Development of a direct shear testing method using true triaxial apparatus

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Abstract. Instability of faults and weak joints of rock mass is affected by underground three-dimensional loading conditions as well as hydrostatical fluid pressure within pores and cracks. This paper presents a direct shear testing method to characterize the shear behavior of Kimachi sandstones under various pore pressures and joint roughnesses. The direct shear test was conducted under three mutually perpendicular loads and with various levels of pore pressure through effective utilization of a true triaxial loading system. An overview of the experimental method, its advantages, and results showing the usefulness of the experiment were presented. Sample permeability in the direction parallel to the joint was measured during the shear test.

1. Introduction

Instability of faults and weak joints of rock mass is affected by underground three-dimensional loading conditions as well as hydrostatical fluid pressure within pores and cracks. For example, the intermediate principal stress modifies the shear strength of rock mass, and elevated pore pressure can promote opening or sliding of the existing faults. Effects of these conditions on shear strength of rock joint are important for predicting and mitigating geohazards related to fault and rock joint instability.

Direct shear test under high pore pressure using the conventional triaxial loading machine has been conducted to investigate the shear behavior of geomaterials. Carey et al. (2015) conducted a direct shear test with a cylindrical specimen using the conventional triaxial testing machine to study the effect of the anisotropy of shale on the shear behavior [1]. Zhang et al. (2019) also conducted a direct shear test to study the effect of supercritical carbon dioxide injection on the shear behavior of sandstone under high pore pressure and temperature [2]. Welch et al. (2020) conducted experiments on the relationship between shear behavior and permeability of shear surfaces in cementitious materials [3]. The flow rate at the boundary between the cementitious and steel materials was measured during the direct shear test to understand the hydraulic characteristics before and after the shear slip.

Although the shear behavior under high pore pressure has been studied, research on the effects of pore pressure and joint roughness on shear behavior under controlled loading conditions are still limited. This is partly caused by the difficulty of (i) avoiding the fluid leak during the direct shear testing with the elevated pore pressure, and (ii) mimicking three-mutual perpendicular loading by the shear box used for the conventional direct shear test, in which the friction between the specimen and the inner wall is generally uncontrollable.
This paper presents a direct shear testing method to characterize the shear behavior of Kimachi sandstone under elevated pore pressures. The direct shear test of rock joint was conducted in a pressure vessel to investigate the effect of pore pressure on the shear behavior and its permeability. The advantages of using a true triaxial testing machine and a pressure vessel are: (i) relatively high pore pressure can be applied, (ii) the three principal stresses can be controlled independently, and (iii) the generation of the moment due to shear loading can be reduced. This paper presents an overview of the direct shear experimental method and results demonstrating the usefulness of the experiment.

2. Experimental Program

2.1. Testing equipment

The TTT apparatus in Geological Survey of Japan, comprising of a pressure vessel within a biaxial load frame, was used to conduct the direct shear tests (figure 1). The test equipment consisted of three systems that control the load frames, confining oil pressure, and pore-fluid pressure. Details and application studies of this TTT apparatus can be found elsewhere (e.g., [4], [5], [6], and [7]). Three mutually perpendicular loads can be independently applied by the digital servo-controlled system. As shown in figure 1a, loads in X-, Y-, and Z-direction were applied by oil pressure in the vessel, load frame in Y-, and Z-direction, respectively. The axial loads in both Y- and Z-directions were measured by external/internal load cells, and their load capacities are 2500kN in Z-direction and 500kN in Y-direction. Pore pressure and flow rate are measured and controlled by two TELEDYNE ISCO syringe pumps, which can be used to conduct permeability tests of rock samples (figure 1b).

![Figure 1. Apparatus and experimental configuration: (a) Schematic representation of the TTT apparatus showing vertical and horizontal loading pistons and the pressure vessel, (b) Schematic representation of specimen assembly.](image)

In this study, a pair of L-shaped end-loading plugs were used to apply the shear and normal loads (figure 2a, 2b). As shown in figure 2b, the rock sample was placed between two L-shaped loading plugs, and shear and normal loads were applied by the rigid pistons of the true triaxial machine. The rock joint was placed perpendicular to the Y-axis, so the shear load was in the Z-direction, the normal load was in the Y-direction, and the lateral load is in the X-direction (figure 2d). The shear load (vertical) was applied by raising the bottom piston, whereas the normal load (horizontal) was applied by the left and right Y-direction pistons. The left piston was load-controlled and the right piston was displacement-controlled so that constant stress was applied to the joint surface of the rock sample. The friction between the piston and the L-shape loading plugs in the Y-direction is reduced by the roller at the connection of the piston (figure 1a). Furthermore, the lateral load, which is generally not controlled in the conventional direct shear testing, was controlled by the confining pressure.
The L-shaped end-loading plugs were connected to permeability measurements units, which in turn, were connected to up- and downstream lines along Z-axis (figure 2b, figure 2c). Pore pressure and flow rate were controlled by these units. As shown in figure 2a, a groove was made on the contact surface of plug to allow water to pass through. Low-viscosity silicon and silicon sealant were used to seal the rock sample surface and to bond the rock sample to the L-shape loading plugs (figure 2c). The low-viscosity silicon and silicon sealant can stretch and follow the shear deformation of ~4.0 mm and prevent the inflow of confining oil during deformation with large dilation.

