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CLASSIFICATION AS A TOOL IN ROCK ENGINEERING

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Summary

The role of classification in rock engineering and design is discussed. It is important to distinguish between characterization, classification and empirical design method. The classification systems used today should, strictly speaking, either be described as rock mass characterization systems or empirical design methods, as long as the outcome is not organised into classes.

The main requirements for a true classification system capable of solving rock engineering problems are as follows. 1) The reliability of the classes to assess the given rock engineering problem must be estimated. 2) The classes must be exhaustive (every object belongs to a class) and mutually exclusive, (no object belongs to more than one class). 3) The principles of division (rules) governing assignment into the classes must be based on suitable indicators (ground parameters etc.) and must include the possibility of being updated during construction using the experience gained. 4) These rules must also be so flexible that additional indicators can be incorporated. 5) The uncertainties, or the quality, of the indicators must be established so that the probability of mis-classification can be estimated. 6) The useful system should be practical and robust, and give an economic and safe design.

In the author's opinion, none of the main classification systems in use today fulfils these requirements. They may, however, serve as supervised systems as a basis in the development of local systems adapted to the actual site conditions.

keywords: classification system, characterization, rock engineering

1 INTRODUCTION

> *"Most classification systems are continuously misused because the premises for and assumptions made in developing them have not been carefully studied by users, and because they have been given a validity for "quantification" of rock mass behaviour that is far more general than was intended by their authors."*
> Brekke T.L. and Howard T.R. (1972)

As is evident from the quotation above, classification systems are used and misused in numerous connections. This was a main topic in the GeoEng 2000 workshop in Melbourne on "Reliability of classification systems", from which the following was concluded:

– *The concept of rock mass classification is unclear. It is an ongoing debate regarding the application of rock mass classification as a design tool. New data is needed from the field (case histories), linking characterization with design (classification).*

– *Practitioners need to be aware of the limits of the various classification databases and the input sensitivity of whichever rock mass classification system they use.*

– *It is important to separate characterization from classification.*

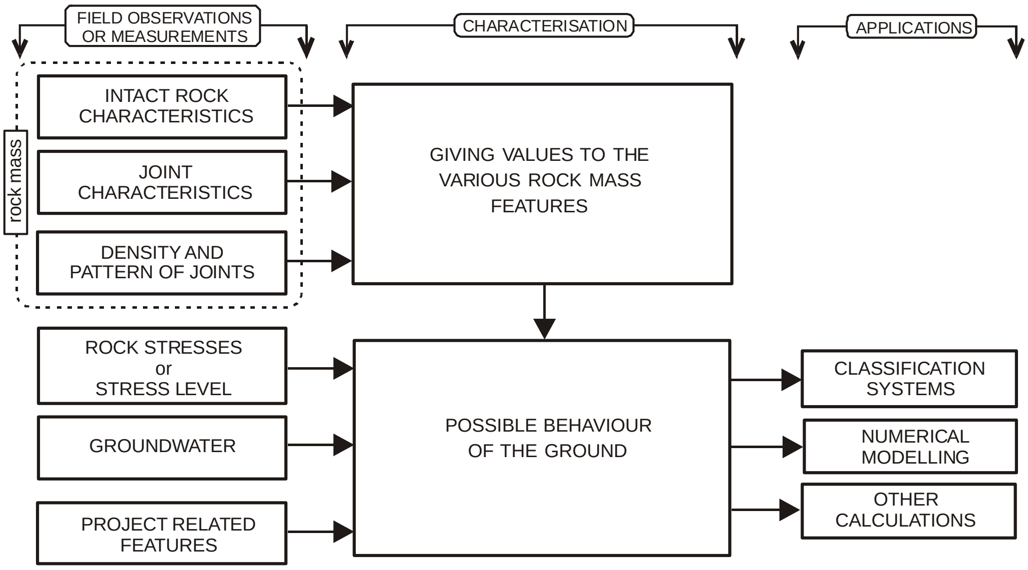

Figure 1 Observation, measurement and characterization applied in rock engineering (from GeoEng2000 workshop on classification systems)

In this paper, we want to discuss the role of classification in rock engineering and design. Our aim is to outline useful applications of classification for design purposes, and to pinpoint some misuses of both terminology and application in today's design works. Firstly, we will theoretically discuss the requirements of true classification systems, and then the rock engineering procedures required by their use. Finally, we will examine some of the existing classifications systems in order to evaluate how they fulfil these requirements and their practical applicability.

In a subsequent paper, we will discuss rock mechanics and geological aspects of the art of rock engineering classification, and related requirements.

2 DEFINITIONS

Firstly, it is important to define the terms “classification”, “characterization", and “classification system”.

The term classification can be used in various ways. This has led to confusion when the rules and roles of classification are discussed. The word “classification” comes from Latin, from the root words "classfica´tio", which means “class”, and "fa´cio" which means “to do”. Thus, classification is the result of putting objects into different classes. The purpose of such classification is to get a better overview of a phenomenon or set of data, to try to gain an improved understanding of them.

By contrast, characterisation is the procedure of describing the condition of, for example, a substance or material, and defining or giving value to the various features it displays. In practical rock engineering, the task is to:

1. *Identify* the features or parameters of importance or relevance to a project and the assessments to be performed.
2. *Measure and/or describe* the properties of these parameters, giving them values or ratings according to their structure, composition and properties.

Thus, the process of rock mass characterisation consists of describing and quantifying the parameters that govern or influence the rock mass behaviour. These can be expressed as intact rock characteristics, discontinuity (joint) characteristics, and the density and pattern of discontinuities, as shown in Figure 1. The characterization can be simplified by putting the different properties into classes - in other words, by classifying them. There are many examples of this process in engineering geology, such as describing the strength of the rock material or the joint spacing and density, and placing them into pre-defined and general accepted categories.

Generally, the result of the characterization process will be used to assess the rock mass quality, according to some pre-defined system. This procedure is normally given the name *rock mass classification*. It is important to point out that, strictly speaking, this is truly a process of classification only if the outcome is a recognizable class description, such as "poor rock" for example, and not if the procedure leads to a single number or value, which has been evaluated from a rating system.

