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Classification systems and use of geological data

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ABSTRACT

The main rock engineering classification systems use the main parameters representing the properties of a rockmass: The rock material, the joint characteristics, the degree of jointing, and in addition the rock stresses and groundwater acting.
The paper shortly describes these input parameters. It then shows a description of main rockmass compositions, as well as various modes of ground behaviour.
The main rock engineering classification systems are briefly mentioned. They mostly use similar input parameters, but with different characterization applied differently. As not all parameters are used in the systems, the calculated value in the different systems cannot directly be compared, i.e. a value in the Q system cannot correctly be transformed to a value in the RMR system. To overcome this, the paper shows a general description of main input parameters, and a method how to calculate the values in the Q, RMR and RMi systems from this.
The last chapter discusses uncertainties in rock engineering arising from investigations and from description of geological features. As there always will be uncertainties and inaccuracies in the geological data used in rock engineering, these must be met in the estimates, calculation, design and during construction.

KEYWORDS: CLASSIFICATION SYSTEMS, ROCK ENGINEERING, GROUND FEATURES, ROCKMASS BEHAVIOUR

1 INTRODUCTION

I am very glad to have this opportunity to present to you some of my experience on rock engineering. The aim of this paper is to give an overview of:

- Geological features influencing on rockmass properties and behaviour;
- Classification systems and their use; and
- On the collection and use of geological information.

1.1 Background

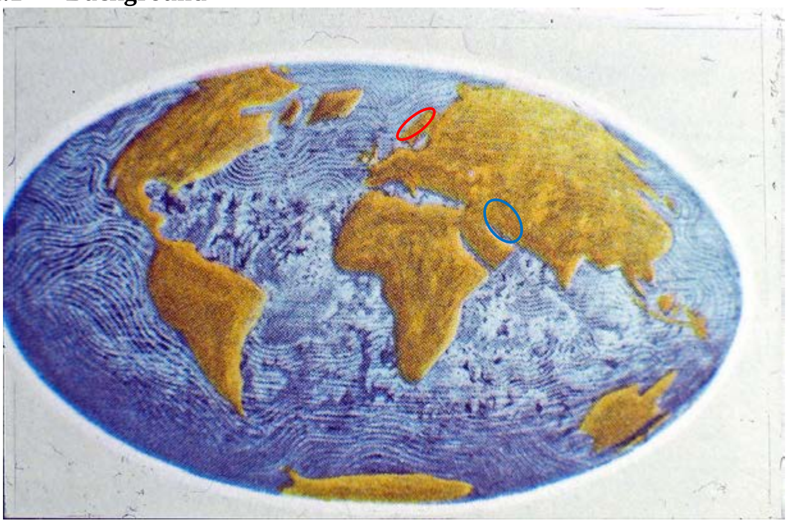


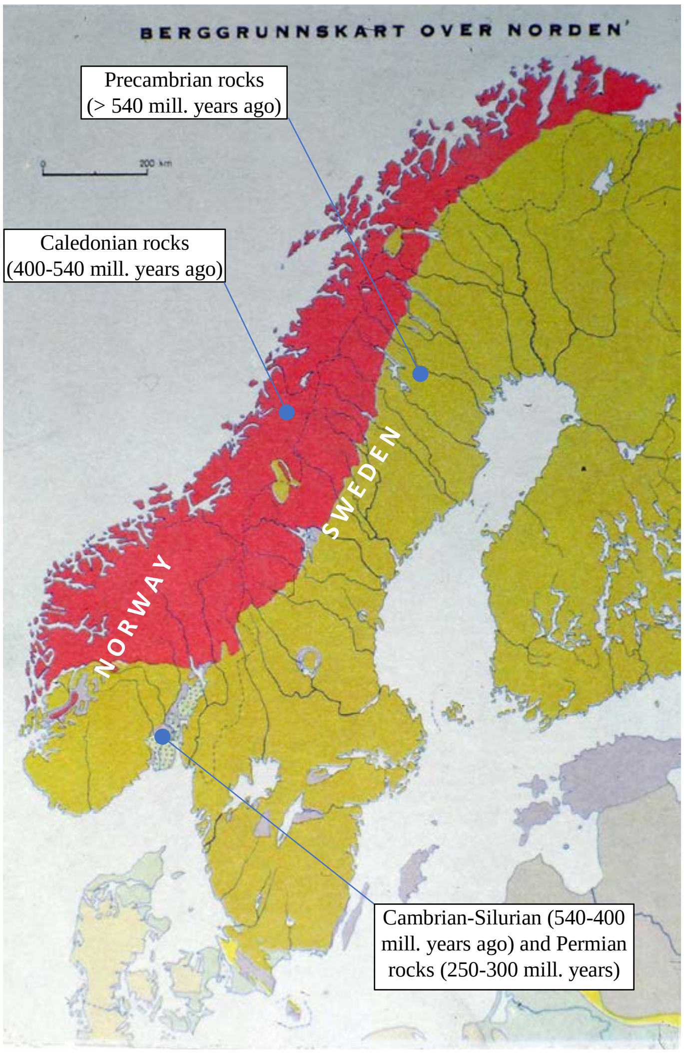
Figure 1: Location of Iran (blue) and Norway (red)

First, a little about my background, short on my education, practise and in what geological conditions that have given my main experience. I was born in Norway 74 years ago. In 1967 I became civil engineer (in engineering geology), and I took my PhD in 1995 on rock mass classification, introducing the Rock Mass index (RMi) system.
I have 50 years of experience as consultant in rock engineering/engineering geology, mainly for hydropower projects, road tunnels, especially undersea tunnels, both in Norway and other countries.
I have worked for the Norwegian Geological Survey, Norwegian Geotechnical Institute (NGI), and several Norwegian consulting companies in hydropower and underground constructions. In 2007, I formed my own firm RockMass, on consultancy in rock engineering.

Figure 1 shows the locations of our two counties. Though the two counties are situated far from each other, there are some similarities. Both are mountainous, and both have an active underground construction industry. As my experience is mainly based on the conditions in Norway, I will inform a little about the geological conditions here.

1.2 Short on the ground conditions in Norway and the need for investigations

Almost all bedrocks in Norway and Sweden consist of old, hard and crystalline rocks. As can be seen on Figure 2, most of the rocks belong to the Caledonian mountain chain, which was formed some 400 – 540 mill. years ago. However, tectonic activities over the long periods after the rocks were formed, have created faults and joints. Much of this paper is dealing with these features.



The glacial erosion ending 10,000 years ago caused that the weathered rock surface was eroded, leaving a rock surface with mostly fresh or slightly weathered rocks.
This means that the rocks observed at the terrain surface are similar to those met in the underground excavation. Thus, the rockmass conditions can be estimated from studies of outcrops; costly field investigations are seldom needed. More on this is presented in Chapters 2 and 4.

Figures 3 and 4 shows that weakness zones can often easily be detected in the terrain surface. In many locations the size of the zone can be estimated (see Figure 3). Figure 5 shows a picture of an eroded, exposed rock surface, which gives a very good understanding of the geological setting and the rockmass conditions. As there are fresh rocks or only slightly weathered rock, the rockmass conditions observed are more or less similar to those underground. Weakness zones (fault zones) occur as long lines; also the pattern of joints can be seen on the photo.

Much of the rock constructions in Norway rock have been in hydropower, as tunnels and underground powerhouses. Altogether there are about 5000 km of tunnels in Norway. Of these, there are about 40 undersea tunnels, most of them road tunnels. A Norwegian speciality is unlined pressure tunnels and shafts used in hydropower; another is large underground storage caverns for petroleum products.

Figure 2: Red: Caledonian rocks (400 – 540 mill. years). Greenish: Precambrian rocks (older than 540 mill. years) of mostly gneisses. The youngest (yellowish) rocks are Permian volcanic rocks (250 – 300 mill. years old)

Figure 3: Large weakness zones (fault zones) can easily be detected in the terrain surface as depressions.

Figure 4: Fiords and valleys are often formed along large weakness zones (mostly representing fault zones)

Figure: 5: Aerial view of a glacier eroded terrain surface without vegetation and loose materials. Important geological features can be observed as lines, indicating weakness (fault) zones. Also, distribution of old Precambrian rocks and Cambrian – Silurian rocks can be assessed a different (greenish) colour. In addition, the pattern of joints can be seen.

2 TYPES OF ROCKMASSES AND ROCKMASS FEATURES

Two areas are marked in Figure 6. Area (1) indicates an area with jointed rockmasses. These are also named "detailed jointing" by the late Prof. Selmer-Olsen [5]. They consist of rock material(s) intersected by joints. The other (area 2) is an area with weakness zone.

2.1 Jointed rock masses (between weakness zones)

The main rockmasses along tunnels generally consist of rock penetrated by rocks. A description of the conditions here includes: The type of rock and its strength properties.

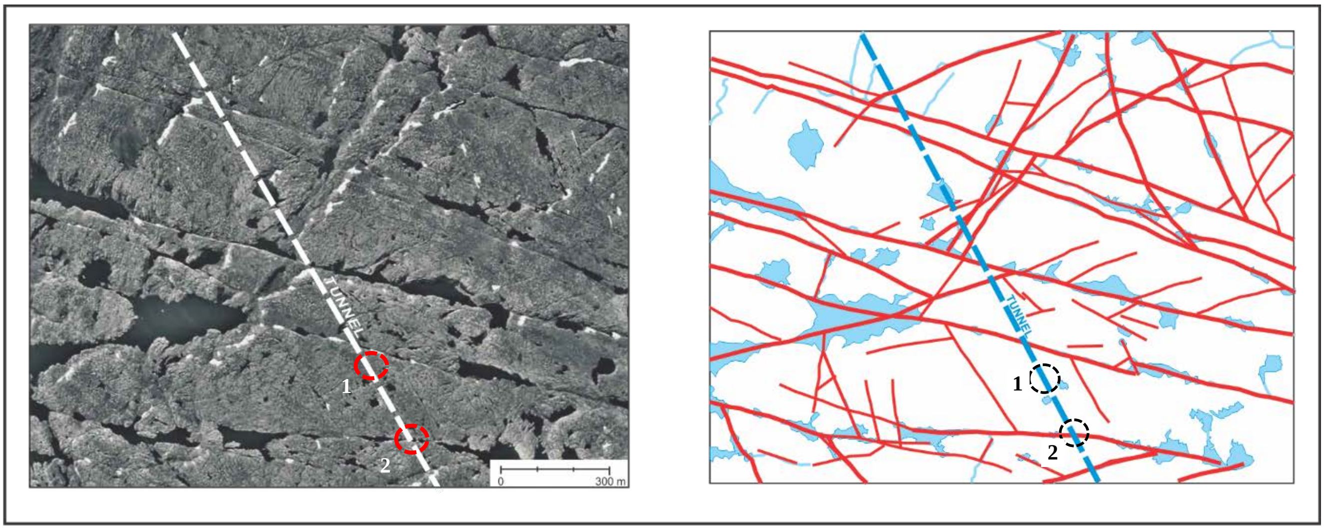


Figure 6: Left: aerial photo. Right: Interpretation of weakness zones observed in the aerial photo. The two main groups of rockmasses are (1) jointed rock masses; and (2) weakness zone (probably fault zone)

2.1.1 Rock material

The main groups of rock in rock engineering are as shown in Figure 7:

- Fresh hard, crystalline rocks (homogeneous, banded, schistose, and flaggy rocks);
- Weak sedimentary, sometimes porous rocks, which sometimes can be friable;
- Weathered, or altered rock, sometimes with swelling properties;
- Special materials, see Table 3.

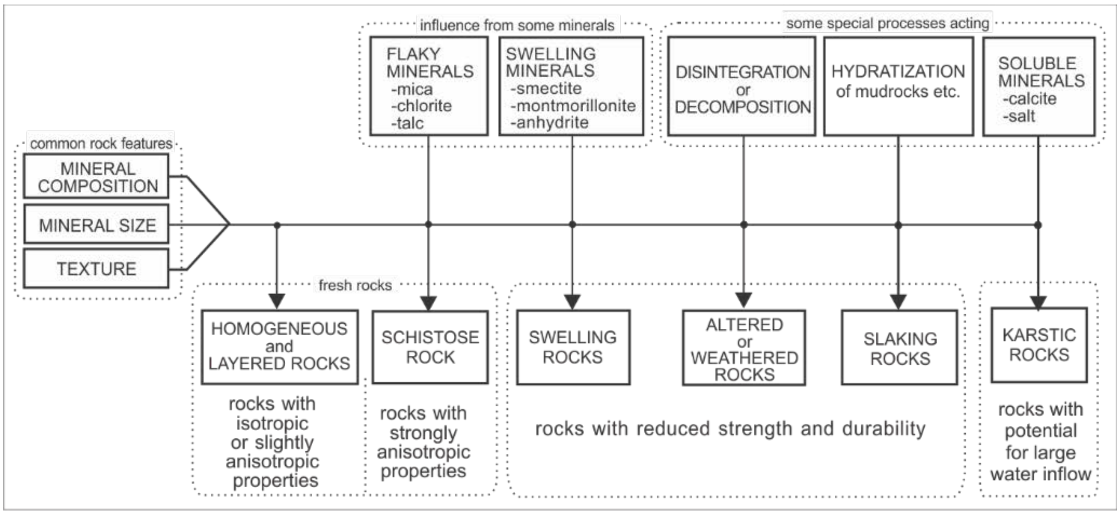


Figure 7: Main rock features influencing on rock construction [1]

Rock properties

The rock strength is a main property in rock engineering. However, it is important to aware that the rock properties often are overruled by the joints intersecting the rock. Thus, the Q system and partly the Terzaghi system have no input for rock features.

In rock construction, it is important to be aware of following rocks

- porous rocks;
- altered and weathered rocks;

and of materials having the following properties (see Section 2.4.1):

- swelling;
- slaking, and friable/loose rocks;
- soluble rocks.

Weathering and alteration of rock

Weathering refers to the various processes of physical disintegration and chemical decomposition that occur when rocks at the Earth's surface are exposed to the atmosphere (mainly in the form of rainfall) and the hydrosphere. These processes produce soil, unconsolidated rock detritus, and components dissolved in groundwater and runoff. Figure 8 shows a classification often used in rock engineering.

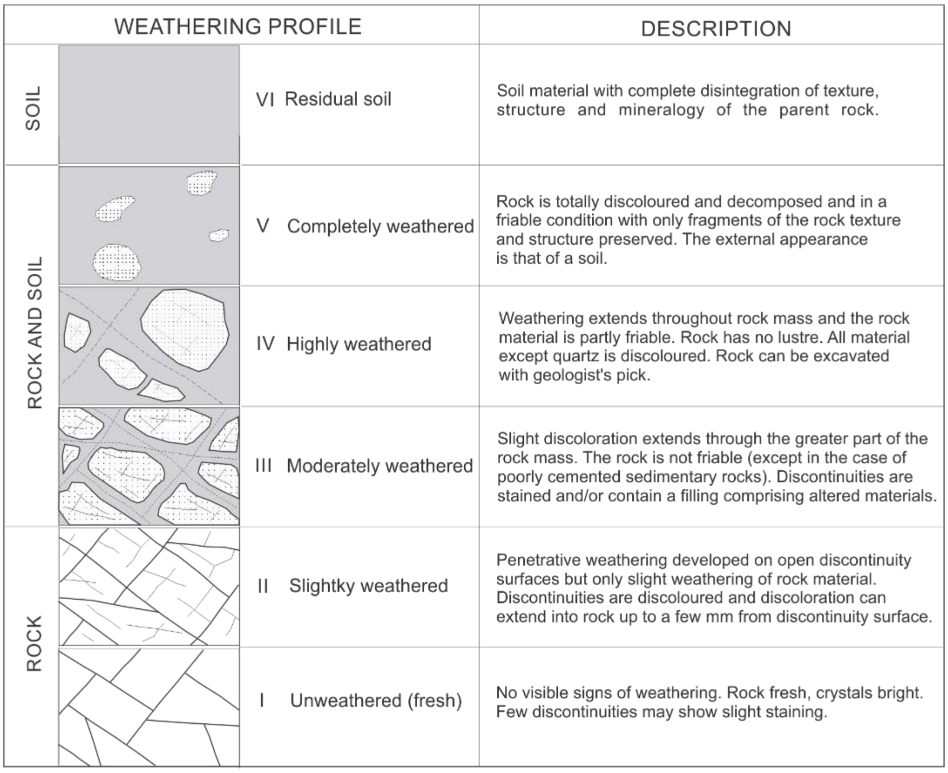


Figure 8: Weathering profile, partly from [2] and [3]

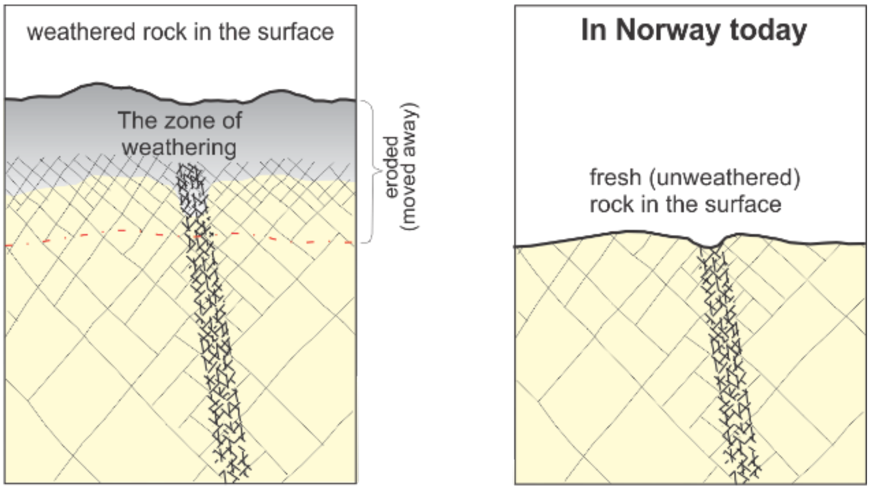


Figure 9: Left: Common weathering profile. Here, the weakness zone may not appear in the surface as indicated.

