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DIRECT SHEAR TESTS ON SATURATED JOINTS IN SIERRA WHITE GRANITE

Specimen Preparation

Laboratory shear tests were conducted on induced tension-fractured Sierra White granite joints with rough contact surfaces. Rough contact surfaces were created by axial splitting of granite blocks to simulate a natural rock discontinuity as a tension-fractured joint. Granite blocks, with dimensions of 152.4 mm × 127.0 mm × 50.8 mm (6 in × 5 in × 2 in), were acquired from a quarry in Raymond, California. A notch along the sides of the block, with a depth of 15 mm (0.6 in), was made with a saw to induce fracture propagation of the block during compression (see Figure 1(a)). Hence, the net area of the joint surface was 122.4 mm × 97.0 mm (4.8 in × 3.8 in). Then, the notched blocks were fractured using a Brazilian technique (Jaeger and Cook, 1979) or split cylinder method (ASTM D3967) to obtain well-mated joint surfaces as shown in Figure 1(b).

Saturation of tension-fractured granite joints was achieved prior to shear, through a two-step process: (a) vacuum saturation of the rock specimen for 24 hours; and then (2) increase the back pressure beyond a required minimum magnitude determined from B-value tests. The previous experimental results showed that pore water pressures greater than 5.0-5.5 MPa were required to fully saturate Sierra White granite (Han et al., 2022a). In this study, a pore pressure of 8 MPa was applied to the specimens for full saturation.

Experimental Setup and Test Procedure of Direct Shear Tests

The experimental setup for the direct shear test is shown in Figure 2. Figure 2 shows a water-pressurized chamber and a horizontal loading frame placed on the platform of a conventional loading machine. The jointed rock specimen is placed inside the chamber, where it is loaded in biaxial compression. The horizontal loading frame applies the normal stress to the specimen using a computer-controlled flat-jack. The shear load is imposed to the specimen by the conventional loading machine with a constant displacement rate. Seismic wave transducers are housed inside the loading platens inside the chamber. Source and receiver arrays are placed next to both sides of the rock specimen to record seismic waves that are transmitted across the rock joint.

During the experiments, the chamber pressure (pore water pressure), the normal load, the shear load and the slip displacement were monitored. The loads were obtained from strain gauges, attached to the tips of the loading shafts, placed inside the chamber to measure the actual load imposed and thus evaluate any friction that may develop between the chamber seals and the shafts. The displacements were measured by an external LVDT. During the tests, seismic signals were captured at a sampling rate of 100 MHz and transmitted waves across the specimen were recorded every two seconds.

The procedure for the direct shear tests involved the following steps:

(a) A tension-fractured Sierra White granite specimen was prepared.

(b) The specimen was vacuum-saturated for 24 hours to reduce any air bubbles trapped in the joint and the pores of the rock matrix. Deionized water was used as a pore fluid, to minimize any chemical reaction with the rock specimen.

(c) The rock joint specimen was placed inside the chamber, and the chamber and loading frame were placed on the platform of the loading machine.

(d) A target effective normal stress of 2 MPa was applied first to the rock specimen and was held constant for the duration of the shear test.

(e) The total normal stress and chamber pressure (pore water pressure) were incrementally increased, while keeping the effective normal stress constant, until the chamber pressure reached the desired value (8 MPa in this study).

(f) The shear load was applied to the rock specimen by imposing a constant displacement rate of 8 μm/s. An electronic feedback-loop controller adjusted the pressure of the hydraulic flat jack to keep the normal stress constant during shearing, even when the rock joint dilated from slip.

Test Results: Mechanical Behavior and Geophysical Response of Saturated Granite Joints

Direct shear experiments were performed on three saturated granite joints, SWG-J-1, SWG-J-2 and SWG-J-3, under a total stress of 10 MPa, consisting of an effective normal stress of 2 MPa and a pore water pressure of 8 MPa.

