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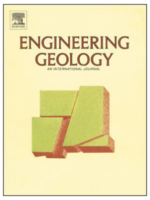

# Comprehensive characterization and clustering of orientation data: A case study from the Songta dam site, China

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ABSTRACT

The quantitative description of orientation data in rock masses is fundamental for understanding the engineering geological properties of rock masses. However, the features of joint orientation distributions are still not easy to describe in practical projects. Orientation data are randomly distributed in a rock mass, and its poles are also randomly distributed on a stereonet. The delineation of orientation data on the stereonet is difficult, but the density of poles on the stereonet indicates some characteristics of joint geometric patterns, which will influence the mechanical and hydraulic properties of rock masses. Considering the nonlinear distribution of poles density, fractal geometry is introduced to describe the orientation data in this study. Accordingly, a framework combining the idea of fractal geometry, graphic display and the Schmidt upper-hemisphere equal-area projection plot is proposed for comprehensive characterization of orientation data. The monofractal and multifractal descriptions have been used to delineate the orientation data, and a fractal indicator is proposed for the dispersion of orientation data. In addition, the identification and delineation of joint sets with similar orientations are discussed, and the optimal method is recommended. Finally, the methods proposed in this study were further applied to a real data set collected from a survey at the dam site of the Songta hydropower station, China.

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## 1. Introduction

It is widely known that joints play a pivotal role in the strength, deformation and conductivity of rock masses (Priest, 1993; Ren et al., 2015; Singh and Seshagiri Rao, 2005; Tsesarsky, 2012). Characterization of joints within a rock mass is an essential and fundamental task for rock-mass classification and geotechnical engineering design (Alavi Nezhad Khalil Abad et al., 2016; ISRM, 1978; Zheng et al., 2014). Orientation, spacing, roughness, infilling materials, aperture and wall rock strength are the most important parameters for describing jointed rock masses (Priest, 1993). Because of lack of the effective means for the comprehensive characterization of rock masses, practical applications suffer from the inability to incorporate more parameters simultaneously (Zhou and Maerz, 2002). The orientation of joints is usually the dominant characteristic influencing the behavior of rock masses. Therefore, only the joint orientation is considered in some engineering applications such as slope stability (Zhang et al., 2013), determination of structural domain (Martin and Tannant, 2004) and clustering of joint sets (Jimenez-Rodriguez and Sitar, 2006; Shanley and Mahtab, 1976). To better understand the engineering geological properties of rock masses, the quantitative description of orientation data is urgently needed.

Orientation data are often expressed in terms of dip direction and dip angle, which are also called bivariate parameters. However, it is usually hard to deal with bivariate parameters when trying to obtain a conventional mathematical analytical solution. In addition, research shows that there are non-zero correlations between the different orientation components (i.e. dip direction and dip angle) (Tran, 2007). Therefore, bivariate distributions are widely used to represent orientation data. However, in reality, the features of joint-orientation distributions are still not easy to describe in practical projects. Many bivariate probability density functions, such as the Fisher distribution (Fisher et al., 1987), Bingham distribution (Bingham, 1974), and bivariate normal distribution (Kulatilake, 1986), have been proposed by researchers to represent the distribution of orientation data. However, the distribution of orientation data in nature is always very complex, and sometimes the existing distributions cannot well describe the orientation data. Consequently, the stereographic projection is usually used to describe the distribution of orientation data. The most widely used stereonets are equal-area (Schmidt) stereonets and equal-angle (Wulff) stereonets. The orientations of joints are plotted as poles on the stereonet, and poles are randomly distributed on the stereonet. In general, it is difficult to quantitatively interpret orientation data on the stereonets. However, the density of poles on the stereonet indicates some characteristics of joint geometric patterns, which will influence the mechanical and hydraulic properties of rock masses (Desroches et al., 2014; Tomás et al., 2012; Zheng et al., 2015).

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Fractal geometry, proposed by Mandelbrot (1982), is a type of systematic method to quantify the scaling properties of irregular patterns in nature that do not obey Euclidean geometry. Since its introduction, it has provided a useful tool to interpret complex shapes or phenomena. Fractals can be expressed as self-similar or self-affine in a statistical sense. This suggests that if a part of the fractal object is magnified, the magnified part is similar to the whole object. It is well known that a tremendous number of geological and geophysical phenomena exhibit fractal behaviors (Peitgen et al., 2004). Monofractal and multifractal methods can provide valuable information about the geometrical and statistical features of the phenomena. Therefore, fractal theory has found increasingly broad applications in many fields of geosciences. Examples include rock mass characterization (Kulatilake et al., 1997), earthquakes (Malamud and Turcotte, 1999), drainage networks (Fac-Beneda, 2013), soil science (Montero, 2005), and geological disasters (Sezer, 2010). Inspired by fractal theory, the monofractal- and multifractal-based methods were applied to quantitatively describe geometrical and statistical properties of orientation data that are randomly distributed on the stereonet.

