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Surface roughness characterization of open and closed rock joints in deep cores using X-ray computed tomography

Melvin Diaz[a], Kwang Yeom Kim[b,*], Sun Yeom[b], Li Zhuang[b], Sehyeok Park[c], Ki-Bok Min[c]

[a] University of Science and Technology, 217, Gajeong-ro, Yuseong-gu, Daejeon 34113, Republic of Korea
[b] Korea Institute of Civil Engineering and Building Technology, 283, Goyang-daero Ilsanseo-gu, Goyang-si, Gyeonggi-do 10223, Republic of Korea
[c] Department of Energy Resources Engineering, Seoul National University, 1, Gwanak-ro, Gwanak-gu, Seoul 08826, Republic of Korea

1. Introduction

Rock discontinuities are planes of separation that influence the hydraulic and mechanical behavior of rock masses because they are main conduits for fluid flow and sources of major deformations.[1–5] Joints can be open fractures, or closed when chemical alteration or decomposition of materials heal the surfaces.[6] Discontinuities in rock masses are significant, because they affect slope stability, underground excavations, and reservoir engineering.[7–9] For example, joints influence not only shear strength, but also rock mass permeability and seepage flow in rock structures. Moreover, in reservoir engineering, joints affect wellbore stability during drilling,[10] stimulation when fractures are critically stressed,[11–13] production in propped fractures, and well lifetime due to the evolution of the fracture–reservoir behavior.[14]

Rock joints are mainly characterized through estimation of the shear strength of their walls[15–17] and measurements of their apertures and spacings.[18–20] Shear strength can be estimated experimentally or theoretically. Barton and Choubey[16] proposed one of the first theoretical approaches for shear strength calculation, which in turn requires estimation of the joint roughness coefficient (*JRC*) by visual comparison with 10 typical profiles. Subsequent studies[21] developed equations for the *JRC* as a way to reduce the subjectivity associated with the original method. Tse and Cruden[22] proposed two equations based on the root mean square of the first derivative of the profile (Z_2) and the structural function (*SF*) respectively, and they have been incorporated into many equations with relatively good correlation. Later, Yu and Vayssade[23] demonstrated the sensitivity of these parameters to the sampling interval. Furthermore, Li and Zhang[21] argued that given that most previous *JRC* equations are based on Barton's 10 profiles, they lack statistical significance, and therefore they recalculated the most commonly used equations based on 112 profiles from the literature.

Shear strength and *JRC* are generally estimated only along the shearing direction, neglecting other orientations. However, Huang and Doong[24] did consider the anisotropic shear strength of some rocks by evaluating *JRC* along six orientations. They found that shear strength depends on the orientation, and more precisely on the roughness characteristics along a given orientation. They also obtained shear strengths for in six different directions. Indeed, roughness anisotropy was later discussed by other studies.[17,25] Although some methods have been proposed to account for the roughness anisotropy no standard methodology has been established, and the current methods generally focus on regular, particularly square, sampling areas like the variogram approach.[26]

Field and laboratory methods for assessing joint profiles range from the simple to the sophisticated, and can be divided into contact and non-contact methods. Early contact methods include using a base line ruler to provide details along a profile[27] and using a roughness profilograph disc to measures dip angles of different disc sizes.[28] Later, Barton and Choubey[16] employed the profile comb, a simple tool that adapts its teeth to the rock surface, and recorded profiles for further comparison. Non-contact methods include the shadow profilometer,[29] and advances of technology have led to the development of mechanical and laser profilometers to record differences in height along one direction of the rock surface. They operate under the same principles, using either a moving stroke or light.[24,30] Alternative technologies that have been reported include photogrammetry in the laboratory and at the field scale for the 3D characterization of rock surfaces,[31] and visual laser scanners for rock-face mapping.[32] All these techniques examine open joint surfaces, and there is an acknowledged critical need to characterize deep closed joint surfaces, as they are important for petroleum and geothermal engineering. Given that the direct characterization of underground reservoirs is possible only through core samples, it is important to develop a technology that allows for the extraction of detailed 3D representations of entire specimens, including external features, as well as internal features such as closed joints. In particular, roughness characteristics of rock joint play a significant role in coupled hydromechanical processes in terms of caprock leakage for CO_2 geosequestration,[33] and improving fluid flow for enhanced geothermal systems (EGS). To the authors' knowledge, extensive characterization of deep rock joint from more than 4 km depth has not be conducted so far, which make it difficult to estimate the associated coupled hydromechanical processes which is directly affected by joint roughness. Furthermore, roughness charac-

* Corresponding author.
E-mail address: kimky@kict.re.kr (K.Y. Kim).

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teristics can reveal the origin of fault genesis.[34]

This study assesses the roughness of open and closed joints in rock core samples extracted at around 4.2 km, a rarely studied depth. It pays particular attention to the morphological description of the joint surfaces. *JRC*, skewness, kurtosis, and maximum surface height were measured to characterize the joints, and the anisotropy or roughness directionality was considered in detail. The cores come from the PX-2 well of an EGS project located in the Pohang region of South Korea. To tackle the problem related to surface data acquisition of closed joints, we used X-ray computed tomography (CT) technology.

2. Rock joints samples and methods

2.1. Rock core extraction and physical properties

Core samples (diameter = 10 cm) were obtained with a total length of 3.6 m at depths of 4219–4223 m during the completion of the PX-2 well.[35] The extracted rocks were medium-grained granite with no signs of weathering. Open and closed joints intersect the specimens, and two main sets were identified. As the samples were sequentially received at the surface, they were stored in four core boxes (each 1 m in length). Within each box, the pieces were grouped into eleven sections to facilitate their identification. Fig. 1 shows the core sections observed by X-ray CT scanning to inspect their different internal features as well as to determine other physical parameters.