Right: Typical weathering profile in Norway. Caused by the glacier erosion, most of the weathered rocks have been moved, leaving an almost fresh rock surface.

Both *weathering* and *alteration* produce changes of the mineralogical composition of a rock, resulting in reduced mechanical properties. Deterioration from weathering and alteration generally affects the walls of the discontinuities more than the interior of the rock [4]. The weathered rocks at the rock terrain surface, cause that the condition of the fresh (unweathered) rocks underground cannot be studied from surface mapping; investigations must be carried out to collect relevant information.

2.1.2 Joints and jointing

See definitions of discontinuities in Chapter 4, Nomenclature

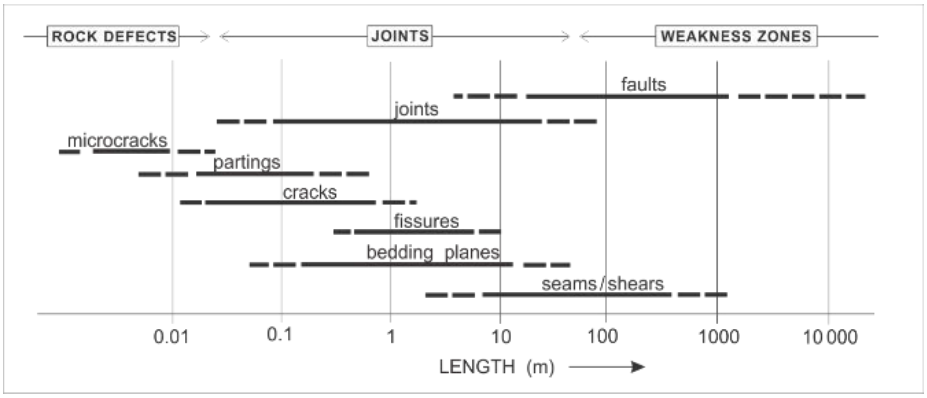
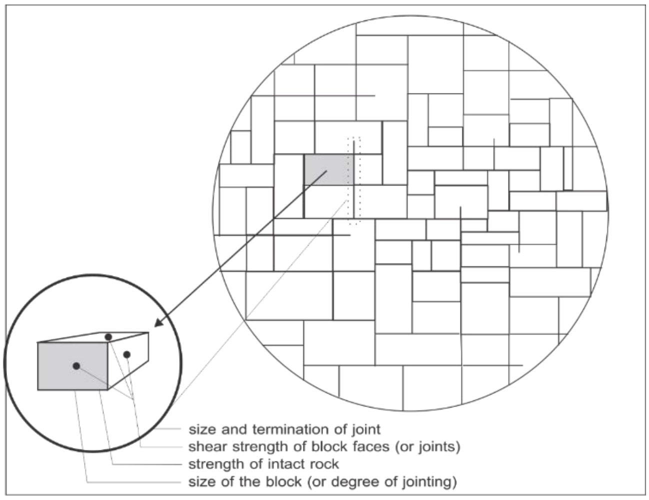


Figure 10: Various sizes of discontinues divided into joints and weakness zones [1].



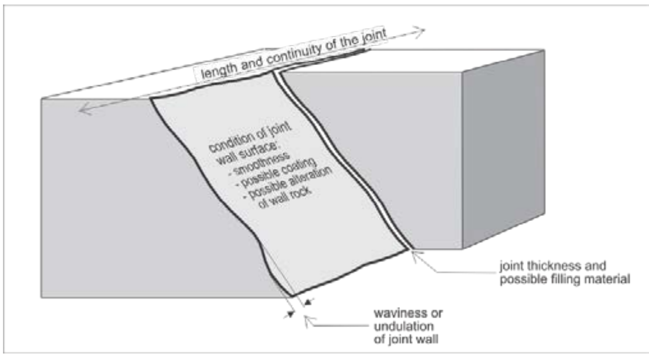


Figure 12 (above): Main joint characteristics [1]

Figure 11 (left): Jointed rock mass showing the jointing (pattern of joints and the joint characteristics [1]

Joint characteristics are (see Tables 11 and13 in the Appendix):

- The roughness of the joint (Jr or jR), composed of:
  - the smoothness of the joint wall (js), and
  - the waviness (planarity) of the joint plane (jw)
- The alteration of the joint surface (Ja or jA)
- The size (type) of the joint (jL)

Jointing characteristics are:

The degree of jointing (or density of joints), measured as

- The rock quality designation (RQD), the volumetric joint count (Jv, number of joints in a rockmass volume), the size of the individual blocks (Vb), or the distance (spacing) between joins in a joint set (S)
- The jointing pattern; often in engineering geology measured as the number of joint sets (Jn),

They represent the properties applied in the rock engineering classification systems described in Chapter 3.

There are numerous types of joins and jointing. Figures 13 – 20 show some examples. Simplifications have to be made in order to have useful descriptions. Significant simplification has been made in the input parameters for joints in the classification systems. This is further described in Chapter 3.

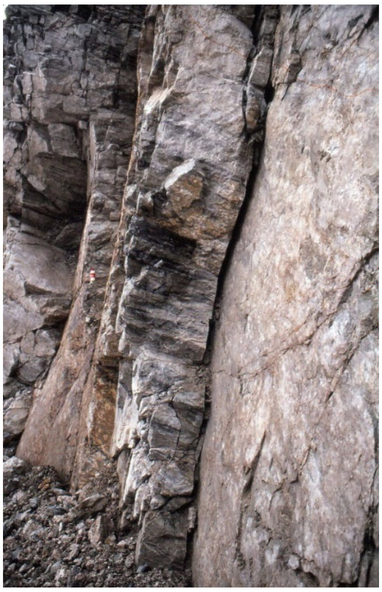


Figure 13: Part of a steeply dipping joint set

Figure 14: A set of steep, long joints

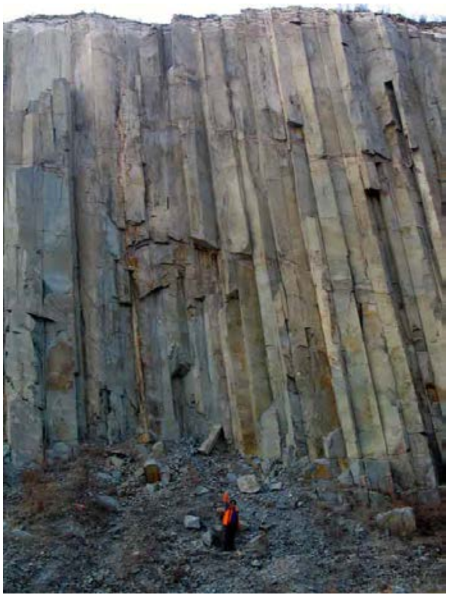


Figure 15: Columnar jointing in a basalt

Figure 16: A filled joint/shear (singularity) intersecting a volume of jointed rocks.

Figure 17: Tree joints sets in a granite.

The expression "massive rock" is often used to characterize rock masses with few joints, see Chapter 5, Nomenclature.

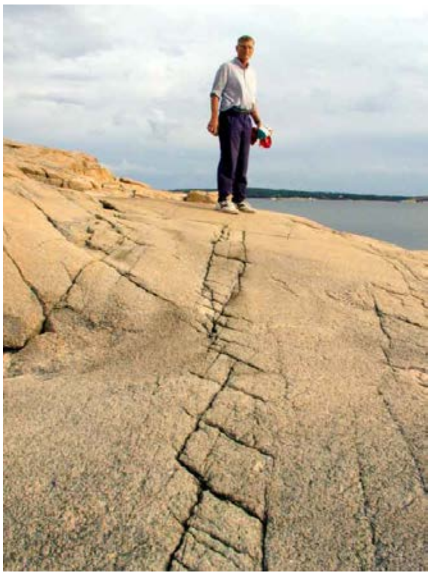


Figure 18: Very short joints in a granite.

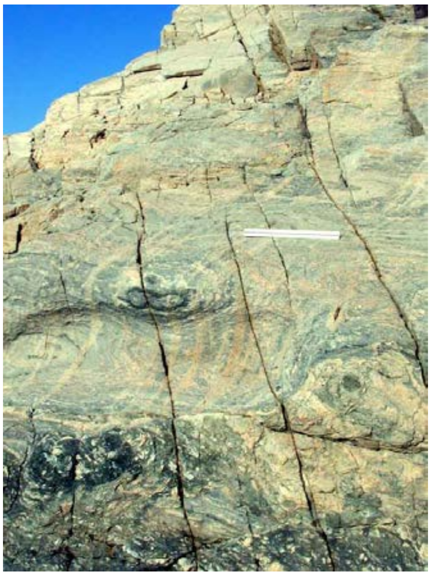


Figure 19: Discontinuous joints (ending in solid rock).

Figure 20: A joint where displacement can be observed (in geological terms this would be named as a (small) fault).

2.2 Weakness zones / faults

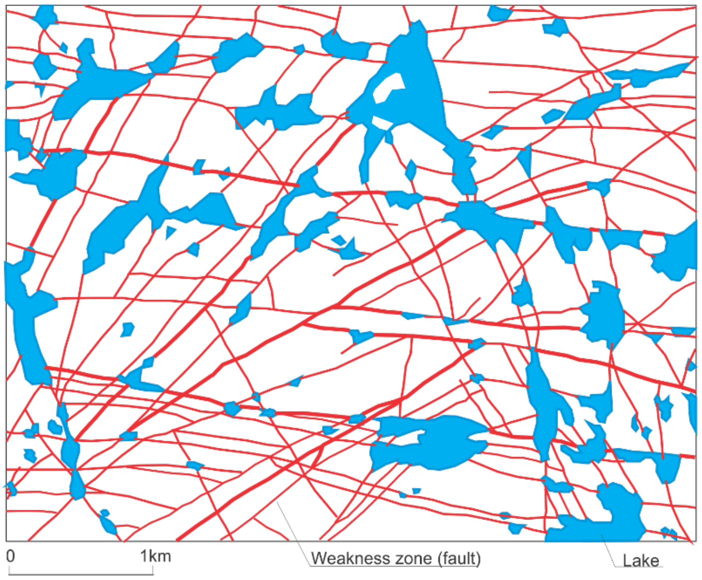


Figure 21: Pattern of weakness zones (mainly faults) in a large area 20 km^2 interpreted from aerial photos. Weakness zones may partly occur as sets, often parallel with the joint sets in the same area [5].

As Figure 21 shows, weakness zone occurs as long lines in the earth's crust. Also, these zones may occur as sets, as can be seen in this figure.

My experience is that weakness zones represent the most challenging geological conditions in underground rock constructions. They may show very unstable conditions, difficult to excavate, especially where clay materials occur and/or with water is flowing into the excavation. There are numerous types and sizes of weakness zones. And caused by this, it is almost impossible to present a classification which cover all the variations. Simplifications have been developed, but even these are not covering weakness zones in a satisfactorily way. See Chapter 4.

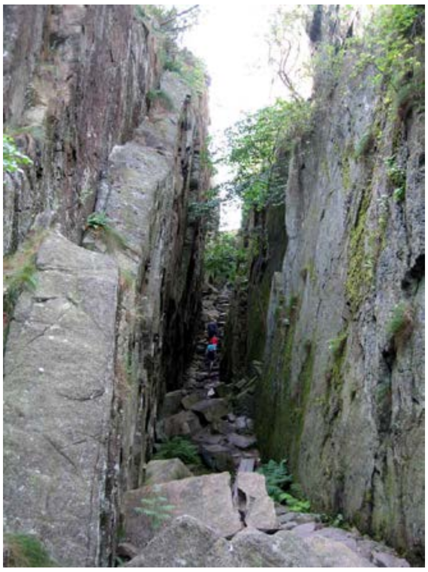
Some weakness zones contain materials and minerals that have special properties in an excavation; some of these may cause collapse during excavation or later during the use of the tunnel or cavern.

It is important to be aware of weakness zones and to investigate them thoroughly, especially those with significant influence on the excavation.

Figures 22 to 24 show photos of some weakness zones.

Table 1. The main groups of weakness zones (partly after [5])

Weakness zones and faults	Composed of
1. Zones of weak materials a. Layers of soft or weak minerals and rocks	- layers and lenses of clay, mica, talc, or chlorite - coal seams (layers) - some heavily jointed or brecciated dykes or layers
b. Layers or zones of highly weathered rock masses	- clayey or particulate materials
2. Fault zones a. Tension fault zones with a filling of soft minerals between parallel walls and generally a sharp boundary to the adjacent rocks.	- filling mainly of clay/chlorite, calcite, or soil-like materials
b. Shear fault zones, crushed and brecciated by many intersecting joints and/or seams. The central part may be altered to clay.	- crushed zones with coarse to fine fragmentation - crushed zones, sand- and/or clay-rich - foliation shears
c. Altered faults (of type 2a and 2b)	- clay-rich or leached (crushed) materials



Figures 22: Weakness zones in the surface. Eroded weakness zone/fault

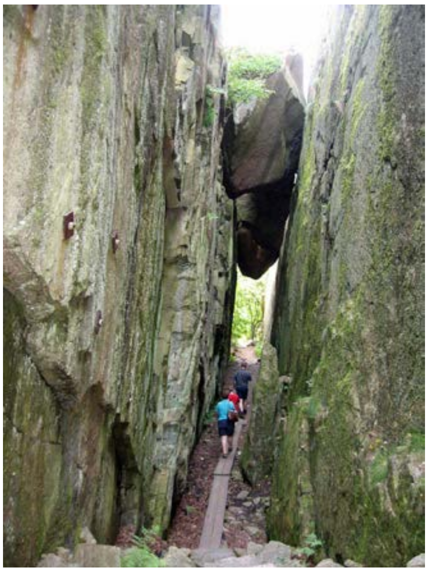


Figure 23: A cleft eroded along a moderate weakness zone

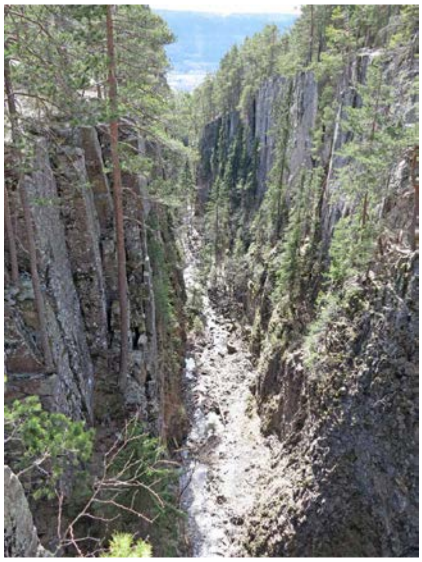


Figure 24: A very steep valley eroded along a significant weakness zone

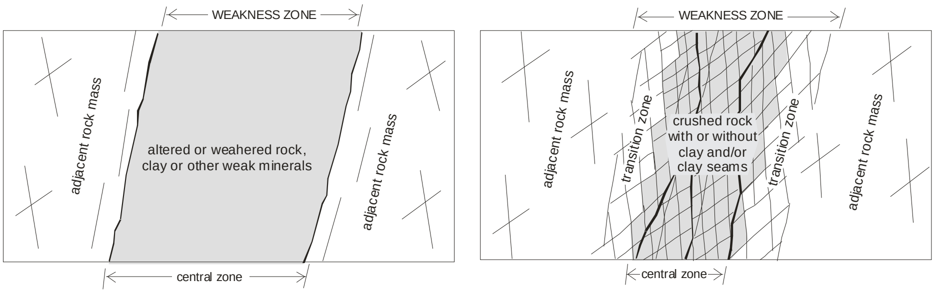


Figure 25. Sketches of the two main groups of weakness zones: Zone of *weak materials or fault* (left) and *crushed zone* (right). The transition to the surrounding, overall rock masses may be sharp (left) or gradual. A zone may be composed of one or more types of rock mass compositions in Figure 30, as shown in Table 1

Faults and weakness zones require often special attention in underground works [6], as they can have significant impact upon the stability as well as on the excavation process. For instance, flowing and running ground, which are mainly connected to weakness zones, may cause severe stability problems and delay for the construction of a tunnel. See Table 3.

As shown in Figure 7 and Table 2, a weakness zone may contain one or more of the rock masse types in Figure 6.

The behaviour of weakness zones will often behave differently than the surrounding, overall rock. Caused by a great variation in structure and a complex composition, weakness zones are often difficult to describe and characterize. Therefore, it is hardly possible to include all weakness zones in the general division shown in Table 2. As their variations in composition and size are generally too complex to be characterized correctly, [11] and [12] recommend that they are mapped and treated as regions or structures of their own, which is agreed upon by the author.

The Q and the RMi classification systems apply classifications of weakness zones. However, weakness zone may occur in many more and complicated forms as can be presented in a table. See Chapter 4.

2.3 Groundwater and stresses

2.3.1 Water inflow to excavation

A suggested classification of the inflow of water into an underground excavation has been presented by [8]:

- Dry conditions = inflow volumes < 6 dm^3/h (0.1 litres/min)
- Seepage = inflow volumes of 6 dm^3/h to 0.06 m^3/h (0.1 – 1 litres/min)
- Dripping = inflow volumes of 0.06 – 0.6 m^3/h (1 – 10 litres/min)
- Flowing = inflow volumes of 0.6 – 30 m^3/h (10 – 500 litres/min)
- Heavily flowing = inflow volumes of 30 – 300 m^3/h (0.5 – 5 m^3/min)
- Water in-burst = inflow volumes more than 300 m^3/h (> 5 m^3/min)

(The volumes are measured along 10 m length of the tunnel)

The Q system uses the classification of groundwater occurrence in an excavation shown in Table 2.

