(115) Analysis of In-situ Joint Strength Anisotropy and Apertures

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Abstract

Unrolled digital images of a borehole wall in porphyritic granite are obtained using the Borehole Scanner System. The roughness profiles of the opposing joint walls are then extracted from these images using image processing techniques. The opposing profiles are analyzed for joint shear strength anisotropy and apertures. Results are presented for typical joints.

1. INTRODUCTION

The surfaces of natural joints may have structures Suppe (1985) that lead to anisotropic surface roughness. Roughness angle anisotropy leads to anisotropic joint strength. This fact makes roughness angle anisotropy a critical element in the stability of discontinuous rockmasses, since blocks defined by intersecting discontinuities are kinematically constrained to move in certain directions only. As a result of the roughness angle anisotropy, the directions in which key blocks may move could be relatively weak or strong.

In-situ roughness profiles of joints in porphyritic granite were obtained from digital images of borehole walls taken using the Borehole Scanner System (BSS). The BSS (Tanimoto, 1992), is a recently developed instrument that provides an unrolled true color digital image of the borehole wall at a resolution of 0.10 mm. The porphyritic granite boreholes used in this study are located in GIfu Prefecture, the central part of Honshu Island.

2. ROUGHNESS PROFILE EXTRACTION

2.1 Thresholding method of profile extraction

Image processing techniques are used to extract the joint roughness profiles from the BSS image. All of the profile extraction processing is done on a monochrome transform of the BSS image in four steps. The first step involves thresholding of the original image $f(x,y)$ between two thresholds T_1 and T_2 to produce a binary image $g(x,y)$ such that

$$g(x,y) = \begin{cases} 255 \text{ if } T_1 < f(x,y) \leq T_2 \\ 0 \quad \text{otherwise} \end{cases} \qquad (1)$$

In Eqn. (1), the coordinates (x,y) refer to the row and column number of each pixel of the unrolled borehole wall image. The thresholds T_1 and T_2 are chosen so that in the binary image $g(x,y)$, all pixels falling inside the joint aperture are white while the pixels outside the aperture on the rock wall, are black. To accomplish this segmentation, the selection of T_1 and T_2 has to be made so as to cover only the dark range of intensities of the pixels in the aperture region between opposing joint walls. T_1 and T_2 can be determined from a histogram of the image intensities or by probing the image with a mouse on a screen display of the image. The value of T_1 can usually be set to zero. After obtaining the binary image $g(x,y)$, the pixels on the roughness profile are isolated by detecting the discontinuity separating the rock wall from the joint aperture region. No differential operators are needed to detect the discontinuity in the binary image. Instead, the roughness profile pixels are isolated by using the fact that only pixels on the profile and pixels in the aperture region will have at least one white adjacent pixel in the binary image. The pixels on the profile and those in the aperture region can be further distinguished by the fact the profile pixels in the binary image will be black while the pixels in the aperture region will be white. Only the pixels on the rock wall qualify as points on the roughness profile. These rules are applied on the binary image $g(x,y)$ to produce another binary image $h(x,y)$ in which pixels on the roughness profile have an intensity of zero and all other pixels have intensities of 255.

The next step involves using a pixel connectivity routine to produce an ASCII file listing of consecutive roughness profile pixel image coordinates. The connectivity routine begins at the first pixel on the profile and searches for the next pixel on the profile until no further connected pixels can be found. The center pixel in the 3X3 pixel box of Figure 1 is a pixel on the roughness profile and the adjacent pixels are candidate consecutive profile points. The numbers in the adjacent cells identify the cell. The search sequence for the upper profile is 2,3,6,8,9 and the search sequence for the lower profile is 8,9,6,3,2. The first adjacent pixel with an intensity of zero is identified as the next profile point. That point then becomes the center pixel in Figure 1 and the search is repeated.

1	2	3
4	X, Y	6
7	8	9

Figure 1 Pixel connectivity search sequence

The final step in the profile extraction procedure is a transformation of coordinates. The ASCII file produced by the connectivity routine contains profile points in image (x,y) coordinates. A utility program is used to substitute borehole coordinates of azimuth and depth for the image coordinates by comparison to the original BSS image. The roughness profile may further be unrolled as described by Thapa (1994). The unrolled profile for joint 13-1 is shown in Figure 2.

2.2 *Aperture measurement*

Joint aperture is defined by the magnitude of the vector connecting points on the lower profile to points on the upper profile. The vector connecting opposing profile points is directed normal to the mean joint plane. When the mean joint plane has a dip greater than 0° and less than 90°, and the borehole is vertical, the aperture vector originating on a lower profile point will generally not intersect any upper profile point. This situation is shown in Figure 3. Since the majority of joints intersected by the borehole will have a geometric configuration similar to Figure 3, measurement of joint aperture requires some method of accounting for this problem.