Another important challenge that the engineers face when interpreting orientation data is the identification and delineation of joint sets with similar orientations. Shanley and Mahtab (1976) proposed a counting method using stereographic projections to identify the joint sets. However, this method has two difficulties: the interpretation is subjective and it is hard to predefine the proper radius of the small sphere to determine the density points (Ma et al., 2014). Within the last few decades, significant efforts have been made for automatic clustering of joint orientations, and many algorithms were proposed to achieve this goal. Among the many clustering algorithms, the spectral clustering algorithm (Jimenez-Rodriguez and Sitar, 2006) and partition clustering algorithms (Li et al., 2015; Ma et al., 2014; Tokhmechi et al., 2011; Xu et al., 2013) are widely used. In the traditional clustering methods, the results of clustering can't directly provide the statistical information and probability distribution for each joint set. Recently, with the development of spherical statistical techniques, model-based clustering has been gradually applied to the classification of orientation data (Peel and Mclachlan, 2001; Yamaji and Sato, 2011).

The main goals of the current research are to present a comprehensive characterization of orientation data in jointed rock masses. A method combining the idea of data visualization and fractal geometry was proposed in this study to quantitatively describe the geometrical and statistical properties of orientation data. In addition, a fractal indicator was adopted to characterize the dispersion of orientation data. Considering that the fractal structure of poles is heterogeneous on the stereonet, multifractal analysis was introduced to characterize the heterogeneity of orientation data in a fully quantitative fashion. Moreover, various clustering methods of joint orientation were discussed and reviewed. Each method provides a good clustering result and the optimal method is recommended. In the end, the methods proposed in this study were further applied to a real data set collected from a survey at the dam site of the Songta hydropower station in China.

## 2. Database

### 2.1. Study area

The Songta hydroelectric power station, located at the junction of the Tibet Autonomous Region and Yunnan Province in southwest China, will be one of the highest arch dams in the world when construction is completed. As shown in Fig. 1, the power station is situated on the upper reaches of the Nu River and the flow direction is approximately 188° SW at the dam site. The elevation of the normal water level is 1700 m.

A concrete double-curved arch dam with a maximum height of 318 m is designed for the Songta hydroelectric power station. Because the maximum elevation of the storage water is 1925 m, the station will have a total storage capacity of 4.55 billion $m^3$. The hydroelectric generating capacity of the Songta hydroelectric power station will be 3600 MW.

The landscape type of the dam site is a typical mountain-canyon geomorphology, and the valley exhibits an asymmetric "V" shape (Fig. 2(a)). The maximum altitudes of the mountain on the left bank and the right bank are 2851– 3091 m and 3421– 4361 m, respectively. The average slope of the left bank is 40°, and the right bank is 55°.

There are two main types of lithology from the Late Yanshanian (Cretaceous) period exposed at the dam site: biotite monzonitic granite and plagioclase amphibolite (Fig. 2(b) and Fig. 3(a)). Biotite monzonitic granite is the predominant lithology, and it is mainly composed of quartz, potassium feldspar, biotite and plagioclase. Affected by the tectonism, the biotite granite has a cataclastic texture characterized by the fragmentation of feldspar phenocrysts (Fig. 2(c)). This shows that the biotite granite has been slightly metamorphosed. Plagioclase amphibolite is exposed as dykes with widths varying from 0.05 to 5 m at the dam site (Fig. 2(b)). In the region connecting the two types of lithology, because the plagioclase amphibolite (mafic intrusive rocks) has experienced compression and hydrothermal alteration, the mineral alteration phenomenon can be observed.

The nearest regional fault is Gebu-Songta fault, which is 2.5 km from the dam site. At the dam site, there is no regional fault. However, as shown in Fig. 3(b), two conjugate fault sets composed of numerous trending NW-SE and NE-SW small-scale faults occur at both banks (Kong and Hao, 2010; Zhao et al., 2014). In addition, numerous joints are randomly distributed in the rock slope.

### 2.2. Data collection

To study the engineering geological properties of the rock mass at the dam site, over 60 exploration tunnels were excavated at different elevations on both banks of the Nu River. The directions of the tunnel axes are approximately E-W, which are perpendicular to the flow direction of the river (188°). The window sampling method (Mauldon et al., 2001; Song and Lee, 2001; Zhang et al., 2012) was used to collect joint data in the tunnels. There are a limited number of faults and dykes within the rock masses, and these discontinuities are not considered in this study. Only the joints with trace lengths >0.3 m that intersected or were located within the left wall of each tunnel were mapped. To speed up the progress of measurement, an improved sampling method was adopted. As shown in Fig. 4(a), each tunnel is divided into sections of 10 m, and each section is divided into three subsections: two rough measuring nets (0– 3 m and 7– 10 m) and one fine measuring net (3– 7 m). In the fine measuring net, joint information, including the orientation, trace length, spacing, aperture, filling, weathering and roughness, was measured. In the rough measuring nets, only orientation and traces were measured. Because the orientation data are raw data collected from the field, no bias correction was introduced in this study.

A total of 3947 joint orientation data collected from 13 adjacent exploration tunnels (Fig. 3(b)), which are at same elevation of 1720 m on both banks, were selected for a case study. For example, the joints collected from tunnel PD231 are illustrated in Fig. 4(b).

## 3. Visualization and clustering of orientation data

### 3.1. Representation of orientation data

Conventionally, joints are often assumed to be planar structures and unit normal vectors are used to describe orientations of joints in rock mechanics (Priest, 1985). As shown in Fig. 5, a unit normal vector is always expressed in terms of dip direction ($0° \le \alpha \le 360°$) and dip angle

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