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

Chapter 2

ROCK MASSES AS CONSTRUCTION MATERIALS

> *"Rock masses are so variable in nature that the chance for ever finding a common set of parameters and a common set of constitutive equations valid for all rock masses is quite remote."*
> Tor L. Brekke and Terry R. Howard, 1972

A rock mass is a material quite different from other structural materials used in civil engineering. It is heterogeneous and quite often discontinuous, but is one of the materials in the earth's crust, which is most used in man's construction. Ideally, a rock mass is composed of a system of rock blocks and fragments separated by discontinuities forming a material in which all elements behave in mutual dependence as a unit (Matula and Holzer, 1978). The material is characterized by shape and dimensions of rock blocks and fragments, by their mutual arrangement within the rock mass, as well as by joint characteristics such as joint wall conditions and possible filling (see Fig. 2-1).

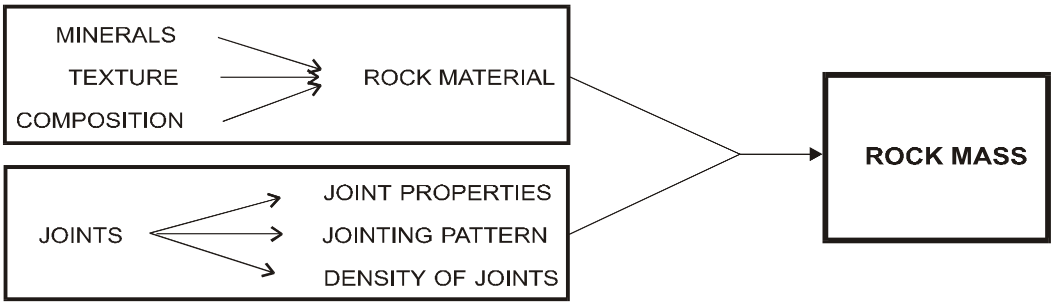

Fig. 2-1 The main features constituting a rock mass

The complicated structure of the rock mass with its defects and inhomogeneities and the wide range of its applications cause challenges and problems in rock engineering and construction which often involve considerations that are of relatively little or no concern in most other branches of engineering. One of these challenges is, according to Einstein and Baecher (1982), the uncertainties about geological conditions and geotechnical parameters. This is perhaps one of the most distinctive features of engineering geology compared to other engineering fields, therefore 'engineering judgement', adaptable design approaches, and other procedures for dealing with uncertainty or hedging against it have been taken into use.

Important in all rock mechanics, rock engineering and design are the quality of the geo-data that form the basis for the calculations and estimates made. This quality depends on two main features.

1. The understanding and interpretation of the geological setting of the area of interest.
2. The way the (known) rock mass at the site is described or measured.

The <u>first</u> feature is important mainly in the pre-construction phase and is a result of the geological understanding based on field investigations and the experienced interpretation of available results. To a great extent this is often wholly dependent on the skill of the geologist(s) who decide how the investigations should be done and how the geo-data should be combined. Thus, this process can in many instances be said to be more an "art" than a science. The details concerning the geological part are not dealt with further here, but the influence of the geology is discussed in Chapter 3.

The second feature is mainly connected to the present work. Brown (1986) is of the opinion that *"inadequacies in site characterization of geo-data probably present the major impediment to the design, construction and operation of excavations in rock. Improvements in site characterization methodology and techniques, and in the interpretation of the data are of primary research requirements, not only for large rock caverns, but for all forms of rock engineering."*

TABLE 2-1 BASIC ELEMENTS AND RELEVANT CONSIDERED AREAS (based on Natau, 1990)

BASIC ELEMENT	**SIZE RANGE**	**STRUCTURES**	**CONSIDERED AREA**
Crystal lattice	Angstrom size (10^{-7} mm)	Micro structures	Electron microscope
Mineral grain	µm - cm	Grain structures in rock	Microscope, hand piece, test sample of rock
Rock material	cm - 10 m	Massive rock	Hand piece, stone ornaments, building stone, test of rock samples.
Jointed rock (composed of 'bricks')	cm - 10 m	Joint pattern, rock mass	Foundations, small underground structures, test samples of rock masses, test pits/adits
Geological-tectonical units	10 m - km	Rock mass volumes between large faults	Slopes, tunnels, large underground structures, mines (geological maps and sections)
Geological-tectonical large size units	Several km	Regional plates	Oil reservoirs, (general geological maps and sections)

