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Influence of rock properties on blasting vibration propagation

In order to know the relationship between mechanical properties of rock and blasting vibration propagation laws during the process of blasting excavation in opencast iron mine, attenuation trends of blast vibration velocity in migmatite, granite, magnetite quartzite are studied by testing the mechanical parameters in blasting area and blasting vibration. What is more, explosive energy' utilization characters in the process of blasting are analyzed based on the blasting vibration data. The results show that different attenuation trends are showed in different directions on different rocks. Besides, explosive's energy availability factor is related to attenuation coefficient of the rock, it is shown that explosive's energy availability factors of granite and magnetite quartzite are inferior to that of migmatite. Furthermore, the integrity of rock structure can be estimated if the attenuation features of blasting vibration velocity are known, which can provide guidance to the optimization of blasting design.

1. Introduction

Blasting vibration was affected by many factors, such as rock mechanical properties, explosive quantity, delay time, aperture, free face, and so on [1]. Among these factors, geological condition was usually the main factor, so it is very important to distinct the influence of different lithological characters' change on the vibration according to rock mechanical properties test. Rock's cracking process mainly included the elastic potential energy in the phase of elastic deformation, the plastic potential energy in the phase of plastic deformation, the kinetic energy in the phase of cracking and also other kinds of energy [2]. Researchers usually applied the change of stress and strain to the exposition of rock's mechanical properties in the process of cracking [3]. In the bench blasting, the seismic wave energy changed from explosive energy had direct relation to rock's elastic potential energy [4].

The Dagushan iron mine in Ansteel was one of the main mineral production sites of Ansteel. At the present stage, borehole order blasting in open-pit bench blasting was used in the blasting, at the same time, the high-performance emulsified oil explosive developed by Ansteel explosive plant itself was used cooperatively. Along with the change of mining range and the increasing of mining depth, mine rocks' kinds and characters would also change a lot [5, 6]. What is more, rock properties had great influence on the blasting effect, and the study of rock properties and blasting vibration propagation laws was good to the further study of blasting energy utilization.

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2. Rock mechanics parameters

Rock mechanics tests were made on rock samples in the blasting area, the indexes got included rock density, Protodyakonov coefficient, compressive strength, extension strength, elastic modulus, Poisson's ratio, cohesion, friction angle, and so on. What is shown in Fig.1 are physical mechanics experiments of the three typical rock samples, and the determination results summary are shown in Table.1.

3. Blasting vibration test

3.1 Monitoring Basis

Borehole order blasting was adapted in the blasting design in the Dagushan iron mine blasting area. Besides, detonators with high precision and high strength produced by Orica Limited, and the interval of their explosive time were 17 ms, 25 ms, 42 ms respectively, and in-blasthole delay was 400 ms; the explosive was emulsified explosive; the drillhole layout was square with the pitch of 6.5 m and the hole depth of 15 m; the hole diameter was 250 mm; the bench height was 13 m.

Blasting designing schemes whose single hole's maximum charges were almost the same, and whose blast areas design were similar and adapted to monitor vibration data. The main form used in vibration monitoring was measured in the fixed point. What is more, vibration instrument was set along the boundary of the upper bench. In this way, the comparison could be made between the vibration points' vibration damping characteristics of the three kinds of lithological characters in the similar blasting design parameters: on the one hand, it is in favour of the formation of striking contrast in different distances on the same types of rocks; it also helps

