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3D geostatistical modeling of fracture system in a granitic massif to characterize hydraulic properties and fracture distribution

Katsuaki Koike [a,*], Taiki Kubo [a], Chunxue Liu [b], Alaa Masoud [c], Kenji Amano [d], Arata Kurihara [e], Toshiyuki Matsuoka [f], Bill Lanyon [g]

[a] *Graduate School of Engineering, Kyoto University, Katsura, Kyoto 615-8540, Japan*
[b] *School of Urban and Environment, Yunnan University of Finance and Economics, Kunming, China*
[c] *Geology Department, Faculty of Science, Tanta University, 31527 Tanta, Egypt*
[d] *Japan Atomic Energy Agency, Horonobe, Hokkaido 098-3224, Japan*
[e] *Dia Consultant, Ltd., Tokyo, Japan*
[f] *Japan Atomic Energy Agency, Mizunami, Gifu 509-6132, Japan*
[g] *Fracture Systems Ltd., UK*

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ABSTRACT

This study integrates 3D models of rock fractures from different sources and hydraulic properties aimed at identifying relationships between fractures and permeability. The Tono area in central Japan, chiefly overlain by Cretaceous granite, was examined because of the availability of a unique dataset from deep borehole data at 26 sites. A geostatistical method (GEOFRAC) that can incorporate orientations of sampled data was applied to 50,900 borehole fractures for spatial modeling of fractures over a 12 km by 8 km area, to a depth of 1.5 km. GEOFRAC produced a plausible 3D fracture model, in that the orientations of simulated fractures correspond to those of the sample data and the continuous fractures appeared near a known fault. Small-scale fracture distributions with dominant orientations were also characterized around the two shafts using fracture data from the shaft walls. By integrating the 3D model of hydraulic conductivity using sequential Gaussian simulation with the GEOFRAC fractures from the borehole data, the fracture sizes and directions that strongly affect permeable features were identified. Four fracture-related elements: lineaments from a shaded 10-m DEM, GEOFRAC fractures using the borehole and shaft data, and microcracks from SEM images, were used for correlating fracture attributes at different scales. The consistency of the semivariogram models of distribution densities was identified. Using an experimental relationship between hydraulic conductivity and fracture length, the fractures that typically affect the hydraulic properties at the drift scale were surmised to be in the range 100–200 m. These results are useful for a comprehensive understanding of rock fracture systems and their hydraulic characteristics at multiple scales in a target area.

1. Introduction

The importance of detailed and precise 3D modeling of geological structures and physical/chemical properties using data from geological investigations is continually increasing in the areas of natural resource exploration and development for petroleum, geothermal resources, and groundwater. An ideal 3D model covers a wide range in both the horizontal and vertical directions, but with high spatial resolution. In particular, representative geo-engineering subjects such as deep geologic disposal of high-level radioactive waste (HLW), CO_2 capture and storage (CCS), and groundwater management need advanced geological models for long-term prediction of geological phenomena (Chapman, 2006; Gasda et al., 2012; Koide and Kusunose, 2011; Quental et al., 2012; Raiber et al., 2012; Smith et al., 2011). The accurate prediction of natural fracture distributions in 3D space, covering length scales from several hundred meters to several kilometers is one of the critical issues for the above applications. Fractures strongly affect the mechanical properties and, particularly in low permeable crystalline rocks, hydraulic properties of a rock mass (Adler and Thovert, 1999; Faybishenko et al., 2000; Haneberg et al., 1999). Fractures often serve as preferential flow paths for fluids. The general term “fracture” is used here to indicate a geologic discontinuity that includes faults, joints, fissures, cleavage planes, or cracks.

