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An Environment-Friendly Rock Excavation Method

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Highlights:

- High-pressure CO_2 can be used to break rocks.
- Compared with blasting, excavating rock with CO_2 does not produce toxic gases.
- Vibration can be reduced by controlling the direction of the high-pressure gas injection.

Abstract. Blasting is used as an economical tool for rock excavation in mines. However, part of the explosive energy is converted into elastic waves, resulting in ground vibration and excessive vibration, which may cause damage to nearby buildings. Meanwhile, toxic gases are also produced during the explosion. In this paper, an environment-friendly method for rock excavation is proposed. A series of vibration tests were conducted, and the peak particle velocity was monitored. The results showed that the proposed method can replace the conventional blasting method in mines. Besides that, the vibration caused by the proposed method is much smaller than by the conventional method. By adjusting the direction of the high-pressure gas injection, buildings around the mine can be protected well from vibration. Also, the production of toxic gases during excavation will no longer be a problem. Thus, a milder environmental impact can be achieved. However, the rocks excavated by the proposed method are relatively large, which still need to be broken further. On this issue, further study is required.

Keywords: *CO_2; environment-friendly; high-pressure gas injection; rock excavation; vibration direction control.*

1 Introduction

As an economical tool for rock excavation, blasting has a negative impact on the surrounding environment because part of the explosive energy is converted into elastic waves [1-3]. This causes ground vibration and excessive vibration, which can have a huge damaging impact on nearby buildings [4-6]. The same happens in tunnel excavation [7]. Investigations have been conducted by many researchers to evaluate the influence of blasting vibration on the surrounding environment and buildings [8,9]. Low & Hao analyzed its effect on the reliability of concrete structures [10]. Fujikura, *et al.* [11] analyzed the behavior of bridge pier systems

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under blast loadings based on recommendations from the Federal Emergency Management Agency (FEMA) [12] and the Federal Highway Administration (FHWA) [13] in the USA. Peak particle velocity (PPV) is also an important indicator for evaluating blasting vibration. Many methods have been conducted to assess and predict blast induced PPV [14,15]. For example, random forest (RF) and support vector machine (SVM) algorithms were used by Longjun, *et al.* [16] for modeling different mines, while regression models were used by Chandar, *et al.* [17]. For the representation of the intensity of blasting vibration, many countries have issued PPV standards in view of controlling blasting vibration [18-20]. Table 1 gives an example.

Table 1 Permissible peak particle velocity in mm/s at the foundation level of structures in mining areas (DGMS Circular 7 of 1997).

	Dominant excitation frequency/ Hz		
	<8 Hz	**8-25 Hz**	**>25 Hz**
(A) Buildings/structures not belonging to the owner			
1. Domestic houses/structures (mud/ *kuchcha*, brick and cement)	5 mm/s	10 mm/s	15 mm/s
2. Industrial buildings	10 mm/s	20 mm/s	25 mm/s
3. Objects of historical importance and sensitive structures	2 mm/s	5 mm/s	10 mm/s
(B) Buildings belonging to the owner with a limited life span			
1. Domestic houses/structures	10 mm/s	15 mm/s	25 mm/s
2. Industrial buildings	15 mm/s	25 mm/s	50 mm/s

In order to achieve the requirements of the standards, many methods for reducing ground vibration have been developed [21,22]. For instance, the water jet technique [23] is widely used in ground vibration reduction. Jung-Gyu Kim [7] assessed the controlling effect of abrasive water jet cutting on blast-induced ground vibration during tunnel excavation.

At the same time, passive vibration control has also been widely applied to reduce vibration [24,25], which can be classified into three major categories:(1) passive energy dissipation [26,27]; (2) passive energy transfer [28,29]; and (3) passive vibration isolation [30]. However, some of these methods cannot be applied to open-pit mines and cannot reduce the release of toxic gases [31]. The details of toxic gas and dust production by blasting can be seen in Figure 1. In view of the current situation, an environment-friendly method of rock excavation is proposed in this paper. A series of vibration tests were conducted, while the PPV was monitored. The results showed that this environment-friendly method can dramatically reduce PPV without generating toxic gases, which is of great significance for the protection of the surrounding environment and buildings.

