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Blasting cumulative damage effects of underground engineering rock mass based on sonic wave measurement

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Abstract: The principle of sonic wave measurement was introduced, and cumulative damage effects of underground engineering rock mass under blasting load were studied by in situ test, using RSM-SY5 intelligent sonic wave apparatus. The blasting test was carried out for ten times at some tunnels of Changba Lead-Zinc Mine. The damage depth of surrounding rock caused by old blasting excavation (0.8−1.2 m) was confirmed. The relation between the cumulative damage degree and blast times was obtained. The results show that the sonic velocity decreases gradually with increasing blast times, but the damage degree (D) increases. The damage cumulative law is non-linear. The damage degree caused by blast decreases with increasing distance, and damage effects become indistinct. The blasting damage of rock mass is anisotropic. The damage degree of rock mass within charging range is maximal. And the more the charge is, the more severe the damage degree of rock mass is. The test results provide references for researches of mechanical parameters of rock mass and dynamic stability analysis of underground chambers.

Key words: sonic wave measurement; cumulative damage effects; damage degree; blasting load; surrounding rock of underground engineering; RSM-SY5 intelligent sonic wave apparatus

1 Introduction

Drilling and blasting construction is used in many underground rock engineering, such as traffic tunnels, mining tunnel and hydraulic tunnels. Blasting will bring damage to retaining rock unavoidably during excavation, and the safety of whole engineering will be threatened[1−2]. The damage problems of surrounding rock caused by blasting have caught worldwide experts' great attention for a long time[3]. Combined with in situ observation, a mass of researches have been carried out by a great deal of scholars in theoretical, numerical and experimental aspects and so on, using the methods of explosive mechanics, fracture mechanics and damage mechanics. Researches[4−8] show that the action mechanism of rock mass damage is a continuous cumulative process of damage evolution. And during the process, plenty of micro-cracks inside rock generate, extend and transfix, then lead the macro-mechanical capability of rock to deteriorate under blasting load.

In fact, the process that damage cumulative causes macro-invalidation isn't result of one times blasting. For example, there are plentiful recurrent or repetitive blasting operations in tunnel excavation and mining production. To analyze the damage of rock mass for one times blasting, we cannot open up the mechanism of damage and instability under blasting load. So it is necessary to study the damage cumulative effects of rock mass under many times blasting. NAPIER et al[7] took forward the concept of seismic recurrence effects when he studied multi-pole expansion. KARAMI(1999)[3] studied the fatigue life problems of rock mass under repetitive blasting vibration. The results are helpful to predict the stability of surrounding rock and choosing proper supporting methods. YANG[8] studied the blasting vibration cumulative effects preliminarily, combined with in situ blasting vibration test. Whereas the problem of blasting damage cumulative effects is so complicated, former researches are only preliminary and elementary. Proper theoretical models have not been set up, and feasible experimental methods have not been taken forward yet. Cumulative damage effects of surrounding rock in some tunnels at Changba Lead-Zinc Mine were studied by in situ sonic wave measurement in the present study, using RSM-SY5 intelligent sound wave apparatus based on the sonic wave measuring theory. The relation between damage degree of rock mass and blasting times was obtained. The damage cumulative laws under blasting load for many times and anisotropic characters of rock mass were analyzed. The results provide data references for researches on mechanical parameters of rock mass and dynamic stability analysis under ground chambers.

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2 Theoretical basis of sonic wave measure

2.1 Instability condition

Sonic wave is one kind of elastic waves. Its propagation obeys the laws of elastic wave propagation. During undulation, the medium is at moving state. If the vibration displacement component in x direction is expressed with u, then it can be obtained

$$(\lambda+G)\frac{\partial e}{\partial x}+G\nabla^2 u-\rho\frac{\partial^2 u}{\partial t^2}=0 \tag{1}$$

where e is the bulk strain of element, and λ is a lame coefficient, G is the shear modulus, ∇^2 is the Laplacian. The equation in y and z direction can be worked out analogically by the same way.

In infinite elastomer, the movement equation of P wave and S wave can be deduced according to Eqn.(1).