Borehole investigations including direct observations of drilled cores and borehole video imaging can provide detailed information on multiple fracture attributes such as location, orientation (strike and dip),

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* Corresponding author. Tel.: +81 75 383 3314.
E-mail addresses: koike.katsuaki.5x@kyoto-u.ac.jp (K. Koike), chunxueliu@gmail.com (C. Liu), alaa_masoud@science.tanta.edu.eg (A. Masoud), amano.kenji@jaea.go.jp (K. Amano), a.kurihara@diaconsult.co.jp (A. Kurihara), matsuoka.toshiyuki@jaea.go.jp (T. Matsuoka), bill@fracture-systems.co.uk (B. Lanyon).

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shape, aperture, filling minerals, alteration, and spacing. When multiple boreholes are available, spatial changes in fracture attributes and, in some cases, their continuity may be interpreted. Thus a borehole dataset must be a useful source for examining the architecture of a regional facture system, as demonstrated by Dezayes et al. (2004) and Renard and Courrioux (1994). However, fracture distributions (or fracture networks, where the connectivity of fractures is considered) have been imaged by assuming the geometry of each fracture plane to be a polygon or disc (Dershowitz and Einstein, 1988; Renard and Courrioux, 1994; Sausse et al., 2010) or present only around the boreholes by extrapolating fracture density from a borehole into the surrounding rocks (Wu and Pollard, 2002). Another example is a combination of borehole and seismic tomography data to enable a stochastic simulation of fractures over a wide area, assuming that seismic velocity is related to fracture density (Escuder Viruete et al., 2003). This combination provides indirect imaging of a fracture system, whereas a direct method is more appropriate for examining plausible architectures.

In general, direct 3D simulation using borehole data from multiple sites is difficult because of the small amount of available fracture data in comparison to the size of a study area and the biases of borehole sites, site intervals, and data location methods. Another difficulty with such simulations originates with the conditioning of orientation data for the simulation. Various methods of simulating fracture distributions and networks have been proposed during the last three decades, the orientations of fractures are generally presented: as random or directly related to fracture sets (Andersson and Thunvik, 1986; Andersson et al., 1984; Billaux et al., 1989; Cacas et al., 1990; Chilès, 1988; Jafari and Babadagli, 2012; Long et al., 1985), by assuming probabilistic functions such as those of Fisher (Min et al., 2004; Xu and Dowd, 2010), or by a stochastic realization within a tolerance angle for each dominant fracture set (Dowd et al., 2007; Rafiee and Vinches, 2008). A realistic simulation requires the conditioning of the orientation data for observed fractures, in addition to the position and length, because spatial correlation of the orientation has been shown to exist (i.e., similar orientations tend to appear at nearby fractures) by Guo et al. (2009) and La Pointe (1980). Following Koike et al. (2012), we apply a method, GEOFRAC (the GEOstatistical FRACture simulation method) that has merit in its extension to 3D modeling and suitable assignments of fracture density and orientations. Another merit of using GEOFRAC is that shapes and sizes (areas and lengths) of fracture planes are estimated without assuming probabilistic functions for them, by connecting nearby fracture units with similar orientations.

The resulting 3D discrete fracture network model (DFN) can contribute to groundwater flow simulations that consider the complexity of a natural fracture system (Castaing et al., 2002), optimal site selection of groundwater pumping wells from an aquifer or production wells for petroleum and geothermal reservoirs, assessment of rock mass stability (Elmo and Stead, 2010; Merrien-Soukatchoff et al., 2012), and the interpretation of generation mechanisms for fracture systems and their formation history. Another crucial advantage is that a DFN can be combined with hydraulic test data for a rock mass to estimate hydraulic properties and regional groundwater flow (Kurtzman et al., 2005; Voeckler and Allen, 2012), and assess anisotropy in the hydraulic behavior using permeability or conductivity tensors (Hitchmough et al., 2007; Min et al., 2004; Müller et al., 2010; Oda et al., 1987).