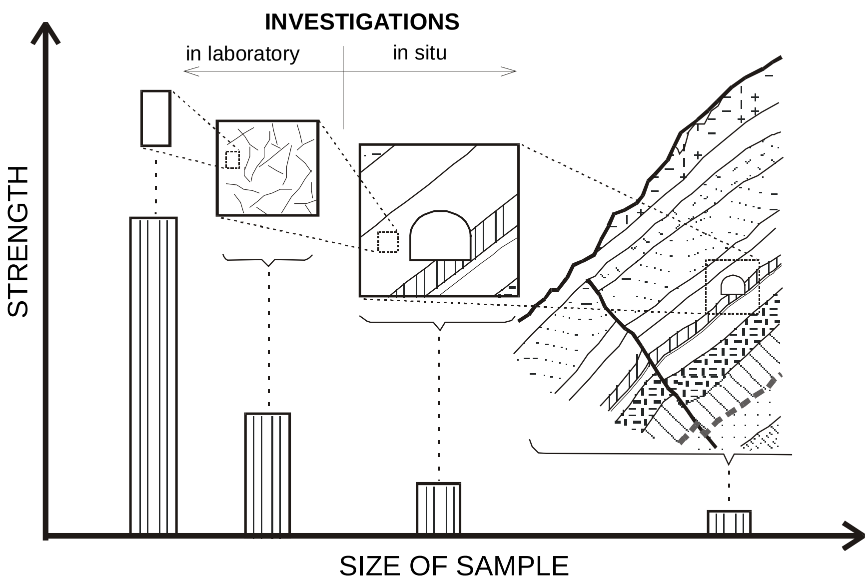

Fig. 2-2 The scale factor of rock masses and the variation in strength of the material depending on the size of the 'sample' involved. (After Janelid, 1965)

Other special features in a rock mass and its utilization in contrast to other construction materials are:

- the *size* or volume of the material involved, see Fig. 2-2 and Table 2-1,
- the *structure* and composition of the material,
- the many *construction and utilization* purposes of it, see Table 2-2, and
- the difficulties in measuring the *quality of the material* (see also Appendix 4).

TABLE 2-2 MAIN TYPES OF WORKS CONNECTED TO ROCKS AND ROCK MASSES

TYPE	**ACTUAL PROCESS OR USE**
Treatment of rocks	- drilling (small holes) - boring (TBM boring, shaft reaming) *) - blasting*) - fragmentation*) - crushing - grinding - cutting*)
Application of rocks	- rock aggregate for concrete etc. - rock fill - building stone
Utilization of rock masses	- in underground excavations (tunnels, caverns, shafts) *) - in surface cuts/slopes/portals *)
Construction works in rock masses	- excavation works - rock support *) - water sealing

*) Areas where the system is of particular interest.

These factors imply that other methods of data acquisition are used, and that other procedures in the use of these data for construction purposes have been developed. Thus, the material properties of rock masses are not measured but estimated from descriptions and indirect tests. The stress is not applied by the engineering but is already present; the construction, however, leads to stress changes.

In the remainder of this chapter the main features of the rock mass and their effect on its behaviour related to rock construction are briefly outlined.

2.1 ROCKS AND THEIR MAIN FEATURES

Geologists use a classification, which reflects the origin, formation and history of a rock rather than its potential mechanical performance. The rock names are defined and used not as a result of the strength properties, but according to the abundance, texture and types of the minerals involved, in addition to mode of formation, degree of metamorphism, etc. According to Franklin (1970) there are over 2000 names available for the igneous rocks that comprise about 25% of the earth's crust, in contrast to the greater abundance of mudrocks (35%) for which only a handful of terms exist; yet the mudrocks show a much wider variation in mechanical behaviour.

2.1.1 Fresh rocks

Each particular rock type is characterized by its minerals, texture fabric, bonding strength and macro and micro structure, see Fig. 2-3.

Igneous rocks tend to be massive rocks of generally high strength. Their minerals are of a dense interfingering nature resulting in only slight, if any, directional differences in mechanical properties of the rock. These rocks constitute few problems in rock construction when fresh.

Sedimentary rocks constitute the greatest variation in strength and behaviour. The minerals of these rocks are usually softer and their assemblage is generally weaker than the igneous rocks. In these rocks the minerals are not interlocking but are cemented together with inter-granular matrix material. Sedimentary rocks usually contain bedding and lamination or other sedimentation structures and, therefore, may exhibit significant anisotropy in physical properties depending upon the degree of their development. Of this group, argillaceous and arenaceous rocks are usually the most strongly anisotropic. Some of the rocks are not stable in the long term, as for example mudrocks, which are susceptible to slaking and swelling. This group of rocks therefore creates many problems and challenges in rock construction.

Metamorphic rocks show a great variety in structure and composition and properties. The metamorphism have often resulted in hard minerals and high intact rock strength; however, the preferred orientation of platy (sheet) minerals due to shearing movements results in considerable directional differences in mechanical properties. Particularly the micaceous and chloritic schists are generally the most outstanding with respect to anisotropy.

2.1.2 The influence from some minerals

Certain *elastic and anisotropic minerals* like mica, chlorite, amphiboles, and pyroxenes may highly influence the mechanical properties of the rocks in which they occur (Selmer-Olsen, 1964). Parallel orientation of these minerals is often found in sedimentary and regional metamorphic rocks in which weakness planes may occur along layers of these flaky minerals. Where mica and chlorite occur in continuous layers their effect on rock behaviour is strongly increased. Thus, mica schists and often phyllites have strong anisotropic mechanical properties of great importance in rock construction. Also other sheet minerals like serpentine, talc, and graphite reduce the strength of rocks due to easy sliding along the cleavage surfaces, see Fig. 2-3.

Quartz is another important mineral in rock construction. This mineral is grade 7 in the Mohs scale of hardness. Sharp, obtuse-angled edges of the quartz grains have an unfavourable shape regarding drill bit and cutter wear in percussion drilling and TBM boring respectively, while the effect from rounded quartz grains is significantly less.

