Excerpt from Palmström A.: RMi – a rock mass characterization system for rock engineering purposes. PhD thesis, Oslo University, Norway, 1995, 400 p.

COLLECTION OF GEO-DATA - LIMITATIONS AND UNCERTAINTIES

by Arild Palmström, Norconsult, Norway

SUMMARY

As most of the geo-data collection is based on observations **-** either on outcrops, on tunnel surfaces or on drill cores **-** it is important to know whether the condition of the rock mass observed is representative.

As a result of possible errors, many of the measurements and tests used in rock mechanics, while useful in identifying rock behaviour characteristics and in empirical comparisons of rock behaviour, have limited use in design.

The great spatial variability and great volumes involved result in that only a limited number of measurements can be made. The subsurface must, therefore, be described by a limited number of imprecisely known parameters. Interpretations and extrapolations that are made to work out the geological setting may introduce considerable uncertainties. Also, the fact that horizontal and other features, which do not outcrop, may be overlooked, adds to these errors.

> *"The geotechnical engineer should apply theory and experimentation but temper them by putting them into the context of the uncertainty of nature. Judgement enters through engineering geology."*
> Karl Terzaghi, 1961

1. INTRODUCTION

In contrast to most other materials used for construction purposes, judgement of the quality of the rock mass is based on observations rather than test results. The large volume of the material involved, and the "given properties" of the material, in addition to the lack of access to "see" the actual material involved, cause great challenges in the execution of investigations, interpretation of the results as well as characterization of the complex material called rock mass. Thus, there are no clearly established guidelines when attempting to define the extent or scope of methods to be applied in collection of relevant geo-data for a project (Merritt and Baecher, 1981). The investigations and procedures may vary according to:

- the nature of the project,
- the complexity of the geology,
- the background of the engineering company, and
- the experience of the individual geologists or rock mechanics engineers involved.

The fact that geological formations are spatially variable, and that only a limited number of measurements or observations can be made, has important consequences. The principal one is that:

- the subsurface must be described and characterized by a limited number of parameters, and
- that the values of these parameters are imprecisely known.

Further, it is important to accept the fact that:

- a geotechnical parameter is expressed by a range, and
- the actual range may be greater than that observed.

Thus, in most cases it is recommended not to make too large an effort to obtain accurate values of the various parameters. Often it is better to obtain a wider statistical material (Einstein and Baecher, 1982).

Almost all types of geo-data collection require some degree of extrapolation, with projection from the known to the unknown. How well this extrapolation is performed has obvious practical implications, since the method(s) used often can influence the amount of necessary subsurface exploration. Some principles of extrapolation are shown in Figures 1 and 2.