2.2. Joint selection and description

Of the two sets of open joints identified, the first crossed the specimens at around 80° with respect to the coring direction, while the second set crossed at nearly 20°. Some cores exhibited closed joints (e.g., sections IV and IX in Fig. 1), which were later confirmed by X-ray CT observations. Surface mapping and MT survey estimated the existence of a major fault with a dip direction of 25°, and a dip angle of 67°. Given that this study focuses on the examination and comparison of open and closed joints, we decided to consider joint surfaces of similar size and angle relative to the vertical or coring direction. The angles that these joints formed with the coring direction ranged from approximately 10–30°. The X-ray CT data were used to render 3D models that were later used to extract the selected surfaces, especially for the closed joints that otherwise are nearly impossible to examine. The scanning process and conditions are given in Section 2.3.

Using point cloud data, wireframe images of the seven selected joint surfaces are plotted in Fig. 2. OJ-1 appears to have a parallelogram-like area, while OJ-2, OJ-3 and OJ-4 have nearly rectangular areas. OJ-5 has an irregular shape. The closed joint surfaces CJ-1 and CJ-2 have areas that resemble vertical parabolas.

2.3. Scanning conditions and surface acquisition

The CT equipment employed in this study was the X-EYE CT system at the Korea Institute of Civil Engineering and Building Technology as described by Kim et al.[36]

To assure the high quality of the images, each core specimen was scanned, taking into consideration the coring direction for joint surface angle calculations. Parameters of X-ray CT scanning such as the source–object distance, and pixel pitch were varied while other parameters were kept constant. Table 1 lists a summary of these testing conditions. In addition, the temperature was kept at 21° and the humidity at 31%. The exposure time and the number of projections were fixed at 1 s and 1800, respectively. The voxel data obtained after individual scanning carry different vector values such as density, volume, and voxel position. A voxel is a volume element analogous to the 2D pixel within an image. These values allow for the 3D rendering of the specimens, which is useful when inspecting the internal structures or mineral changes within the rock. 3D rendering technology is used in this study to extract the joint surfaces (Fig. 3). For open joints, this could be also done with a laser profiler or any other imaging technique. Nevertheless, X-ray CT offers the advantage of recording not only the surface, but also the entire specimen volume. X-ray technology is useful for the extraction of closed joints that other techniques cannot analyze. It works by identifying the material density difference between the rock and the interface present at closed joints.

After joint surface selection, the next step was point cloud data generation by setting a specific square grid size. A fixed value of 0.1 mm was selected here after evaluating the evolution of four roughness parameters with respect to the square grid size. Detailed description is given in Section 3.1. The angle between the joint surface and the coring direction was then estimated by fitting a plane through the cloud data. Fig. 4 illustrates this entire process for the acquisition of joint OJ-1.

2.4. Surface roughness parameters

The roughness of joints were quantified via *JRC*, skewness, kurtosis

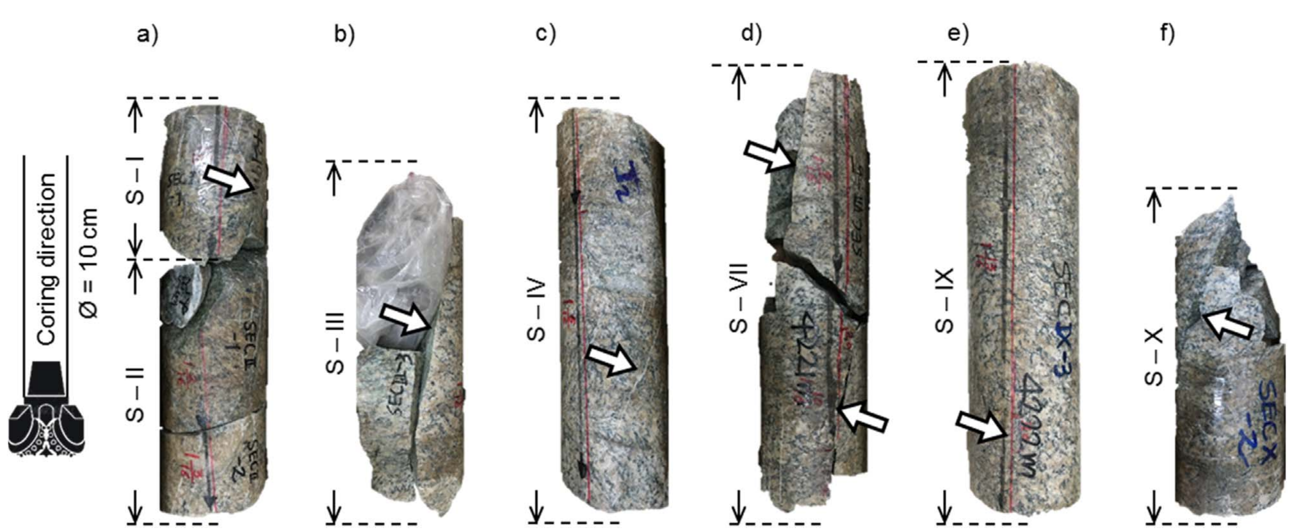

Fig. 1. Deep rock core samples extracted from a depth of 4219 m in the PX-2 well at the Pohang geothermal site. Seven rock joint surfaces were considered. Open and closed joints are labeled as OJ and CJ respectively, and "S-" indicates the sector the specimen belongs to. The selected joints are oriented between 10° and 30° with respect to the vertical or coring direction, and the white arrows are approximately perpendicular to the joint planes. a) OJ-1, b) OJ-2, c) CJ-1, d) OJ-3 (top) and OJ-4 (bottom), e) CJ-2, and f) OJ-5. All joint surfaces were acquired by X-ray CT scanning.