Change of moisture content in *swelling minerals* of the smectite (montmorillonite) group can cause significant problems related to high swelling pressures (Piteau, 1970). These minerals, occurring either as infilling or alteration products in seams or faults, have in addition to expansion, a low shear strength, which may contribute to rock falls and, in some cases, slides in underground openings and cuttings. Also some rocks may show swelling properties. These rocks can be montmorillonitic shales, altered or weathered basalts, in addition to other igneous, metamorphic rocks, or sedimentary rocks containing anhydrite.

Some rocks may slake (hydrate or "swell", oxidize), disintegrate or otherwise weather in response to the change in humidity and temperature consequent on excavation. As mentioned above, an abundant group of rocks, the mudrocks, are particularly susceptible to even moderate weathering (Olivier, 1976). Refer to Fig. 2-3.

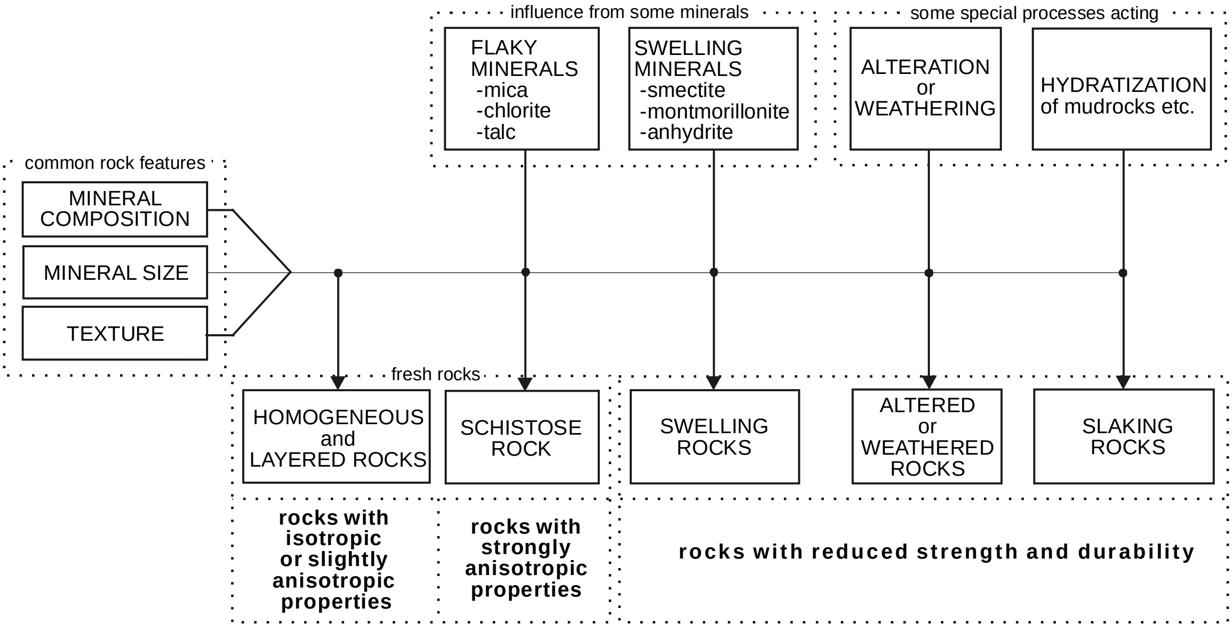

Fig. 2-3 The main variables influencing rock properties and behaviour

2.1.3 The effect of alteration and weathering

The processes of alteration and weathering with deterioration of the rock material have reducing effect on the strength and deformation properties of rocks, and may completely change the mechanical properties and behaviour of rocks (refer to Fig. 2-3). For most rocks, except for the weaker types, these processes are likely to have great influence on engineering behaviour of rock masses. Hence, the description and characterization of rock masses should pay particular attention to such features.

Rocks are frequently *weathered* near the surface, and are sometimes *altered* by hydrothermal processes. Both processes generally first affect the walls of the discontinuities[1]. The main results of rock weathering and alteration are:

1. Mechanical *disintegration* or breakdown, by which the rock loses its coherence, but has little effect upon the change in the composition of the rock material. The results of this process are:
   - The opening up of joints.
   - The formation of new joints by rock fracture, the opening up of grain boundaries.
   - The fracture or cleavage of individual mineral grains.

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[1] In this work, the following terms have been applied for the various types of discontinuities:

Joints	-	Minor and medium sized discontinuities, including fissures, cracks, fractures, breaks, etc.; also some minor seams are included in this group.
Seams	-	Filled discontinuities, including shears; they are also named 'singularities'.
Weakness zones	-	Including faults, crushed zones and zones of weak rocks surrounded by stronger rocks.

The characteristics of these features are further described in Appendices 1 and 2.

2. Chemical *decomposition*, which involves rock decay accompanied by marked changes in chemical and mineralogical composition results in:
   - Discoloration of the rock.
   - Decomposition of complex silicate minerals (feldspar, amphibole, pyroxene, etc) eventually producing clay minerals; some minerals, notably quartz, resist this action and may 'survive' unchanged.
   - Leaching or solution of calcite, anhydrite and salt minerals.

The *disintegration* leads mainly to a greater number of joints in rock masses located in the upper zone of weathering, while *decomposition* influences the joint condition as well as the rock material.

