CO₂ in the tubes enters a supercritical state. Supercritical CO₂ is a special phase state. Its molecular diffusion coefficient is large and close to a gas and has a high density, which is close to the fluid density. When the pressure is higher than 7.38 MPa, and the temperature is higher than 31.4 °C, the CO₂ will be transformed into a supercritical state [24]. The phase transition process of the CO₂ is shown in Figure 2.

At that time, the pressure levels in the pipes will rise sharply. When the pressure reaches the ultimate strength of the constant pressure shear sheets, the SC-CO₂ will break through the constant pressure shear sheets and be released from the energy releasers (Figure 3). High-pressure jets act on the rock masses and generate stress waves with energy levels far greater than the dynamic compressive strength of the rock mass. As a result, crushed areas of compressive damages will be produced around the boreholes, and the rock mass in the far areas will produce radial fracturing and tangential tension cracks. At the same time, the pressure will gradually decrease, and the outer boundaries of SC-CO₂ jets will become gasified. The volume will rapidly expand by 500 to 600 times. Then, under the effects of the gas wedges, the cracks will continue to expand until the stress intensity factors at the crack tips become less than the fracture toughness of the rock. During the entire fracturing process, the stress wave action times will be very short. Meanwhile, the gas CO₂ action times will be longer and reach up to 10 to 30 ms, which will result in the cracks becoming fully expanded, extended, and penetrated within the rock masses [14,16,25,26].
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Figure 2. Phase transformation diagram of CO$_2$.

Figure 3. Working principal diagram of liquid CO$_2$ phase-transition rock fracturing: (1) riser; (2) heater; (3) CO$_2$-Frac; (4) constant pressure shear sheet; (5) energy releaser; (6) gaseous CO$_2$.

Generally speaking, the entire liquid CO$_2$ phase-transition fracturing process mainly includes two stages: the dynamic actions of the stress waves, and the quasi-static actions of the gas expansion. The stress wave actions mainly form the micro-cracks in the crushed zone, and the gas expansion actions are the main driving forces for the radial and circumferential cracks in the fracture zones. The results of this study’s experiments are shown in Figure 4. It is not difficult to conclude from the figure that the CO$_2$ rock-breaking processes were a combination of tensile failures and compressive failures.
Figure 4. Schematic diagram of liquid CO$_2$ phase-transition rock fracturing: (1) crushed zone; (2) crack area; (3) vibration area; (4) radical crack; (5) circumferential crack.

2.3. Advantages of CO$_2$ Phase-Transition Fracturing

At the present time and under general conditions, rock excavations are still mainly dependent on controlled blasting methods, which have the clear advantages of high efficiency, good rock breakage effects, and low cost; however, explosive blasting methods also have high safety risks and strict control requirements. Blasting excavations are strictly prohibited in many special environments, such as areas with dense populations or buildings, vibration-sensitive areas, and so on. The conventionally used non-explosive rock-breaking methods, such as mechanical rock-drilling, hydraulic splitting, and static breaking agents, have been found to have low excavation efficiency and difficulties meeting the needs of the low cost and time limitations in engineering projects. However, it has been found that liquid CO$_2$ phase-transition fracturing excavation methods have overcome the defects of explosive blasting methods, and have displayed the following major advantages:

(1) High safety and reliable operations

The fracturing pipes which are used in liquid CO$_2$ phase-transition fracturing excavation methods are made of high-strength heat-resistant steel alloy, which can withstand high-pressure conditions without plastic deformations. Furthermore, since CO$_2$ is a non-explosive gas, accidental explosions and combustion can be inhibited. The process of CO$_2$ fracturing and blasting is a physical process that does not involve sparks or open flames. Further, there is less risk from dust and flying stones, and no destructive vibrations or harmful gases are produced.

(2) Controllable fracturing energy

When liquid CO$_2$ phase-transition fracturing excavation methods are used, the sizes and directions of the fracturing energy release actions can be controlled by shearing sheets and energy release heads. Medium-deep hole fracturing can be realized by a series of connections, and combined fracturing can be realized simultaneously by parallel connections.

