Effect of intermediate stress on permeability of sedimentary rock under true triaxial compression

D Asahina¹, T Takemura², M Sato¹,³, S Kawakita⁴,⁵ and Y Li²

¹Geological Survey of Japan, AIST, Ibaraki, JAPAN
²Department of Earth and Environmental Sciences, Nihon University, Tokyo, JAPAN
³now at Central Research Institute of Electric Power Industry, Chiba, JAPAN
⁴Department of Oceanic Architecture and Engineering, Nihon University, Tokyo, JAPAN
⁵now at Obayashi Corporation, Tokyo, JAPAN

Email: d-asahina@aist.go.jp

Abstract. In this paper, we conducted lab-scale experiments on siliceous mudstone from Horonobe URL to study the effect of the stress state of rock mass during the excavation of underground openings on their mechanical and hydraulic properties. A true triaxial testing apparatus was used to simulate the changes in the stress field of sedimental rock mass around the opening. A hydraulic line was equipped in two principal directions allowed direct measurement of permeability anisotropy during the test. Two stress states, before and after excavation, were considered to simulate the stress field near the opening. Besides, two intermediate principal stresses were also considered so that rock failure occurred in the stress field corresponding to the top and sidewalls of the opening. The results of siliceous mudstones show that the permeability can be lower under residual stress after macrocrack failure than under intact initial stress. Studies on the effect of crack direction and stress field changes on permeability are limited, especially in sedimentary rocks, and therefore, the results of this study can contribute to the development of a coupled hydraulic-mechanical model with a proper constitutive model to evaluate the excavation damage zone.

1. Introduction

Excavation of underground openings induces rock mass deformation due to the release of overburden/tectonic stress and pore pressure, causing damage to the rock mass and changing its permeability. Fracture developments around the openings can cause mechanical instability, and can also be a new flow path for groundwater. The region where such mechanical and hydraulic changes occur is called the excavation damage zone, EDZ. The concept, idea, and importance of the EDZs have been discussed and studied, especially in the field of geological disposal of radioactive waste [1].

Aoyagi and Ishii (2018) carried out in-situ tests of the EDZ about its development and hydraulic conductivity in the Horonobe Underground Research Laboratory (URL) at a depth of 350 m. The observations of crack distribution show that EDZ cracks (cracks in the EDZ) extend from the wall to about 0.6 m for the sidewall and 1.6 m for the floor, and hydraulic conductivity in the EDZ is about 2 to 5 orders of magnitude higher than that around EDZ. Sato, et al. (2000) also conducted in-situ tests at the Tono Mine and found that the EDZ was at least 0.3-0.5 m, and hydraulic conductivity showed an increasing trend of more than two orders of magnitude in the range of 0.5 m-1.0 m from the wall [2]. Bossart, et al. (2002, 2004) studied the relationship between geological structure and hydraulic
properties in the EDZ of the Mont Terri Rock Laboratory [3,4]. They proposed a conceptual model of the EDZ, and comprehensively discussed the data from various tests, such as visualization of crack networks by injection of resin, and permeability tests. Their conceptual model of EDZ shows that the crack network is formed within 1.0 m from the tunnel wall and it affects the increase of hydraulic conductivity.

Although many studies have been conducted to investigate the mechanical and hydraulic properties of EDZ, studies on the effect of crack direction and stress field changes on permeability under controlled triaxial stress conditions are still limited, especially in sedimentary rocks. This is partly due to the difficulty in measuring permeability anisotropy during the test.

This paper presents the laboratory experiments on siliceous mudstone to study the effect of stress state change caused by the excavation of a rock mass on its permeability. The permeability was measured at the several stress states which were controlled by the true triaxial testing (TTT) apparatus. The anisotropy of permeability was investigated when the intermediate principal stress was changed. The presented TTT apparatus can evaluate the permeability anisotropy under various stress conditions, and enables the investigation of hydraulic-mechanical characteristics.

2. Experiment

2.1. Equipment

Figure 1 shows schematic diagrams of the true triaxial test (TTT) apparatus at the Geological Survey of Japan. Details of the TTT apparatus can be found elsewhere ([5], [6], and [7]). The digital servo-controlled TTT apparatus is capable of independently applying three principal compressive stresses. Loads in maximum and intermediate stress directions (corresponded Z- and Y-direction in Figure 1, respectively) were applied by two rigid pistons, whereas minimum principal stress was directly applied by oil pressure in the vessel. Under the employed triaxial stress condition (i.e., $\sigma_X < \sigma_Y < \sigma_Z$), the direction of the failure plane became parallel to the Y-direction. The axial loads in both Y- and Z-directions were measured by external/internal load cells, and their load capacities are 2500 kN in Z-direction and 500 kN 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). A hydraulic line was equipped in two principal directions, $\sigma_Z$ and $\sigma_Y$, which allowed direct measurement of permeability anisotropy during the test.

