Structural Domain Identification by Fracture Orientation and Fracture Density in Rock Mass

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Abstract
A structural domain characterizes a volume of rock mass with similar rock properties, their strength characteristics, fracture orientations and the rock type. The identification of structural domains allows a better understanding of geologic structure and the potential failure of rock blocks. For failures in rock mass, geologic structure plays an important role that controls the sliding and falling of rock blocks, hence structural domains should be identified to analyse the mode and the mechanism of failure model. In this paper, two approaches are used to divide fracture pattern of rockmass into homogeneous domains: Stereonet correlation and fracture density analysis. The stereonet plots of fracture frequencies represented as poles at adjacent sections are used to calculate correlation coefficient to quantify the degree of similarity. Fracture domain boundaries were established wherever the correlation coefficient is low. The fracture density analysis is also performed along adjacent sections of reference line to track for the similarity of Rock Quality Designation (RQD) values. The change in RQD values indicates the change of fracture domains.

1. Introduction

The characterization of the rock mass into the structural zones or regions could provide information about the similar geological conditions and hence similar physical properties can be derived. A domain characterizes a volume of rock mass with similar rock properties, typically defined by the orientations of major fracture sets, the rock type and its strength. Rock mass stability is largely based on fracture distributions, it is necessary to examine the spatial distribution of fractures to identify structural domains that show similar fracture sets. In most excavation site, geological contacts of rock types could not be used to define structural domains as the rock at the site was basically similar. The term fracture domain is applied if fracture orientations are considered only. A fracture domain refers to a rock volume in which rock units show similar fracture frequency characteristics. Many techniques are developed for quantifying fractures into subsets (Hammah and Curran, 1998, Zhou and Maerz, 2002, Martin and Tannant, 2004, Jimenez-Rodriguez and Sitar, 2006 and Surrette et al., 2008). Normally, domains are divided by analysing fracture orientations on stereonet (Priest, 1993) and visually compared dominant joint sets of surrounding areas. Structural boundary is usually subjectively determined by looking at differences between stereonets from adjacent regions. However, if the fracture orientations are dispersed and randomly distributed, it is hard to determine whether the data were collected from the same structural domain. The division of a rock mass into structural domains involves the location of regions, hence, the spacing of fractures should also be put into account. A structural domain is a unique set of rock properties and should characterize by both orientation and spatial distribution. Therefore, this study uses two approaches, stereonet correlation and fracture density analysis, to divide fracture pattern of rock mass into homogeneous domains in a quantitative way.

2. Fracture Domain Analysis

2.1 Stereonet Correlation of Fracture Data

The method could be summarized as: Stereonet plots of fractures at adjacent sections are used to calculate correlation coefficient to calculate the degree of similarity. Fracture domain boundaries were established wherever the correlation coefficient is low. Stereonet is divided into grids as shown in Figure 1. The grid size has to be chosen appropriately as too large grids tend to overly smooth the data, thereby masking important trends and too small grids certainly contain few data, and any trends are rendered unrecognizable due to the scattered plotting of random poles. Having smaller window sizes would result in many containing little to no discontinuity data (Martin and Tannant, 2004). The current approach use 10° interval window on the stereonet for fracture pole plots and the total number of window is 9 x 36 = 324. Figure 2 shows an example of number of fracture poles in spreadsheet type where dip angles and dip directions are put vertically and horizontally, respectively. The scattering of data can cause biases in correlation calculation as too many windows containing no fracture are accounted. This problem can be eliminated by normalization algorithm of averaging data using moving windows (3x3 or 5x5). Then the number of "no fracture" windows will be reduced. The correlation coefficient describes the degree of relationship between the two variables.

The correlation coefficient can be calculated via equation 1.

$$Correl(x, y) = \frac{\Sigma (x - \bar{X})(y - \bar{Y})}{\sqrt{\Sigma (x - \bar{X})^2} \sqrt{\Sigma (y - \bar{Y})^2}}$$

Equation 1

Domain boundary was established wherever the correlation coefficient is low. The clustering of data into fracture sets is not required and windows that contain no discontinuities give no influence into result.