Compared to the conventional direct shear testing, the proposed shear apparatus utilizing true triaxial equipment exhibited three primary advantages. First, relatively high pore pressure can be applied during the shear loading. This is because the pore pressure inside the rock sample is suppressed by the confining pressure using a pressure vessel to prevent leakage. In contrast to the conventional direct shear test, the pore pressure can be as high as 50 MPa based on the allowable pressure of the pressure vessel and the hydraulic lines.

Second, three mutually perpendicular loads can be independently controlled during shear deformation through a true triaxial apparatus. In particular, the ability to control the lateral load (X direction) is a unique feature of this method (figure 2d). The lateral load can be controlled by the confining oil pressure without friction. A shear box used in the conventional direct shear test generally restricts the stress and deformation perpendicular to the shear loading direction, which corresponds to the minimum principal stress in the X direction in this test (figure 2d). The friction between the inner surface of the shear box and the rock sample affects the shear behavior, including the shear strength. The rock surface of the X plane in this test is exposed to silicon jacket and the confining oil so that the stress and deformation are not restricted.

Third, the rotational moment caused by the shear load can be counteracted by two rigid pistons in the Y direction. The pistons, which are sufficiently rigid compared to the rock sample, control the displacement of the steel plugs so that the angle of the surface subjected to the vertical load (vertical) and the load on the surface are kept constant during shear. For example, in the direct shear test using the conventional triaxial apparatus with a half-split cylindrical sample, the normal load to the joint surface is applied by confining oil pressure. In such a case, the deformation of the rock sample due to the rotational moment is not controlled, and the shear behavior may not be properly evaluated.

2.2. Specimen Description

Kimachi sandstone was used in this study. Kimachi sandstone is distributed around Lake Shinji, Shimane Prefecture (western Japan), and the porosity and permeability of intact samples are 21.3%, 1.6×10⁻¹¹m/s, respectively [8]. A rock sample of rectangular parallelepipeds with dimensions of 35×35×70 mm³ was split in half lengthwise, and the area of 35×70 mm² (sheared in the longitudinal...
direction) was the joint surface. The experimental parameters were the normal stress, the roughness of the rock joint, and the pore pressure. Two types of joint roughness were prepared: smooth and rough. The smooth surface was made by using a grinder, and the rough surface was created by hammering a chisel. The cases shown in table 1 were tested to confirm the basic performance of the proposed direct shear test and to investigate the effect of pore pressure on the shear surface.

| Table 1. Experimental condition. |
|----------------------------------|
| Roughness | Normal stress (MPa) | Confining stress (MPa) | Pore pressure (MPa) | Loading rate (mm/min) |
|----------|---------------------|-----------------------|--------------------|-----------------------|
| Case 1   | smooth              | 5.7                   | 3.0                | 1                    | 0.002                |
| Case 2   | smooth              | 8.0                   | 6.0                | 1,2,3,4              | 0.02                 |
| Case 3   | rough               | 7.5                   | 3.0                | 1                    | 0.02                 |

2.3. Experimental procedure
The procedure of this experiment is described below.
(1) The saturated rock sample was covered with silicon.
(2) After attaching the displacement transducer and hydraulic line, place the rock sample in the pressure vessel. To apply constant normal stress to the rock joint, the left piston was load-controlled and the right piston was displacement-controlled (displacement was fixed during the experiment).
(3) Confining pressure and pore pressure were increased to a specified value.
(4) Shear load in the Z direction (vertical) was increased under the condition of displacement control at a constant loading rate.
(5) Flow pump tests were performed to measure rock sample permeability. According to Darcy’s law, permeability can be expressed as

\[ k = \frac{LQ}{S\Delta P} \]  

where \( k \) is permeability, \( L \) is length, \( Q \) is flow rate, \( S \) is cross section of the sample, \( \Delta P \) is hydraulic head difference. In the flow pump test, after the pore pressure in the rock sample reached equilibrium, the fluid was flown at a constant rate from one end of the specimen to measure the water head between upstream (syringe pump A) and downstream (syringe pump B) reservoirs. The syringe pump in the upstream and downstream side were controlled by a constant flow rate and constant pressure, respectively.

