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SLOPES IN ROCK

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ABSTRACT: Education and research have been successfully combined in the Falset area. Slopes in various rock types and excavated with different means create an excellent educational area for discontinuous rock mechanics. The research resulted in a rock slope classification scheme leading to slope stability assessment in which factors are introduced to compensate for weathering and excavation disturbance and produce a rating for an imaginary unweathered and undisturbed 'reference' rock mass. The classification thence allows assessment of the stability of the existing or any new slope in the reference rock mass, with allowance for any influence of excavation method or (future) weathering. A secondary benefit is that the students who had to use and help develop the system had to assess discontinuous rock masses and to critically evaluate the importance of rock mass parameters.

KEYWORDS: rock, slope, stability, classification, discontinuous rock mass, discontinuity, reference rock mass, education

INTRODUCTION

Slopes in rock are considered as pretty simple by many. All engineers have had some or the other form of applied mechanics during their education and applying this to a slope seems easy enough. Some engineers might consider looking into a standard book, for example Hoek & Bray's 'Rock Slope Engineering' (Hoek, 1981) and following their recommendations calculate the stability. However often the engineer does not realize the simplifications he makes during his slope stability calculation. Even if the standard books are followed the simplifications recommended and that have to be made to calculate the stability analytically, are considerable. The simplifications introduce errors and often lead to a total mis-conception of the stability of a slope.

A 'slope in rock' normally means a slope in a rock mass and not in (intact) rock. If the engineer realizes that, he might avoid most pitfalls during the calculation of the stability of a slope. Rock mass is not simple and therefore structures developed in a rock mass cannot be simple, including slopes.

The study of discontinuous rock masses does also apply for other structures in or on rock (mass). Foundations on or in rock are probably even more simple than slopes as long as the engineer does not know what rock is. ('he is not hampered by knowledge'). For those who consider rock as something massive consisting of the same material then obviously foundations on rock are very simple to calculate. In The Netherlands the author has often heard expressions like 'Ahh, het is **rots**' (meaning: 'Ahh, it is rock'). Implied in that phrase is: there are no problems to be expected. If rock is the foundation layer then there seems no problem at all. Settlement and/or consolidation problems are supposed not to exist and further study of the '**rots**' is deemed not necessary.

In the construction of underground structures not many Dutch engineers have been encountered by the author however also engineers from countries with plenty of rock seem often to mis-understand rock. Expressions like 'the rock is hard' (normally meaning: do not bother with further study because everything will be OK) or 'weak' (do not bother with further study because the rock will always collapse) are often the only information available before a tunnel or other underground excavation is made. That also tunnels in 'hard' rock can fail or tunnels in 'weak' rock can be stable, seems a strange phenomena to this category of engineers and results in an outcry for a specialist engineer who then has to solve the problem.

In geophysical investigations has been assumed for a long time that rock behaves as a layered material but massive in-between the layers. That discontinuities ranging from micro cracks to large joint structures can have a major influence on the geophysical and in particular on seismic methods is only realized during the last decades.

In the opinion of the author part of the mis-understanding of rock originates in the too limited education of (some) engineers. They have not learned to properly inspect and describe or characterize a rock mass. The fieldwork done during the last four years in the area of Falset has had two objectives. The slopes are a structure which can be studied by the students to explain them the details of discontinuous rock masses. Secondly the research resulted in the development of a rock mass classification system. Using the classification system forced the students to study and critically evaluate rock mass parameters.

DISCONTINUOUS ROCK MASS

In the last decades it has been realized that rock is not massive but discontinuous. The development started in near surface applications where was established that discontinuities in a rock mass had a severe and often decisive influence on the physical properties of the rock mass as a whole. In near surface applications a simplified rock mass modelled as a continuum gave unsuitable results. More recently it is observed that also in deeper applications discontinuities cannot be disregarded.

