International Journal of Rock Mechanics and Mining Sciences 100 (2017) 10–22

Contents lists available at ScienceDirect

International Journal of
Rock Mechanics and Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Estimation of the highest potential transmissivity of discrete shear fractures using the ductility index

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ARTICLE INFO

Keywords:
Ductility index
Paleostress analysis
Shear fractures
Transmissivity

ABSTRACT

Previous studies indicated that the highest potential transmissivities of fractures in fault zones might be well estimated by a mechanical indicator: the ductility index (DI). The DI is defined as the effective mean stress normalized to the tensile strength of the intact rock mass. The mechanism of formation and preservation of pore structures in fault-zone fractures can be explained by local shear-induced tensile stresses, and pore structures in discrete shear fractures may form in the same way. I investigated, therefore, whether the DI model can correctly predict the highest transmissivities of shear fractures recorded in fractured Neogene diatomaceous mudstone (Koetoi Formation), where fault zones and joints are rare but discrete shear fractures, without mineral fillings, are abundant. Analyses of the shear fractures reveal that the detected states of paleostress are nearly equal to the current stress state, implying the shear fractures have potentially been tectonically active. Thus, the highest transmissivities detected at fractures by flowing-fluids electric conductivity (FFEC) borehole logging may potentially be treated as the highest potential transmissivities in terms of the given DIs. Relationships between the transmissivities of flow anomalies and DIs fit the existing DI model well, which suggests the model is applicable to discrete shear fracture systems as well as fault zones.

1. Introduction

Understanding the transmissivities of fractures in underground rock masses is critical in the siting, design, and safety assessment of radioactive waste disposal facilities.[1–4] In particular, knowing the highest potential transmissivities of individual fractures are important for a conservative assessment in the evaluation of groundwater flow velocities. However, it is not realistic to measure the transmissivities of all possible fractures at a site. Thus, it is essential to elaborate an indirect indicator, whose spatial distributions can be mapped.[5]

Deep underground in situ stresses are compressive, except where pore pressures significantly exceed the minimum principle stress. Thus, maintaining open fractures requires locally induced tensile stresses,[5] although mineral bridges in fractures can also maintain local fracture opening.[6] The opening in releasing sections of shear zones can be preserved as long as shear-induced tensile stresses remain[5] (Fig. 1). However, they may be filled by mineral precipitates.[7]

With regard to the highest potential transmissivities of fault-zone fractures, and based on Barton's critical state model,[8] Ishii[5] pointed out semi-empirically that the potential of shear-induced tensile stresses generated within fault-zone fractures has a close relationship with the ductility index (DI): the smaller the DI, the greater the potential for shear-induced tensile stress. The DI is defined as the far-field effective mean stress (σ'_m: MPa) normalized to the tensile strength (σ_t: MPa) of intact rock. The highest potential transmissivities of fractures in fault zones (T: m^2/s) can be predicted by the following relationships (Fig. 2a):

$$\log T = -3.51 \log DI - 6.54 \text{ (standard error} = 1.25 \text{ in logT)}, \tag{1}$$

$$DI = \frac{\sigma'_m}{\sigma_t}, \tag{2}$$

$$\sigma'_m = \frac{\sigma_1 + \sigma_3}{2} - p, \tag{3}$$

where σ_1 and σ_3 are the maximum and minimum principal stresses (MPa), respectively, and p is pore pressure (MPa). Although rock strength in a fault zone may be partly reduced by fault deformation, the DI model uses the strengths of intact host rocks for the following reasons: (1) a harder rock (high σ_t) is likely to allow greater dilation, thus the strength of intact rock gives a more conservative prediction of the highest potential transmissivities; and (2) the strengths of intact rocks can be more consistently defined and measured.[5] Although the mean stresses around faults can be perturbed by failure within the damage zone,[9] the DI model uses the mean stresses calculated from the far-field stresses.[5] Ishii[5,10] discussed in detail the influence of fracture mineralization/mineral dissolution, fracture orientation, and hydrogeological

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http://dx.doi.org/10.1016/j.ijrmms.2017.10.017
Received 22 February 2017; Received in revised form 1 June 2017; Accepted 17 October 2017

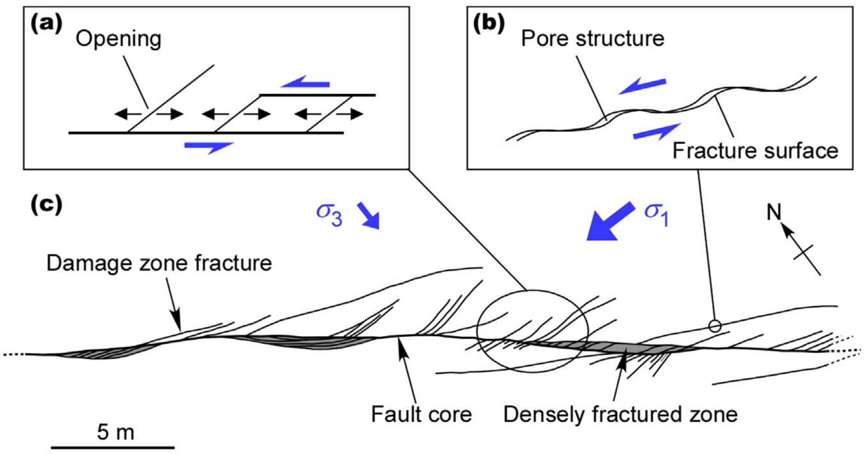

Fig. 1. Schematic diagrams of (a) opening of secondary fractures caused by shear-induced tensile stresses in a damage zone, and (b) pore structures formed by mismatch of the shear-fracture walls.[5] (c) Sketch of a sinistral strike-slip fault zone exposed at a horizontal outcrop in the Wakkanai Formation at the Horonobe site, and the directions of the maximum and minimum principal stresses.[5].