Supposing u=u(x,t), Eqn.(1) turns to

$$\frac{\partial^2 u}{\partial t^2}=v_P^2\frac{\partial^2 u}{\partial x^2} \tag{2}$$

$$v_P=\sqrt{\frac{\lambda+G}{\rho}}=\sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \tag{3}$$

Eqn.(2)is the movement equation of P wave in infinite elastomer, v_P is the velocity of P wave.

In the same way, we can obtain

$$\frac{\partial^2 u}{\partial t^2}=v_S^2\frac{\partial^2 u}{\partial x^2} \tag{4}$$

$$v_S=\sqrt{\frac{G}{\rho}}=\sqrt{\frac{E}{2\rho(1+\mu)}} \tag{5}$$

Eqn.(4) is the movement equation of S wave in infinite elastomer, v_S is the velocity of S wave.

2.2 Influence of damage on sonic velocity

Engineering practices prove that there are plenty of randomly distributed initial damage(such as joints, micro-cracks). New cracks in rock mass generate near the blasting sources under the blasting loads. The already existing abundant joints and cracks extend, nucleate and transfix, then form the main crack. According to Huygens' Principle, when sonic wave reaches interfaces of rock structure, reflecting, scattering and diffracting will take place. Therefore, these cracks and fractures prolong the traveling route, and lead sonic velocity to decrease. What's more, the decreasing degree of sonic velocity relates with the number and width of cracks close[9]. With increasing times of blasting, the cracks generate, extend and stretch gradually, and lead sonic velocity to decrease gradually. Blasting damage degree of rock mass can be estimated, according to variance of sonic velocity. As is the theoretical basis to study the blasting cumulative damage of rock mass, using sonic wave measurement.

2.3 Standards of rock mass damage

The relations among damage degree of rock mass （D）, integrality coefficient （K）and decreasing rate of sonic velocity（η）were set up in Ref.[10], based on sonic wave methods,

$$D=1-\frac{E}{E_0}=1-\left(\frac{v}{v_0}\right)^2=1-K=1-(1-\eta)^2 \tag{6}$$

where E_0 is the elastic modulus of rock mass before blasting, E is the equivalent elastic modulus after blasting, v_0 is the sonic velocity before blasting, v is the sonic velocity after blasting.

Chinese “Construction Technical Specification on Rock Foundation Excavation Engineering of Hydraulic Structures” (SL47−94) ordains that rock mass reaches damage when η > 10%. The corresponding damage threshold of rock mass is

$$D_{cr}=0.19 \tag{7}$$

3 Testing process

3.1 In situ arrangement of measuring point

The measuring site locates at some tunnels of Changba Lead-Zinc Mine, which are between 73 and 75 line, 1 202 m level in Lijiagou diggings. Blasting hole and sonic wave measuring holes are all arranged at side wall of the tunnel, as shown in Fig.1.

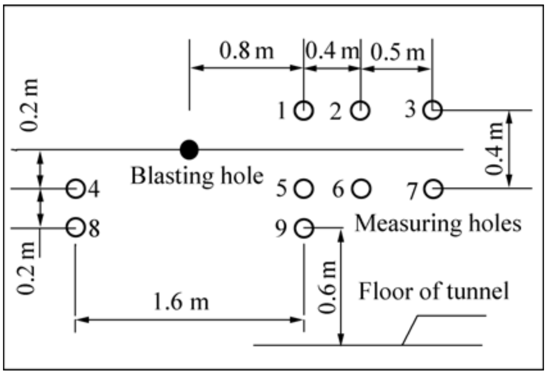

Fig.1 Arrangement of holes

All holes were drilled with YG 90 drill. Their depths were all 4.90 m, and their diameters were all 60 mm. There were nine sonic wave measuring holes and one blasting hole. All holes declined adown to 5°, and kept parallel. The fifth drill rod of No.7 hole was locked suddenly during drilling, and water flowed out from No.2 hole. This illuminates that No.7 hole has been transfixed with No.2 hole at bottom, and there maybe local cracked zones between them. These two holes were not used in test.