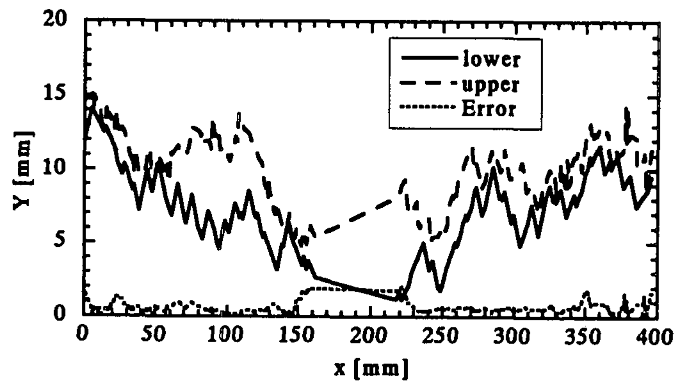

Figure 2 Unrolled roughness profiles of joint 13-1

Figure 3 shows two smooth opposing joint walls with the same orientation being intersected by a vertical borehole. The intersection produces traces of the borehole wall in the upper and lower profiles. These traces, in discrete form, would be the equivalent of the BSS profiles. The true aperture of the joint is shown by the vector $\vec{n}$ connecting the lower profile point o to its true opposing point a. However, in the BSS profiles, the vector $\vec{n}$ cannot be found since point a does not lie on the curve defined by the intersection of the borehole with the upper joint wall. Since the true aperture cannot be found, one of two alternative approaches may be taken to estimate $\vec{n}$ One approach involves correction of an apparent aperture

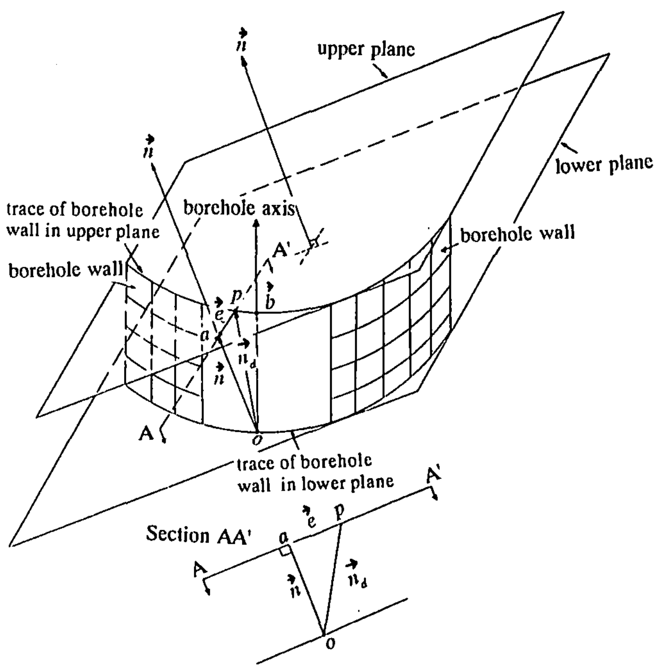

Figure 3 Aperture measurement error

vector such as $\vec{b}$, which is directed vertically parallel to the borehole axis:

$$\|\vec{n}\| = \|\vec{b}\|\cos(\theta) \qquad (2)$$

The apparent aperture approach assumes the upper joint wall is a smooth plane between points b and a as shown in Figure 3. This assumption contradicts the entire exercise of measuring roughness and apertures where deviations from a mean plane are being sought. The other approach to aperture measurement uses the vector $\vec{n}_a$ as the estimate of $\vec{n}$ Point p on vector $\vec{n}_d$ is chosen so that the error vector $\vec{e}$ is a minimum along one or more segments of the profile. This second approach, based on error minimization, was used to obtain the apertures for joint 13-1 shown in Figure 4.