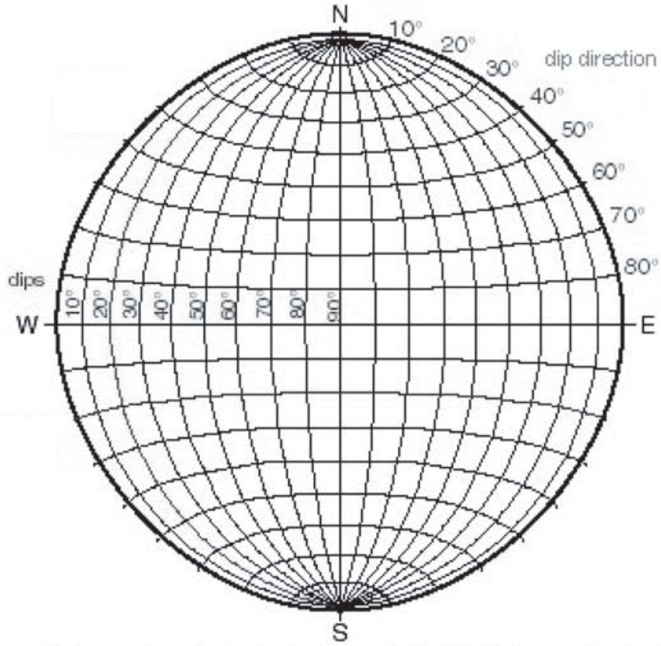


Figure 1: Lower hemispherical stereonet divided into small windows

	10	20	30	40	50	60	70	80	90
10					1	1		1	
20			1		2	1	1		
30			1		3				
40	1			2	1				
50	1						2		
60			1		1	1	2	1	
70							3		
80		2	1	1	1	1	2		
90						1			
100		2	2			1			
110			3	2		1		1	
120		1	3		3	2		2	

	10	20	30	40	50	60	70	80	90
10				1	1			1	
20						1			
30									
40					1		1		
50				1		1	1	2	
60				2		1	2	2	
70		1			1	2	1	3	
80					2	1	6	8	
90				2	1	2	2	3	
100			1	4		2	2	2	
110				2	1	5	1	1	
120			2	4	2	4	1	2	

Figure 2: Fracture pole number on stereonet representing in spreadsheet type. Horizontal and vertical rows represent dips and dip directions, respectively

2.2 Fracture Density Analysis

Another approach to define structural domains in rockmass is the use of fracture density or fracture spacing. This approach bases on the concept that different domains would have different fracture densities. The fracture density can be represented as RQD values. The RQD calculation originates from rock classification of borehole data (Deere, 1964), however, its concept can be adapted to analyse fracture spacing. The calculation of RQD is shown in equation 2.

$$RQD = \frac{\sum \text{Length of core pieces} > 10\,\text{cm length}}{\text{Total length of core run}} \text{ X } 100\%$$

Equation 2

This approach ignores fracture orientations and uses RQD values as the representative for fracture density along the tunnel line. The fracture frequency can be tracked for different intervals to identify potential boundaries between fracture domains. However, this approach could not distinguish populations of different orientations if they have similar spacing, and hence, the identified boundary does not show the real boundary in term of fracture orientations. The combination use of correlation method and this method would give better results of domain division.

These two methods could easily be performed on a GIS platform by following the procedures as outlined below:

- Fracture data from a particular section can be projected to a reference line or whole section (Figure 3a).
- Fracture orientation data for predefined segments will be plotted on a stereonet. The length of the segments will be defined by adjudging from the real data (Figure 3b).
- Calculate a correlation coefficient of fracture occurrence in each window between two stereonets from two adjacent segments or regions.
- Repeat the process by running along the reference line or section and the correlation coefficient versus location is plotted continuously.

The differences between fracture orientations show relatively low correlation coefficients, and hence, structural domain boundaries can be delineated. The fracture density analysis is also performed to track for the similarity of RQD values. The abrupt change in RQD values indicates the change of potential domain. The agreement of boundaries in two methods helps define the structural domains confidently.

