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Determination of discontinuity friction by rock mass classification
Détermination de friction de discontinuiteé par un système de classification d'un massif rocheux
Bepalung von Reibungswiderstand von Discontinuiteiten mit ein Klassifikationssystem

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ABSTRACT: An empirical relation ('sliding criterium') was found between simple field descriptions of discontinuity characteristics and friction angle for discontinuities under low normal stress. The relation was established by analysing the stability of a large amount of slopes. The large amount of slope stability assessments and descriptions of discontinuity characteristics on which the relation is based, made a probability analysis of the relation possible.

RÉSUMÉ: Une rélation empirique ('sliding criterium') est déterminée entre des descriptions simples du terrain des caractéristiques de discontinuité et l'angle de friction sons des conditions du stress bas normal. Cette rélation est obtenne par l'analyse la stabilité d'un grand nombre de pentes. Ça, en combination avec les descriptions des caractéristiques de discontinuité en ce qui se base la rélation a facilité une analyse de probabilité de ladite rélation.

ZUSAMMENFASSUNG: In diesem Aufsatz wird eine empirische Beziehung (sliding criterium) zwischen der einfachen Beschreibung von Diskontinuitäten im Feld und dem Reibungswinkel für Diskontinuitäten unter niedrige Normalspannung vorgestellt. Grundlage für die Formulierung dieser Beziehung bildet die Untersuchung von Diskontinuitäten und der Standfestigkeit einer grossen Anzahl von Böschungshängen. Auf dieser Basis wurden Wahrscheinlichkeitsrechnungen durchgeführt.

1 INTRODUCTION

A relation between discontinuity friction parameters and field descriptions was found during the development of a rock mass classification scheme for slope stability (Hack et al. 1993a, 1993b, 1995). The rock slope classification system was developed during four years of research in the Falset area in the north-east of Spain. Here new roads have recently been built through a mountainous terrain, necessitating a large number of new road cuts.

Rocks in the Falset area vary from Tertiary conglomerates to Carboniferous slates and include rocks containing gypsum, shales, granite (fresh to completely weathered), limestone and sandstone. Existing old and new slopes with heights between 3 and 20 m have been classified and assessed on stability by the staff and students of ITC and the Technical University, Delft. Nearly all slopes have been classified and their stability assessed by more than one person to avoid observer bias. About 60 different persons did the descriptions and bias in the overall results is therefore not very likely. Also the quantity of different slopes (253) increases the reliability of the final results.

The slope orientation and orientations of all discontinuity sets were measured and the stability of the slope was assessed visually. The discontinuity sets were described on roughness, infill and alteration of discontinuity walls, to provide data to establish the discontinuity friction parameters.

2 DISCONTINUITY CHARACTERIZATION

Various authors have given sets of standards for the description of discontinuities with the option to establish the friction parameters of a discontinuity (ISRM, 1978, 1981, Barton et al., 1977, 1980, Bieniawski, 1989, Laubscher, 1990). This research used that developed by Laubscher as this is one of the most detailed description systems.

The Laubscher system includes descriptions for roughness (small and large scale), material friction, alteration of discontinuity walls, infill of discontinuities and the influence of water. As a result of the research this description system was modified (table 1) Major changes are that the presence of karst features along discontinuities had to be added as a factor and that alteration of discontinuity walls could be omitted. The factor for 'cemented' infill is related to calcitic cement. Discontinuities with a very strong type of cement, e.g. quartz, which is also strongly cemented to the adjacent rock, should not be considered as a discontinuity. Easily dissolvable and deformable types of cement, e.g. gypsum, should be characterized as non-cemented infill. The factor for infill 'gouge > irregularities' should always be combined with the small scale roughness factor for 'polished'. Non-persistent discontinuities are classified as rough stepped/irregular. The roughness should be considered in the direction of the slope dip if the roughness is anisotropic.

3 VISUAL ESTIMATED SLOPE STABILITY

The research was directed towards designing a slope stability system that includes all possible mechanisms and modes causing instability. None of the analytical or numerical methods to calculate a slope can incorporate all possible causes and therefore a visual estimation of the stability of the slopes is the only possible approach. Three classes have been used for the visual estimation of slope stability (table 2) It is obvious that a visual estimation of stability can in some situations be subjective. The estimation of stability is distinct for slopes that have failed or for slopes where major problems causing instability are clearly visible. Also for definitely stable slopes the estimation can be assumed to be reliable. For slopes that have minor instability problems estimation is more subjective.