3. ANISOTROPY ANALYSIS

3.1 *Estimation of roughness angle using BSS profiles*

The roughness angle is calculated from the angle between chords connecting profile points and the normal vector to the mean translation plane:

$$i = 90 - \tan^{-1}\left(\frac{\vec{c} \bullet \vec{n}}{\|\vec{n}\|}\right) \qquad (3)$$

where $\vec{c}$ is the chord vector connecting two profile points and $\vec{n}$ is the joint unit normal vector. The unit joint normal vector $\vec{n}(a,b,c)$ is obtained from the strike (α) and dip (β) of the joint as

$$\begin{aligned} a &= \sin(\alpha)\sin(\beta) \\ b &= \sin(\alpha)\cos(\beta) \\ c &= \cos(\alpha) \end{aligned} \qquad (4)$$

The magnitude of the base length, d, for each chord is

$$d = \|\vec{c}\|\cos(i) \qquad (5)$$

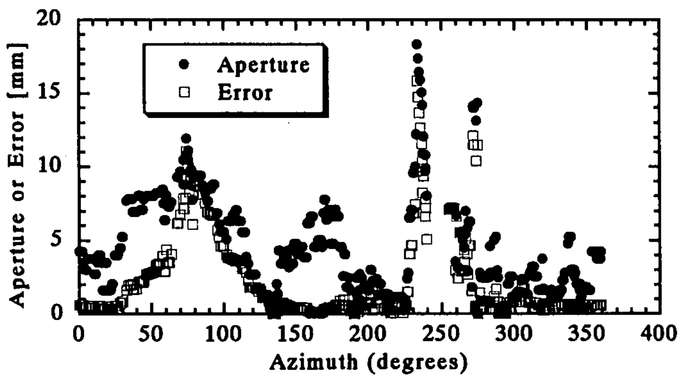

Figure 4 Aperture measurement errors fot joint 13-1

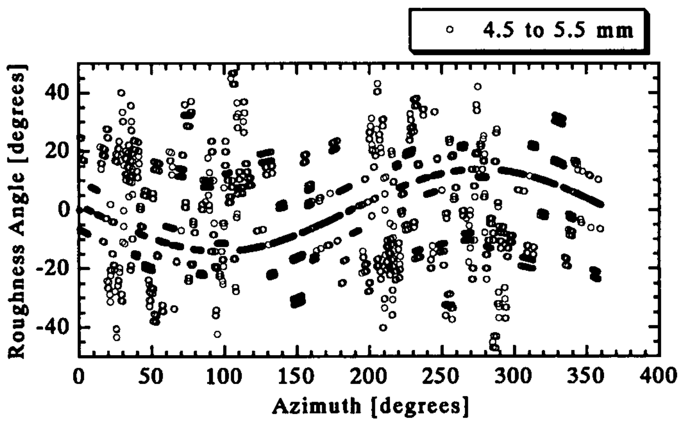

Figure 5 (a) Anisotropy pattern of upper profile of joint 19-1 at scale of 4.5 to 5.5 mm (dip = 14 degrees, dip dir. = 277 degrees)

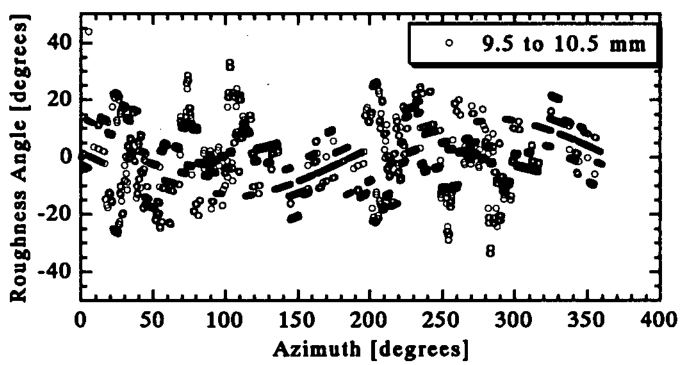

Figure 5 (b) Anisotropy pattern of upper profile of joint 19-1 at a scale of 9.5 to 10.5 mm (dip = 14 degrees, dip dir. = 277 degrees)

Each measurement of the roughness angle results in the triplet (i, d, a) where a is the azimuth of the roughness angle vector having angle i and a base length d. Figure 5 (a), (b), (c) and (b) shows the anisotropy pattern for the upper profile of joint 19-1.

3.2 *Interpretation of anisotropy curve*

Interpretation of the joint surface topography from the anisotropy curve of Figure 5 is an inverse problem. Different surface shapes will produce different anisotropy curves. Furthermore, as with any inverse problem, the solution to the surface topography problem may not be unique -- i.e. more than one surface topography model may satisfy the anisotropy curve. The simplest anisotropy curve would be a flat line within a small roughness angle interval. For this case, the joint surface model would simply consist of a smooth plane. As the shape of the anisotropy curve becomes more complex, the interpretation also becomes more difficult.

