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Characterization of rock discontinuity openings using acoustic wave amplitude — Application to a metamorphic rock mass

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ABSTRACT

Determining discontinuities is a key step in studying rock mass stability, as they represent potentially weak planes. The determination and description of discontinuity openings currently rely on qualitative analysis based on visual inspections of drill cores or drilling logs by engineers. The purpose of this research work is to improve the characterization of discontinuities to ensure easier classification and aid classical manual and visual processing. Quantity-based approaches are suggested using acoustic imaging log data. This method will facilitate sorting the discontinuities in a rock mass according to their openings, by quantitative analysis of drilling log data. Here, a method is proposed to determine discontinuity openings by analyzing acoustic wave amplitudes. The method is based on determining two statistical parameters for each discontinuity: the *resulting discontinuity amplitude*, which provides the average amplitude value as measured on the discontinuity, and the discontinuity amplitude *standard deviation*, which determines the extent of scattering of the amplitude values on the discontinuity. The method was applied to a metamorphic rock mass of a Canadian dam foundation at each stage of the study.

1. Introduction

Characterizing discontinuities is a key step in studying rock mass stability as most of them are potentially weak planes. These rock discontinuities are the potential shear surfaces on irregular and anisotropic rock masses (Hoek and Bray, 1981; Hoek and Brown, 1997; Johansson, 2005). On rock masses regarded as isotropic, the potential shear surfaces include rock matrix surfaces and limited extension discontinuities (Hoek and Brown, 1980; Johansson, 2005). Regardless of rock mass fracturing, break mechanisms above all bring the shear strength properties of discontinuities into play. These can change primarily according to the surface state of the discontinuity, as determined by its opening, roughness, weathering and filling (Patton, 1966; Barton and Choubey, 1977; Barton et al., 1985). A number of quantitative parameters can be used to assess specific characteristics of a discontinuity surface state. Indeed, the roughness, which is linked to the friction angle (Φ) may be determined using the JRC roughness coefficient or Z2 parameter (Tse and Cruden, 1979; Yu and Vayssade, 1991), and weathering may be determined using the JCS seal wall compressive strength (Tse and Cruden, 1979; Yu and Vayssade, 1991).

This article deals specifically with the opening characteristics of a discontinuity. Indeed, our objective is to determine discontinuities that are potentially dangerous for the mechanical stability of a rock foundation, in view to then determining the conditions of mechanical stability. Discontinuity opening is the parameter that permits characterizing the most potentially damaging discontinuities and for which determinations of stability must be established. In this framework, the work presented does not focus on classifying the geological types of discontinuity. It focuses more on fractures: open fractures, partially opened fractures and closed fractures. Neither does it focus on other lithological discontinuities such as contacts, foliations, veinlets, and dikes. Its purpose is to establish a classification of discontinuity openings in order to perform subsequent mechanical stability studies.

However, describing a discontinuity opening still relies on a qualitative analysis based on visual inspection of drill cores or drilling logs, considering that the discontinuity filling is dependent on the discontinuity opening. Therefore the research work compiled herein seeks to improve the characterization of discontinuity openings.

Images of borehole walls can be obtained using a tool called a *televiewer* that provides the required structural and geotechnical information that might not be obtained from conventional core logging, especially in a moderate to highly fractured rock mass. The first acoustic televiewer was developed in the late 1960s for the petroleum industry (Zemanek et al., 1969). Acoustic image logging is a fairly efficient method for exploring discontinuities in a timely and cost-efficient fashion

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(RIFP, 1991) and is a complement to the visual analysis of drill cores (Mari and Coppen, 1993). Several televiewer applications for improving the geotechnical and structural analysis of the subsurface can be found in the literature (Schepers et al., 2001; Kabir et al., 2009; Blake, 2010; Gasc-Barbier et al., 2010; Altadonna and Fulton, 2012; Hallahan et al., 2013). The televiewer can also be adapted to the specific geological context. For example, Massiot et al. (2015) reported the modification of televiewer processing techniques and the creation of a descriptive feature classification for hydrothermally altered, volcano-sedimentary-basement type reservoirs lacking other complementary information common in hydrocarbons or lower temperature geothermal systems.

As part of rock foundation assessment, the acoustic images are processed by an expert operator who visually analyzes discontinuities and compiles an inventory of them in relation to their altitude. This inventory includes their name and orientation (azimuth and dip), and is sorted into three categories: closed discontinuities, partially open discontinuities and open discontinuities, with their orientation and dip characteristics. This qualitative practice based on the visual analysis of acoustic imaging forms the basis for the development of alternative methods of classifying discontinuities according to quantitative log data. In this context, the purpose of this research work is to suggest quantity-based approaches for better characterization of discontinuity openings using acoustic image log data.