Table 1. Discontinuity description (for examples of roughness profiles refer to Laubscher, 1990).

Roughness large scale (Rl)	wavy multi-directional		:1.00
	wavy uni-directional		:0.95
	curved		:0.85
	slight undulating		:0.80
	straight		:0.75
Roughness small scale (Rs) (on an area of 20 x 20 cm^2)	rough stepped/irregular		:0.95
	smooth stepped		:0.90
	slickensided stepped		:0.85
	rough undulating		:0.80
	smooth undulating		:0.75
	slickensided undulating		:0.70
	rough planar		:0.65
	smooth planar		:0.60
	polished		:0.55
Infill material (Im)	cemented infill		:1.07
	no infill - surface staining		:1.00
	non softening & sheared material, e.g. free of clay, talc, etc.	coarse	:0.95
		medium	:0.90
		fine	:0.85
	soft sheared material, e.g. clay, talc, etc.	coarse	:0.75
		medium	:0.65
		fine	:0.55
	gouge < irregularities		:0.42
	gouge > irregularities		:0.17
	flowing material		:0.05
Karst (Ka)	none		:1.00
	karst		:0.92

Table 2. Classes for visually estimated stability.

class		description
1	stable	No signs visible of failure or possible failure.
2	small problems	Small parts of the slope have failed or are failing. For example small blocks roll down the slope during rain; run-off water causes material to be transported down the slope.
3	large problems	Parts of the slope have failed or are failing.

The description small or large is independent from the size (height or length) of the slope.

4 ROCK SLOPE FAILURE

Slope failure mechanisms and their different modes, such as plane sliding, wedge failure, toppling and, to some extent, buckling are discontinuity related. Also non-discontinuity related agencies such as deterioration of rock material, progressive weathering, intact rock creep, erosion due to (surface-) water and internal water (flow and pressure) can cause slope failures.

In general, the method to analyze slope stability in the literature is to identify the mechanism and mode causing instability (plane sliding, toppling, etc.) and then calculate the related rock mass parameters that have allowed failure under the presumed mechanism and mode. In this way a relation is established between one or more rock mass parameters and one failure mechanism and mode. However the identification of the failure mechanism and mode is often not straightforward and/or more than one mechanism or mode is causing failure. If the failure mechanism or mode is not recognized properly then consequently the relation found is erroneous or inaccurate. The amount of mechanisms and modes causing slope instability and the amount of parameters that governs the mechanisms and modes are, in general, very large. Therefore a misconception of the failure mechanism or mode and related failure function is easily made.

To avoid this type of error, the analysis of the rock mass parameters related to failure mechanisms and modes is mirrored in this research. Rather than investigating instability an analysis is done of the stable slopes, for certainly failure has not (at the moment of investigation) occurred in a stable slope. Therefore recognition of the mechanisms and modes is not necessary.

5 'SLIDING' CRITERIUM

It is likely that any form of sliding along discontinuities in a slope, whether wedge or plane sliding, depends (partly or completely) on the condition of the discontinuities and on the driving forces in the direction of the slope working on the rock (mass) above the discontinuity. Release surfaces which allow sliding are present in (nearly) all slopes considered. Figure 1 shows the discontinuity condition factor TC (which is a multiplication of the factors from table 1; TC = Rl x Rs x Im x Ka) versus β (= the apparent discontinuity dip in the direction of the slope dip) for discontinuities that dip in the direction of the slope and β < slope dip. β, the apparent discontinuity dip in the direction of the slope dip is:

$$\beta = \arctan \left[\left| \cos \left(\mathit{dip\ direction}_{slope} - \mathit{dip\ direction}_{discontinuity} \right) \right| * \tan \left(\mathit{dip}_{discontinuity} \right) \right] \quad \textbf{(1)}$$

The accuracy of measuring dip and dip directions is certainly not less than 5° (see below), therefore only discontinuities are included for which: $dip_{slope} > \beta + 5°$. If the difference is less than 5° the dip_{slope} and β are assumed to be equal and the discontinuity plane forms the slope. The later are obviously not a cause for slope instability due to sliding. The dashed line in Figure 1 indicates the boundary below which no discontinuity condition factors of discontinuities in stable slopes plot except for two discontinuities (which have a difference just over 5° between slope dip and β).