Figure 1 Toxic gases and dust produced when explosives are used.

2 Experimental Site and Details

The experiment was conducted in an open pit located in the east of Hebei Province, China. The open pit is shown in Figure 2. Explosives were replaced by liquid CO_2 stored in a special expansion tube, which is shown in Figure 3. Firstly, the liquid CO_2 was compressed by a compression filling machine and filled into a special expansion tube. Secondly, the special expansion tube was put into a hole whose top was sealed. The activator in the tube quickly emits heat, transforming the liquid CO_2 into gas in a very short time to form a high-pressure CO_2 gas mass. When the gas mass pressure exceeds the rupture disc pressure threshold, the high-pressure CO_2 gas is ejected from a jet nozzle to break the rock.

The direction of the high-pressure gas injection can be controlled by the jet nozzle, which can be manipulated, as shown in Figure 4. In this way, the high-pressure gas can be injected in a specific direction. The vibration perpendicular to the ejection direction will be reduced and no toxic gases are produced. However, the rock mass excavated by this method is still relatively large.

Figure 2 Experimental site.

Figure 3 Special expansion tube for storing liquid CO_2.

Figure 4 Jet nozzle of the special expansion tube.

Four types of experiments were conducted in the open pit. The materials used included 240 kg of CO_2 in the first type of experiment and 240 kg of explosives in the second type of experiment. The monitoring point is shown in Figure 5.

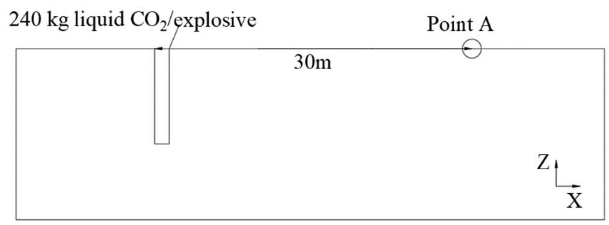


Figure 5 The monitoring point of the first and second experiment.

In the third type of experiment, the jet nozzle direction of the special expansion tube was the same as the X direction in Figure 6. The monitoring points are also shown in Figure 6. The fourth type of experiment was conducted with the monitoring points as shown in Figure 7.

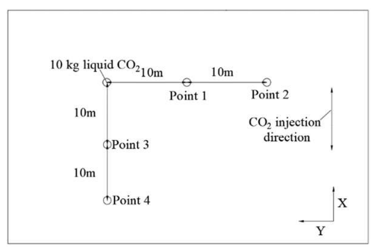


Figure 6 Monitoring points of the third experiment.

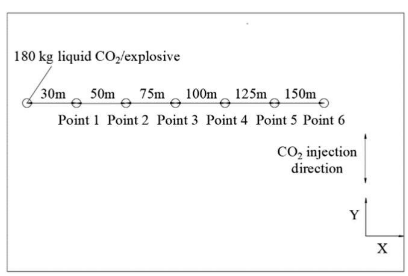
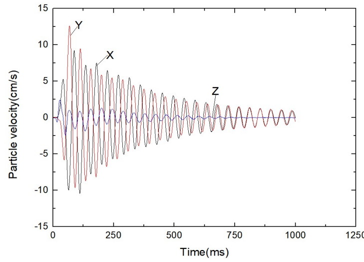


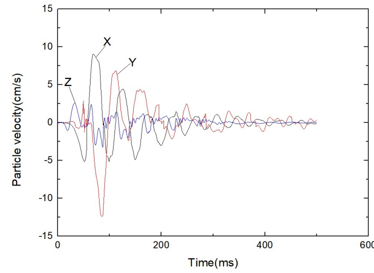
Figure 7 Monitoring points of the fourth experiment.