Intact rock versus rock-mass

A rock mass contains rock material and discontinuities. The discontinuities are defined as planes of physical weakness. The blocks of rock material in-between the discontinuities are defined as the intact rock (Fig. 1). The properties of the intact rock material are not influenced by the discontinuities. The overall effect of discontinuities which are defined as planes of physical weakness, is that a rock mass containing discontinuities is weaker than the intact rock. A rock mass containing discontinuities will be more deformable than intact rock, the deformation will be rather plastic than elastic, the shear strength and the compressive strength will be smaller. Tensile strength of a rock mass containing discontinuities is virtually always zero. Porosity of a discontinuous rock mass is higher and the permeability is often considerable higher. All rock mass properties, like deformation, strength and permeability, etc. are normally strongly anisotropic.

Geotechnical units

Theoretically a proper calculation of a rock mass should include all properties for all features in a rock mass including all variations in space of the properties. This is usually not feasible and a normal procedure is to divide a rock mass in geotechnical units. Within a unit the properties of a rock mass should be more or less constant; eg. within a geotechnical unit the intact rock material should be broadly the same in each block of intact rock, the discontinuity properties, like: orientation, spacing, roughness, etc. should not change, the degree of weathering should be the same, etc.. Within a calculation this will be one unit. The unit is homogeneous if it fulfils the above criteria, however this does not imply that the rock mass or intact rock is also isotropic.

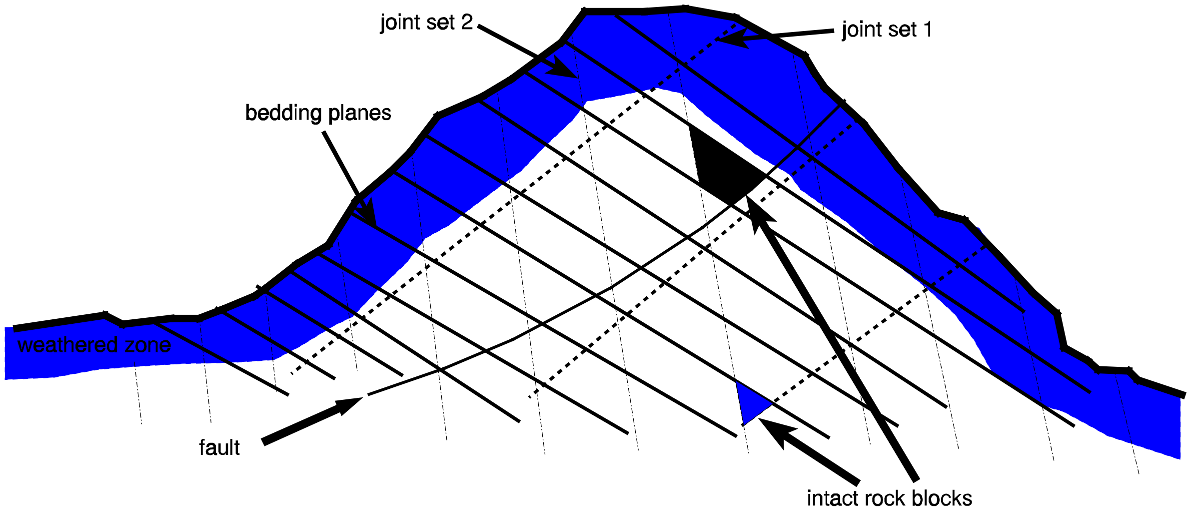

Figure 1: Intact rock vs rock-mass.

Three- and two-dimensions

Discontinuous rock masses are a three-dimensional feature. Virtually by definition the rock mass is anisotropic in three dimensions. A section through the rock mass will nearly always be a highly simplified and erroneous model. However most analytical calculations are done in two-dimensions because adding the third dimension makes the calculations too laborious. Numerical three-dimensional rock mechanical calculation methods do exist but are expensive and require considerable computer power and computation time.

