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Development of coupled shear-flow-visualization apparatus and data analysis ☆

H. Park [a,*], M. Osada [b], T. Matsushita [a], M. Takahashi [c], K. Ito [c]

[a] *Graduate School of Science and Engineering, Saitama University Saitama, Japan*
[b] *Geosphere Research Institute of Saitama University, Saitama, Japan*
[c] *National Institute of Advanced Industrial Science and Technology, Tsukuba, Ibaraki 305 8567, Japan*

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ABSTRACT

A new type apparatus for shear-flow coupling test, named coupled shear-flow-visualization apparatus, was developed to investigate the hydromechanical behavior and the fracturing process of intact soft sedimentary rock. With this apparatus, it is possible to simultaneously carry out direct shear test and constant head flow test, and also to observe specimen surface during the experiment. Under controlled shear load, normal load, flow rate and shear displacement can be obtained as raw data. Moreover, fracture area and fracture apertures can be estimated using image-processing techniques. The shear and normal stress capacities of load cells are 4.08 MPa and 3.33 MPa, respectively. The measurable maximum permeability of apparatus is about 5.80×10^{-3} cm/s under a hydraulic gradient of 40 cm/cm. According to the observation of visible fractures on specimen surface, the fractures were not completely propagated at the peak of shear stress. The developed testing method with image processing techniques enabled us to analyze the relationships between fracture flow rate, hydraulic aperture and two fracture apertures defined in this study.

1. Introduction

Understanding of deformation-related fluid flow is required to various research fields for example, shale as cap rock of hydrocarbons, underground excavation field for a radioactive waste repository, or stimulation of tight gas fields, or stimulation of hard rock in geothermal reservoirs, etc. Although rock mass with fewer fractures is carefully selected to build underground facility, newly created fractures due to underground excavation cause mechanical and hydrological problems around the excavated space [1,2]. Especially, excavation damaged zone (EDZ) [3] that is formed along the underground excavated space has the potential to create pathways for water flow. If hazardous substance such as radioactive waste leaks through the fractures from repository to human environment, the EDZ can raise serious problems.

The EDZ fractures are generated through a variety of mechanisms (e.g. tensional, shear or mixed deformation) with various scales (size, frequency, distance from tunnel wall, etc.) [4–6]. In the Mont Terri Rock Laboratory of Switzerland, Thury and Bossart [7] performed their case study, mapping unloading joints in EDZ using fluorescene-doped epoxy resin. Resin-filled joints were observed in the drill cores from boreholes to depths of about 80 cm from the tunnel wall. Bossart et al. [6] presented a structural data set of fracture orientations, frequencies and extent of the EDZ in a newly excavated side niche. Tomita et al. [8] reported spalling and core disking phenomena in a research gallery of 100 m underground located at Rokkasho in Aomori prefecture of Japan. Most of these researches are involved with newly created fractures in EDZ. It is fundamental to understand the process of fracture initiation and propagation in intact rock to understand the in situ behavior of hydromechanical properties. According to the conceptual model of EDZ by Bossart et al. [9], the stress relief due to underground excavation forms unloading joints parallel to the tunnel wall. On the other hand, shear fractures are also created in conjunction with the unloading joints. These fractures induced by shear deformation connect the neighboring unloading joints that are isolated in the beginning of EDZ formation.

We focused on the fractures due to shear deformation that mainly influence the flow rate change in EDZ. First of all, a test apparatus called coupled shear-flow-visualization apparatus was developed by Saitama University of Japan to perform the shear-flow coupling test and visualize the entire shearing process simultaneously. The relationships between shear stress, normal stress, water flow rate and fracture apertures were comprehensively investigated.

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* Corresponding author. Now at: National Institute of Advanced Industrial Science and Technology, Tsukuba, Ibaraki 305 8567, Japan. Tel.: +81 298613809.
E-mail addresses: park-h@aist.go.jp, geosaico@daum.net (H. Park).

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In this paper, Section 2 introduces the mechanism and components of the developed test apparatus that improves conventional shear-flow coupling test. Section 3 presents the application and the experimental results of the developed test apparatus to intact soft sedimentary rock. In Section 4, we discuss about relationships between the obtained data.

2. Development of coupled shear-flow-visualization apparatus

2.1. Previous studies

The shear-flow coupling tests are classified into two different groups, depending on whether a specimen with a naturally (or artificially) generated single fracture or an intact specimen is employed. Simple-shear type instruments [10–12] and rotary shear type instruments [13,14] were used to examine specimen with a single fracture, whereas the conventional triaxial test apparatus [15–17] was mostly used to assess intact specimen. Recently, a new direct shear apparatus [18,19], which can be applied to intact samples, has been introduced. Esaki et al. [11] compared mechanical aperture and hydraulic aperture using a shear-flow test apparatus of their own design. They indicated that Barton's model [20] is not able to predict the change of joint hydraulic conductivity during residual shear deformation. Zhang et al. [21] pointed out several problems of shear-flow coupling method with mentioning advantages and disadvantages of direct-shear testing methods and indirect-shear testing methods. They suggested preconditions for advanced shear-flow coupling test apparatus as follows: (i) it must be possible to carry out the hydraulic conductivity test during the entire experiment. In addition the shear strain needs to be measured, (ii) water flow direction and shear plane must be clearly defined, (iii) structure of apparatus and test procedure must be simplified and accuracy must be guaranteed as high as possible, (iv) it must be flexible to diverse flow tests, (v) volume loss or erosion must be inhibited in the case of weak material.

