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Modeling the spatial variability of the shear strength of discontinuities of rock masses: Application to a dam rock mass

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ABSTRACT

The shear strength of discontinuities plays a key role in the stability of rock masses, particularly in the case of analyzing the sliding stability of the rock foundations of gravity dams. This paper proposes a methodology for analyzing the spatial variability of shear strength along the joints of rock mass, based on the input parameters of the Barton and Choubey's model. The aim of this approach is to evaluate the reduction of the variance of the parameters involved at full-scale by identifying a deterministic trend varying in depth and a spatial correlation calculated from a variographic analysis. An advantage of this methodology is to use a simple experimental protocol (a laser profilometer, a portable shear test apparatus and a concrete sclerometer), which generates large sets of shear strength properties for assessing their spatial variability. The methodology is illustrated in the case of the rock foundation of a concrete gravity dam. Analysis of the spatial variability conducted for this case study led to a significant reduction of the variance of the variable analyzed. The advantage of this method is demonstrated through the evaluation of the probability of failure performed in a study of this structure's stability. Taking variance reduction into account in the case study led to significantly reducing the probability of failure assessed through a reliability analysis.

1. Introduction

The shear strength of discontinuities plays a key role in the stability of rock masses, particularly in the case of analyzing the sliding stability of the rock foundations of gravity dams. Rock masses often present vertical and horizontal variability regarding the shear strength properties of their joints (Phoon and Kulhawy, 1999). The question of characterizing the spatial variability of the shear strength of rock masses appears crucial for providing a more satisfactory evaluation of their stability, since doing so would lead to reducing the variance of strength properties in limit state calculations and thus to optimizing the stability assessment. Indeed, taking into account the reduction in the variance of strength properties permits optimizing the estimation of: i) the values of conservative calculations for deterministic justifications, ii) the characteristic values corresponding to a fractile in semi-probabilistic justifications (Peyras et al., 2010), iii) the variance of random strength variables in probabilistic justification (Vanmarcke, 1983; Carvajal et al., 2009).

The variance of shear strength properties involved at the joint scale is lower than that evaluated at the laboratory scale. This reduction of variance results from the larger surface involved (linked to an average of punctual values) and from the spatial correlation of shear strength properties. Analyzing spatial variability through random fields makes it possible to take this reduced variance into account (Gravanis et al., 2014; Vanmarcke, 1983).

Several authors have focused on modeling the spatial variability of rock masses, such as (Duzgun et al., 2002), (Gravanis et al., 2014) and (Shamekhi and Tannant, 2015). (Duzgun et al., 2002) proposed a probabilistic model to estimate the in-situ shear strength of rock joints based on shear strength measurements obtained in the laboratory. (Gravanis et al., 2014) put forward an analytical solution for the probabilistic evaluation of rock mass slope stability. The methodology proposed by (Gravanis et al., 2014) was based on random fields defined for the shear strength parameters of the Mohr-Coulomb criterion and was applied to the case of a joint along a predefined flat surface. (Shamekhi and Tannant, 2015) also proposed a probabilistic method for evaluating the slope stability of a rock mass, in which the variability of the

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geometric properties of the joints were taken into account in a finite element model.

Modeling the spatial variability of a soil/rock strength property can be a difficult task because the number of test data obtained during site investigation is usually too sparse to carryout meaningful statistical analysis. Bayesian methods have been recently developed to address this issue in geotechnical and rock engineering (e.g., Wang and Cao, 2013; Wang and Aladejare, 2015; Wang et al., 2016).

Performing direct shear tests provides reference data for quantifying the shear strength of joints. However, these tests are expensive and only a limited number are performed with the test pieces available, which does not provide a statistically representative range of samples of the dispersion of shear strength properties. To solve this, we proposed a modified procedure using the Barton and Choubey (1977) to characterize joint shear strength (Sow et al., 2015). Our methodology is based on an experimental approach that uses simple resources to determine the parameters of the Barton and Choubey criterion: a laser profilometer, a portable shear test device and a concrete sclerometer. This experimental approach generates large sets of shear strength properties, through the application of a simple and inexpensive experimental protocol. The statistical sample of shear strength properties thus generated can then be analyzed and the spatial variability modeled.

The present paper continues in this direction in view to developing a methodology for analyzing the spatial variability of the shear strength of the joints of rock masses. The proposed methodology, based on the input parameters of the Barton and Choubey's model aims to evaluate the effects of reduced variance of the shear parameters involved in limit state calculations (Sow, 2015). An advantage of this methodology is to use a simple experimental protocol (a laser profilometer, a portable shear test apparatus and a concrete sclerometer), which generates large sets of shear strength properties for assessing their spatial variability.