FIELD AND LABORATORY TESTING

Field and laboratory tests are supposed to provide the 'hard' input data for analytical and numerical calculations. But how 'hard' is or can be this data? For discontinuous rock masses the shear strength along discontinuities is the most important parameter. Large scale (100 x 100 cm shear area) in-situ field tests are very expensive and are only a feasible option for very large and costly projects (large dams, nuclear power stations, etc.). Medium scale (30 x 30 cm shear area) in-situ testing is still very expensive and for average structures not possible. Small scale (10 x 10 cm shear area) tests consist of taking a sample and testing it at a later stage in the laboratory. Preferably the test sample includes an undisturbed natural discontinuity. Anyone who has ever tried to obtain such a sample from a discontinuous rock mass knows that it is virtually an impossible task. If a sample is obtained at all (they normally break during the sawing process) it can nearly never be called undisturbed. Sawing the sample out of the rock mass can easily take two hours. Taking into account the amount of samples necessary to cover the variation in a rock mass, the engineer should realize that testing very seldom can provide the type of 'hard' and statistically justified data that he would prefer.

Scale effects

In a discontinuous rock mass test data cannot be simply scaled. The test results of a 10 x 10 cm shear test might well give totally different results from a large scale test. The mechanism governing shear strength and related parameters like deformation are not fully understood in a natural rock mass. Therefore small scale test data can only be used as an estimate of the real values in a rock mass.

CALCULATION

Analytical

One of the most wide spread methods to assess slope stability is the kinematic approach. Kinematic analysis is based on the principle that a potential instable block of rock must be able to move. This requires that the block of material is free to move in a particular direction (the sliding plane should be 'day-lighting'). The principle is fairly simple and by using a stereographic projection method it is a fast method to determine potential instable blocks for plane and wedge sliding and for toppling. Adding friction factors of the sliding planes to the projection give the possibility to assess the maximum mobilized shear strength in the direction of possible movement. The method of kinematic analysis does not consider the cohesion or apparent cohesion along sliding planes. The form, volume and weight of the rock blocks and the position in space of the force vectors is not necessary in the assessment because cohesion is not included. This is the reason that the method is so simple and easy to conduct. However cohesion and in particular apparent cohesion is a factor that cannot be neglected in slope stability assessments. In some stable slopes the stepped form of the potential sliding plane, causing an apparent cohesion, prohibits movement of the potential instable block.

Analytical safety factor calculation methods exist in every form of complexity. Starting with the simple problem of a safety factor for plane sliding in two dimensions (eq. 1.), which also disregards cohesion, ranging to highly complicated three dimensional slice calculation methods.

$$\phi = \arctan\left(\frac{W \sin \psi + V \cos \psi}{W \cos \psi - U - V \sin \psi}\right) \qquad \textbf{(1)}$$

(W = weight of the block, ψ = dip of sliding plane, U = water force at bottom of block, V = water force at rear of block, ϕ = friction angle along sliding plane). The more complicated the calculation methods become the more parameters are included and the more test data are necessary.

Numerical

Numerical calculation methods can be used for slopes. Finite, boundary and distinct element programs can be used. In the first two the rock has to be modelled as a continuum with depending on the program some limited amount of faulting or jointing. In the distinct element programs the slope can be modelled as a reality model. If is attempted to model the slope as a continuum the problems inherent to scale effects and transforming discontinuity data into a continuum deformation model have to be solved first. If the problem is modelled as a reality model in a distinct element model the amount of blocks and consequently the amount of calculation time and computer memory is increasing rapidly for larger models. Therefore solving a problem in a discontinuous rock even if all mechanical parameters are known works often out to be impractical.

The amount of discontinuities in a rock mass can be (and normally is) enormous, even for a relative small volume of rock mass. Analytical calculations become troublesome and result in an unrealistic amount of work; effectively it becomes impossible to calculate a rock mass analytical. Numerical discontinuous computer programs are not restricted in the amount of discontinuities but to calculate a rock mass accurate it is necessary to have the properties of the rock material and the discontinuities. Variations along the same discontinuity plane can be considerable. There may be hundreds of discontinuities which properties may vary along one discontinuity but also may vary from one discontinuity to the next and together with inhomogeneity of the intact rock material, the amount of properties needed for a proper input in a discontinuous model is tremendous. Laboratory and field tests are available to obtain the properties needed. However in large quantities it is expensive, troublesome and thus often impossible to obtain all the values needed. The alternative and often applied practice is to guess properties or to use literature values and utilize these into a computer program. Whether the result is still representative for the real situation is a question mark and cannot be answered.

