DETECTION OF ROCK INSTABILITIES : MATTEROCK METHODOLOGY

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In rugged topographies, numerical elevation model allows to detect the most dangerous areas. The simplest method consists in the detection of steep cliffs. In addition, numerical elevation model coupled with a characterisation of the main discontinuity sets leads to the identification of the zones where discontinuities can induce instability, rockfalls or rock slides. Probability of occurrence of dangerous events can be assigned to these zones. Then the zones of highest probability may be subject to more detailed studies such as field work and slope stability calculations. After such a detection stage, impact areas and their hazards can be estimated for example by field work or by trajectography studies that can be used to establish danger and hazard maps.

Key Words : *Rock instability, discontinuity, detection, numerical elevation model.*

1. INTRODUCTION

Rock instabilities are one of the numerous dangers faced by mountainous countries like Japan and Switzerland. Both have high population density requiring the detection of rock instabilities on large scale and recent history demonstrates the need for large surveys. For instance in 1853 the famous Elm (Switzerland) “Sturzstrom” and more recently, the 30 million m^3 rockfall of Randa, near Zermatt, underlined the necessity of such studies in Switzerland. The role of the discontinuities have been demonstrated[2)3)4)], but in the case of Randa the dangerous layout of the discontinuities was shown after the last disaster, it was then decided to develop a method called "Matterock" to detect the zone where discontinuities may produce rockfalls. This method can be applied to the detection of small or large rock instabilities.

Appreciating the potential danger associated with rock slopes depends on the scale, the money available and the period of validity of the study. The cost and approaches change if the study is performed for a region, a valley, a road, etc.

As the stability of a cliff can fluctuate with seasonal or climate changes or modifications of local hydrogeology, all potentially dangerous cliffs must be detected in the first stage. At that stage, only geometrical properties of the discontinuity sets are used to detect potentially unstable zones produced by discontinuities. Stability and trajectory analysis are beyond the scope of this article, but are the logical continuation of such a study.

2. GEOMETRICAL CHARACTERISTICS OF DISCONTINUITES

The survey of discontinuity sets begins with the definition of structurally homogeneous areas. In each of those areas, the mean orientations of the essential discontinuity sets are synthesised on stereonets[5)6)7)]. To achieve this, the method depends on the scope (precision) of the study. Experienced geologist can get the essential trend of the structure very quickly, while less experienced ones will proceed to systematic measurements, grouping data with similar orientations and similar geological properties (**Fig. 1**).

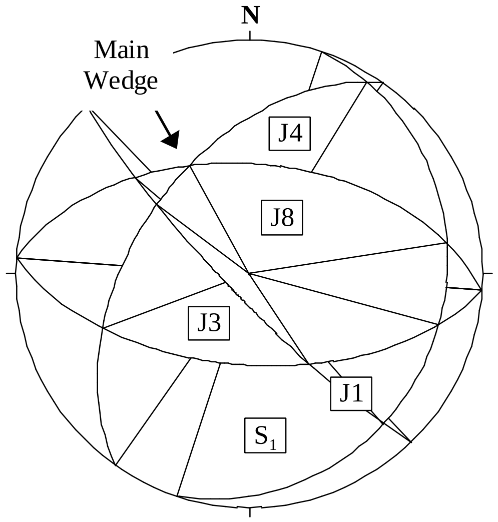

Fig. 1 Stereonet example (Schmidt-Lambert upper hemisphere) of synthesised main discontinuity sets, the main wedge is also indicated.