That only a relative limited amount of slopes fail through plane sliding and that most of the values belonging to instable slopes are relatively near to the dashed line (thus near to equilibrium) is not unreasonable. The slopes analyzed are only those that have existed for some time. Slopes containing discontinuities with a very low discontinuity condition factor combined with a high apparent discontinuity dip in the direction of the slope dip (thus those plotting further below the dashed line in figure 1) are likely to have failed before the assessment took place. Generally failure will have resulted in a stable slope but with a lower slope dip.

The relation found is independent of the intact rock material and of the alteration of the discontinuity wall. In most discontinuities there is no tensile strength between the discontinuity planes and also the normal stress on the discontinuity plane is (very) low (limited or no shearing through asperities) which explains that the cohesion is ≈ 0 MPa.

For toppling a similar relation has been found. However due to limited space this can not be discussed in detail in this paper.

6 CORRELATION WITH TEST VALUES

β is plotted versus the small scale roughness factor in figure 2 together with the results of field tilt tests (tilt angle) and laboratory shearbox tests. The shearbox values are not corrected for dilatation. Also are plotted the averages of shearbox tests performed on artificial plaster samples (Grima, 1994). The correlation for the different data sets is quite reasonable, certainly for the lower values. The scatter of the test results is such that the linear regression lines in the graphs are rather an indication of a trend than a correlation. No dependency on rock material

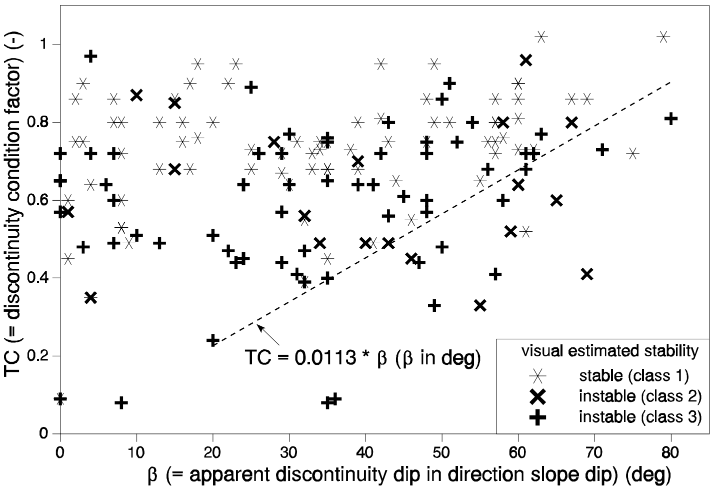

Figure 1. Discontinuity condition factor TC vs β for 'day-lighting' discontinuities in stable and unstable slopes.

could be established for the tests.

The difference between β and tilt angle and shearbox friction for the higher values might be explained by the difference in obtaining the data. The values resulting from the 'sliding criterium' represent the friction values for in-situ and fitting planes. Also the discontinuity in-situ might have some (small) amount of cohesion between asperities on the discontinuity walls. The tilt and shearbox tests were done on sample blocks extracted from the slope. The extraction process can easily break the cohesion and damage the discontinuity planes. In particular sharp asperities, that cause the highest *i-angle*, are easily broken. Furthermore, during extraction and preparation of the sample, the sample halves are nearly always taken apart and re-fitted for the tilt or shearbox tests. The cohesion that might have been present is broken and the re-fitting will often not be as good as the original in-situ fit of the sample halves. A not so good fit will result in a lower *i-angle* (Rengers, 1970) and thus also in a lower tilt angle or shearbox friction value and as it is likely that the higher values result from a high *i-angle* rather than a high material friction value; the influence of the sample preparation is obvious.

This is confirmed by the tests on the artificial plaster samples (Grima, 1994). The samples where made exactly according to the graphs for roughness description of Laubscher (1990) and the ISRM standard graphs (ISRM, 1978, 1981). Testing started with perfect fitting sample halves. Each value is the average of 11 to 12 tests. The average values are considerably higher than the shearbox results on real rock samples but confirm the 'sliding criterium'.

7 CORRELATION WITH LITERATURE VALUES

7.1 *Basic friction*

Values reported in the literature for basic friction range from 23° to 40° (Giani, 1992, Barton, 1973a - values for a clean, smooth diamond saw cut). The friction for a straight polished surface without infill equals 36.5° according to the 'sliding criterium', which is fairly well comparable. The differences between basic friction for different rock materials reported in the literature are small and for many less than the range measured for one rock material. This is also found for the 'sliding criterium' which does not show any significant difference in friction values for different rock materials.