(3) Reusable main parts

After a CO$_2$ fracturing device is put into operations, other parts can be reused thousands of times, with the exception of the heating devices, constant pressure shear pieces, and sealing gaskets. The sources of liquid CO$_2$ are widespread, and the prices are considered to be low; therefore, the overall economic benefits are considerable.
4. Relatively low safety control levels

At the present time, there are no special regulations for the management and regulation of liquid CO\textsubscript{2} phase-transition fracturing excavation methods, and the control requirements only refer to the fireworks safety approval and safety standards for trial implementation.

3. Field Test Study on Liquid CO\textsubscript{2} Phase-Transition Rock Fracturing

3.1. Study Area

This study’s field test relied on a foundation pit excavation project of a resettlement house in the Fangshan District of Beijing in China (Figure 5). The terrain of the study area was relatively flat with exposed bedrock. Further, the formation lithology was relatively single, and had mainly included Ordovician Majiagou Formation limestone, dolomitic limestone, and so on. The stratum had inclined southward with a dip angle of approximately 30°. The study area had displayed either no or slight weathering, and the rock mass was observed to be relatively complete with a Grade III rock quality rating.

![Figure 5. Excavation location and photos.](image)

The study area was located in a scenic sports and residential area. In order to protect the natural landscape and ensure the safety of the existing houses and roads, explosives were not permitted to be used in the excavation of foundation pits; therefore, as a supplementary and local alternative method, liquid CO\textsubscript{2} phase-transition fracturing technology, with its known high safety, good fracturing effects, and excavation efficiency, was the first choice for the excavations under the study area’s complex working and special environmental conditions.

3.2. Test Program

Different types (Types 95 and 108) and different numbers of fracturing tubes (equipment parameters and hole arrangement parameters are shown in Tables 1 and 2) were used in this study’s fracturing tests. At the same time, a “UAV camera shooting + MIPS image processing” method was used to acquire the characteristics of the fractured rock blocks, and a Blast-UM type blasting vibrometer was utilized to monitor the vibrations caused by fracturing.
Table 1. Parameters of CO$_2$ phase-transition fracturing device.

| Item                                      | Type 95 | Type 108 |
|--------------------------------------------|---------|----------|
| Outer diameter of CO$_2$ phase-transition fracturing device (mm) | 95      | 108      |
| Length of CO$_2$ phase-transition fracturing device (mm)            | 1300    | 2000     |
| Weight of single CO$_2$ phase-transition fracturing device (kg)     | 44      | 100      |
| Drill size (mm)                                                      | 120     | 140      |
| Number of single cracked holes                                      | Several | Single   |
| Filling volume of liquid CO$_2$                                    | 2.5     | 7        |

Table 2. The pore network parameters of CO$_2$ phase-transition fracturing device.

| Item                                      | 95-Single | 95-Several | 108-Single | 108-Several |
|--------------------------------------------|-----------|------------|------------|-------------|
| Diameter of drilling hole (mm)             | 120       | 120        | 140        | 140         |
| Depth of drilling hole (m)                 | 4         | 4          | 4          | 4           |
| Number of single cracked holes             | 2         | 2          | 1          | 1           |
| Number of drilling hole                    | 1         | 13         | 1          | 13          |
| Distance of drilling hole (Average m)      | 0         | 1.5        | 0          | 1.5         |
| Row spacing of drilling hole (Average m)   | 0         | 1.5        | 0          | 1.5         |
| Regional height facing vacancy (m)         | 5         | 5          | 5          | 5           |
| Minimum distance of resistance line (Average m) | 0.3     | 0.3        | 0.3        | 0.3         |

Throughout the entire field-testing process, the first step was to drill a blast-hole. Then, the fracturing device was assembled and filled with the liquid CO$_2$. The installed cleaver was placed into the borehole. At the same time, a blasting vibrometer was connected in order to test the seismic waves during the blasting process. The UAV began to acquire images of the pre-cracking in the rock mass. Then, after the aforementioned preparation work was completed, the detonation switch was turned for the purpose of performing the blasting. Following the completion of the blasting, the UAV was again used to document the post-blasting cracking images. Further, the before and after images were compared and analyzed in order to comprehensively evaluate the cracking effects. Finally, the split tube was recovered. During the testing processes, special attention was paid to the filling operation after the blast-holes were drilled. The drill cuttings and dry fine stone powder were generally used as the filling materials in order to prevent “flying pipe” actions.