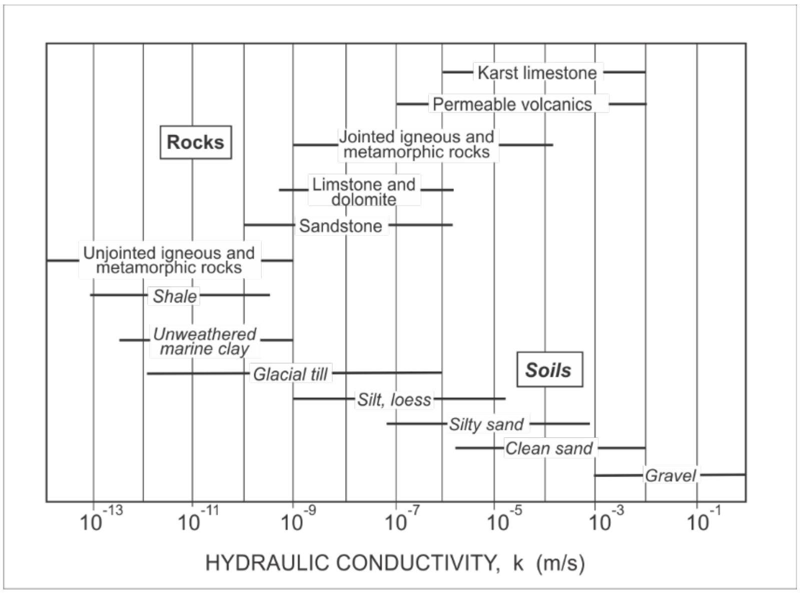


Figure 26: Some hydraulic conductivities of rock materials and of soils [7].

Table 2: The classification of groundwater inflow into an underground excavation applied in the Q system.

- Dry excavations or minor inflow, i.e. < 5 l/min locally.
- Medium inflow or pressure, occasional outwash of joint fillings.
- Large inflow or high pressure in competent rock with unfilled joints.
- Large inflow or high pressure, considerable outwash of joint fillings.
- Exceptionally high inflow or water pressure at blasting, decaying with time.
- Exceptionally high inflow or water pressure continuing without noticeable decay.

As the rock material generally is impervious[1] (see Figure 26), the joints are mostly responsible for the movement and distribution of the ground water in the rockmasses. In connection with weakness zones, the water often follows the rockmasses adjacent to the zone, especially when the zone contains clay materials.

The effect (inflow) of groundwater in an excavation below the ground table is often difficult to assess from observations and field investigations, caused by the complicated composition and structure of rockmasses.

2.3.2 Rock stresses acting

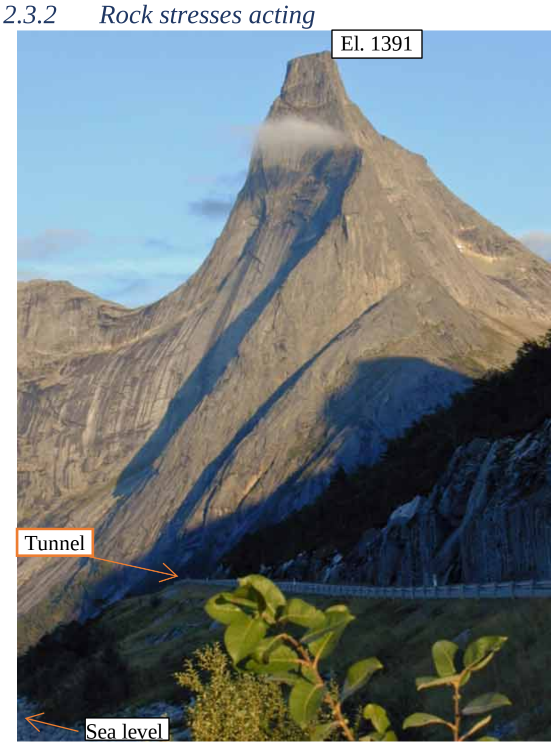


Figure 27: The Stetind mountain, 1319 metres high, Norway's national peak. A road tunnel penetrates its base, in which heavy rock burst took place during construction.

There are generally two different modes of stress problems in tunnels and caverns.

a. Rock bursting in overstressed massive, hard rocks
b. Squeezing in overstressed soft rocks, such as schistose rocks, and in overstressed densely jointed rocks.

I will not here present theories and how to estimate the rock stresses acting, but concentrate on rock stress problems by rock bursting. The experience in Norway is that rock bursting takes place in tunnels located in massive granite and gneiss when they are more than approx. 500 m below surface. This is especially the case for tunnels near the valley side where the stresses are anisotropic[2].
Remnant or residual stresses may cause rock bursting in massive rocks even when the gravitational stress (from overburden) are smaller than the 500 metres of overburden mentioned.
High, anisotropic stresses are often acting when the exposed rocks show sheeting or "stress roses" as shown in Figure 29.

Figures 27 - 29 show examples of the topography where tunnel excavation had rock bursting during construction. In all of them the rocks are massive granite or gneiss.

[1] Except of some porous rocks, e.g. sandstones.
[2] The horizontal stresses are generally high in Norway. This influences on the effect of rock bursting.

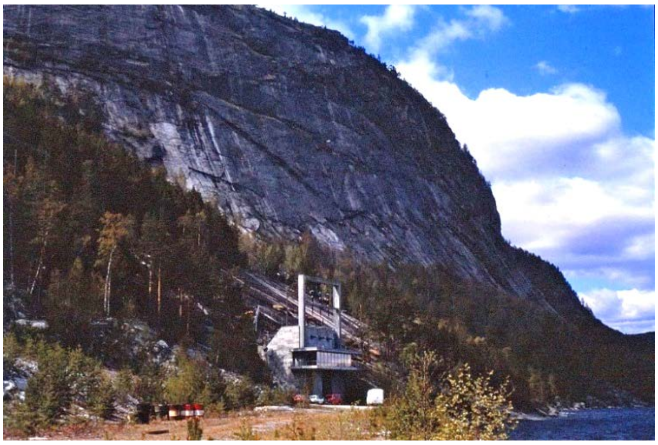


Figure 28: Entrance to the Fjone underground power station located at the foot of a large granite mountain. Severe rock bursting was experienced in the access tunnel and underground powerhouse during excavation.

Figure 29: "Stress roses" in a Norwegian valley side of massive granite. The headrace tunnel along the valley side experienced heavy rock burst.

2.4 Classification of rockmass compositions

In order to better understand the behaviour and hence the stability of an underground opening, the structure and composition of rockmasses can be classified into groups of similar properties. This is shown in Figure 30 with the following main classes for the degree of jointing:

- Classes A: Massive. Few joints or very wide joint spacings where the properties of the rock material dominate the behaviour.
- Classes B and C: Jointed or blocky, i.e. slightly to strongly jointed rock masses. Here, the joints have the main influence on the behaviour.
- Class D: Particulate rock mass, including heavily jointed or crushed rock, loose sedimentary (friable) rocks, and materials of particles, grains or fragments with no or little bonding. The behaviour in this group is a result of the interactions between the blocks or fragments, as is the case in a bulk material.
- Class E: Rocks or rock masses with special properties, different from the other four classes.

Weakness zones (Figure 31) are often composed of materials in classes D and E.

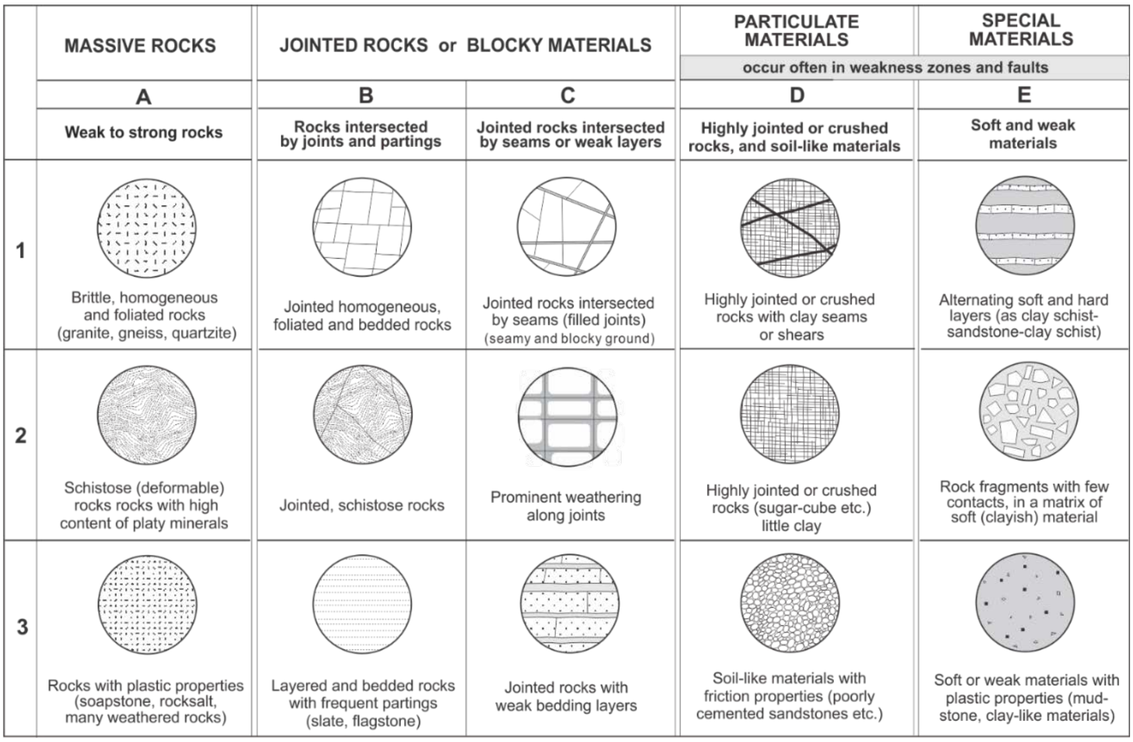


Figure 30: Main types of rock mass compositions [8].

An important rockmass feature is weathered and altered rocks, which is partly included (in class C, D or E). Such rocks may also occur in weakness zones (see Figure 31). Figure 32 presents an example of rockmass compositions along a tunnel estimated after the field investigation have been made.

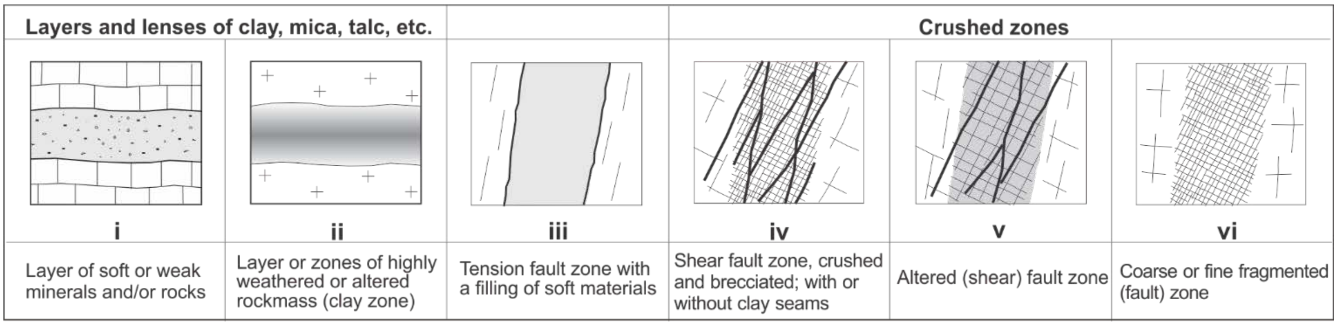


Figure 31: Main types of weakness zones

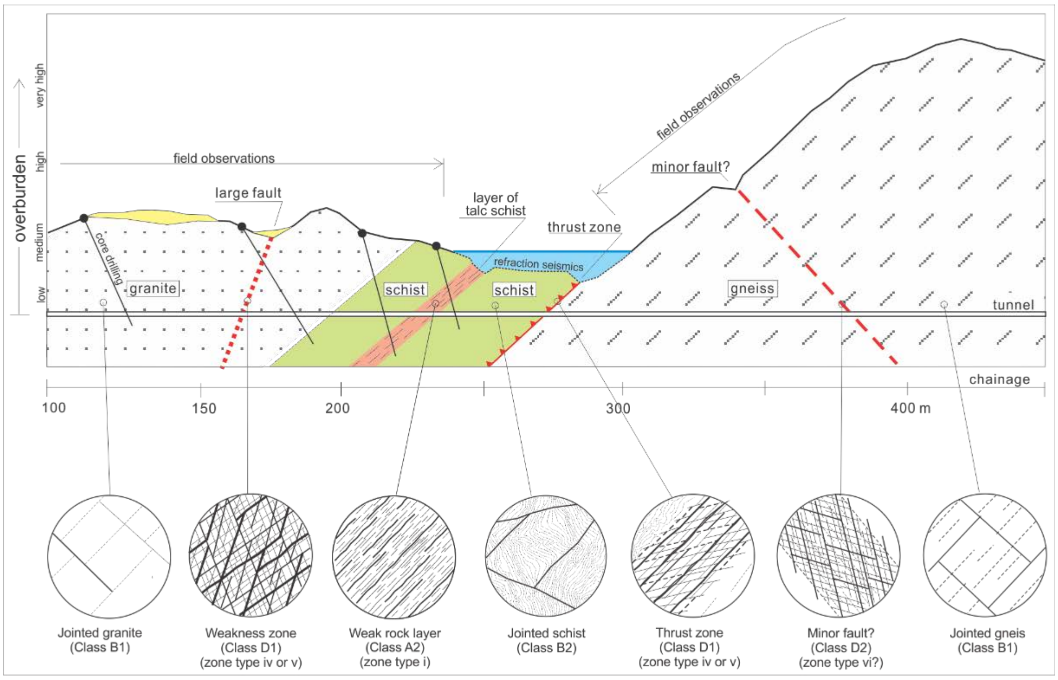


Figure 32: Example. Based on the results from field investigations, typical rock-mass compositions have been estimated along a tunnel. These can be used to work out a prognosis of the ground conditions likely to meet during tunnel excavation.

2.4.1 Some geo-materials with special properties

The properties of some special minerals and rock types may strongly influence or determine the ground behaviour in underground openings. Some of these materials are shown in Table 3. As shown, they occur in some of the rock mass compositions in Figure 30.

Table 3 Influence from some minerals and rocks showing special properties (in parts after [6])

Type of minerals and/or rocks	Description	Possible occurrence of rock mass composition types (see Figure 30)
Clay minerals	Occur either as rock constituent (e.g. in highly weathered or altered rocks) or as filling and coating material in seams and filled joints as a result of alteration and/or hydrothermal actions. A special group of clays are the smectites (swelling clay) mentioned below.	Most types
Swelling minerals (smectite, anhydrite)	Change of moisture content in swelling minerals of the smectite (montmorillonite) group can cause significant instability problems related to high swelling pressures. These minerals, occurring either as rock constituent or 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. Swelling rocks with clay are montmorillonitic shales, altered or weathered basalts or other crystalline rocks. Anhydrite is one of the major minerals in evaporite deposits; it is also present in dolomites and limestones, and as a gangue mineral in ore veins.	As rock forming mineral in C3 and E1 types. Also as filling material in seams and filled joints in C1, C2 and D1 types
Porous rocks	Such rocks may be porous sandstones and some deteriorated or decomposed rocks where parts of the minerals or mineral bonds have been dissolved. Such rocks may contain abundant of water and cause flowing ground or other water inflow problems to tunnels.	Especially in type D3
Slaking rocks	Some rocks may slake (hydrate or "swell", oxidize), disintegrate or otherwise weather in response to the change in humidity and temperature consequent on excavation.	Types C3, E1, also in types B1 and C1

Anisotropic and elastic minerals	Minerals like mica, chlorite, amphiboles, and pyroxenes may strongly influence the mechanical properties of the rocks in which they occur. Also other minerals like serpentine, talc, and graphite reduce the strength of the rock mass due to easier sliding along the cleavage or coated joint surfaces. Continuous layers of mica and chlorite may in addition cause drilling and blasting problems. Typical rocks are mica schists and some phyllites. Both show strong anisotropic properties.	Types A2, B2 + in most types of joints
Friable rocks	Loosely cemented, mostly sedimentary rocks	Type D3
Soluble minerals (calcite, salt)	Calcite is susceptible to being dissolved by groundwater. This process may cause permeable parts in calcite-containing weakness zone, as well as development of cavities in limestones (karstification). Karst cavities can form large drainage systems causing water problems during tunnelling when encountered in a tunnel.	Calcite is a rock forming mineral in limestone and marble (type A1, B1, C1, C2) and as filling in many joints
Quartz content *)	High content of especially fine-grained interlocking quartz minerals in some rocks often causes high drill bit wear and TBM cutter wear.	Some igneous, sedimentary and metamorphic rocks

*) has generally little impact on ground behaviour in excavations

A major group includes altered and weathered rocks. Both the alteration and the weathering processes lead to deterioration of the rock material with a reducing effect on its strength and deformation properties. These processes first affect the walls of the discontinuities, and may for highly weathering, completely change the mechanical properties and the behaviour of rocks. Mostly, the effect of weathering and alteration is estimated from visual observations. A more precise characterization of alteration and weathering can be found from analysis of thin sections in a microscope.

Table 4. Main types of ground behaviour in underground excavations [8].

