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Ultrasonic S-wave responses of single rock joints filled with wet bentonite clay

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Abstract. Clay minerals are prevalent in rock discontinuities and have significant effects on mechanical, hydraulic and seismic properties of rock masses. Understanding seismic behaviours across individual clay-rich rock joints is of great importance in the fields of geology and earth sciences. However, the wave responses of individual clay-rich rock joints have not been well understood until now. This paper reports a laboratory investigation of ultrasonic S-wave propagation and attenuation across single rock joints filled with bentonite clays with varying degree of water saturation. In this study, a series of acoustic measurements were conducted on specimens of the bentonite clay-filled rock joint using a self-developed ultrasonic pulse-transmission test system that equipped with a S-wave transducer pair with a dominant frequency of 250 kHz. Based on the obtained laboratory data, the wave velocity, transmission ratio and the time-frequency-energy distribution of the S-waves transmitted through the bentonite clay-filled joint were calculated and evaluated. The experimental results show that the degree of water saturation of the bentonite clay greatly affects S-wave responses of the filled rock joint. In particular, an increase in the degree of saturation causes a nonlinear decrease in S-wave velocity. In addition, as the water saturation of the bentonite clay increases, the wave attenuation decreases; the minimum wave attenuation is reached at a saturation degree of 71.4% and then the attenuation increases slightly. Additionally, with the increase of the water saturation, the magnitudes of the S-wave energy transmitted across the bentonite clay-filled joint firstly increases and then decreases. The S-wave energy is mostly stored in the frequency range of 150 - 300 kHz regardless of the degree of



water saturation of the bentonite clay. This finding indicates that the frequency partition of the transmitted S-waves rarely changes with the changing water saturation. The present work could not only compensate for the lack of laboratory-based research on wave behaviours across clay-rich rock joints but also provides insights into the interpretation of acoustic data from field tests for detecting, characterizing and monitoring rock discontinuities.

1. Introduction

Rock joints are pervasive in the Earth's crust, and are often filled with gas, water, oil, quartz sand and clay, etc. Filled rock joints are known to highly affect the mechanical, hydraulic and seismic characteristics of rock masses [1]. Understanding wave propagation and attenuation across filled rock joints is of great interest to geologists, geophysicists, seismologists, and engineers from fields related to rock mechanics and earth sciences.

In recent years, wave behaviors across filled rock joints were widely studied in the laboratory. With respect to the P-wave attributes of filled rock joints, Li and her coworkers [2,3] performed a series of split Hopkinson pressure bar (SHPB) tests on single rock joints filled with sand and found that P-wave transmission across the rock joint decreased as the joint thickness and water content of the filling sand layer increased. Wu et al. [4] conducted SHPB tests on single rock joints filled with the clay-sand mixture. Their test results showed that the P-wave transmission increased and then decreased with increasing clay weight fraction. More recently, Yang et al. [5-7] conducted massive ultrasonic tests on individual fluid-filled rock joints and reported that P-wave velocity and transmission were enhanced to some extent by the substitution of air with liquid. On the other hand, regarding S-wave responses of filled rock joints, Liu et al. [8] developed a split shear plates apparatus and used it to investigate the effects of the normal stress, joint thickness, and particle size of filling sand on S-wave propagation through single rock joints. They found that the higher normal stress, S-wave transmission across single rock joints filled with quartz sand increased as the normal stress increased, the joint thickness decreased, and the particles became finer.

Despite of the progress in wave propagation across filled rock joints, the S-wave responses of individual rock joints filled with clay materials remain unknown. Note that the rock joint surfaces are often coated with thin layers of clay, and the liquid-clay interaction can lead to various degrees of swelling, dispersion and migration and then alter characteristics of rock joints [9]. Hence, it is necessary to conduct more investigations into the S-wave propagation and attenuation across clay-rich rock joints.