Shear strength: dry vs. saturated

Three direct shear tests on dry granite joints were conducted under an effective normal stress of 2 MPa. Table 1 summarizes the results of direct shear tests on both dry and saturated granite joints. Figure 3 shows the shear strength as a function of effective normal stress. The test results for dry joints validate the saturation tests by comparing their shear strength with those obtained from saturated joints. The desired effective normal stress was 2 MPa, on average, for all shear tests, but the actual effective normal stress imposed to the saturated joints fluctuated between 1.76 MPa and 2.10 MPa. Specimen SWG-J-3 had a comparatively smaller shear strength of 3.2 MPa because the actual effective normal stress was 1.76 MPa, which was lower than the target value (2 MPa). The peak friction angles of the dry joints were 66.1° ~ 69.7°, while those of the saturated joints were 61.2 ° ~ 69.0°, which coincide with each other within experimental error.

Shear Behavior of Saturated Granite Joints

Representative shear stress – shear displacement curves are shown in Figure 4 for specimen SWG-J-1 along with the normal stress and normal displacement. The zero shear displacement is set at the peak shear strength. In addition, for normal displacement, a negative sign refers to contraction, while a positive sign is dilation. Figure 4 shows that the shear stress increased with increasing shear displacement until it reached the peak shear strength (5 MPa) of the saturated joint. During this stage, the normal stress was kept constant. The figure shows some fluctuations of the pore water pressure that were caused by switching injection pumps (in the tests, two pumps were placed in series to be able to supply the fluid to the chamber during the tests to manage a leak). These fluctuations were small enough such that they did not affect the effective normal stress applied. The figure also shows that, during shear, the joint contracted, as indicated by the negative normal displacements. After the peak shear strength, the shear stress decreased indicating brittle failure and the joint dilated. The final normal stress was 1.99 MPa, an increase of 3.86% with respect to the normal stress applied during shear (1.92 MPa). The increase was caused by dilation. However, the change was modest, and within experimental error.

Geophysical Response and Seismic Precursors

Using a wavelet analysis (Nolte et al., 2000), transmitted P-waves amplitudes were obtained by tracking the peak amplitudes at each wave transducer's dominant frequency. The obtained wave amplitudes were normalized with respect to their initial value prior to shear. Three pairs of P-wave transducers were used in the tests, as depicted in Figure 2. Figure 5 shows the changes in transmitted P-wave amplitudes during shear, for three tests. The transmitted P-waves showed either a small increase or a continuous decrease in amplitude at the early stages of shear, but all exhibited a sudden change in the rate of amplitude prior to the peak shear strength. A change in transmitted P-wave amplitude in the form of a distinct peak or a dramatic change in slope are seismic precursors to joint shear failure (Han et al., 2022b). Thus, all three shear tests showed seismic precursors to shear failure, as determined from P-wave transmission.

References

1. ASTM. (2016). Standard Test Method for Splitting Tensile Strength of Intact Rock Core Specimens.

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Table 1. Summary of the peak shear strength of dry and saturated Sierra White granite joints.

Conditions	Specimen	Peak shear strength (MPa)	Effective normal stress (MPa)	Friction angle (degrees)
Saturated Joints	SWG-J-1	5.00	1.92	69.0
	SWG-J-2	4.28	2.10	63.9
	SWG-J-3	3.20	1.76	61.2
Dry Joints	SWG-J-4	4.52	2.00	66.1
	SWG-J-5	5.39	2.00	69.7
	SWG-J-6	4.69	2.00	66.9