(1) Simple estimation of observed parameters by window sampling

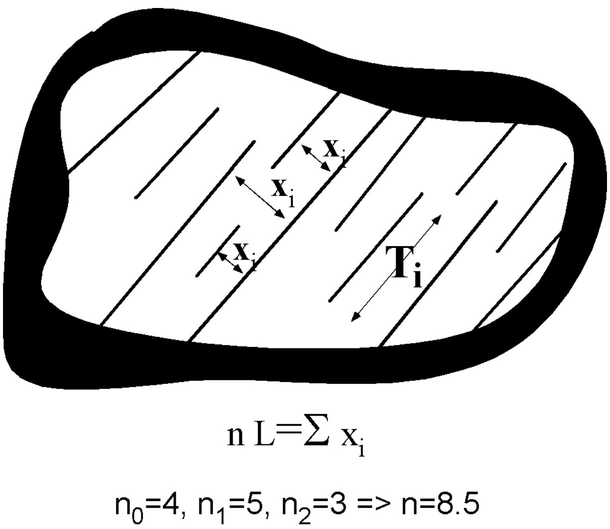

Fig. 2 Window sampling example: trace length, and mean spacing can be evaluated from the x_i and T_i sums respectively. The calculated effective number of discontinuities in the window sampling is lower than the counted traces. The white area of the window correspond to S_{obs}.

Once the discontinuity sets have been defined, their geometrical characteristics must be quantified. One of the quickest way to define these characteristics is to use window sampling[8] from which the number, the trace length and the spacing of the discontinuity sets can be evaluated (**Fig. 2**). In the text below it is assumed that S_{obs} is the surface of the window sampling, n the number of discontinuities which are contained in S_{obs}, L their mean spacing and $\overline{T}$ the mean trace length.

To simplify the developments, we assume that surfaces of observation are perpendicular to discontinuities. If it is not the case, the discontinuity spacing must be multiplied by the sine of the angle between the directions normal to the discontinuities and the surface of observation.

a) The number of discontinuities contained in a window sampling

The number of discontinuity traces counted in a window sampling does not correspond to the number of discontinuities n occurring on the surface S_{obs} (**Fig. 2**). In fact not all the extremities of the traces are contained in the window. Putting n_0 the number of traces completely contained in the window, n_1 the number for which only one extremity lies in the window and n_2 for which no extremity lies in the window. It can be shown[9] that n is approximately given by:

$$n \approx n_0 + \frac{n_1^2}{2(n_1 + n_2)} + n_2 \qquad (1)$$

The estimation of n is less accurate when the observed area has similar or smaller dimensions than $\overline{T}$ [8)9)10)].

b) The mean trace length of discontinuities

Putting T_i the lengths of the discontinuity traces in the window sampling and T_{tot} the total length of the traces contained in the window, the mean trace length $\overline{T}$ is given by (**Fig. 2**):

$$\overline{T} = \frac{\sum_{window} T_i}{n} = \frac{T_{tot}}{n} \qquad (2)$$

c) The mean spacing of discontinuities

The average surface or section $\overline{s}$ delineated by two successive discontinuities observed perpendicular to them is given by the product of the mean spacing L and the mean trace length $\overline{T}$, thus:

$$\overline{s} = L\overline{T} \qquad (3)$$

and

$$n\overline{s} = S_{obs} = nL\overline{T} \qquad (4)$$

then L is given by:

$$L = \frac{n\bar{s}}{n\bar{T}} \frac{S_{obs}}{\sum_{window} T_i} = \frac{S_{obs}}{T_{tot}} \qquad (5)$$