The present study aims to study the S-wave responses of single rock joints filled with bentonite clay with varying water saturation degrees in the laboratory. For this purpose, a self-designed ultrasonic test system equipped with a S-wave transducer pair with the central frequency of 250 kHz was adopted to conduct substantial ultrasonic tests on the bentonite-filled rock joint. The collected testing data were processed to evaluate the wave velocity, transmission ratio and the time-frequency-energy distribution of the transmitted S-waves across the bentonite-filled rock joint. The findings of the current work could improve the understanding of S-wave attributes of clay-rich rock joints and provide additional insights for interpreting acoustic data obtained from field tests on filled rock joints.

2. Experiments

2.1. Sample description

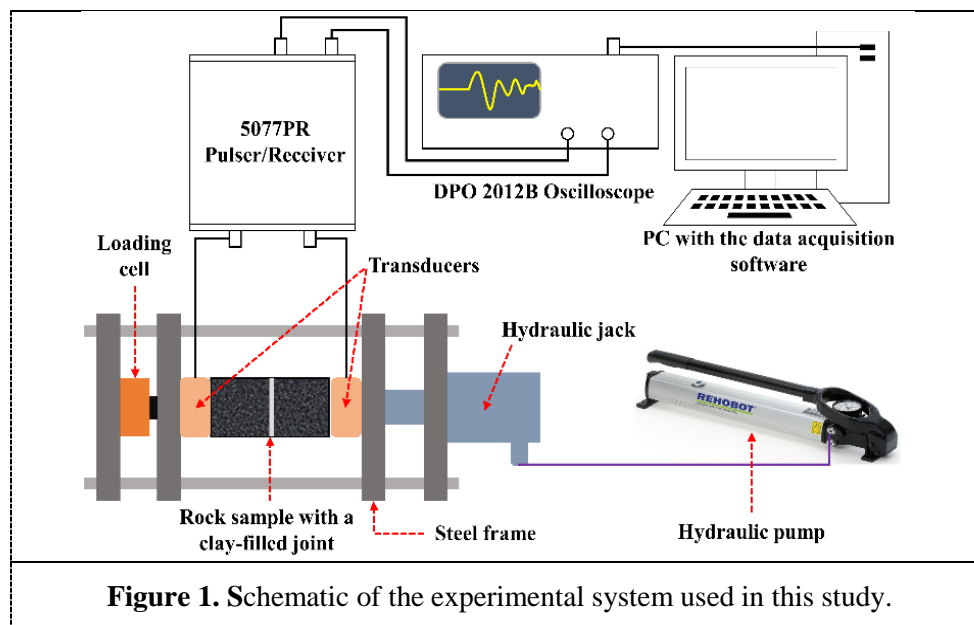
In this study, gabbro from Shanxi province, China was chosen to prepare the jointed rock specimen. The basic physical and mechanical properties of the selected gabbro rock were reported in our previous work [5-7]. Following the method described in the previous studies [5-7], the rock specimen of the height about 100 mm with a planar open joint was produced by combining two identical rock cylinders using a small polymethyl methacrylate (PMMA) tube with the help of 3M DP460NS epoxy adhesive. The

diameter and height of those two rock cylinders were 50 mm and 49 mm, respectively, indicating that the joint thickness was around 2 mm. The PMMA tube had a pre-set hole of diameter 2 mm for adding wet bentonite clay into the synthetic rock joint. In addition, an intact rock specimen with the same dimensions as the jointed rock specimen was manufactured using the same rock material to obtain reference pulses. Additionally, bentonite clay mined from Germany was utilized to prepare a series of filling bentonite specimens with different water saturation degrees. The fully water-saturated bentonite specimen was first produced using oven-dried bentonite clay powders. Then, the prepared fully water-saturated bentonite was separated into five equal parts with identical weights. These bentonite specimens were air-dried for 72, 90, 108, 126, 144h to obtain partially water-saturated bentonite specimens with different degrees of water saturation. Information about those specimens is summarized in Table 1. The prepared bentonite clay specimens were subsequently filled into the synthetic rock joint in sequence to generate various bentonite-filled rock joints for ultrasonic tests.

Table 1. Basic properties of the bentonite clay specimens used in the study.