ROCK MASS CLASSIFICATION

An altogether different approach to assess a discontinuous rock mass is rock mass classification. The empirical relations between rock mass parameters and properties and the resulting stability in a particular application has proven to work. For a considerable amount of time rock mass classification has been done and used in mining and civil engineering applications. The reason for the development of classification systems is that even a simplified analytical stability calculation for a tunnel in a discontinuous rock mass was impossible in the time before computers became general available. This brought some engineers on the idea that empirical relations might be an alternative. The results are the well known classification systems.

A secondary but important benefit of rock mass classification is that the rock mass is characterized according a standard set of rules with standard sets of descriptions for each parameter. The characterization is done visually or by simple tests avoiding the problems of in-situ testing. Characterizations of the rock mass can be used to define geotechnical units and comparison of geotechnical units is possible. Also rock masses described by different engineers at different locations can be compared due to the standard method of characterization.

The rock slope classification system (Hack et. al., 1993) (Fig. 2) 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, thus giving the opportunity to assess slopes in different materials. Different methods of excavation were used for the old and the new road cuts, allowing comparison of different excavation methods. Road cuts made for old roads some 40 to 60 years ago could be compared to road cuts not more than 4 years old. Also local variations in weathering, the influence of weathering, and the susceptibility of the rocks to weathering as a factor in slope stability could be studied in detail in the area.

Existing old and new slopes 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.

The rock mass classification system from Bieniawski (1989) as modified by Laubscher (1990) has been used as basis for the development of the slope classification system. The advantage of the system as modified by Laubscher is that it includes the most detailed description for the friction parameters along discontinuities, also includes a block size/form factor and incorporates so-called compensation factors for, amongst other things, the excavation method. The concept of compensation factors for the rock mass before and after use (excavation of underground space or slope cuts) is very attractive (Laubscher, 1990, Romana, 1985). This gives the opportunity to compensate for local variations which might be present at the location of the rock mass observed but which might not be present at the location of any proposed slope.

The rock slope classification scheme developed consists of two elements. These are:

1. The development of a 'reference rock mass'. To do this rock mass parameters of importance for rock slope stability are rated. Local factors such as weathering and nature of the excavation method which produced the outcrop are

