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Development of the permeability anisotropy of submarine sedimentary rocks under true triaxial stresses

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ABSTRACT

The true triaxial test, which can simulate in-situ stress fields of nature which have different scalar quantity along three principal axes of stress, is the most effective experimental method for obtaining the mechanical and permeability property of rocks under overburden and tectonic stresses. The intermediate principal stress (σ_2) is a control on the fracture strength, mechanical behavior and crack distribution of the deformed rocks. Thus, understanding the effect of the stress on the development of permeability anisotropy is crucial. To evaluate the influence of the σ_2 on the permeability anisotropy, the permeability measurement lines in the σ1 and σ_2 directions were added into an upgraded Mogi-type true triaxial test apparatus. We measured the permeability of Berea sandstone and Amatsu mudstone in the σ_1 and σ_2 direction under the conditions of true triaxial compression ($\sigma_3 < \sigma_2 < \sigma_1$) with a constant σ_3. In the Berea sandstone, we found that the permeability reduced with increasing mean stress and the magnitude of permeability anisotropy correlated with the intermediate principal stress. Photomicrographs and X-ray computed tomography observations for post-failure Berea sandstones revealed a phenomenon related to permeability: under high σ_2 conditions, the fault gouge generated along final fractures causes permeability reduction of σ_1 direction. For the Amatsu mudstone is too soft to be subject to brittle deformation. Thus, the development of the permeability anisotropy with increasing mean stresses was more pronounced in the Berea sandstone than the Amatsu mudstone.

1. Introduction

Studies on the permeability of rocks/sediments are important from scientific and engineering perspectives such as underground reservoir engineering. Understanding the permeability behavior of submarine sediments is of fundamental importance to elucidate mechanisms of failure and geomorphological development of accretionary prisms, accumulation, and production of methane hydrate. The direction of fluid flow in rocks depends on the hydraulic gradient and the permeability anisotropy of rocks.[1] In accretionary prism sediments, distribution of fractures, fault gouge and/or cataclasite may affect the permeability anisotropy. A hydraulic gradient may be occasionally caused by, or modified by thermal pressurization during seismic rupturing[2] and/or over-pressurization as a result of methane hydrate dissociation.[3] A number of field and laboratory experiments have been conducted on the permeability anisotropy of fault zones.[4] Researchers previously conducted permeability experiments during conventional triaxial compression ($\sigma_3 = \sigma_2 < \sigma_1$) and extension ($\sigma_3 < \sigma_2 = \sigma_1$) using a cylindrical specimen of weakly-cemented sandstone,[5,6] or porous sandstone including Berea sandstone.[7,8] Recent efforts focusing on permeability change during deformation have also incorporated improvements to the experimental methods of the conventional triaxial compression experiments; Cases in point are the permeability measurements during cyclic loading conditions for investigating cumulative damage and permeability hysteresis of granodiorite and Westerly granite,[9] hydro-mechanical coupling during compressive deformation and development of damage zone of granite,[10] measurements of permeability and structural changes of several kinds of rocks (welded tuff, sandstone and granite) using thin section analysis and X-ray computed tomography,[11] and permeability measurements of fault gouge in mudstone[12].

However, these conventional triaxial compression methods have a clear limitation arising from the cylindrical geometry of the specimen: uni-axial compression or extension must be applied under the isotropic confining pressure. In addition, because only the upper and lower ends of the specimen are attached to the end-pieces, the permeability measurement is limited to the vertical direction only. Fracturing at a low angle to the maximum principal stress (σ_1) eventually occurs by

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increasing axial stress. However, conventional triaxial testing using cylindrical specimens is unable to measure accurate permeability values parallel to the fracture. Conversely, the true triaxial experiment that uses rectangular prismatic specimens enables the accurate measurement of permeability parallel to the final fracture, which is parallel to the intermediate principal stress (σ_2) direction.[13] Since the 1970s, researchers have become aware through true triaxial testing that the σ_2 is also control on the fracture strength, mechanical behavior, crack distribution, and permeability anisotropy of the deformed rocks.[13–17] Thus, understanding the effect of the stress ratio on the development of permeability anisotropy is crucial. In the case of an accretionary prism, numerous faults of various types could occur because of the complicated stress state. The existence of chemosynthetic bio-communities reported from several accretionary prisms indicates the frequent occurrences of seepage of cold fluid that contains methane and/or hydrogen sulfide.[18,19] Near the trench, *Calyptogena* or other chemosynthetic bio-communities were observed to form en échelon assemblages reflecting the underlying fracture patterns[20]. Fluids containing methane and other nutrients seep through these fractures and support the chemosynthetic bio-communities. Ogawa et al. proposed that these orientations indicate the existence of a strike-slip stress regime with a vertical σ_2. Ogawa and Asada[21] proposed that this regime is common in deformation fronts. Ogawa and Vrolijk[22] and Ogawa and Asada[21] presumed that the proto-thrust zone and decollement have high permeability in the σ_2 direction.

