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Experimental study of the stress effect on attenuation of normally incident P-wave through coal

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ABSTRACT

The purpose of this study is to experimentally investigate the stress effect on normally incident P-wave attenuation through coal specimens. Laboratory tests were carried out using a Split Hopkinson pressure bar (SHPB) system, and a modified method was proposed to determine the quality factor (Q) of P-waves through coal specimens. Larger quality factor denotes less energy attenuated during P-wave propagating through coal. Experimental results indicate that the quality factor and stress (σ) within coal specimens are positively correlated. The P-wave propagation through coal specimens causes crack closure at the beginning of the coal fracture process in SHPB tests, an innovative model was thus proposed to describe the relationship between the crack closure length and the dynamic stress induced by P-wave. Finally, the stress effect on P-wave attenuation through coal was quantitatively represented by a power function $Q = a(c–b\sigma)^{-6}$, and the material constants a, b, and c were determined as 1.227, 1.314, and 0.005, respectively. The results obtained in this study would be helpful for engineers to estimate seismic energy attenuation and coal mass instability in coal mines.

1. Introduction

Coal is the primary source of energy consumption worldwide and is the major energy source (>60%) in China. The safety and efficiency of coal mining are of great importance to Chinese coal industries. However, underground coal mining activities (i.e., blasting, fault slip, and roof fall) frequently generate seismic waves known as mining-induced seismicity (Li et al., 2007), which might result in strong seismic motions in mining space and thereby cause serious seismic hazards to mining personnel and equipment or even triggers a rock burst (Fig. 1). For example, on November 3, 2011, a rock burst due to a fault slip in the Qianqiu Coal Mine caused 10 deaths and left 75 people trapped underground (Li et al., 2014). On March 27, 2014, another rock burst was triggered by a hard roof fall in the Qianqiu Coal Mine, and a total of 6 miners were unfortunately killed (Lu et al., 2015). Among those in situ cases, there usually exists a considerable distance between the seismic source and mining space; therefore, a thorough understanding of the seismic wave propagation from seismic source to mining space, especially the attenuation properties of the seismic wave in coal, is essential to estimate the seismic energy attenuation and coal mass instability in coal mines.

The P-wave attenuation in various rock materials such as shale (Delle Piane et al., 2014), limestone (Cadoret et al., 1998), and sandstone (Xue et al., 2013) has been extensively investigated using different laboratory techniques, including the resonant bar (McCann and Sothcott, 2009), ultrasonic pulse transmission technique (Aydin, 2014), ultrasonic pulse-echo technique (Amalokwu et al., 2014), and forced oscillation setups (Subramaniyan et al., 2014). The P-waves in those laboratory tests are generally characterized by high frequency (>2 kHz) and small strain amplitude (<10^{-5}). In addition, researchers have also carried out various experiments to study the effects of fluid saturation (Muller et al., 2010), confining pressure (Diallo et al., 2003), and strain amplitude (Mashinskii, 2014) on P-wave attenuation, and the results indicate that P-wave attenuation is sensitive to the saturation state, and those effects are closely related to the discontinuities within rock materials. Furthermore, the research on P-wave attenuation across a filled fracture with different water contents has been conducted using a modified SHPB system (Wu and Zhao, 2015). The results show that the attenuation coefficient increases with higher water content. In recent years, P-wave attenuation of rock saturated with CO_2 has drawn increasing interest, which has practical applications in monitoring and estimating the amount of injected supercritical CO_2 in deep subsurface reservoirs (Lepore and Ghose, 2015; Zhang et al., 2015).

The P-wave attenuation in coal mines has been investigated using in situ blasting tests (Lu et al., 2010), which merely focus on the frequency spectrum distribution of seismic waves and proves that the energy attenuation coefficient increases with the increased frequency. However,

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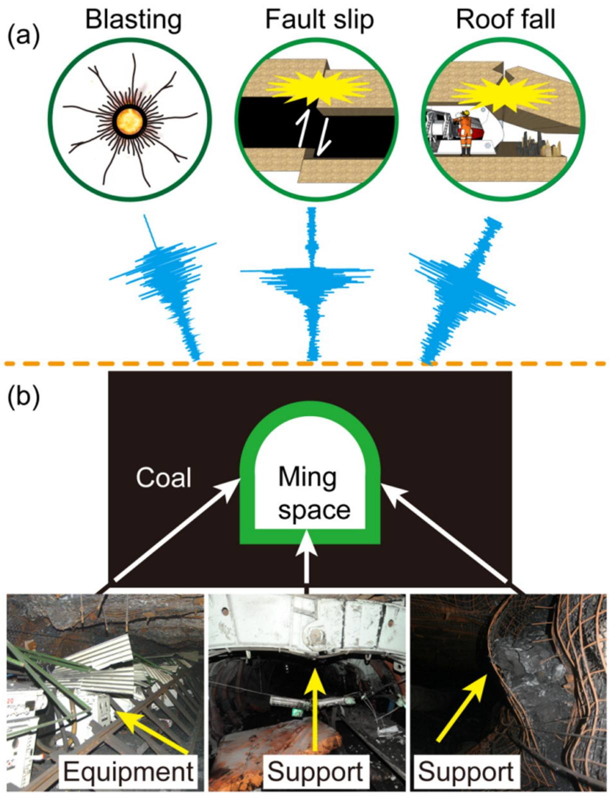

