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Determination of structural domain boundaries in jointed rock masses: An example from the Songta dam site, China

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ABSTRACT

This paper presents an application of the Kolmogorov–Smirnov and Wilcoxon rank sum nonparametric statistical tests for identifying structural domain boundaries in jointed rock masses. In the method, the upper hemispherical surface is divided into 100 nearly equal-area windows. The similarity between two samples of joint orientations is measured by comparing the frequencies or the number of joint poles occurring in the windows. Over 2400 joints collected from 8 adjacent exploration tunnels at the Songta dam site in southwest China are used to demonstrate the method. By applying the technique to the study area, structural domain boundaries in the rock mass are determined. Our results suggest that the study area, with an area of approximately 17,850 m^2, can be classified into four structural domains. However, the traditional method with the correlation coefficient fails to reveal the structural changes. Since the correlation coefficient is only a measure of strength of the linear relation between two samples, it has limitations in measuring the similarity between joint orientation distributions. A comparison between the proposed method and previous methods indicates that the new technique could provide more reliable results. Besides, the new method can be applied to structural populations with small sample sizes.

1. Introduction

It is generally recognized that joints play a pivotal role in the deformability, permeability and strength of rock masses (Goodman, 1976; Hudson and Harrison, 1997; Smith, 2004; Larsen et al., 2009; Yamaji and Sato, 2011; Ye et al., 2012a, b). Characterizing joints within a rock mass is a basic step for rock mass classification and rock engineering design (Kruhl, 2013; Stavropoulou, 2014). Recently, the statistical joint modeling technique has been widely applied to the delineation of rock joints (Song et al., 2001; Grenon and Hadjigeorgiou, 2003; Tóth, 2010; Zhang et al., 2013a, b). One of the essential procedures in joint modeling is the determination of the boundary of structural domains or statistically homogeneous regions. A structural domain can be considered as a structural population characterized by a distinct pattern of joint orientations (Miller, 1983). For any specific rock unit in a jointed rock mass, the identification of structural domains is important because mechanical and hydrologic properties vary from one structural domain to another (Ye et al., 2009; Escuder Viruete et al., 2010).

Traditionally, structural domains are determined by identifying the dominant joint sets, and then visually comparing the similarity between joint orientation distributions collected from different regions (Martin and Tannant, 2004). However, when joint orientations appear dispersed and random on the equal-area projection, visual comparisons are not sufficient to determine whether samples of joint orientations are collected from a single structural domain (Miller, 1983).

To overcome the subjectivity in examining the similarity between joint orientation distributions, several methods have been developed (Miller, 1983; Mahtab and Yegulalp, 1984; Kulatilake et al., 1996; Martin and Tannant, 2004). Noticeable methods include the methods proposed by Miller (1983) and Martin and Tannant (2004). Miller (1983) introduced a statistical technique to determine structural domains by dividing the equal-area projection into nearly equal surface area sectors. This method utilizes a Chi-square test to evaluate the similarity between samples of joint orientations. Nevertheless, a minimum sample size of 150 joint orientations is required for the application of this method, which is sometimes unachievable in real applications. By dividing the upper hemispherical surface into 100 nearly equal-area windows, Martin and Tannant (2004) adopted a parameter known as the correlation coefficient to quantify the similarity between joint orientation

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distributions. However, the correlation coefficient only gives the strength of the linear relation between two samples of joint orientations, and no threshold values for this parameter were provided by Martin and Tannant (2004) to determine if the samples of joint orientations being compared are from the same structural domain.

Methods which ignore joint orientations have also been proposed. Kulatilake et al. (1997) used the box fractal dimension as an index of the combined effect of joint density and joint-size distribution to determine homogeneous regions. Escuder Viruete et al. (2001) adopted geostatistics to extrapolate discontinuity density from known locations to nearby areas in a rock mass. Fan et al. (2003) used joint spacing to analyze the homogeneity of rock masses. Liu et al. (2004) introduced a Weibull statistical method to model rock homogeneity. A Chi-square test was utilized by Li et al. (2012) to delineate homogeneous regions using joint trace length.

Joints in a structural domain are deemed to have similar distributions for various parameters such as orientation, spacing, roughness, aperture and filling (Kulatilake et al., 1997). In practice, only joint orientation is used to delineate structural domains because it is usually the principal factor affecting the behavior of a rock mass (Martin and Tannant, 2004; Ye, 2012; Li et al., 2014). In this paper, a new technique is developed for the identification of structural domains using joint orientations. Our method is based on the previous work conducted by Mahtab and Yegulalp (1984), in which the upper hemispherical surface is divided into 100 nearly equal-area windows. The similarity between two samples of joint orientations is determined by comparing the frequencies or the number of joint poles occurring in the windows using the Kolmogorov–Smirnov and Wilcoxon rank sum nonparametric tests. To assess the performance of the new method, we compare the results of the new method with those obtained by the methods proposed by Miller (1983) and Martin and Tannant (2004).