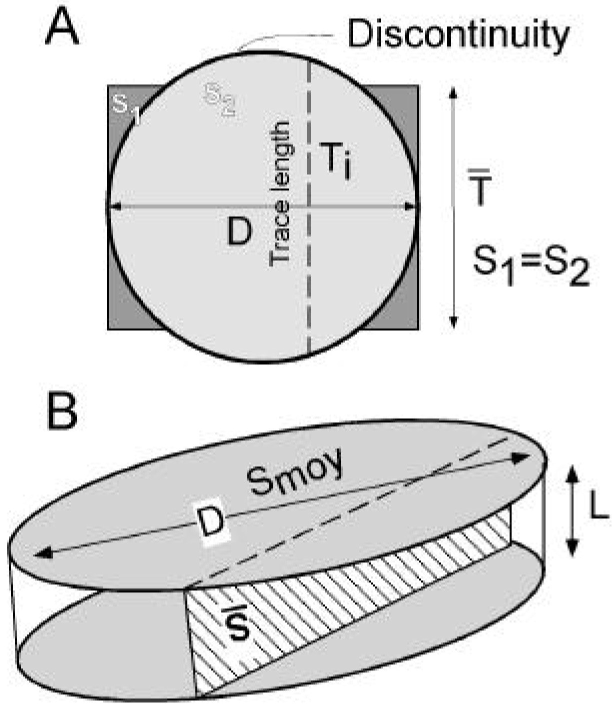

Fig. 3 A) Relationship between the mean trace of the discontinuity set and its diameter, assuming a circular shape. B) Mean geometrical characteristics of the discontinuities.

(2) Relationship between observed and used characteristics

The geometrical characteristics of the discontinuities such as their average diameter and average spacing allow to calculate the mean surface and the mean volume (**Fig. 3**).

In the case of a "geometrical" approach, it is better to characterise the dimensions of the discontinuities[8)9)]. It is assumed that discontinuities are on average planar and circular. Thus the mean diameter D of discontinuities can be deduced from the mean trace length of discontinuities $\bar{T}$ (**Fig. 3**):

$$\bar{T} = p \frac{\left(D/2\right)^2}{D} = p \frac{D}{4} \qquad (6)$$

It is then possible to calculate the average surface S_{moy} of discontinuities of one discontinuity set:

$$S_{moy} = \frac{4}{p} \bar{T}^2 \qquad (7)$$

as well as the average volume of rock which they cut out:

$$\bar{V} = \frac{4}{p} \bar{T}^2 L \qquad (8)$$

The discontinuity frequency is defined by:

$$l = \frac{1}{L} \qquad (9)$$

λ is defined by calculating the total length of n discontinuities traces, observed on a surface of area S_{obs}. Using (3) it leads to:

$$l = \frac{1}{L} = \frac{n\bar{T}}{S_{obs}} = \frac{\sum T_i}{S_{obs}} \qquad (10)$$

remembering that T_i are the lengths of the observed traces.

3. THE PROBABILITY OF DISCONTINUITY PRESENCE

Once the average characteristics of a set of discontinuity have been established, the probability to find a discontinuity in a direction may be defined, in a surface as well as in a given volume. Assuming a random distribution of the spacing, the probability to find at least a discontinuity in the orthogonal direction of a set of discontinuities within an interval x from any point is given by:

$$F(x) = 1 - e^{-lx} \qquad (11)$$

The probability to find at least one discontinuity perpendicular to an area A can be evaluated in a similar way. Knowing the average sections (3), the probability to find at least one discontinuity on the surface A is given by:

$$F_s(x) = 1 - e^{-A/L\bar{T}} = 1 - e^{-N_s} \qquad (12)$$

where N_S is the average number of discontinuities which should be in an area A. If the topographic surface and the discontinuities are not orthogonal, the $L\bar{T}$ must, of course, be corrected.

Such a calculation can also be applied to the volume [8)].

4. POTENTIAL ZONE OF INSTABILITES

Depending on the scope of a study, different criteria can be used to detect zones of potential instabilities.

(1) Topographic slope criteria

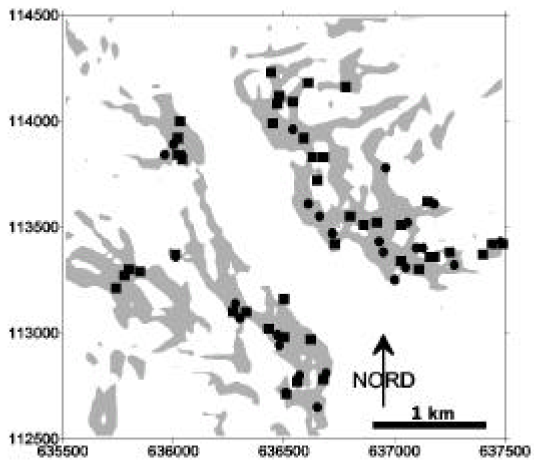

Fig. 4 Map of the slopes steeper than 50º in an area of the Saastal in Switzerland (after [7]). The majority of the rock instabilities are located within the steepest slopes areas. Squares are scars of past rockfalls and circles are observed present rock instabilities (topographic data are used with the authorisation of the federal topographic office).