Fig. 1. (a) Schematic diagrams illustrating seismic waves caused by blasting, fault slip, and roof fall. (b) Photographs of support system and equipment destroyed by strong seismic motions.

few laboratory studies have been found on P-wave attenuation through coal, especially the studies on the stress effect on P-wave attenuation. In this study, a series of laboratory tests was conducted using an SHPB system, and a modified method was put forward to determine the energy attenuation coefficient of the P-wave through coal. Subsequently, an innovative model was proposed for describing the relationship between crack closure length and the dynamic stress induced by P-wave. At last, the stress effect on P-wave attenuation through coal was theoretically analyzed by combining the Hudson's model (Mavko et al., 2009) with the crack closure model. The results obtained in this paper would provide a better understanding of the P-wave attenuation through coal, and make it possible to quantitatively assess the influence of stress on P-wave attenuation.

2. Experimental method

2.1. Preparation of coal specimens

Raw coal materials were obtained from the Sanhejian Coal Mine located in Jiangsu province (Fig. 2a) and then processed uniformly through drilling, slicing, and polishing to obtain cylindrical specimens (Fig. 2b and c). To eliminate the inertial effects (i.e., the axial inertial effect and the radial inertial effect) and the interfacial friction effect, which affect the homogeneity of the sample deformation (Zhou et al., 2012), the sample length to diameter ratios of 1:1 was selected, and the bar/specimen interfaces were lubricated sufficiently with vacuum grease. The density, proximate analysis result (moisture, ash, volatile matter), and calorific value are presented in Table 1.

Quasi-static mechanical properties of Sanhejian coal were obtained using an MTS C60 hydraulic servo-control testing machine (Fig. 3a) based on the ISRM suggested method (Bieniawski and Bernede, 1979). The results are presented in Table 2, including uniaxial compressive strength, Young's modulus, and Poisson's ratio. In addition, the wave velocities of Sanhejian coal are determined by the ultrasonic pulse transmission technique (Fig. 3b), according to the ISRM suggested method (Aydin, 2014). The ultrasonic pulse is generated by an arbitrary waveform generator board (ARB-1410) and received by an acoustic emission board (Express-8). The average P-wave velocity and shear wave velocity of Sanhejian coal are 2126.89 m/s and 1074.24 m/s, respectively (Table 2).

2.2. Split Hopkinson pressure bar system

The experiments were conducted using a split Hopkinson pressure bar (SHPB) system (Zhou et al., 2012) (Fig. 4), which consists of a striker bar (Ø50 × 600 mm), an incident bar (Ø50 × 2400 mm), and a transmitted bar (Ø50 × 1200 mm), all made of 40Cr alloy steel, with Young's

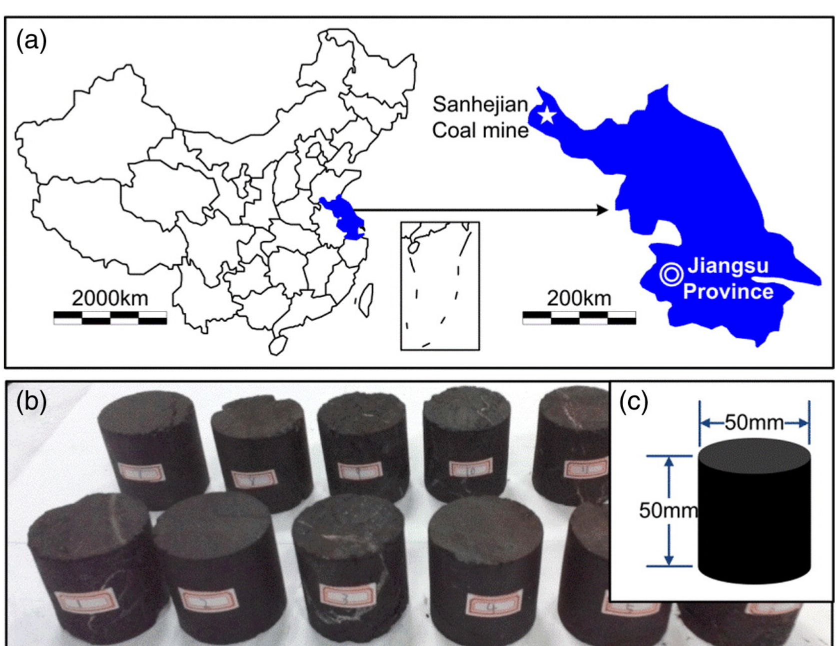

Fig. 2. (a) Map showing the location of the Sanhejian Coal Mine in China; (b) processed coal specimens; (c) dimensions of coal specimen.