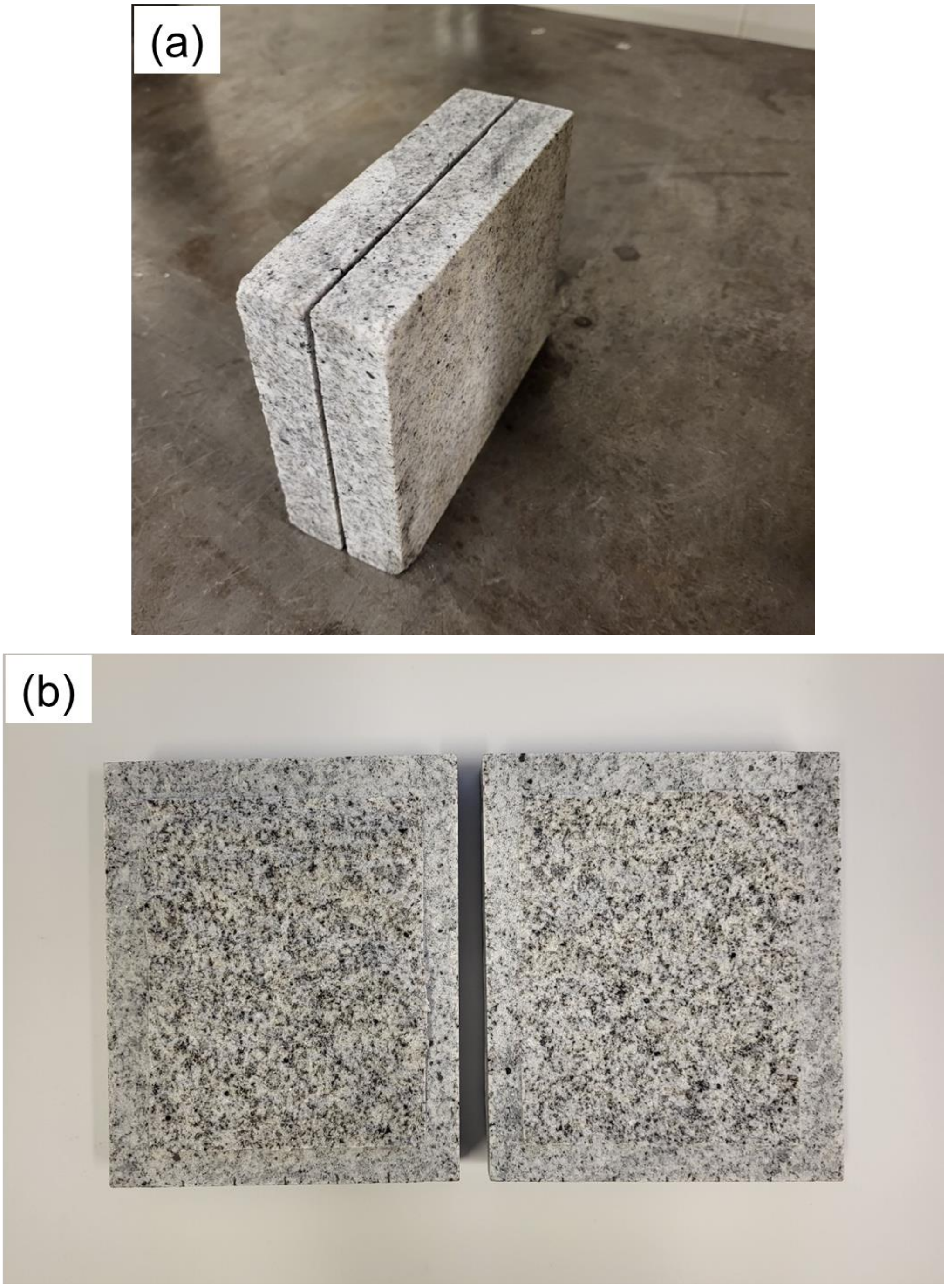


Figure 1. Specimen preparation: (a) A notched granite block; (b) A jointed specimen with rough contact surfaces.