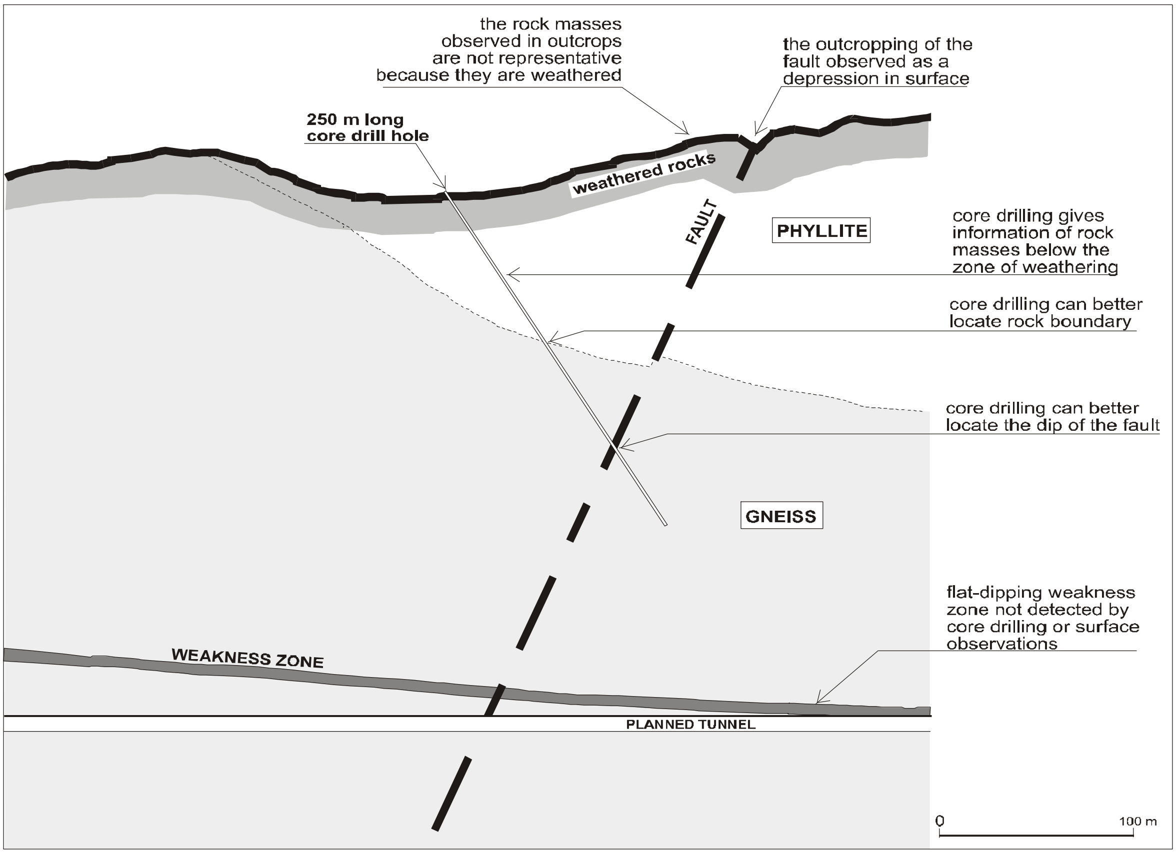

Figure 1 *For deep tunnels the main source of geological information before construction is from surface observations in outcrops. Core drillings combined with the surface information can improve the accuracy of the geological interpretation and yield additional information of the rock mass condition. But as no information is available of the conditions where the tunnel is planned, unexpected rock mass conditions may be encountered (from Palmström, 1995).*