7.2 *Small scale roughness*

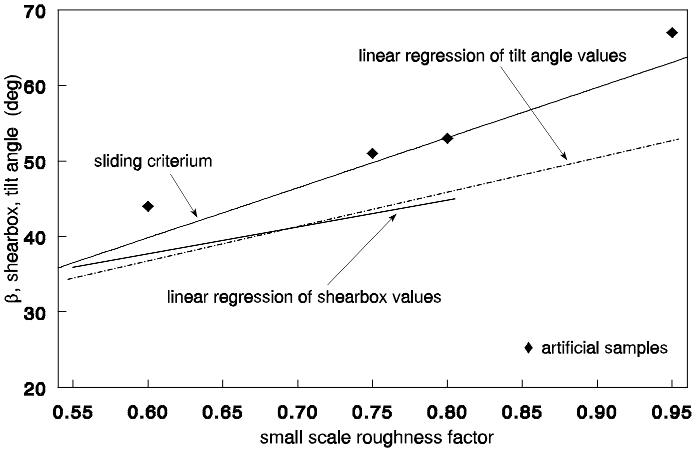

Figure 2. β, shearbox test friction and tilt angle vs small scale roughness factor.

It is difficult to compare literature values for small scale roughness with the 'sliding criterium' because the descriptions of the roughness in the literature are not uniform, standards (if any) are often not reported or a reference is made to the JRC number. Conversion of JRC numbers into the ISRM roughness descriptions is subjective and only for some roughness profiles possible without ambiguity (Barton, 1987, 1990).
An attempt to compare literature values with the 'sliding criterium' has been undertaken in figure 3. The friction values for small and intermediate scale roughness description (J_r) from the Q-system classification, as reported by Barton et al. (1990), are dependent on the joint alteration number (J_a factor in the Q-system). $J_a = 1.0$ (surface staining) and $J_a = 2.0$ (non-softening mineral coating) should be compared with the 'sliding criterium' in figure 3. The values agree reasonably with the 'sliding criterium'. The values reported by Barton et al. are established by tilt tests that are reported to be unreliable for stepped surfaces (Barton et al., 1990). 'Rough stepped/irregular' in the 'sliding criterium' is therefore compared with 'discontinuous joints' in the Q-system.

7.3 *Large scale roughness*

During the research a number of large scale roughness profiles have been measured. Large scale i-angles (base > 20 cm) measured on discontinuity planes in slate and limestone resulted in large scale roughness angles between 6° and 10° for wavy multi-directional and 5° for slight undulating surfaces. This is lower than the additional friction due to large scale roughness based on the 'sliding criterium'. The measurements were done on exposed planes, probably resulting from sliding of overlying rock. This sliding has most likely reduced the roughness *i-angles*.

The number of large scale roughness friction values reported in the literature is very limited. Tilt tests on large scale artificial samples (Chryssanthakis et al., 1990) gave higher friction values than the 'sliding criterium' and also higher than the *i-angles* measured. However the roughness description of these profiles was not reported and the description has been estimated from scale drawings in the publication. This might well underestimate the large and small scale roughness.

7.4 *Infill material*

In figure 4 the shear friction values belonging to different infill materials based on the 'sliding criterium' are plotted. The values are calculated for discontinuities with large scale roughness: straight, small scale roughness: polished, and no karst. For comparison literature values are added. The literature values are peak shear strength for filled natural discontinuities. If infill thickness were reported these are included in the

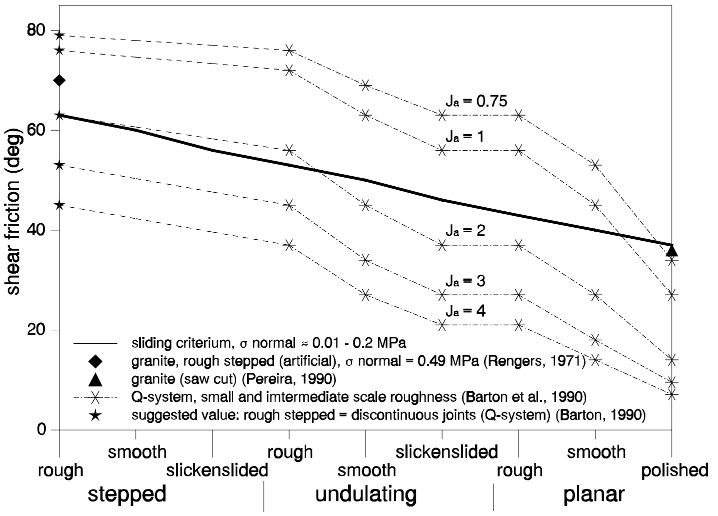

Figure 3. Small scale roughness literature values and 'sliding criterium' vs surface description.