GROUND BEHAVIOUR TYPE			DEFINITION	COMMENTS	
Type 1: Gravity driven	a. Stable		The surrounding ground will stand unsupported for several days or longer.	Massive, durable rocks at low and moderate depths.	
	b. Block fall(s)	of single blocks	Stable with potential fall of individual blocks	Discontinuity controlled failure.	
		of several blocks	Stable with potential fall of several blocks (slide volume < $10 m^3$).		
	c. Cave-in		Inward, quick movement of larger volumes (> $10\ m^3$) of rock fragments or pieces.	Encountered in highly jointed or crushed rock.	
	d. Running ground		A particulate material quickly invades the tunnel until a stable slope is formed at the face. Stand-up time is zero or nearly zero.	Examples are clean medium to coarse sands and gravels above groundwater level.	
Type 2: Stress induced	e. Buckling		Breaking out of fragments in tunnel surface.	Occurs in anisotropic, hard, brittle rock under sufficiently high load due to deflection of the rock structure.	brittle behaviour
	f. Rupturing from stresses		Gradually breaking up into pieces, flakes, or fragments in the tunnel surface.	The time dependent effect of slabbing or rock burst from redistribution of stresses.	
	g. Slabbing		Sudden, violent detachment of thin rock slabs from sides or roof.	Moderate to high overstressing of massive hard, brittle rock. Includes popping or spalling.[1)]	
	h. Rock burst		Much more violent than slabbing and involves considerably larger volumes (Heavy rock bursting often registers as a seismic event).	Very high overstressing of massive hard, brittle rock.	
	i. Plastic behaviour (initial)		Initial deformations caused by shear failures in combination with discontinuity and caused by overstressing	Takes place in plastic (deformable) rock from overstressing. Often the start of squeezing.	plastic behaviour
	j. Squeezing		Time dependent deformation, mainly associated with creep caused by over-stressing. Deformations may terminate during construction or continue over a long period	Overstressed plastic, massive rocks and materials with a high percentage of micaceous minerals or of clay minerals with a low swelling capacity.	
Type 3	k. Ravelling from slaking		Ground breaks gradually up into pieces, flakes, or fragments.	Disintegration (slaking) of some moderately coherent and friable materials. Examples: mudstones and stiff, fissured clays.	hydratization

	l. Swelling	of certain rocks	Advance of surrounding ground into the tunnel due to expansion caused by water adsorption. The process may sometimes be mistaken for squeezing.	Occurs in swelling of rocks, in which anhydrite, halite (rock salt) and swelling clay minerals, such as smectite (montmorillonite) constitute a significant portion.	swelling minerals
		of certain clay seams or fillings	Swelling of clay seams caused by adsorption of water. This leads to loosening of blocks and reduced shear strength of clay.	The swelling takes place in seams having fillings of swelling clay minerals (smectite, montmorillonite)	
	m. Flowing ground		A mixture of water and solids quickly invades the tunnel from all sides, including the invert.	May occur in tunnels below groundwater table in particulate materials with little or no coherence (and clay).	
	n. Water ingress		Pressurized water invades the excavation through channels or openings in rocks	May occur in porous and soluble rocks, or along significant openings or channels in fractures or joints.	

1) This term was often used by Terzaghi (1946) as synonymous with the falling out of individual blocks, primarily as a result of damage during excavation

2.5 Main types of ground behaviour

Failure is the result of instability. Both expressions are used rather inconsistently in the literature, as they often overlap. In such complex building material as a rock mass, several different behaviour types may occur, see Table 4. They depend on several factors, like the rock mass composition, the effect of stresses and groundwater acting as well as the size of the underground excavation.

For a certain rock mass or a weakness zones, some of the behaviour types are mutually exclusive, while in other cases, the same rock mass and tunnel section may contain two or more possible types of failures. Combinations of behaviour types may often occur, especially block falls in combination with, for example, swelling, rupturing, and plastic behaviour. These often take place in weakness zones.

3 ON ROCK ENGINEERING CLASSIFICATION SYSTEMS

3.1 Main classification systems

3.1.1 The Terzaghi system

Terzaghi [19] launched his rockmass classification system for rock support in 1946 after numerous site visits to tunnelling projects, most of them in North America. Even today, more than 70 years later, it is very interesting to read the 150 pages Terzaghi presented. It contains a lot of useful information on the geology, rockmass features and support considerations. The classification is as follows:

1. Rock tunnels in unweathered (fresh), stratified rocks and in schists
2. Tunnels through moderately jointed, massive rocks
3. Tunnels in crushed rock
4. Tunnels in blocky and seamy rock
5. Earth pressure phenomena in decomposed rock and in clay
6. Tunnels in squeezing rock
7. Rock pressure in swelling rock.

The Terzaghi classification is further described in the Appendix.

Terzaghi concluded that knowledge of the type and frequency of the rock discontinuities often is more important than of the types of rock to be encountered. However, the support estimate is outdated, as most support is composed of steel sets and steel liner plates.

3.1.2 The rock quality designation (RQD) method

The RQD was developed by [9] to provide a quantitative estimate of rockmass quality (i.e. the degree of jointing) through logging of drill cores. It is defined as 'the percentage of intact core pieces longer than 100 mm in the total length of core'. The RQD is an easy and quick measurement, as only certain core pieces (longer than 10 cm) are included. It is, therefore, frequently used in core logging for measuring the degree of jointing along the core drill hole. The most important use of the RQD is as a component of the RMR and Q systems.

3.1.3 The RMR (Rock Mass Rating) system

The RMR or the Geomechanics classification system was first published in 1973 by Bieniawski [10]. Significant changes have been made over the years, with revisions in 1974, 1976, and 1989 ([11], [12], [13]). The following six parameters are used to classify a rockmass in the RMR system:

1. uniaxial compressive strength of rock material
2. RQD value
3. spacing of discontinuities
4. condition of discontinuities
5. groundwater conditions
6. orientation of discontinuities.

Numerical ratings of these input parameters are found from tables, see Table 9 in the Appendix. The values of each of these parameters are summarised to give a value for the RMR. The calculated RMR value may be used to find which of five predefined rockmass classes the rockmass belongs to. All parameters can be characterized in the field, and some of them may also be obtained from borehole data.

3.1.4 The Q system

The *Q* system was originally developed for rockmass and ground classification with the aim of being a helpful tool for evaluating the need for support in tunnels and rock caverns. It was first published in 1974 by Barton et al. [14], based on evaluations of a large number of tunnel case histories. It is a quantitative classification system expressing the ground (stability) quality.
The *Q* values are combined with the dimensions of the tunnel or cavern in a *Q* support chart (see Figure 47 in the Appendix). From engineering geological observations in the field, in tunnels or from logging of rock cores, the ratings for the different input parameters can be found from a set of tables with a number of footnotes. The numerical value of the index Q is defined by six parameters and the following equation:

$$Q = \frac{RQD}{Jn}\,\frac{Jr}{Ja}\,\frac{Jw}{SRF}$$

where
RQD = rock quality designation
Jn = joint set number
Jr = joint roughness number
Ja = joint alteration number
Jw = joint water reduction factor
SRF = stress reduction factor

SRF is the most complicated, empirical factor, and has been debated in several papers and workshops. It should be given special attention, as it represents four groups of rockmasses:
1. stress influence in brittle blocky and massive ground (rock bursting);
2. stress influence in deformable (ductile) rockmasses (squeezing);
3. weakness zones (poor rockmass conditions);
4. swelling rock.

The *Q* system is normally used as an empirical design method for rock support. Together with the ratio between the span or wall 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.

3.1.5 The RockMass index (RMi) system

<u>The basic RMi value (for rockmasses)</u>

The rockmass index (RMi) is a volumetric parameter indicating the approximate uniaxial compressive strength of a rockmass. The system was first presented by Palmström in 1995 [1], and has been further developed in several 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 = $\sigma_c \cdot JP$ for jointed rockmasses [3]

In massive rock, i.e. few joints intersect the rock, the reducing effect of the joints is small, the RMi is given as:

RMi = $\sigma_c \cdot f_\sigma$ for massive rock (this is where $f_\sigma > JP$, i.e. the block volume Vb > ~5 m^3)

The *massivity parameter* (f_σ) represents the scale effect of the uniaxial compressive strength (from rock samples (cm^3) to rock volumes (m^3) has a value of $f_\sigma \approx 0.5$).

The jointing parameter (*JP*) is related to
- The block volume (V_b) by empirical relations as shown in Figure 33, and
- The joint condition factor (*jC*) which is a combination of:

[3] The RMi can be adjusted for the low or high interlocking of the rockmass, as is further described in Section 5.4.1 in the Appendix.

- *jR* = joint roughness factor
- *jA* = joint alteration factor
- *jL* = the joint size and continuity factor

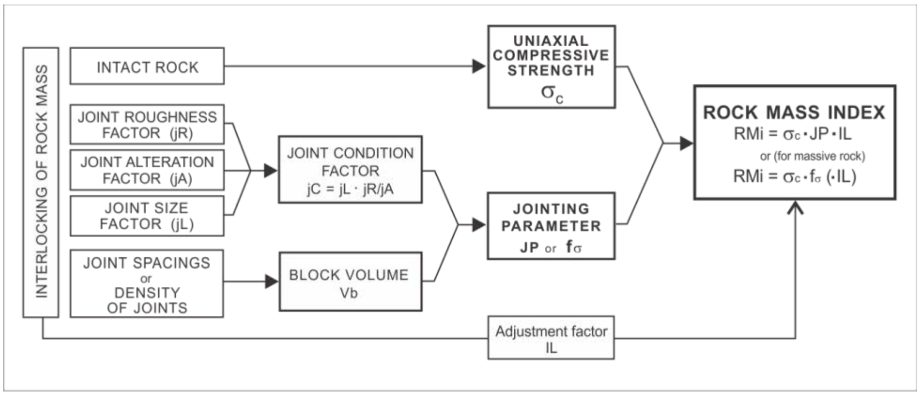


Figure 33: The input parameters used in the RMi basic system [1].

The *jR* and *jA* are almost the same as Jr and Ja in the *Q* system. The RMi value can be used as an input in other rock engineering methods, such as numerical modelling, the Hoek-Brown failure criterion for rockmasses, and to estimate the deformation modulus for rockmasses [15].

<u>Support estimate using RMi</u>

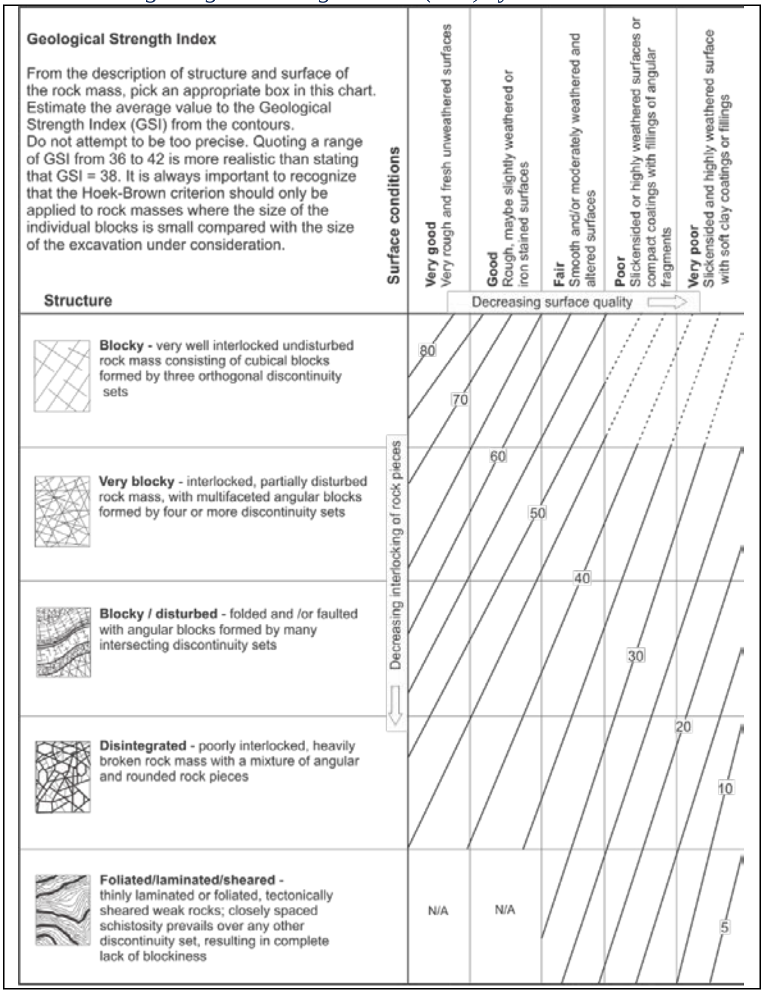
RMi can be used for estimating rock support, as presented in Section 5.4.2 in the Appendix. For support, the RMi value is adjusted for groundwater and rock stresses, and for the orientation of joints and weakness zones. Support estimates in the RMi system are obtained by two different approaches [1], [16]:

1. *Continuous ground*, i.e. massive rocks and strongly jointed rocks. To estimate the support, the ratio between the rockmass strength (RMi) and the tangential stresses is used. A chart based on this has been produced for slabbing and bursting rock and for squeezing rock, see Figure 52 in the Appendix.
2. *Discontinuous (blocky) ground*. The support estimate found from a chart (Figure 51) based on the *ground condition factor* (G_c), which is found from the RMi value combined with the following parameters (see Section 5.4.2):
   – rock stresses
   – tunnel wall and other inclined tunnel surfaces
   – water inflow.

The other factor used in the rock support chart is the size ratio (S_r), representing the ratio between the dimension of the tunnel or cavern (span or wall height) and the average dimension (diameter) of the blocks adjusted for the number of joint sets and the orientation of the main joint set.
In addition, support of weakness zones can crudely be estimated using the support chart in Figure 51.

The two support charts have been developed from analyses of several projects as well as personal experience from numerous other underground constructions in hard rock.

3.1.6 The geological strength index (GSI) system



The GSI system was presented in 1994 by Hoek and Brown [17]. It is a system for estimating the rockmass strength for different geological conditions from field observations. The rockmass characterisation is straightforward and based on the visual impression of the rock structure, in terms of the degree of jointing (block size) and joint characteristics (roughness and alteration). Note that there is no input for the strength of the rock material.

Figure 34: The GSI value can be found from this chart [17].

3.2 Correlation between the main classification systems

To improve the classification results, Bieniawski [12], [13] advises that at least two classification systems are used when the rock engineering and design are based on such empirical tools. This recommendation is by many rock engineers solved by finding the value for rockmass quality in one classification system from a value in another by applying some sort of transition equation(s). The best-known of these transitions is between the Q and the RMR systems, as presented in Figure 35. This is, however, a crude approximation where there is an inaccuracy of +/- 50% or more between these two systems. Thus, severe errors may be imposed, which reduce the quality of the rock engineering, such as support estimates. This may for example, happen for rock bursting where RMR does not cover such condition.

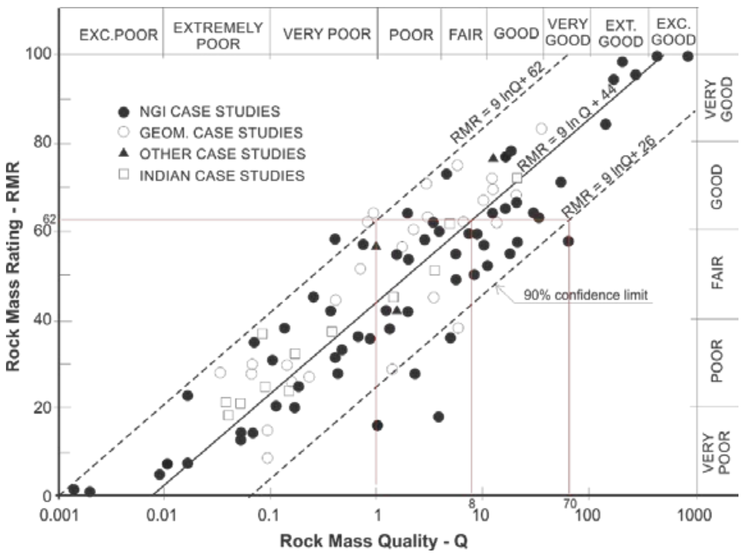


Figure 35: Correlation between RMR values and Q values [12]. From the centre correlation line (RMR = 9lnQ + 44) there is a severe inaccuracy. As shown, Q varies between 1 and 70 for RMR = 62.

Table 5: Main geological parameters contributing to ground quality and stability. The applications of these parameters in four classification systems are shown.