3.3. Fracturing Effects

3.3.1. Acquisition of the Feature Information of the Rock Masses after Fracturing

In this research, a “UAV camera shooting+image processing” method was used for the fast acquisition of the granular information. The small UAV cameras were flexible and visually controllable, could be combined with self-developed image processing software to acquire the granular information more accurately and comprehensively. The small UAV, which was used in this experiment was “DJI Phantom 4”. The main technical parameters of the UAV used in this experiment were as follows: A one-inch 20-megapixel camera sensor; 4K/60 fps video; 14 static pictures per second; 5-way environmental sensing; mechanical shutter; double coding; 30-min endurance; 7 km flight distance. While the image acquisition, the overlap rates of the course and side directions were not less than 80% and 60%, respectively. The UAV height was 3 m, and an automatic shooting mode was adopted. The flight speed was 0.3 m/s and the automatic shooting interval was 0.3 m/s. The shooting path diagram is shown in Figure 6.
A self-developed digital image processing software system was used to process the UAV images. First, the pre-processing of the images was accomplished using a mean filtering method. The filtering window was $3 \times 3$. Mean filtering is a type of linear spatial filtering, with a simple algorithm and fast calculation speed. The second step was image binarization. The brightness of each pixel in the pre-processed images was expressed by 256 gray levels between 0 and 255. The threshold was selected by an OSTU algorithm. Each of the images was divided into two categories according to the gray characteristics of the images, and the optimal threshold occurred when the separation degree between the within-class variance and the between-class variance was the largest. After the binary images were obtained, manual processing was carried out for the parts with larger interference factors. Then, the images were cut and eliminated in order to improve the accuracy. A processed image is shown in Figure 7 (taking a 108-type several-hole test as an example). Finally, the pixel information is transformed into the actual block feature information using scale transformation.

3.3.2. Distribution Characteristics of the Granularity of the Rock after Fracturing

In the current study, since only the projected areas of the fractured rock blocks could be obtained using the above-mentioned “UAV camera shooting + MIPS image processing” method, when the number of rock blocks in each grain size was large enough, the plane
projection sizes (such as the areas or perimeters) of the rock fragments were used as the geometric characteristic quantities in order to detect the granularity after fracturing. It was determined that the plane projection sizes had accurately reflected the actual fracturing effects. There was observed to be a certain quantitative relationship between the planar sizes and the volumes of the rock blocks. At the present time, the following formulas are commonly used [28]:

\[
\begin{align*}
    a &= \frac{P}{\pi} + \frac{\sqrt{P^2 - 4S\pi}}{2} \\
    b &= \frac{P}{\pi} - \frac{\sqrt{P^2 - 4S\pi}}{2} \\
    D &= 1.16b \sqrt{1.35f} \\
    V &= D \times S
\end{align*}
\]

where \(S\) represents the area of the rock mass; \(P\) is the perimeter of the rock mass; \(D\) indicates the screen size of the rock mass; \(a\) is the maximum radius of the optimal ellipse; \(b\) represents the minimum radius of the optimal ellipse; \(V\) denotes the volume of the rock mass.