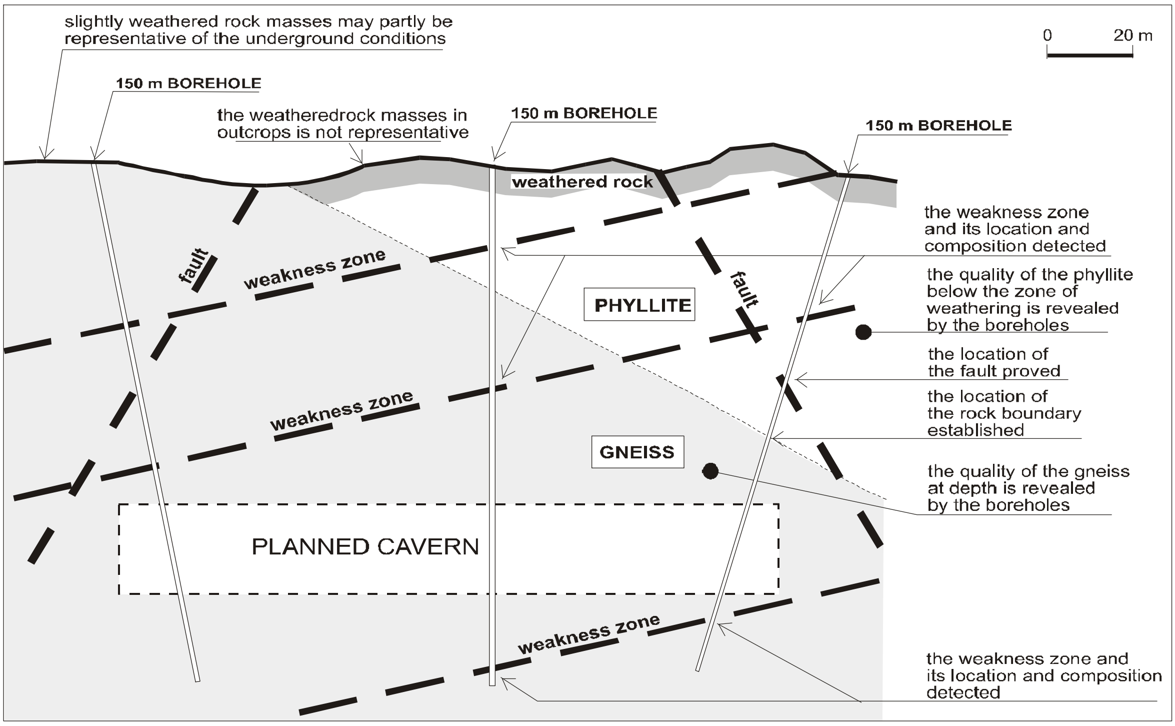

Figure 2 *For shallow caverns and tunnels the rock mass conditions can be found from core drillings penetrating the planned location. Surface mapping and geophysical measurements (refraction seismic) may further improve the quality of geo-data (from Palmström, 1995).*

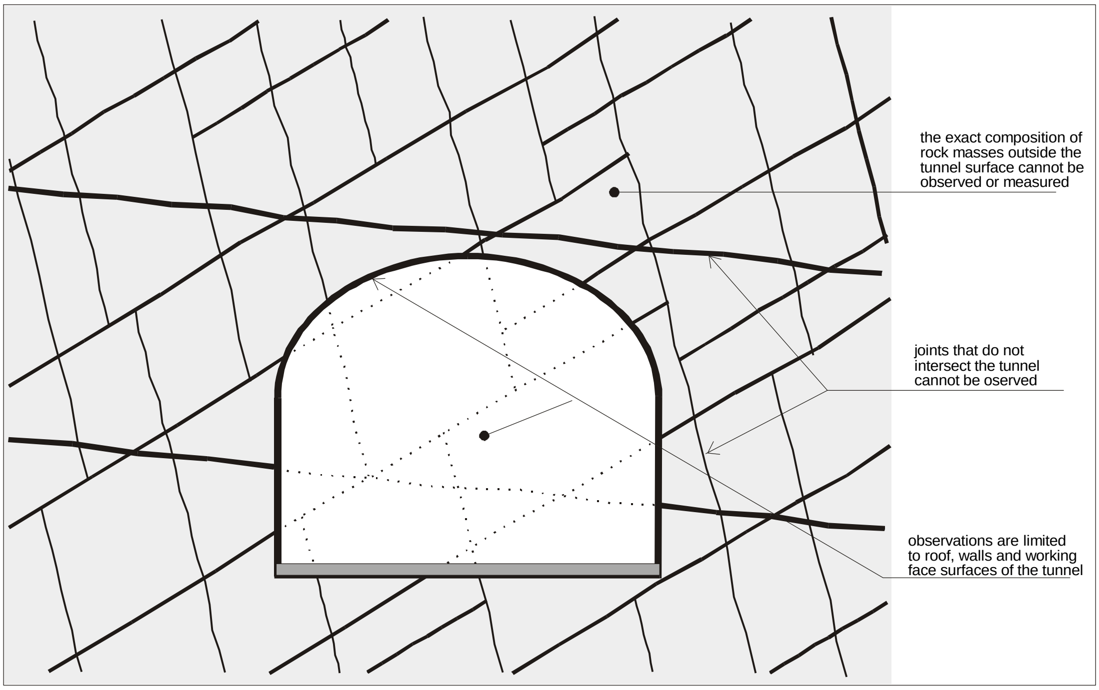

Figure 3 In tunnels and in man made cuttings the 'real' rock masses can be observed in the excavated surfaces. The rock mass behaviour is often governed by the conditions in the volumes surrounding the tunnel. It is not possible to observe or measure the properties of the rock mass exactly (from Palmström, 1995).

