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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.

Keywords: automatic, trace mapping, rock mass, 3D, curvature, edge.

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 (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; 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 (Figure 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 (2011).

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 (Figure 2) is improved. Therefore, the method generally allows one to detect traces whose surface dimensions are larger than the resolution.

Figure 1: Detail of a shaded surface portion of a Digital Surface Model (DSM), representing discontinuity planes separated by convex and concave edges.
Figure 2: Triangulated vertices which constitute portion of DSM in Fig.1; a) high resolution DSM produces a better representation of edges than b) low resolution.

A test-object called *stairs* will be used to explain the procedure (Figure 3); edges are straight and their paths follow one of the three axes X,Y,Z. Considering a vertex P of a surface (Figure 4) and its normal N, it is possible to define the normal plane $\pi$, 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 ($k_{\text{max}}$) of P as the maximum value of normal curvature of $C$ (convexity). Correspondingly, the Minimum Principal Curvature ($k_{\text{min}}$) of P is the minimum value of normal curvature of $C$ and it describes the concavity of the local surface.

Figure 3: Example of convex and concave edges detected on test-object: DSM stairs is composed by 116601 points and 231909 triangles.

Figure 4: Definition of principal curvature of a vertex P of a surface requires definition of normal N and normal plane $\pi$. a) Plane $\pi_1$ generates a curve $C_1$ whose osculating circle in P has a radius $r_1$; b) plane $\pi_2$ is obtained rotating $\pi_1$ about the normal N; it generates a curve $C_2$ whose osculating circle in P has a radius $r_2$ greater than $r_1$.

Step 1 of the procedure is therefore the curvature calculation for each vertex of the DSM: the method proposed by Chen and Schmitt (1992) and extended by Dong and Wang (2005) is used. This method is accurate and requires one to solve only simple equations; it has been applied considering a two-ring neighborhood around each vertex to calculate the normal (N). A one-ring neighborhood of vertex P is formed by all the triangles that contain P (Figure 5a); a two-ring neighborhood of P is formed by all the
one-ring triangles and all the triangles that contain at least 1 vertex belonging to the one-ring neighborhood (Figure 5b).

Figure 5: a) One-ring neighborhood of vertex P is formed by all the triangles that contain P; b) two-ring neighborhood of P is composed by one-ring triangles and triangles that contain at least 1 vertex belonging to one-ring neighborhood.

The normal $N_t$ of a triangle is calculated as the normal of the plane containing the triangle. The normal $N$ of vertex P is then calculated as the weighted mean of all the normals $N_t$ of its two-ring neighborhood, in which weights consist of the inverse distances between P and the triangle centroids.

Since a greater convexity is characterized by a greater positive value of maximum principal curvature, while a greater concavity is characterized by a greater absolute value of minimum principal curvature and a negative sign, it is possible to identify paths that connect vertices with similar curvature values: in particular maximum $k_{max}$ values identify convex edges (Figure 6a), while minimum $k_{min}$ values identify concave edges (Figure 6b). Therefore the algorithms detect discontinuity traces as edges that significantly differ from the model mean surface.

Figure 6: Example of a (a) convex and a (b) concave edge.

At this point, the aim is to determine which vertices are potentially pertaining to significant edges: among those vertices the algorithms will choose the vertices to connect to define the edge paths. So, Step 2 is the selection of two threshold values, one for maximum principal curvature, $T_{max}$, and the other for minimum principal curvature, $T_{min}$. Each vertex of the mesh has a maximum and a minimum principal curvature value; if one of these values is greater (in absolute value) than the respective threshold, the vertex is allowed to be connected to the other significant vertices to create an edge. Decreasing the threshold's absolute values means that more vertices are considered as possible parts of traces (Figure 7 and 8). Therefore, different thresholds can lead to a different number of detected traces.
and/or traces of different length. There could be two possible strategies for the choice of the thresholds:
an automatic one, based on some statistical criteria on curvature values, and a manual one, in which an
operator is given some instruments to decide. The choice is not simple, since the optimum threshold
can be defined as the curvature value which allows one to satisfy two requirements:

1. To remove all vertices not belonging to any edge;
2. To optimize, for each edge, the number of vertices among which the algorithms will perform
   the following linking procedure.