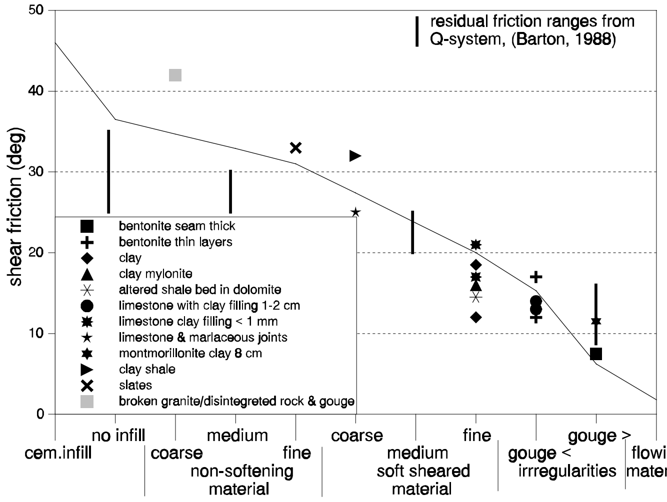

Figure 4. Shear friction angle vs infill material (values from Hoek et al., 1981, vertical lines from Barton, 1988).

graph. The residual friction ranges listed in the Q-system (Barton, 1988) are also indicated. The shear strength friction values based on the 'sliding criterium' are in good agreement with the literature values.

Comparison of infill friction angles from the 'sliding criterium' to laboratory tests on artificial discontinuities and/or infill materials reported in the literature (Papaliangas et al., 1990, Pereira, 1990) is difficult. The materials and the circumstances under which these discontinuities were tested are, in general, very different from natural materials and circumstances. Additionally the normal stress on the samples during testing is often far higher then those acting in slope stability problems.

In figure 5 values from Papaliangas (1990) are compared to the infill friction values resulting from the 'sliding criterium'. The roughness of the sample discontinuity is not described according to ISRM standards, but the friction angle (33°) for a saw cut (planar surface) and the friction angle (52°) for the surface of the test sample without infill, is reported and from these values the roughness factor according the 'sliding criterium' was back calculated and resulted in 'rough undulating' (small scale roughness). This is approximately in agreement with the reported JRC number of 8. The samples were not large enough for a large scale roughness which therefore equals 'straight'.

The values (figure 5) are fairly well in agreement with the 'sliding criterium' except for the thick infill (infill thickness/roughness amplitude > 1). The high value (24°) for the thick infill compared to the 'sliding criterium' (7°) might well be attributed to the differences in circumstances between laboratory testing and in-situ discontinuities. Most failures of slopes occur during or directly after rainy periods, and it is therefore not unlikely that in a natural state thick layers of cohesive infill material (clay gouge) causing slope failure will be nearly always saturated. During failure it is likely that this leads to (pore) water pressures in the infill. The kaolin in the tests was tested with a moisture content of 50 % but the degree of saturation was not reported so that these samples might have been tested in a unsaturated state with none or less (pore) water pressure. The shear velocity in real slopes is often (far) higher than in the laboratory tests (laboratory: 0.4 - 1 mm/min), reducing the possibilities for water discharge in slopes. Therefore it is likely that, in slopes, water pressures in the clay gouge cause an undrained shear behaviour whereas in the laboratory tests, with no or smaller water pressures, the shear behaviour is drained. The values found by Pereira (1990) (figure 5) and Phien-wej (1990) (not in graph) for an open air dried, silty clay infill and an oven dried bentonite infill (38° for 20 mm infill, roughness amplitude 10 mm) respectively, seem to confirm this behaviour.

The values for non-cohesive soils of Pereira (1990) show that for the two larger grain sizes the friction angle reduces. This effect is attributed by Pereira to rolling friction rather than shear friction because the silicious river sand tested had rounded grains.

A thick layer of infill material ('gouge > irregularities') in an undrained environment should show some cohesion effect. However, this is not found for the 'sliding criterium'.