No. of soil samples	Degree of saturation Sr (%)	Bulk density ρ (Mg/m ³)	Dynamic viscosity η (Pa·s)	Shear modulus G (Pa)
BC-1	59.2	1.304	2634.05	8275.10
BC-2	65	1.295	1770.43	5562.02
BC-3	71.4	1.287	1347.99	4553.82
BC-4	79.1	1.279	996.80	3131.53
BC-5	87.1	1.273	552.82	1376.67

2.2. Experimental procedure



The ultrasonic pulse-transmission test system adopted in this study mainly consists of an Olympus pulser/receiver (model 5077PR), a Tektronix digital oscilloscope (model DPO 2012B), an ultrasonic S-wave transducer pair with a dominant frequency of 250 kHz, a personal computer (PC) equipped with an exclusive software, and loading configuration, as shown in Figure 1. Before each test, the transducer pair and tested specimen are clamped by the steel loading frame, and then a small constant stress (0.7

MPa) was applied on the assembly of the tested specimen and transducers via the loading system to ensure good contact at the interfaces. During the test, the pulser/receiver first emitted a square pulse with an amplitude of 200 V and a width of 10 μ s at a repetition rate of 100 Hz. This pulse was converted to an input signal with a dominant frequency of 250 kHz by one transducer connected to the pulser/receiver. After propagating through the tested specimen, the transmitted pulse was detected by the other transducer connected to the pulser/receiver. Subsequently, 64 transmitted signals were stacked and averaged by the digital oscilloscope to collect the transmitted pulse at a high signal-to-noise ratio. The recorded transmitted pulses were eventually saved on a hard disk by the PC. For all the test cases, measurements were performed five times to guarantee the reliability and stability of the received data. Vaseline was applied to the interfaces between the S-wave transducers and the tested specimen to ensure good coupling.

3. Results and discussion

3.1. S-wave velocity across single rock joints filled with wet bentonite clay

The methods presented in ASTM D2845-08 [10] and reported by Fratta and Santamarina [11] were used to calculate the S-wave velocities across single bentonite-filled rock joint and the corresponding rock specimen are calculated from the experimental data obtained in this study. In Figure 2, the calculated S-wave velocities are plotted as a function of the degree of water saturation of bentonite clay. The tendency of the S-wave velocity across the whole jointed rock specimen resembles that across the bentonite-filled rock joint, indicating that the bentonite-filled rock joint dominates the wave behaviours in the rock specimen. Figure 2 also shows that the S-wave velocity decreases nonlinear with increasing degree of water saturation of the bentonite clay. This phenomenon can be attributed to the reduction in the shear modulus of the bentonite clay induced by the increase in water saturation (see Table 1). Specifically, the effect of clay hydration is strengthened by an increase in water saturation, resulting in the greater consumption of surface energy consumption and thus weaker stiffness of grain contacts in the bentonite clay [12]. On the other hand, matric suction diminishes with water saturation, reducing the interparticle contact forces in the bentonite clay [13]. Consequently, the shear modulus of the bentonite clay decreases with increasing water saturation, resulting in a decrease in the S-wave velocity across the bentonite-filled rock joint.

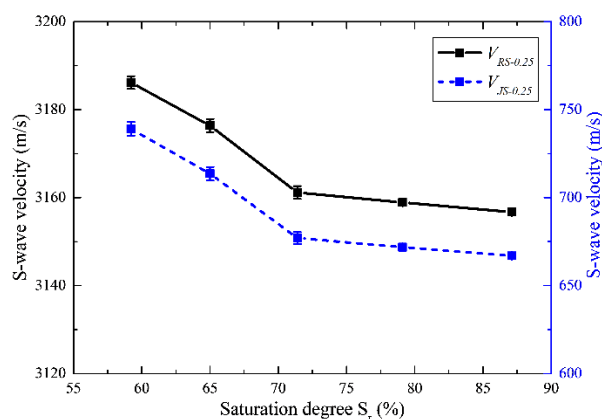


Figure 2. S-wave velocity across the bentonite-filled rock joint and corresponding rock specimen.