Whereas on the one hand it is quite easy to find a value that meets the first requirement, it is, on the
other hand, more complex to find a value that meets the second one. In fact, generally edges in the
same object can vary depending on their shape and their position. Therefore vertices belonging to the
same edge could have different principal curvature values, varying within a certain range; moreover
different edges could have, in general, different principal curvature ranges. These are the reasons that
led the authors towards a manual choice: the user, by means of colorbars and images, can iteratively
choose a threshold value $T_{max}$ and see what will be the accepted vertices to create convex edges,
operating directly a manual optimization procedure. Then the procedure will be repeated to choose $T_{min}$
(in general different in absolute value from $T_{max}$), to create concave edges. This operation is the only
one subject to the user’s decision.

Figure 7: Threshold $T_{max}$ on maximum principal curvature values allows one to extract convex edges.
Number of accepted vertices (black) changes with threshold: (a) $T_{max} = 0.1$ (b) $T_{max} = 1$. A higher value
of $T_{max}$ corresponds to a smaller number of accepted vertices, namely a thinner band along the edges.

Figure 8: Threshold $T_{min}$ on minimum principal curvature values allows one to extract concave edges.
The number of accepted vertices (black) changes with threshold: (a) $T_{min} = -0.1$ (b) $T_{min} = -1$. A higher
absolute value of $T_{\text{min}}$ corresponds to a smaller number of accepted vertices, namely a thinner band along the edges.

Then the connection of vertices is performed with algorithms (Umili, 2011), which use information about principal curvature values and directions to automatically create edge paths along vertices. The paths are then segmented with the RANSAC (Random Sample Consensus) algorithm (Fischler and Bolles, 1981): for each path the lines that better interpolate it are obtained and used to split the path according to their different directions (Figure 9). Operating in 3D space, a line is defined as (Equation 1):

$$
\begin{align*}
X &= X_0 + l \cdot t \\
Y &= Y_0 + m \cdot t \\
Z &= Z_0 + n \cdot t
\end{align*}
$$

[1]

where $(X_0, Y_0, Z_0)$ is a point of the line, $(l, m, n)$ are the parameters related to the slope along the 3 directions and $t$ is an independent variable.

Figure 9: Path segmentation with RANSAC algorithm; example of a path interpolated by 3 different lines and split in 3 parts; each part can be approximated by a segment.

At the end of this procedure, a certain number of paths, that will be called *edges* in the following, and their interpolating segments are stored. Each edge is a list of vertices and each segment is described using the 6 parameters $(X_0, Y_0, Z_0, l, m, n)$.

After that, the ISODATA algorithm (Ball and Hall, 1965) is used to perform automatic cluster analysis, in order to partition the obtained segments into $k$ clusters (Figure 10); the main advantage of this algorithm, with respect to other methods (i.e. k-means, tree-clustering) based on distance between elements, is that it does not require the exact number of clusters as input.
Figure 10: DSM stairs: edges have been correctly classified into 3 clusters: edges along X (K₁), edges along Z (K₂), edges along Y (K₃); each edge is colored depending on the cluster to which it belongs.

### 4. Trace sampling

After the automatic edge identification, a dataset of discontinuity traces is available for further investigations, such as sampling and detailed measurements. Therefore two trace sampling methods have been implemented to operate on the dataset: circular window sampling (Zhang and Einstein, 1998) and circular scanline sampling (Mauldon et al., 2001).

The procedure is based on the following idea: edges, which are assumed to represent discontinuity traces in the 3D space, need to be sampled in a 2D window/scanline, therefore they need to be projected on the same plane in which the window/scanline is created. This plane, called “sampling plane” (πc), is calculated as the rock mass mean front. Each edge is then an orthogonally projected, which transforms the edge into a polyline in the sampling plane (Figure 11).

Also boundary vertices of the DSM are projected on the plane, creating a contour of the DSM (Figure 11); in case holes are present in the DSM surface, also their boundaries are projected on the plane.

Figure 11: Example of an edge projected on sampling plane πc; also DSM boundary vertices and possible holes are projected.