The actual rock mass conditions are not known until they are encountered in the tunnel. But still it is not possible to determine the exact nature of the rock mass involved as parts of these are located outside the tunnel surface, as indicated in Figure 3.

2. SOME METHODS USED IN GEO-DATA COLLECTION

The methods for the collection of geological data have not changed very much over the past 20 years and there is still no acceptable substitute for the field mapping and core logging carried out by an experienced engineering geologist (Hoek, 1986). However, only a limited amount of testing is likely, and the main investigation is restricted to field observations. The reason is often the high cost of sub-surface exploration by core drilling or by the excavation of trial shafts and adits.

The field observations are mainly carried out in the following types of locations:

- outcrops or cuttings;
- pilot tunnels, adits or shafts made before construction; and
- excavated tunnels/shafts/caverns.

The various kinds of observations and tests used in description, characterization, tests and measurements of rock mass features are:

- In outcrop and surface observations, in the form of:
  - geological mapping;
  - engineering geological mapping; and joint surveying.
- In bore holes, performed as:
  - core logging of joint density
- Geophysical methods
- Laboratory tests of geological and mechanical properties of rock samples and limited volumes of rock masses, some of the tests are:
  - compressive strength;
  - shear strength;

  - elastic constants; as well as
  - density, porosity, anisotropy, and
  - durability.
- Various field investigations and tests, such as:
  - shear strength measurements of joints:
  - modulus measurements of rock masses;
  - in situ stress measurements;
  - permeability tests.

For various reasons the simple observations made on the surface provide the most reliable data of rock mass parameters (Bieniawski, 1984).

2.1 Engineering geological mapping and joint surveys

These are mainly made during the planning stage of a rock construction to provide more detailed information on the jointing. They can also be conducted for special engineering purposes, such as for slope stability analyses in open cast mines, rock slopes, cuttings or valley sides.

Some form of *statistical* approach can be beneficial in such surveys because of the inherent stochastic nature of joints and because complete information concerning their geometry can never be obtained. Hudson and Priest (1979) find that the ability to express block lengths, areas and volumes by statistical distribution functions will be of great assistance in the characterization of rock mass geometry.

In common joint surveys, Einstein and Baecher (1983) use three geometric properties, which can be described statistically. These, which might be recorded in a number of equivalent measures, involve:

- Density of joints (joint spacings, numbers per rock volume or per outcrop area).
- Size (trace lengths, joint surface areas or radii).
- Planar orientation (strike or dip direction and dip).

Also joint waviness (planarity) and joint surface smoothness show variations, whichshould be included in a statistical description.

2.2 Core drilling

The information from drill cores can greatly improve the results from outcrop mapping, and can also preferably be used to improve knowledge of the underground when combined with geophysical measurements (Hoek and Brown, 1980; Hoek, 1981).

The weighted jointing method for logging of drill cores, where the intersections between the core and the joints are included in the measurement, represents improved core measurement.

Considering the very high cost of good quality core recovery, Hoek and Brown (1980) comment that it is invariably worth spending a little more to provide for good routine core examination and carefully prepared reports with high quality photographs of the cores before they are placed in storage.

Table 1 Information on characteristic rock mass parameters obtained from various types of data collection (from Palmström, 1995).