<table>
<tr><th colspan="5">Ground parameters</th><th colspan="2" rowspan="2">Symbol $^{9)}$</th><th colspan="3">Use in classification systems:</th></tr>
<tr><td rowspan="19">GROUND</td><th colspan="4">Rockmass parameters</th><th>Q</th><th>RMR</th><th>RMi</th></tr>
<tr><td rowspan="16">ROCKMASS</td><td rowspan="2">Rock</td><td colspan="2">Uniaxial compressive strength $^{3)}$</td><td colspan="2">σ_c or UCS</td><td></td><td>x</td><td>x</td></tr>
<tr><td colspan="2">Weathering $^{4)}$</td><td colspan="2"></td><td></td><td>(x)$^{8)}$</td><td>(x)$^{8)}$</td></tr>
<tr><td rowspan="3">Degree of jointing</td><td colspan="2">Rock quality designation</td><td colspan="2">RQD</td><td>x</td><td>x</td><td></td></tr>
<tr><td colspan="2">Block volume</td><td colspan="2">Vb</td><td></td><td></td><td>x</td></tr>
<tr><td colspan="2">Joint spacing or Block diameter</td><td colspan="2">Sa or Db</td><td></td><td>x</td><td>x$^{1)}$</td></tr>
<tr><td>Rock mass</td><td colspan="2">Rockmass interlocking and structure</td><td colspan="2">IL and β</td><td></td><td></td><td>x$^{2)}$</td></tr>
<tr><td rowspan="2">Jointing pattern</td><td colspan="2">Number of joint sets in the location</td><td colspan="2">Jn or Nj</td><td>x</td><td></td><td>x$^{1)}$</td></tr>
<tr><td colspan="2">Orientation of main joint set</td><td colspan="2">Co</td><td></td><td>x</td><td>x</td></tr>
<tr><td rowspan="5">Characteristics of joints in main joint set</td><td rowspan="2">Joint roughness</td><td>smoothness</td><td rowspan="2">Jr</td><td>js</td><td rowspan="2">x</td><td>x</td><td>x</td></tr>
<tr><td>waviness</td><td>jw</td><td></td><td>x</td></tr>
<tr><td colspan="2">Joint alteration</td><td colspan="2">Ja or jA</td><td>x</td><td>x</td><td>x</td></tr>
<tr><td colspan="2">Joint size (persistence), continuity</td><td colspan="2">jL</td><td></td><td></td><td>x</td></tr>
<tr><td colspan="2">Joint aperture or Separation</td><td colspan="2">e</td><td></td><td>x</td><td></td></tr>
<tr><td rowspan="3">Weakness zone</td><td colspan="2">Size / thickness of zone</td><td colspan="2">Tz</td><td></td><td></td><td>x$^{1)}$</td></tr>
<tr><td colspan="2">Orientation of the zone</td><td colspan="2">Co_w</td><td></td><td></td><td>x$^{1)}$</td></tr>
<tr><td colspan="2">Type of zone $^{5)}$</td><td colspan="2">SRF</td><td>x</td><td></td><td>$^{7)}$</td></tr>
<tr><td colspan="2">Rock stresses</td><td colspan="2">Rock stress factor or Stress level</td><td colspan="2">SRF or SL</td><td>x</td><td></td><td>x$^{1)}$</td></tr>
<tr><td colspan="2">Ground water</td><td colspan="2">Water pressure or Water inflow</td><td colspan="2">Jw or GW</td><td>x</td><td>x</td><td>x$^{1)}$</td></tr>
<tr><td></td><td colspan="6">Special materials responsible for swelling, durability, slaking, abrasiveness etc.</td><td>(x)$^{6)}$</td><td></td><td></td></tr>
<tr><td colspan="5">$^{1)}$ Used in the RMi support method
$^{2)}$ Included in the extended RMi system
$^{3)}$ Can be crudely calculated from simple field test or from rock name
$^{4)}$ Weathering tends to reduce the rock strength; therefore, the effect is generally included in the σc</td><td colspan="5">$^{5)}$ Needs special description to be appropriately used as input
$^{6)}$ The Q-system includes input of swelling
$^{7)}$ Approximate RMi values are given in Table 7
$^{8)}$ This effect is indirectly included in the σ_c
$^{9)}$The RMR system does not use symbols for many of the input parameters</td></tr>
</table>

Where exposed rock can be observed, most of the parameters in Table 5 can be observed and the values of input parameters determined, see Figure 37. Some of the parameters can also be found from observations on drill cores. The parameters for rocks and jointing characteristics can usually be well observed during field mapping[4], while the parameters for groundwater and stresses in the underground excavation can only be assumed if observations are made at terrain surface.[5]

The geo-registrations scheme (Figure 36) is a documentation of the site conditions. For documentation and use in the report from the investigation, the field registrations can be transferred to a computer spreadsheet[6] in which ground qualities in three classification systems can be calculated independently.[7]

It is important to bear in mind that most empirical methods in rock engineering give averaged values, and that there might be significant variation between the lowest and highest values. The input parameters in Figure 36 represent all three classification systems. Thus, from a set of input parameters in a location, the values in all three systems can be found. The use of spreadsheets is of great benefit here.

Some comments to the scheme: The white cells in the 'Field observation and/or measurements' part can in the computer be marked with a fill colour indicating the characteristic class of the actual property. This part is the documentation of the field observation and characterization made. Caused by the interpretation made, the rating (letter) given in the 'Input column' may be different than the observed one.

[4] Provided that there is only limited degree of rock weathering.
[5] In addition to the geo-observations, laboratory and field test are required to find values for some of the parameters used in FEM and other calculations.
[6] The spreadsheet can be downloaded from www.rockmass.net.
[7] This can be made because the three systems partly use the same input parameters.

GEO-CALCULATIONS (write text in green cells)			Project:	example			Locality:		Observer:	RKS		Date:	2017-06-13
			FIELD OBSERVATIONS and/or MEASUREMENTS							interpretation →		INPUT for calculations	
Locality	Type of locality		outcrop	cutting	in tunnel	Size of locality =	20 m2	Orientations of main joint set(s)				For observations been made at surface, some **interpretations** are often made to estimate the ground conditions at tunnel level. Approximate distance from obser-vation to the excavation =	
								strike (°)	dip (°)	dip direction	spacing (m)		
	Description of locality		A flat outcrop surrounded by loose deposits					**N80E**	**90**		**0.3-0.6**		
Rock	Type of rock and description		Folded gneiss with lenses of quartz with alternating light grey and meduim grey layers or lenses					N30W	60	NE	0.5-2		
	Weathering of rock[1]		fresh	slightly	moderately	highly	completely						
			-	-	-	-	-	some random joints					200 m
	Rock strength	UCS	< 1MPa	1 - 5 MPa	5 - 25MPa	25 - 50MPa	50 - 75MPa	75 - 100MPa	100-150MPa	150 - 250MPa	> 250MPa	UCS =	**g**
			a	b	c	d	e	**f**	g	h	i		
Degree of jointing (fill in for RQD and/or Vb and/or Jv)	RQD	RQD	< 10	10 - 25	25 - 40	40 - 50	50 - 60	60 - 75	75 - 90	90 - 100	100	RQD =	
			a	b	c	d	e	f	g	h	i		
	Block volume	Vb	< 1cm3	1 - 100cm3	0.1 - 1dm3	1 - 15dm3	15 - 125dm3	0.125- 1m3	1 - 8m3	8 - 50m3	> 50m3	Vb =	**f**
			a	b	c	d	e	f	g	h	i		
	Vol. joint count (joints/m3)	Jv	> 60	60 - 45	45 - 30	30 - 20	20 - 10	10 - 5	5 - 3	3 - 1	< 1	Jv =	
			a	b	c	d	e	f	g	h	i		
	Joint spacing	Sa	> 2 m	0.6-2m	0.2 - 0.6 m	0.06 - 0.2m	< 0.06m	(This is the smallest joint spacing, often the main joint set)				Sa =	
			a	b	c	d	e						
Rockmass condition	Interlocking (IL) and structure	IL	very tight	tight	poor	**Block shape**	cubical	slightly long or flat	mod. long or flat	very long or flat	extr. long or flat	IL =	**b**
			a	**b**	c	(β)[1] →	a	**b**	c	d	e	β =	
Jointing pattern	Number of joint sets	Jn	random only	1 joint set	1 set + random	2 joint sets	2 sets + random	3 joint sets	3 sets + random	4 joint sets	crushed	Jn or Nj =	**d**
			a	b	c	d	e	f	g	h	i		
	Orientation of main joint set	Co	very favourable	favourable	fair	unfavourable	very unfavour.	**Strike/dip (°) of main set →**		N80/90		Co roof =	**a**
			a	**b**	c	d	e	related to tunnel axis =		70 / 90		Co wall =	**d**
Charac-teristics of joints in main joint set	Joint roughness (Jr) – Joint smoothness	js	very rough	rough	slightly rough	smooth	polished	slickensided	filled joint (seam)	(Jr = jw x js)		js =	**c**
			a	b	**c**	d	e	f	g				
	Joint roughness (Jr) – Joint planarity	jw	discontinuous	strongly undul.	mod. undul.	slightly undul.	planar	filled joint (seam)				jw =	**d**
			a	b	c	**d**	e	f					
	Joint alteration (Ja) – A. without filling	Ja or jA	healed	fresh	slightly weath.	weathered	sand/silt coat.	clay coating	**Direction(°) → of tunnel or cavern**		N10E	Ja or jA =	**b**
			a	**b**	c	d	e	f					
	Joint alteration (Ja) – B. with filling		sand /silt	hard clay	soft clay	swelling clay		sand /silt	hard clay	soft clay	swelling clay		
	filling < 5mm →		h	j	l	n	filling > 5mm →	i	k	m	o		
	Type of joints (joint length)	jL	crack	fissure	very short joint	short joint	mod. joint	long joint	seam (filled joint)	← (short joint = 1 - 3m) (mod. joint = 3 - 10m)		jL =	**e**
			a	b	c	d	**e**	f	g				
	Joint separation	e	none	< 0.1mm	0.1 - 1mm	1 - 5mm	5 - 25mm	(The gap between the two joint walls)				e =	**b**
			a	**b**	**c**	d	e						
Weakness zone (fault zone)	Size (thickness) of zone	Tz	no zone	very small	small 0.3-1m	moderate 1-3m	large 3-10m	v. large 10-30 m	**Indicate if thickness** of zone is larger than 30 m →			Tz =	
				a	b	c	d	e					
	Orientation of zone	Coz	very favourable	favourable	fair	unfavourable	very unfavour.			related to North	related to tunnel	Co_z roof =	
			a	**b**	c	d	e	**Strike/dip (°) of zone →**				Co_z wall =	
	Type of zone	SRF	complex zone	clayzone <50m	clayzone >50m	freq. shears	simple <50m	simple >50m	crushed zone		no zone	SRF =	**c**
			j	k	l	m	n	o	p				
Stress level or stress type			stress at surface	low stress	moderate stress	high stress	slight burst	mod. burst	strong burst	mild squeeze	high squeeze		
			a	b	**c**	d	e	f	g	h	i		
Groundwater conditions / inflow		Jw	dry / above GWL	damp	wet	dripping	gushing	flowing	inburst			Jw =	**b**
			a	**b**	c	d	e	f	g				
Description of weakness zone								**CALCULATED GROUND QUALITY**					
								Q_{roof} =	**43,581**	*very good*	Q_{wall} =	217,906	
Information / comments			As it is 250 to 300 m from observed terrain surface to tunnel, some interpretations are made					RMR_{1989} =	**79**	*good*	**RMi =**	**26,295**	*high*
								[1] For information only		RMi indicates approximately the rockmass compr. strength (MPa)			

Figure 36: Form used for registration of observation of rockmass conditions covering the RMR, Q and RMi systems. Classification of input parameters shown in yellow cells; the grey cells mark the actual *observed class*. The input parameters on the right side are the interpretation made to estimate the conditions at tunnel level. The spreadsheet automatically calculates the Q, RMR and RMi values

The comparisons made between the three classification systems show that there are inaccuracies between them in their ability to arrive at the same ground quality with respect to instability in an excavation. Therefore, during the field characterisation and description, it is important to select a relevant size for the observation area. Generally, it should be related to the size of the tunnel, and some 3 - 5 m length along the tunnel. This condition is of particular importance when measuring the number of joint sets.

4 SOME COMMENTS ON THE COLLECTION OF GEOLOGICAL INFORMATION

This is a wide topic, only shortly commented upon here. My main aim is to point out:

1. Difficulties in investigations and to evaluate/interpret the rockmass conditions in the underground tunnel or cavern before excavation
2. Difficulties and inaccuracies in describing correctly when the rockmass conditions can be observed (e.g. at site)
3. The limitations in the calculating/estimating tools available.

4.1 Field investigations and interpretations

Very much of the investigations performed for an underground excavation take place on the terrain surface. Some of the limitations here can be summarized as:

- Core drilling: There are inaccuracies in the drilling process and in the core logging.
- Geology: Inaccuracies in the geological setting and in the types of rock used.
- Joint survey: Inaccuracies in the description of the degree of jointing, and in the joint characteristics.
  - Except for observations during and after excavation, it is seldom possible to observe the composition, size and structure of faults/weakness zones,
  - The conditions observed at the surface may not be representative for the conditions in the underground excavation.

Information from construction of existing nearby tunnels or caverns are important in the engineering geological evaluations, especially when these are in the same geological regime.

Uncertainties in geology and in inaccuracies in the characterization of the investigation results cause that the rockmass and ground conditions will be approximate and sometimes inaccurate. Figure 37 shows some of the difficulties involved in the estimated quality of the ground from investigations performed from the terrain surface before construction.

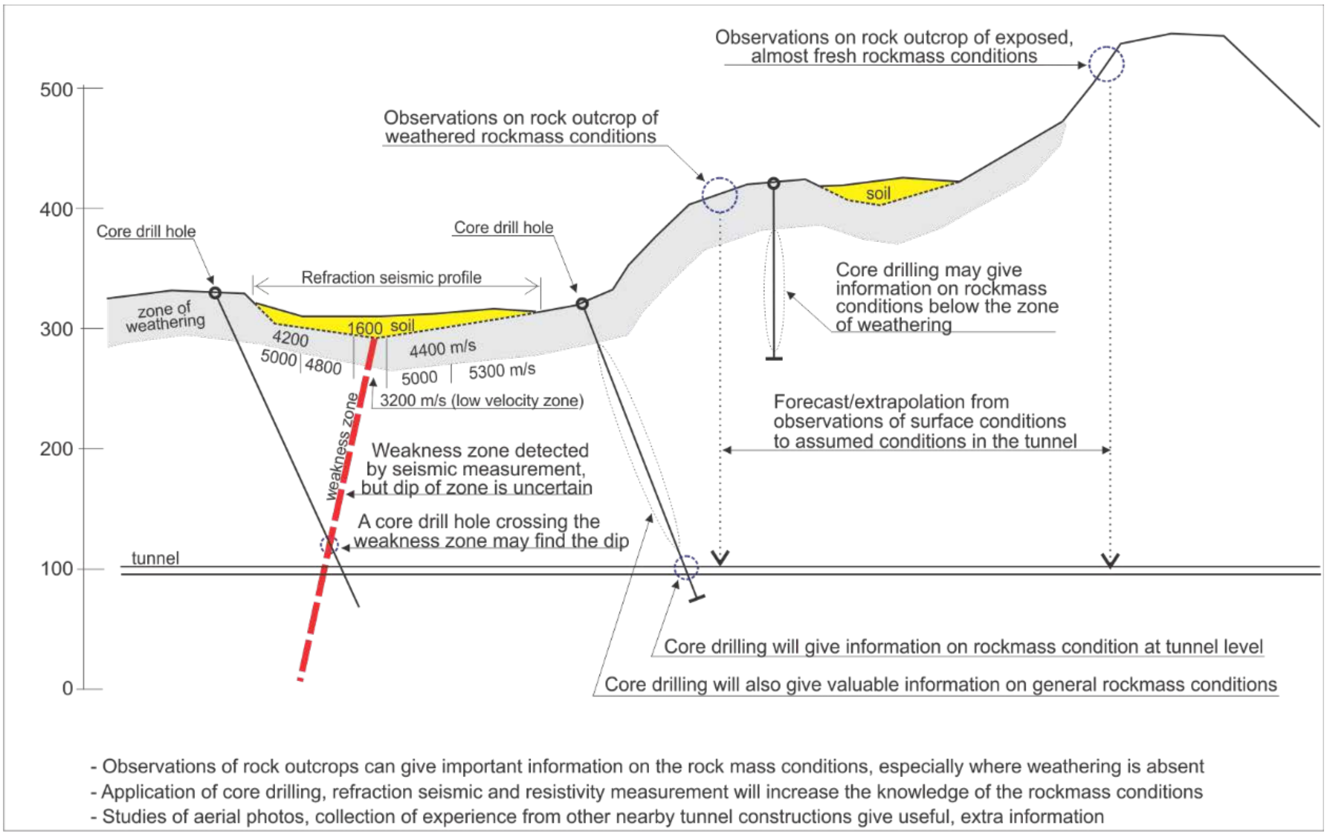


Figure 37: Various principle investigation methods to collect rockmass information and to estimate the conditions in an underground excavation (tunnel).

In outcrops with fresh or slightly weathered rockmasses (Figure 38), engineering geological observations will give valuable information on the ground conditions. Where there are none or few rock outcrops in the area (Figure 39), little information on the underground, geological conditions can be found from surface observations. Core drillings or other drillings, refraction seismic measurements and other geophysical measurements must be made to collect information on the rockmasses. Also, where significant weathering occurs at the surface, such investigations are necessary.

Figure 38: Interpretation of aerial photos of exposed, almost fresh rocks gives valuable information rockmass conditions. Combined with field observations, good assessments can be made of the conditions in the planned tunnel or cavern.

Figure 39: Photo of area with loose materials. In such conditions, little information of the rockmass conditions can be found. Hence, a large volume of costly investigations must be carried out.

4.2 Characterization of the rockmass conditions in the excavation

When the rockmass conditions can be observed and mapped/described in outcrops or in the tunnel, there may generally be difficult to correctly describe the rockmass conditions correctly. Some problems during the mapping may be as follows:

- Inaccurate characterization of joints and the degree of jointing (block size distribution).
- Wrong or inaccurate rock properties are described.
- The properties of possible clay or other special materials are not fully understood or detected.
- Difficult to assess the magnitude and distribution of the rock stresses acting.
- Weathering may hide the real rockmass conditions below the zone of weathering.
- The effect of groundwater is often difficult to estimate.

A few examples of joining are shown in Figures 40 – 41, indicating that to give a simple description useful in the estimate of the site conditions can be challenging.

Figure 40: Irregular jointing. How to estimate RQD or block size correctly here?

Figure 41: Irregular jointing. Block sizes varying from 1 dm^3 to 100 dm^3. What block size (or RQD) to be applied?

It is even more difficult to make a good description of a fault (weakness) zone. As earlier described in Section 2.2, weakness zones consisting of numerous types and sizes, are often difficult to observe and to characterize correctly. Figures 42 – 45 illustrate this. Only in the tunnel or in blasted rock cuttings the composition and size (thickness) of the weakness zone can be sufficiently observed. But as the figures show, the composition of the zones can vary much.