A regular grid of centers that are contained within the whole contour is created on the plane (Mauldon et al., 2001) (Figure 12) and different radius values are used. Each one of the Nn nodes of the grid will be the center of Nw concentric circles with different radius values: in all, NnNw circular windows/scanlines are created. The maximum circle radius is automatically calculated: considering the sampling plane (e.g. πc ≡ XY), the maximum dimensions of the area within the contour can be measured along 2 axes (e.g. Dx,Dy). The maximum diameter will be equal to the minimum dimension.
(e.g. if $D_X = 10m$, $D_Y = 5m$ then the maximum radius will be 2.5 m). So it is possible to automatically create windows of different radii, e.g. fixed percentages of the maximum radius. A condition is also checked for each circle: if it is completely within the contour (Mauldon et al., 2001) and it does not include DSM hole boundaries (Figure 13), it will be used to perform the sampling (Figure 14), otherwise not. Holes in general could be due to occlusions or to the clearing of vegetation and artificial elements and they must be discarded from the analyzed area.

Figure 12: Creation of the grid and calculation of maximum radius $c$.

Figure 13: Creation of concentric windows/scanlines of different radii. Dotted circle 1 will not be used in sampling procedure because it is not completely within the boundary; dotted circle 2 will not be used because it contains a hole.

Figure 14: Traces, i.e. mapped projected edges on sampling plane, are sampled using circular windows/scanlines.

**4.1. Sampling methods**

The circular window sampling method (Zhang and Einstein, 1998) allows one to calculate the mean trace length, expected discontinuity diameter and intensity of rock discontinuities. The trace sampling procedure is based on a classification of the traces that are visible on the considered sampling window (Figure 15); the lengths of observed traces and the distribution of trace lengths are not required. The major advantage of this method is that it does not need sampling data about the orientation of discontinuities: its orientation distribution-free nature comes from the symmetric properties of the circular sampling windows. Therefore, it can be used to estimate the mean trace length of more than one set of discontinuities.
For each window (Figure 15), traces are classified in the following categories: traces with both ends outside the window \( (N_0) \), traces with both ends within the window \( (N_2) \) and traces with only one end within the window \( (N_1) \). From the sampling on a window of radius \( c \) it is possible to obtain traces samples (called \( \hat{N}_0, \hat{N}_1, \hat{N}_2 \)) to estimate a value for mean trace length \( \mu (\hat{\mu}) \) (Equation 2); the total number \( \hat{N} \) of considered traces in a window is the sum of \( \hat{N}_0, \hat{N}_1 \) and \( \hat{N}_2 \).

\[
\hat{\mu} = \frac{\left( \hat{N} + \hat{N}_o - \hat{N}_2 \right)}{\left( \hat{N} - \hat{N}_o + \hat{N}_2 \right)} c
\]  

Figure 15: Classification of traces visible on a sampling window, laying on the sampling plane \( \pi_c \): type \( N_0 \) (dark grey), \( N_1 \) (light grey) and \( N_2 \) (grey) with respect to the considered window. Dashed traces will not be sampled because they cannot be classified.

The following two special cases should be avoided:

1. If \( \hat{N}_o = \hat{N} \), then \( \hat{N}_2 = 0 \) and \( \hat{\mu} \to \infty \). In this case, all the discontinuities intersecting the sampling window have both ends censored and the denominator of Equation 2 is 0. This implies that the area of the window used for the discontinuity survey may be too small and therefore not representative of the rock mass. To avoid this problem it is necessary to increase window radius.

2. If \( \hat{N}_2 = \hat{N} \), then \( \hat{N}_o = 0 \) and \( \hat{\mu} = 0 \). In this case, all the discontinuities intersecting the sampling window have both ends observable and the numerator of Equation 2 is 0. To avoid this problem it is necessary to decrease window radius.

In practice, the exact values of \( N, N_0 \) and \( N_2 \) are not known and thus \( \mu \) has to be estimated using sampled data. In other words, the \( \hat{\mu} \) of several sampling windows can be used to evaluate \( \mu \). Zhang and Einstein (1998) show how the effect of non-uniformity of trace distribution on an outcrop is decreased by averaging. Therefore, they recommend that, in practical sampling, multiple windows of the same
size and at different locations should be used. This is the reason why an algorithm to create a large number of windows has been implemented. Figure 16 shows an example: there is a grid consisting of 6 window centers and for each one there are 4 concentric windows of different radius (1-2-3-4 m). In the following, parameters will be shown in relation to the window radius: actually, mean values will be shown, calculated from all the windows with a certain radius. So, for a radius equal to 1 m, the resulting value of the mean trace length $\mu$ from Figure 16 is calculated as the mean of the values obtained from the 6 considered windows with radius 1 m.

Figure 16: Example of regular grid composed by 6 nodes; each one is center of 4 circular windows with different radius values.