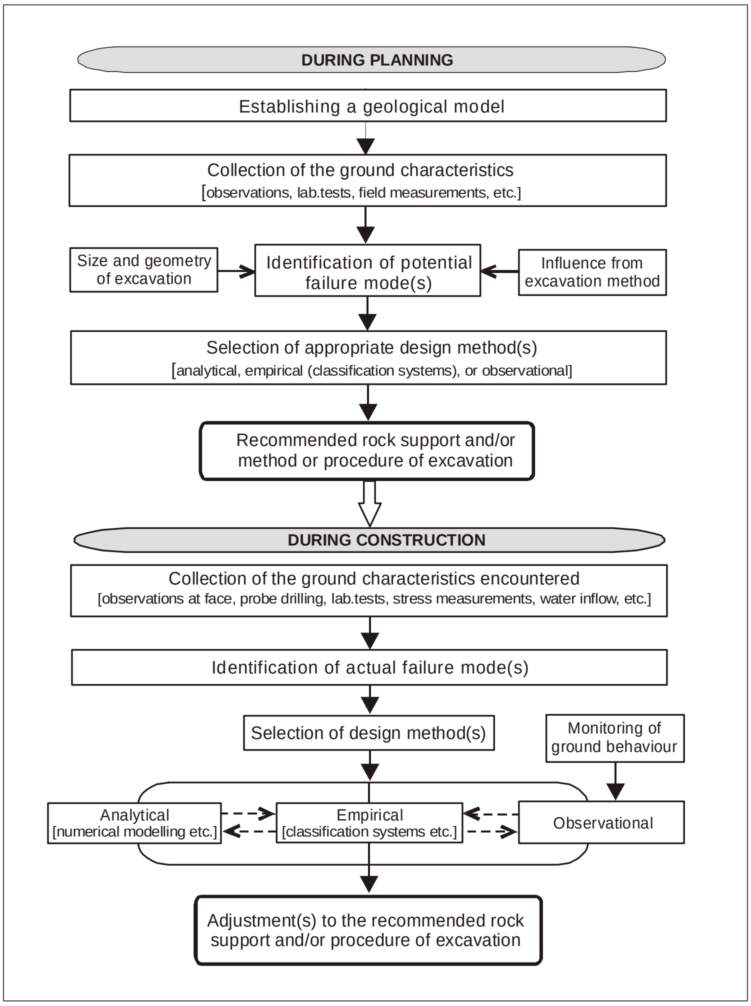

Figure 2. The main principles of the design process for underground constructions in rock including the use of classification systems as an empirical design method.

In projects involving rock construction, a particular group of empirical design tools (based on adopting experience gained previously in circumstances that can be characterized as similar), are known as classification systems. Strictly speaking, it would be better if such tools always were identified as part of an overall group of empirical methods used in rock engineering design. Frequently, such empirical design is used in conjunction with engineering assessment and other design approaches. See Figure 2. Rock mass classifications form the backbone of the empirical design methods. In fact, on many projects, the classification system serves as a main practical basis for the design of complex underground structures. Most of the tunnels constructed at present make use of some classification system. The ratings or values of the input parameters (indicator) are often found from a sort of characterization of the different relevant rock mass properties.

The much used term “classification system” is correct and justified only if the design tool divides the assessment into certain classes or categories. In general, the term "rock engineering classification" or more correctly "rock engineering classification system" is recommended only for the practical use of classification to solve various rock engineering aspects.

3 GENERAL ASPECTS OF CLASSIFICATION

3.1 Basic types of classification

Bieniawski (1989) defined classification as *"the arrangement of objects into groups on the basis of their relationship"*. The role of classification is generally to get a better overview of a phenomenon or set of data in order to understand them or to take different actions concerning them. It is possible to distinguish between two main types of classification, as defined by Hands (1997):

> *Unsupervised classification* refers to the process of defining classes of objects. This is sometimes called cluster analysis. That is, we are presented with a collection of objects and the aim is to formulate a class structure. In an unsupervised classification, we have to decide how many classes to use, and to link the objects in the collection to the appropriate classes. The development of many of the classification systems used today is an example of this type of cluster analysis.
>
> In a *supervised classification,* the class structure is known a priori and the principles (rules) of division are formulated, allowing one to allocate objects to their appropriate classes. This is sometimes called supervised pattern recognition. Examples from existing classifications include the ISRM classification of rock strength, or the geotechnical classification of soils.

Characterisation, on the other hand, is not a priori classification, since it is just an exercise to describe an object in terms of words like colour, strength, grain size distribution, and so on. Characterisation may be a supervised classification - if the aim is to place the object in predefined classes or groups.

3.2 Requirements of and usefulness of a classification

The logical requirement of a classification is that it should be both exhaustive and mutually exclusive. This means that every object in the area of interest has to belong to a class and no object can belong to more than one class.

The usefulness of a classification depends on the *principle of division (rule)* applied in separating the objects into different classes. To be able to talk about a common principle of division, the criteria for the decision of putting an object in a certain class should have some relation to each other. Thus, the objects in a certain class may have some similar property of interest.

The benefit of the classification is also related to the purpose it is meant to serve. Here, two main objectives of the classification can be distinguished:

1. *Communication* between different users will be easier if the classification system is well defined and related to common understanding and language. From the name given to a

sample of rock, a geologist will usually understand how the rock has been formed and whether it has been subjected to different geological processes. However, the name will not give him definitive information on the mechanical properties of the rock. The information is only qualitative, and the aim is to facilitate communication between the parties involved, to get a mutual understanding of the object.

2. *Decision-making.* The central problem here is not only to allocate an object into pre-defined classes, but also to obtain information on the quality of the classification and the possibility that it may have been mis-classified. This is maybe the most interesting use of classification in rock engineering. The special conditions related to most rock engineering problems imply that the supervised classification will be the most suitable.

3.3 Linking indicators/objects to design or construction classes.

The archetypal *supervised* classification problem may be described as follows: Each object is described in terms of a vector of features or indicators. Taken together, the indicators span a multivariate space termed the indicator space. For a particular object, the vector of measurement corresponds to a particular point in the indicator space (see Figure 3). Often, the vector can contain numerical values, but it is possible also to include general features. The aim is to decide to which class the object and its measurement vector should be assigned. In order to be able to do this, rules (principles of division) must have been constructed in advance, which can be used to predict the classes of new objects based solely on their measurement vector.

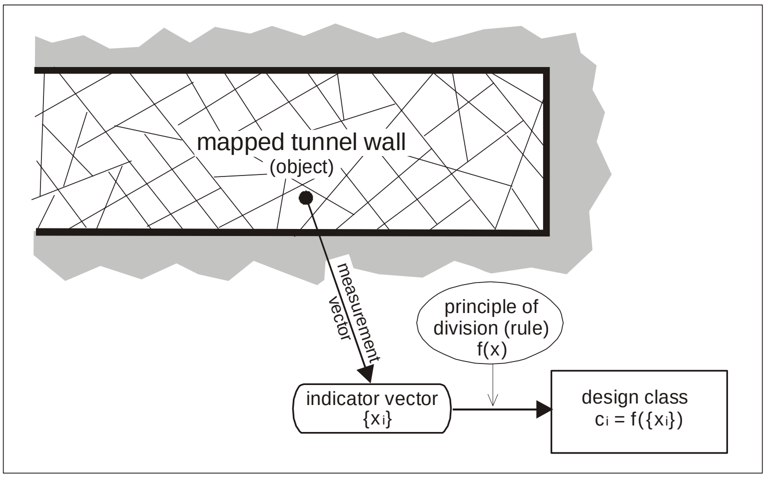

Figure 3 The process of engineering classification for design

An example of this process is as follows: In a fractured rock mass, observation of the joint sets and their individual properties will be adequate for describing the vector of measurements. To define support classes from these data, the rule may be to calculate the indicator (Q- or RMR-value) based on the measurement vector.