The simplest criterion is geomorphological, assuming that the steepest slopes contain preferentially instabilities. According to the rock type, a slope limit can be established beyond which rock instabilities can appear, using empirical arguments or not. For example in the alpine gneissic rocks near Zermatt, most past and present rock instabilities are in slopes steeper than 50° (**Fig. 4**).

(2) Comparison of discontinuity orientation with topography

If the characteristics of the discontinuity sets of the studied area are known, it is possible to compare the orientation of the discontinuity sets to a numerical elevation model. This permits to detect zones where a set of discontinuity may generate rock-slides, (assuming sliding as the principal mechanism in generating rock instabilities).

Generally only a limited number of discontinuity sets generates the majority of rock instabilities. The contribution of structural geologists is of primary importance for the recognition and the definition of the important discontinuity sets, which are certainly caused by recent tectonic constraints[11].

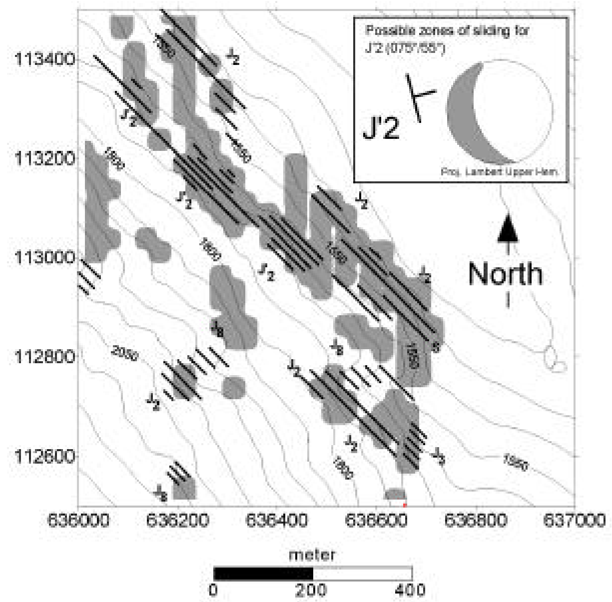

Fig. 5 The shaded area represents the topographic part where the discontinuity set J'2 (075º/55º) could induce rock sliding. The black lines indicate the observed rockfall activity produced by rock sliding on discontinuities. J2 set has the same orientation but is slightly steeper than J'2 set. This area is the central southern part of the Fig. 4 (topographic data are used with the authorisation of the federal topographic office).

The comparison of the automatic detection of potential zones of rock instabilities with the ones detected by field survey indicates a good correlation. For example a detailed survey underlines clearly that the zones of blockfalls which are produced by sliding are caused by only a few sets of discontinuities (**Fig. 5**). This is also true for larger rock instabilities.

(3) Probability of discontinuities presence in a given topographic area

When the direct observation of rock instabilities is not possible, because of accessibility problem, cost or other reasons, the geometrical characteristics of the discontinuity sets lead to a quantification of the probability of presence of discontinuities in a given perimeter of topography using equation (12). To calculate this probability, the mean "discontinuity section" (3) is projected on the topographic surface along the discontinuity, perpendicularly to the intersection of the discontinuity and the topography. The mean number of discontinuities is obtained by the division of topographic surface A of constant orientation by the surface of the projected discontinuity section. In practice the mean number of discontinuities is counted using the numerical elevation model.

The grey scale of **Fig. 6** indicates the number of discontinuities per surface unit. The outlined area contains approximately 0.26 discontinuities, which leads using (12) to 23% of chance to find at least one discontinuity J3 in this area.