2.1.4 Geological names and mechanical properties of rocks

Rocks that differ in mineral composition, porosity, cementation, consolidation, texture and structural anisotropy can be expected to have different strength and deformation properties. Geological nomenclature of rocks emphasizes mainly solid constituents, whereas from the engineer's point of view, pores, defects and anisotropy are of greater mechanical significance (Franklin, 1970). For each type of rocks the mechanical properties vary within the same rock name. Petrological data can, however, make an important contribution towards the prediction of mechanical performance, provided that one looks beyond the rock names to the observations on which they are based. It is, therefore, important to retain the names for the different rock types, for these in themselves give relative indications of their inherent properties (Piteau, 1970).

2.2 DISCONTINUITIES IN ROCK

Any structural or geological feature that changes or alters the homogeneity of a rock mass can be considered as a discontinuity. Discontinuities constitute a tremendous range, from structures which are sometimes thousands of meters in extent down to - per definition - mm size, see Fig. 2-4.

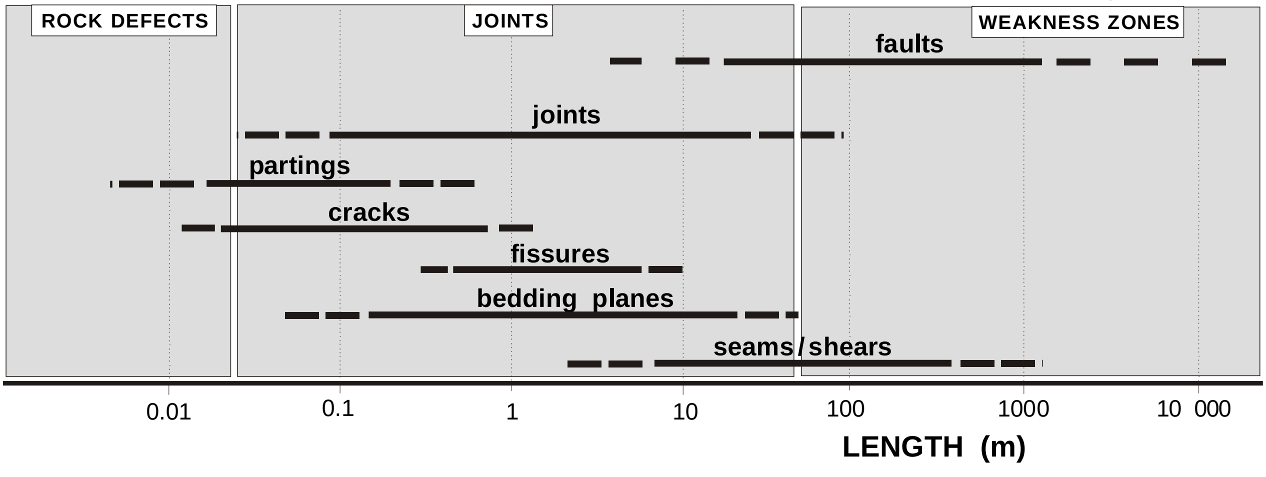

Fig. 2-4 The main types of discontinuities according to size. The size range (length) used for joints in this work is indicated.

The different types, such as faults, dykes, bedding planes, tension cracks, etc. have completely different engineering significance (Piteau, 1970). The roughness, nature of their contacts, degree and nature of weathering, type and amount of gouge and susceptibility to ground water flow will vary greatly from one type of discontinuity to another since their cause, age and history of development are fundamentally different. The effect on rock masses due to these localised discontinuities

varies considerably over any given region depending on structure, composition and type of discontinuity.
The great influence of discontinuities upon rock mass behaviour calls for special attention to these features when characterizing rock masses for practical applications. Joints and faults have numerous variations in the earth's crust, this is probably the main reason that it has been so difficult to carry out common observation and description methods (Terzaghi, 1946).

2.2.1 Faults

Faults are breaks along which there has been displacement of the sides relative to one another parallel to the break. Minor faults range in thickness from decimetre to meter; major faults from several meters to, occasionally, hundreds of meters. It is important to realise that most fault zones are the result of numerous ruptures throughout geological time, and that they quite often are associated with other parallel discontinuities that decrease in frequency and size in the direction away from the central zone.

Faults and fault zones often form characteristic patterns in the earth's crust consisting of several independent sets or systems, see Fig. 2-5. The main directions, which mainly were determined by the state of stress, have often the same orientations as the joint sets within the same structural area.