8 PROBABILITY ANALYSIS

The quantity of data available allows a probability analyses. The reliability of the 'sliding criterium' as an estimate for shear friction parameters is dependent on the accuracy of the description of the discontinuity. During the research for this thesis it was found that although different persons made the descriptions, these rarely differed by more than one class. Obviously, if for all factors the class is consequently taken one lower, then the difference in friction value for the discontinuity becomes larger. However this has not been observed to happen, because the class differences were randomly lower or higher for the different factors, which resulted in approximately the same final results.

The error and resulting distributions of input (field) data are not known in detail. During the research multiple measurements of the same parameter at the same location have been done by different students and staff and distributions for the input data could be derived. The distributions of input (field) data are 5° for dips, and 10° for dip-directions (95 % confidence interval). Both are virtually independent of the measured value and are normally distributed. Each of the factors describing the discontinuity has an uniform and discrete distribution of one class below until one class above the sample class, except for those classes at the limits, for which an uniform and discrete distribution from the sample class until one class above the minimum respectively one class below the maximum is used. Based on these distributions the resulting probability for sliding failure in a slope based on the 'sliding criterium' is shown in figure 6.

9 DISCUSSION & CONCLUSIONS

Apparent cohesion should have been found for the sliding (and toppling) criteria, in particular for the rougher or stepped surfaces. However as the relation only considers the minimum *TC* value related to the apparent discontinuity dip in the direction of the slope dip,

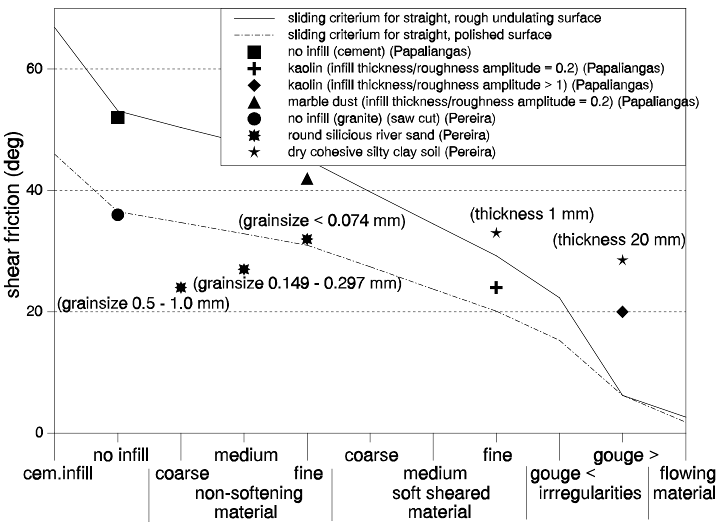

Figure 5. Shear friction angle vs infill material compared to infill thickness laboratory tests. Papaliangas et al. (1990) undertook tests with straight, rough undulating surfaces and Pereira (1990) with straight, polished sample surfaces.

(apparent-) cohesion might be present but cannot be established. The 'sliding criterium' results in a straight line relation between φ and the factor for the condition of discontinuities, passing through (or very near) the origin.

The 'sliding criterium' is confirmed by laboratory tests and literature friction values. This proves that the approach of an apparent dip angle in the direction of the slope dip related to the factors for the condition of discontinuities is valid.

The 'sliding criterium' is (for low normal stresses) independent of the rock material adjacent to the discontinuity. Alteration of the discontinuity wall is not important because nearly always the alteration of discontinuity wall will be accompanied with infill material which will, generally, have a lower shear strength than the altered wall material.

Water does not need to be included as a separate factor as might be assumed that all slopes have been subject to extensive rainfall.

All slopes observed are in a Mediterranean and mountainous climate. Whether the relation is also valid in strongly different climates is not known.

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REFERENCES

Barton N.R. (1973a). Review of a new shear strength criterion for rock joints. *Engineering Geology* 7, pp 287-332.

Barton N.R. (1973b). Review of a new shear strength criterion for rock joints. *Engineering Geology* 7, pp 509-513.

Barton N.R. & Choubey V. (1977). Shear strength of rock joints in theory and in practice. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.* 10, pp.1-54.

Barton N.R., Løset F., Lien R. & Lunde J. (1980). Application of Q-system in design decisions concerning dimensions and appropriate support for underground installations. *Int. Conf. on Sub-surface Space, Rockstone, Stockholm.* Sub-surface Space, Vol. 2, pp. 553-561.