The circular scanline sampling method (Mauldon et al., 2001) allows one to calculate mean trace length, trace density and trace intensity, parameters that measure fracture size and abundance. The trace sampling procedure is based on a classification of the traces with respect to the circular scanline (Figure 17); the lengths of observed traces and the distribution of trace lengths are not required.

For each window it is necessary to count the number $n$ of traces intersecting the circular scanline and the number $m$ of trace end points within the circular area delimited by the scanline. From each scanline sampled $\hat{n}$ and $\hat{m}$ can be obtained and used to estimate $\hat{\mu}$ (Equation 3).

$$\hat{\mu} = \frac{\pi \cdot c}{2} \left( \frac{\hat{n}}{\hat{m}} \right)$$  \[3\]

Figure 17: Classification of traces points: $n$ traces intersecting scanline (grey); $m$ traces end points within circular area (black).

### 4.2. Parameters definition

The parameters used in the following are defined first:
• Mean trace length $\mu$: it is defined as the mean of the true trace length distribution $f(l)$ (i.e. the trace length distribution on an infinite sampling surface). It is calculated using Equation 2 (Zhang and Einstein, 1998), based on the count of traces classified according to their position with respect to the circular window, or Equation 3 (Mauldon et al., 2001), based on the count of nodes that represents traces end points and intersections between a trace and the circular scanline.

• Expected discontinuity diameter $E(D)$: it is defined as the mean of the discontinuity diameter distribution $g(D)$, whose form is assumed choosing among lognormal, negative exponential and Gamma. The best distribution of $g(D)$ is chosen using a test (Zhang and Einstein, 2000) and it can be different from the trace length distribution $f(l)$ form. These authors propose a different expression for $E(D)$ for each of the three distribution forms.

• Intensity of rock discontinuities $P_{32}$: the adopted measure to express the intensity of rock discontinuities is $P_{32}$, fracture area per unit volume. Zhang and Einstein (2000) proposed to calculate the mean fracture area per unit volume of the rock mass as:

$$P_{32} = \frac{N_T \cdot E(A)}{V} \quad [4]$$

where $N_T$ is the total number of sampled discontinuities in a window, $E(A)$ is the mean discontinuity area calculated with the equation:

$$E(A) = \int_0^\infty \frac{\pi}{4} D^2 g(D) dD = \frac{\pi}{4} E(D^2) = \frac{\pi}{4} [(\mu_D)^2 + (\sigma_D)^2] \quad [5]$$

and $V$ is the unit volume, here considered as a cylinder:

$$V = \pi c^2 h \quad [6]$$
where \( c \) is the radius of the considered sampling window and \( h \) is the cylinder depth. Two values of \( h \) have been used here: 1m (fixed for all windows) and a value equal to the relative window radius \( c \) (varying with the windows dimensions).

5. **Comparison of two sampling methods on a case study**

The new trace detection and mapping method proposed here has been applied in a case study, the North face of the Aiguilles du Marbrées (Mont Blanc), on which also the manual trace detection method was performed (Ferrero and Umili, 2011). At this site a close-range photogrammetric survey was performed to create an orthophotograph and a DSM of the rock face. Manual trace detection and circular window sampling was performed on the orthophotograph of the rock mass (Figure 18). Four centers were placed on the image and, for each one, five radius values were used to draw sampling windows. So 20 sampling windows were used to calculate the final parameter values (Figure 19).

![Figure 18: Orthophotograph (base 90 m, height 60 m) with mapped traces.](image1)

![Figure 19: Mapped traces are sampled using 20 circular windows.](image2)

Then the DSM (medium resolution, approximately 50 pts/m\(^2\)), representing the same part of the rock mass shown in the orthophotograph, but with smaller dimensions (Figure 20), was used as input data for the new method.

![Figure 20: a) Orthophotograph, b) DSM (base 62 m, height 52 m, 163 963 vertices); white rectangular window on the left is common portion of rock mass between 2D orthophotograph and 3D model.](image3)

Three curvature threshold couples \((T_{\text{max}}, T_{\text{min}})\) were used to detect traces on the DSM to check if significant variations of detected traces and parameter values could occur when varying the thresholds. Comparing the traces detected in the three different cases (Figure 21) it is possible to notice small
variations of trace lengths and an increasing number of traces when thresholds decrease, as expected.

Comparing the detected traces obtained with the two methods, one can see that sub-horizontal traces detected in the orthophotograph are longer and their number is greater than in the DSM (Figure 18 and 21). This kind of situation can be due to three different reasons: the first one is that traces were actually longer but the automatic detection process did not produce a complete result. In fact, the density of the DSM vertices could have been not sufficient to clearly define sub-horizontal edges and so curvature values in these surface areas do not have the correct curvature range. Another possibility is that the chosen curvature thresholds were not suitable to completely detect traces (e.g. thresholds were too high and many vertices were not allowed to be part of the edges). The third reason could instead be that the operator, during the manual sampling on the orthophotograph, connected different portions of traces that were not actually connected in the real rock mass, due to perspective distortion and to occlusions. Also, he could have detected “false” traces, due to rock color or shadows. This particular case is referable to the first reason: sub-horizontal discontinuity planes are not well described by the DSM because the model is created using images taken from below, so the relative traces cannot cannot be detected.

2500 centers were placed on a regular grid on the sampling plane and, for each one, nine radius values were used to automatically draw sampling windows and to perform the sampling procedure.

Figure 21: DSM (base 62 m, height 52 m); traces are detected using three different combinations of thresholds \([T_{\text{max}}; T_{\text{min}}]\): a) \(T_1=[0.9; -0.7]\), b) \(T_2=[0.8; -0.6]\), c) \(T_3=[0.7; -0.5]\).

One of the main advantages of the automatic method is the opportunity to have a very large number of sampling windows analyzed in a short time. Table 1 shows the numbers of windows used for the manual sampling on the orthophotograph and the automatic sampling on the DSM, performed on circular windows and circular scanlines. Manual and automatic trace detection needed both about 2
hours; considering only the sampling procedure, the time needed for manual sampling on the orthophotograph was about 5 hours, while the time needed for automatic sampling on the DSM was about 2-3 hours using an Intel 2.8GHz workstation.

Table 1: Number of windows used to calculate parameters with manual method on an orthophoto and with automatic methods on DSM (circular window/scanline, 3 different threshold couples $T_1,T_2,T_3$).

From the data obtained during the window sampling procedure on the DSM, the previously described parameters (mean trace length $\mu_4$, expected discontinuity diameter $E(D)$ and intensity of rock discontinuity $P_{\mu_2}$) have been automatically calculated using Zhang’s and Einstein’s (1998, 2000) equations and were compared to those obtained from the orthophotograph. Mean trace lengths were calculated from data obtained considering circular scanlines only using Mauldon’s et al. (2001) equation, and were compared to results obtained using Zhang’s and Einstein’s (1998) equation.

Figure 22 shows the comparison between the values of mean trace lengths $\mu_4$ obtained with varying window radius $c$. The orthophoto results are on average 1 m lower than DSM results, but the trends are similar. The three DSM trends have a maximum difference of about 0.6 m for the maximum radius; it is interesting to notice that in this case the smaller thresholds couple $(T_3)$ produces smaller values than $T_2$. This fact could be the proof that, once the actual amount of traces is recognized and the corresponding $\mu$ value is obtained, even decreasing the curvature thresholds and so allowing more vertices to be part of a trace will not increase the mean trace length beyond this value.

Figure 22: Mean trace length calculated according to Zhang and Einstein (1998) from data sampled on orthophoto and on DSM (3 threshold couples).

Figure 23 shows the comparison between orthophoto and DSM trends of expected discontinuity diameter $E(D)$ when varying window radius $c$. The three DSM trends are similar and their maximum
The difference is less than 0.2 m. The difference between orthophoto and DSM trends decreases when increasing the radius and they intersect for a radius of about 18 m (that is the maximum radius used in manual sampling). This fact is quite interesting and it suggests that it is important to use large radius values to be sure to obtain data that are representative of the rock mass.

**Figure 23:** Expected discontinuity diameter calculated according to Zhang and Einstein (2000) from data sampled on orthophoto and on DSM (3 threshold couples).

Figure 24 shows the comparison between orthophoto and DSM trends of the intensity of rock discontinuities $P_{32}$, calculated with a cylindrical volume whose base is equal to the windows area and whose depth $h$ is equal to 1 m, with varying window radius. The three DSM trends are similar and their maximum difference is about 0.22 m$^{-1}$. Similar to Figure 23, the difference between orthophoto and DSM trends decreases when increasing the radius and they intersect for a radius of about 12-15 m.

**Figure 24:** Intensity of rock discontinuities calculated according to Zhang and Einstein (2000) from data sampled on orthophoto and on DSM (3 threshold couples); cylinder volume depth is equal to 1m.

Figure 25 shows the comparison between orthophoto and DSM trends of the intensity of rock discontinuities $P_{32}$, calculated with a cylindrical volume whose base is equal to the windows area and whose depth $h$ is equal to the radius $c$ with varying window radius. The trends are similar to a negative exponential function but with different coefficients. This way of calculating $P_{32}$ could be used to define an analytical relation between $P_{32}$ and window radius, that could be easily introduced in a rock mass fracture model.

**Figure 25:** intensity of rock discontinuity calculated according to Zhang and Einstein (2000) from data sampled on orthophoto and on DSM (3 threshold couples); cylinder volume depth is equal to radius $c$. 
Figure 26 shows the comparison between the values of mean trace lengths $\mu_2$ obtained with circular window (Zhang and Einstein, 1998) and scanline (Mauldon et al., 2001) sampling with varying window radius $c$; sampling has been performed on the traces detected using threshold couple $T_1$. The window method (ZE) trend is on average 0.5 m lower than scanline (MDR) trend, but they are similar.

Figure 26: Mean trace length calculated according to Zhang and Einstein (1998) and Mauldon et al. (2001) from data sampled on DSM (threshold couple $T_1$).

6. Conclusions

The intensity of discontinuities in a rock mass depends on the areas of the discontinuities, which usually cannot be measured. However, they can be estimated on the basis of the discontinuity trace length and the expected diameter, which can be evaluated in a statistical way; two different proposed approaches for mean trace length estimation are compared in this paper. However, the soundness of this kind of estimation is based on a reliable sampling method. For this reason a new automatic approach is proposed in this work, which is based on trace mapping and sampling on a DSM. The need for an automatic tool is due to the long time length of the manual operations; meanwhile, a subjective traces evaluation phase is included in the proposed method, to reproduce the manual procedure. A manual trace sampling on an orthophoto is available, opening the possibility to validate the proposed procedure. This method only requires the input DSM and two thresholds on principal curvature values, then all the operations are automatically performed. The results depend on the quality of the DSM (point cloud density, noise, possible holes in the surface). Compared to the manual trace sampling on the orthophoto, the automatic procedure allows one to quickly perform sampling on a very large number of windows for different locations on the rock face and with different radii; it has also the great advantage of using only geometric information, without need to interpret colors and shades as in the manual identification. In this way colors have no influence on the choice of what is a trace or not and
results are less affected by false traces. At present, considering the obtained results, it is possible to
observe that parameter values and trends from orthophoto and DSM are getting closer for larger radius
values: this is a very important achievement, especially to prove that the new method can be a useful
tool to quickly obtain order of magnitude of parameters values and it becomes more reliable when the
data sample becomes larger and, consequently, more representative of the rock mass. In other words,
although the results obtained with the automatic method differ from the manual ones for small window
radii, they come closer as the data are getting closer to the rock mass representative volume and they
are therefore more interesting from the scientific point of view. Moreover, the larger differences at
small radii could also be affected by the presence of false traces identified by the manual procedure:
this bias error becomes naturally less influencing when the data sample dimension becomes larger.
However this approach raises new issues, that need to be solved and that will be analyzed with further
investigations on this topic. The first one is to define a simple way to decide which curvature threshold
couple is best suited to map traces. Considering the similarity of parameter trends (Fig. 22-23-24-25)
obtained from DSM data using 3 different curvature threshold couples (Fig. 21), the suggestion could
be to define a range of threshold values that allow one to correctly map traces; then it would be
possible to define the corresponding range of parameters trends and evaluate its reliability.
In order to define a general method to determine the quoted thresholds, the application of this
methodology to other rock masses with different features will be performed and possible relations with
classical rock characteristics determined during discontinuities survey will be tested.


**Image list:**

Table 1: Number of windows used to calculate parameters with manual method on an orthophoto and with automatic methods on DSM (circular window/scanline, 3 different threshold couples $T_1, T_2, T_3$).

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

Figure 2: Triangulated vertices which constitute portion of DSM in Fig.1; a) high resolution DSM produces a better representation of edges than b) low resolution.

Figure 3: Example of convex and concave edges detected on test-object: DSM stairs is composed by 116601 points and 231909 triangles.

