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A new method for automatic discontinuity traces sampling on rock mass 3D model

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ABSTRACT

A new automatic method for discontinuity traces mapping and sampling on a rock mass digital model is described in this work. The implemented procedure allows one to automatically identify discontinuity traces on a Digital Surface Model: traces are detected directly as surface breaklines, by means of maximum and minimum principal curvature values of the vertices that constitute the model surface. Color influence and user errors, that usually characterize the trace mapping on images, are eliminated. Also trace sampling procedures based on circular windows and circular scanlines have been implemented: they are used to infer trace data and to calculate values of mean trace length, expected discontinuity diameter and intensity of rock discontinuities. The method is tested on a case study: results obtained applying the automatic procedure on the DSM of a rock face are compared to those obtained performing a manual sampling on the orthophotograph of the same rock face.

1. Introduction

One of the fundamental parameters to characterize a rock mass is discontinuity persistence, defined as the ratio between the total discontinuity area and a reference area (surface); direct measurements of discontinuity area are quite impossible to obtain, and therefore another discontinuity feature is used to infer discontinuity area and this is the discontinuity trace. Discontinuities are an intrinsic characteristic of rock masses and they appear at every scale of a technical survey. The traditional discontinuity sampling procedure consists of a manual survey performed by an operator directly on the rock mass (ISRM, 1978). However, issues related to the duration of the procedure, to the operator's safety during the survey and to direct access problems lead many authors to propose non-contact methods, namely, procedures which allow one to perform the trace survey on a representation of the rock mass, such as an image or a digital model.

Trace detection on images can be a long and complex operation; in fact, the manual operation is time consuming and an expert operator is needed. Mapping performed by means of edge detection algorithms (Barrow and Tenenbaum, 1981; Canny, 1986; Lindeberg, 2001; Kemeny and Post, 2003) or segmentation techniques (Maerz, 1990; Reid and Harrison, 2000; Post et al., 2001; Lemy and Hadjigeorgiou, 2003) are faster but results could be very complex and a manual editing phase could be needed. In fact, these methods suffer from common issues related to the bidimensional nature of the representation. Depending on the camera asset (defined by 3 angles, relative to the axes of the reference system) and position in relation to the rock mass surface (e.g., at the top or at the foot of the rock face), some orientations could be disadvantaged during the identification. Moreover, a single image can contain occlusions: they are defined as a rock mass portion that, with respect to the camera asset and position, cannot be seen because it is hidden by a rock protrusion, so not all the rock mass surface will be available for the trace sampling. Also digital models created with photogrammetry or laser scanner surveys can contain occlusions, but they can be avoided acquiring data (images or points) from different viewpoints and merging all the surfaces. In addition, since traces identification is based on color data contained in the image, it must be considered that light in an uncontrolled environment can significantly vary, locally and globally, depending on the sun position with respect to the rock mass, weather conditions (e.g., presence or absence of cloud cover), rock type, color and conditions (e.g., wet rock) (Reid and Harrison, 2000), etc. So different light conditions could lead to very different results in terms of completeness and accuracy.

Automatic or semi-automatic methods for discontinuity planes identification on digital models have been also proposed

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(Roncella and Forlani, 2005; Slob et al., 2007; Gigli and Casagli, 2011): these methods are based on the segmentation of the surface, and traces are obtained as the boundaries of the identified planes.

Once traces are identified with a contact or non-contact method, a sampling method can be used to infer data from an homogeneous rock mass unit: it is possible to sample the traces (a) that intersect a line (*scanline*); (b) that intersect a circle (circular scanline) (Mauldon et al., 2001); or (c) within a finite size area, usually rectangular or circular in shape (*window*) (Kulatilake and Wu, 1984; Zhang and Einstein, 1998; Mauldon, 1998). Circular scanlines are simply circles drawn on a rock surface, on a fracture trace map or on a digital image. A circular window is the region enclosed by a circular scanline (Rohrbaugh et al., 2002).

The sampling procedure usually involves mapping the fracture pattern on a surface and recording characteristics of visible fractures (Wu and Pollard, 1995). Trace maps also have the advantage of recording the trace pattern, termination relationships and other aggregate properties of the areal sample (Dershowitz and Einstein, 1988). Construction of fracture trace maps for areal samples, however, tends to be very time consuming (Rohrbaugh et al., 2002).