ROCK MASS PARAMETER	DATA COLLECTED FROM				
	Drill cores	Adits	Underground openings	Outcrops	Refraction seismic profiles
Rocks					
- distribution of rocks	x	x	x	x / (x)	-
- sample for strength tests	x	x	x	x / (x)	-
Joints and jointing					
- joint spacing	(x)	x	x	x	(x)
- joint length	-	(x)	(x) / x	x / (x)	-
- orientation	-	x	x	x	-
- waviness	-	x	x	x	-
- smoothness	(x)	x	x	x / (x)	-
- filling or coating	(x) / x	x	x	(x) / -	-
Faults and weakness zones					
- persistence	-	-	-	(x)	-
- orientation	-	(x)	x	(x)	-
- thickness of zone	-	(x) / x	x	(x) / -	(x)
- gouge material	(x)	x	x	-	-

here is: x parameter or task can be measured
(x) parameter or task may partly or sometimes be measured
\- not possible to measure the parameter or task

3. UNCERTAINTIES AND ERRORS IN GEO-DATA COLLECTION

> *"In thinking about sources of uncertainty in engineering geology, one is left with the fact that uncertainty is inevitable. One attempts to reduce it as much as possible, but it must ultimately be faced. It is a well recognized part of life for the engineer. The question is not whether to deal with uncertainty, but how?"* Herbert H. Einstein and Gregory B. Baecher (1982)

The following expressions need an explanation:

Uncertainty or lack of absolute sureness in geology means that the observations, measurements, calculations and evaluations made are not reliable. The consequences are that the use of geological data often may involve some kind of guesswork.

Error is defined as the difference between computed or estimated result and the actual value.

A *bias* is the difference between the estimated value and the true value of a statistic obtained by random sampling. For example, R. Terzaghi (1965) pointed out that joints sub-parallel to an outcrop have less chance of being sampled than joints perpendicular to an outcrop. This is a bias in sampling for orientation.

Einstein and Baecher (1982) have defined three main sources for uncertainties and errors in engineering geology and rock mechanics:

1. Innate, spatial variability of geological formations, where wrongly made interpretations of geological setting may be a significant consequence.
2. Errors introduced in measuring and estimating engineering properties, often related to sampling and measurements.
3. Inaccuracies caused by modelling physical behaviour, including incorrect type of calculations or models.

In any engineering study, one can never know what has been left out of an analysis. Thus, in addition to the three major uncertainties above, there is also uncertainty due to *omissions*. The real world has variations and properties that can never entirely be included in a characterization or an analysis. According to Einstein and Baecher (1982) most of the major failures of constructed facilities have been attributed to omissions.

3.1 Measurement errors

Farmer and Kemeny (1992) show that, apart from a few simple physical property tests, virtually none of the methods used in rock testing give reliable data. The main reason for inadequacy in test results - which is accepted in most engineering design in rock - can be explained by the complex and variable composition and structure of rocks and rock masses.

Another significant measurement error is associated with the angular measurement of dip and strike. This error varies with the inclination of the joint, increasing as the joint tends to be horizontal. For flat-lying structures of the order of 5 - 10^o, where the horizontal line of projection is extremely limited, such as for joint in a tunnel wall, Robertson (1970) has experienced that the measured strike may vary as much as ± 20^o. For attitude measurements of planar features, Friedman (1964) estimates accuracy of ± 1^o for dips greater than 70^o and ± 3^o for inclinations of 30 - 70^o. The latter estimates may apply to mapping of large surface outcrops, but not to observations of limited dimensions such as in tunnels.
Ewan et al. (1983) reports from an interesting investigation carried out in the Kielder aqueduct tunnels, UK, to see the reproducibility of joint spacing and orientation measurements:

> Three 10 m long scanlines were set up in each of the three rock types: sandstone, mudstone and limestone. On each scanline 6 experienced observers recorded the position and the orientation of each joint (less than 15 m long), see Figure 4.