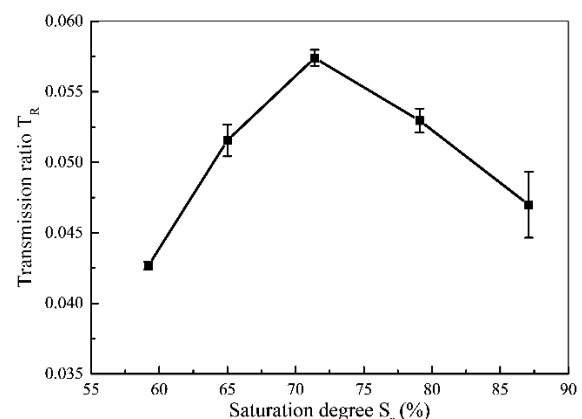


Figure 3. S-wave transmission ratio across individual bentonite-filled rock joints.

3.2. S-wave transmission ratio across single rock joints filled with wet bentonite clay

According to Nagata et al. [14], the transmission ratio of S-waves across single bentonite-filled rock joints can be computed as the ratio between the peak-to-peak amplitudes of the initial pulses of

transmitted S-waves across the jointed rock specimen and the intact rock reference. In Figure 3, the calculated S-wave transmission ratio across single bentonite-filled rock joints is shown with respect to the water saturation degree of the filling bentonite clay. The S-wave transmission ratio increases with water saturation and reaches its peak at a water saturation of around 71.4%. Subsequently, the continuously increasing water saturation causes a decrease in the S-wave transmission ratio as the water saturation degree increases continuously to 87.1%. These observations indicate that wave attenuation caused by single bentonite-filled rock joints first decreases and then increases with progressively increasing water saturation. The reduction in the wave attenuation is mainly attributed to the gradual decrease in the viscosity of the bentonite clay with an increasing degree of water saturation (see Table 1). More specifically, as the water saturation degree increases, the friction loss caused by the relative fluid-solid motion and solid-solid motion in the bentonite clay gradually diminishes, causing less wave attenuation across the bentonite-filled rock joint [15]. In contrast, the enhancement of the wave attenuation can be explained by the fact that the shear modulus decreases significantly with increasing water saturation, leading to greater wave reflection at the clay-rock interface [16].

3.3. Time-frequency analysis on the transmitted S-wave across single rock joints filled with wet bentonite clay

Based on the continuous-wavelet transform (CWT) technique [17], the time-frequency-energy distribution of the S-wave transmitted across single bentonite-filled rock joints was obtained. Figure 4 shows the typical time-frequency-energy maps for the S-waves transmitted across the intact rock reference (see Figure 4a) and rock specimens with different bentonite-filled joints (see Figure 4b-4f). The transmitted S-wave energy was significantly attenuated by the bentonite-filled rock joint. Specifically, the magnitudes of the S-wave transmitted through the intact rock reference are approximately two orders greater than those transmitted across rock specimens with bentonite-filled joints. In comparison, the bentonite-filled joint has a modest effect on the frequency partition of the transmitted S-waves. In particular, the transmitted S-wave energy was mostly stored in the frequency range of 150 - 300 kHz for both intact and jointed rock specimens.