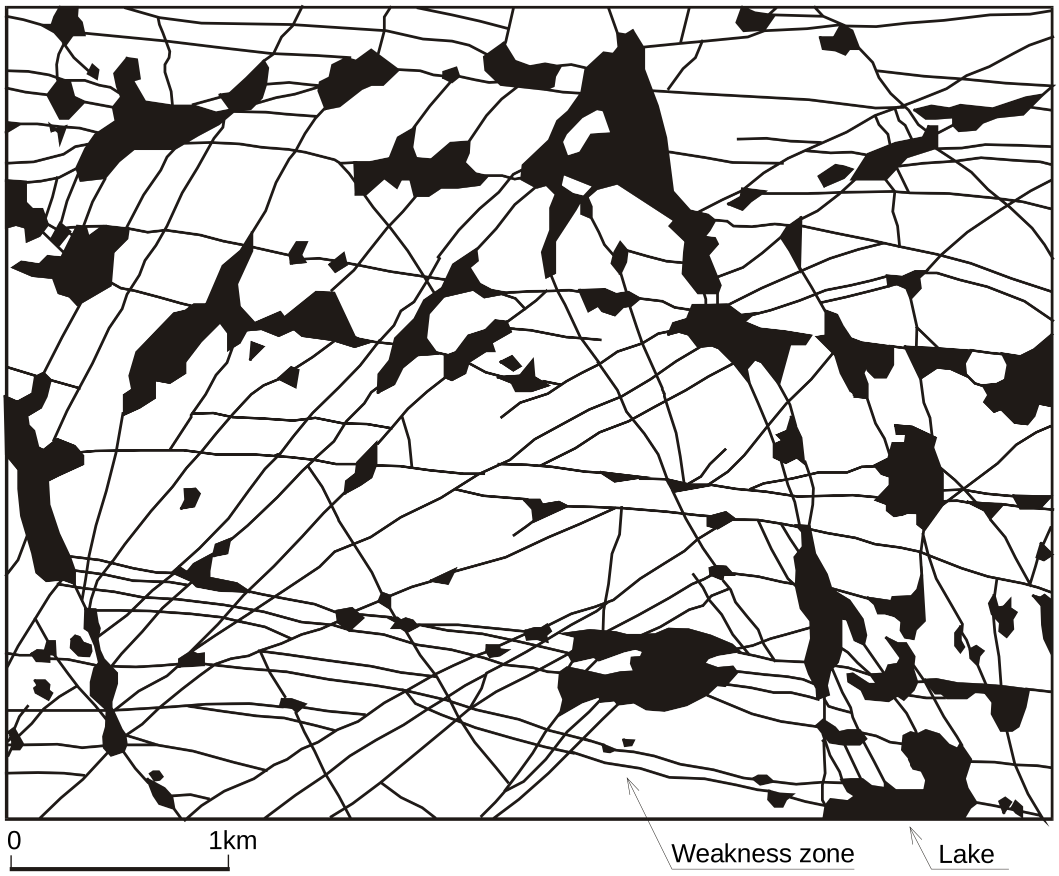

Fig. 2-5 Pattern of weakness zones and faults in the earth's surface. (After Selmer-Olsen, 1988)

Hydrothermal activity and other processes may have caused alteration of minerals into clays, often with swelling properties. Many faults and weakness zones thus contain materials quite different from the 'host' rock. The problems related to weakness zones may, therefore, depend on several factors which may all interplay in the final behaviour.

Weakness zones and faults show numerous variations in their structures and compositions, see Fig. 2-6. In cases where the zones or faults are composed mainly of joints and seams they may be characterized by the same descriptions as for jointing. In other cases it may be necessary to characterize them by special descriptions and measurements or tests, as further described in Appendix 2. The fact that faults and weakness zones of significant size can have a major impact upon the stability as well as on the excavation process of an underground opening necessitates that special attention, follow-up and investigations often are necessary to predict and avoid such events.

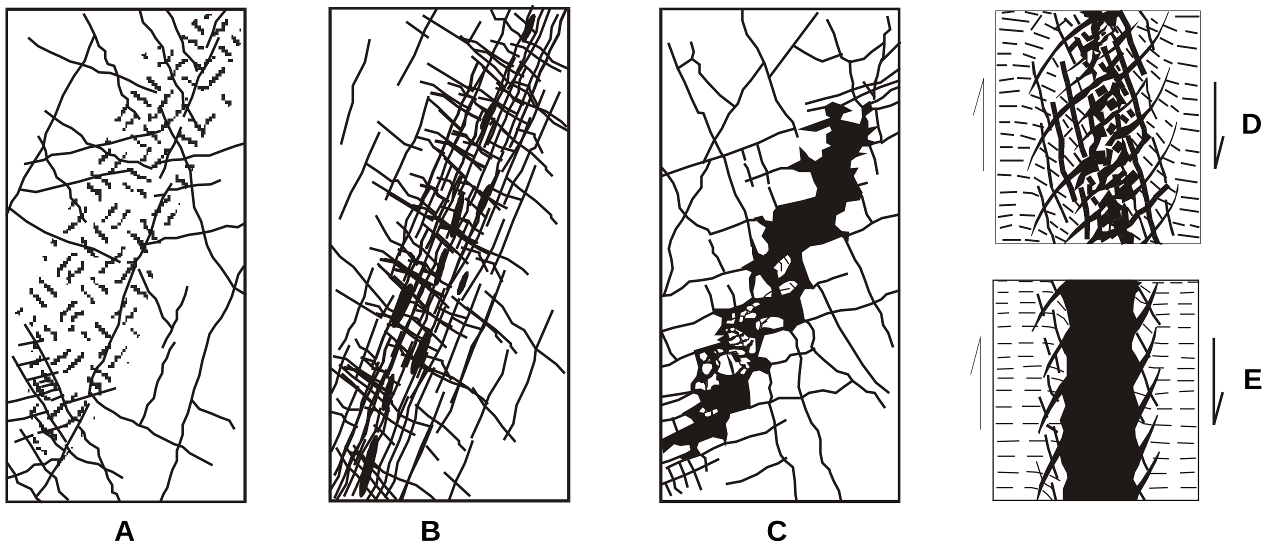

Fig. 2-6 Sketches of some types of weakness zones. A - C are from ISRM (1978) and D - E from Selmer-Olsen (1950).