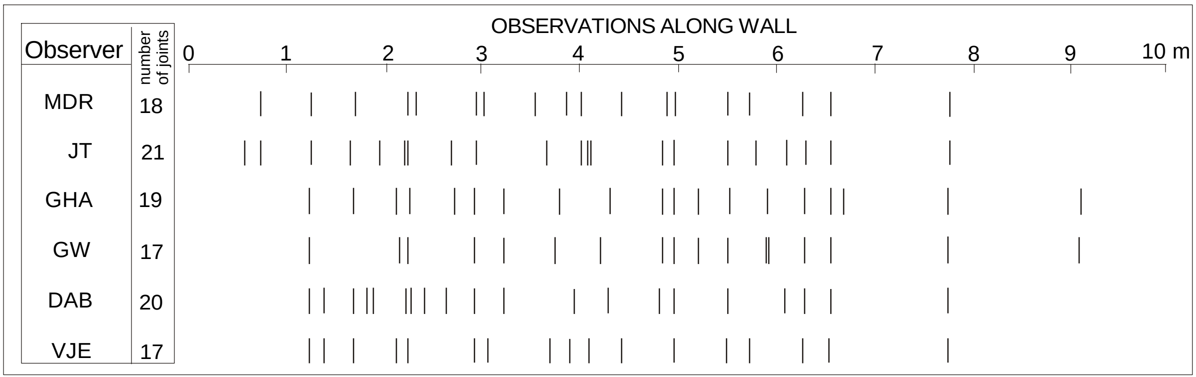

Figure 4 Position of joints recorded by different observers on one of the scanlines (modified from Ewan et al., 1983)

By comparing the results of the measurements carried out by the 6 persons it was found that:

- The variation in the number of joints recorded by different observers along any one scanline varied considerably. The ratio between the highest and lowest number of joints recorded was as high as 3.8 , but with a mean of about 2. (The maximum number of joints along a scanline was 37.)
- The average maximum error in measurement of joint orientation was ±10^o for dip direction and ±5^o for dip angle.

The fact that different observers did not identify joints at the same position underlines the difficulty of interpretation of joints and jointing.

Piteau (1973) mentions that since many joints are highly undulating and the scale of the tunnel or observation area often is much smaller than that of the joint, measurements of both strike and dip may be extremely erroneous, depending where the joint is measured.

A more serious error may come in mapping of joints in outcrops exposed to the effect of weathering. Extrapolating data from weathered outcrops should, therefore, be done carefully.

In addition to the errors mentioned above, significant errors may be introduced by the characterizations caused by poor definitions and/or personal interpretations.

A complete description of joints is difficult because of their three-dimensional nature and their limited exposure in outcrops, borings or tunnels. According to Dershowitz and Einstein (1988), the ideal characterization of jointing would involve the specific description of each joint in the rock mass, exactly defining its position and geometric and mechanical properties. This is not possible for a number of reasons, among others:

1. The visible parts of joints are limited, for instance to joint traces only, and thus prevent complete observation.
2. Joints at a distance from the exposed rock surfaces cannot be directly observed.
3. Direct (visual or contact measurements) and indirect (geophysical) observations have limited accuracy.

For these reasons joints in the rock mass are usually described as an assemblage rather than individually. The assemblage has a stochastic character in that joint characteristics vary in space.

Joints show great variation in properties and some of the most significant errors due to selection of joints to be characterized are according to Robertson (1970):

- Small joints are often disregarded.
- Very large fracture surfaces may be measured more than once.
- Joints almost parallel to the foliation or bedding may be overlooked.

Baecher and Lanney (1978) have confirmed similar trends from their studies.

3.2 Model uncertainties

Models used in assessments of rock mass behaviour are mainly based on theory and/or empirical relations. As they are simplifications of reality, modelling errors are introduced. Modelling errors are caused by errors in the theory assumed to apply to physical processes, boundaries and initial conditions, which must be chosen, errors introduced by numerical or mathematical approximations, and important factors left out of the model. Sometimes, of course, modelling errors in predicting engineering performance and modelling errors in estimating material properties, partially compensate (Einstein and Baecher, 1982).