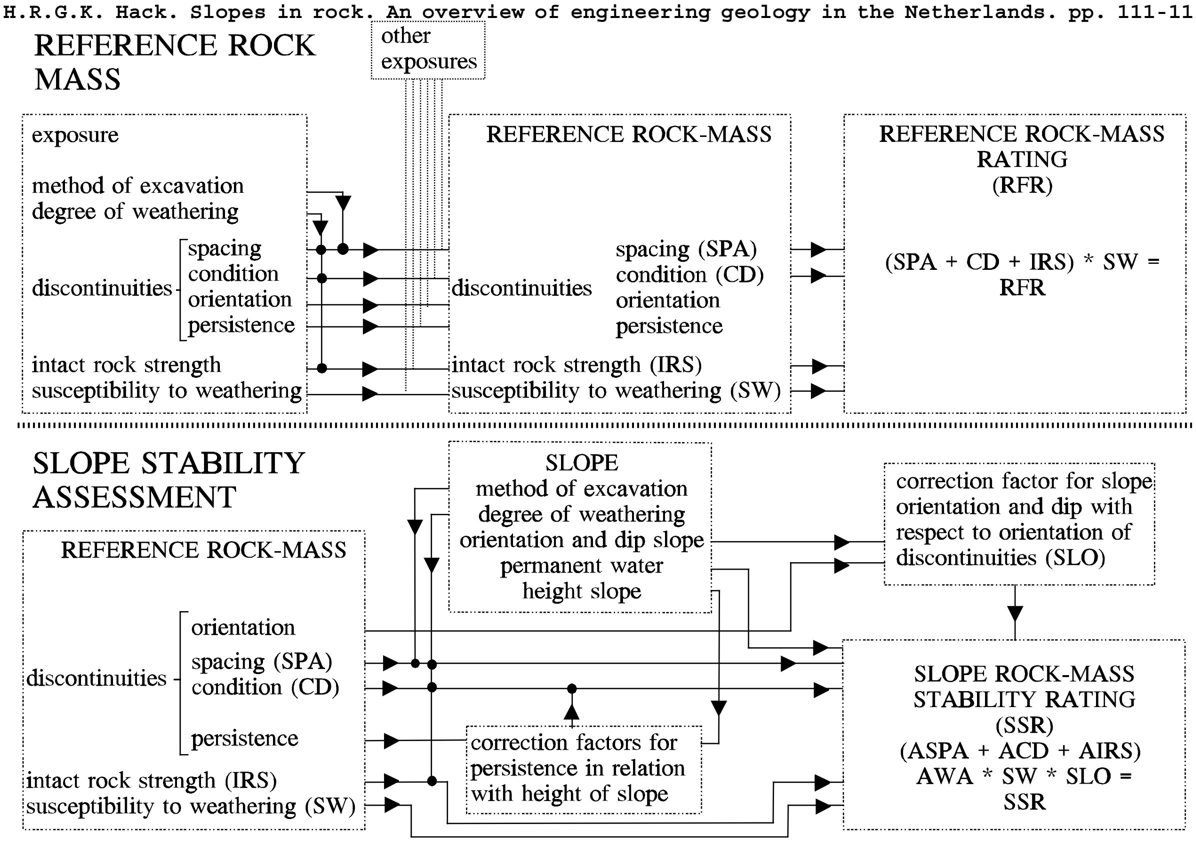

Figure 2: Classification scheme (• = correction factor applied to rock mass parameter).

compensated for in order to convert the rating for the existing mass to that of the theoretical unweathered and undisturbed mass. This compensation is done with the aid of rating multipliers which have been developed for some of the components in the rock mass classification scheme. The resulting rock mass quality rating is that of the 'reference rock mass'. By this technique rock masses which, in the same geotechnical unit, show different degrees of weathering and differing degrees of excavation disturbance are brought back to a rating reflecting their basic geotechnical properties and structure.
The reference rock mass contains factors for: Intact Rock Strength (IRS), discontinuity spacing, condition of discontinuities, method of excavation, weathering and susceptibility to weathering. The intact rock strength, spacing factor, the condition of discontinuities and the susceptibility to weathering are considered rock mass parameters which have at a particular location been influenced by weathering while the discontinuity spacing has been influenced by the method of excavation.

2. The actual slope whose stability is to be assessed is made in the reference rock mass. A stability assessment, incorporating ratings dealing with joint set orientation relative to proposed slope orientation, discontinuity roughness etc. is made and factors are introduced to allow for future weathering and rock mass disturbance as a consequence of the proposed method of excavation. The essential elements of this assessment include:
1) A comparison between the orientation of the proposed slope with that of the observed discontinuities, relative to the dimensions of the slope. 2) A modification of the discontinuity spacing rating to allow for the anticipated method of excavation. 3) An allowance for the weathered condition of the rock mass into which the slope will be cut. 4) An allowance for the development of weathering in the cut slope after excavation.