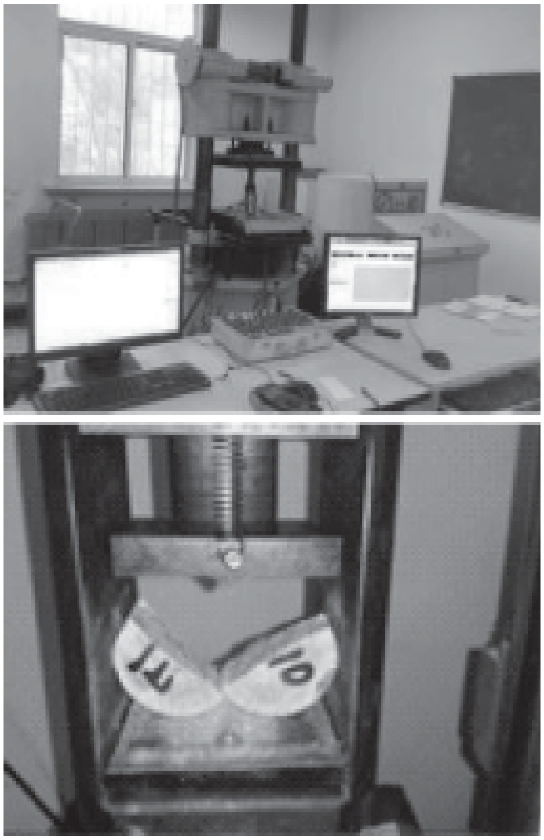

Fig.1 Rock mechanical properties test

TABLE 1: ROCK MECHANICS PARAMETERS

Project / Rock	Bedding	Density /g·cm^{-3}	Compressive strength /MPa	Extension strength /MPa
Migmatite	Parallel		37.89	2.85
	Vertical	2.65	68.40	7.10
	Average		53.15	4.975
Granite	Parallel		54.93	5.35
	Vertical		81.47	5.12
	Average	2.57	68.2	5.235
Magnetite Quartzite	Parallel		120.57	8.94
	Vertical	3.63	98.37	15.60
	Average		109.47	12.27
Project	Shear strength parameter		Deformation parameter	
Rock	Cohesion /MPa	Frictional angle /º	Elastic modulus /GPa	Poisson's ratio
Migmatite	6.73	42.64	42.53	0.39
	9.00	40.00	66.32	0.20
	7.865	41.32	54.425	0.295
Granite	17.06	40.82	42.44	0.19
	15.20	41.84	41.28	0.26
	16.13	41.33	41.86	0.225
Magnetite Quartzite	15.90	42.03	97.62	0.22
	25.69	40.43	79.08	0.24
	20.795	41.23	88.35	0.23

the formation of comparison between different rocks' attenuation laws [7, 8].

3.2 Monitor on blasting vibration

Monitoring points should be placed on the points respectively 30 m, 60 m, and 90 m apart from the blasting aera, and these points should be placed on the same line. Furthermore, three blasting vibration testers should be placed respectively on these three points, and the blasting vibration testers were numbered. Monitoring diagram is shown in Fig.2. No. 1, No. 2, and No. 3 are monitoring points of magnetite quartzite's blasting area; No. 4, No. 5, and No. 6 are monitoring points of granite's blasting area; No. 7, No. 8, and No. 9 are monitoring points of migmatite's blasting area.

Blasting vibration testing sensor was triaxials sensor. X was horizontal tangential; Y was horizontal radial; Z was vertical direction. What is more, blasting vibration monitoring data are shown in Table 2.

4. Analysis of blasting vibration signal

4.1 Blasting Vibration Velocity

In the study of energy intensity indexes of blasting earthquake waves, the maximum section between vibration velocity curves are usually chosen [9]. Dimensional physical quantities related to blasting vibration are counted and analyzed to show the change conditions of the energy utilizations of the rocks [10, 11]. The variations of peak value of blasting earthquake waves are shown in Figs.3 to 5.

The attenuation trends of the three kinds of rocks were obviously distinguished from Fig.3 to Fig.5. The peak velocities of vibration of the three rocks' blasting areas in the three directions of different monitoring points were different. On the whole, what was found was that the peak value on the vertical direction was the highest, but along with the increasing of distance, the attenuation of vibration velocity became quicker, and it would approach or became less than the vibration velocity of the parallel direction in a very short time.

Within the monitoring distance of 90 m, the velocity attenuations on the monitoring points in the vertical direction were superior to those in the horizontal direction. Such phenomena were the best responses to the propagation medium which was the typical layered fracture structure. Due to the plane heterogeneity of the medium, the waves' amplitude faded.