3.2 Measuring apparatus

The measuring apparatus was RSM−SY5 intelligent sonic wave apparatus, which was made by the Institute of Rock and Soil Mechanics, Chinese Academy of Sciences. Its main capability parameters are as follows: double channels, minimum sampling rate 0.1 μs, 12 bits A/D transformation, gain range of point or floating-point 1−10 000, more than one burst modes and level choice, and simple spectra analysis function. Double-hole increasing-pressure transducers were used in test, and its frequency was 25−35 kHz. The sonic wave measuring apparatus is shown in Fig.2.

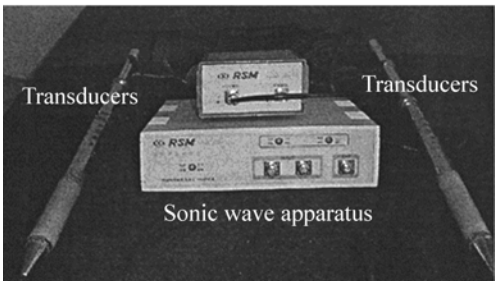

Fig.2 Sound wave testing apparatus

3.3 Measuring process

The blasting with little charge was used during measuring process, and blasting was carried out for ten times in total. Blasting parameters are listed in Table 1. The blasting for ten times was carried out in one same hole, so it was hard to avoid that the wall of blasting hole crashed and distorted within the charge. In order to overcome the disadvantages, the part of blasting hole crashed was filled and tamped with clay and rock, and the position of charge moved outside gradually at the same time. The distance between the position of charge and the entrance of blasting hole was measured before blasting every time, and the parameters are listed in Table 1. The concreted charge was used during blasting test, and the charge was tamped to cling with wall at bottom of blasting hole. In order to improve blasting effect, the blasting hole was tamped with self-made clay, and the tamped length was 20−30 cm. In order to find the distribution of sonic velocity in surrounding rock, sonic wave measurement must be carried out for all measuring holes before blasting. It can confirm the damage degree and deep range caused by old blasting excavation, and provides references for determining the range of blasting damage cumulative effects researches. There were five measuring section (Refer to Fig.1) totally, whose number were 4−5, 8−9, 1−4, 1−6 and 3−6, respectively. The transducers moved from the bottom to the mouth of measuring holes during measurement, and the moving distance was 0.20 m for every time. The sonic measuring parameters must be set before measurement. These parameters included section plane numbering, sampling rate, gain, delaying time, checking zero, location of holes and distance between holes, etc.

Table 1 Blasting parameters

Serial No.	Charge/ g	Depth of charge/m	Type of explosive	Filling effect
1	70	4.90		
2	75	4.85		
3	70	4.80		
4	72	4.75		
5	70	4.70	Emulsion explosives	Rather good
6	75	4.65		
7	70	4.60		
8	72	4.55		
9	80	4.50		
10	120	4.50		

4 Results and analysis

4.1 Damage range caused by old blasting

It is found after measurement that the damage degree caused by old blasting is rather little, and damage range is only 0.9−1.2 m. The main reasons are good integrality and relative high intensity of surrounding rock. The distribution of sonic velocity in surrounding rock presents anisotropy, since measuring sections are not in the same axes. For example, the distributing laws of measuring data of 4−5 and 8−9 sections are basically accordant, while measuring data of 1−5, 1−6 and 3−6 sections have basically the same law. In addition, sonic velocity doesn't always increase with increasing depth of holes. For example, the sonic velocity decreases suddenly within 3.0-3.5 m of 4-5 sections. The reasons maybe are local cracked zones or little cavities. The typical rock mass damage curve of sonic velocity and depth caused by blasting excavation is shown in Fig.3. The measuring and analytical results are listed in Table 2.

4.2 Analysis of blasting damage cumulative effects

To study the blasting damage cumulative effects of rock mass, the influence of damage caused by old blasting must be avoided. Therefore, the depth range of blasting damage cumulative effects is 3.5−4.8 m, according to measuring and analytical results of damage caused by old blasting. The rock mass can be regarded as original rock within the test range.