Figure 42: Part of weakness zone (coarse fragmented zone)

Figure 43: Weakness (crushed) zone. A central core of sand/clay, filled joints (shears?) branch out.
A borehole along the zone will give completely different results compared to a borehole across the zone.

Figure 44: A small weakness zone with thin seams of swelling soil/clay

Figure 45: Drill cores from a weakness zone. It is very difficult to assess the outlook/characteristics of the zone from such information.

Investigation by core drilling is often difficult. Often no cores can be taken (core loss) when boreholes penetrate weakness zones, i.e. no information other than poor conditions is found. The main information may be whether the zone contain clay. If cores have been taken (see Figure 45) they may e.g. show crushing and a content of possible gouge (clayish) material. From this limited information, the structure of the weakness zone can hardly be found, but sometimes the size (thickness) of the zone is approximately found. It may, however, sometimes to estimate the type of zone according to Table 1, Table 6 or Table 7.

The Q and the RMi classification systems use approximate ground qualities from a few important features, see Tables 6 and 7. But the ground quality found from input of these features must be considered as very approximate.

Table 6: The classification of weakness zones applied in the Q system. The size of the zone (thickness) is not included in the rock support estimation in the Q support chart in Figure 47.

Types of weakness zones	Approximate, typical input values					Value of SRF given	Approx. Q value
	RQD	Jn	Jr	Ja	Jw		
Multiple weakness zones with clay or chemically disintegrated rock, very loose surrounding rock (any depth)	10	20	1	12	0.66	**10**	**0.003**
Single weakness zones containing clay or chemically disintegrated rock (depth of excavation < 50 m)	10	15	1	12	0.66	**5**	**0.07**
Single weakness zones containing clay or chemically disintegrated rock (depth of excavation > 50 m)	10	15	1	12	0.66	**2.5**	**0.015**
Multiple shear zones in competent rock (clay-free), loose surrounding rock (any depth)	10	12	1	4-8	0.66	**7.5**	**0.009-0.018**
Single shear zones in competent rock (clay-free), loose surrounding rock (depth of excavation < 50 m)	10	12	1	4-8	0.66	**5**	**0.014-0.028**
Single shear zones in competent rock (clay-free), loose surrounding rock (depth of excavation > 50 m)	10	12	1	4-8	0.66	**2.5**	**0.028-0.055**
Loose, open joints, heavily jointed or "sugar-cube", etc. (any depth)	10	15	1	4	0.66	**5**	**0.022**

Table 7: Typical values of the rock mass index (RMi_z) for various types of weakness zones. (Also, the thickness of the zone is used in the RMi support estimation (revised from [16])

Type of weakness zones	Approximate, typical input values				Approximate, typical value
	uniaxial compressive strength	joint condition factor	block size		
			volume	diameter	
	σ_c	jC	Vb	Db **)	**RMi_z**
	strength of rock blocks				
Coarse fragmented zones	50 - 100 MPa	0.5	0.01 m^3	0.2 m	**1 - 2**
Small fragmented zones	100 MPa	0.5	0.0001 m^3	0.05 m	**0.3**
Clay-rich (simple) zones	80 MPa	0.1	0.01 m^3	0.2 m	**0.3**
Clay-rich (complex) zones	20 - 40 MPa	0.1	0.001 m^3	0.1 m	**0.02 - 0.04**
Clay zones *)	strength of clay material 1 MPa	0.15 (nominal)	10 cm^3 (nominal)	0.02 m (nominal)	**0.002**

*) For zones containing mainly clay, approximate support estimates may be carried out using a nominal block volume of Vb = 10 cm^3
**) Used as input in the RMi rock support estimate

Caused by the difficulties in describing and measuring the conditions in weakness zones, i.e. classes F and G ($Q < 1$) in the Q system (Figure 46), are encumbered with uncertainties. The engineering geological evaluations should be done carefully, and there is a question whether the Q system is covering the conditions in a proper way [18]. For the conditions in faults and weakness zones, the supports should be checked or designed by complimentary engineering methods.

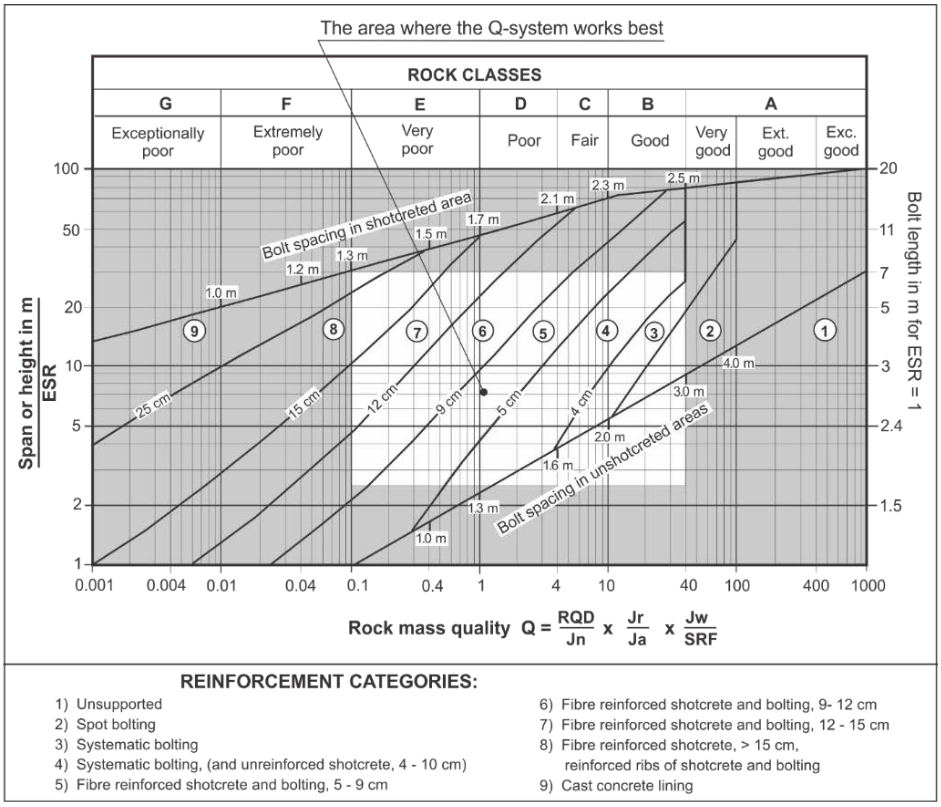


Figure 46: Limitation of the Q system [18].

5 NOMENCLATURE

Alteration = A process which involves changes in the composition of rocks caused by hydrothermal solutions and chemical weathering.

Decompose = Break down into component elements or simpler constituents.

Discontinuity = A plane or surface that marks a change in physical or chemical characteristics in a soil or rockmass. A discontinuity can be, for example, a bedding, schistosity, or foliation plane; a joint, crack, fracture, fissure cleavage, or a fault plane. A discontinuity makes a soil or rock mass anisotropic.

Disintegrate = Break up into small parts, typically as a result of impact or decay / deterioration.

Fault = Fracture or fracture zone along which there has been displacement of the sides relative to one another parallel to the fracture.

Fault gouge = Pulverized, claylike material, commonly a mixture of minerals, found along some faults; a slippery mud that coats the fault surface or cements the fault breccia. It is formed by the grinding of rock material as the fault developed, as well as by decomposition caused by circulating solutions.

Fault zone = Fault that is expressed as a zone of numerous small fractures or of fault breccia or gouge. A fault zone may be hundreds of meters wide.

Friable = Term for a soil that crumbles very easily in the hand.

Ground = The in-situ rock mass subjected to stresses, ground water, and other external factors.

Joint = Geological definition: A discontinuity of natural origin along where it has been no visible displacement. In rock engineering and engineering geology joint is used as a scale term and therefore also includes minor shear ruptures.

Jointing = The occurrence of joint sets forming the system or pattern of joints as well as the amount or intensity of joints.

Massive = Structural term for an igneous or metamorphic rock with homogeneous texture over large areas, i.e. with no layering, foliation or other planar structures. May also be applied to sedimentary rocks with no evidence of stratification (i.e. no bedding or lamination).

Massive rock = Few joints or very wide joint spacing.

Rockmass = Rocks penetrated by discontinuities, i.e. the structural material which is being excavated and in which the tunnel or underground opening is located.

Slaking = Breaking-up, crumble or disintegration of a rock or soil when exposed to moist air, saturated or immersed in water.

Singularity = Small weakness zone or seam.

Weakness zone = A part or zone in the ground in which the mechanical properties are significantly lower than those of the surrounding rock mass. Weakness zones can be faults, shears / shear zones, thrust zones, weak mineral layers, etc.

Weathering = Refers to the various processes of physical disintegration and chemical decomposition that occur when rocks at the Earth's surface are subjected to physical, chemical, and biological processes induced or modified by wind, water, and climate.

APPENDICES – SOME DETAILS OF ROCK ENGINEERING CLASSIFICATION SYSTEMS

5.1 The Terzaghi system

Table 8: The Terzaghi ground classification [19].

Type of rock mass		Description
1	Hard and intact	*Intact rock* contains neither joints nor hair cracks. Hence, if it breaks, it breaks across sound rock After injury to the rock due to blasting, spalls may drop off the roof several hours or days after blasting. This is known as the *spalling* condition. Hard, intact rocks may also be encountered in the popping condition, involving the spontaneous and violent detachment of rock slabs from the sides or roof.
2	Hard stratified and schistose	*Stratified rock* consists of individual strata with little or no resistance against separation along the boundaries between strata. The strata may or may not be weakened by transverse joints. In such rock, the spalling condition is quite common.
3	Massive and moderately jointed	Moderately jointed rock contains joints and hair cracks, but the blocks between joints are locally grown together or so intimately interlocked that vertical walls do not require lateral support. In rocks of this type, both the spalling and the popping conditions may be encountered.
4	Moderately	*Blocky and seamy** rock consists of chemically blocky and seamy intact or almost intact rock fragments which are entirely separated from each other and imperfectly interlocked. In such rock, vertical walls may require support.
5	Very blocky and seamy	
6	Completely crushed, but chemically intact	Crushed but chemically intact rock has the character of a crusher run. If most or all of the fragments are as small as fine sand grains and no re-cementation has taken place, crushed rock below the water table exhibits the properties of a water-bearing sand. Considerable side pressure is expected on tunnel supports.
7	Squeezing rock - moderate depth	*Squeezing rock* slowly advances into the tunnel without a perceptible volume increase. A prerequisite for squeeze is a high percentage of microscopic and sub-microscopic particles of micaceous minerals or of clay minerals with a low swelling capacity.
8	Squeezing rock - great depth	
9	Swelling rock	*Swelling rock* advances into the tunnel chiefly on account of expansion. The capacity to swell seems to be limited to those rocks which contain clay minerals such as montmorillonite, with a high swelling capacity. In practice, there are no sharp boundaries between these rock categories and the properties of the rocks indicated by each one of these terms can vary between wide limits.

*Seams are clay-containing joints; *B*, span width; H_t; height of tunnel

5.2 The Rock Mass Rating (RMR) system

Classification and ratings of the input parameters to RMR are shown in Table 9. In applying this classification system, the rockmasses are divided into a number of structural regions with similar properties. The boundaries of these usually coincide with major structural features ([12] and [13]).

5.2.1 Limitations of the RMR system

The RMR is restricted to support design to counter block fall instability, as stresses are not specifically included, although it is stated by [10] to be limited to stresses <25 MPa. The input of the RQD has limitations, as it does not adequately cover variations in massive rock or crushed rock.

Recommendations for excavation and rock support is only given for 10 m-wide horseshoe-shaped tunnels (Table 10). The recommendation is old, as modern support measures like steel fibre shotcrete can normally replace both wire mesh and steel ribs. As for the *Q* system, the influence of water on stability and therefore on rock support requirements is unclear.

A. Classification parameters and their ratings

PARAMETER			Range of values // RATINGS				For this low range: Use uniaxial		
1	Strength of intact rock material	Point-load strength	> 10 MPa	4 - 10 MPa	2 - 4 MPa	1 - 2 MPa			
		or Uniaxial compr. strength	> 250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5 - 25 MPa	1 - 5 MPa	< 1 MPa
		RATING	**15**	**12**	**7**	**4**	**2**	**1**	**0**
2	Drill core quality, RQD		90 - 100%	75 - 90%	50 - 75%	25 - 50%	< 25%		
		RATING	**20**	**17**	**13**	**8**	**5**		
3	Spacing of discontinuities		> 2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm	< 60 mm		
		RATING	**20**	**15**	**10**	**8**	**5**		
4	Condition of discon-tinuities	Length, persistence	< 1 m	1 - 3 m	3 - 10 m	10 - 20 m	> 20 m		
		Rating	**6**	**4**	**2**	**1**	**0**		
		Separation	none	< 0.1 mm	0.1 - 1 mm	1 - 5 mm	> 5 mm		
		Rating	**6**	**5**	**4**	**1**	**0**		
		Roughness	very rough	rough	slightly rough	smooth	slickensided		
		Rating	**6**	**5**	**3**	**1**	**0**		
		Infilling (gouge)	none	Hard filling		Soft filling			
			-	< 5 mm	> 5 mm	< 5 mm	> 5 mm		
		Rating	**6**	**4**	**2**	**2**	**0**		
		Weathering	unweathered	slightly w.	moderately w.	highly w.	decomposed		
		Rating	**6**	**5**	**3**	**1**	**0**		
5	Ground water	Inflow per 10 m tunnel	none	< 10 litres/min	10 - 25 litres/min	25-125 litres/min	> 125 litres /min		
		$p_w / \sigma1$	0	0 - 0.1	0.1 - 0.2	0.2 - 0.5	> 0.5		
		General conditions	completely dry	damp	wet	dripping	flowing		
		RATING	**15**	**10**	**7**	**4**	**0**		

p_w = joint water pressure; $\sigma1$ = major principal stress

B. Rating adjustment for discontinuity orientations

Strike and dip orientation of joints		Very favourable	Favourable	Fair	Unfavourable	Very unfavourable
RATINGS	Tunnels	**0**	**-2**	**-5**	**-10**	**-12**
	Foundations	**0**	**-2**	**-7**	**-15**	**-25**
	Slopes	**0**	**-5**	**-25**	**-50**	**-60**

C. Rock mass classes determined from total ratings

Rating	100 - 81	80 - 61	60 - 41	40 - 21	< 20
Class No.	I	II	III	IV	V
Description	VERY GOOD	GOOD	FAIR	POOR	VERY POOR

D. Meaning of rock mass classes

Class No.	**I**	**II**	**III**	**IV**	**V**
Average stand-up time	10 years for 15 m span	6 months for 8 m span	1 week for 5 m span	10 hours for 2.5 m span	30 minutes for 1 m span
Cohesion of the rock mass	> 400 kPa	300 - 400 kPa	200 - 300 kPa	100 - 200 kPa	< 100 kPa
Friction angle of the rock mass	< 45°	35 - 45°	25 - 35°	15 - 25°	< 15°

Table 9: The input parameters to RMR with ratings [13].

Table 10: The RMR classification guide for excavation and support in rock tunnels. Shape, horseshoe with, 10 m span. Vertical stress < 25 MPa. Excavation by drill and blast [13].

Rock mass class		Excavation	**Rock support** (for 10 m-wide tunnels)		
			Rock bolts (20 mm diameter, fully bonded)	Shotcrete	Steel sets
1.	Very good rock RMR: 81 - 100	Full face: 3 m advance	Generally, no support required except for occasional spot bolting		
2.	Good rock RMR: 61 - 80	Full face: 1.0 -1.5 m advance Complete support 20 m from face.	Locally bolts in crown, 3m long, spaced 2.5 m with occasional wire mesh	50 mm in crown where required	None
3.	Fair rock RMR: 41 - 60	Top heading and bench: 1.5 -3 m advance in top heading. Commence support after each blast. Commence support 10 m from face	Systematic bolts 4 m long, spaced 1.5 – 2 m in crown and walls with wire mesh in crown	50 -100 mm in crown, and 30 mm in sides	None
4.	Poor rock RMR: 21 - 40	Top heading and bench: 1.0 -1.5 m advance in top heading. Install support concurrently with excavation 10 m from face	Systematic bolts 4 -5 m long, spaced 1 -1.5 m in crown and walls with wire mesh	100 -150 mm in crown and 100mm in sides	Light ribs spaced 1.5 m where required
5.	Very poor rock RMR < 21	Multiple drifts: 0.5 -1.5 m advance in top heading Install support concurrently with excavation; shotcrete as soon as possible after blasting	Systematic bolts 5 - 6 m long, spaced 1-1.5 m in crown and walls with wire mesh. Bolt the invert	150 -200 mm in crown, 150 mm in sides, and 50 mm on face	Medium to heavy ribs spaced 0.75 m with steel lagging and forepoling if required. Close invert

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

5.3 The Q system

Table 11 shows the input parameters with ratings used to calculate the Q value. Figure 47 shows the Q rock support chart.