In more complex conditions, like squeezing ground, a combination of measurements like rock mass characterization, description of the minerals, or deformation measurements should be used to define the support classes or support actions to be taken. In this case, the principle of division may not be uniquely definable. It will normally be build up by "and", "or" qualifications and "if" statements. It is obvious that, in such a case, a single numerical value cannot fully describe the complex situation.

Since the principles of division may be based on one of the existing empirical methods normally called classification systems, (e.g. the Q or RMR systems), the requirements regarding classification will be those put forward by Einstein et al. (1979) for empirical methods.

Ideally, the principles of division (rules) should be selected to match the actual problem. However, this is not the case in many situations, which can give different problems:

- One problem with classification is that, typically, the true class of the objects is unknown. This problem arises when it is not possible to describe or measure the objects with exactly the same features or indicators as were used to define the true classes. This situation is very common in rock mechanics. For example, rock support can be decided by numerical calculations based on input data like the strength and deformation properties of the rock mass, but such properties cannot be observed directly. Instead, other indicators such as general geological observations of the rock mass quality can be used. This will introduce additional uncertainties and therefore a risk for mis-classification. The measurement vector may indicate a certain class in circumstances where the true class should be another. Once the object has been mis-classified, any decision based on the classification will imply a probability of unexpected behaviour. One strategy to avoid this problem may be to collect more information. However, in this case, the rule (principle of division) must be constructed in such way that it allows the user of the classification system to wait until more information has been collected before the decision is taken. This makes it clear that the possibility that additional information can be used in the design decision is an important option. The theoretical background of the observational method is rooted in this problem, Peck (1969) and Stille (2000).

- Another problem with classification will arise if the chosen principles of division do not define a space that is exhaustive when compared with the actual conditions. If the measurement vector falls outside the indicator space defined by the design set, a meaningful classification cannot be carried out. One strategy to avoid this is to assess the typicality of the new object to each class, and classify it as "other" if it is atypical of them all. In this way, the logical demand for the classification to be exhaustive may be fulfilled - but the action required for the “other” class normally will be different. For example, it may involve carrying out further investigations or asking for advice from a panel of experts. An example of this is the observation of slaking ground in a fractured rock mass in a water transfer tunnel. The presence of such ground will require the use of special support measures in order to guarantee the tunnel stability. The vector describing the support to stabilize the fractured ground will not normally contain a mineral analysis of the rock or an observation of slaking so that, in this case, a special “other” class has to be defined.

The problem of deciding which design decisions are appropriate, i.e. the *accuracy* of the actions taken, is a general rock mechanical problem and is related to the reliability of the design. For the example of designing supports, and given a certain class, what is the probability that the proposed support will fail? To answer this question, several important issues have to be addressed, such as the model uncertainty, uncertainties in the data base arising from natural variations, and the investigations performed.

3.4 Practical requirements

It is very important that the principles of division and the corresponding indicators frame a practical system with easily measurable parameters that result in an economic and safe design of the underground opening (Einstein et al., 1979).

The support measures and construction procedures defined by the classification should not be overly conservative, nor should they fail. The method of classification should be relatively insensitive to normal variation, as well as robust and repeatable. The parameters should be easily obtained from outcrops and boreholes, as well as easily observed or measured in the tunnel.

3.5 Summing-up

The requirements of a system for classification for rock engineering purposes can be summarized as follows:

- Use a supervised classification system;
- The classes must be exhaustive and mutually exclusive;
- The indicators must be defined;
- The principles of division (rules) must be established;
- It must be possible to incorporate additional indicators in the system;
- It must be possible to update the rules (principles of division);
- The uncertainties and the probability of mis-classification must be estimated;
- The system should be practical and robust and give an economic and safe design.

4 ROCK ENGINEERING AND CLASSIFICATION SYSTEMS

4.1 General

In all civil construction and building activities, different decisions have to be taken. A decision can only be taken based on a choice of different available alternatives. In principle, there can be an infinite number of alternatives but, normally, they are divided into classes or groups in order to facilitate the choice. In many cases, we have to choose between two classes. For example, we can accept a result of a calculation or reject it. We can also make estimations with different assumptions and get different results. The choice will then be based on some kind of evaluation of the uncertainties involved, and the consequences of an improper decision. Normally, this is called a *decision analysis* based on risk analysis or risk assessment. This is described in Section 4.3.

4.2 The use of classification in rock engineering

In comparison to many other civil engineering situations, the uncertainties in underground rock engineering are high. The design and different construction actions have to be based on:

a) the geological model and assumed ground conditions from various types of investigations during the planning stage; and
b) the actual rock conditions encountered in the tunnel or underground opening during construction.

Pre-defined actions based on the use of classification systems have been shown to be an economic option in many cases. This is a very common situation in rock engineering and will be discussed further here. Some examples are:

- A common situation during the tunnelling process is to take the decision whether or not to use forepoling or spiling. This is a typical choice between two classes (alternatives).
- Another example is when to reduce the length of the blast holes drilled to advance a tunnel. It is not very practical to use a continuous reduction; instead, classes are used like full round length, half round length or a quarter round length.
- Even for rock support, it is very common and convenient to use classes with a stepwise increase in level of support measures. Often, choosing between pre-defined classes has been found to speed up the tunnel works. One reason for this is that it has often been found practical to use multiples of the thickness of a single shotcrete layer instead of a continuous variation. The inaccuracy in the site characterization is in many cases so high that it is not

meaningful to discuss the difference in support between, for example, 2.1m or 2.2m rock bolt spacing. In such cases, stepwise-defined classes will be adequate.

Figure 4 gives examples of two common situations where classification is used in rock engineering.