![Figure 1](image1.png)

**Figure 1.** (a) Schematic representation of the TTT apparatus showing vertical and horizontal loading pistons and the pressure vessel, and (b) schematic representation of specimen assembly, where 1 is the specimen, 2 and 3 are the endloading plugs for Y- and Z-directions, respectively; 4 indicates porous metal plates for water dispersion; 5, 6, and 7 are LVDTs for X-, Y-, and Z directions, respectively; and 8 is the silicon sealant. (after [7]).
2.2. Specimen description

The rock samples were taken from the Wakkanai formation, which is categorized as massive (thickness > 200 m) and lithologically homogeneous siliceous mudstones, from the Horonobe URL (Figure 2a). The mechanical properties of Wakkanai formation siliceous mudstone can be found in literature [1]. The porosity and permeability of the intact sample are approximately 40% and $2.0 \times 10^{-12} - 2.0 \times 10^{-11}$ m/s, respectively. The rock samples were cut into rectangular parallelepipeds with dimensions of 70 x 35 x 35 mm$^3$. As shown in Figure 2b, the rock sample attachment consists of metal plates for water dispersion, copper foil, and a Teflon sheet sandwiched between the rock sample and the endloading plugs placed vertically and horizontally. The surface of the rock sample was covered with silicone sealant, and the rock sample and endloading plugs were bonded as shown in Figure 2c. The rock specimens were then placed on the test stand and connected to the permeability lines in the vertical Z and horizontal Y directions (Figure 1b). The rock samples were saturated with distilled water for more than one month.

![Image 1](image1.png)

![Image 2](image2.png)

![Image 3](image3.png)

Figure 2. (a) Siliceous mudstone sample, (b) rock sample attachment, and (c) a rock sample in the assembly showing LVDTs, two fluid lines, and the silicon sealant-coated rock sample.

2.3. Experimental procedure

In this experiment, we consider the effect of the following three factors on the stress state of tunnel walls: (i) direction of the initial in-situ stresses and the axis of the tunnel, (ii) location of the tunnel cross-section (the top and sidewall), and (iii) progress of the excavation front [8]. The loads were controlled so that failure occurred in two stress conditions: stress state close to uniaxial compression which corresponding to the top face of the tunnel (Case 1), and that to biaxial compression which corresponding to the side walls (Case 2).
The initial stress setting in the experiment is based on the value at the Horonobe URL (350m depth). In the Horonobe URL, the stress ratios are 1.3, 1.0, and 0.9 in the order of $\sigma_1$, $\sigma_2$, and $\sigma_3$. The three stages of the experimental procedure are described below.

Stage 1: The confining pressure, $\sigma_X$, was increased to a stress value of 8.5 MPa. Then, the loads in $\sigma_Z$ and $\sigma_Y$ were increased to 10.8 MPa and 8.9 MPa, respectively. The pore pressure was set to 3.5 MPa.

Stage 2: In the uniaxial compression test (Case 1), the $\sigma_Y$ and $\sigma_X$ were kept constant, and the $\sigma_Z$ was increased until failure. In the biaxial compression test (Case 2), the $\sigma_Z$ and $\sigma_Y$ were increased to 80% of the peak stress of Case 1 while the $\sigma_X$ was kept constant. Then the $\sigma_Z$ was increased until failure. After the rock sample failed, the displacement in the $Z$ direction was increased until the residual stress stabilized.

Stage 3: Stresses were decreased to represent the stress state after the excavation. The stress values were 13, 10.5, and 3 MPa for $\sigma_Z$, $\sigma_Y$, and $\sigma_X$. Although the pressure near the excavation wall should be released, we set $\sigma_X$ and pore pressure to 3.0 and 1.0 MPa to measure the permeability.

Permeability tests in two directions, $\sigma_Z$ and $\sigma_Y$, were conducted for each stage. Permeability was measured at room temperature using two syringe pumps (Figure 1b). After the complete flow line was degassed using a vacuum pump, we measured the permeability through the flow pump test. Sample saturation was confirmed by monitoring the pore pressure stability. After confirming the steady state of the water head difference at both ends of the specimen, we calculated the permeability using the following equation.

$$ k = \frac{LQ}{S\Delta P} \quad (1) $$

Where $k$ is permeability, $L$ is sample length, $Q$ is flow rate, $S$ is cross section of the sample, $\Delta P$ is hydraulic head difference. During the flow pump experiments, the differences between the hydraulic heads of reservoirs were maintained at a constant within the measurable range. The fluid was flown at a constant rate of 0.002 mL/min from one end of the specimen to conserve the water head between upstream and downstream reservoir.

3. Results and discussion

Figure 3 shows the time history of principal stresses for two cases. Figure 4 shows the relationship between the differential stress ($\sigma_Z-\sigma_X$), strain in the three directions ($\varepsilon_Z$, $\varepsilon_Y$, $\varepsilon_X$) and volumetric strain ($\varepsilon_V=\varepsilon_Z+\varepsilon_Y+\varepsilon_X$) for each case. In Case 1, the stress-strain curve is linear at first, and gradually shows nonlinear behavior from 40-50% of the peak stress. Case 2, on the other hand, shows nonlinear behavior when loaded in the horizontal Y direction ($\sigma_Y$), but then deforms almost linearly and reaches the peak compressive stress. Comparing Case 1 and Case 2, the behavior of $\varepsilon_Y$ and $\varepsilon_V$ is clearly different. $\varepsilon_Y$ shows a constant value after the load in the Y direction was applied, indicating that it was properly controlled. In Case 1, $\varepsilon_Y$ was on the expansion side, while in Case 2 it was on the compression side. In addition, $\varepsilon_V$ turns to dilation after the peak in case 1, but the change is less in case 2.