2.2.2 Joints and their main features

Joints are the most commonly developed of all structures in the earth's crust, since they are found in all competent rocks exposed at the surface. Yet, despite the fact that they are so common and have been studied widely, they are perhaps the most difficult of all structures to analyse. The analytical difficulty is caused by the number of fundamental characteristics of these structures. There is, however, abundant field evidence that demonstrates that joints may develop at practically all ages in the history of rocks (Price, 1981).

A joint can be open or closed. Closed joints may be nearly invisible. Yet they constitute surfaces along which there is no resistance against separation. In quarries the spacing of joints determines the largest size of blocks of sound rock which can be obtained. Therefore, joints and joint systems have attracted the attention of builders ever since cut stones have been used.

A joint is composed of several characteristics. In addition to length and continuity of the joint the main are:

- roughness and strength of the joint wall surface,
- waviness or planarity of joint wall,
- alteration or coating of the joint wall, and
- possible filling. Refer to Fig. 2-7.

All these parameters influence on the shear strength of the joint (Brekke and Howard, 1972; Price, 1981; Hoek and Brown, 1980; Barton et al., 1974; Barton and Choubey, 1977; Bieniawski, 1984; Turk and Dearman 1985; and several other authors). They also determine the amount of water that can flow through the joint.

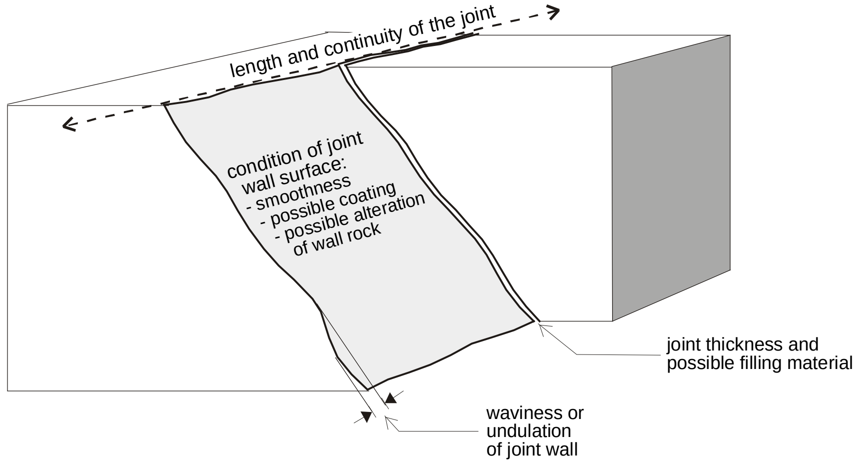

Fig. 2-7 Sketch showing the main features of a joint.

The distance between the two matching joint walls controls the extent to which these can interlock. In the absence of interlocking, the properties of the filling of the joint determine the shear strength of the joint. As separation decreases, the asperities of the rock wall gradually become more interlocked, and the rock wall properties are the main contributor to the shear strength.

2.2.3 The main jointing characteristics

By jointing is meant the pattern and frequency or density of joints. Field studies of several workers have shown that the joints preferentially are found in certain directions. One to three prominent sets and one or more minor sets may occur; in addition several individual or random joints are often present.

The joints delineate blocks. Their dimensions and shapes are determined by the joint spacings, by the number of joint sets and by random joints. ISRM (1978), Barton (1990) and several other authors state that the block size is as an extremely important parameter in rock mass behaviour. A number of scale effects in rock engineering can be explained by this feature including compressive strength, deformation modulus, shear strength, etc.

Different methods are used for measuring the jointing density. The most common are:

- Joint spacing, either in surfaces or in drill cores or scan lines.
- Density of joints, either in surfaces, or in bore holes or scan lines.
- Block size, in surfaces, and
- Rock quality designation (RQD), in drill cores.

They are further outlined in Appendix 3, where also correlation equations between them have been developed.

2.2.4 The rock mass

Discontinuities ranging in lengths from less than a decimetre to several kilometres divide the bedrocks into units, volumes or blocks of different scales (Fig. 2-8):

1. The regional pattern or first order fault blocks are bounded by the larger weakness zones or faults (see Fig. 2-5).
2. The second order blocks formed by singularities, i.e. small weakness zones or seams.
3. The third order blocks formed by normal joints.
4. The small joints in the appearance of bedding or schistosity partings form the smallest pattern or fragments, which are of interest for engineering purposes.
5. The microcracks are responsible for making up small fragments or grains in the rock. These discontinuities are, however, mostly considered a rock property and are therefore generally included in the strength characterization of the rock material.

Based on this it has been found useful for engineering geological and design purposes to divide the ground into:

- "The detailed jointing" formed mainly by the third and fourth order blocks or units, and
- "The coarse pattern of weakness zones" formed by the first order blocks or units by faults and weakness zones.