4. SUMMING UP

> *"I am more and more amazed about the blind optimism with which the younger generation invades this field, without paying attention to the inevitable uncertainties in the data on which their theoretical reasoning is based and without making serious attempts to evaluate the resulting errors."* Karl Terzaghi (in his latest years)

From the foregoing it has been found that the following features may cause uncertainties and errors and hence reduced quality of rock mass classification:

- The geological interpretation, on which the characterizations are based.
- The spatial occurrence, variations and large volume of the material (i.e. rock masses) involved in a rock construction.
- How the investigations are performed.
- Uncertainties connected to the joints measured, as they may only be a portion of the joints exposed which are considered to be representative of the joints within the entire rock mass.
- Outcrops or surfaces, where they occur, may not be representative due to weathering.
- In excavated surfaces and in drill cores it may be difficult to distinguish between natural and artificially induced discontinuities.
- Limitations in drill core logging: soft gouge is lost during core recovery and information relating to the waviness and the continuity of joints is minimal.

- The way the description is performed or the quality of the characterization made of the various parameters in rock masses. As most of the input parameters in rock engineering and rock mechanics are found from observations, additional errors may be introduced from poorly defined descriptions.

All these aspects have important consequences in the application of geo-data in rock mechanics, rock engineering, and construction design. The main conclusions are therefore:

1. Although extensive field investigation and good quality descriptions will enable the engineering geologist to predict the behaviour of a tunnel more accurately, it cannot remove the risk of encountering unexpected features.
2. A good quality characterization of the rock mass will, however, in all cases, except for wrong or incorrect interpretations, improve the quality of the geological input data to be applied in evaluation, assessment or calculations and hence lead to better designs.
3. The methods, effort and costs of collecting geo-data should be balanced against the probable uncertainties and errors.

5. REFERENCES

Baecher G.S. and Lanney N.A. (1978): Trace length biases in joint surveys.
19th US Symp. on Rock Mechanics, Stateline, Nevada, pp. 56-65.

Bieniawski Z.T. (1984): Rock mechanics design in mining and tunneling.
A.A. Balkema, Rotterdam, 272 pp.

Dershowitz W.S., Einstein H.H. (1988): Characterizing rock joint geometry with joint system models.
Rock Mech. and Rock Engn., Vol 21, 1988, pp 21 - 51.

Einstein H.H. and Baecher G.S. (1982): Probabilistic and statistical methods in engineering geology.
1. Problem statement and introduction to solution.
Rock Mechanics, Supp. 12, pp. 47-61.

Einstein H.H. and Baecher G.B. (1983): Probabilistic and statistical methods in engineering geology.
Rock Mechanics, Vol. , pp 3972.

Ewan V.J., West G., Temporal J. (1983): Variation in measuring rock joints for tunnelling.
Tunnels & Tunnelling, April 1983, pp 15 -18.

Farmer I.W. and Kemeny J.M. (1992): Deficiencies in rock test data.
Proc. Int. Conf. Eurock '92, Thomas Telford, London, pp. 298-303.

Hoek E. and Brown E.T. (1980): Underground excavations in rock.
Institution of Mining and Metallurgy, London 1980, 527 pp.

Hoek E.: (1981): Geotechnical design of large openings at depth.
Rapid Exc. & Tunn. Conf. AIME 1981.

Hoek E.(1986): Practical rock mechanics - development over the past 25 years
Keynote address delivered 24.2.1986

Hudson J.A., Priest S.D. (1979): Discontinuities and rock mass geometry.
Int. J. Rock Mech. Min. Sci & Geomech. Abstr., Vol 16, 1979, pp 339 - 362.

Merritt A.H. and Baecher G.B. (1981): Site characterization in rock engineering.

22nd U.S. Symp. on Rock Mechanics, pp. 49-66

Piteau D.R. (1973): Characterizing and extrapolating rock joint properties in engineering practice.
Rock Mechanics, Suppl. 2, pp. 5-31.

Robertson A.MacG. (1970): The interpretation of geological factors for use in slope theory.
Proc.Symp. Planning Open Pit Mines, Johannesburg, South Africa, 1970. pp. 55-71.

Terzaghi R. (1965): Sources of error in joint surveys.
Geotechnique, Vol 15, 1965, pp 287-304.