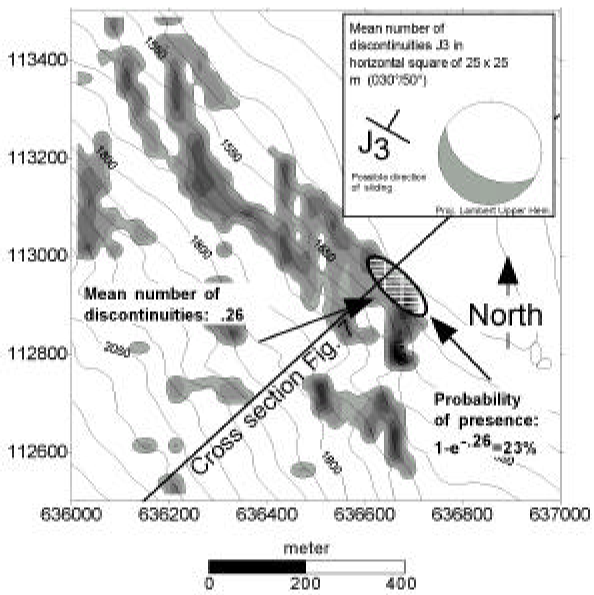

Fig.6 The grey scale represents the calculated mean number of discontinuities J3 (030°/50°) that could be found on the topographic surface and could induce rock sliding. The mean trace length is 220m and the mean spacing 100m. This area is the central southern part of the Fig. 4 (topographic data are used with the authorisation of the federal topographic office).

This probability can be used as a quantification of the hazard: the higher it is, the highest is the probability of instability presence. Of course the hazard scale must be calibrated for a rock type and climatic conditions.

Exactly the same kind of approach can be applied to discontinuity wedges.

(4) Probability of presence of a discontinuity in a given position

For a given geometrical situation, it is possible to calculate the probability to find a discontinuity in a dangerous position.

A cross section of the rocky spur across the area of the previous example allows to evaluate the chance to find a discontinuity affecting the rocky spur (**Fig. 7**). The cross-section is performed along the direction of sliding of the discontinuity J3. It is assumed that the discontinuity J3 is long enough to ignore its position. The probability to find a discontinuity within the rocky spur is calculated along the direction orthogonal to J3 by the equation (11). The thickness in which a J3 discontinuity can work as a slip plane is 30m. Then the probability to find such a discontinuity is 26%.

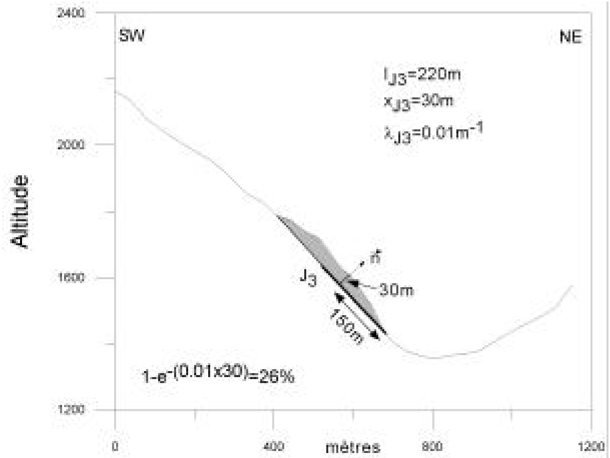

Fig. 7 Cross section perpendicular to the sliding direction of the Fig. 6. The liming condition of the example are drawn. See text and Fig. 6 for details.

The comparison with the previous method indicates the same order of magnitude. There is 25% chance to find a dangerous situation. In the case of a detailed survey, a check on field is necessary, otherwise it may be indexed as danger affected by a medium hazard.