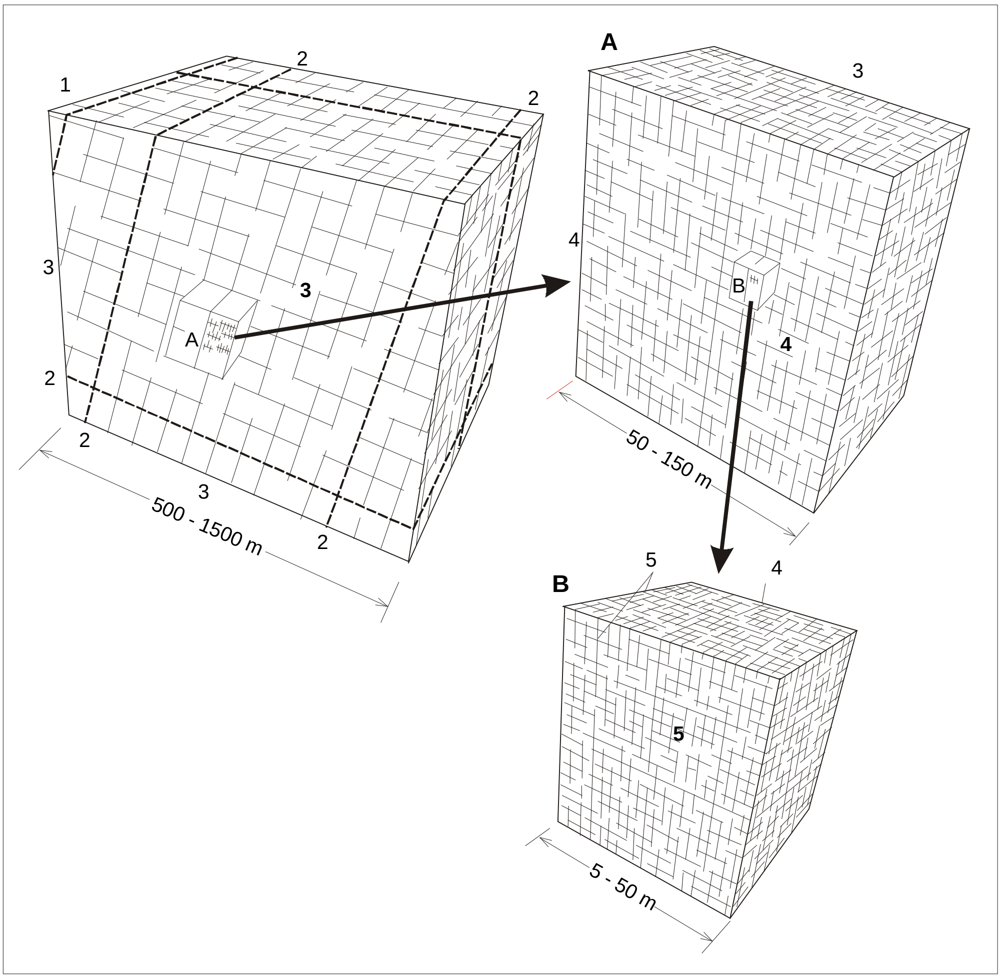

Fig. 2-8 Simplified model of various dimensions units or blocks formed by discontinuities of different size (after Pusch and Morfeldt, 1993).

This corresponds with the division suggested by Selmer-Olsen (1964). The rock blocks in the detailed jointing pattern including the rock fragments or pieces caused by the small joints/fissures is a main feature in the rock mass characterization developed herein.

2.3 ROCK MASS CHARACTERIZATION FOR DESIGN AND CONSTRUCTION PURPOSES

An important issue in rock mass description and characterization is to select parameters of greatest significance for the actual type of design or construction. There is no single parameter or index, which can fully designate the properties of jointed rock mass. Various parameters have different significance and only if combined can they describe a rock mass satisfactorily (Bieniawski, 1984). Testing of rock masses in situ has brought out very clearly the enormous variations that exist in the mechanical behaviour of a rock mass from place to place. According to Lama and Vutukuri (1978) the engineering properties of a rock mass depend far more on the system of geological discontinuities within the rock mass than of the strength of the rock itself. Further, the strength of a rock mass is often governed by the interlocking bonds of the unit "elements" forming the rock mass.

Terzaghi (1946) also concludes that, from an engineering point of view, a knowledge of the type and frequency of the rock discontinuities may be much more important than of the types of rock which will be encountered. Similarly, Piteau (1970) has stressed the importance of distinguishing between the behaviour of the rock and the rock mass, especially for hard rocks. Thus, characterizing a discontinuity system in a way that describes the variability of its geometric parameters constitutes an essential step in dealing with stability problems in discontinuous rock masses (Tsoutrelis et al., 1990).

This does not mean that the properties of the intact rock material should be disregarded in the characterization. After all, if discontinuities are widely spaced, or if the intact rock is weak, the properties of the intact rock may strongly influence the gross behaviour of the rock mass. The rock material is also important if the joints are discontinuous. In addition, the rock description will inform the reader about the geology and the type of material at the site. Although rock properties in many cases are overruled by discontinuities, it should be brought to mind that the properties of the rocks highly determine the formation and development of discontinuities.

Therefore, an adequate and reliable estimation of the nature of the rock is often a primary requirement. For some engineering or rock mechanics purposes the mechanical characterization of rock material alone can be used, namely for drillability, crushability, aggregates for concrete, asphalt etc. Also, in assessment for the use of fullface boring machines (TBM), rock properties like compressive strength, hardness, anisotropy are among the more important parameters.