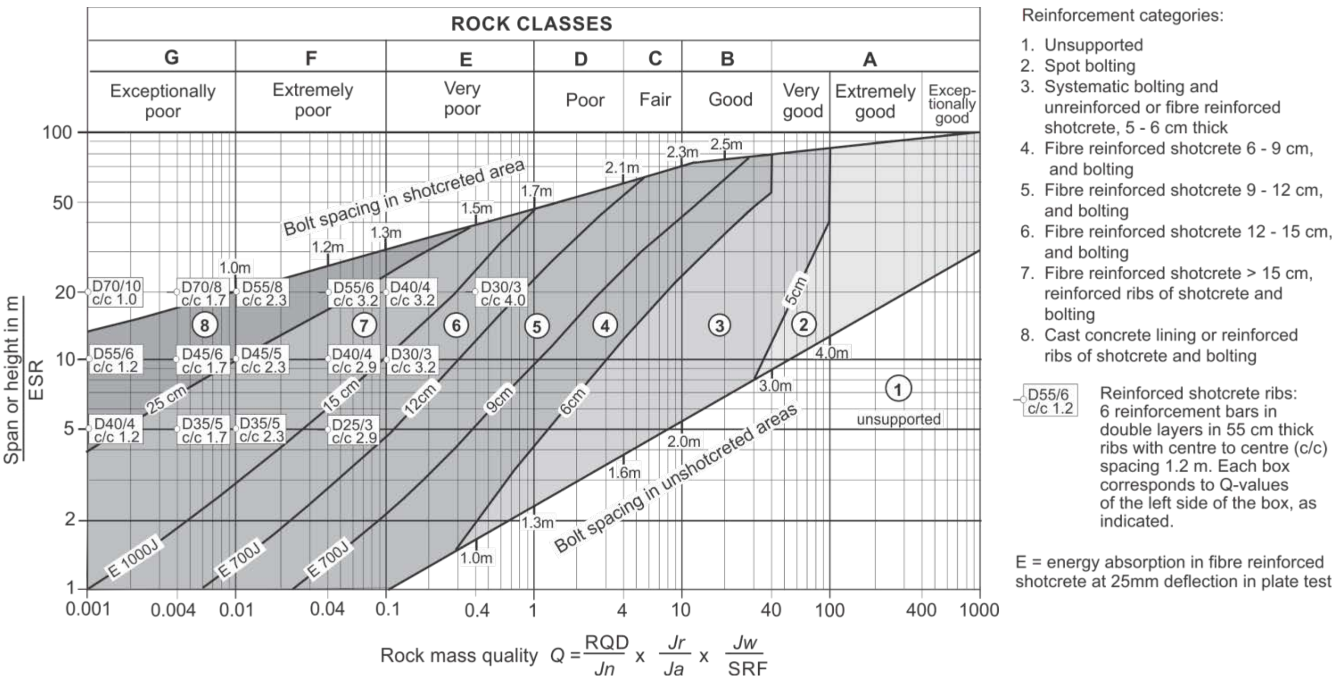


Figure 47: The *Q* chart for estimates of rock support after modification in 2004 [20].

5.3.1 Estimating rock support

According to the experience of [18], the Q system works best in ground conditions where block falls are likely to occur. It also includes input parameters for slabbing, for which adequate rock support may be estimated. The Q value used in Figure 47 is related to the total amount of support (temporary and permanent) in the roof. The diagram is based on numerous tunnel support cases. Wall support can also be found using the same figure by applying the wall height and the following adjustments: For $Q > 10$: use $Q_{wall} = 5Q$; For $0.1 < Q < 10$: use $Q_{wall} = 2.5Q$; For $Q < 0.1$: use $Q_{wall} = Q$

Table 11: Classification and values of the input parameters in the *Q* system [14].

Rock quality designation (RQD)

Very poor	RQD = 0 - 25%
Poor	25 - 50
Fair	50 - 75
Good	75 - 90
Excellent	90 - 100

Notes:
(i) Where RQD is reported or measured as < 10 (including 0), a nominal value of 10 is used to evaluate Q
(ii) RQD intervals of 5, i.e. 100, 95, 90, etc. are sufficiently accurate

Joint set number (Jn)

Massive, no or few joints	Jn = 0.5 - 1
One joint set	2
One joint set plus random	3
Two joint sets	4
Two joint sets plus random	6
Three joint sets	9
Three joint sets plus random	12
Four or more joint sets, heavily jointed, "sugar-cube", etc.	15
Crushed rock, earthlike	20

Notes: *(i) For tunnel intersections, use (3.0 x Jn); (ii) For portals, use (2.0 x Jn)*

Desciption and ratings for the parameter Jr *(joint roughness number)*

a) Rock-wall contact, b) rock-wall contact before 10 cm shear		c) No rock-wall contact when sheared	
Discontinuous joints	Jr = 4	Zone containing clay minerals thick enough to prevent rock-wall contact	Jr = 1.0
Rough or irregular, undulating	3		
Smooth, undulating	2	Sandy, gravelly or crushed zone thick enough to prevent rock-wall contact	1.0
Slickensided, undulating	1.5		
Rough or irregular, planar	1.5		
Smooth, planar	1.0		
Slickensided, planar	0.5		

Note*: i) Descriptions refer to small scale features, and intermediate scale features, in that order*

Notes:
i) Add 1.0 if the mean spacing of the relevant joint set is greater than 3 m
ii) Jr = 0.5 can be used for planar, slickensided joints having lineations, provided the lineations are oreintated for minimum strength

Descriptions and ratings for the parameter Ja *(joint alteration number)*

	Joint wall character		Condition	Wall contact
Contact between joint walls	Clean joints	Healed or welded joints:	filling of quartz, epidote, etc.	Ja = 0,75
		Fresh joint walls:	no coating or filling, except from staining (rust)	1
		Slightly altered joint walls:	non-softening mineral coatings, clay-free particles, etc.	2
	Coating or thin filling	Friction materials:	sand, silt calcite, etc. (non-softening)	3
		Cohesive materials:	clay, chlorite, talc, etc. (softening)	4

	Filling of:	Type	Partly wall contact Thin filling (< 5 mm)	No wall contact Thick filling
Partly or no wall contact	Friction materials	sand, silt calcite, etc. (non-softening)	Ja = 4	Ja = 8
	Hard cohesive materials	compacted filling of clay, chlorite, talc, etc.	6	5 - 10
	Soft cohesive materials	medium to low overconsolidated clay, chlorite, talc, etc.	8	12
	Swelling clay materials	filling material exhibits swelling properties	8 - 12	13 - 20

Description and ratings for the parameter Jw *(joint water reduction factor)*

Dry excavations or minor inflow, i.e. < 5 l/min locally	$p_w < 1$ kg/cm^2	Jw = 1
Medium inflow or pressure, occasional outwash of joint fillings	1 - 2.5	0.66
Large inflow or high pressure in competent rock with unfilled joints	2.5 - 10	0.5
Large inflow or high pressure, considerable outwash of joint fillings	2.5 - 10	0.3
Exceptionally high inflow or water pressure at blasting, decaying with time	> 10	0.2 - 0.1
Exceptionally high inflow or water pressure continuing without noticeable decay	> 10	0.1 - 0.05

Note: *(i) The last four factors are crude estimates. Increase Jw if drainage measures are installed*
(ii) Special problems caused by ice formation are not considered

Description and ratings for parameter SRF *(stress reduction factor)*

A. Weakness zones intersecting excavation	Multiple weakness zones with clay or chemically disintegrated rock, very loose surrounding rock (any depth)			SRF = 10
	Single weakness zones containing clay or chemically disintegrated rock (depth of excavation < 50 m)			5
	Single weakness zones containing clay or chemically disintegrated rock (depth of excavation > 50 m)			2.5
	Multiple shear zones in competent rock (clay-free), loose surrounding rock (any depth)			7.5
	Single shear zones in competent rock (clay-free), loose surrounding rock (depth of excavation < 50 m)			5
	Single shear zones in competent rock (clay-free), loose surrounding rock (depth of excavation > 50 m)			2.5
	Loose, open joints, heavily jointed or "sugar-cube", etc. (any depth)			5
Note:	*(i) Reduce these valued of SRF by 25 - 50% if the relevant shear zones only influence, but do not intersect the excavation*	σ_c / σ_1	σ_θ / σ_c	
B. Competent rock, rock stress problems	Low stress, near surface, open joints	> 200	< 0.01	SRF = 2.5
	Medium stress, favourable stress condition	200 - 10	0.01 - 0.3	1
	High stress, very tight structure. Usually favourable to stability, may be except for walls	10 - 5	0.3 - 0.4	0.5 - 2
	Moderate slabbing after > 1 hour in massive rock	5 - 3	0.5 - 0.65	5 - 50
	Slabbing and rock burst after a few minutes in massive rock	3 - 2	0.65 - 1	50 - 200
	Heavy rock burst (strain burst) and immediate dynamic deformation in massive rock	< 2	> 1	200 - 400

Notes: *(ii) For strongly anisotropic stress field (if measured): when 5 < σ_1/σ_3 <10, reduce σ_c to 0.75 σ_c. When σ_1/σ_3 > 10, reduce σ_c to 0.5 σ_c*
(iii) Few case records available where depth of crown below surface is less than span width. Suggest SRF increase from 2.5 to 5 for low stress cases

			σ_θ / σ_c	
C. Squeezing rock	Plastic flow of incompetent rock under the influence of high pressure	Mild squeezing rock pressure	1 - 5	SRF = 5 - 10
		Heavy squeezing rock pressure	> 5	10 - 20
D. Swelling rock	Chemical swelling activity depending on presence of water	Mild swelling rock pressure		5 - 10
		Heavy swelling rock pressure		10 - 15

The input values to *Jr* and *Ja* should be for the weakest significant joint set or clay-filled discontinuity.

The *Q* system includes the ESR factor for the stability requirement of the actual type of tunnel or underground cavern, see Table 12.

Table 12: Classification of the excavation support ratio (ESR) [14].

Type or use of underground opening	ESR
Temporary mine openings	3.5
Vertical shafts, rectangular and circular respectively	2.0 - 2.5
Water tunnels, permanent mine openings, adits, drifts	1.6
Storage caverns, road tunnels with little traffic, access tunnels, etc.	1.3
Power stations, road and railway tunnels with heavy traffic, civil defence shelters, etc.	1.0
Nuclear power plants, railroad stations, sport arenas, etc.	0.8

5.3.2 Scope and limitations of the Q system

Barton and the other originators of the *Q* system have given little information on the limitations of the *Q* system. From the rock mechanics point of view, it is obvious that instability is much more complicated than can be given by a single number such as the Q value. Nevertheless, a classification system is needed for the practical handling of many rock design issues.
Palmström and Broch [18] mentions that:

- Important joint features (orientation, size, aperture etc.) are not included in the *Q* system.
- *Rock strength* is not an input in the Q system. For jointed rock where instability is caused by block falls, rock strength has little impact on the ground behaviour. However, for other types of ground, e.g. rock stress problems, the compressive strength of rock material has a significant influence.

Other notable comments are, as pointed out by several authors:

- The SRF is a complicated factor. Its application is unclear for buckling, rock burst and/or squeezing conditions, or for weakness zones. SRF seems to be a sort of 'correction factor' or 'fine tuning factor', rather than a factor expressing 'active stresses' aiming at arriving at a *Q* value that gives appropriate rock support.
- The use of the RQD as an input has several limitations in characterising the degree of jointing; as the RQD does not adequately cover variations in massive rock or crushed rock.
- The effect of water on stability, and therefore on rock support requirements, is unclear.

5.4 The RMi (rockmass index) system

5.4.1 The basic RMi

The RMi support method was introduced in 1995 by Palmstrom [1]. The outline of the system is shown in Figure 49. Applying the three-dimensional block volume as the main input into the RMi, several benefits are achieved, both in characterising a rockmass and in rock engineering calculations. Methods to assess the block volume from various types of field measurements have been shown by [21].

The RMi is a volumetric parameter indicating the approximate uniaxial compressive strength of a rockmass. It is expressed as follows:

1. For massive rock: $RMi = \sigma_c \cdot f_\sigma \cdot IL = \sigma_c\, (0.05/Db)^{0.2} \cdot IL \approx 0.5\sigma_c \cdot IL$

   σ_c = uniaxial compressive strength of intact rock, measured on 50 mm samples.

   f_σ = massivity parameter: $f_\sigma = (0.05/Db)^{0.2}$. It is an adjustment for the scale effect of compressive strength from 50 mm samples to rock blocks when $D_b >$ approx. 2 m.[8] (for which $f_\sigma \geq 0.5$).

   D_b = block diameter: $D_b \approx (V_b)^{1/3}$ and

   V_b = block volume (m^3)

   IL = interlocking adjustment factor, see Table 13.

2. For jointed rock (when $JP < f_\sigma$, (this is where $JP <\sim 0.5$), i.e. $f_\sigma < 0.5$):

   $$RMi = \sigma_c \cdot JP \cdot IL = \sigma_c \cdot 0.2\sqrt{jC} \cdot Vb^{D} \cdot IL$$

   JP = jointing parameter, which incorporates the main joint features in the rockmass. Its value can be found from Figure 48 or from equation: $JP = 0.2\sqrt{jC} \cdot Vb^{D}$ (where $D = 0.37\, jC^{-0.2}$)

   jC = joint condition factor, which is a combined measure for the joint size (jL), joint roughness (jR) and joint alteration (jA): $jC = jL \cdot jR/jA$ (their values are shown in Table 13).

Computer spreadsheets have been presented (see www.rockmass.net) to calculate the RMi value from field observations. Figure 48 shows a graphical method to find the RMi value.

[8] When smooth, planar joints occur

Table 13: Input parameters to the basic RMi [1].

Compressive strength of intact rock (σ_c)	use the value of σ_c (in MPa) as input
Degree of jointing, given as block volume (*Vb*)	use the block volume (in m^3) as input

Joint roughness factor (jR), similar to *Jr* in the Q-system

(The ratings in ***bold italic*** are similar to *Jr*)		Undulation or waviness of joint plane (jw)				
		Planar	Slightly undulating	Undulating	Strongly undulating	Stepped or interlocking
Smoothness of joint surface (js)	Very rough	2	3	4	6	6
	Rough	***1.5***	2	***3***	4.5	6
	Smooth	***1***	1.5	***2***	3	4
	Polished or slickensided *)	***0.5***	1	***1.5***	2	3
	For filled joints jR = 1 For irregular joints a rating of jR = 6 is suggested					

**) For slickensided surfaces the ratings apply to possible movement along the lineations*

Joint alteration factor (jA), mostly based on *Ja* in the Q-system)

Contact between joint walls	JOINTS	Healed or welded joints	filling of quartz, epidote, etc.		jA = 0.75
		Fresh joint walls	no coating or filling, except from staining (rust)		1
		Altered joint walls	- one grade higher alteration than the rock		2
			- two grades higher alteration than the rock		4
	COATING or THIN FILLING OF:	Frictional materials	sand, silt calcite, etc. without content of clay		3
		Cohesive materials	clay, chlorite, talc, etc.		4
Partly or no wall contact	THICK FILLING OF:			Thin filling (< 5mm)	Thick filling
		Frictional materials	sand, silt calcite, etc. (non-softening	jA = 4	8
		Hard, cohesive materials	clay, chlorite, talc, etc.	6	5 - 10
		Soft, cohesive materials	clay, chlorite, talc, etc.	8	12
		Swelling clay materials	material exhibits swelling properties	8 - 12	13 - 20

Joint size factor (jL), composed of the length and continuity of the joint		Continuous joints	Discont. joints*)
Cracks	length < 0.5m	jL = 6	jL = 12
Bedding or foliation partings	length < 0.5m	3	6
Joints	with length 0.1 - 1m	2	4
	with length 1 - 10m	1	2
	with length 10 - 30m	0.75	1.5
(Filled) joint, seam or shear **)	length > 30m	0.5	1

Interlocking (IL), compactness of rockmass structure		
Very tight structure	Undisturbed rockmass	IL = 1.3
Tight structure	Undisturbed rockmass with some joint sets	1
Disturbed / open structure	Folded / faulted with angular blocks	0.8
Poorly interlocked	Broken rockmasses with angular and rounded blocks	0.5

*) Discontinuous joints end in massive rock **) Often a singularity and should in these cases be treated separately

Note: The effect of interlocking has recently been introduced, based on its use in the GSI system

The value of the RMi represents a crude estimate of the compressive strength of a rockmass. The classification of the RMi is:
RMi < 0.01 (very low); RMi = 0.01 – 0.1 (low); RMi = 1 – 10 (high); RMi > 10 (very high)

The RMi method applies more parameters in the ground than the other systems mentioned above (see Table 5). The different input parameters can be determined by commonly used measurements and mapping, as well as from empirical relationships as presented in [1]. The RMi requires more calculation than the RMR and the *Q* systems. Diagrams have been presented to graphically ease the calculations (see Figure 48). The use of a computer spreadsheet simplifies the calculations considerably.

5.4.2 The RMi support estimate method

The RMi support method applies adjustments to the RMi value by including the effect of rock stresses, groundwater, joint orientation and the number of joint sets, see Figure 49.