5. AFTERWARDS APPLICATION OF THE METHOD TO THE RANDA ROCKFALL

Above the top of the Randa rock failure, 3D movements monitoring are currently performed. The measurements indicate a sliding in a direction of approximately 140°/30°. This can be attributed to a set of discontinuities which was involved in the Randa rockfall. Because spacing and length of these discontinuity sets are not known, the results are qualitative.

To indicate more precisely the direction of sliding the previous method is slightly modified. The discontinuities are considered as a prisms of section identical to that of the "mean discontinuity" ($L\overline{T}$) with an axis parallel to the sliding direction. This method brings out where the biggest rock masses are involved.

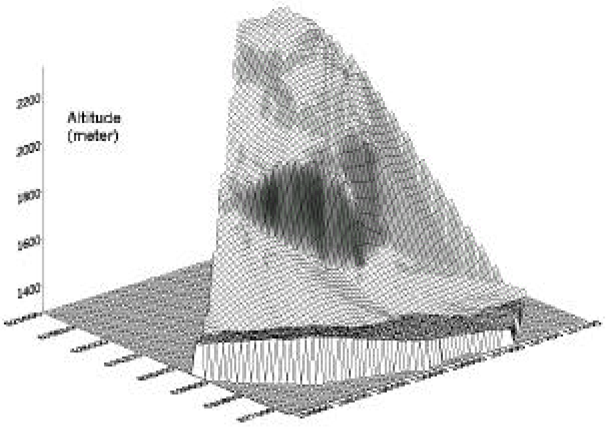

Fig. 8 3D representation of the Randa rockfall area before the disaster. The grey scale indicates a slip direction equivalent to the present slip direction (140º/30º) measured in the upper part of the scar. This indicates that such movements could have produced rockfall. See text for explanation.

This method applied to the topography prior to the Randa rockfall indicates that the fallen cliff is clearly the most affected by the discontinuity set (**Fig. 8**). For the present topography, the rock mass above the rock failure is sensitive to this direction of sliding, as well as its northern part (**Fig. 9**). This indicates that rockfalls can continue to affect the cliff.

If for the top of the rock failure the movement are clearly demonstrated, it is not the case in the present cliff. In fact the sensitivity to a set of discontinuities also depends on the alteration state[12)]. As a consequence case, the fresh rock failure must be weathered during a sufficient period of time before a new rockfall will be produced. On the contrary, the rocks on the top of the scar are not fresh and will produce rockfall in a shorter period.

6. CONCLUSION

The geometrical characterisation of discontinuities sets and their simple modelling appears sufficient to detect the danger on large territories at a first stage using a numerical elevation model, and to focus on smaller zones containing danger to refine studies. The arrival of powerful data processing at low prices, such as GIS, opens many perspectives.

Application to the Randa rockfall indicates that this site would have been indexed in such a study.

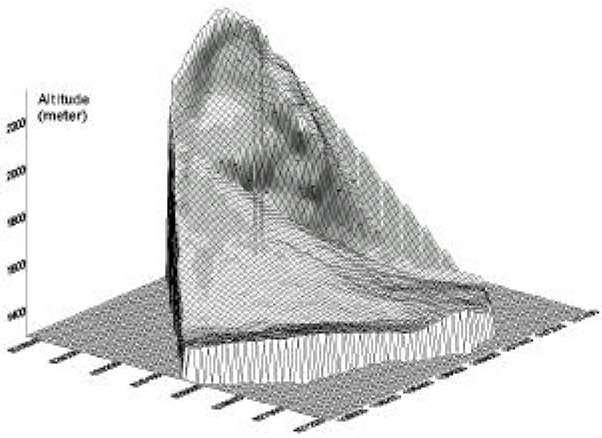

Fig. 9 Same as Fig. 9 but applied to the present topography. The darker part of the scale indicates that small rockfalls will certainly occur.

The combinations of the methodology presented here with other "layers" such as geology (petrography and structure), rock mechanics, history etc. will make it possible to obtain in the near future automatic maps very close to maps of danger.

Applications to other mechanism than sliding such as toppling are under development.

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