Some previous studies have been conducted on the permeability measurements of the σ_2 direction under true triaxial conditions using rectangular prismatic specimens. Li et al.[23] and Takahashi et al.[24] investigated the permeability of the σ_2 direction for Shirahama sandstone using Mogi-type true triaxial testing apparatus.[13,14] Li et al.[23] determined that the permeability in the σ_2 direction decreased with increasing σ_1 and σ_2 before yield stress. Takahashi et al.[24] showed that the permeability after the failure increased at a low confining pressure (i.e. 8 MPa). Conversely, at a higher confining pressure (i.e. 63 MPa) in a ductile regime, the permeability after the failure was less than the initial value. These methods allow the measurement of the permeability along the σ_2 direction; however, no previous study has measured the σ_1 and σ_2 directions simultaneously.

This study aimed to evaluate how the stress ratio affects the permeability anisotropy. For this purpose, the flow pump method was incorporated and permeability measurement lines in the σ_1 direction were added for the permeability anisotropy measurement into an upgraded Mogi-type true triaxial testing apparatus.[24] Using this apparatus, experiments were conducted on Berea sandstone and Amatsu mudstone.

2. Experimental procedure

2.1. Experimental equipment

The tests were conducted using Mogi-type true triaxial testing apparatus at the National Institute of Advanced Industrial Science and Technology of Japan. In this apparatus, maximum and intermediate stresses are applied through two pairs of rigid pistons and minimum stress (σ_3) directly by oil pressure. The servo-controlled apparatus enables three principal compressive stresses to be applied independently. Fig. 1 shows a schematic drawing of the permeability test system under true triaxial stress conditions. The specimen (1) was jacketed with silicone rubber (9). The porous metals (4) of the σ_2 direction have sixty-six holes, and a copper foil was placed between the porous metals (4) and the end-pieces (2). Metal meshes (5) were placed between the specimen (1) and the end-pieces of the σ_1 direction (3). Three local deformation transducers (LDT) (6, 7, 8) were used to measure the deformation of the specimen. In this test system, pore fluid could be easily drained to four ways during loading. In the σ_1 and σ_2 directions, each upstream and downstream line was connected to an ISCO syringe pump, shown as (a) and (b), respectively. The permeability was measured using a flow pump. Li et al.[23] used a transient pulse method to shorten the experimental time; however, this method cannot be used for high-permeability specimens such as Berea sandstone. A wide range of permeability values (10^{-21} to 10^{-11} m^2) can be measured using the flow pump method[25,26]. Therefore, this method was adopted to ease the response to permeability changes caused by deformation during the experiments. In this method, the permeability of a saturated specimen is estimated by measuring the induced flow rates under a constant hydraulic gradient. A rigorous solution to the flow pump method that accounts for the storage capacities of the specimen and the equipment was developed in previous works.[27–29] We calculated the permeability of specimens using this method.

2.2. Specimen description

The specimens used were rectangular prismatic blocks with dimensions of 70 mm × 35 mm × 35 mm and surface parallelism was ± 50 µm. The specimens were prepared to ensure that the longer sides were perpendicular to the bedding planes. The selected rocks were Berea sandstone (USA) and Amatsu mudstone (Boso Peninsula, Japan). The Berea sandstone was chosen as a control because there are numerous previous reports on its various mechanical behaviors and/or permeability. Thus, by comparing the results of this study and previous studies we can assess the reliability of our measurements. The mechanical behavior and permeability of the Amatsu mudstone is unknown. Similar rocks to Amatsu mudstones are widely distributed in the Boso peninsula in an arc–arc collision zone and forearc basin[30], and such sedimentary stones are thought to have been important controls in the deformation of the whole sequence to form an accretionary prism. The permeability of mudstone is important in the subsurface stress environment because mudstone has a large changeable permeability as a result of the pore collapse or flow/failure caused by compressional or extensional stress. Before conducting the experiments, we measured the porosity of Berea sandstone to be 19.5%, and that of Amatsu mudstone to be 40% using a mercury intrusion porosimetry.

2.3. Test procedure

This study focused on investigating the effect of intermediate principal stress and permeability anisotropy development. Therefore, the confining pressure was kept constant at 10 MPa for the Berea sandstone and 3 MPa for the Amatsu mudstone after initial isotropic loading. The pore pressure was also kept constant at 1 MPa after the initial loading. In the experiment described herein, the three principal stresses were applied in the following order, as shown in Fig. 2. Firstly, a hydraulic pressure of 2 MPa was applied. At this time, specimen and fluid flow line were evacuated to remove air from pore. After the specimen was saturated with distilled de-aired water, the saturation was confirmed by checking pore pressure stability at 1 MPa using syringe pump. Following this, the hydrostatic pressure σ_3 was applied up to the value A. Afterwards, loading in the σ_2 and σ_1 directions were increased simultaneously by load control up to the σ_2 value B. Finally, the load along σ_1 direction was increased by stroke control at constant strain rate (0.015% / min) to the final strength C. During the above processes, permeability measurement was conducted as necessary during temporary pauses.

Flow pump experiments were performed by injecting distilled de-aired water at a constant rate from an upstream reservoir into the specimen using an ISCO syringe pump, and measuring the differential pressure between the top and bottom surfaces of the specimen. The analytical solution of the flow pump experiment is shown in the following equations[28]: