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

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17
18 **ABSTRACT:**

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

27 results obtained applying the automatic procedure on the DSM of a rock face are compared to those
28 obtained performing a manual sampling on the orthophotograph of the same rock face.

29

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

31

32 **1. Introduction**

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

43 Trace detection on images can be a long and complex operation; in fact, the manual operation is time
44 consuming and an expert operator is needed. Mapping performed by means of edge detection
45 algorithms (Barrow and Tenenbaum, 1981; Canny, 1986; Lindeberg, 2001; Kemeny and Post, 2003) or
46 segmentation techniques (Maerz, 1990; Reid and Harrison, 2000; Post et al., 2001; Lemy and
47 Hadjigeorgiou, 2003) are faster but results could be very complex and a manual editing phase could be
48 needed. In fact, these methods suffer from common issues related to the bidimensional nature of the
49 representation. Depending on the camera asset (defined by 3 angles, relative to the axes of the reference
50 system) and position in relation to the rock mass surface (e.g. at the top or at the foot of the rock face),

51 some orientations could be disadvantaged during the identification. Moreover, a single image can
52 contain occlusions: they are defined as a rock mass portion that, with respect to the camera asset and
53 position, cannot be seen because it is hidden by a rock protrusion, so not all the rock mass surface will
54 be available for the trace sampling. Also digital models created with photogrammetry or laser scanner
55 surveys can contain occlusions, but they can be avoided acquiring data (images or points) from
56 different viewpoints and merging all the surfaces. In addition, since traces identification is based on
57 color data contained in the image, it must be considered that light in an uncontrolled environment can
58 significantly vary, locally and globally, depending on the sun position with respect to the rock mass,
59 weather conditions (e.g. presence or absence of cloud cover), rock type, color and conditions (e.g. wet
60 rock) (Reid and Harrison, 2000), etc. So different light conditions could lead to very different results in
61 terms of completeness and accuracy.

62 Automatic or semi-automatic methods for discontinuity planes identification on digital models have
63 been also proposed (Roncella and Forlani, 2005; Slob et al., 2007; Gigli and Casagli, 2011): these
64 methods are based on the segmentation of the surface, and traces are obtained as the boundaries of the
65 identified planes.

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

73 The sampling procedure usually involves mapping the fracture pattern on a surface and recording
74 characteristics of visible fractures (Wu and Pollard, 1995). Trace maps also have the advantage of

75 recording the trace pattern, termination relationships and other aggregate properties of the areal sample
76 (Dershowitz and Einstein, 1988). Construction of fracture trace maps for areal samples, however, tends
77 to be very time consuming (Rohrbaugh et al., 2002).

78 **2. A new approach**

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

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

95 **3. The new trace mapping method**

96 Natural outcrops can have an infinite variety of shapes and their dimensions can be very different, but a
97 common characteristic is their non-planar surface. In fact, generally the surface has edges, that can be
98 both asperities or depressions, most of them created by the intersections of different discontinuity

99 planes. Therefore, the method presented here is based on the assumption that a discontinuity trace can
100 be geometrically identified as an edge of the surface. This assumption is generally valid in natural
101 outcrops, while on tunnel surfaces or other artificially profiled rock faces its validity could significantly
102 decrease due to the presence of artificial edges mixed to natural edges. This method allows one to
103 detect traces created by the intersection of different visible planes, i.e. edges that are asperities or
104 depressions of the DSM surface (Figure 1). The DSM must contain only rock mass surface, namely
105 every other element (e.g. vegetation, artificial objects, etc) must be removed from the model. This
106 requirement could create holes in the surface: they are not considered as edges, but they can limit the
107 completeness and continuity of detected edges.

108 The edge detection procedure presented here is based on the classification of each vertex of the model
109 surface according to its principal curvature values; in fact asperities and depressions are composed of
110 convex or concave surface portions, i.e. a certain number of triangulated vertices. In the following a
111 concise definition of principal curvature and a brief description of the edge detection method applied to
112 a DSM are given. For a detailed description of the algorithms see Umili (2011).

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

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

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

123 A test-object called *stairs* will be used to explain the procedure (Figure 3); edges are straight and their
124 paths follow one of the three axes X,Y,Z. Considering a vertex P of a surface (Figure 4) and its normal
125 N, it is possible to define the normal plane π , which contains P and N and cuts the surface generating a
126 curve C which, among all possible curves, has the minimum osculating circle radius r in P (Euler,
127 1760). The smaller the osculating circle radius, the faster the slope variation of the surface and the
128 higher the absolute value of the normal curvature. Normal curvature is positive if the osculating circle
129 is on the same side of the surface as N with respect to P, otherwise it is negative. It is therefore possible
130 to define the Maximum Principal Curvature (k_{max}) of P as the maximum value of normal curvature of C
131 (convexity). Correspondingly, the Minimum Principal Curvature (k_{min}) of P is the minimum value of
132 normal curvature of C and it describes the concavity of the local surface.

133 Figure 3: Example of convex and concave edges detected on test-object: DSM stairs is composed by
134 116601 points and 231909 triangles.

135 Figure 4: Definition of principal curvature of a vertex P of a surface requires definition of normal N
136 and normal plane π . a) Plane π_1 generates a curve C_1 whose osculating circle in P has a radius r_1 ; b)
137 plane π_2 is obtained rotating π_1 about the normal N; it generates a curve C_2 whose osculating circle in P
138 has a radius r_2 greater than r_1 .

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

144 one-ring triangles and all the triangles that contain at least 1 vertex belonging to the one-ring
145 neighborhood (Figure 5b).

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

149 The normal N_t of a triangle is calculated as the normal of the plane containing the triangle. The normal
150 N of vertex P is then calculated as the weighted mean of all the normals N_t of its two-ring
151 neighborhood, in which weights consist of the inverse distances between P and the triangle centroids.
152 Since a greater convexity is characterized by a greater positive value of maximum principal curvature,
153 while a greater concavity is characterized by a greater absolute value of minimum principal curvature
154 and a negative sign, it is possible to identify paths that connect vertices with similar curvature values:
155 in particular maximum k_{max} values identify convex edges (Figure 6a), while minimum k_{min} values
156 identify concave edges (Figure 6b). Therefore the algorithms detect discontinuity traces as edges that
157 significantly differ from the model mean surface.

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

159 At this point, the aim is to determine which vertices are potentially pertaining to significant edges:
160 among those vertices the algorithms will choose the vertices to connect to define the edge paths. So,
161 Step 2 is the selection of two threshold values, one for maximum principal curvature, T_{max} , and the
162 other for minimum principal curvature, T_{min} . Each vertex of the mesh has a maximum and a minimum
163 principal curvature value; if one of these values is greater (in absolute value) than the respective
164 threshold, the vertex is allowed to be connected to the other significant vertices to create an edge.
165 Decreasing the threshold's absolute values means that more vertices are considered as possible parts of
166 traces (Figure 7 and 8). Therefore, different thresholds can lead to a different number of detected traces

167 and/or traces of different length. There could be two possible strategies for the choice of the thresholds:
168 an automatic one, based on some statistical criteria on curvature values, and a manual one, in which an
169 operator is given some instruments to decide. The choice is not simple, since the optimum threshold
170 can be defined as the curvature value which allows one to satisfy two requirements:

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

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

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

187 Figure 8: Threshold T_{\min} on minimum principal curvature values allows one to extract concave edges.
188 The number of accepted vertices (black) changes with threshold: (a) $T_{\min} = -0.1$ (b) $T_{\min} = -1$. A higher

189 absolute value of T_{\min} corresponds to a smaller number of accepted vertices, namely a thinner band
190 along the edges.

191 Then the connection of vertices is performed with algorithms (Umili, 2011), which use information
192 about principal curvature values and directions to automatically create edge paths along vertices. The
193 paths are then segmented with the RANSAC (Random Sample Consensus) algorithm (Fischler and
194 Bolles, 1981): for each path the lines that better interpolate it are obtained and used to split the path
195 according to their different directions (Figure 9). Operating in 3D space, a line is defined as (Equation
196 1):

$$197 \quad \begin{cases} X = X_0 + l \cdot t \\ Y = Y_0 + m \cdot t \\ Z = Z_0 + n \cdot t \end{cases} \quad [1]$$

198 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
199 directions and t is an independent variable.

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

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

205 After that, the ISODATA algorithm (Ball and Hall, 1965) is used to perform automatic cluster analysis,
206 in order to partition the obtained segments into k clusters (Figure 10); the main advantage of this
207 algorithm, with respect to other methods (i.e. k-means, tree-clustering) based on distance between
208 elements, is that it does not require the exact number of clusters as input.

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

211 4. Trace sampling

212 After the automatic edge identification, a dataset of discontinuity traces is available for further
213 investigations, such as sampling and detailed measurements. Therefore two trace sampling methods
214 have been implemented to operate on the dataset: circular window sampling (Zhang and Einstein,
215 1998) and circular scanline sampling (Mauldon et al., 2001).

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

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

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

225 A regular grid of centers that are contained within the whole contour is created on the plane (Mauldon
226 et al., 2001) (Figure 12) and different radius values are used. Each one of the N_n nodes of the grid will
227 be the center of N_w concentric circles with different radius values: in all, $N_n \cdot N_w$ circular
228 windows/scanlines are created. The maximum circle radius is automatically calculated: considering the
229 sampling plane (e.g. $\pi_c \equiv XY$), the maximum dimensions of the area within the contour can be
230 measured along 2 axes (e.g. D_X, D_Y). The maximum diameter will be equal to the minimum dimension

231 (e.g. if $D_x = 10\text{m}$, $DY = 5\text{m}$ then the maximum radius will be 2.5 m). So it is possible to automatically
232 create windows of different radii, e.g. fixed percentages of the maximum radius. A condition is also
233 checked for each circle: if it is completely within the contour (Mauldon et al., 2001) and it does not
234 include DSM hole boundaries (Figure 13), it will be used to perform the sampling (Figure 14),
235 otherwise not. Holes in general could be due to occlusions or to the clearing of vegetation and artificial
236 elements and they must be discarded from the analyzed area.

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

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

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

243 **4.1. Sampling methods**

244 The circular window sampling method (Zhang and Einstein, 1998) allows one to calculate the mean
245 trace length, expected discontinuity diameter and intensity of rock discontinuities. The trace sampling
246 procedure is based on a classification of the traces that are visible on the considered sampling window
247 (Figure 15); the lengths of observed traces and the distribution of trace lengths are not required. The
248 major advantage of this method is that it does not need sampling data about the orientation of
249 discontinuities: its orientation distribution-free nature comes from the symmetric properties of the
250 circular sampling windows. Therefore, it can be used to estimate the mean trace length of more than
251 one set of discontinuities.

252 For each window (Figure 15), traces are classified in the following categories: traces with both ends
 253 outside the window (N_0), traces with both ends within the window (N_2) and traces with only one end
 254 within the window (N_1). From the sampling on a window of radius c it is possible to obtain traces
 255 samples (called $\hat{N}_0, \hat{N}_1, \hat{N}_2$) to estimate a value for mean trace length μ ($\hat{\mu}$) (Equation 2); the total
 256 number \hat{N} of considered traces in a window is the sum of \hat{N}_0, \hat{N}_1 and \hat{N}_2 .

$$257 \quad \hat{\mu} = \frac{(\hat{N} + \hat{N}_0 - \hat{N}_2)}{(\hat{N} - \hat{N}_0 + \hat{N}_2)} c \quad [2]$$

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

261 The following two special cases should be avoided:

262 1. If $\hat{N}_0 = \hat{N}$, then $\hat{N}_2 = 0$ and $\hat{\mu} \rightarrow \infty$. In this case, all the discontinuities intersecting the sampling
 263 window have both ends censored and the denominator of Equation 2 is 0. This implies that the area of
 264 the window used for the discontinuity survey may be too small and therefore not representative of the
 265 rock mass. To avoid this problem it is necessary to increase window radius.

266 2. If $\hat{N}_2 = \hat{N}$, then $\hat{N}_0 = 0$ and $\hat{\mu} = 0$. In this case, all the discontinuities intersecting the sampling
 267 window have both ends observable and the numerator of Equation 2 is 0. To avoid this problem it is
 268 necessary to decrease window radius.

269 In practice, the exact values of N , N_0 and N_2 are not known and thus μ has to be estimated using
 270 sampled data. In other words, the $\hat{\mu}$ of several sampling windows can be used to evaluate μ . Zhang and
 271 Einstein (1998) show how the effect of non-uniformity of trace distribution on an outcrop is decreased
 272 by averaging. Therefore, they recommend that, in practical sampling, multiple windows of the same

273 size and at different locations should be used. This is the reason why an algorithm to create a large
274 number of windows has been implemented. Figure 16 shows an example: there is a grid consisting of 6
275 window centers and for each one there are 4 concentric windows of different radius (1-2-3-4 m). In the
276 following, parameters will be shown in relation to the window radius: actually, mean values will be
277 shown, calculated from all the windows with a certain radius. So, for a radius equal to 1 m, the
278 resulting value of the mean trace length μ from Figure 16 is calculated as the mean of the values
279 obtained from the 6 considered windows with radius 1 m.

