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Spatial correlation structures of fracture systems for deriving a scaling law and modeling fracture distributions

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Abstract

An understanding of fracture systems in geological media requires two fracture properties clarification: fracture distributions and the scaling law of fracture systems over different scales. To investigate fracture systems in different scales, we used remotely sensed images from LANDSAT and SPOT satellites, borehole-fracture data in two drilling directions, and a thin-section of rock core sample. The eastern part of the Tohoku district, northeastern Japan, overlain by Cretaceous granite and a Jurassic accretionary complex, was chosen as the study area. Assuming that part of the line features detected in satellite and thin-section images correspond with real fractures, the spatial correlation structures of fractures were clarified by semivariograms to identify an alternative scaling law. For this we focused on joint's line density along boreholes, area density of linear features, and directional relations of strikes between a fracture pair to produce semivariograms of densities and cross-semivariograms of the strikes transformed into binary data sets. The same model independent of the scales could approximate the semivariograms of each parameter. Spatial correlation distances were obtained from the range of the semivariogram model. An important characteristic was that linear trends between representative and correlation distances of fractures were found in log–log plots. Scaling law can contribute to estimating correlation distances at arbitrary fracture scales. A conditional distribution modeling at the borehole-fracture scale was presented as an application of the semivariograms obtained by the three steps: generation of fracture-density map by a sequential gaussian simulation, assignment of strikes to each simulated fracture, and connection of fractures considering distances and differences in strikes between a closely located fracture pair. Additionally, nonconditional simulation at arbitrary fracture scales and changes of permeabilities with scales using a permeability tensor analysis are discussed.

Keywords: Fracture system; Scaling law; Linear feature; Semivariogram; Permeability

1. Introduction

Fractures with diverse origins and sizes from micro- to kilometer orders are generally present in geological media. We use "fracture" as a general term of geologic discontinuity that involves fault, joint, fissure, cleavage, and/or crack. There are two types of fractures in a mechanical sense, tensile and shear types. Their formation has been attributed to emplacement and cooling of rock bodies, crustal movements, and regional stress fields at different geologic stages. Characterizing fracture systems at

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several scales, modeling of fracture distributions, and clarifying scaling laws that correlate total fracture systems are important in various fields in both science and engineering. This is because the genetic mechanism of fracture systems contributes to the comprehension of tectonic history; and fracture systems affect both the mechanical and hydrological behaviors of geological media, especially crystalline rocks. Fields concerned include hydrogeology for fracture-dominated channel flows, and resource explorations for vein-type mineral deposits and fluids in fractured reservoirs (e.g., National Research Council, 1996; Coward et al., 1998; Adler and Thovert, 1999). Elucidation of the hydraulic properties of rock masses in consideration of fracture systems has recently been stressed, because it closely relates to environmental problems over long periods. The scaling law in this study is a law expressing scale-dependent change of fracture properties.

In spite of the importance of the issue above, it is difficult to get a general view of fracture systems from data that are limited in amount, location, and range of scale. Many papers have tried to clarify the scaling laws of fracture systems using fractal geometry (e.g., Vignes-Adler et al., 1991; Davy et al., 1992; Dawers et al., 1993; Watterson et al., 1996; Koike and Kaneko, 1999; Bonnet et al., 2001), but most have dealt with length distribution over wide ranges. In addition to length, location of fractures needs to be considered for an understanding of the spatial correlation structures that are characteristics of clusters. Geostatistics can incorporate the structures, which mean spatial dependence of regionalized variables at different locations in space, and some applications of it have been reported in fracture-distribution modeling (Long and Billaux, 1987; Young, 1987; Chilès, 1988; Gringarten, 1996). Density, appearance pattern, and orientation of fractures are typical attributes that are indispensable in such distribution modeling.

As a first step in fracture-distribution modeling at multi-scales, this paper presents an alternative scaling law by focusing on the relationship between the representative trace and the spatial correlation distances, the maximum distances of data pair that has any statistical dependence, of fractures. Two parameters, fracture density, and the directional relation of strikes between a fracture pair are investigated for the spatial correlation structures; and their semivariograms are produced to determine correlation distances. Two types of satellite images, borehole-fracture data, and a thin-section of granite core sample are used for the analyses. A detection method of the line features from the satellite and thin-section images is first proposed, and then a two-dimensional distribution of joint-sized fractures is inferred using borehole data and geostatistics as an application of the obtained semivariograms. We demonstrate that the scaling law can be used in nonconditional simulations for fracture distribution and presumes the scale effect of permeabilities.

2. Data for analysis of fracture systems

Three types of data, lineaments, joints, and microcracks, which are different in scales, were examined for characterizing fracture systems; hereafter termed "fracture-related elements". Although lineaments are topographic features that are not directly related to fractures, dominant directions of lineaments have been reported to have accordance with those of joints and faults in rock masses (Rowan and Wetlaufer, 1981; Arlegui and Soriano, 1998; Koike et al., 1998). An eastern part of Tohoku district, northeastern Japan, which is overlain chiefly in Cretaceous granite and Jurassic accretionary complex, was chosen as the case study area.

Lineament analysis was carried out using LANDSAT TM and SPOT HRV satellite images with acquisition dates of October 28, 1993 and December 5, 1989, respectively. Two kinds of lineaments were extracted from the LANDSAT near-infrared image (band 4) and the SPOT panchromatic-mode image by utilizing the differences in spatial resolution; 30 m (LANDSAT) and 10 m (SPOT). Due to this difference, two fracture systems with different length distributions were expected to be obtained. Band 4 was selected because the intensity values of it correlate well with the reflectance of shaded-relief images derived from a DEM of the forested area of Japan (Koike et al., 1995). Fig. 1 shows satellite images east–west of 2300 pixels (= 69 km) and north–south of 5600 pixels (= 168 km) for LANDSAT, and 5120 pixels (= 51.2 km) by 6000 pixels (= 60 km) for SPOT.

As joint-sized fractures in rock mass, the data obtained by eight horizontal boreholes in the Kamaishi mine, located in the middle of SPOT image, was used. The geology of the mine is Early Cretaceous dioritic granite and partly diorite. The boreholes were dilled over 215-m length in total in two perpendicular directions, N15°W and N75°E, at