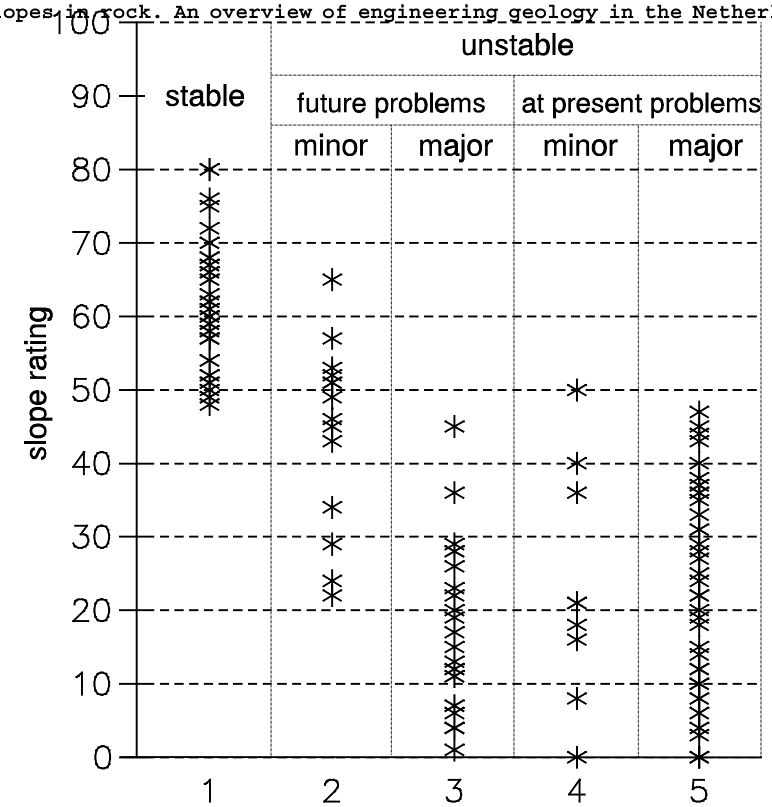

Figure 3: Slope rating vs visually anticipated stability.

A flow chart showing how the reference rock mass is developed and giving the factors incorporated into the slope stability assessment is shown in Fig. 2.

Results

So far 140 rock slopes have been classified, generally from 5 to 15 m high but ranging up to 50 m, and representing a large variety of rock types excavated by various means. Mostly the stability assessment has been made on the slopes already existing. Ratings range from about zero to about 80 and have been compared with either visual or calculated assessments of stability. A comparison between rating and stability is given in Fig. 3, in which minor and major future problems are those which are anticipated to occur within about 10 years. Minor present problems imply minor rock falls; major present problems implies immediate danger from major instability.