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

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

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

289
$$\hat{\mu} = \frac{\pi \cdot c}{2} \left(\frac{\hat{n}}{\hat{m}} \right) \quad [3]$$

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

292 4.2. Parameters definition

293 The parameters used in the following are defined first:

- 294 • Mean trace length μ : it is defined as the mean of the true trace length distribution $f(l)$ (i.e. the
 295 trace length distribution on an infinite sampling surface). It is calculated using Equation 2
 296 (Zhang and Einstein, 1998), based on the count of traces classified according to their position
 297 with respect to the circular window, or Equation 3 (Mauldon et al., 2001), based on the count of
 298 nodes that represents traces end points and intersections between a trace and the circular
 299 scanline.
- 300 • Expected discontinuity diameter $E(D)$: it is defined as the mean of the discontinuity diameter
 301 distribution $g(D)$, whose form is assumed choosing among lognormal, negative exponential and
 302 Gamma. The best distribution of $g(D)$ is chosen using a test (Zhang and Einstein, 2000) and it
 303 can be different from the trace length distribution $f(l)$ form. These authors propose a different
 304 expression for $E(D)$ for each of the three distribution forms.
- 305 • Intensity of rock discontinuities P_{32} : the adopted measure to express the intensity of rock
 306 discontinuities is P_{32} , fracture area per unit volume. Zhang and Einstein (2000) proposed to
 307 calculate the mean fracture area per unit volume of the rock mass as:

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

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

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

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

$$V = \pi c^2 h \quad [6]$$

314 where c is the radius of the considered sampling window and h is the cylinder depth. Two
315 values of h have been used here: 1m (fixed for all windows) and a value equal to the relative
316 window radius c (varying with the windows dimensions).

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

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

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

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

327 Then the DSM (medium resolution, approximately 50 pts/m²), representing the same part of the rock
328 mass shown in the orthophotograph, but with smaller dimensions (Figure 20), was used as input data
329 for the new method.

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

332 Three curvature threshold couples (T_{\max} , T_{\min}) were used to detect traces on the DSM to check if
333 significant variations of detected traces and parameter values could occur when varying the thresholds.

334 Comparing the traces detected in the three different cases (Figure 21) it is possible to notice small

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

350 2500 centers were placed on a regular grid on the sampling plane and, for each one, nine radius values
351 were used to automatically draw sampling windows and to perform the sampling procedure.

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

354 One of the main advantages of the automatic method is the opportunity to have a very large number of
355 sampling windows analyzed in a short time. Table 1 shows the numbers of windows used for the
356 manual sampling on the orthophotograph and the automatic sampling on the DSM, performed on
357 circular windows and circular scanlines. Manual and automatic trace detection needed both about 2

358 hours; considering only the sampling procedure, the time needed for manual sampling on the
359 orthophotograph was about 5 hours, while the time needed for automatic sampling on the DSM was
360 about 2-3 hours using an Intel 2.8GHz workstation.

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

363 From the data obtained during the window sampling procedure on the DSM, the previously described
364 parameters (mean trace length μ_l , expected discontinuity diameter $E(D)$ and intensity of rock
365 discontinuity P_{32}) have been automatically calculated using Zhang's and Einstein's (1998, 2000)
366 equations and were compared to those obtained from the orthophotograph. Mean trace lengths were
367 calculated from data obtained considering circular scanlines only using Mauldon's et al. (2001)
368 equation, and were compared to results obtained using Zhang's and Einstein's (1998) equation.

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

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

378 Figure 23 shows the comparison between orthophoto and DSM trends of expected discontinuity
379 diameter $E(D)$ when varying window radius c . The three DSM trends are similar and their maximum

380 difference is less than 0.2 m. The difference between orthophoto and DSM trends decreases when
381 increasing the radius and they intersect for a radius of about 18 m (that is the maximum radius used in
382 manual sampling). This fact is quite interesting and it suggests that it is important to use large radius
383 values to be sure to obtain data that are representative of the rock mass.