In the current study, Formula (1) was used for the volume conversion. Figure 8 shows a comparison of the fracturing volumes of the different schemes of liquid CO\(_2\) phase-transition fracturing. The total volume of the several fractured granules was obviously larger than that of the single-hole fracturing. This was mainly due to the different CO\(_2\) storage in the fracturing pipe, and major changes in the released energy. Further, the fracturing volume of the 108-type fracturing test was found to be larger than that of the 95-type fracturing test. Figure 9 shows the granule composition after four tests. According to the comparison of the two several-hole tests, the granularity distribution of the 108-type several-hole test was more uniform, and the boulder content was smaller than that in the 95-type test. At the same time, the fracturing volume of the 108-type several-hole test was observed to be larger than that of the 95-type several-hole test. In summary, the fracturing effects of the 108-type several-hole test were found to be superior to those of the 95-type several-hole test. Further, according to this study’s comparison of the two single-hole test results, the 95-type single-hole boulders were found to have a smaller content and better fracturing effects. The reasons for these results were that the rock weathering at the test site of the 95-type single-hole fracturing test was more serious and the rock mass itself was looser. This had reduced the transmission of the energy force and resulted in less effective fracturing.

Figure 8. The total volume of fragmentation caused by liquid CO\(_2\) phase-transition rock fracturing.
It has been observed that fractured rock blocks have statistical self-similarity in both geometric shape and fractal distribution. The fractal description of the rock mass fracturing process is as follows: A rock mass will be initially broken into a finite number of blocks with similar shapes; some of those blocks will become separately broken into sub-blocks of similar shapes as the original rock mass under load conditions; some of the sub-blocks will become further broken into smaller sized rock blocks with similar shapes; each repetition of the process will produce smaller blocks \cite{29,30}; therefore, in the present study, the distributions of the fractured rock, which were the result of the liquid CO\textsubscript{2} transition were analyzed from a fractal point of view. The fractal dimensions were used to reflect the distributions of rock granularity, and to quantitatively evaluate the fracturing effects.

It was determined that if a rock sample contained zero-grade fragments and each grade of the fragment was broken into \( n \) fragments at a failure probability of \( P \), with the similarity ratio of the adjacent fragments set as \( 1/r \), then the total number of grade \( i \) fragments would be as follows \cite{29}:

\[
N_i = (1 - P)n \left[ 1 +nP + \left( nP \right)^2 + \ldots + \left( nP \right)^{i-1} \right] \tag{2}
\]

Then, it can be known from the basic fractal definition that:

\[
\frac{N_{i+1}}{N_i} = \left( \frac{1}{r} \right)^D \tag{3}
\]

Further, since \( i \gg 1 \), and by assuming that \(nP > 1 \), the following can be obtained:

\[
D = \frac{\log(nP) / \log\left( \frac{1}{r} \right)}{\log\left( \frac{1}{r} \right)} \tag{4}
\]

Then, by assuming that the total volume of the rock mass granularity model will remain unchanged during the fracturing process, the original block can be divided into the next grade of the block with a failure probability \( P \) and similarity ratio \( r \). This process can be infinitely repeated. As shown in Figure 10, a series of fragments with similar shapes and different sizes were generated during this experimental study.

The volume of the secondary rock blocks in the fracturing process was:

\[
N = nP = \left( \frac{1}{r} \right)^3 P \tag{5}
\]

Therefore,

\[
D = \frac{\log N}{\log(1/r)} = 3 - \frac{\log P}{\log r} \tag{6}
\]
The total volume \( V_i \) of the rock blocks with line sizes smaller than or equivalent to \( x_i \) was as follows:

\[
V_i = \lim_{j \to \infty} \sum_{k=i}^{j} v_k = C_v x^3 p^i M
\]  

(10)

Therefore, the proportion of the volume of the rock blocks with line sizes smaller than or equivalent to \( x_i \) in the total volume was as follows:

\[
y_i = \frac{V_i}{V_k} = p^i
\]  

(11)

where \( i = \log(x_i/x_m)/\log r \) was be obtained from the formula, and when combined, the following formula was obtained:

\[
y_i = \left( \frac{x_i}{x_m} \right)^{3-D}
\]  

(12)

Therefore, the relationship between the fractal dimension and cumulant under the sieves of the fracturing granule sizes was determined, and a fractal model of the granular distribution of the fractured rock (in which \( x_m \) is the largest size of the rock blocks) was obtained. The advantage of a fractal model is that the granular distribution can be understood by calculating the fractal dimension \( D \) from the fractured rock without considering the occurrence state, geological structure conditions, or fracture parameters of the original rock.
As a result, the concept of the fractal dimensions was made clearer, and its applicability was found to be wider.