3 Results and Discussion

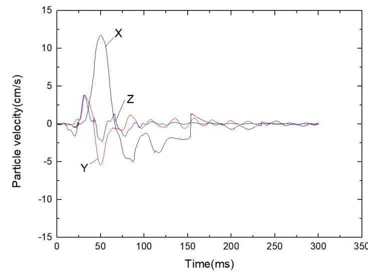
The velocity time histories of the first experiment are shown in Figure 8. The velocity time histories of the second experiment are shown in Figure 9.



(a) No. 1

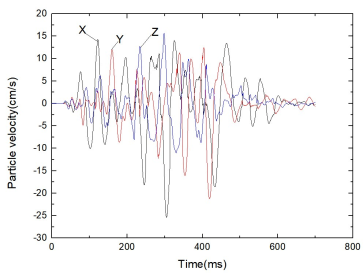


(b) No. 2

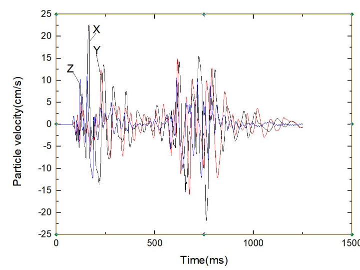


(c) No. 3

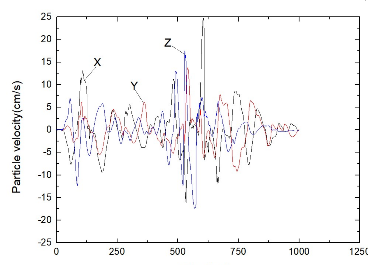
Figure 8 Velocity time histories at point A in the first experiment.



(a) No. 4



(b) No. 5



(c) No. 6

Figure 9 Velocity time histories at point A in the second experiment.

With further analysis of the velocity time histories at point A, the PPV and principal frequency of the first and second experiments were gotten, which are compared in Table 2. The average PPV in the X direction in the first experiment was 57%, i.e., smaller than that in the second experiment. Meanwhile, the average PPV in the Y direction in the first experiment was 40%, i.e., smaller than that in the second experiment. In addition, the average PPV in the Z direction in the first experiment was 78%, i.e., still smaller than that in the second experiment. The PPV in the first experiment was smaller because the pressure produced by liquid CO_2 is lower than the pressure produced by explosives.

By virtue of the liquid CO_2 it is easier to cut the rock along the jet nozzle direction. Therefore, the PPV in the Z direction hits rock bottom.

Table 2 PPV and principal frequency in the first and second experiments.

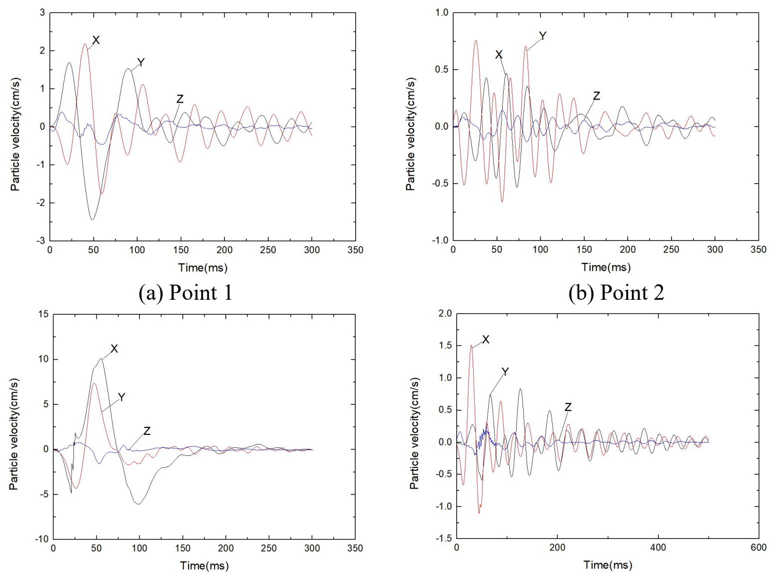
	Points	Number	X		Y		Z	
			PPV/ $cm \cdot s^{-1}$	Principal frequency/ Hz	PPV/ $cm \cdot s^{-1}$	Principal frequency/ Hz	PPV/ $cm \cdot s^{-1}$	Principal frequency/ Hz
First experiment	A	1	10.43	20.49	12.61	17.73	2.42	23.15
		2	9.04	16.34	12.40	14.79	3.30	24.04
		3	11.73	12.69	5.38	13.51	3.82	23.81
Second experiment	A	4	25.39	18.78	21.23	24.10	15.67	20.00
		5	22.62	30.30	15.85	26.32	12.16	20.00
		6	24.70	22.86	13.84	9.85	17.49	29.63

The PPV and principal frequency are presented in Table 3 through analysis of the velocity time histories (Figure 10) from the third experiment.

Table 3 PPV and principal frequency from the third experiment.

	Distance	Points	X		Y		Z	
			PPV/ $cm \cdot s^{-1}$	Principal frequency/ Hz	PPV/ $cm \cdot s^{-1}$	Principal frequency/ Hz	PPV/ $cm \cdot s^{-1}$	Principal frequency/ Hz
Third experiment	10 m	1	2.20	21.51	2.44	12.54	0.46	21.98
		3	10.12	9.80	7.39	13.70	1.57	14.82
	20 m	2	0.53	38.83	0.76	33.61	0.15	38.84
		4	1.51	26.14	0.84	25.16	0.23	25.45

The PPV at points 3 and 4 in the direction of the high-pressure gas injection was greater than the PPV at points 1 and 2 in the direction perpendicular to the high-pressure gas injection. This phenomenon is more obvious at close range. Based on the above, it can be concluded that the proposed method can effectively protect buildings around the mine from vibration by adjusting the direction of the high-pressure gas injection.



(a) Point 1 (b) Point 2

(c) Point 3 (d) Point 4

Figure 10 Velocity time histories of the third experiment.

The PPV and principal frequency of the fourth experiment are presented in Tables 4 and 5. The PPV obtained by explosives to excavate rock was larger than the one obtained for CO_2 for the same distance. Meanwhile, the principal frequency obtained by explosives was lower than the one obtained for CO_2. Besides that, the principal frequency of the blasting wave can be close to the natural frequency of a building when the frequency is low. In this case, even a small PPV can cause damage to a building. The principal frequency of blasting waves generated by excavating rock with explosives is low, but the PPV is large. This is more likely to cause damage to buildings. The principal frequency of blasting waves generated by excavating rock with CO_2 is high, but the PPV is low. This is more conducive to protecting buildings.

Eq. (1) was mainly used to calculate the peak particle velocity. Eqs. (2)-(4) were acquired via the data in Table 4, while Eqs. (5)-(7) were acquired via the data in Table 5. The attenuation coefficients of Eqs. (2)-(4) are larger than those of Eqs. (5)-(7). This indicates that the PPV obtained by explosives decayed faster. Although the experimental site was the same, the field coefficients of Eqs. (2)-(4) are also larger than those of Eqs. (5)-(7). This indicates that the propagation of waves generated by the two excavation methods were different. Eqs. (5)-(7) were used to calculate the PPV obtained by CO_2.

$$V = K\left(\frac{Q^{1/3}}{R}\right)^{\alpha} \tag{1}$$

where K denotes the field coefficient, α denotes the attenuation coefficient, Q denotes the charge of the explosive, R denotes the blasting distance, and V denotes the peak particle velocity.

Excavation by explosives:

$$\text{Y}: V = 329.5338\left(\frac{Q^{1/3}}{R}\right)^{2.0865} \quad (\text{R}^2\text{=0.9518}) \tag{2}$$

$$\text{X}: V = 138.8673\left(\frac{Q^{1/3}}{R}\right)^{1.8859} \quad (\text{R}^2\text{=0.9563}) \tag{3}$$

$$\text{Z}: V = 348.4175\left(\frac{Q^{1/3}}{R}\right)^{2.124} \quad (\text{R}^2\text{=0.9766}) \tag{4}$$

Excavation by CO_2:

$$\text{Y}: V = 104.0639\left(\frac{Q^{1/3}}{R}\right)^{1.918} \quad (\text{R}^2\text{=0.9685}) \tag{5}$$

$$\text{X}: V = 37.0937\left(\frac{Q^{1/3}}{R}\right)^{1.7852} \quad (\text{R}^2\text{=0.9492}) \tag{6}$$

$$\text{Z}: V = 29.8195\left(\frac{Q^{1/3}}{R}\right)^{1.9792} \quad (\text{R}^2\text{=0.9149}) \tag{7}$$

Table 4 PPV and principal frequency in the fourth experiment (excavation by explosives).

	Distance	Points	Y		X		Z	
			PPV/ $cm·s^{-1}$	Principal frequency/ Hz	PPV/ $cm·s^{-1}$	Principal frequency/ Hz	PPV/ $cm·s^{-1}$	Principal frequency/ Hz
Fourth experiment	30 m	1	10.62	20.63	5.64	22.34	8.86	27.25
	50 m	3	2.82	33.45	1.83	34.55	3.42	32.56
	75 m	2	2.33	34.02	1.65	12.53	2.11	40.87
	100 m	4	0.59	14.21	0.68	13.89	0.67	32.53
	125 m	5	0.45	25.49	0.35	19.85	0.44	24.29
	150 m	6	0.42	10.66	0.25	22.32	0.32	23.42

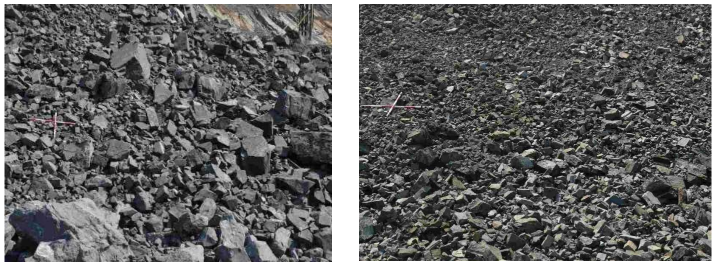
Table 5 PPV and principal frequency in the fourth experiment (excavation by CO_2).

	Distance	Points	Y PPV/ $cm{\cdot}s^{-1}$	Y Principal frequency/ Hz	X PPV/ $cm{\cdot}s^{-1}$	X Principal frequency/ Hz	Z PPV/ $cm{\cdot}s^{-1}$	Z Principal frequency/ Hz
Fourth experiment	30 m	1	4.26	34.63	1.89	43.72	1.02	39.42
	50 m	3	1.29	25.89	0.61	38.54	0.29	30.59
	75 m	2	0.89	30.55	0.44	31.42	0.27	37.42
	100 m	4	0.56	30.50	0.32	28.61	0.16	24.78
	125 m	5	0.22	19.87	0.11	19.87	0.06	21.56
	150 m	6	0.11	23.54	0.10	25.55	0.03	16.86

Rock can be excavated by the method as shown in Figures 11 and 12. Toxic gases will not be produced during the excavation of rock with CO_2 used to produce high-pressure gas, which will prevent destruction of the surrounding environment of the mine. However, compared with conventional blasting, the rocks excavated by CO_2 blasts are relatively large (Figure 13), which makes it difficult to break them further. More research on this issue is required.

Figure 11 Before excavation.

Figure 12 After excavation.



(a) Excavation by CO_2 (b) Excavation by explosives

Figure 13 Rock size.

4 Conclusion

Conventional blasting can be substituted by the proposed environment-friendly method, which generates smaller vibration than explosives. The proposed method can effectively protect buildings around the mine from vibration by adjusting the direction of the high-pressure gas injection and toxic gases are not produced. This method does not adversely affect the surrounding environment of the mine, but the size of the rocks excavated by this method is larger. Further research on how to break the rocks further is required.

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