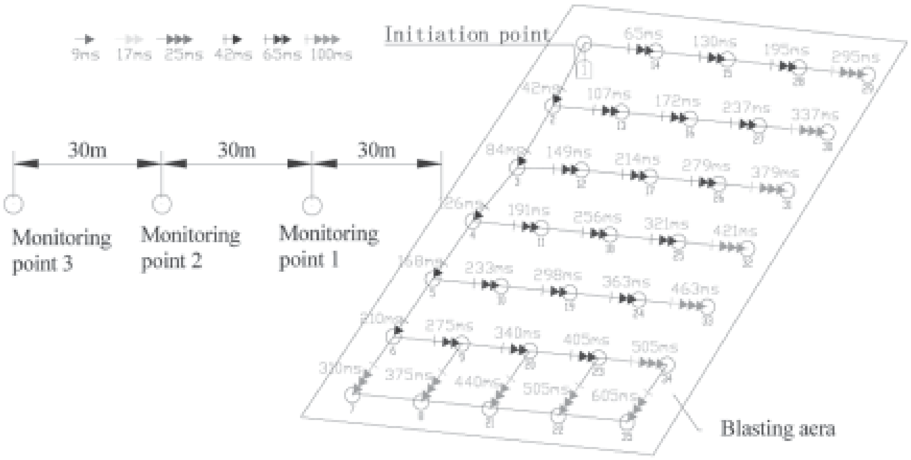

Fig.2 Blasting vibration monitoring diagram

What could be found in the vibration velocity's peak of the point which was 30 m away from the monitoring point was that the vibration velocity's peak of the seismic waves in the blasting area of magnetite quartzite was higher. Besides, attenuation's speed degree was decided by lithological characters. The harder the rock was, the quicker the vibration attenuation was, and the reason was possibly that there were not too much diffractions and refractions. What was found through analysis was that the vibration attenuation rate of magnetite quartzite was the lowest, and that of the granite was the highest.

The regression analysis of attenuation law was preceded to the vibration data of the three kinds of rocks in the vertical direction, it was found that the blasting correlation coefficient in the magnetite quartzite area was 0.94, and K and α were 171 and 1.57 respectively; that in the granite area was 0.94, and K and α were 185 and 16 respectively; that in migmatite area was 0.85, and K and α were 46.5 and 0.82 respectively. What is more, what the comparison of the three kinds of rocks' relation between explosive charge and vibration velocity showed basically in line with the requirements of correlation coefficients. The attenuation coefficients of the three kinds of rocks were different with the same charge mass.

TABLE 2: BLASTING VIBRATION MONITORING DATA

Monitoring point	Distance /m		Amplitude /cm·s^{-1}	Basic frequency /Hz	Vibration time /s
		X	14.68	10.70	
1#	30	Y	10.14	12.42	0.8
		Z	18.59	21.74	
		X	5.89	16.00	
2#	60	Y	5.88	16.67	0.8
		Z	10.24	20.41	
		X	2.9	25.97	
3#	90	Y	4.43	28.57	0.8
		Z	2.87	32.26	
		X	10.20	11.17	
4#	30	Y	12.02	13.38	0.9
		Z	17.86	16.60	
		X	4.15	27.40	
5#	60	Y	4.59	24.24	0.9
		Z	9.45	22.99	
		X	4.29	17.17	
6#	90	Y	4.01	20.62	0.9
		Z	2.63	23.39	
		X	10.45	13.65	
7#	30	Y	10.08	9.17	0.9
		Z	13.35	20.41	
		X	5.78	19.80	
8#	60	Y	6.37	25.81	0.9
		Z	12.70	25.48	
		X	2.13	14.82	
9#	90	Y	1.86	24.10	0.9
		Z	4.93	27.77	

4.2 ANALYSIS OF ENERGY UTILIZATION

In the process of open pit blasting, the effective utilization of the explosive energy had never been directly measured, and generally, the utilized situation of the explosive was evaluated through indirect measurement. What is more, the energy produced in the process of explosives' explosion in the rocks were mainly used in rocks' crush, the seismic waves' propagation, and the cast of the rocks, which could be expressed as [12]:

$$E_E = E_F + E_S + E_K + E_{NM} \quad ...(1)$$

In the expression, E_E was explosive energy, E_F was crushing energy, E_S was wave energy, E_K was kinetic energy, and E_{NM} was loss energy. All energy were expressed in the way the ratio between them and the total explosion energy. The first three in this expression were the main consumption composition of explosives' explosion energy.

Blasting seismic energy was got according to the controllable area of the distance the energy went through, and the research focus was E_S.

