The quality evaluation of the grout in rock bolts based on the stress wave propagation

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Abstract: Nondestructive testing of rock bolt is essential for evaluating the grouted quality in rockmass. The stress wave propagation in the fully grouted rock bolts and defectively anchored bolt was investigated, where the mortar between the rock and bolt is subjected to different curing ages and stress wave induced by a dynamic excitation hammer impacting the bolt. First of all, it is found that both velocity and amplitude decrease with the increment of curing age of the anchor agent, based on the experiment of stress wave propagation in the fully grouted rock bolts. Velocity and amplitude attenuation decrease drastically within the first 14 curing ages and maintain steadily thereafter. The energy proportion manifests no change in the same waveform with the increment of curing ages, but the proportion taken by high-frequency harmonic wave increases. The crossing point of energy proportion curves moves towards low-frequency area, whereas the decrease of total energy tends to be stable. Secondly, the experiment of stress wave propagation in anchored bolt with different size of defects is also investigated. The variation of velocity and amplitude of stress wave in the defectively anchored bolt is similar to that of stress wave propagation in the fully grouted rock bolts. The crossing point of energy proportion curves moves towards low-frequency area, which is similar to the fully grouted rock bolts. But the velocity and amplitude attenuations in defectively anchored bolt are less than those in fully grouted rock bolts. The larger the defect size is, the smaller the amplitude attenuation is. Finally, the experiment of stress wave propagation in anchored bolt with different location of defects is also conducted. The magnitude of amplitude attenuation increases with the increase of distance. But the crossing point of energy proportion curves remains unchanged. The anchoring quality of bolts can be evaluated by the anchoring effect of anchoring agent, which can be estimated by the attenuation amplitude of stress wave velocity and amplitude, based on the experiment of stress wave propagation in defectively anchored bolt.

Keywords: Fully Grouted; Rock bolt; Grouted quality, stress wave

1. Introduction
In the underground mining engineering, rock bolt support has gradually become the main support and reinforcement method. The anchoring quality not only influences the stability of the surrounding rock
but also relates to the safe and efficient mining. Nondestructive testing of rock bolt is essential for evaluating the anchoring quality in rockmass. Especially, it is very important to test the anchoring quality of anchoring agent in the early stage to ensure the quality and safety of anchoring engineering.

Nondestructive testing of rock bolt includes two methods which are nondestructive testing based on stress wave and ultrasonic guided wave. A lot of theoretical and laboratory studies have been done to test the anchoring quality of rock bolts by use of the ultrasonic guided waves [1,6], but it is seldom used in the field. The nondestructive testing of rock bolt based on stress wave mainly uses the stress wave excited by the shock excitation hammers to test its propagation characteristics in the rock bolt, which is used to evaluate the anchoring quality of the rock bolt in the field. The longitudinal vibration mechanical model of rock bolt is established to investigate the dynamic response of rock bolt [7,9]. The velocity of stress wave propagation in anchoring rock bolt is also investigated [10,12].

Although some research has been conducted on the nondestructive testing of rock bolt based on stress wave, some of the propagation behaviors of stress wave have not been fully analyzed. In the early stage of anchoring construction, it is necessary to study the stress wave propagation to evaluate the anchoring effect. Therefore, the stress wave is generated by the shock excitation hammers and its propagation characteristics are investigated under different curing age, size and location of defects. The propagation characteristic of stress wave is explored in the initial stage of anchoring construction. It provides a reference for the data analysis of nondestructive testing and the quality evaluation of anchor construction.

2. Experimental device

2.1. Anchor pulling and stress wave detecting system

As shown in Fig. 1, anchor pulling and stress wave detecting system is consisted of three significant components, which are shock excitation hammers, holder system and data acquisition system. The stress wave is generated by the shock excitation hammers impacting the rock bolt. The different amplitude and shape of stress wave are excited with different shock excitation hammers and impact velocities. The holder system includes rock bolt, holder, concrete, mortar, mould and pressure flange. The data acquisition system includes strain gauges pasted on the rock bolt, dynamic strain indicator, a digital oscilloscope and computer. There are four measurement points and the interval between two points is 500mm. The distance of the first point and impacting interface is 700mm. Two strain gauges are symmetrically pasted at every point to avoid the influence of bending wave.