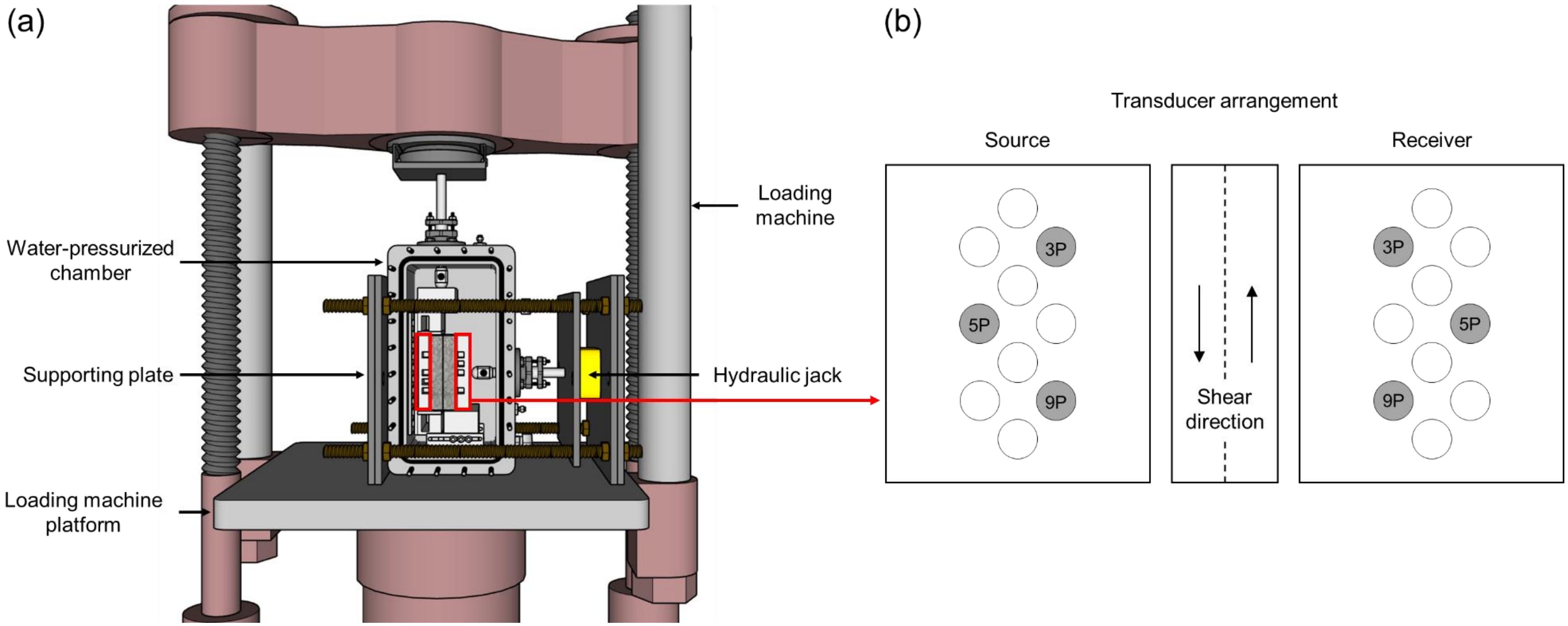


Figure 2. Experimental setup for direct shear tests: (a) Overall setup; (b) P-wave transducer arrangement inside loading platens.