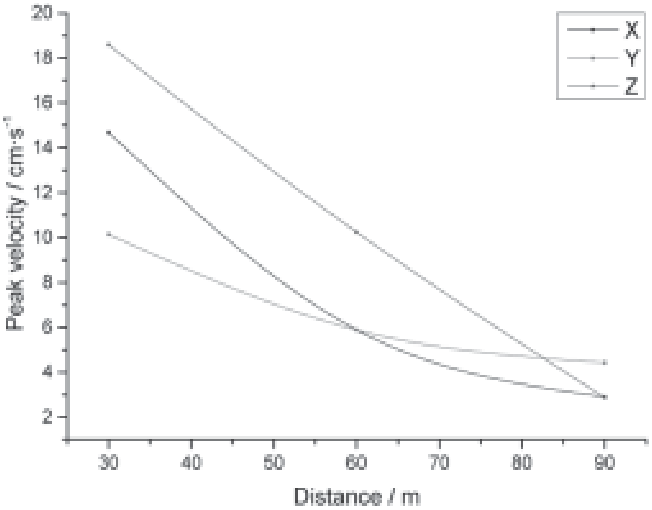

Fig.3 Peak of blasting vibration (migmatite)

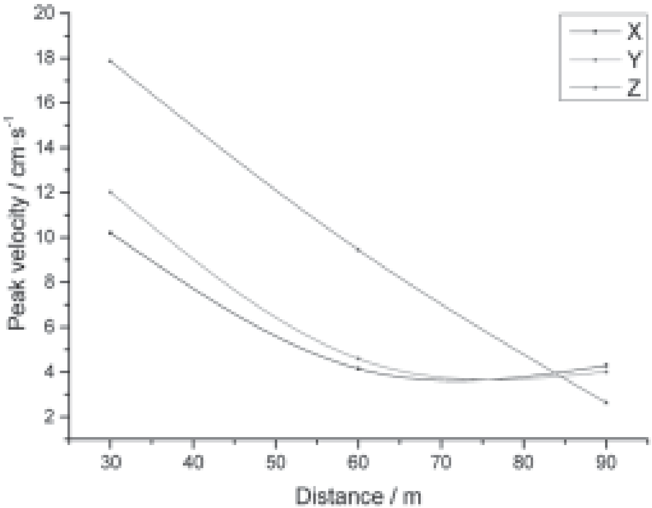

Fig.4 Peak of blasting vibration (granite)

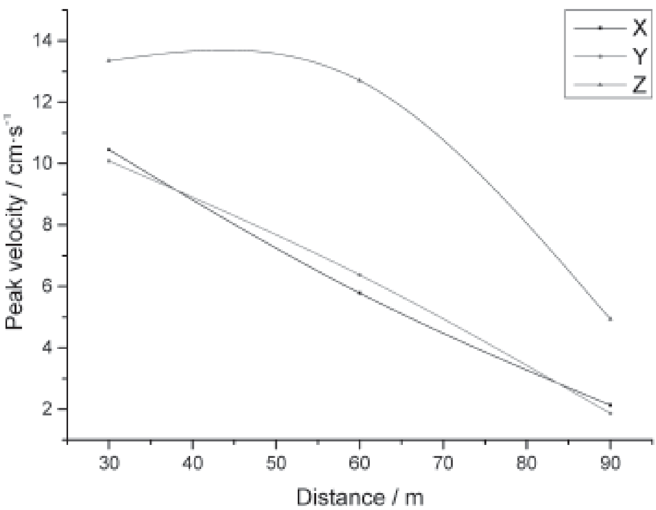

Fig.5 Peak of blasting vibration (magnetite)

Energy flux was the vector product of the surface stress and the particle velocity, it was [13]:

$$\Phi = \tau_{ij} n_i v_j \quad \text{...} \quad (2)$$

In order to make a connection with the velocity, seismograph's reading, stress values, and some assumptions must be provided in advance. If seismic waves were seen as the longitudinal spherical waves in the infinite and even medium, the stress tensor's main elements in the spherical coordinates were:

$$\tau_{11} = (\lambda + \mu)\frac{\partial u_1}{\partial r} + 2\lambda \frac{u_1}{r}$$

$$\tau_{22} = \tau_{33} = \lambda \frac{\partial u_1}{\partial r} + 2(\lambda + \mu)\frac{u_1}{r} \quad \text{...} \quad (3)$$

$$\tau_{ij}(i \neq j) \neq 0$$

In the expression, r referred to the distance to the blasting source center; u_1 referred to radial components of the particle displacement; λ and μ were lame constants.