The methodology proposed to analyze spatial variability comprises the following steps:

- The probabilistic description of the joints of a rock mass on the basis of a stereographic analysis;
- Using the Barton and Choubey criterion to characterize joint shear strength;
- Modeling spatial variability at the scale of the sample (from core samples) of parameters measured in the experimental campaign and the parameters of the Barton and Choubey criterion. Modeling the variability of the parameters studied highlights a deterministic trend as a function of spatial localization, a random measurement error variable and random error variable of the model linked to a deterministic trend;
- Modeling the spatial variability at the scale of the structure of the rock joint shear strength parameters on the basis of a variance reduction analysis.

The first two steps have already been used or published in the scientific literature to analyze rock masses and joint shear strength and are developed briefly in the first part of this paper. The second part of the paper presents the core of the methodological developments proposed to model the spatial variability of the joint shearing parameters. The methodology is illustrated in the third part of this article using the example of a rock foundation of a concrete gravity dam situated in Canada. Its efficiency is demonstrated through the presentation of a reliability analysis of the shear strength of a dam rock mass with a geo-modeling application using the finite elements method. The article ends with a discussion on the methodology and the results.

2. Material and methods

This section briefly describes the tools and the methods already available in the literature that will be used in the methodology proposed in this paper in order to model the spatial variability of the shear strength of the discontinuities.

2.1. Probabilistic description of the joints of a rock mass

Rock masses are usually jointed heterogeneous media encompassing two types of element: rock blocks and joints. Due to their low stiffness, low strength regarding certain stresses (shear) and their hydraulic conductivity, joints play a predominant role in the behavior of rock masses (Panet, 1976).

The parameters that allow describing joint geometries are orientation, spacing and persistence (Blès and Feuga, 1981).

The joints of a rock mass do not have a random orientation and are often organized in directional sets whose number is linked to the geological and mechanical phenomena involved during its formation and tectonic history (AFTES, 2003).

A stereographic projection was used for studying the distribution of joints in directional sets. When the different sets have been identified, we then analyze each set statistically by creating histograms of the distribution of geometric parameters relating to orientation, spacing and persistence (Hoek and Brown, 1980; AFTES, 2003).

This probabilistic description of the joints of a rock mass provides the input data for the geomodelers and permits simulating the spatial distribution of the joints.

2.2. Available data and the joint shear strength criterion

The shear strength developed along the joints can be evaluated using two different approaches. The first entails direct shear testing while the second the use of an empirical failure criterion corresponding to a shear strength envelope (ISRM, 1978).

The shear strength evaluated by direct shear tests on rock joints is a reference experimental approach (Panet, 1976; ASTM D5607-08, 200r8, 2008). However, the experimental procedures associated with these tests lead to obtain a limited number of samples available and therefore characterizing the shear strength variability of the rock studied.

The second approach uses empirical failure criteria and employs experimental protocols that are often quick and simple to use. The use of empirical failure criteria makes it possible to acquire shear data and get round the problem linked to the representativeness of the sampling (Grasselli and Egger, 2003). These empirical failure criteria include the Barton and Choubey (1977)'s model, which is recommended by the ISRM (1978) and remains widely used in engineering (Tatone and Grasselli 2012).

In our approach, the Barton and Choubey's criterion was used to characterize the joint shear strength. This criterion (Eq. (2) introduces a parameter that takes roughness into account called *JRC* (*Joint Roughness Coefficient*), a mechanical strength parameter, *JCS*, that takes rock alteration into account (*Joint Compressive Strength*) and the residual friction angle, denoted φ_r. The term σ_n represents the normal stress and τ_{pic} the peak shear strength.

$$\tau_{pic} = \sigma_n \tan\left(\varphi_r + JRC\log_{10}\left(\frac{JCS}{\sigma_n}\right)\right) \quad (1)$$

The experimental protocols for evaluating Barton and Choubey (1977) parameters can be performed easily on almost every joint or test piece obtained from coring. The methodology chosen for our research is based on an experimental approach (Sow et al., 2015) which uses fewer resources in comparison to classical shear tests to determine the parameters of the Barton and Choubey criterion: a concrete sclerometer to evaluate the *JCS* parameter, a portable shear test device to determine φ_r and a laser profilometer to scan the surface to evaluate the *JRC*.

The parameters measured directly by this experimental methodology are: i) the rebound values of altered and non-altered joints, r and R