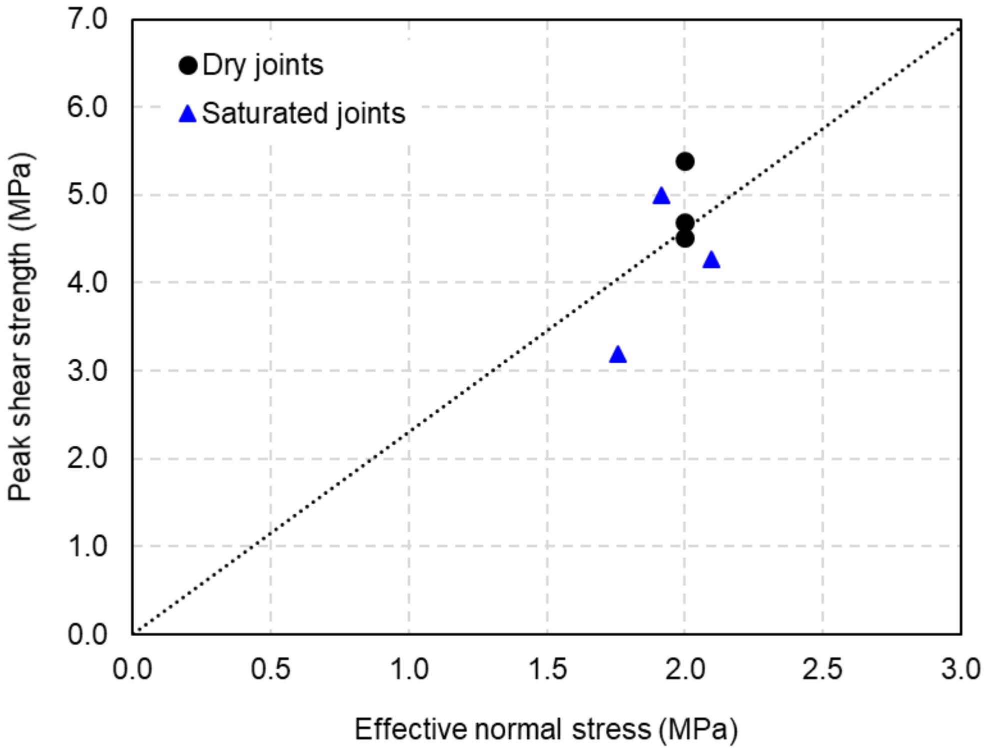
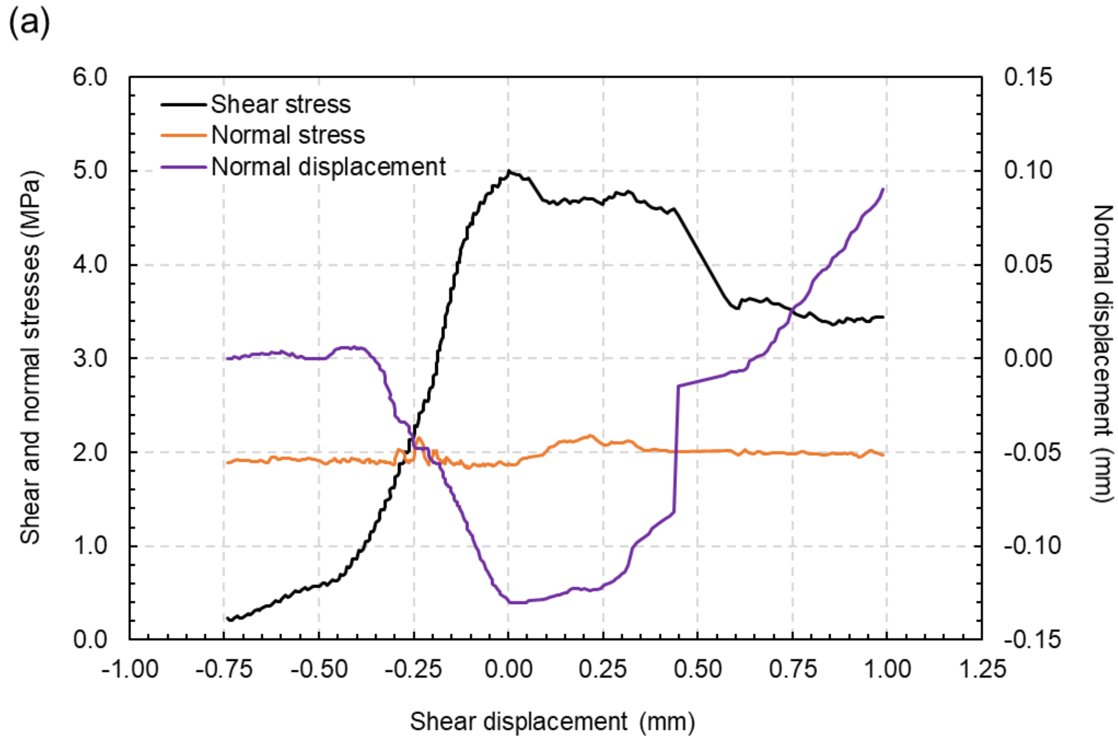


Figure 3. Peak shear strength versus effective normal stress.