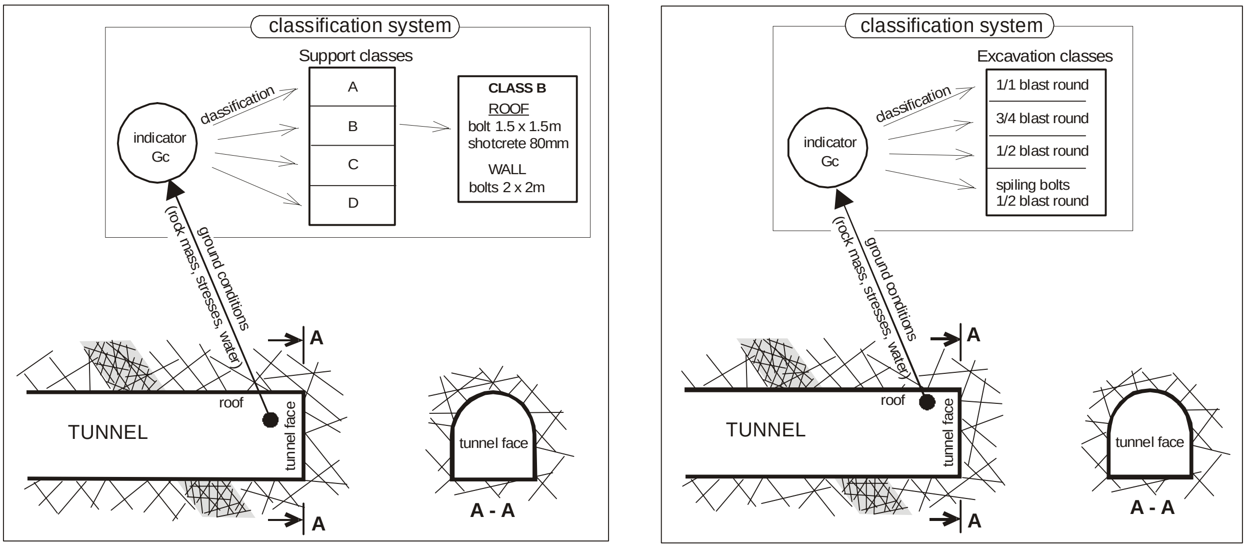

Figure 4 Examples of classification into support classes (left) and excavation classes (right)

What is also special for many rock engineering problems is that the decision has to be taken during the ongoing work and it is therefore under time constraints. Examples of such activities are:

- Decisions on rock support at the tunnel excavation face;
- Decisions on the need for grouting before blasting;
- The evaluation of excavation and support procedures in complex ground conditions.

It is quite obvious that the time and the cost needed to obtain better information must be compared with what can be saved by refining the design.

In principle, there are two ways that can be used in order to establish the classes:

- One way is to use classes based on some existing classification system. Better or more correctly pre-defined actions are selected, based on the existing empirical design methods. However, as pointed out in many recent publications, such systems are not perfect and can sometimes lead to the selection of inadequate ground support or an inappropriate design. This will be further discussed in Chapter 5.
- The other way is to develop a specific system tailored for the site in question, based on adequate site information. It is the authors' experiences that, in many cases, this approach will give the optimum design, Nilsen et al. (1999) and Brantmark et al. (1998). The reason for this is logical. Every tunnel project is unique. A tailor-made system can take into account the actual conditions and local construction experience in a more accurate way. This approach has more chance of creating the best solutions than the application of a general system developed to meet every condition worldwide. It also implies that a combination of empirical design rules and refined rock mechanics models can be used, and both can serve as input to the prescribed support classes.

Rock engineering problems may be solved by different means (existing empirical methods, analytical methods, numerical modelling, or observational methods) depending on the situation, see Figures 2 and 5. All these methods are associated with uncertainties related to the problems of ground conditions and project related features. In some cases, experience alone may be adequate. In other cases, when the possible consequences are serious, all the available tools have to be used. This is illustrated in Figure 6.

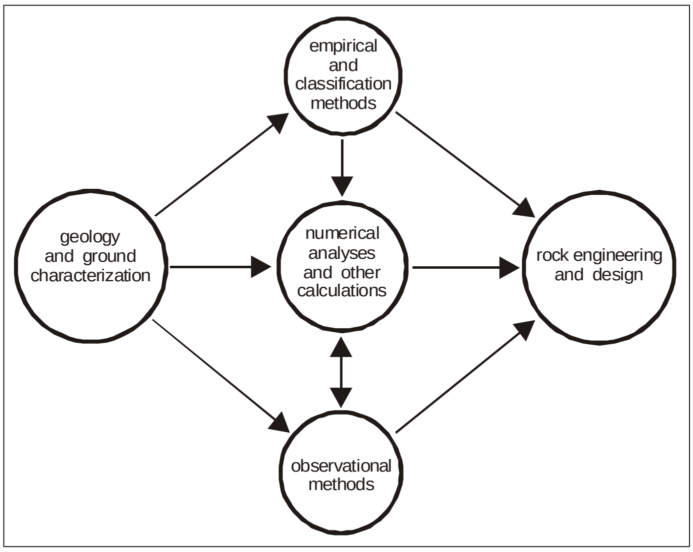

Figure 5 Main principles in the process of ground characterization and rock engineering

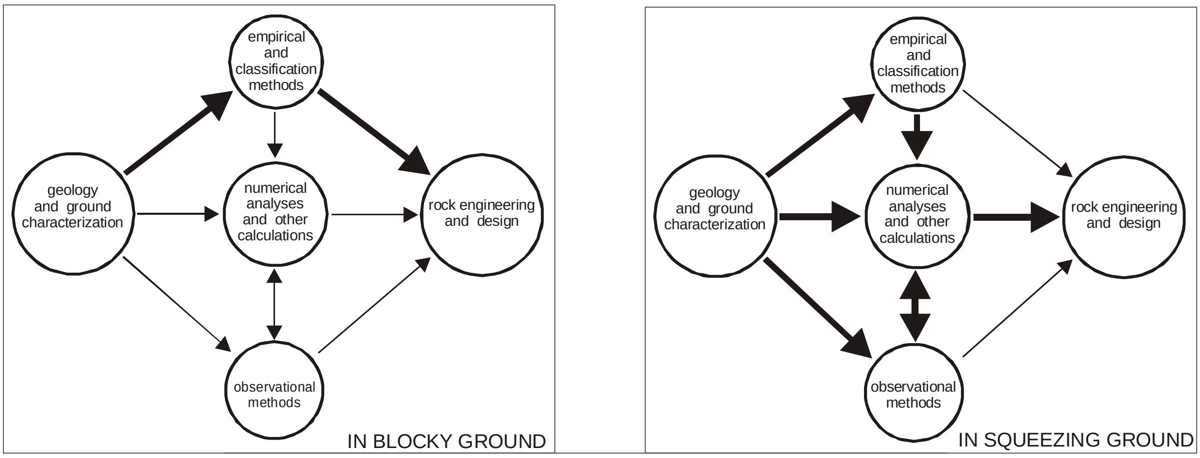

Figure 6 Examples of procedure for block instability (left) and squeezing (right)

The design of an underground project is a result of a long and complex process involving different steps like characterization, description of the project related features, and the processing of the acquired information with different design tools. Many authors have described this, maybe in different ways, with more emphasize on the complexity of the process than the fact that there exist fundamental different opinions on the design procedure, as illustrated in Figure 7.