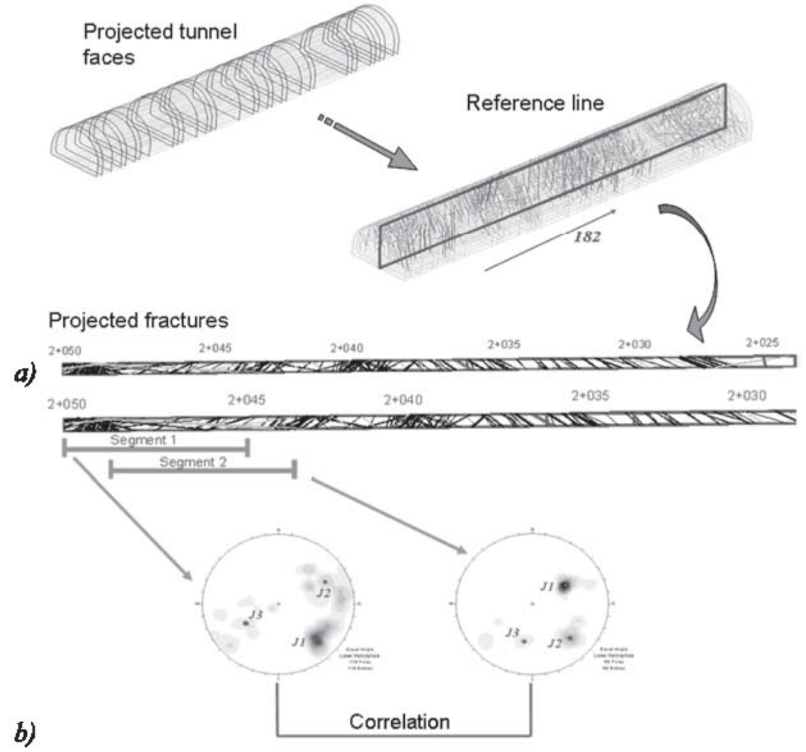


Figure 3: Stereonet correlation performance: a) Projected fractures on reference line, fracture sets are plotted in different colors, b) Stereonet plotting windows

3. Application and Discussion

The Bong Hwang tunnel is 415m long and locates at about 16km east of CheongJu city, Chungbuk province, South Korea. The study area is composed mainly by metamorphosed sedimentary rocks of Ogcheon Group. The rock types are consisted of calcareous shale, limestone, slate, phyllite, mica schist and coal-bearing shale. At the tunnel site, shale and slate/limestone are major rock types (Figure 4) and the rock near surface has been deeply weathered. The contacts between the formations are transitional and are usually characterized by the presence small intercalations of limestone.