It is not always necessary to find a surface topography model to use the anisotropy curve. For mechanical stability problems for instance, just knowing whether there is any anisotropy will enable further analysis to account for the effect of surface shape. If the surface is found to be anisotropic, Rengers envelopes (1970, Figure 6) will have to be taken in the sliding direction only. Direct shear tests should also be done in the sliding direction in this case. Thapa (1994) provides further examples and discussion of anisotropy analysis using in-situ roughness profiles.

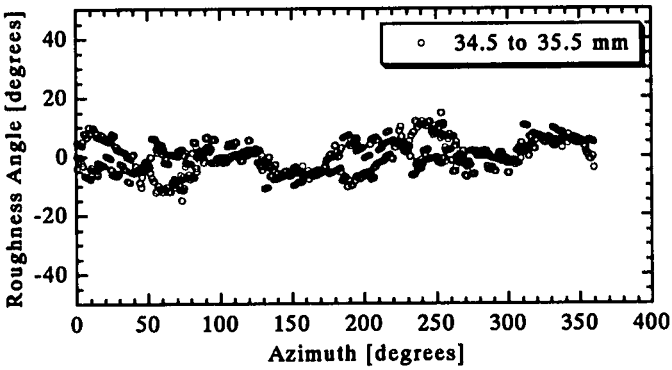

Figure 5 (c) Anisotropy pattern of upper profile of joint 19-1 at a scale of 34.5 to 35.5 mm (dip = 14 degrees, dip dir. = 277 degrees)

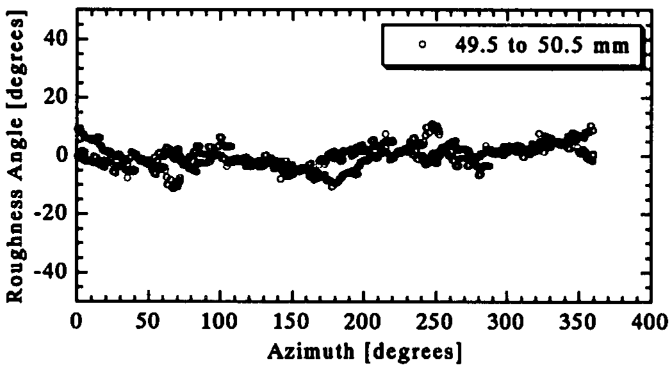

Figure 5 (d) Anisotropy pattern of upper profile of joint 19-1 at a scale of 49.5 to 50.5 mm (dip = 14 degrees, dip dir. = 277 degrees)

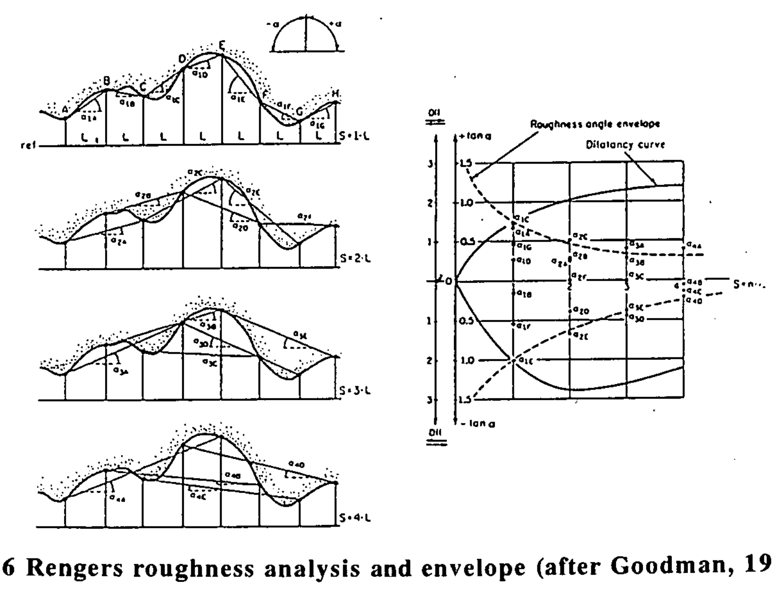

Figure 6 Rengers roughness analysis and envelope (after Goodman, 1976)

4.CONCLUSIONS

The image processing method described in Chapter 2 to extract the joint roughness profile takes about one hour per joint to excute due to the need for eztensive user interaction. This analysis rate needs to be improved to make it feasible to extract roughness profiles within the time and budget constraints of constraction projects. In order to improve the extraction rate, the edge extraction method has to be automated as much as possible so that user interaction is minimized. Improvements in automation appear to be feasible using existing image processing methods.

A method of obtaining the in-situ roughness profile of joints using the BSS has been described. The in-situ profile was used in the analysis of joint apertures and of anisotropic joint shear strength.

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