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

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

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

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

399 Figure 25: intensity of rock discontinuity calculated according to Zhang and Einstein (2000) from data
400 sampled on orthophoto and on DSM (3 threshold couples); cylinder volume depth is equal to radius c .

401 Figure 26 shows the comparison between the values of mean trace lengths μ_l obtained with circular
402 window (Zhang and Einstein, 1998) and scanline (Mauldon et al., 2001) sampling with varying
403 window radius c ; sampling has been performed on the traces detected using threshold couple T_1 . The
404 window method (ZE) trend is on average 0.5 m lower than scanline (MDR) trend, but they are similar.

405 Figure 26: Mean trace length calculated according to Zhang and Einstein (1998) and Mauldon et al.
406 (2001) from data sampled on DSM (threshold couple T_1).

407 6. Conclusions

408 The intensity of discontinuities in a rock mass depends on the areas of the discontinuities, which
409 usually cannot be measured. However, they can be estimated on the basis of the discontinuity trace
410 length and the expected diameter, which can be evaluated in a statistical way; two different proposed
411 approaches for mean trace length estimation are compared in this paper. However, the soundness of
412 this kind of estimation is based on a reliable sampling method. For this reason a new automatic
413 approach is proposed in this work, which is based on trace mapping and sampling on a DSM. The need
414 for an automatic tool is due to the long time length of the manual operations; meanwhile, a subjective
415 traces evaluation phase is included in the proposed method, to reproduce the manual procedure. A
416 manual trace sampling on an orthophoto is available, opening the possibility to validate the proposed
417 procedure. This method only requires the input DSM and two thresholds on principal curvature values,
418 then all the operations are automatically performed. The results depend on the quality of the DSM
419 (point cloud density, *noise*, possible holes in the surface). Compared to the manual trace sampling on
420 the orthophoto, the automatic procedure allows one to quickly perform sampling on a very large
421 number of windows for different locations on the rock face and with different radii; it has also the great
422 advantage of using only geometric information, without need to interpret colors and shades as in the
423 manual identification. In this way colors have no influence on the choice of what is a trace or not and

424 results are less affected by false traces. At present, considering the obtained results, it is possible to
425 observe that parameter values and trends from orthophoto and DSM are getting closer for larger radius
426 values: this is a very important achievement, especially to prove that the new method can be a useful
427 tool to quickly obtain order of magnitude of parameters values and it becomes more reliable when the
428 data sample becomes larger and, consequently, more representative of the rock mass. In other words,
429 although the results obtained with the automatic method differ from the manual ones for small window
430 radii, they come closer as the data are getting closer to the rock mass representative volume and they
431 are therefore more interesting from the scientific point of view. Moreover, the larger differences at
432 small radii could also be affected by the presence of false traces identified by the manual procedure:
433 this bias error becomes naturally less influencing when the data sample dimension becomes larger.
434 However this approach raises new issues, that need to be solved and that will be analyzed with further
435 investigations on this topic. The first one is to define a simple way to decide which curvature threshold
436 couple is best suited to map traces. Considering the similarity of parameter trends (Fig. 22-23-24-25)
437 obtained from DSM data using 3 different curvature threshold couples (Fig. 21), the suggestion could
438 be to define a range of threshold values that allow one to correctly map traces; then it would be
439 possible to define the corresponding range of parameters trends and evaluate its reliability.
440 In order to define a general method to determine the quoted thresholds, the application of this
441 methodology to other rock masses with different features will be performed and possible relations with
442 classical rock characteristics determined during discontinuities survey will be tested.

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529

530 **Image list:**

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

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

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

537 Figure 3: Example of convex and concave edges detected on test-object: DSM stairs is composed by
538 116601 points and 231909 triangles.

539 Figure 4: Definition of principal curvature of a vertex P of a surface requires definition of normal N
540 and normal plane π . a) Plane π_1 generates a curve C_I whose osculating circle in P has a radius r_I ; b)

541 plane π_2 is obtained rotating π_1 about the normal N ; it generates a curve C_2 whose osculating circle in P
542 has a radius r_2 greater than r_1 .

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

585 Figure 25: intensity of rock discontinuity calculated according to Zhang and Einstein (2000) from data
586 sampled on orthophoto and on DSM (3 threshold couples); cylinder volume depth is equal to radius c .

587 Figure 26: Mean trace length calculated according to Zhang and Einstein (1998) and Mauldon et al.
588 (2001) from data sampled on DSM (threshold couple T_1).