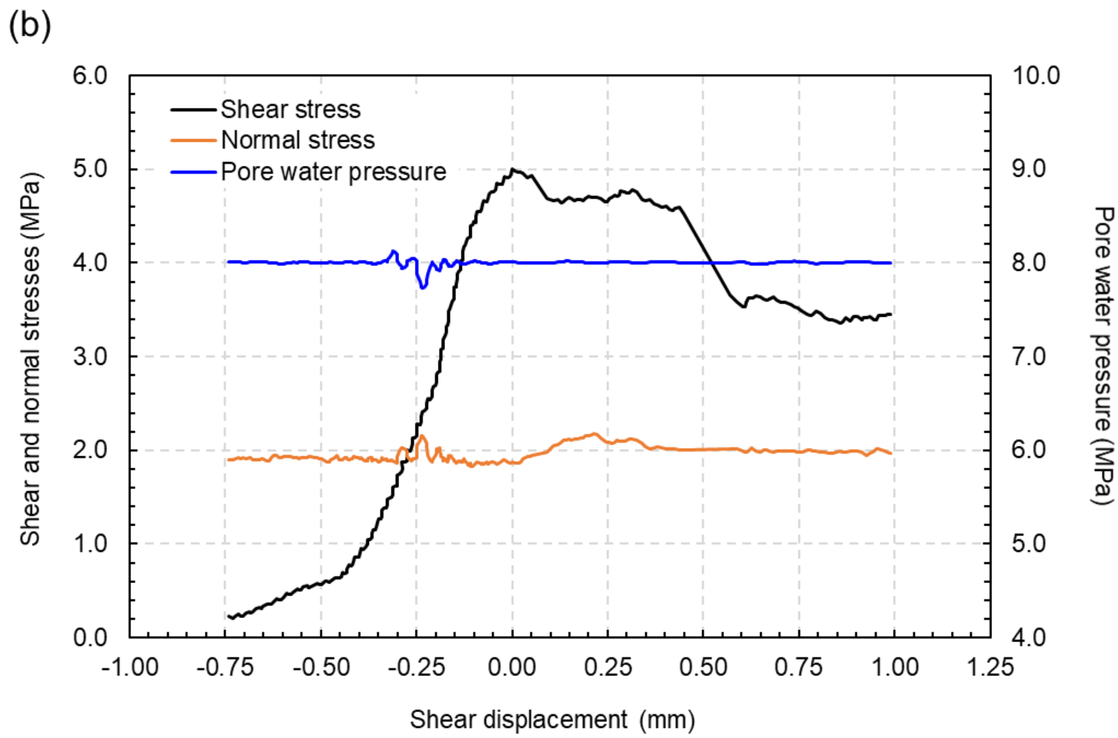


Figure 4. Representative shear stress – shear displacement curve of saturated joint (SWG-J-1), along with the normal stress: (a) normal displacement; (b) pore water pressure. Note that, for normal displacement, a negative sign refers to contraction, while a positive sign is dilation.