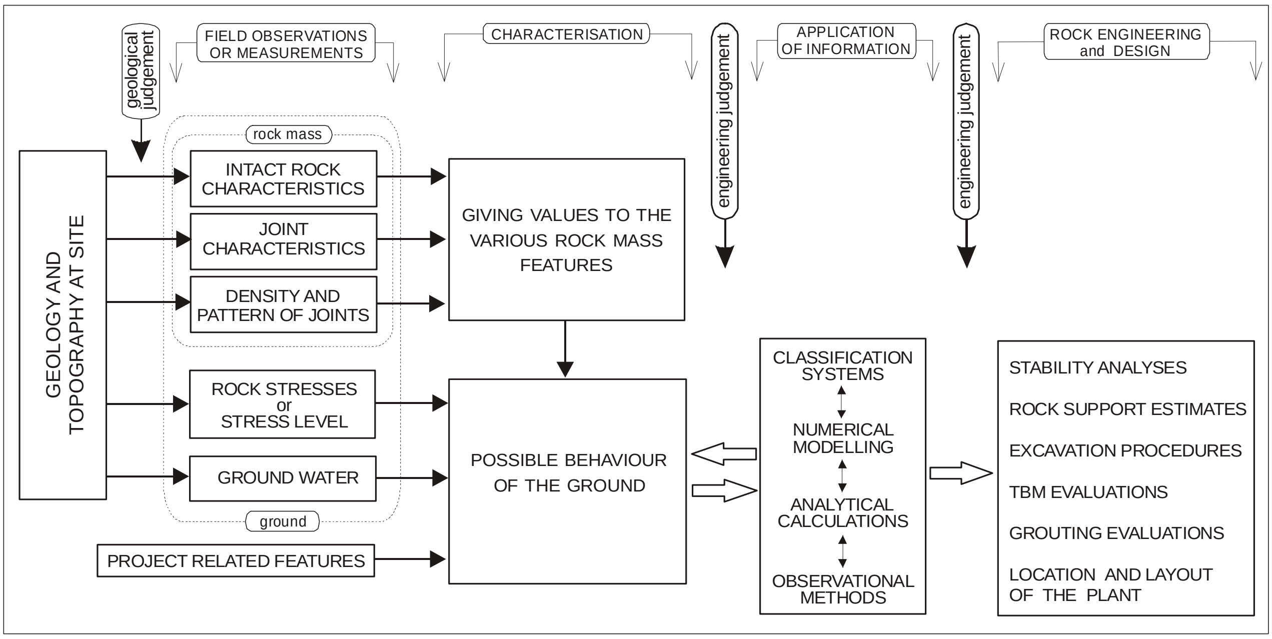

Figure 7 The process of rock engineering based on the principles in Figure 1.

As discussed above, more than one design tool will normally be used for complex underground structures. This implies that it is reasonable to require that a classification system should be structured according to the information from the different design methods used in the engineering process.

The key question is to use a classification system that has an acceptable level of uncertainties. This is the basic question for all designers. In one way or another, every design must evaluate the safety level, and reliability of the design and describe its factor of safety, or probability of failure, or some related parameter. The accuracy of the classification system and the risk for mis-classification must always be evaluated.

As they are empirical methods, it is essential to understand how the use of classification systems is structured and what requirements have to be satisfied. From the most interesting paper of Einstein et al. (1979) on this issue, the following requirements of classifications systems are summarized:

- They should promote economic, yet safe designs.
- They must be correctly calibrated against test cases, and those test cases must be representative of the field of application.
- They should be complete in that all relevant factors are included, yet they must be practical.
- They should have general applicability and robustness to the varieties of use.

In this connection, it is important to recall that Bieniawski (1988) pointed out: *"Rock mass classifications were never intended as the ultimate solution to design problems, but only as a means towards this end. Nor were they intended to replace analytical considerations, field observations and measurements, or engineering judgement. Rock mass classifications were developed to create some order out of chaos in site investigation procedures and to provide desperately needed design aids."*

"Nevertheless, these new 'tools' were so powerful and successful that soon a tendency developed to ignore everything else and use rock mass classifications as the ultimate answer. If this did not work, then rock mass classifications were blamed!"

4.3 Decision analysis

In recent years, a new philosophy has been developed for the use of applied probability in decision-making. The new theory, Bayesian statistical decision theory, provides a mathematical model for making engineering decision in the face of uncertainty (Benjamin and Cornell, 1970). The basic principle is that the consequences of a decision depend on some factor, which is not known with certainty. This factor is called a "state of nature" which has a certain probability to be the true state. The decision-making problem will be formulated so as to choose an action between a set of available alternatives. To every combination of states and actions, the engineer will be able to understand the consequence.

It is also possible to incorporate new information in the decision-making process by a process known as terminal analysis. This type of analysis will give the engineer the possibility of evaluating the benefit of searching for new information (e.g. by further investigations) before the search has been carried out.

Strictly, when based on decision theory, the requirements to solve rock engineering problems are therefore the following:

- The possible states of nature have to be defined.
- The different actions that may be undertaken have to be defined.
- Provided that the true state of nature is known, the accuracy of any action to solving the given problem, must be estimated.
- The probability for any state to be the true state of nature has to be estimated.
- The consequence of different combinations of actions and states of natures has to be estimated.
- It must be possible to take the necessary decision during ongoing work without exceeding time constraints.

The different states of nature correspond to the different possible rock conditions. The different actions correspond to classes of measures to be taken. The accuracy for the design and the probability to be the true state describe the uncertainties, and the corresponding probability of unexpected behaviour or failure.

5 THE SYSTEMS OF TODAY - HOW DO THEY FULFIL THE REQUIREMENTS?

> *"After over a decade of extensive use, rock mass classifications can indeed serve as useful design aids in tunnelling. However, there are a number of pitfalls in using rock mass classifications and these must be understood by potential users."* Bieniawski (1988)

5.1 General

The classification of rock masses continues to be a subject of discussion, as shown by the great number of new proposals that are being made in the literature. As pointed out in many recent publications and government manuals, (e.g. USACE, 1997), the classification systems of today are not perfect, and can sometimes lead to the selection of inadequate ground support.

Rock mass classification systems (or more correctly, rock engineering classification systems) have been developed over the years to describe the rock mass or ground and to formalize an empirical approach to tunnel design. Most of the classification systems were developed from civil engineering case histories. The different classification systems place different emphasis on various engineering geological parameters.

Many systems are developed and used for different purposes. The same rock mass classification system can be used both to describe and to characterise the rock mass and to estimate different design measures by empirical design rules. They are also used to give indicators to rock engineering classifications. Nevertheless, it is important to distinguish their fields of application, either as a part of the process of characterization, or as an empirical method of design (Russo et al., 1998)

Many classification systems have evolved as engineers have attempted to apply their experience of rock mass behaviour to a wider range of engineering problems. In recent years, classification systems have often been used in tandem with analytical and numerical tools. Therefore, there has been a proliferation of work linking classification indexes to material properties, such as modulus of elasticity, rock mass strength, *m* and *s* for the Hoek and Brown failure criterion, etc. The values are then used as input parameters for the numerical models. Consequently, the importance of rock mass classification systems has increased over time (Milne et al., 1998).