In accordance with the above-mentioned theoretical analysis results, Table 3 and Figure 11 illustrate the screening percentages and fractal values of the four groups of liquid CO$_2$ transient fracturing tests.

**Table 3.** The cumulative percentage under the rock sieve and fractal results of liquid CO$_2$ phase-transition rock fracturing.

| Test Project                  | Cumulative Percentage of Volume under the Rock Sieve/% | b          | Fractal Dimension (D) | Correlation Coefficient |
|------------------------------|-------------------------------------------------------|------------|------------------------|-------------------------|
|                              | <5 <10 <20 <30 <50 <70 <90 <130 <150 <190 <230       |            |                        |                         |
| 95-type single-hole          | 0.71 7.19 21.92 42.45 42.45 99.99                    | 2.030      | 0.970                  | 0.982                   |
| 95-type several-hole         | 0.01 0.26 1.56 2.90 5.39 8.10 11.52 25.14 25.14 42.64 100.00 | 2.073      | 0.927                  | 0.978                   |
| 108-type single-hole         | 0.08 1.36 11.39 26.89 59.26 100.00                     | 2.817      | 0.183                  | 0.988                   |
| 108-type several-hole        | 0.02 0.40 2.38 3.49 6.79 11.36 14.45 20.53 37.67 99.99 | 1.959      | 1.041                  | 0.978                   |

![Figure 11. The fractal results of liquid CO$_2$ phase-transition rock fracturing.](image1)

The results shown in Table 3 illustrate that the fractured rock mass still had a good fractal structure, even though the parameters of the four tests were different. Then, through a comparison of two single-hole tests and two several-hole tests, it was not difficult to
see that the higher the proportion of small fragments after fracturing was, the larger the fractal dimensions would be. In contrast, it was observed that the lower the proportion of small fragments after fracturing were, the smaller the fractal dimensions would be. The fractal dimension of the 108-type single-hole test was determined to be 0.183. Meanwhile, the fractal dimension of the 95-type single-hole test was 0.970, which was abnormal. The reason for these results was determined to be that the 95-type single-hole test boreholes had a high content of clay, which was a soil-rock accumulation layer and strong weathering layer with poor rock properties. This had led to increases in the fractal dimensions.

The fracturing effects of rock mass excavations using liquid CO$_2$ phase transition methods are better than those obtained using conventional non-blasting excavation methods. The fracturing volumes have been found to be more ideal. Further, the fractal dimension D can be used to characterize the granular distributions, which provides favorable conditions for the subsequent optimization of the fracturing modes.

3.4. Vibration Monitoring

In this study’s field tests, a Blast-UM blasting vibrometer was used to record the vibration signals, and vibration monitoring was carried out for the liquid CO$_2$ phase-transition fracturing tests. The 108-type several-hole fracturing test was taken as an example for analysis and research purposes, and its distribution pattern is shown in Figure 12.

![Figure 12. Boreholes distribution of liquid CO$_2$ phase-transition rock fracturing field test.](image)

3.4.1. Velocity Analysis

The vibration velocities and vectors in the three directions of the vibrometer are shown in Figure 13. The fast Fourier transform of the velocity signal $f(t)$ was made using MATLAB software, and the time domain signals were transformed into frequency domain signals $F(\omega)$, as shown in Figure 14. This study’s three charts reveal the following: At a position 10 m away from the fracturing point, the particle vibration duration was short (approximately 0.1 s), and the peak vibration velocity was 0.3667 cm/s. Moreover, the attenuation speed was fast, and the high-frequency component was observed to be small. The energy was mainly concentrated in the low-frequency parts. The main frequency band of each sub-velocity was generally below 100 Hz, and the main frequency had ranged between 10 and 20 Hz, which successfully met the vibration safety standards for general civil buildings in China.
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3.4.2. Energy Analysis