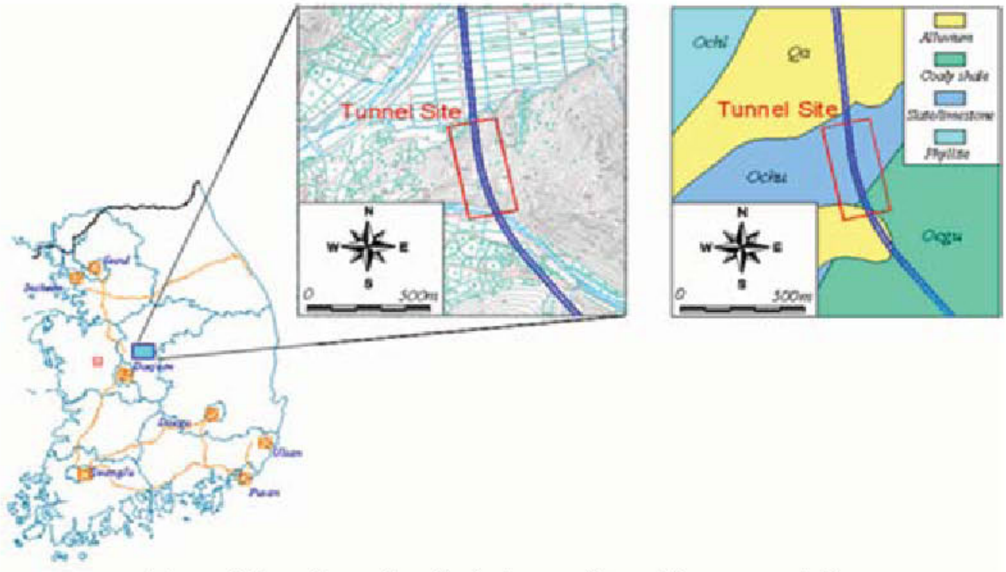


Figure 4: Location and geological map of BongHwang tunnel site

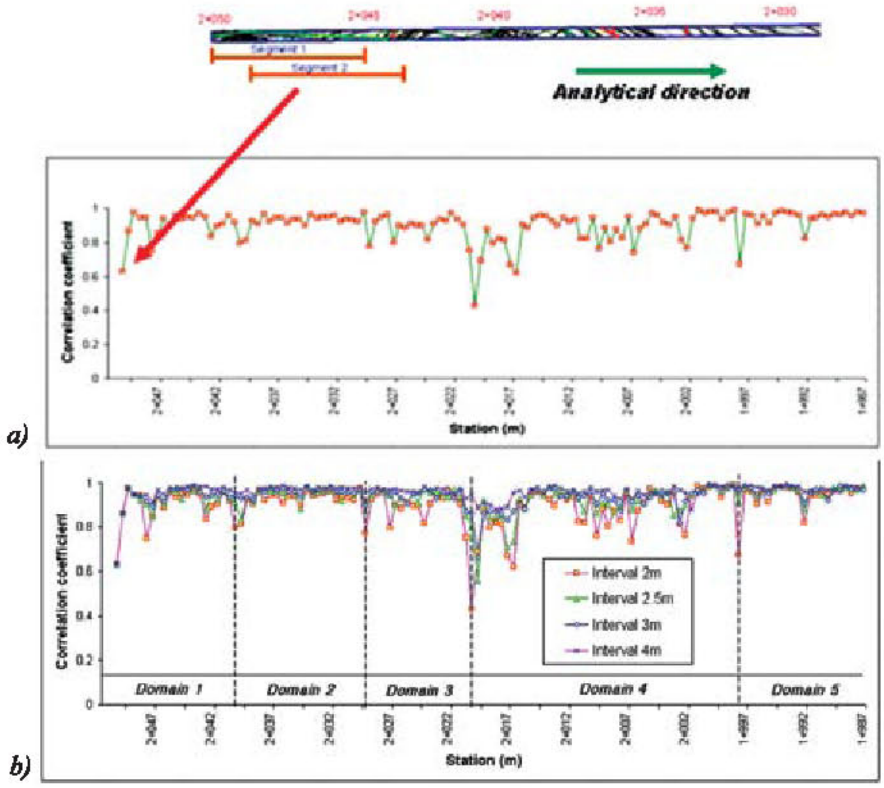
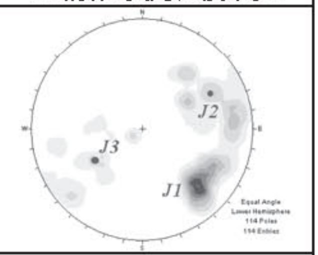
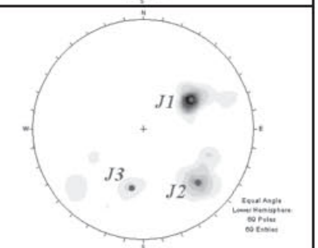
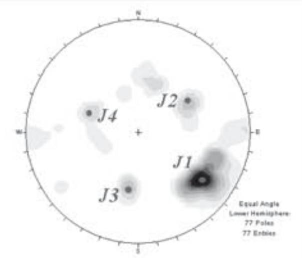
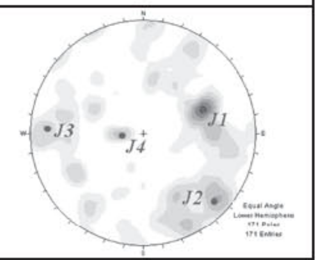
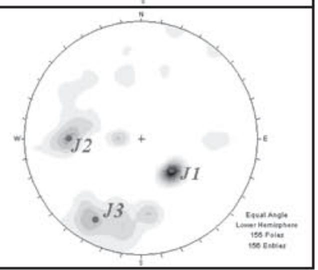


Figure 5: Correlation versus position along tunnel line: a) Correlation plotting of running windows, b) Domain divisions of BongHwang tunnel site after several runs

To test the applicability of these methods, 606 fractures over 62m tunnel length from southern entrance have been used. There are two small faults cut through the tunnel in the surveyed section. Both faults are narrow and very steep. The first fault (310/85) cuts the tunnel entrance and the second one (275/80) runs sub-parallel to tunnel axis for 10m. Foliation planes dip towards northwest and the dip angle of foliations in shale (313/67) is higher than that of limestone (313/42). In the correlation analysis, overlapping windows are compared and plotted as a graph of correlation coefficient versus tunnel position. Analytical intervals are adjusted by running several trials. Too long interval gives scattered plot to define domain boundaries, while too short interval gives general and indistinct plot as much overlapping data were used. A structural boundary is defined by the lowest correlations and the analysis along the Bong Hwang tunnel has delineated 4 main structural domains (Figure 5).