Kirkaldie (1988) mentions a total of 28 parameters present in rock masses which may influence the strength, deformability, permeability or stability behaviour of rock masses: 10 rock material properties, 10 properties of discontinuities and 8 hydrogeological properties. Because it is often difficult or impossible in a general characterization to include the many variables in such a complex natural material, it is necessary to develop suitable systems or models in which the complicated reality of the rock mass can be simplified by selecting only a certain number of representative parameters. For this purpose several classification and design systems have been developed, of which some are shown in Table 2-3 for information. Further, Table 2-4 indicates the main rock mass and ground features and which of these that have been applied and combined in the various systems.

From Table 2-4 it is seen that the following parameters are most frequently applied in design and classification systems:

- the rock material (rock type, geological name, weathering and alteration, strength);
- the degree of jointing (joint spacing, block size, RQD); and
- in situ stresses.

Also such features as:

- orientation of main discontinuities or joint set;
- joint conditions;
- block shape or jointing pattern;
- faults and weakness zones; and
- excavation features (dimension, orientation, etc.)

have been considered as important parameters in rock masses.

TABLE 2-3 SOME OF THE MAIN DESIGN AND CLASSIFICATION SYSTEMS IN USE

Name of classification	**Form and Type***)	**Main applications**	**Reference**
The Terzaghi rock load classification system	Descriptive and behaviouristic form Functional type	For design of steel support in tunnels	Terzaghi, 1946
Lauffer's stand-up time classification	Descriptive form General type	For input in tunnelling design	Lauffer, 1958
The new Austrian tunnelling method (NATM)	Descriptive and behaviouristic form Tunnelling concept	For excavation and design in incompetent (overstressed) ground	Rabcewicz, Müller and Pacher, 1958 - 64
Rock classification for rock mechanical purposes	Descriptive form General type	For input in rock mechanics	Patching and Coates, 1968
The unified classification of soils and rocks	Descriptive form General type	Based on particles and blocks for communication	Deere et al., 1969
The rock quality designation (RQD)	Numerical form General type	Based on core logging; used in other classification systems	Deere et al., 1967
The size-strength classification	Numerical form Functional type	Based on rock strength and block diameter; used mainly in mining	Franklin, 1975
The rock structure rating (RSR) classification	Numerical form Functional type	For design of (steel) support in tunnels	Wickham et al., 1972
The rock mass rating (RMR) classification	Numerical form Functional type	For use in tunnel, mine and foundation design	Bieniawski, 1973
The NGI Q classification system	Numerical form Functional type	For design of support in underground excavations	Barton et al., 1974
The typological classification	Descriptive form General type	For use in communication	Matula and Holzer, 1978
The unified rock classification system	Descriptive form General type	For use in communication	Williamson, 1980
Basic geotechnical classification (BGD)	Descriptive form General type	For general use	International Society for Rock Mechanics (ISRM), 1981

*) **Definition of the following expressions:**

Descriptive form:	the input to the system is mainly based on descriptions
Numerical form:	the input parameters are given numerical ratings according to their character
Behaviouristic form:	the input is based on the behaviour of the rock mass in a tunnel
General type:	the system is worked out to serve as a general characterization
Functional type:	the system is structured for a special application (for example for rock support)

As for most other construction materials, there is also in rock engineering and construction a need for a strength specification of the material, i.e. the rock mass. The strength of other construction materials can be determined from the process of refining or ensured during production of the material. In rock construction, however, the material already exists, the task is to evaluate the strength properties it possesses (and not to produce them).

The considerations outlined above have been important in the development of the present system for rock mass characterization.

TABLE 2-4 APPLICATION OF ROCK MASS AND GROUND PARAMETERS IN VARIOUS DESIGN AND CLASSIFICATION SYSTEMS

CLASSIFICATION SYSTEM NO. →	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
ROCK													
- Origin, name, or type				x				x			x		x
- Weathering	o		:			"					+	x	
- Anisotropy													
ROCK PROPERTIES													
- Unit weight											+	x	
- Porosity											+		
- Rock hardness								x					
- Strength	:	:	:	x			x		x		+	x	x
- Deformability			:	o							+		
- Swelling	o		:										
JOINT CONDITIONS													
- Joint size/length				o				o					
- Joint separation											x	o	
- Joint wall smoothness									x	x			:
- Joint waviness									x	x			
- Joint filling										x	x		
DEGREE OF JOINTING													
- Block size					x		x						
- Joint spacing/frequency	o	:	:	o		x			x		x		x
- RQD									x	x			
- Number of joint sets										x			
JOINTING GEOMETRY OR STRUCTURE													
- Joint orientation with respect to excavation								x	+				
- Jointing pattern											x		
- Continuity		:	:	o	o								
- Structure (fold, fault)	:		:					+					
EXTERNAL FEATURES													
- Water conditions								x	x	x			
- Rock stress conditions	o		:				x		+	x			
- Blasting damage									+				
- Excavation dimensions			:					x	x	x			
CLASSIFICATION SYSTEM NO. →	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**

Legend:
x well defined input
: included, but not defined
\+ used as additional information (in RMR as adjusted value)
o very roughly defined or included
" partly included (in other parameters)

Classification system no.:
1 Terzaghi (1946)
2 Lauffer (1958)
3 NATM (1957-64)
4 Coates and Patching (1968)
5 Deere et al. (1969)
6 RQD (1966)
7 Franklin (1970, 1975)
8 Wickham et al. (1972)
9 RMR (1973)
10 Q-system (1974)
11 Matual and Holzer (1978)
12 Williamson (1980)
13 BGD (1981)