In spite of the difficulties to observe fracturing process in rock, many researchers have tried to develop several test apparatus. For example, Means [22] has used transmitted light photomicrographs to perform a deformation experiment with a thin slab of granular material. Iwamatsu and Yamada [23] have challenged the direct observation of rock fracturing with the bore-scope that was installed in high-pressure vessel. Also, some researchers executed the observation using scanning electron microscope (SEM) [24–26] or stereomicroscope [27], and other recent studies acquired continuous data from charge-coupled device (CCD) camera [28,29]. For capturing of flow through rock joint, Jiang et al. [28] designed replica rock joints consisted of a transparent epoxy rock that was covered with a natural joint surface.

2.2. Coupled shear-flow-visualization apparatus

Even though it is difficult to satisfy all the preconditions as Zhang et al. suggested that the developed test apparatus responds to the preconditions as follows: (i) the entire test includes constant-head flow test. The shear strain is obtained from an image processing using the CCD images. Enough shear distance is secured to make it possible that shear stress value reaches to the residual strength, (ii) the specially designed shear frames are used to gain the center located fractures. The water flow direction is set in the direction from the bottom of specimen to the top, (iii) the simple shear type is considered to simplify the test and to visualize fractures, (iv) the new apparatus allows the constant-head method, (v) further consideration is still needed for the volume loss or erosion during shear-flow coupling test.

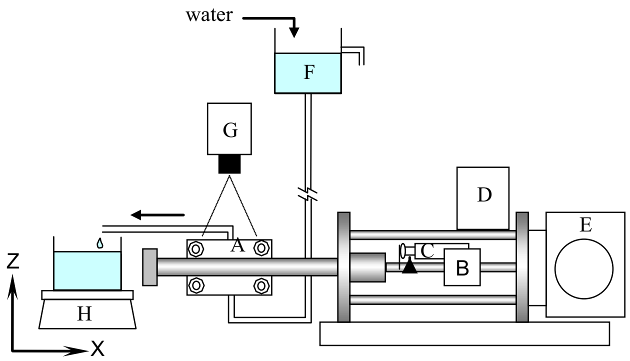

Fig. 1. Schematic of shear-flow-visualization coupling test apparatus (side view). (A) Shear-normal loading unit, (B) shear load cell, (C) linear variable differential transformer (LVDT), (D) controller, (E) electronic motor, (F) water tank (constant head), (G) CCD camera, (H) electronic balance.

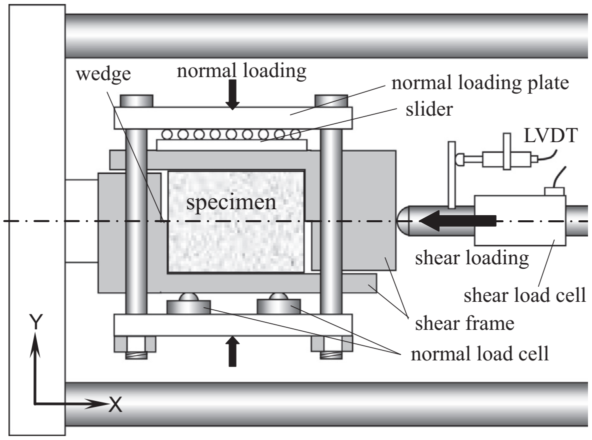

Fig. 2. Schematic of shear-normal loading unit (plane view, specimen size: length 60 mm, width 40 mm, height 20 mm).

One of the main characteristics of the developed test apparatus is to observe specimen surface directly during the test. Fig. 1 presents the schematic of coupled shear-flow-visualization apparatus. It consists of a shear-normal loading unit, a flow testing unit and a digital image recording unit.

2.2.1. Shear-normal loading unit

The shear-normal loading unit (Fig. 2) has two L-shaped shear frames that are the same height (20 mm) as specimen. Each frame has 90° wedge to create fractures in the middle of specimen. Therefore, the wedges of shear frames, the center of specimen and the shear load cell are arranged on the same axis. One load cell (capacity 4.9 kN) and two load cells (capacity 2.0 kN each) are used to measure shear loading and normal loading, respectively. According to the capacities of load cells and specimen size, the ranges of shear stress and normal stress are 4.08 MPa and 3.33 MPa. The friction between shear frames does not occur since they are fully separated. The slider reduces friction between the shear frame and the normal loading plate. The displacement of shear frame can be measured with a linear variable differential transformer (LVDT). The normal loading plates are bounded manually by four beams. Thus, the normal directional expansion is restricted. Note that the normal stress was not servo-controlled in this study. The required specimen shape is a rectangular parallelepiped in 60 mm × 40 mm × 20 mm size.