Figure 4: Definition of principal curvature of a vertex $P$ of a surface requires definition of normal $N$ and normal plane $\pi$. a) Plane $\pi_1$ generates a curve $C_1$ whose osculating circle in $P$ has a radius $r_1$; b)
plane $\pi_2$ is obtained rotating $\pi_1$ about the normal $N$; it generates a curve $C_2$ whose osculating circle in $P$ has a radius $r_2$ greater than $r_1$.

Figure 5: a) One-ring neighborhood of vertex $P$ is formed by all the triangles that contain $P$; b) two-ring neighborhood of $P$ is composed by one-ring triangles and triangles that contain at least 1 vertex belonging to one-ring neighborhood.

Figure 6: Example of a (a) convex and a (b) concave edge.

Figure 7: Threshold $T_{\text{max}}$ on maximum principal curvature values allows one to extract convex edges. Number of accepted vertices (black) changes with threshold: (a) $T_{\text{max}} = 0.1$ (b) $T_{\text{max}} = 1$. A higher value of $T_{\text{max}}$ corresponds to a smaller number of accepted vertices, namely a thinner band along the edges.

Figure 8: Threshold $T_{\text{min}}$ on minimum principal curvature values allows one to extract concave edges. The number of accepted vertices (black) changes with threshold: (a) $T_{\text{min}} = -0.1$ (b) $T_{\text{min}} = -1$. A higher absolute value of $T_{\text{min}}$ corresponds to a smaller number of accepted vertices, namely a thinner band along the edges.

Figure 9: Path segmentation with RANSAC algorithm; example of a path interpolated by 3 different lines and split in 3 parts; each part can be approximated by a segment.

Figure 10: DSM stairs: edges have been correctly classified into 3 clusters: edges along $X$ ($K_1$), edges along $Z$ ($K_2$), edges along $Y$ ($K_3$); each edge is colored depending on the cluster to which it belongs.

Figure 11: Example of an edge projected on sampling plane $\pi_c$; also DSM boundary vertices and possible holes are projected.

Figure 12: Creation of the grid and calculation of maximum radius $c$.

Figure 13: Creation of concentric windows/scanlines of different radii. Dotted circle 1 will not be used in sampling procedure because it is not completely within the boundary; dotted circle 2 will not be used because it contains a hole.
Figure 14: Traces, i.e. mapped projected edges on sampling plane, are sampled using circular windows/scanlines.

Figure 15: Classification of traces visible on a sampling window, laying on the sampling plane $\pi_c$: type $N_0$ (dark grey), $N_1$ (light grey) and $N_2$ (grey) with respect to the considered window. Dashed traces will not be sampled because they cannot be classified.

Figure 16: Example of regular grid composed by 6 nodes; each one is center of 4 circular windows with different radius values.

Figure 17: Classification of traces points: $n$ traces intersecting scanline (grey); $m$ traces end points within circular area (black).

Figure 18: Orthophotograph (base 90 m, height 60 m) with mapped traces.

Figure 19: Mapped traces are sampled using 20 circular windows.

Figure 20: a) Orthophotograph, b) DSM (base 62 m, height 52 m, 163963 vertices); white rectangular window on the left is common portion of rock mass between 2D orthophotograph and 3D model.

Figure 21: DSM (base 62 m, height 52 m); traces are detected using three different combinations of thresholds $[T_{max}; T_{min}]$ a) $T_1=[0.9; -0.7]$, b) $T_2=[0.8; -0.6]$, c) $T_3=[0.7; -0.5]$.

Figure 22: Mean trace length calculated according to Zhang and Einstein (1998) from data sampled on orthophoto and on DSM (3 threshold couples).

Figure 23: Expected discontinuity diameter calculated according to Zhang and Einstein (2000) from data sampled on orthophoto and on DSM (3 threshold couples).

Figure 24: Intensity of rock discontinuities calculated according to Zhang and Einstein (2000) from data sampled on orthophoto and on DSM (3 threshold couples); cylinder volume depth is equal to 1m.

Figure 25:Intensity of rock discontinuity calculated according to Zhang and Einstein (2000) from data sampled on orthophoto and on DSM (3 threshold couples); cylinder volume depth is equal to radius c.
Figure 26: Mean trace length calculated according to Zhang and Einstein (1998) and Mauldon et al. (2001) from data sampled on DSM (threshold couple $T_1$).