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Identification of structural domains considering the size effect of rock mass discontinuities: A case study of an underground excavation in Baihetan Dam, China

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ABSTRACT

This study used a case study of an underground excavation in Baihetan Dam, China to identify structural domains, which are highly affected by size effects. The magnification and reduction methods involving nonparametric hypothesis tests of the KS, *T*-, and *F*-tests were proposed for the identification of structural domains. This process considers the fracture properties of orientation, trace length, position, and density. An ideal fractured rock mass model, whose structural domain identification reliability can easily be assessed, was generated and the size effect was proved to be significant. A sampling window with 159 stochastic fractures along an underground excavation was then presented. Calculations showed that different calculation sizes produce apparently different identification results. Given the objective of the analysis and further calculations, reliable results for the magnification and reduction methods were obtained.

1. Introduction

Rock masses are characterized by inhomogeneous features, resulting in domains with various properties. Geotechnical, geological, and structural domains can be categorized by considering different aspects. Geological domains can be identified based on the spatial continuity of the rock grades and their geological features such as lithology, mineralogy, and alteration (Emery, 2007; Emery and González, 2007). Identifying the geotechnical domains of rock mass requires consideration of various properties such as its planes of weakness, degree of weathering, uniaxial compressive strength, deformation modulus, stress field, and permeability of the rock mass (Jakubec et al., 2004). Structural domains can be identified based on the discontinuity characteristics (Kulatilake et al., 1997; Li et al., 2014a,b,c). The geological domain focuses on the geological properties of rock masses, whereas the two other domains focus on the engineering properties of rock masses. Compared with the geotechnical domain, the structural domain, which is investigated in this study, simplifies rock mass analysis by emphasizing the discontinuity characteristics. Structural domain identification is useful for analysis of tunnels and other underground openings. The region within the same structural domain is characterized by similar forms of deformation and destruction types derived from similar discontinuity distributions. Therefore, stability calculation and support design of the tunnels and other underground openings can be investigated aiming at respective structural domain.

Discontinuity characteristics, such as orientation, trace length, and spacing, significantly vary across different areas of a rock mass, resulting in different physical and mechanical properties (Chen et al., 1995; Escuder-Viruete et al., 2001). A structural domain is characterized by volumes of a rock mass with similar properties, which is typically defined by its strength characteristics and rock type. In project engineering, a rock mass can be divided into different domains, and the properties of each individual domain are analyzed. The features of an integral rock mass can be derived from a comprehensive consideration of all the structural domains (Michael et al., 2004; Li et al., 2014a,b,c).

Structural domains were traditionally determined using discontinuity orientations. For example, Piteau and Russell (1971) and Piteau (1973) used the orientation of joints in rock mass measured along a scan line as calculation data. They proposed a cumulative sum technique, which can detect significant and consistent changes in discontinuity orientations, to indicate the location of structural domains. Miller (1983) plotted the discontinuity

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orientations on a stereonet as poles by using the lower-hemisphere Schmidt projection and then compared the stereonets with data from different areas of the rock mass using a contingency table derived by the chi-square method. Mahtab and Yegulalp (1984) subsequently divided the upper-hemisphere Schmidt diagram into 100 quadrilateral squares of equal area and identified the structural domains by comparing similar samples. Based on stochastic mathematics, Michael and Tannant (2004) and Liu et al. (2004) used the Pearson product-moment correlation coefficient and the Weibull statistical method to identify structural domains based on fracture orientation data.

In addition to orientation, other discontinuity characteristics, such as trace length and frequency, have an important role in identifying structural domains. For instance, Kulatilake et al. (1997) applied fractal theory to calculate fracture dimensions, taking into account the trace length and density. Dershowitz et al. (1998) used fracture dip, dip direction, and frequency at different intervals along a borehole to detect structural domains. Zhang et al. (2011) applied a contingency table of chi-square tests to identify structural domains by comprehensively considering the mean dip, dip angle, trace length, and width of the fractures. Quoc et al. (2012) employed stereonet correlation and fracture density analysis to divide fracture patterns into homogeneous domains; thus accounting for both fracture orientation and density to identify structural domains. Furthermore, Xue et al. (2014) considered fracture orientation and trace length to identify structural domains using hypothesis tests.