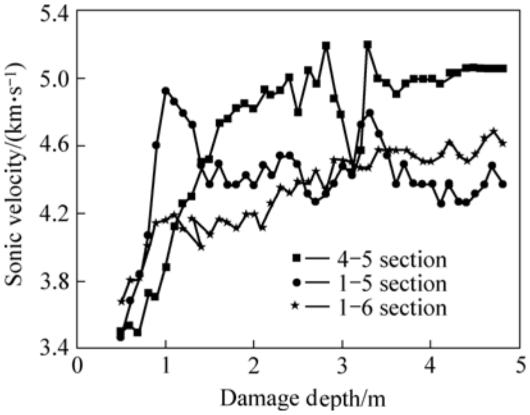

Fig.3 Typical rock mass damage curves of velocity and depth caused by blasting excavation

Table 2 Analysis of measuring results before blasting

Section	Distance between holes/m	Distance from blasting source/m	Average of sonic velocity / (m·s^{-1})	Depth of damage/m (Dcr=0.19)
4−5	1.60	0.20	4968	1.1
8−9	1.60	0.40	4978	1.2
1−5	0.40	0.80	4432	0.9
1−6	0.57	1.00	4533	0.9
3−6	0.64	1.45	4451	1.0

Figs.4−6 show the typical relation curves between sonic velocity and depth with different times of blasting. They correspond to 4−5, 1−5 and 3−6 sections, respectively. It can be found that sonic velocity decreases gradually with increasing blasting times within the range (3.5−4.8 m). The distance between blasting source and measuring site will influence the law of damage cumulative effects. For example, the distances from blasting source and 4−5, 1−5 and 3−6 section planes increase in turn, and the according damage degree and range decrease gradually. It can be seen from Fig.6 that 3−6 section plane isn't influenced by blasting loads on the whole.

The variance of sonic velocity and damage degree at 4.5 m depth after ten times blasting is listed in Table 3. The relation curve of damage degree and blasting times at 4.5 m depth is shown in Fig.7. It can be found according to Table 2 and Fig.7 that sonic velocity of all section planes at 4.5 m depth decreases with increasing blasting times. Damage degree of rock mass presents the trend of monotonous increasing with increasing blasting times. However, the decreasing rate of sonic velocity after ten blasting times is not the simple sum of decreasing rate after every blasting times. It is a non-linear cumulative relation between total decreasing rate of sonic velocity and decreasing rate of sonic velocity after every time blasting. So the cumulative of blasting damage has non-linear character. The decreasing rate of sonic velocity and damage degree of 4−5, 8−9, 1−5, 1−6 and 3−6 section planes at 4.5 m depth reduce in turn with the distance from blasting source and measuring site. The broken line in Fig.7 is damage threshold (D_{cr}) line. If damage degree exceeds this line, then it is regarded that damage or destruction has taken place. It is found out from the figure that the damage degree of 4−5 section plane after five blasting times and 8−9 section plane after eight blasting times has closed or exceeded D_{cr}. While the rock mass damage degree of other section planes does not exceed D_{cr}. It is relative to the little charge.

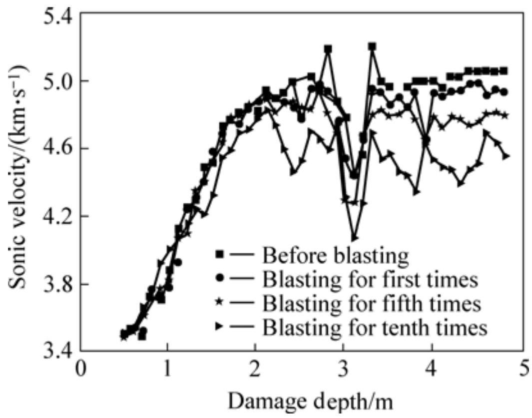

Fig.4 Relation curves of velocity and depth of 4−5 section for different blasting times