For the wave crest of the spherical waves, its standard spindle unit vector was the unit vector of (1,0,0), and the third expression was brought into the second one, and then the following flux formula could be got:

$$\Phi = \left[(\lambda + \mu)\frac{\partial u_1}{\partial r} + 2\lambda \frac{u_1}{r}\right] v_1 \quad \text{...} \quad (4)$$

Suppose the total energy which went through the sphere whose radius was r was a definite value, then the flux was:

$$P = 4\pi r^2 \Phi \quad \text{...} \quad (5)$$

The expression of seismic waves' energy was:

$$E_S = \int_0^{\infty} 4\pi r^2 \Phi dt =$$

$$4\pi r^2 \times \int_0^{\infty} \left[(\lambda + \mu)\frac{\partial u_1}{\partial r} + 2\lambda \frac{u_1}{r}\right] v_1 dt \quad \text{...} \quad (6)$$

$$u_1(t) = \int_0^t v_1(t) dt \quad \text{...} \quad (7)$$

The space's reciprocal of displacement could approximately have the following relation:

$$\frac{\partial u}{\partial r} = -\frac{v}{c} \quad \text{...} \quad (8)$$

In the eighth expression, c was the wave velocity; the expression was adaptable when $v \leq c$, so the calculation formula of seismic waves' energy was:

$$E_S = -4\pi r^2 \int_0^{\infty} \left[(\lambda + 2\mu)\frac{v_1^2}{c_p} + 2\lambda \frac{u_1 v_1}{r}\right] dt \quad \text{...} \quad (9)$$

C_p in the expression was speed of longitudinal waves. For a simple harmonic wave, the second item's time integral in the ninth expression was almost zero. In the recorder of the seismic waves, the percentage of it was less than 0.05 %. For this reason, the ignorance of the second item would not cause too much error to the result. Besides, the negative sign showed that the energy left the sphere which was been studied, so the total energy reduced, and the above expression could be shown as:

$$E_S = -4\pi r^2 \rho c_P \int_0^{\infty} v_1^2 dt \quad \text{...} \quad (10)$$

In the actual computation, the absolute value of the tenth expression should be achieved, and then the following expression gained:

$$E_S = 4\pi r^2 \rho c_P \int_0^{\infty} v_1^2 dt \quad \text{...} \quad (11)$$

The earthquake energy obtained in the above expression was the particle velocity's radial component v_1, a spherical wave or plane P wave had in the elastic medium. Site measurement was needed in the longitudinal component. Suppose velocity's horizontal and vertical components, v_2 and v_3, were shear wave velocities, the following relational expression could be had according to approximation theory of the plane waves:

$$E_S = 4\pi r^2 \rho c_L \int_0^{\infty} v_2^2 dt \quad \text{...} \quad (12)$$

$$E_S = 4\pi r^2 \rho c_T \int_0^{\infty} v_3^2 dt \quad \text{...} \quad (13)$$

In order to get the general formula of energy further, the expression was always simplified further, and then the following expression was gained:

$$E_S = 4\pi r^2 \rho c \int_0^{\infty} \left(v_1^2 + v_2^2 + v_3^2\right) dt \quad \text{...} \quad (14)$$

On this basis, Li shunbo and others introduced particle's vibration velocity, that is:

$$v = K\left(\frac{\sqrt[3]{Q}}{R}\right)^{\alpha} \quad \text{...} \quad (15)$$

and they also took damp's function into account, and then the following expression was got [14]:

$$E_S = 30\sqrt{2}\pi r^2 \rho K^2 \left(\frac{\sqrt[3]{Q}}{r}\right)^{\alpha} \quad \text{...} \quad (16)$$

In the expression, v was vibration velocity; K, α were site coefficients; Q was maximum explosive charge; r was the distance from the measure point to the explosion area; r_0 was the radius of cavity.

In order to state further the energy' conversion rate, the concept of percentage which was got by converting explosive energy to blasting seismic wave energy was used to analyze the influence of blasting source factors on the strength of the blasting seismic waves η was defined as the percentage which was got by converting explosive energy to blasting seismic waves' initial energy. The following expression could be reached:

$$\eta = \frac{E_S}{E_E} \times 100\% \quad \text{...} \quad (17)$$

From the seismic wave energy formula, what could be inferred was that the seismic wave energy were related to the explosive charge, rock property, and the distance from the blasting source. Further more, the amount of energy was reflected by velocity to some extent, and the consumption of the explosive energy was reflected by the seismic wave energy to some extent. In the case of the same energy input, as long as the seismic wave energy were determined, the utilization rate of the explosive could also be determined, and seismic waves' wave velocities were always monitored by vibration monitor.

