Engineering Geology 195 (2015) 185–195

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Discontinuity spacing analysis in rock masses using 3D point clouds

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ARTICLE INFO

Article history:
Received 18 August 2014
Received in revised form 5 May 2015
Accepted 14 June 2015
Available online 19 June 2015

Keywords:
Spacing
Discontinuity
3D point cloud
Rock mass
LiDAR 3D laser scanner

ABSTRACT

The complete characterization of rock masses implies the acquisition of information of both, the materials which compose the rock mass and the discontinuities which divide the outcrop. Recent advances in the use of remote sensing techniques – such as Light Detection and Ranging (LiDAR) – allow the accurate and dense acquisition of 3D information that can be used for the characterization of discontinuities.

This work presents a novel methodology which allows the calculation of the normal spacing of persistent and non-persistent discontinuity sets using 3D point cloud datasets considering the three dimensional relationships between clusters. This approach requires that the 3D dataset has been previously classified. This implies that discontinuity sets are previously extracted, every single point is labeled with its corresponding discontinuity set and every exposed planar surface is analytically calculated. Then, for each discontinuity set the method calculates the normal spacing between an exposed plane and its nearest one considering 3D space relationship. This link between planes is obtained calculating for every point its nearest point member of the same discontinuity set, which provides its nearest plane. This allows calculating the normal spacing for every plane. Finally, the normal spacing is calculated as the mean value of all the normal spacings for each discontinuity set.

The methodology is validated through three cases of study using synthetic data and 3D laser scanning datasets. The first case illustrates the fundamentals and the performance of the proposed methodology. The second and the third cases of study correspond to two rock slopes for which datasets were acquired using a 3D laser scanner. The second case study has shown that results obtained from the traditional and the proposed approaches are reasonably similar. Nevertheless, a discrepancy between both approaches has been found when the exposed planes members of a discontinuity set were hard to identify and when the planes pairing was difficult to establish during the fieldwork campaign. The third case study also has evidenced that when the number of identified exposed planes is high, the calculated normal spacing using the proposed approach is minor than those using the traditional approach.

1. Introduction

Rock mass, which can be defined as blocks of rock material separated by discontinuities, such as joints, faults, bedding planes, and so on (Bieniawski, 1989), is one of the most important concepts in rock engineering. The discontinuity properties (i.e., spacing, persistence, roughness, infilling, weathering and presence of water) have a capital importance on the geomechanical behavior of the rock mass (Bieniawski, 1973; Priest and Hudson, 1976), and are usually characterized through classical time-consuming techniques (e.g., compass which are commonly utilized in order to obtain discontinuity orientation and also conventional measuring tapes which are used for the estimation of discontinuity spacing; Palmstrom, 2001). Alternatively to manual discontinuity characterization, it is possible to use remote sensing techniques to acquire 3D information of the terrain with high accuracy and high spatial resolution (Jaboyedoff et al., 2012). The two most commonly employed remote sensing techniques for discontinuity analysis are Light Detection and Ranging (LiDAR) and digital photogrammetry.

Nowadays, LiDAR and digital photogrammetry techniques are widely accepted techniques for discontinuity analysis (Abellán et al., 2014; Jaboyedoff et al., 2012; Oppikofer et al., 2009; Viero et al., 2010). The number of publications has exponentially grown in the last years and has been able to successfully extract the orientation of discontinuities (Slob et al., 2005; Olariu et al., 2008; Sturzenegger and Stead, 2009b; Sturzenegger et al., 2011; Jaboyedoff et al., 2007; Garca-Sellés et al., 2011; Khoshelham et al., 2011; Gigli and Casagli, 2011; Lato and Vöge, 2012; Riquelme et al., 2014). Once discontinuities are identified and the 3D point cloud is classified, it is then possible to use this information to analyze spacing (Oppikofer et al., 2009; Slob, 2010), persistence (Sturzenegger and Stead, 2009a; Sturzenegger et al., 2011; Umili et al.,

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http://dx.doi.org/10.1016/j.enggeo.2015.06.009
0013-7952/

2013) and roughness (Haneberg et al., 2007; Sturzenegger and Stead, 2009a; Oppikofer et al., 2011).

The aim of this paper is to present a new method for the calculation of discontinuity spacing from a rock mass using 3D point clouds. The main novelty of this method is that the proposed methodology allows computing the discontinuity spacing of persistent and non-persistent discontinuities, which are usually studied considering an infinite plane approach. The studied area must be representative of the rock mass properties and only those discontinuities that can reasonably be considered as planes should be studied, otherwise this method could lead to significant errors in the determination of the discontinuity spacing. The input of this method is a 3D point cloud, where each point has previously been classified by an assignment to a discontinuity set and to an aggregation of points belonging to the same discontinuity plane (hereinafter referred to as 'cluster'). Any reliable method that classifies the points and extracts their cluster planes can be applied. The approach used in this paper is the Discontinuity Set Extractor (DSE, available on http://personal.ua.es/en/ariquelme/), an open source software developed by Riquelme et al. (2014), which allows the user to calculate the cluster planes with the discontinuity set orientation or with the best fitting plane.