Figure 3. (a) Rock sample with: (a) smooth joint surface, and (b) rough joint surface.
3. Results and Discussion

3.1. Case 1
Figure 4 shows the shear stress and permeability as a function of shear displacement as a result of the Case 1 experiment. The shear stress reached 4.4 MPa at a shear displacement of 0.22 mm, after which the shear stress was almost constant. The peak shear stress, 4.6 MPa, was reached at a shear displacement of 1.34 mm. The loading was stopped when the shear displacement exceeded 2.0 mm. The permeability test was performed by controlling upstream flow rate as 0.005 ml/min and downstream pressure as 1 MPa, and the hydraulic head between upstream and downstream was measured continuously during the shear test. The shear displacement rate in Case 1 was set to 0.002 mm/min to ensure stable differential hydraulic head measurements. The permeability was initially $2.97 \times 10^{-10}$ m/s and decreased with increasing shear stress, and the decreasing rate was decreased at the stage of constant shear stress. The minimum permeability, $1.31 \times 10^{-10}$ m/s, was observed at the shear displacement of 1.74 mm. The experimental results show that the permeability of rocks with joint is closely related to the shear stress.

![Figure 4](image_url)

**Figure 4.** Shear stress and permeability as a function of shear displacement.

3.2. Case 2
Figure 5a shows the relationship between shear stress, pore pressure, permeability, and shear displacement. In Case 2, pore pressure was incrementally increased as 1, 2, 3, and 4 MPa during the shear test to investigate the effect of pore pressure. The peak shear stress reached 4.26 MPa at the shear displacement of 0.20 mm and the shear stress softened slightly. Permeability was measured by the flow pump method at two points: before shear loading and after the peak shear stress. The permeability was $4.37 \times 10^{-10}$ m/s at the first point and $1.55 \times 10^{-10}$ m/s at the second point. As in Case 1, the permeability decreased after the peak shear stress.

In this experiment, the pore water pressure was increased by 1 MPa for every 0.5 mm increase in shear displacement. As expected, the increase in pore pressure affected shear stress. Figure 5b shows the relationship between shear stress and effective normal stress at the peak and immediately after the change in pore pressure. Figure 5b shows the effect of the pore pressure on the shear stress.

![Figure 5](image_url)

**Figure 5.** (a) Shear stress and permeability as a function of shear displacement, and (b) relationship between shear stress and effective normal stress.
3.3. Case 3

Figure 6 shows the relationship between shear stress, permeability, normal displacement to shear displacement. The peak shear stress reached 17.5 MPa at a shear displacement of 0.42 mm, and then tended to soften gently and stabilize at the residual shear stress. The rock sample in Case 3 showed higher peak shear stress than Cases 1 and 2 due to its rough surface and the higher normal load. The normal displacement increased with the increase in shear displacement. Permeability was measured at four points: before shear loading and after the peak shear stress via the flow pump method. The permeability was $3.12 \times 10^{-10}$ m/s at the first point, $1.30 \times 10^{-10}$ m/s at the second point, $1.14 \times 10^{-10}$ m/s at the third point, and $1.30 \times 10^{-10}$ m/s at the fourth point. As in Case 1 and 2, the permeability after the peak shear stress was lower than before. Because a steady-state flow in rock samples was achieved about one hour, the shear stress drops were observed due to relaxation. However, when the shear load was applied again, the shear stress increased to the original level and started to slip again. Assuming that the opening of the joint surface is directly related to the vertical water flow, it is expected that there is a certain relationship between permeability and normal displacement, but in this experiment, there was no clear relationship between the two values. This result may indicate that the aperture of the shear surface does not simply control the permeability of the rock joint.

Figure 6. Shear stress, permeability, and normal displacement (in the Y direction, dilation is positive) as a function of shear displacement.

4. Conclusion

In this study, the direct shear tests were conducted using the true triaxial apparatus that can control mutually perpendicular principal stresses and pore pressures independently. The L-shape loading plugs, which were used to apply shear and normal load in the pressure vessel, was devised. The observed results showed the effect of effective normal stress on the shear strength. In the future, we plan to investigate the effect of rock roughness and effective normal stress on shear behaviors, the effect of the lateral (X direction) loading on shear behaviors, and the hydraulic and mechanical responses associated with fracture plane reactivation induced by elevated pore pressure.

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