Figure 5 shows the results of permeability measurements for each case. The permeability at initial stress was slightly higher in Case 2. In both cases, the permeability in the $\sigma_Z$ direction was higher than that in the $\sigma_Y$, indicating permeability anisotropy. The permeability was lowest at point B of the residual strength after failure. The residual stress at point B is higher than that at points A and C, and it is unlikely that the macrocrack affected the permeability as a flow channel at point B. As discussed by Sato et al. (2018), macrocracks usually increase permeability in crystalline rocks, whereas the effect of macrocracks on permeability is not clear in sedimentary rocks such as sandstone and mudstone. The result obtained in this test indicates that the presence of cracks does not simply lead to an increase in permeability, but that it is necessary to consider the stress field and the conditions of the crack as well.
In stage C, the permeability increased in both cases, which indicates that unloading affects the permeability.

Studies on the effect of crack direction and stress field variation on permeability are limited, especially in sedimentary rocks, and therefore it is important to obtain further experimental data for a proper constitutive model and detailed evaluation of hydraulic-mechanical processes.

![Figure 3](image_url)
**Figure 3.** Stress time histories for: (a) Case 1 (uniaxial compression dominant stress condition), and (b) Case 2 (biaxial compression dominant stress condition). Note that (i), (ii), and (iii) in the figure indicate the time when the permeability test was conducted.

![Figure 4](image_url)
**Figure 4.** Stress-strain curves recorded during test for: (a) Case 1 (uniaxial compression dominant stress condition), and (b) Case 2 (biaxial compression dominant stress condition).

![Figure 5](image_url)
**Figure 5.** Results of permeability measurement at each stress stage shown in Fig 3 for: (a) Case 1 (uniaxial compression dominant stress condition), and (b) Case 2 (biaxial compression dominant stress condition).

Figure 6 shows micro-focused X-ray CT images of the fractured rock sample in Case 1 after removing the applied load and pore pressure. Two inclined macroscopic fractures and a conjugate shear plane can be observed in the rock sample after the experiment (Figure 6a and d). In addition to the shear planes, horizontal cracks propagating outward from the shear planes are also observed. These cracks do not extend through the shear cracks, indicating that they are secondary cracks after the shear
planes are formed. Since shear fracture is usually formed at peak stress, the secondary horizontal cracks were probably formed during residual stress or stress release after the peak stress. The horizontal cracks formed in this test are considered to be caused by friction between the horizontal Y-directional piston and the rock during stress release after residual strength.

Figure 6. Micro-focused X-ray CT images of a rock sample (Case 1, uniaxial compression dominant stress condition): (a) 3D image, (b) X-Y section, (c) Y-Z section, (d) X-Z section.

Figure 7 shows micro-focused X-ray CT images of the fractured rock sample in Case 2. In contrast to Case 1, several vertical cracks can be clearly observed along with diagonal shear cracks in Case 2. The stress state of Case 2 is a biaxial compression dominant stress condition with a large load in Y-directional. Therefore, the dilation of the rock sample only occurred in the $\sigma_X$ direction (X direction), and the vertical cracks are caused by tension in the extensional stress field. In Case 2, the horizontal cracks observed in Case 1 were almost absent. Figure 7b shows that the shear cracks are almost parallel to the Y direction, while the tensile cracks are slightly inclined. This is a result of not only pure tension but also the shear effect due to compressive loading in the horizontal Y direction. As shown in Figure 5, there was no significant difference in the permeability between Cases 1 and 2 after the initial stress in (i) and after the failure in (ii). However, the increase in permeability in the vertical Z direction of Case 2 was relatively large during the stress release (iii). The reason for this is possible that the crack in the vertical direction of Case 2 acted as a water channel due to the stress release.

Figure 7. Micro-focused X-ray CT images of a rock sample (Case 2, biaxial compression dominant stress condition): (a) 3D image, (b) X-Y section, (c) Y-Z section, (d) X-Z section.

4. Conclusion
We conducted laboratory experiments on siliceous mudstone from Horonobe URL to study the effect of stress state change caused by the excavation of a rock mass on permeability. A TTT apparatus was used to control the stress state and measure permeability anisotropy. Flow pump tests were performed to measure permeability in the direction nearly parallel to the fracture plane. As a result, the
permeability of the rock sample at residual stress was lower than that at intact initial stress. The permeability increased when the loads were unloaded. The effect of macroscopic cracks on hydraulic conductivity is not simply based on the presence of cracks, but also on the stress field and differences in roughness due to the opening of fracture widths and particle sizes in rocks.

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