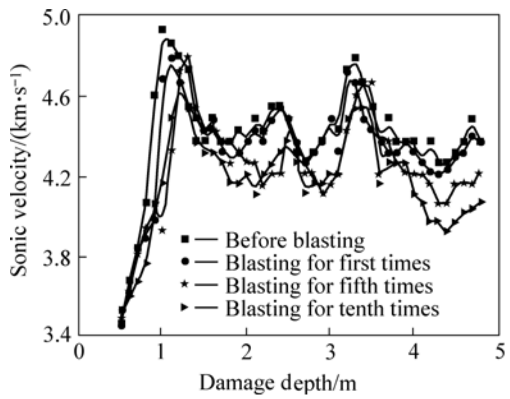

Fig.5 Relation curves of velocity and depth of 1−5 section for different blasting times

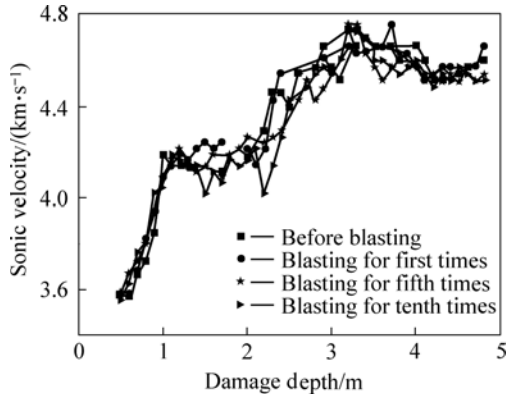

Fig.6 Relation curves of velocity and depth of 3−6 section for different blasting times

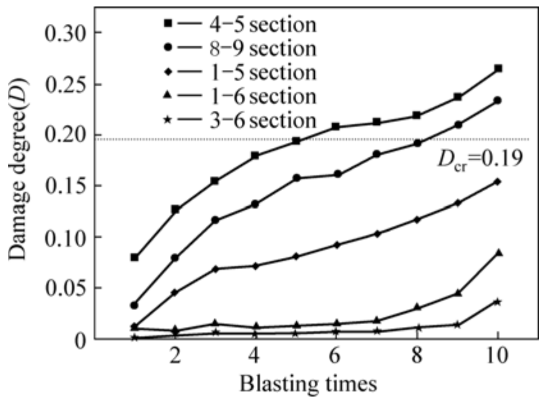

Fig.7 Relation curves of damage degree and blasting times at 4.5 m depth

The variance of sonic velocity and damage degree of 8−9 section plane within 3.6−4.8 m is listed in Table 4. The variance of damage degree of 4−5 section with damage depth within 3.6−4.8 m is shown in Fig.8. It can be found from Fig.8 and Table 4 that charge position can influence the damage cumulative effects to some degree. The damage degree decreases with increasing blasting times, and the position corresponded by the maximum damage degree moves from bottom to mouth of holes gradually. It is mainly caused by decreasing depth of charge position in blasting hole, and the concrete position of charge is listed in Table.1. The damage degree of rock mass within charging range is most severe, which is accordant with the research results in Ref.[11].

In addition, the more the charge is, the more severe the damage degree of rock mass is. In Fig.7, the interval of rock mass damage curves of third times blasting, fifth times blasting and seventh times blasting is relatively little, while the interval of damage curves of seventh times blasting and tenth times blasting is relatively large. Its main reason is that the charge of ninth times blasting and tenth times is more. The concrete charge is listed in Table 1.

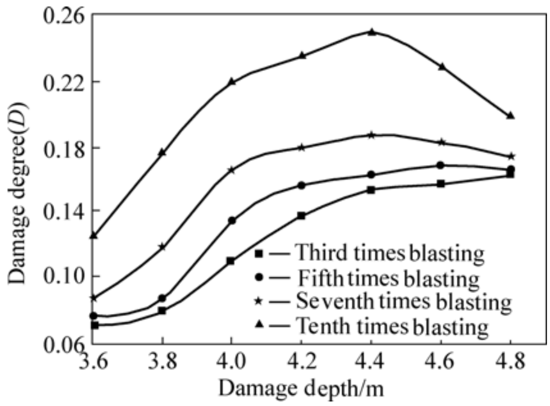

Fig.8 Change of damage degree with damage depth of 4−5 section plane within 3.6−4.8 m

Concreted charge at bottom is used during blasting test, while the charge structure is often cylindrical in engineering practice. The damage effects for rock mass caused by two different charge structures are different. Therefore, how to consider the influence brought by different charge structures await to be studied further.