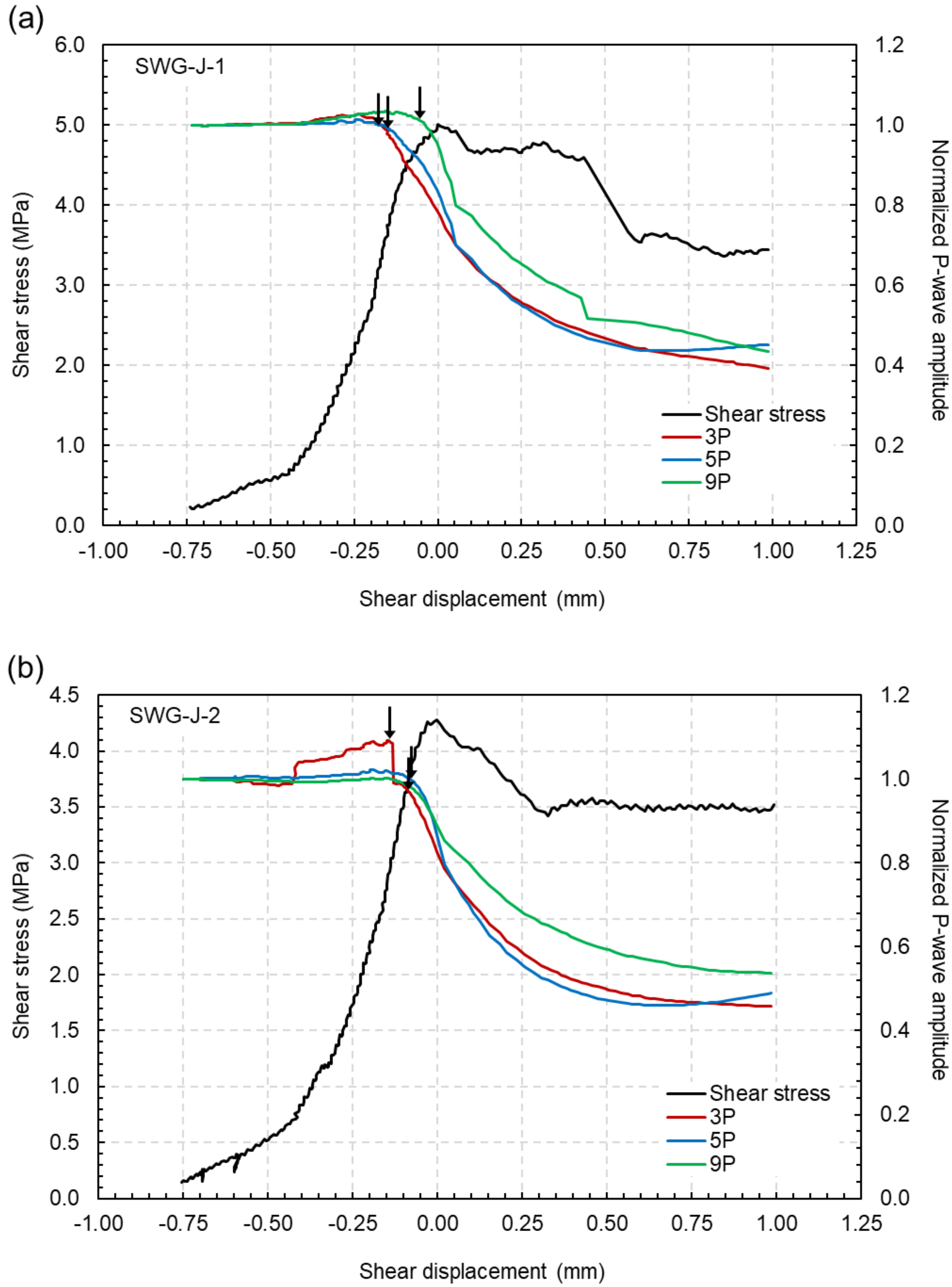


Figure 5. Transmitted P-wave amplitudes through saturated granite joints: (a) SWG-J-1; (b) SWG-J-2; (c) SWG-J-3.

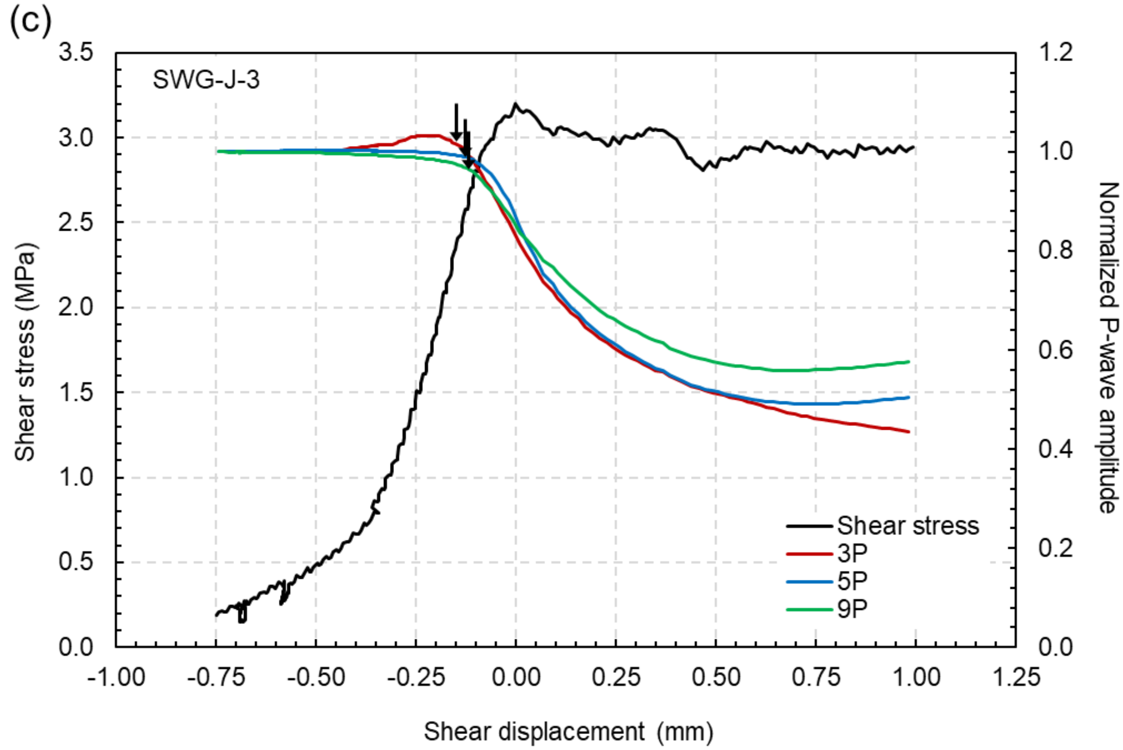


Figure 5. Transmitted P-wave amplitudes through saturated granite joints: (a) SWG-J-1; (b) SWG-J-2; (c) SWG-J-3. (continued)