Barton N.R. (1988). Rock Mass Classification and Tunnel Reinforcement Selection using the Q-system. *Proc. Symp. Rock Class. Eng. Purp., ASTM Special Technical Publication 984.* Philadelphia. pp. 59-88.

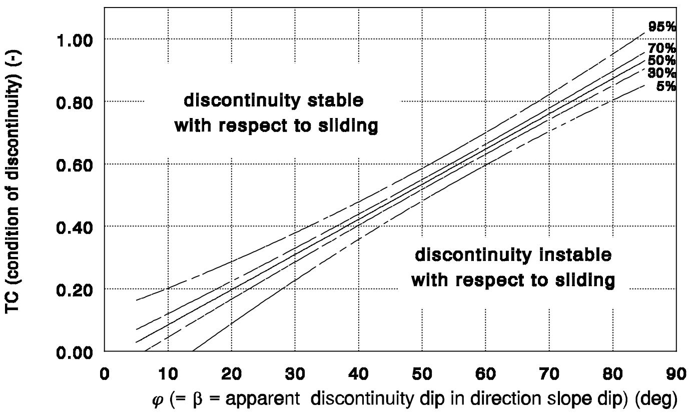

Figure 6. Sliding probability.

Barton N. & Bandis S. (1990). Review of predictive capabilities of JRC-JCS model in engineering practice. *Rock Joints.* Barton & Stephansson (eds). Balkema, Rotterdam. ISBN 90 6191 109 5. pp. 603-610.

Bieniawski Z.T. (1989). *Engineering Rock Mass Classifications.* New York: Wiley-Interscience. ISBN 0-471-60172-1. 251 pp.

Chryssanthakis P. & Barton N. (1990). Joint roughness (JRC_n) characterization of a rock joint and joint replica at 1 m scale. *Rock Joints.* Barton & Stephansson (eds). Balkema, Rotterdam. ISBN 90 6191 109 5. pp. 27-33.

Giani G.P. (1992). *Rock slope analysis.* Balkema, Rotterdam. ISBN 90 5410 122 9. 361 pp.

Grima M.A. (1994). Scale effect on shear strength behaviour of ISRM roughness profiles. *MSc. thesis Engineering Geology.* ITC, Delft, The Netherlands.

Hack H.R.G.K. & Price D.G. (1993a). A rock mass classification system for the design and safety analyses of slopes. *Proc. Symp. ISRM EUROCK'93, Lissabon.* pp. 803-810.

Hack H.R.G.K. (1993b). Slopes in rock. *Proc. An overview of engineering geology in the Netherlands.* Ed. DIG. Technical University Delft, The Netherlands. pp. 111-119.

Hack H.R.G.K. (1995). Slope stability classification probability. ITC, Delft, The Netherlands. (in preparation).

Hoek E. & Bray J.W. (1981). *Rock slope engineering, 3rd edition.* Inst. of Mining and Metallurgy, London. ISBN 0 900488 573. 358 pp.

ISRM (1978). Suggested methods for the quantitative description of discontinuities in rock masses. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.* 15, pp. 319-368.

ISRM (1981). *Rock Characterization, Testing and Monitoring, ISRM suggested methods.* Ed. E.T. Brown. Pergamon Press, Oxford.

Laubscher D.H. (1990). A geomechanics classification system for rating of rock mass in mine design. *J. South African Inst. of Mining and Metallurgy*. 90, No. 10, pp. 257-273.

Papaliangas T., Lumsden A.C., Hencher S.R. & Manolopoulou S. (1990). Shear strength of modelled filled rock joints. *Rock Joints.* Barton & Stephansson (eds). Balkema, Rotterdam. ISBN 90 6191 109 5. pp. 275-282.

Pereira J.P. (1990). Shear strength of filled discontinuities. *Rock Joints.* Barton & Stephansson (eds). Balkema, Rotterdam. ISBN 90 6191 109 5. pp. 283-287.

Phien-wej N., Shrestha U.B. & Rantucci G. (1990). Effect of infill thickness on shear behaviour of rock joints. *Rock Joints.* Barton & Stephansson (eds). Balkema, Rotterdam. ISBN 90 6191 109 5. pp. 289-294.

Rengers N. (1970). Influence of surface roughness on the friction properties of rock planes. *Proc. 2nd Cong. ISRM (Belgrade),* 1, pp. 229-234.