![Figure 1. Anchor pulling and stress wave detecting system](image)

2.2. Sample preparation

The rock bolt is C20 threaded steel and the length and diameter of rock bolt are 2500 mm and 20 mm, respectively. The surrounding rock is concrete and the length and diameter of concrete are 1500 mm and 150 mm. The concrete is comprised of ordinary Portland cement (17.3%), fine aggregate (22.4%), coarse aggregate (52.2%) and water (8.1%). The fine aggregate is river sand whose diameter is 0.3 -
1.18 mm. The coarse aggregate is river stone whose diameter is 5 – 20 mm. The uniaxial compressive strength of the ordinary Portland cement is 42.5 MPa at 28 days. The anchoring agent is cement mortar, which is comprised of ordinary Portland cement (19.2%), fine aggregate (61.6%) and water (19.2%).

3. The stress wave propagation in the full grouted rock bolts

3.1. The stress wave propagation in the rock bar
The stress wave propagation in the rock bolt will provide parameters and reference for the further study of the stress wave propagation in the anchoring bolt. As shown in Fig. 2(a), the propagation velocity in the rock bolt is 5176 m/s. The amplitudes attenuation is 0.7dB, 0.95dB and 1.08dB at SG1, SG2 and SG3, respectively. As shown in Fig. 2(b), the three spectrograms are similar, which indicates there is almost no dispersion for stress wave propagation in the rock bolt.

3.2. Attenuation of the amplitude and velocity for the stress wave
As shown in Fig. 3, the rock bolt is fully grouted and the anchoring effect is influenced by the curing age. When the curing age is 14 and 28 days, the amplitude attenuation of stress wave from SG1 to SG2 is 3.19dB and 3.04dB, respectively. The variety of amplitude attenuation is small for the first two measuring points at 14 and 28 days. However, the stress wave can be measured at the SG3 at 28 days, while it can’t be measured at 14 days. So the cement mortar has not been fully solidified, when the curing age is 14 days. The velocities of stress wave propagation in the grouted rock bolt are 3344 and 3356 m/s at 14 and 28 days, respectively. These velocities are similar. According to the amplitude attenuation and propagation velocities of stress wave, the anchoring effect of mortar is stable after 28 days.

As shown in Fig. 4 (a), the propagation velocity of stress wave decreases with the curing time. It indicates that the anchoring effect of anchoring agent increases with the curing time. The propagation velocity of stress wave in rock bolt decreases rapidly with the curing time during 14 days. When the
curing time is 3 days, the wave velocity decreases the most. This is because the strength of anchoring agent increases with the curing time. It leads that the bonding force between the anchoring agent and the rock bolt becomes stronger. The anchoring effect of the anchoring agent is stable and the propagation velocity of stress wave does not change after 14 days. These results are the same with that in the paper [11] and [13]. According to the paper [13], the propagation velocity of stress wave in anchoring rock bolt is related to the cross-sectional area, density and bond strength of rock bolt and anchoring agent. When the curing time is short, the bond strength between the rock bolt and anchoring agent is low. It leads stress wave propagation velocity of anchoring rock bolt is closer to that of rock bolt. The bond strength between anchoring agent and rock bolt gradually increases and tends to be stable with curing time, which leads to the stress wave velocity gradually decreases and tends to be stable. As shown in Fig. 4(b), the amplitude attenuation of stress wave is consistent with the wave velocity. Due to the different curing degrees of anchoring agent with time, the amplitude attenuation of stress wave rapidly decreases in 3-7 days and stay stable after 14 days.

Figure 4. The curing time history of wave velocity and amplitude attenuation

3.3. Spectral analysis of the stress wave
Fourier transform was used to analyze the frequency spectrum of stress wave measured at SG1 and SG2 at different curing ages. Based on the equation (1), the energy proportion ($k_i$) is calculated.

$$k_i = \frac{1}{2} \sigma_i \epsilon_i = \frac{E \epsilon_i^2}{\sum_{i=1}^{n} \frac{1}{2} \sigma_i \epsilon_i} = \frac{\sum_{i=1}^{n} \epsilon_i^2}{\sum_{i=1}^{n} \epsilon_i^2}$$

where $E$ is the elastic modulus, $\sigma_i$ and $\epsilon_i$ are the stress and strain when the frequency is $i$ Hz.

Based on the spectrograms analysis in Fig.2 (b), the range of analysis is in 0-5k Hz. As shown in Fig. 5(a), when the stress wave propagates from SG1 to SG2, the amplitudes of each harmonic are attenuated, but the attenuation magnitude of low frequency harmonic wave is larger than that of high frequency harmonic wave. The frequency of stress wave generated by the shock excitation hammers is mainly low frequency, so the proportion of high frequency is small and the attenuation is not obvious. As shown in Fig. 5(b), the attenuation magnitude of low frequency harmonic wave energy is too large, which leads to the increase of the proportion of high frequency harmonic energy. The curves of the energy proportion measured at SG1 and SG2 are crossed with the stress wave propagation. However, the energy proportion of the same waveform remains invariant and still decreases with the increase of frequency.