As summarized by Riedmüller and Schubert (1999) and discussed in USACE (1997), the major shortcomings of the rock mass classification systems used for design of underground structures include:

- Classification parameters are not well defined or sufficient to select adequate design parameters and rock support;
- Complex properties of a rock mass cannot be satisfactorily described by a single number;
- The same rating can be achieved by various combinations of classification parameters, even though the rock mass behaviour could be different;
- The user is led directly from the geological characterization of the rock mass to a recommended ground support without the consideration of possible failure modes. It is necessary to examine the available rock mass information to determine if there are any applicable failure modes not addressed by the empirical systems. A number of potential modes of failure are not covered by some or all of the empirical methods, and must be considered independently;
- The understanding of the geological setting and features of importance for the underground construction is not seriously evaluated;
- Normally, the use of skilled people experienced in the collection and assessment of data is not specifically required.

The most common classifications systems used worldwide today are the RMR system published by Bieniawski in 1973 and the Q system first described in 1974 by Barton et al. More recently developed systems are the RMi system, developed by Palmström in 1995. These classification systems have a quantitative estimation of the rock mass quality linked with an empirical design rule to estimate adequate rock support measures.

Quantitative rock mass classification systems (such as the RMR, Q, or RMi systems) are most usefully applied during the early phases of design. These methods provide a means to compare quantitatively different cavern layouts or tunnel alignments when only limited rock mass data are available. They also provide a means to communication and to develop construction cost parameters, either for comparative purposes or to develop a construction cost budget, (Hoek, 2002).

The support charts or tables used by the various classification systems to determine rock support are based on experience from numerous underground projects. Being statistically based, a support chart can never replace or accurately represent the ground conditions at site. A main reason for this is, for example, that all the actual geometrical features of discontinuities cannot be included in a support chart. During tunnel construction, application of these rock mass classification systems can, however, be very useful as one way of documenting actual conditions encountered by tunnel and caverns construction.

Summaries of these systems are presented below, together with a discussion of their merits for characterising the rock mass or being used in an empirical design method, or as an indicator in a true classification system. The systems and their use have been described in numerous papers and reports and it has not been feasible to study all this material. The opinion presented below is, therefore, based on a subjective selection, and on our personal experiences from tunnel projects in Scandinavia and around the world.

5.2 The RMR system

Bieniawski (1973 and 1974) published the details of a rock mass classification called the Geomechanics Classification or the Rock Mass Rating (RMR) system. Significant changes have been made over the years with revisions in 1974, 1975, 1976, and 1989; our discussion is based upon the 1989 version of the classification system.

The following six parameters are used to classify a rock mass in the RMR system:

1. Uniaxial compressive strength of rock material;
2. RQD value;
3. Spacing of discontinuities;
4. Condition of discontinuities;
5. Ground water conditions;
6. Orientation of discontinuities.

The rating of each of these parameters are summarised to give a value of RMR. The rating is an outcome of a supervised classification of each parameter. The calculated RMR value may be used to find which of five pre-defined rock mass classes the rock mass belongs to, (going from very good rock to very poor rock),. In this respect, the system can be described as supervised classification of rock mass quality. All parameters are measurable in the field and some of them may also be obtained from borehole data.

In applying this classification system, the rock masses are divided into a number of structural regions. The boundaries of the structural regions usually coincide with major structural features (Bieniawski 1984,1989). However, from the practical point of view, the rating is also related to length of the blasting round or the recently excavated tunnel section.

Bieniawski (1989) published a set of guidelines for estimating the stand-up time, (Lauffer, 1958), and for selecting rock support in tunnels, based on the RMR value. Other authors have modified the system and given guidelines for design especially for mining engineering and for slope stability. However, Bieniawski strongly emphasises that a great deal of judgement is needed in the application of rock mass classification to support design.

The RMR value has also been used to estimate rock mass properties. Bieniawski (1984, 1989) and Serafim and Pereira (1983) have given a relationship between the RMR and the rock mass deformation modulus. The RMR value is also used as one way to estimate the *m* and *s* factors in the Hoek Brown failure criterion (Wood, 1991; Hoek, 1994; Hoek and Brown, 1998) as well as the GSI value to evaluate the rock mass strength. These give, however, only empirical relations and have nothing to do with rock engineering classification in its true sense.

The experiences of the authors from using the system indicates that it works well to classify the rock mass quality, since it is relatively well defined and the rating for each parameter can be estimated with acceptable precision. The relatively small database makes the system less applicable to be used as an empirical design method for rock support.

The RMR system has been used in many tunnel projects as one of the indicators to define the support or excavation classes. However, RMR cannot be used as the only indicator, especially when rock stresses or time dependent rock properties are of importance for the rock engineering issue.

5.3 The Q system

On the basis of an evaluation of a large number of case histories of tunnel projects, Barton et al (1974) of the Norwegian Geotechnical Institute (NGI) proposed a Tunnelling Quality Index (Q) as a classification system for estimating rock support in tunnels. It is a quantitative classification system based on a numerical assessment of the rock mass quality. Later, Barton et al. have published several papers on the Q system aiming at extending its applications. Some of these use additional adjustments of the Q system.

The numerical value of the index Q is defined by six parameters and the following equation:

$$Q = RQD/Jn \times Jr/Ja \times Jw/SRF$$

where

- RQD is the rock quality designation
- Jn is the joint set number
- Jr is the joint roughness number
- Ja is the joint alteration number
- Jw is the joint water reduction factor
- SRF is the stress reduction factor

In explaining the system and the use of the parameters to determine the value of Q, Barton et al. have given the following explanation:

- The first quotient (RQD/Jn) represents roughly the block size of the rock mass.
- The second quotient (Jr/Ja) describes the frictional characteristics of the rock mass.
- The third quotient (Jw/SRF) represents the active stress situation. This third quotient is the most complicated empirical factor and has been debated in several papers and workshops. It should be given special attention, as it represents 4 groups of rock masses: stress influence in brittle blocky and massive ground, stress influence in deformable (ductile) rock masses, weakness zones, and swelling rock.

The Q system can be used as supervised classification of rock mass quality. Nine different rock mass quality classes are defined, ranging from “exceptionally poor” to “exceptionally good”.

The Q-system is normally used as an empirical design method for rock support. Together with the ratio between the span or height of the opening and an excavation support ratio (ESR), the Q value defines the rock support. The accuracy of the estimation of rock support is very difficult to evaluate. It is the authors' experience from using the system that, especially in the poorer rock class (Q less than 1) the system may give erroneous design. The true nature of the rock mass that is essential for the determination of the support measures (e.g. swelling, squeezing or popping ground) is not explicitly considered in the Q system. Nor are such issues as the timing for installation and the need for an invert strut. For the conditions in faults and weakness zones, the supports should be checked or designed by complimentary engineering methods.