The fracture data from two or more areas can be compared to determine structural domains. When the dataset are statistically the same, the areas can be combined into one domain. However, the size of the compared areas needs to be determined. An ideal model with four sections is presented in Fig. 1 to illustrate the size effect in structural domain identification. The fracture trace lengths and orientations in Sections I and III are identical, and those in Sections II and IV are also the same. Each of the four sections (I, II, III, and IV) can be defined as a structural domain. When 1 m is selected as the size for structural domain identification, the discontinuity characteristics in different areas are remarkably different. Therefore, in this case, none of the sections can be regarded as a structural domain. When 2 m is selected, Sections I, II, III, and IV are all structural domains. When 20 m is selected, the two arbitrary adjacent areas are diverse; therefore, areas with size of 20 m cannot be combined into a structural domain, whereas structural domains of 20 m were indicated. When 40 m is selected, the entire rock mass is a structural domain. Hence, the structural domains vary depending on the size selected for the calculation of the compared areas. Studies should therefore give due attention to the influence of size on structural domain identification.

Thus, the size effect significantly affects the identification of structural domains. In this study, based on nonparametric hypothesis tests (e.g., KS, T-, and F-tests), we proposed magnification and reduction methods to demonstrate the significance of the size effect. The methods are used to identify the structural domains of an ideal model and a sampling window with 159 stochastic fractures along an underground excavation in Baihetan Dam. Multiple fracture characteristics are reasonable considerations for structural domain identification; therefore, fracture orientation, trace length, position, and density are used for analysis in this study.

2. Models for identifying structural domains

This study proposes two methods that involve nonparametric hypothesis tests to identify structural domains by considering the size effect. Sections 2.1 and 2.2 introduce the procedures of the two methods. In Section 2.3, we apply these methods to identify the structural domains of an ideal model (Fig. 1). We demonstrate the significance of the size effect and verify the structural domain identification results.

The engineering properties of rock masses are strongly influenced by the discontinuity characteristics. If the characteristics of the discontinuities distributed in two adjacent areas are statistically identical, then the rock mass in the areas is characterized by similar properties. As such, the areas can be combined into a structural domain. Nonparametric hypothesis tests were applied to determine if the discontinuity characteristics, which can be expressed by parameters such as orientation and trace length, in the two adjacent areas were statistically identical. In brief, we checked the parameters of two areas of discontinuities by applying the nonparametric hypothesis tests. If their difference was accepted by the tests, then the areas were combined into a structural domain. Conversely, if the rock masses in the two areas were characterized by varied properties, then they did not belong to the same domain.

2.1. Magnification method

The method presented here is similar to traditional techniques that combine statistically similar adjacent areas into a structural domain. However, this method improves on such techniques using nonparametric hypothesis tests for similarity judgment. In this method, two small areas are combined to produce a larger structural domain; thus, this technique is called the "magnification method". To analyze an area u and its adjacent area u', the magnification method procedures are described as follows (Fig. 2):

(1) An area of rock mass u and its adjacent area u' with the same size a are selected.
(2) Each discontinuity within any part of the traces located inside u and u' is recorded for calculation. When calculating the fracture trace length, the part of the trace outside the study area is eliminated. Ultimately, two datasets of trace lengths and orientations for u and u' are determined.

Rock mass properties are influenced by geotechnical, geological, and structural characteristics. The strength of the structural discontinuities is much lower than that of the rocks. Consequently, rock masses deform and crack along the discontinuities. Therefore, structural characteristics play a significant role in rock mass analysis. This study investigated the structural domain, influenced only by rock mass discontinuities; thus, the discontinuity parameters (orientation, trace length, position, density, aperture, and roughness) were considered. Of these parameters, the most important features of rock masses are the orientation, trace length, position, and density (Zhang et al., 2012, 2013), which are applied here for the structural domain analysis. Other characteristics, such as aperture and roughness, also influence the identification of the structural domain; however, their values are approximately even for

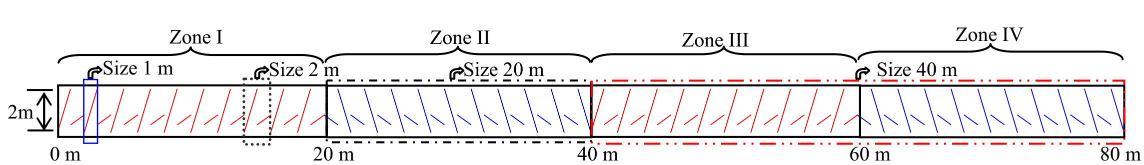

Fig. 1. An ideal model of the fractures for calculating the structural domains.