When the curing age was 7, 14 and 28 days, the total energy was decreased by 52.5%, 43.4% and 43.8%, respectively. The frequency of the energy proportion crossed at 2.7k Hz, 2.6k Hz and 2.4k Hz, respectively. The frequency of the energy proportion crossed moves to low and the total energy attenuation tends to be stable with the curing age.
4. The stress wave propagation in defective anchored bolt

4.1. The stress wave propagation in anchored bolt with different sizes of defects

The anchoring effect of local position may be poor, which is caused by construction and other reasons in the process of field anchoring. It can be simulated by the sample with anchoring defects. The length of the defect is 300 mm. The measurement points and the shock excitation hammer are the same with those in the Part 3. As shown in Fig. 6(a), the amplitude of stress wave measured at SG1 is 2.51dB larger than that of SG2 which is 1.41db larger than that of SG3 during the stress wave propagation in the defective anchored bolt. Comparing with the Fig. 3(a), the attenuation magnitude of stress wave amplitude decreases with the anchoring defects. It indicates that the stress wave amplitude attenuation is influenced by the anchoring defects. As shown in Fig. 6 (b), the attenuation magnitude of stress wave amplitude decreases with the increase of anchoring defects size. So the size of anchoring defect can be calculated by the amplitude attenuation of stress wave.

4.2. The influence of anchoring defects size

Fourier transform was used to analyze the frequency spectrum of stress wave, as shown in Fig. 6(a), whose curing age is 7 days. As shown in Fig. 7(a), the harmonic amplitude attenuates twice, when the stress wave propagate form SG1 to SG3. However, the first amplitude attenuation is larger than the second, because there is an anchoring defect between SG2 and SG3. As shown in Fig. 7(b), the energy proportion of SG1 is different from those of SG2 and SG3 while the energy proportion of SG2 is similar to that of SG3. It indicates that the waveform of stress wave propagation from SG2 to SG2 is similar. Therefore, the size of anchoring defect can be calculated by the amplitude attenuation of stress wave and change of waveform and frequency spectrum.
4.2. The stress wave propagation in anchored bolt with different distances of defects

The stress wave propagation is influenced not only by the size of anchoring defect but also by the distance between anchoring defect and anchoring head. The size of the anchoring defect is 300 mm. The distances between anchoring defect and anchoring head are 200 mm, 400 mm, 600 mm, 800 mm and 1000 mm, respectively. As shown in Fig. 9(a), the amplitude attenuation of stress wave propagation in the different distances of defects are 12.5%, 16%, 13.3%, 18% and 18.7%, respectively. The amplitude attenuation of stress wave increases with the distance between anchoring defect and anchoring head. When the stress wave propagation in the defective anchored bolt, it will be dispersive. The dispersive magnitude increases with the distance. Therefore, the increase of amplitude attenuation of stress wave is caused by the dispersion with the increase of distance. As shown in Fig. 9(b) and (c), the amplitude of each harmonic wave similarly attenuates. However, the magnitude of amplitude attenuation increases with the distance. The frequency of the energy proportion both crossed at 2 kHz. The amplitude attenuation and energy proportion influenced by the distance is different form the size. Therefore, the distance between anchoring defect and anchoring head can be calculated and the reference position of mortar reinjected also can be inferred.
5. Conclusion

The stress wave propagation in the full grouted rock bolts is investigated under different curing age, size and location of the anchoring defect. The propagation velocity, amplitude attenuation and spectrum are analyzed. The influence of the size and location of the initial anchoring defect on the stress propagation is discussed. The following conclusions can be drawn from the experiments analysis:

(1) The propagation velocity and amplitude attenuation of stress wave in the full grouted rock bolts both decreases with the increase of curing time and decreases rapidly in 14 days. When the curing age is 3 days, the decrease is the fastest. But the propagation velocity and amplitude attenuation are basically stable after 14 days.

(2) The excessive amplitude attenuation of low frequency harmonic wave leads to the increase of the proportion of high frequency harmonic wave energy with the stress wave propagation in the full grouted rock bolts. But the variation of energy proportion of the same waveform remains stable, which decreases with the increase of frequency. The crossed point of energy proportion moves to low frequency and the total energy attenuates tends to be stable with the increase of curing age.

(3) The propagation velocity and amplitude attenuation of defective anchored bolt is weaker than that of the rock bolt with good anchoring effect in the early stage of anchoring construction. The size and location of anchoring defects can be inferred by the propagation velocity and amplitude attenuation of stress wave, which can be used to evaluate the anchoring effect and construction quality of anchoring agent.

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