As can be seen in Figures 12 and 13, the vibration signals produced by the liquid CO\(_2\) phase-transition fracturing technology method were non-stationary random signals, which were similar to the blasting seismic waves. Therefore, in the current study, an HHT (Hilbert–Huang Transform) energy analysis principle was adopted to reflect the spectral characteristics and energy distribution concerns of the vibration signals from the perspective of the vibration signal energy [33,34], for the purpose of evaluating the safety of the liquid CO\(_2\) phase-transition fracturing technology method.

It has been determined that HHT methods are suitable for analyzing non-stationary and non-linear signals. The methods consist of two steps: (1) The empirical mode decomposition of the vibration signals in order to obtain a series of intrinsic mode functions representing the time scale of the signal characteristics; (2) Hilbert transforms for each IMF (intrinsic mode function) component. The EMD (empirical mode decomposition) uses the mean of the upper and lower envelopes of the time series to determine the "instantaneous equilibrium position", and then extracts the IMF. An IMF is one of the oscillating modes of data recorded at a given time. The Hilbert spectrum can be obtained by the Hilbert transform of a signal as follows [33]:

\[
\text{Hilbert spectrum} = \text{Hilbert transform of a signal}
\]

The Hilbert marginal spectrum can be obtained by the time integration of the Hilbert spectrum.

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**Figure 13.** Time-history curves of vibration velocity.

**Figure 14.** FFT amplitude spectrum curves of vibration velocity.
3.4.2. Energy Analysis

As can be seen in Figures 12 and 13, the vibration signals produced by the liquid CO$_2$ phase-transition fracturing technology method were non-stationary random signals, which were similar to the blasting seismic waves. The Fourier transform could not accurately analyze the vibration signals. Therefore, in the current study, an HHT (Hilbert–Huang Transform) energy analysis principle was adopted to reflect the spectral characteristics and energy distribution concerns of the vibration signals from the perspective of the vibration signal energy [33,34], for the purpose of evaluating the safety of the liquid CO$_2$ phase-transition fracturing technology method.

It has been determined that HHT methods are suitable for analyzing non-stationary and non-linear signals. The methods consist of two steps: (1) The empirical mode decomposition of the vibration signals in order to obtain a series of intrinsic mode functions representing the time scale of the signal characteristics; (2) Hilbert transforms for each IMF (intrinsic mode function) component. The EMD (empirical mode decomposition) uses the mean of the upper and lower envelopes of the time series to determine the “instantaneous equilibrium position”, and then extracts the IMF. An IMF is one of the oscillating modes of data recorded at a given time. The Hilbert spectrum can be obtained by the Hilbert transform of a signal as follows [33]:

$$H(\omega, t) = \text{Re} \sum_{i=1}^{n} a_i(t) e^{\int \frac{\omega_i(t)}{t} dt} \quad (13)$$

The Hilbert marginal spectrum can be obtained by the time integration of the Hilbert spectrum.

$$h(\omega) = \int_{T}^{0} H(\omega, t) dt \quad (14)$$

The marginal spectrum is the integral of the amplitude of each frequency component in time. The instantaneous energy spectrum of a signal can be obtained by the frequency integration of the square of the Hilbert spectrum.

$$IE(t) = \int_{0}^{\omega} H^2(\omega, t) d\omega \quad (15)$$

Therefore, it can be used to accurately describe the process of signal energy changing with time.