In fractured ground, the orientation of the joints is an essential parameter. In such cases, it is very important to follow the guideline given by Barton et al. (1974) that the parameters Jr and Ja should be related to the joint surface most likely to allow failure to initiate. From the rock mechanics point of view, it is obvious that even such a simple load case as block instability is much more complicated than can be given by a single number like a Q value.

Of course, the Q system can be used as an indicator for rock support or other types of rock engineering classification. The value is, however, normally used as the only indicator to define the classes in question. The authors strongly argue against such use of an engineering classification system, since it may be too rigid and will not allow other types of observations to be taken into account.

Grimstad and Barton (1993) have also presented an equation to use the Q value to estimate the rock mass deformation modulus (for values of $Q > 1$). The Q value is also used as one way to estimate the *m* and *s* factors in the Hoek Brown failure criterion (Hoek, 1983; Hoek and Brown, 1988). In this respect, it is only an empirical relationship and has nothing to do with engineering classification.

5.4 The RMi system

The rock mass index, RMi, is a volumetric parameter indicating the approximate uniaxial compressive strength of a rock mass. The system was first presented by Palmström (1995) and has been further developed and presented in several different papers. It makes use of the uniaxial compressive strength of intact rock (σ_c) and the reducing effect of the joints penetrating the rock (JP) given as:

RMi = $\sigma_c \times$ JP for jointed rock masses

RMi = $\sigma_c \times f_\sigma$ for massive rock having block size larger than approx. 5 m^3 (where $f_\sigma >$ JP)

The jointing parameter (JP) is by empirical relations related to the joint condition factor, jC, and the block volume, Vb. The joint condition, jC, can be estimated by:

– the joint roughness, jR;
– the joint alteration, jA; and
– the joint size, jL.

The massivity parameter, f_σ, represents the scale effect of the uniaxial compressive strength (which for intact rock samples or massive rock has a value of approximately $f_\sigma \approx 0.5$).

The RMi system has some features similar to those of the Q-system. Thus, jR and jA are almost the same as Jr and Ja in the Q-system. The connection between the different inputs parameters applied in the RMi is shown in Figure 8.

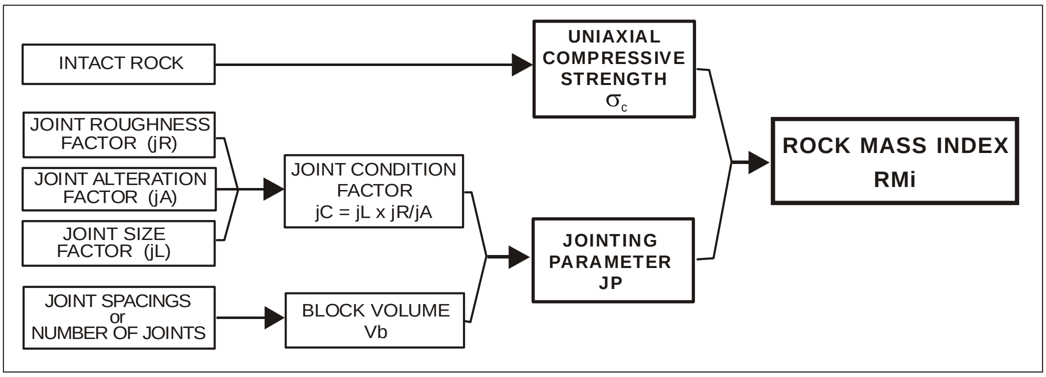

Figure 8. The input parameters to RMi (from Palmström, 1996)

The different input parameters can be determined by commonly used measurements and mapping and from empirical relationships presented by Palmström in his work. It requires more calculation than the RMR and the Q system, but spreadsheets can be used from which RMi values can be found directly.

Based on a characterisation of the rock mass by RMi combined with the geometrical features of the opening and ground factors like rock stresses, different rock engineering issues such as relevant rock support can be estimated using support charts (Palmström, 1996). The charts have been developed from experience of more than 25 different projects and locations as well as personal experience from numerous underground constructions in hard rock.

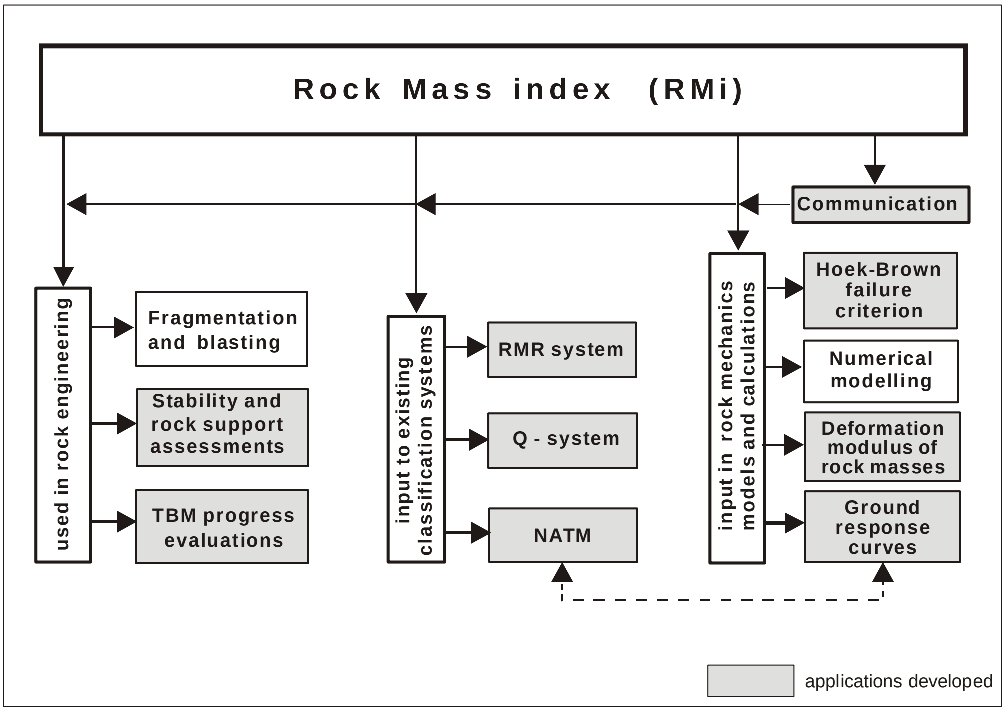

Figure 9 Possible applications of RMi (from Palmström, 1996)

As shown in Figure 9, the RMi value can be applied as input to other rock engineering methods, such as numerical modelling, the Hoek-Brown failure criterion for rock masses, and to estimate the deformation modulus for rock masses (Palmström and Singh, 2001).