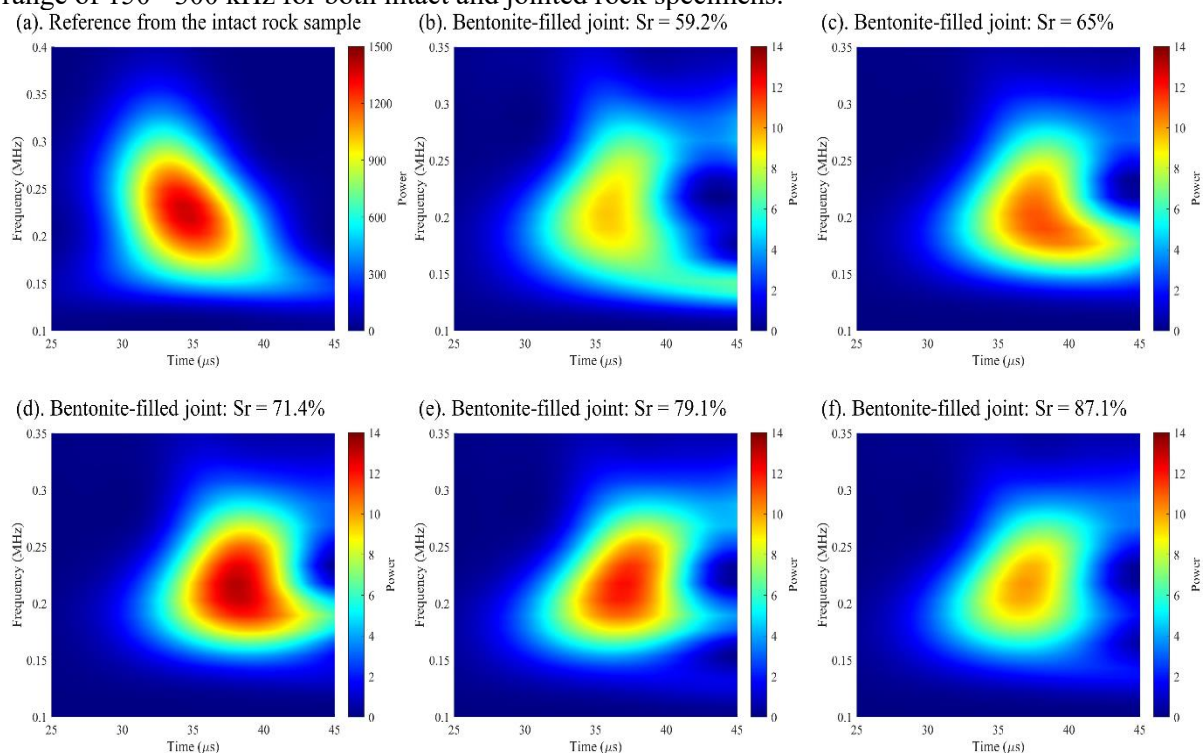


Figure 4. Typical time-frequency-energy maps for the S-waves transmitted across bentonite-filled rock joints at different degrees of water saturation.

In addition, Figure 4 shows that the degree of water saturation of the bentonite clay plays an important role in the time-frequency-energy distribution of the S-waves transmitted across individual rock joints. To be specific, the magnitudes of the S-wave energy transmitted across the bentonite-filled rock joint initially increase and then decrease with progressively increasing water saturation. Furthermore, the transmitted S-wave energy reaches a maximum at a saturation degree of approximate 71.4% for the bentonite-filled rock joints. These observations are consistent with the findings of the S-wave transmission ratio across single bentonite-filled rock joints, which are mainly attributed to the trade-off between the decreasing viscosity and weakening clay stiffness caused by the addition of water. Figure 4 also shows that the frequency partition of the transmitted S-waves seldom changes with varying water saturation, suggesting that water saturation has little influence on the frequency partition of the S-waves transmitted across single bentonite-filled rock joints.

4. Conclusions

The main conclusions drawn from the present work can be summarized as follows.

- (1) The increasing water saturation of the filling bentonite clay leads to a nonlinear decrease in the S-wave velocity across the rock joint.
- (2) S-wave energy transmission across single rock joints increases and then decreases with the water saturation of the filling bentonite clay.
- (3) The spectral amplitudes of the S-wave transmitted across single rock joints initially improved and then reduced with increasing water saturation of the filling bentonite clay.
- (4) The frequency partition of the S-wave transmitted across single bentonite-filled rock joints seldom changes with varying degree of water saturation of the filling bentonite clay.

The findings of this study can contribute to a better understanding of wave propagation and attenuation across individual clay-rich rock joints from scientific and practical perspectives. The test results can be used to validate the existing theoretical models for characterizing wave behaviours across rock joints. Meanwhile, the experimental observations may offer guidance to interpret wave-based field measurements for probing and charactering rock joints.

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