In order to analyze further seismic wave energy transformation of the three kinds of rocks, the formulas of energy were compared and what was found was that when the charge mass, aperture, and distance were the same, seismic wave energy were only related to the value of ρ, K^2 and α. Besides, what was known from energy' peak energy formula was that the difference of α's values was small, and they were almost the same. Based on these, it could be deduced that the seismic wave energy were in a positive correlation with ρK^2, and ρ's value had already been got in the mechanical property test.

A contrastive analysis was proceeded to analyze the conversion of the seismic wave energy of the three kinds of rocks with different lithological characters. What was found was that if the maximum explosive charges of magnetite quartzite and granite were the same, the conversion from explosive energy to seismic wave energy in the two rocks' blasting areas was only related to ρK^2, and then the following expression could be reached:

$$m_1 = \frac{\eta_{magnetite}}{\eta_{granite}} = \frac{\rho_{magnetite}}{\rho_{granite}} \bullet \frac{K^2{}_{magnetite}}{K^2{}_{granite}} < 1 \quad \text{...} \quad (18)$$

It showed that the seismic wave energy converted from granite were more, and the explosive's energy utilization was relatively lower.

The maximum explosive charge in the migmatite's blasting area was 450 kg, and the change of the charge mass's also caused the change of the explosive energy conversion. A comparison was preceded between the energy transformation of magnetite quartzite and migmatite, and the following expression could be made:

$$m_2 = \frac{\eta_{magnetite}}{\eta_{migmatite}} < 1 \quad \text{...} \quad (19)$$

To make a comparison, what could be deduced was that $\eta_{migmatite} < \eta_{magnetite} < \eta_{granite}$, and the larger the value was, the larger the loss was, and also the utilization of energy was low. Explosive's utilization of energy in migmatite was the highest, and that of granite and magnetite quartzite took second place. Different rocks' utilizations of explosive energy were different, which was mainly because different rocks have different mechanical properties. What is more, magnetite quartzite and granite have stronger compression strength and tensile strength, and also elastic modulus. In the case of higher rock strain rate, they could keep stronger tenacity; larger energy were needed when they were cracking, and they were not easy to be broken. When the energy released as the explosive exploded was beyond the reach of rock's cracking strength, more energy were converted to seismic waves. The main difference between the two rocks lied in the difference of the rock structure's direction: the development of the migmatite's structure joint fissure was poorer, which caused gneiss's relative compression strength and tensile strength were lower, and the migmatite was easy to crack. In the blasting condition with the same input energy, energy' utilization level was higher, and was relatively easy to blast.

Transformational relation of seismic wave energy were related to the site coefficients K and α in Sadaovsk formula, and the following theoretical conversion formula was deduced [15]:

$$\eta = \left(K \times 10^{-(2+\alpha)}\right)^{3/\alpha} \quad \text{... (20)}$$

The proposition of this theoretical equation contributed to the quantitative expression of percentage converted from explosive energy to the seismic waves. The result got from the regression analysis to the seismic waves could help the quantitative conclusion of energy transformation ratios of seismic waves in different rocks' blasting areas. When the explosive charges converted were the same, $\eta_{granite}$, > $\eta_{magnetite}$. When the charge masses were different, the conversion coefficient of charge unit was mainly considered, and in this case, $\eta_{magnetite}$ > $\eta_{migmatite}$,. What was shown in the expression was blasting medium worked on the conversion of seismic wave energy, and seismic wave energy' conversion ratios in the blasting areas of magnetite quartzite and granite were higher, and that in the migmatite blasting area was lower.

5. Conclusions

1. What could be found in the vibration data shown in 30 m away from the monitoring point was that the vibration velocity's peak of the seismic waves in the vertical direction was larger than that of the other two directions. Furthermore, what was shown in the attenuation law on the whole was vibration peak's attenuation in the vertical direction was quicker.
2. Blasting vibration attenuation was highly related to the rock property. Besides, magnetite quartzite and granite had higher elastic potential energy, so their seismic wave energy got from counting the speed monitoring was higher, and that of the migmatite was lower.
3. With the same explosive charge, explosive's energy utilization was related to rock's mechanical properties in the blasting area, and the seismic wave energy had a tendency to increase along with the increase of ρK^2.
4. Different attenuation tendencies of blast vibration velocity were shown in different rocks with different structure. For the blasting area of the same lithology, the integrity characteristics of the rocks could be decided through analyzing the blasting vibration's attenuate law under the premise of the rocks' internal structures were unknown.

Acknowledgments

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