The RMi system can be characterised as a typical empirical design method and is not a classification in its true sense. However, Palmström has given five different strength classes of rock masses from very low to very high and, in this respect, it can be used as a supervised classification for rock mass strength.

The system applies best to massive and jointed rock masses where the joints in the various sets have similar properties. It may also be used as a first check for support in faults and weakness zones, but its limitations here are pointed out by Palmström (1995). For special ground conditions like swelling, squeezing, ravelling ground, and weakness zones (fault zones etc.) the rock support should be evaluated separately for each and every case. Other features to be separately assessed are connected to project specific requirements such as the life-time required and safety.

Like all the other empirical design methods, it is not possible to evaluate the accuracy of the system. The factor of safety or the probability of failure for a given set of indicators cannot be evaluated.

5.5 The GSI system

The geological strength index, GSI, introduced by Hoek (1994), and Hoek et al. (1998) provides a system for estimating the reduction in rock mass strength for different geological conditions as identified by field observations. The rock mass characterisation is straightforward and based on the visual impression of the rock structure, in terms of blockiness, and the surface condition of the discontinuities indicated by joint roughness and alteration. The combination of these two parameters provides a practical basis for describing a wide range of rock mass types. Note that there is no input for the strength of the rock material in the GSI.

Visual determination of GSI parameters represents the return to quality descriptions instead of advancing quantitative input data as in RMR, Q and RMi systems. GSI was found mainly useful for weaker rock masses with RMR < 20.

As GSI is used for estimating input parameters (strength), it is only an empirical relation and has nothing to do with rock engineering classification.

5.6 The NATM

The new Austrian tunnelling method was developed by Rabcewicz (1964/65) and Pacher (1975). In practice, the NATM involves the whole sequence of rock tunnelling aspects from investigation during design, engineering and contracting, to construction and monitoring as described by Brown (1981). It is important to notice that the NATM has been developed for tunnelling in weak or squeezing ground. The NATM has been applied successfully in a large number of tunnels in many parts of the world, some of which were constructed in poor and difficult ground conditions. Considerable cost savings have often been gained when compared to traditional tunnelling, as well as reduced construction time. The NATM has, however, also experienced many unpleasant rock falls and some tunnel collapses.

In Austrian tunnelling practice, the ground is described behaviourally and allocated a ground class in the field, based on field observations. Construction and support can be estimated from this classification. The qualitative ground description used is associated, rather inconsistently, with excavation techniques, together with principles and timing of standard support requirements. Therefore, the NATM is not a rock engineering classification system, but a construction strategy (in German "bauweise") containing several methods for assessing the amount and timing of rock support, construction steps etc. (Jodl, 1995).

6 CONCLUSIONS AND RECOMMENDATIONS

Several papers have been published on the use and misuse of classification systems. Some of these are Einstein et al. (1979), Bieniawski, Z.T. (1988), Milne et al. (1998), Hoek (1999), and Riedmuller and Schubert (1999) as discussed above.

The primary object of all rock mass classification systems is to quantify different engineering properties of, or related to, the rock mass, based on past experience. One important use of the classification system today has therefore been to serve as a kind of checklist.

Three different types of output can be distinguished from the rock mass classification systems discussed in this paper.

1. Characterisation of the rock mass expressed as overall rock mass quality, incorporating the combined effects of different geological parameters and their relative importance for the overall condition of a rock mass. This enables the comparison of rock mass conditions throughout the site and delineation of regions of the rock mass from 'very good' to 'very poor', thus providing a map of rock mass quality boundaries.
2. Empirical design with guidelines for tunnel support compatible with rock mass quality and the method of excavation. Traditionally, this is often seen as the major benefit from the use of rock mass classification systems.
3. Estimates of rock mass properties. Rock mass characterisation expressed as an overall rock mass quality has been found useful for estimating the in situ modulus of rock mass deformability and the rock mass strength to be used in different types of design calculations.

However, none of the discussed rock mass classification systems is a “classification” in the true sense. They are all, as a matter of fact, empirical design methods based on characterization of rock masses. The use of the word classification is therefore misleading.

It is interesting to notice the conclusion presented by Einstein et al. (1979) that the accuracy of the existing empirical design methods is not established. The methods probably overestimate the support requirements and the relationships to the ground support pressure are often not very accurate.

In numerous cases, it has been necessary to adapt an existing classification system to the actual condition and problem, and calibrate the existing rock mass classification systems against the experience gained from a specific project. This means that tailor-made supervised classification have been developed, where the index of the rock mass quality derived from the existing classification system has been an indicator to evaluate the support class. In many cases, the index has been used as the only indicator. This has created contractual problems when unforeseen geological conditions have been encountered, and where the system has not been applicable. Typical conditions that are not covered are swelling, squeezing, ravelling, or popping ground.

None of the rock mass classification systems studied is able to incorporate other types of information, such as results from deformation measurements. This is a great disadvantage as, especially for complex underground structures, more than one design tool is normally used and also will be followed up during construction. Guideline for observational systems with alarm thresholds as discussed by Olsson and Stille (2002) may be used in order to form a system for classification that incorporates deformation measurements or visual inspections.

In the early stages of a project, the existing quantitative rock mass classification systems (empirical design methods) can be applied as a useful tool to establish a preliminary design. At least two systems should be applied (Bieniawski, 1984, 1989). They are not recommended for use in detailed and final design, especially for complex underground openings. For this purpose, they need to be further developed.

Classification systems are unreliable for rock support determinations during construction, as local geometric and geological features may override the rock mass quality defined by the classification system. Restrictions on their use here is also pointed out by Bieniawski (1997).

The main core of the classification systems is the assessment of the rock mass quality that, preferably, can be used as one of the indicators for a supervised classification of a rock engineering case.

The following requirements can be put forward to build up such a system to be able to adequately solve rock engineering problems:

- Use a supervised classification adapted to the specific project.
- The reliability of the classes to handle the given rock engineering problem must be estimated.
- The classes must be exhaustive and mutually exclusive.
- Establish the principles of the division into classes based on suitable indicators.
- The indicators should be related to the different tools used for the design.
- The principles of division into classes must be so flexible that additional indicators can be incorporated.
- The principles of division into classes have to be updated to take account of experiences gained during the construction.
- The uncertainties or quality of the indicators must be established so that the probability of mis-classification can be estimated.
- The system should be practical and robust, and give an economic and safe design.

Our conclusion is that none of the existing classification systems fulfils the requirements mentioned above for a true classification system for rock engineering problems. The classification systems, or better the empirical design methods, cannot be used as the principles of division for a true system without further development, since it is not possible to define the accuracy of the methods. They can, however, be used as one of the indicators defined by the principles of division. The authors strongly argue against using the existing classification system as the only indicator to define the rock support or other rock engineering items.

We want also to emphasise that tools like decision theory can be very useful in order to select the most suitable supervised classification for a specific rock engineering problem and project, and also to determine the need for further investigation.

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