Moreover, 3D DFN models can be applied to identify scaling laws for fracture system with micro to mega length scales. Fault or fracture length has been most widely used to demonstrate this scaling law, and is expressed generally using a log–log plot of length versus cumulative number (Bonnet et al., 2001; Nieto-Samaniego et al., 2005; Odling, 1997; Torabi and Berg, 2011). In addition to the length, scaling laws for the distributions of density and orientation may also be extracted as shown in a preliminary examination by Koike and Ichikawa (2006). Previous research on fracture scaling laws has typically used thin-sections of rock samples for observing microcracks, hand-mapping of outcrops for joint-scale fractures, and aerial photography acquired at multiple heights to identify different observation areas and spatial resolutions (Bour et al., 2002; Odling, 1997; Ouillon et al., 1996). These are all information related to the fracture distribution at rock surfaces; there is a possibility that fracture patterns at an engineering-issue scale are different between the external and internal parts of the rock body due to the effect of weathering and other near-surface processes, e.g. ex-foliation joints from uplift. By applying a scaling law in a fracture system and a scale dependence for hydraulic parameters (Zimmermann et al., 2003), the development of a multi-scale model of fracture systems and, furthermore, their hydraulic properties may be possible. Such modeling, for example, contributes to forecasts of groundwater flow and mass transport in long-term targeted HLW projects in hard rocks.

Based on the above background, this study aims to construct a plausible 3D DFN from two data sources (borehole and shaft data). These models will then be applied to identify scaling laws for fracture attributes by integrating lineaments observed in digital elevation model (DEM) data and microcracks from core samples, which will help to characterize the hydraulic properties of a rock body. For this purpose, the GEOFRAC routine is improved and then tested on a granitic massif. Novelty of this study is summarized as construction of an extensive DFN under conditioning of the fracture orientation data, hydraulic characterization of the DFN by integrating with a spatial model of hydraulic conductivity, and a proposal of multi-scaling rock hydrology.

2. Study area and materials

2.1. Location and geological setting

The Japan Atomic Energy Agency (JAEA) has been undertaking interdisciplinary scientific research on deep geological environments within the framework of the Mizunami super-deep geological research plan in the Tono area of Gifu Prefecture in central Japan (Tsuruta et al., 2013). One aspect of this research has been deep borehole investigations ranging from 500 to 1000 m in depth. The Tono area has a substantial accumulation of geological data over a wide depth range, and therefore is suitable for demonstrating the capability of GEOFRAC. The results of this work are expected to provide new insights on deep geological environments. Borehole data from 26 sites were selected for a case study of GEOFRAC and an associated hydraulic model. The arrangement of these boreholes is shown in Fig. 1 overlaid on the topography of the study area.

The main target covers an area 12 km (E–W) by 8 km (N–S), and extends to a depth of 1.5 km. The overall topographic features, valleys and ridges are elongated in a NE–SW orientation. The northeastern edge of the region, in which the DH-10 borehole is located, is relatively high at over 500 masl, and the topography decreases in elevation toward the southwest. The other borehole sites are located at elevations between 200 and 300 m. The horizontal distance between adjacent borehole sites ranges from 95 to 2820 m with an average of about 1000 m.

The surface geology in the study area consists primarily of the Pliocene Seto Group (alternating strata composed of gravel, sand, and mud) and the early to middle Miocene Mizunami Group (alternating strata composed of mud, silt, sand, gravel, tuff, and lignite). The late Cretaceous Toki granite is the basement rock (Itoigawa, 1980). Two active faults, the NW–SE trending Atera Fault, which is representative of many active faults in Japan, and the NE–SW trending Byobuyama Fault are located on the eastern and southern outside of the study area, respectively (Fig. 1). There is no active fault reported in the study area. The best constrained fault is the Tsukiyoshi Fault in the central part of the area, which was identified by the surface-based investigations (Saegusa and Matsuoka, 2011). The orientation of the Tsukiyoshi Fault is generally ENE–WSW, but follows a gentle curve (Fig. 1).

2.2. Fracture data

We used two fracture datasets to construct 3D DFN models. First is the fractures by the boreholes drilled almost vertically. A total of