Table 3 Change of sonic velocity and damage degree at 4.5 m damage depth after ten times blasting

Blasting times	4−5 section		8−9 section		1−5 section		1−6 section		3−6 section	
	Sonic velocity decreasing rate/%	Damage degree	Sonic velocity decreasing rate/%	Damage degree	Sonic velocity decreasing rate/%	Damage degree	Sonic velocity decreasing rate/%	Damage degree	Sonic velocity decreasing rate/%	Damage degree
1	4.03	0.08	1.56	0.03	0.51	0.01	0.45	0.01	0.00	0.00
2	6.50	0.13	3.95	0.08	2.24	0.04	0.38	0.01	0.13	0.00
3	8.01	0.15	5.95	0.12	3.44	0.07	0.66	0.01	0.18	0.00
4	9.37	0.18	6.76	0.13	3.57	0.07	0.48	0.01	0.17	0.00
5	10.18	0.19	8.14	0.15	4.09	0.08	0.59	0.01	0.23	0.00
6	10.92	0.20	8.40	0.16	4.71	0.09	0.65	0.01	0.27	0.00
7	11.22	0.21	9.46	0.18	5.28	0.10	0.78	0.02	0.31	0.00
8	11.61	0.22	10.07	0.19	5.97	0.12	1.40	0.03	0.49	0.01
9	12.63	0.24	11.04	0.21	6.90	0.13	2.18	0.04	0.62	0.01
10	14.23	0.26	12.43	0.23	7.95	0.15	4.24	0.08	1.78	0.03

Table 4 Change of velocity and damage degree of 8-9 section within 3.6−4.8 m of damage depth

Depth/ m	Blasting for third times		Blasting for fifth times		Blasting for seventh times		Blasting for tenth times	
	Sonic velocity decreasing rate/%	Damage degree	Sonic velocity decreasing rate/%	Damage degree	Sonic velocity decreasing rate/%	Damage degree	Sonic velocity decreasing rate/%	Damage degree
3.6	3.60	0.07	3.89	0.08	4.46	0.09	6.41	0.12
3.8	4.05	0.08	4.48	0.09	6.14	0.12	9.22	0.17
4.0	5.66	0.11	6.96	0.13	8.65	0.16	11.61	0.22
4.2	7.10	0.14	8.13	0.15	9.39	0.18	12.51	0.23
4.4	7.97	0.15	8.49	0.16	9.79	0.19	13.32	0.25
4.6	8.19	0.16	8.80	0.17	9.60	0.18	12.14	0.23
4.8	8.48	0.16	8.67	0.16	9.10	0.17	10.43	0.20

5 Conclusions

1) The damage depth of surrounding rock caused by old blasting and excavation is 0.8−1.2 m, blasting damage cumulative effect researches within the deep range(3.5−4.8 m) are feasible, according to the depth of boring holes(4.9 m).

2) Sonic wave velocity decreases gradually with increasing blasting times. Blasting damage cumulative of rock mass presents non-linear law. And the cumulative process of blasting damage has non-linear character.

3) The blasting damage degree decreases with increasing distance from blasting source and measuring site, and damage effects become indistinct.

4) The horizontal measuring results are greatly different with those of vertical, which illuminates that blasting damage of rock mass is anisotropic.

5) The charge and its position can influence the damage cumulative law of rock mass. The damage degree of rock mass within charging range is most severe. And the more the charge is, the severer the damage degree of rock mass is also.

6) The research results can provide references for farther researches of mechanical parameters of rock mass and dynamic stability analysis of underground chambers.

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