To summarize, the proposed methodology extracts rock mass discontinuities from rock masses affected by persistent and/or non-persistent discontinuity sets using 3D point clouds through the open source software DSE. Then, the relative location of the clusters on the space is analyzed and the spacing between the different discontinuities is calculated. Finally, the results obtained in three different case studies using the proposed method have been compared with those derived from field observations and discussed.

2. Previous considerations

Discontinuity spacing plays a key role in the behavior of the rock masses and has to be accurately computed. The ISRM considers the spacing as a descriptive index and recommends measuring it counting the number of discontinuities that cut a traverse line of known length (ISRM, 1977). However, new remote sensing techniques such as LiDAR allow performing a more realistic and accurate measurement of discontinuity spacing in three dimensions for each different discontinuity set.

2.1. Considerations on discontinuity spacings

Piteau (1970) proposed a widely used method to calculate the spacing between discontinuities. This author proposed the use of a scanline survey technique for the calculation of the discontinuity intensity. This parameter was defined as the number of discontinuities per unit distance, assuming a normal direction to the strike of a set of discontinuities (Priest and Hudson, 1976).

Originally, the ISRM defined the spacing between adjacent discontinuities as the distance between two correlative discontinuities which cut a traverse line of known length (ISRM, 1977). The ISRM recommends expressing it as a mean fracture spacing in meters or millimeters (as in core logging). More recently, Palmstrom (2001) stated that the discontinuity set spacing is the normal or minimum distance between individual discontinuities within a discontinuity set. He claimed that in the case of surface observations (traces), it is usual to use the average of spacing for these sets and that frequently, it is possible to find random discontinuities, which do not necessarily belong to any discontinuity joint set. This spacing has influence on the rock mass global behavior, and defines its block size for each discontinuity set.

Consequently, the three types of discontinuity spacings described above can be summarized as (Priest, 1993; Slob, 2010):

- Total spacing: distance between a pair of adjacent discontinuities measured along a specific line, e.g., a scanline.
- Set spacing: distance between subsequent discontinuities or average spacing between discontinuities from the same set.
- Normal set spacing: distance between a pair of adjacent discontinuities, from the same set, perpendicular to the average orientation in that set.

2.2. Existing approaches for the discontinuity spacing calculation

In practice, analysis of discontinuity spacing using digital information (e.g., digital photographs, orthophotos, and 3D point clouds) can be carried out from several approaches:

- Graphical analysis using scaled digital images. This method is quite similar to the fieldwork approach. It requires properly identifying, and accurately measuring, the orientation and frequency of visible discontinuity surfaces or traces in a rock slope.
- 2D approaches and profile sections (Oppikofer et al., 2011; Slob, 2010). This is a widely used approach in order to compute discontinuity spacing using point clouds. Its main drawback is that results strongly depend on the chosen profile or virtual scanline.
- Fracture estimation analyzing two-dimensional fracture trace information gathered from digital images of exposed rockfaces (Kemeny and Post, 2003).
- Spacing analysis using 3D spatial relations. Normal spacing is calculated as the minimum distance (i.e., orthogonal distance) between exposed planes, measured in a perpendicular direction to one of those planes. If the two planes are not parallel, the distance depends on the location of the measuring line, but if they are parallel, it is a non-directional dependent method. This is the approach considered in this work to compute discontinuity spacing.

2.3. Cluster orientation

The rock outcrops members of a discontinuity set are usually not perfectly parallel due to natural structure complexity and to uncertainties of technique.

The normal procedure for measuring discontinuity spacing consists on intersecting both discontinuities by an arbitrary line. Then, the intersection of this line with the two planes defines two points, and the spacing will be equal to the distance between these two points. Although the orientation and spatial location of this line plays a capital role on the calculation of the discontinuity spacing, there is no common agreement on the parametrization of this variable. For instance, some authors define the direction of this line as parallel to the normal vector of the discontinuity set, nevertheless the spacing values are still affected by the arbitrary selection of the line location (Slob, 2010). This problem can be fixed considering that all clusters have the same orientation of the principal plane of the given discontinuity set, which is a reasonable assumption when the discontinuities are parallel within the studied region. Therefore, in this approach it is required that the normal vector of each cluster plane is equal to the normal vector of the discontinuity set.

3. Methodology: the 3D spacing approach

3.1. Input data

Every point of the point cloud has to be previously assigned to a discontinuity set and to a given cluster (see Appendix A). The necessary inputs for every point are:

- (X, Y, Z) coordinates
- Discontinuity set id
- Cluster id
- Normal vector of the discontinuity set (A, B, C) (Eq. (1))