Consequently we provide a methodology that will help sort the discontinuities in a rock mass according to their openings, through the quantitative analysis of drilling log data. It is also designed to characterize discontinuity openings and notably the different fractures and their types of opening (open, partially open and closed), in view to performing a subsequent study of mechanical stability. Furthermore, the potential automation of the discontinuity classification process is considered in view to reducing time-consuming data processing. After a brief reminder of the physical rules and principles, the paper presents the acoustic imaging material and the signal processing used. In the second part, a quantitative method for classifying discontinuities according to their opening level based on amplitude data is proposed. This method uses a number of amplitude data statistical parameters to determine the discontinuity openings. Lastly, the relevance of this method is assessed and discussed on the basis of log data stemming from investigations performed on the metamorphic rock mass of a gravity dam foundation. The foundation of this dam located in Canada is thoroughly analyzed using 4 core drillings paired with acoustic image log inspections.

2. Material and methods for acoustic image logging

2.1. Physical principles

Acoustic image logging relies on wave reflection: when a source sends out a compression wave into the fluid that fills the borehole, compressive reflected waves are induced in the rock, where they spread through the fluid and create other compression waves. The waves are recorded as the durations of the back-propagation of waves and the amplitudes of sinusoidal signals.

The amplitude measured during acoustic image logging is the amplitude of the sinusoidal signal for the P compression wave reflected against the drilling wall and through the fluid. It may be defined as a dimensionless value conveying the sound pressure variation detected by the fluid and caused by the waves sent back by the rock wall (Paillet, 1980; Lurton, 1998). Changes occur to the structure of the sound wave hitting the drilling wall, owing to the type – rock acoustic impedance – and geometry of the obstacle (Lau et al., 1987; Cornet, 1988; Williams and Johnson, 2004). If the wall is perfectly flat and without discontinuity, this regular geometry will return the wave in a single consistent direction, thereby allowing a measurement with a higher amplitude. If the interface is rough due to a discontinuity or a filling, such irregularities will scatter the incident wave back in all directions. However, the incident wave will be partly reflected, without strains but with diminished amplitude in the consistent signal direction. Discontinuities induce a disturbed wave reflection, leading to a reduced amplitude (Lurton, 1998). Amplitude data are reported as wall logs or images. These help gather quality-related information on discontinuity openings since waves are substantially reduced in areas associated with discontinuities (Paillet, 1980; Arditty et al., 1988; AFTES, 2003).

2.2. Materials

The acoustic televiewer used is an ABI40 Televiewer (Mk2) (ALT, 2013). The ultrasonic energy wave is generated by a piezoelectric ceramic crystal and has a frequency of around 1.2 MHz. The acoustic wave is propagated by a reflector that focuses the beam at a point with a diameter of 1.5–2 mm.

The reflector is mounted on the drive shaft of a stepper motor. This enables rotating the position of the measurement through 360°.

In this study, the angular measuring pitch is 1.25° and the altitude measuring pitches are set to 0.8 mm. Therefore, 288 recordings are available per drilling altitude range (0.8 mm). This leads to the recording of thousands of amplitude measures during drilling (Mari and Arens, 1998).

2.3. Signal processing

The data collected are processed by WellCAD software which provides borehole data presentation and data processing tools (ALT, 2014). The results are drilling wall images based on amplitude data. Fig. 1 shows an example: the first image on the left is the actual optical image, the second image is the acoustic image with a color filter applied to highlight amplitudes, and the third image on the right is the 3D view of the borehole. An open fracture can be seen in the lower part of the three images in this figure. Above the open fracture, layers of different mineral contents can be seen clearly on the optical image but cannot be seen on the acoustic one as these layers of different mineral contents have the same density. Irregular fractures can also be seen above the open fracture. They are subvertical, inclined or interrupted. These irregular fractures are not taken into account in our study as we focus only on regular fractures involved in the mechanical stability of the rock mass.

3. Theory and calculation: characterization of discontinuity opening using acoustic wave amplitude

3.1. Objectives

The method proposed is based on amplitude data for identifying and classifying discontinuities according to their opening level, using the quantitative amplitude data related to discontinuities. The purpose is to provide a streamlined, opening-based, classification process for discontinuities and to aid the expert engineer in their classical manual and visual processing. Acoustic images are currently processed visually in three categories: closed discontinuities (Fig. 2, left), partially open discontinuities (Fig. 2, center) and open discontinuities (Fig. 2, right).

The quantitative method of opening-based classification proposed consists in performing local processing of the discontinuity in every orientation (0 to 360°), by retrieving the amplitude values linked to the location, and determining the discontinuity using the statistical parameters obtained from the amplitude data retrieved. This section describes all the steps required to determine these statistical parameters used for developing the proposed quantitative method for classification.

3.2. Analyzing acoustic wave amplitudes along a borehole

A statistical review of acoustic wave amplitude helps in measuring the amplitude variability along a vertical borehole. Fig. 3 shows how amplitudes are distributed for acoustic waves produced in a single direction along the hole.

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