In the current study, the above-mentioned method and MATLAB programming were adopted, and EMD decomposition was carried out by taking the vibration signal in the Z direction as an example. A total of 12 IMF components with different frequencies, and one monotonous residual component, were obtained, as shown in Figure 15. It was found that the frequencies of the IMF components had ranged from large to small from top to bottom. The frequencies of the IMF1, IMF2, and IMF3 components were found to be too high, and had not been in accordance with the characteristics of the vibration waves; therefore, those components were considered to be noise and were eliminated in subsequent analyses. The IMF4 to IMF7 components were considered to be the main components of the measured wave due to their high vibration intensities. The IMF10 to IMF12 components were found to have low intensities and low frequencies, which indicated that the measured waveform was mainly concentrated within a narrow frequency band.
Figure 15. EMD decomposition.

The EMD decomposition of the vibration signals in the X and Y directions was carried out using the same method described previously. The IMF components were obtained and brought into a Hilbert transform, which was obtained using the Hilbert energy spectrum. Figure 16 displays the Hilbert energy spectrum of the signals in the different vibration directions, which accurately shows the energy distribution of the IMF components. Then, by comparing the different Hilbert diagrams, it was found that the overall form of the Hilbert spectrum was basically the same in the three directions. The duration of the low frequency was longer, and the low-frequency components in the three directions had lasted until the end of the vibration wave. Meanwhile, the vibration energy in the three directions had displayed the largest energy in the first 0.2 s. Among those, the high frequency in the x-direction was the highest, followed by the z-direction, while the y axis was observed to be the lowest. Further, there was larger vibration energy observed in the y-direction within the frequency range of 0 to 20 Hz. The main reason for this phenomenon was that the vibration signal in the y-direction had been generated by the superposition of a luff wave and Rayleigh wave, and the components were relatively complex.
Figure 16. Hilbert spectrum of the signals.

Figure 17 shows the instantaneous energy spectrum of the signal. It can be seen in the figure that the vibration waves produced by the liquid CO$_2$ phase-transition fracturing had displayed typical transient responses and the motion characteristics of shock loading at the beginning. There were few differences observed in the times when the energy peaks had appeared in the three directions. In the beginning, the Y-direction was the largest, and then the energy in the Z-direction had exceeded that of the Y-direction. The main reasons for this were that the Z-direction had contained more high-frequency components, and the energy attenuation was faster. Meanwhile, the Y-direction contained more low-frequency components, and the energy attenuation was slower. Further, the energy in the X-direction was determined to be the lowest.

Figure 17. Instantaneous energy spectrum.

When vibration energy acts on a building, its energy component will be magnified when it is close to the natural frequency of the structure. Since the natural frequencies of structures are generally low, although the energy distribution of the liquid CO$_2$ phase-transition fracturing tended to be in a low-frequency band, the vibration energy values were small, and the durations were short; therefore, there was not enough released energy to cause damage to buildings, which met the building safety standards; however, according to the Hilbert energy spectrum, there were many low-frequency components in the Y-direction of the three vibration directions; therefore, attention should be paid to monitoring this in subsequent applications of liquid CO$_2$ phase-transition fracturing technology.

4. Conclusions

The following is a summary of this study’s findings:

1. During the process of the liquid CO$_2$ phase-transition fracturing, there were both dynamic actions of rock breakages by excitation stress wave impacts, and quasi-static
actions of rock breakage by gasification expansion wedges. It was confirmed in this study that liquid CO$_2$ phase-transition fracturing technology could be applied in surface rock excavation and will provide a new idea for the follow-up activities of similar engineering construction projects.

2. It was determined from these results that the liquid CO$_2$ phase-transition fracturing technology method had displayed ideal effects. Further, the granular distributions of fractured rock blocks had conformed to the fractal law. It could be seen that the higher the proportion of small fragments was, the greater the fractal dimensions would be. This study’s quantitative evaluation of the fracturing granularity will potentially provide important technical support for the subsequent optimization of drill-hole arrangements to improve fracturing effects.

3. The duration of the CO$_2$ fracturing vibration waves was short (approximately 0.2 s), with fast attenuation and a small number of high-frequency components. The duration of the main vibration phases was approximately 0.1 s, and the distributions of the frequency bands were observed to be different. Overall, the energy dominant frequency bands of the CO$_2$ fracturing vibration waves were determined to range between 0 and 20 Hz.

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