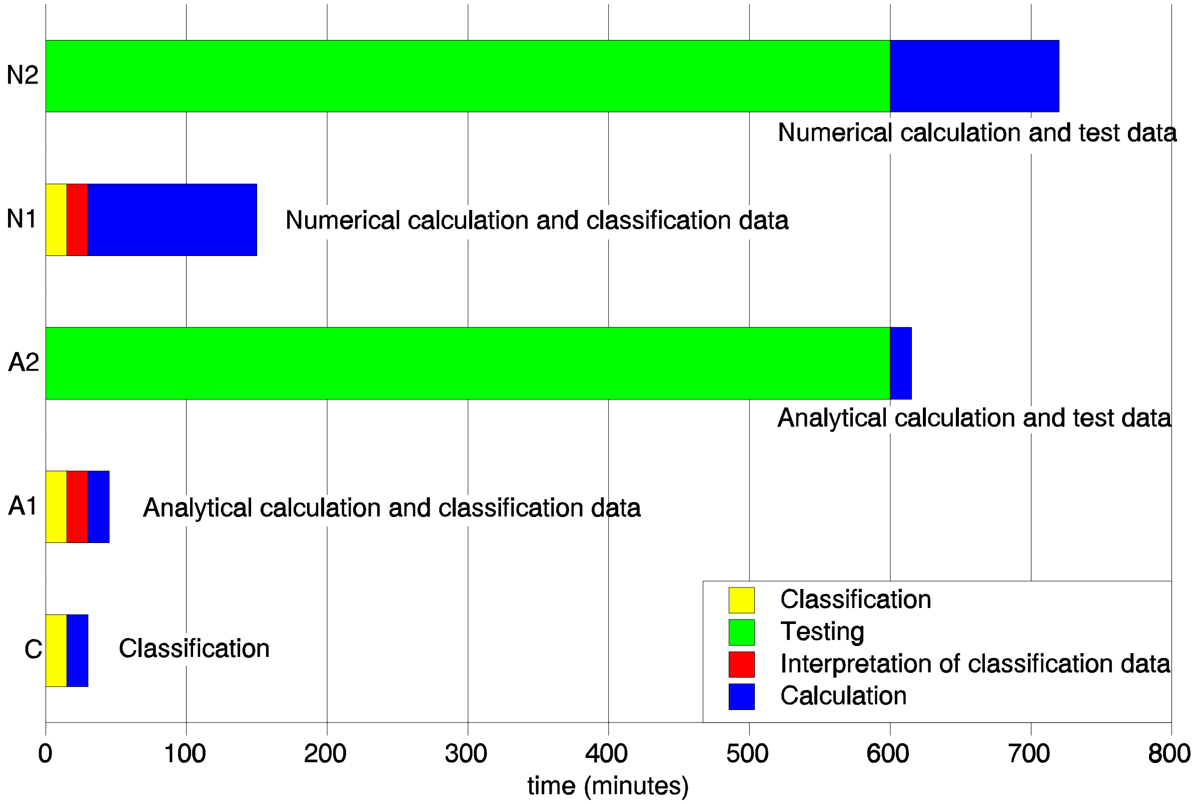

Figure 4: Time estimates for slope stability calculations.

TIME EFFECT

How useful is a classification system with respect to time necessary to arrive at a slope stability estimate. Figure 4 shows time estimates for various methods to arrive at a stability assessment. The analytical and numerical assessments consist of shearbox tests with an analytical or numerical calculation. The data from the classification can be used instead of shearbox data however 15 minutes have been included for interpretation of classification data. Shearbox tests for a slope are estimated to take anything up to 10 hours (obtaining the sample, sawing, etc.: 2 hours; testing: 1 hour, and 3 samples per slope). An analytical computer calculation takes 15 minutes; a numerical calculation will take a minimum of about 2 hours. It is obvious that with respect to time a classification is an attractive option.

DISCUSSION

Analytical methods for calculating slope stability are necessarily constricted in the amount of detail that can be incorporated in the calculations. All analytical calculations are hampered by simplifications that have to be made before an analysis can be made. If no simplifications are made calculations become cumbersome and are often impossible to calculate, even for relative small and simple slopes. Deformation, rotation and translation of intact rock material blocks and variations in parameters along discontinuities and/or in intact rock material cannot be incorporated also not if 'hard' and statistically justified input data had been available. Numerical analyses might well be able to calculate a complicated model however 'hard' data are also not available or limited.

The slope classification system avoids most of the problems inherent to other assessment methods. Advantages of the slope classification system are: 1) It gives the option to define rock mass geotechnical units which have within the unit the same geotechnical characteristics, independent of local weathering and the method of excavation. 2) The characterization and classification can be done visually or by very simple means in a relative very short time. 3) The classification system contrary to most other assessment methods, also gives a stability assessment in cases where the discontinuities are not the main source of failure, but where, for example, buckling of small blocks or susceptibility to weathering causes (in time) failure of the slope. A slope classification system is an empirical system based on a limited amount of case histories. The amount of case histories determine the accuracy of the system and the problems for which the system will be applicable. This might be considered a disadvantage although an empirical system might well give better results than a deterministic method which is highly simplified or lacking accurate input data.

CONCLUSION

Slopes are particularly suitable for the analysis of the behaviour of something as complicated as discontinuous rock. Developing a rock mass classification system for slopes has its merits for slopes but also the ideas developed might well find their way into other applications in geotechnical engineering.

Rock mass classification systems might look simple but are certainly not too simple for calculation of stability problems in discontinuous rock masses. The results are in many situations likely to be of a better quality than deterministic analytical or numerical calculations.

Slopes and rock mass classification systems are excellent tools to illustrate the difficulties of a discontinuous rock mass to students or to non- rock mechanics engineers. A slope is a structure easy to study, large parts of slopes are visible and often easily accessible. Rock mass classification systems force students to assess a rock mass in detail and learn them to critically evaluate a rock mass. Engineers who had fieldwork studying discontinuous rock masses in slopes should therefore never repeat the word '**rots**' as because they are hampered by knowledge and know that 'rots' is the wrong word and that it is not all just one simple '**rots**'.

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