2. Study area

The Songta hydropower station is being constructed on the upper reaches of the Nu River. It is located in 110 km southeast of Chayu county of Tibet in southwest China (Fig. 1a). A concrete double-curved arch dam with a maximum height of 318 m is planned and it will be the highest arch dam in the world. The elevations of the normal water level and normal storage water level will be 1700 m and 1925 m, respectively. The station will have a total storage capacity of 4.55 billion m^3 and a hydroelectric generating capacity of 3600 MW.

The dam site is characterized by a mountain-canyon geomorphology, and the valley has an asymmetric “V” shape (Fig. 1b). The predominant lithology is Cretaceous biotite granite (Fig. 1c), mainly composed of quartz, plagioclase, potassium feldspar and biotite. Affected by tectonism, the biotite granite has been slightly deformed in brittle conditions, developing a cataclastic texture characterized by the fragmentation of feldspar phenocrysts. Mafic intrusive rocks (Fig. 1c) in the same age are also exposed in this area, which outcrop as dykes with width varying from 0.05 to 5 m. The contact zone between mafic intrusive rocks and granite has been hydrothermally altered and their igneous mineral phases have been replaced by other low-temperature minerals. No regional fault lies in the dam area but numerous small-scale faults are exposed on both sides of the dam axis, which can be categorized as two conjugate fault sets trending NW–SE and NE–SW (Kong and Wu, 2010).

3. Data acquisition

Over 50 exploration tunnels located at different elevations on both banks of the Nu River were excavated to investigate the properties of the rock mass. The strikes of the tunnels are approximately E–W, perpendicular to the flow direction of the Nu River. Data collection was conducted in the tunnels using the window sampling method: all joints that intersect the south-side wall of each tunnel, with trace length longer than 0.5 m, were mapped. Faults and dykes do not appear in the studied sections and only joints collected from the granite rock mass are considered in this work.

Joint orientation data obtained from 8 adjacent tunnels at the elevations of 1732 and 1771 m on the right bank of the Nu River (Fig. 2) are selected to demonstrate the new method. The average horizontal distance between these tunnels is about 60 m. The study region around these tunnels covers an area of about 17,850 m^2. The

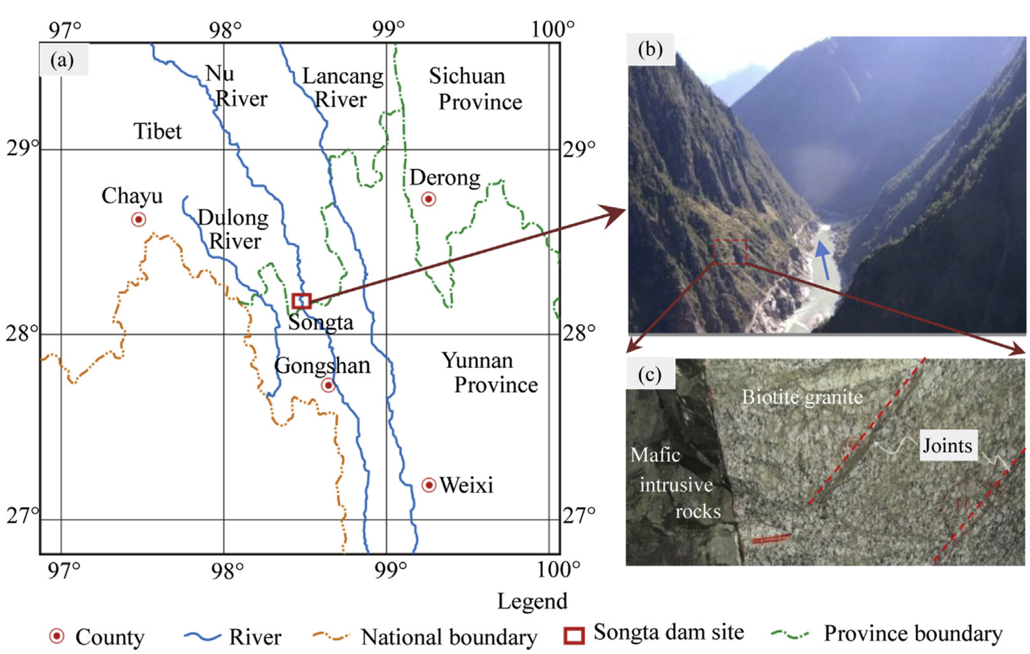

Fig. 1. (a) Location map of the Songta dam site. (b) Geomorphology at the dam site. (c) Lithology exposed at the dam site.