2. A new approach

The issues discussed above led the authors to consider a new mapping approach, which could combine the safety and the efficiency of a non-contact method, with the possibility to obtain a complete representation of the rock mass such as a digital 3D model. Therefore, an automatic procedure was developed to identify and to map discontinuity traces on a Digital Surface Model (DSM), which consists of a triangulated point cloud that approximates the true surface; the triangulation generates a topology, i.e., it defines the spatial relation between the points in the DSM, so for each point its neighbors are known. A DSM can be created with both photogrammetric techniques or laser scanner surveys. Many authors discussed the advantages of such a procedure for rock mechanics purposes (Kemeny and Donovan, 2005; Roncella and Forlani, 2005; Trinks et al., 2005; Feng and Roshoff, 2006; Haneberg, 2006; Ferrero et al., 2009; Sturzenegger and Stead, 2009; Lato et al., 2012), showing how discontinuity orientation, spacing and roughness can be derived from a DSM.

In this paper a new method to automatically identify discontinuity traces on a Digital Surface Model is presented: traces are detected directly as surface breaklines, by means of principal curvature values of the vertices that constitute the model surface. The method will be applied to a case study; then two sampling methods (Zhang and Einstein, 1998; Mauldon et al., 2001) will be used to infer trace data and to calculate values of mean trace length.

3. The new trace mapping method

Natural outcrops can have an infinite variety of shapes and their dimensions can be very different, but a common characteristic is their non-planar surface. In fact, generally the surface has edges, that can be both asperities or depressions, most of them created by the intersections of different discontinuity planes. Therefore, the method presented here is based on the assumption that a discontinuity trace can be geometrically identified as an edge of the surface. This assumption is generally valid in natural outcrops, while on tunnel surfaces or other artificially profiled rock faces its validity could significantly decrease due to the presence of artificial edges mixed to natural edges. This method allows one to detect traces created by the intersection of different visible planes, i.e., edges that are asperities or depressions of the DSM surface (Fig. 1). The DSM must contain only rock mass surface, namely every other element (e.g., vegetation, artificial objects, etc) must be removed from the model. This requirement could create holes in the surface: they are not considered as edges, but they can limit the completeness and continuity of detected edges.

The edge detection procedure presented here is based on the classification of each vertex of the model surface according to its principal curvature values; in fact asperities and depressions are composed of convex or concave surface portions, i.e., a certain number of triangulated vertices. In the following a concise definition of principal curvature and a brief description of the edge detection method applied to a DSM are given. For a detailed description of the algorithms see Umili (2012).

The quality of the DSM is fundamental (Kraus, 1993; Kraus and Pfeifer, 1998; Baltsavias, 1999): it can be evaluated in terms of resolution, i.e., the value of the mean distance between adjacent vertices. A higher resolution means that the mean distance between vertices is small, and that the correspondence between the discretized surface (DSM) and the actual rock mass surface (Fig. 2) is improved. Therefore, the method generally allows one to detect traces whose surface dimensions are larger than the resolution.

A test-object called *stairs* will be used to explain the procedure (Fig. 3); edges are straight and their paths follow one of the three axes *X*,*Y*,*Z*. Considering a vertex *P* of a surface (Fig. 4) and its normal *N*, it is possible to define the normal plane π, which contains *P* and *N* and cuts the surface generating a curve *C* which, among all possible curves, has the minimum osculating circle radius *r* in *P* (Euler, 1760). The smaller the osculating circle radius, the faster the slope variation of the surface and the higher the absolute value of the normal curvature. Normal curvature is positive if the osculating circle is on the same side of the surface as *N* with respect to *P*, otherwise it is negative. It is therefore possible to define the Maximum Principal Curvature (k_{max}) of P as the maximum value of normal curvature of *C* (convexity). Correspondingly, the Minimum Principal Curvature (k_{min}) of *P* is the minimum value of normal curvature of *C* and it describes the concavity of the local surface.

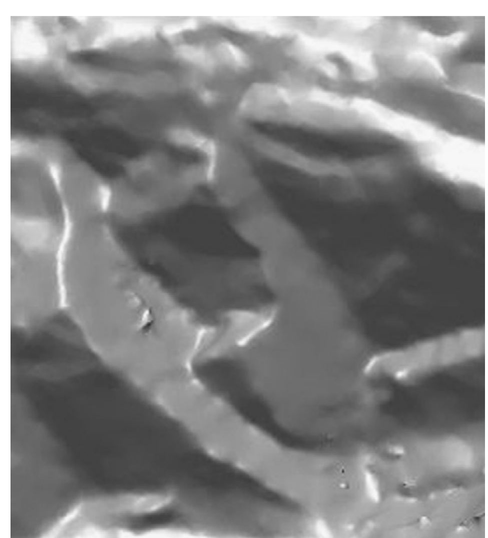

Fig. 1. Detail of a shaded surface portion of a Digital Surface Model (DSM), representing discontinuity planes separated by convex and concave edges.