Table 1: Fracture domain division and stereonet of contoured poles

Domains	Lithology	Fracture sets	Fracture distribution
1	Black slate and coal-bearing shale	J1: 316/70 J2: 244/69 J3: 054/52	
2	Shale and coal-bearing shale	J1: 238/52 J2: 313/68 J3: 012/56	
3	Shale and coal-bearing shale	J1: 308/69 J2: 238/53 J3: 010/54 J4: 110/49	
4	Shale with small intercalations of limestone	J1: 248/58 J2: 314/80 J3: 092/80 J4: 090/22	
5	Limestone	J1: 318/41 J2: 090/63 J3: 028/77	

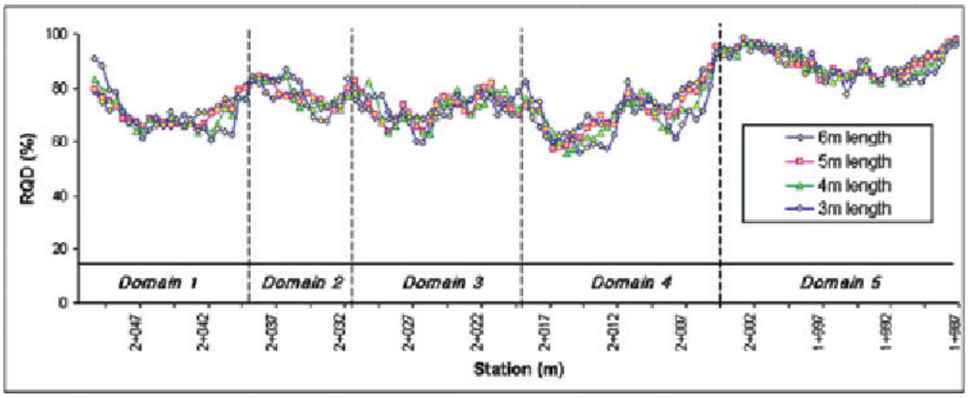


Figure 6: RQD versus position along tunnel line for different core lengths

The RQD analysis is also performed (Figure 6) and the change in RQD values is used to justify dividing the area into separate domains. However, the RQD analysis do not clearly differentiates fracture domains as the fractures are evenly distributed along the tunnel line. Final domain boundaries can be drawn by adjusting the mid position of boundaries from two methods. By combination of the two analyses, it appears that the Bong Hwang tunnel area could be divided into five domains. These domain divisions are then compared with the changes in rock types. The result shows that domain divisions agree very well with lithology boundary (Table 1), especially at the change from limestone to shale. The domain boundaries were fortuitously chosen and the domain divisions reflect the changes in major fracture orientation and the lithologies.

4. Conclusion

The result from Bong Hwang tunnel indicates that stereonet correlation and fracture density analysis are efficient tools in structural domain delineation. The correlation coefficient on stereonet and fracture density represented by RQD value from two adjacent segments give the idea of their similarity in term of fracture orientation and spacing, thus, rock strength of each section. Two different populations of fracture orientations can give similar values of fracture spacing, therefore, the fracture frequency approach does not capture the full distribution of orientations. The combination use of correlation method and fracture frequency method would give better results of domain division. These methods are adaptive as they can be analysed spatially. Experiment at the tunnel site shows reasonable structural domain boundaries between regions by quantifying the degree of similarity between them. Further experience at other sites is needed to make guidance for defining significant correlation and RQD value for domain separation.

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References

Deere, D. U., 1964, Technical Description of Rock Cores. *Rock Mechanics Engineering Geology*, 1, 16-22.

Hammah, R. E. and Curran, J. H., 1998, Fuzzy Cluster Algorithm for the Automatic Identification of Joint Sets. *International Journal of Rock Mechanics and Mining Sciences*, 35, 889-905.

Jimenez-Rodriguez, R. and Sitar, N., 2006, A Spectral Method for Clustering of Rock Discontinuity Sets. *International Journal of Rock Mechanics & Mining Sciences*, 43, 1052-1061.

Martin, M. W. and Tannant, D. D., 2004, A Technique for Identifying Structural Domain Boundaries at the EKATI Diamond Mine. *Engineering Geology*, 74, 247-264.

Priest, S. D., 1993, Discontinuity Analysis for Rock Engineering. London: Chapman and Hall, 473.

Surrette, M., Allen, D. M. and Journeay, M., 2008, Regional Evaluation of Hydraulic Properties in Variably Fractured Rock using a Hydrostructural Domain Approach. *Hydrogeology Journal*, 16, 11-30.

Zhou, W. and Maerz, N. H., 2002, Implementation of Multivariate Clustering Methods for Characterizing Discontinuities Data From Scanlines and Oriented Boreholes. Computers and Geosciences, 28, 827-839.