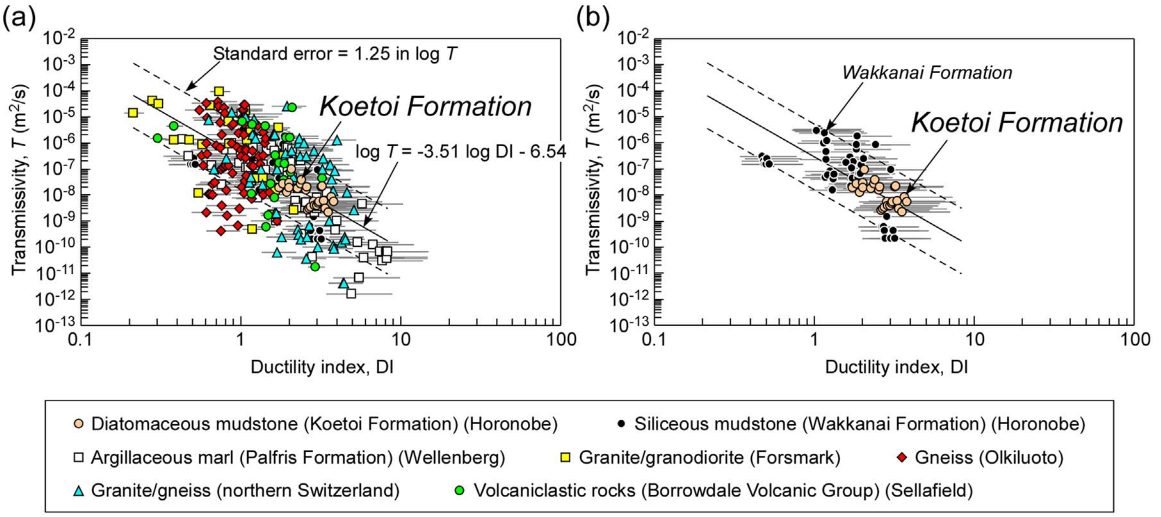

Fig. 2. (a, b) Transmissivities of flow anomalies detected in fault zones of six regions worldwide[5] (including those detected in the diatomaceous mudstone of the Koetoi Formation) plotted against the corresponding DIs. Horizontal error bars show errors due to uncertainties in tensile strength. Also shown is the DI model line (solid line) and standard error (broken lines).[5].

heterogeneity of a fault zone on transmissivity, as well as the effects of strain rate and sample size on tensile strength.

The DI model proposed by Ishii[5] was developed for fault zones, which are usually characterized by zones of intense strain-localization (fault cores, made up of fault rocks) and zones of damage that surround the fault cores.[11,12] However, the DI model proposed for fault zones may hold true for fractured protolith. In these, small discrete fractures may be major flow paths, especially if linked with each other. The transmissivity of discrete fractures has been studied in numerous laboratory experiments,[13–17] and many researchers have proposed that the transmissivity of discrete fractures depends on the effective normal stresses applied to the fractures. However, openings in releasing sections of shear fractures can occur in protolith, too,[18–20] and may be formed and preserved in the same way as openings in fault-zone fractures (Fig. 1).

In order to investigate this possibility further, I examined geological and hydrological data for fractures in the Koetoi Formation (4–2 Ma), an overconsolidated diatomaceous mudstone in the Horonobe area, northern Hokkaido, Japan. In this formation, fault zones and joints are rare, whereas small discrete shear fractures are numerous. These fractures are not filled with minerals, which is a suitable condition for this investigation. Moreover, this formation has been studied intensively as a result of the construction of the Horonobe Underground Research Facility and borehole investigations for the research and development of techniques for radioactive waste disposal. These studies mean that geological and hydrological information, including fracture mapping and fracture transmissivity data, are readily available.[21–24] Swelling clay minerals are also in low abundance (0–11 wt% of smectite),[25] and hence self-sealing of fractures by clays has not been observed during long-term hydraulic tests of an excavation-damaged zone in the underground facility.[26]

2. Geological setting

The Horonobe area is located on the eastern margin of a Neogene–Quaternary sedimentary basin on the western side of northern Hokkaido, Japan, and it is part of an active Quaternary foreland fold-and-thrust belt. It is located close to the boundary of the North American and Eurasia plates (Fig. 3a). The basin fill consists of (from oldest to youngest) the Masuporo, Wakkanai, Koetoi, Yuchi, and Sarabetsu formations (Fig. 3b, c; the Masuporo Formation is not shown). The locations of boreholes and the Horonobe Underground Research Facility are shown on Fig. 3b, c.

The Koetoi Formation is composed of a massive diatomaceous mudstone.[27] The mudstone contains opal-A (40–45 wt%), clay (17–25 wt%), quartz (7–10 wt%), and feldspar (5–10 wt%), and the effective porosity is 55–65% (45–60% near the boundary with the underlying Wakkanai Formation).[27] The (indirect) tensile strength and unconfined compressive strength of intact rock are 0.6 ± 0.3 MPa and 2.86 ± 1.38 MPa, respectively, based on the results of Ishii et al. 27