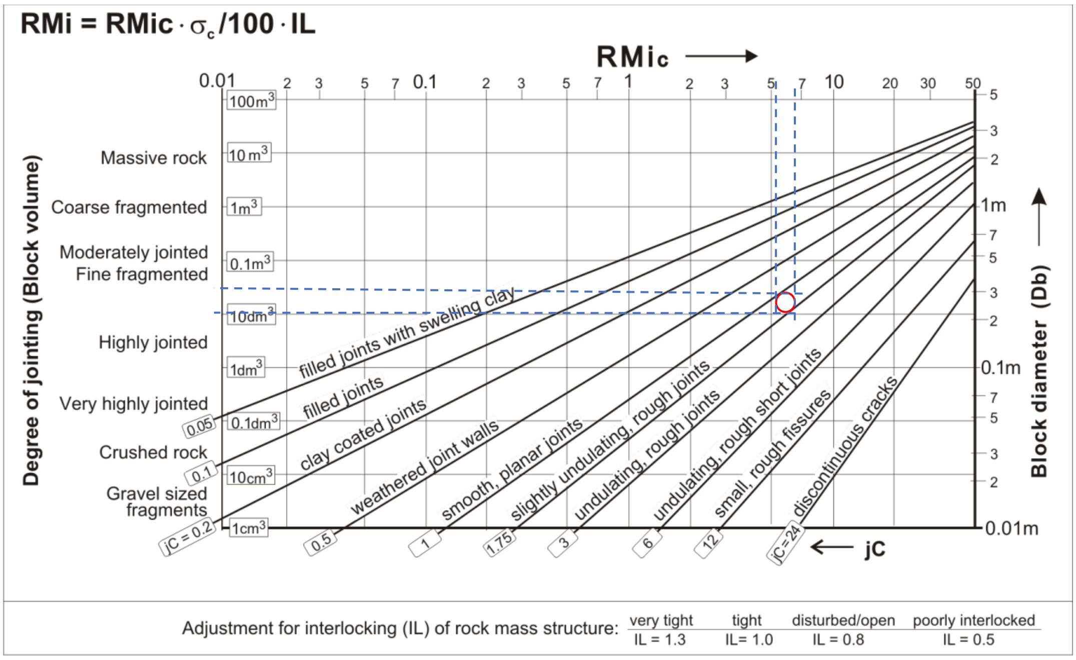
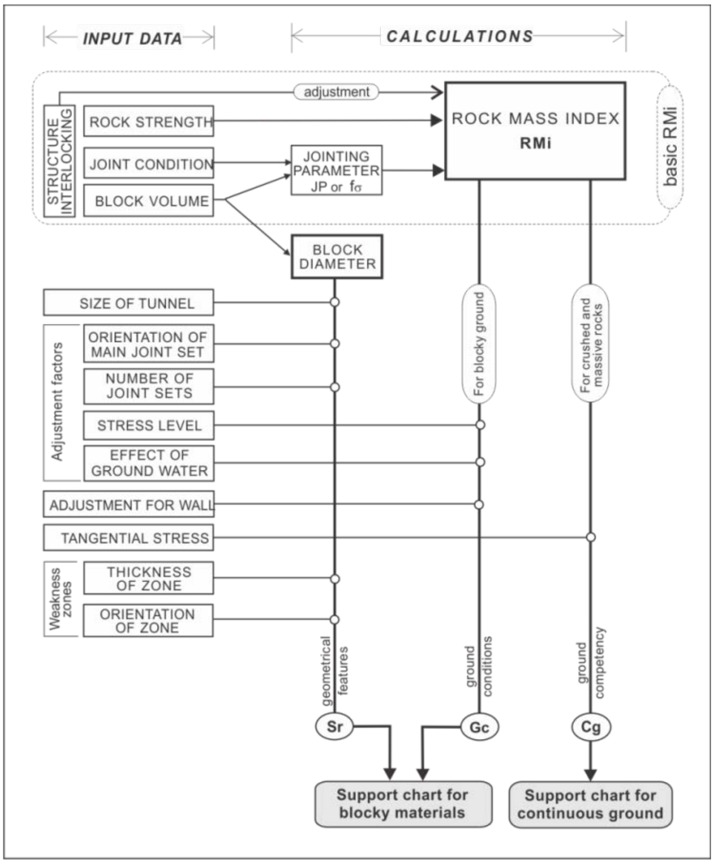


Figure 48: Graphical determination of the RMi-value (revised from [16]).

Example:
Block volumes of 10 – 50 dm^3 (0.01 – 0.05 m^3) and planar, smooth to slightly undulating, rough joints give RMi$_c$ = 5 – 7.

With compressive strength σ_c = 150 MPa, the RMi = 7.5 – 10.5



The number of blocks in the periphery of an underground opening will largely determine whether the surrounding ground will behave as:

1. a discontinuous, *blocky* material, dominated by the individual blocks and the character of the joints; or as
2. a *continuous*, bulk material (where the magnitude of the rock stresses is an important parameter).

The ground ***continuity*** can be assessed from the ratio CF = Dt/Db (tunnel diameter / average block diameter), which is called the *continuity factor*. With a marked difference in behaviour of these two groups (Figure 50), the RMi support method applies different calculations and support charts for continuous and discontinuous (blocky) ground.

Figure 49: Layout of the RMi support system [1].

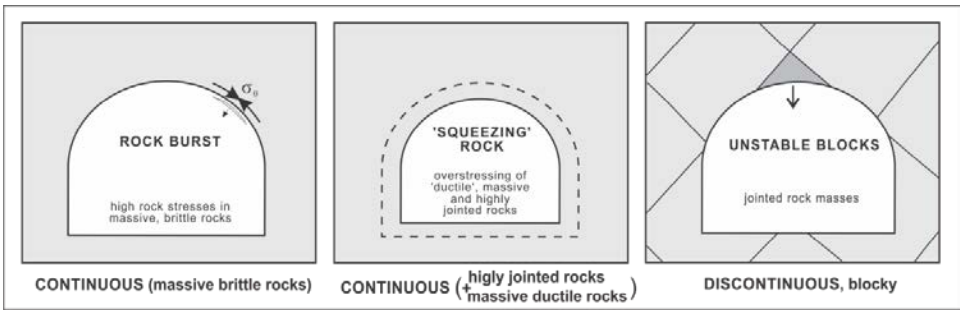


Figure 50: Typical mode of behaviour and ground continuity

1. Discontinuous (blocky) ground

The following two support parameters are used in the support chart in Figure 51:

I. The ground quality, given as the ground condition factor, is

$$Gc = RMi \cdot K_1 = RMi\,(SL \cdot C \cdot GW)$$

The adjustment factor K_1 comprises the following site-specific parameters:

- C = a gravity adjustment factor for support in the walls or in other inclined tunnel surfaces. It can be found from Table 14 or from the expression $C = 5 - 4 \cos \delta$, where δ = angle (dip) of the opening surface measured from horizontal.
- SL = a stress level adjustment
- GW = adjustment for groundwater (see Table 14)

Table 14: The adjustment parameters used in the RMi support method.

K1	Roof and wall (C)					roof	45° *)	60° *)	wall
						1	2.2	3	5
	Stress level (SL)			very low	low	moderate	high	very high	**)
				0.1	0.5	**1**	1.5	1.5	
	Ground water (GW)			influence on stability ⟶		minor	moderate	significant	
						1	2.5	5	
K2	Orientation of joints and zones (Co)				very favourable	favourable	slightly un-favourable	un-favourable	very un-favourable
					0.75	**1**	1.5	2	3
	Number of joint sets (Nj)	1 set	1+random	2 sets	2+random	3 sets	3+random	4 sets	4+random
		3	2	1.5	1.2	**1**	0.85	0.75	0.5
K1 = C x SL x GW; K2 = Co / Nj			*) roof in inclined shaft			**) in massive rock, very high stresses may cause rock burst			

Note that the use of unit values = 1 for normal or common conditions shown in the grey cells

II. The geometrical factor for <u>jointed rock</u>, expressed as the size ratio, is

$$Sr = (D_t/D_b)\,(C_o/N_j) = (D_t/D_b)\,K_2$$

where

- D_t = The diameter or span of the tunnel or cavern (m). (For walls, the wall height W_t is used instead of D_t).

and the site-specific parameters are:

- D_b = The equivalent block diameter $Db \approx \sqrt[3]{Vb}$ (in metre).
- C_o = An adjustment factor for orientation of the main joint set related to the tunnel or cavern, see Table 14.
- N_j = an adjustment factor for the number of joint sets; and hence the freedom for the blocks to fall. Its ratings in Table 14 can also be found from $N_j = 3/n_j$, where n_j is the number of joint sets (n_j = 1 for one set; n_j = 1.5 for one set plus random joints; n_j = 2 for two sets; n_j = 2.5 for two sets plus random joints; etc.).

Table 15: Classification of joint orientation related to the tunnel or cavern, developed from [13].

Term	In one wall		In opposite wall		In roof	
	Strike: °	Dip: °	Strike: °	Dip: °		Dip: °
Very favourable	≥ 70	All	> 60	All	All strikes	> 60
Favourable	< 70	≤ 20	30 - 60	All		45 - 60
Fair	50 - 70	> 20	≤ 30	≤ 45		30 - 45
	≤ 50	20 - 45	≤ 30	≤ 45		
Unfavourable	30 - 50	≥ 45	≤ 30	> 45		15 - 30
Very unfavourable	≤ 30	≥ 45	≤ 30	> 45		≤ 15

NB. Orientation (strike and dip) is related to the tunnel

The adjustment tables for the site-specific ground parameters are shown in Table 14. Note that unit values (= 1) are applied for normal or common conditions, as shown in the grey cells.

The joint orientation class can be found in Table 15.

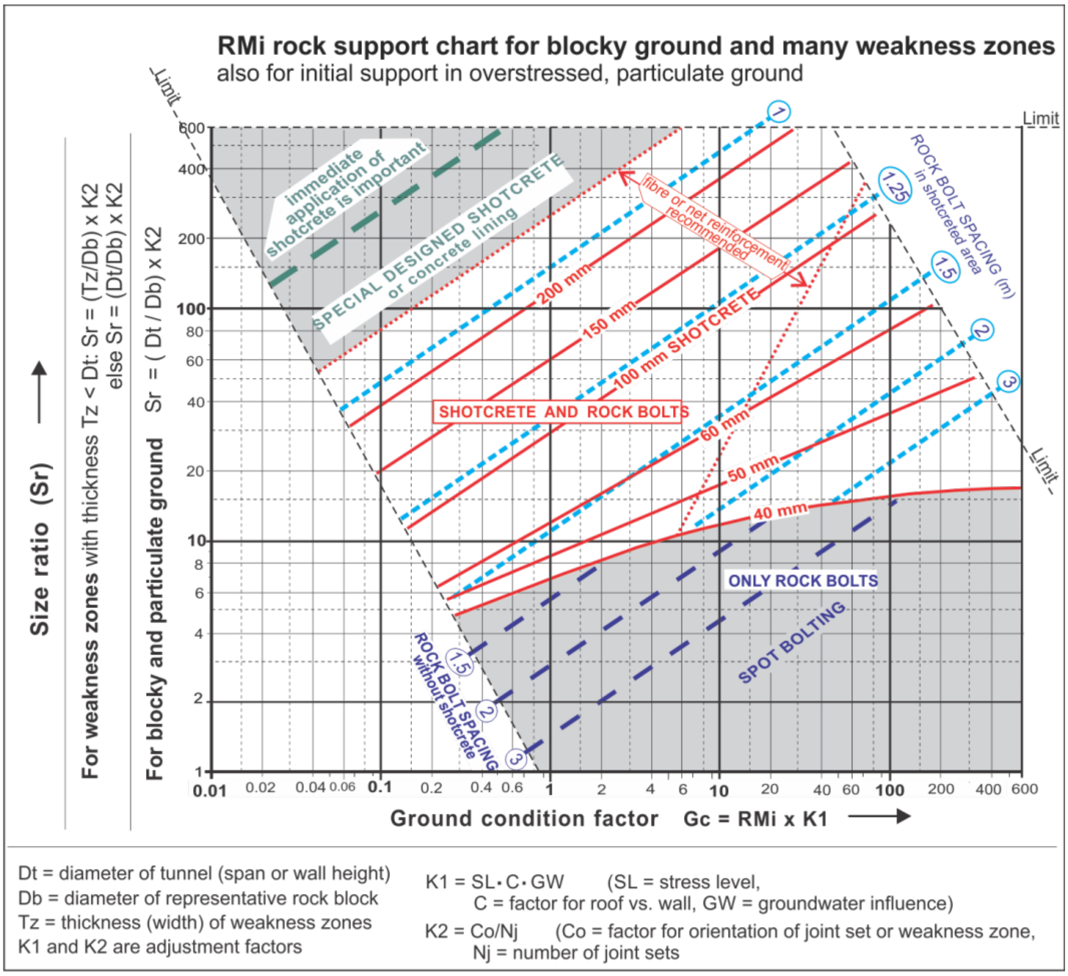


Figure 51: The RMi charts for estimates of rock support in blocky ground and weakness zones and continuous ground (massive or highly jointed), revised from [1].

Weakness zones should in many cases be treated individually without using support or classification systems. Support assessments for crushed zones may, however, be carried out using the support chart for blocky ground in Figure 51 and input parameters as for blocky ground. In small and medium-sized zones (thickness between 1 m and approximately 20 m), the stability is influenced by the interplay between the zone and the adjacent rockmasses. Therefore, the stresses in such zones are generally lower than in the adjacent ground, which will reduce the effect of squeezing.

III. The ground condition factor (Gc) for zones is the same as for blocky ground, while the size ratio for weakness zones is

$Sr = (T_z/D_b)(C_o/N_j)$ for $T_z < D_t$

$Sr = (D_t/D_b)(C_o/N_j)$ for $T_z > D_t$ which is similar to equation for jointed rock.

where T_z is the thickness of the weakness zone.

For zones with $CF > 600$, special rock support evaluations should generally be made. Large zones (thickness $T_z > \sim 20$ m) will often behave similarly to continuous ground described above, as there will be little or no arching effect.

For crushed weakness zones, some typical RMi values for the most common conditions are given in Table 7. They may be used for estimates at an early stage of a project, or for cases where the composition of the zone is not known. The approximate RMi_z values are based on assumed representative block volumes for the various types of zones.

The support chart in Figure 51 shows the estimated total amount and types of support. It is based on installed support in several tunnels in addition to the authors' experience from numerous tunnels and other underground drill and blast excavations in Scandinavia.

2. Continuous ground

Continuous ground occurs when *CF* < ~3 (*massive rock*), in which the properties of intact rock dominate, and when *CF* > ~50 (particulate or highly jointed rock), where the ground behaves as a bulk material. In these types of ground, the main influence on the behaviour in an underground opening comes from the stresses. Therefore, a competency factor (*Cg*, strength of the rockmass/stresses acting) is used. It is expressed as follows:

1. In massive ground:

$$Cg = RMi / \sigma_\theta = f_\sigma \cdot \sigma_c / \sigma_\theta \approx 0.5 \frac{\sigma_c}{\sigma_\theta}$$

2. In particulate ground:

$$Cg = RMi / \sigma_\theta = JP \frac{\sigma_c}{\sigma_\theta}$$

where σ_θ is the tangential stress in the rockmasses around the opening.

Competent ground occurs where *Cg* > 1; else the ground is overstressed. *Cg* is used in the ground support chart (Figure 52).

Massive ground is generally stable (see Figure 52), and does generally not need any support, except for some scaling work in drill and blast tunnels. Massive, overstressed ground, however, requires support because the following time-dependent types of deformation and/or failures may take place:

3. *squeezing* in overstressed ductile rocks (such as schists) and rockmasses (clayey, broken rocks);
4. *slabbing* (*spalling*) or rock burst in overstressed brittle, hard rocks (such as granite, quartzite, marble and gneiss).

Particulate materials (highly jointed rocks) generally require immediate support. Their initial behaviour is often similar to that of blocky ground, i.e. the support chart in Figure 52 can be used. In overstressed (*incompetent*) ground, time-dependent squeezing may, in addition to the initial instability, take place. However, for this type of ground the support chart in Figure 52 needs updating, when more experience in this type of ground is available, or separate calculations and convergence measurements should be performed.

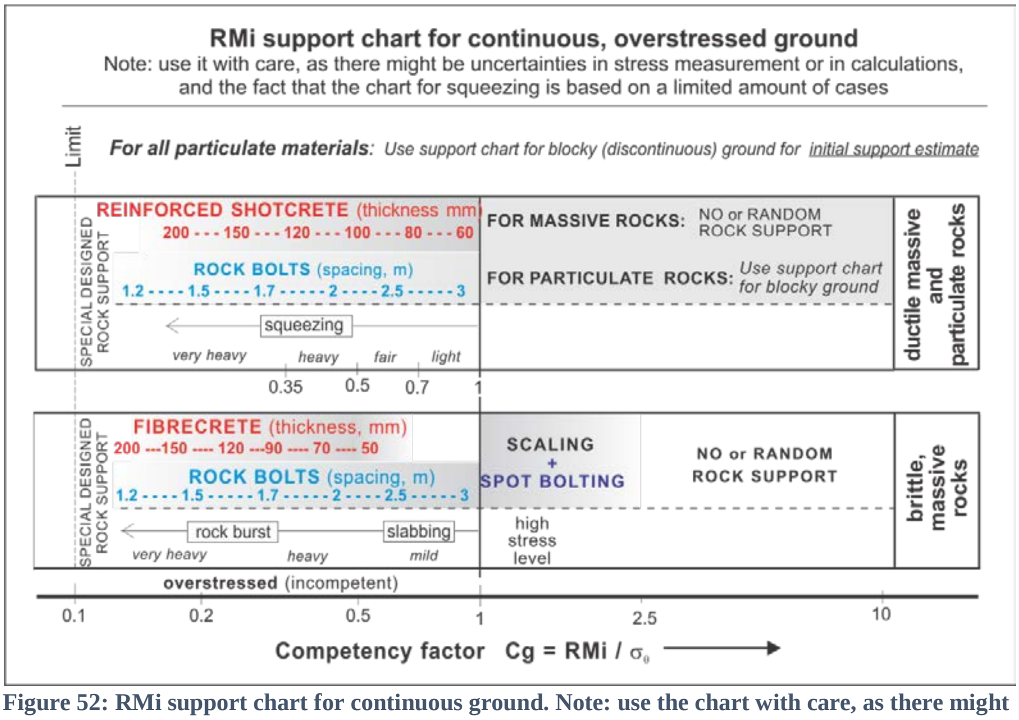


Figure 52: RMi support chart for continuous ground. Note: use the chart with care, as there might be uncertainties in stress measurement or in calculations, and the chart for squeezing is based on a limited number of cases. Modified from [16].

5.4.3 Scope and limitations of the RMi system

The RMi system works best in massive and jointed rockmasses. It may also be used as a first check for support in faults and weakness zones (Figure 51 or 52), but its limitations here are as have been described for the other classification systems.

The system seems difficult to use, as it applies more complicated equations than the other rockmass classification systems, but spreadsheets that have been developed and presented, greatly simplifies the use of RMi.

The RMi system is designed to use 'common values', which have been given unit values (= 1) for most of the input parameters. This is implemented in the spreadsheet for RMi calculation. Thus, simple assessments using the RMi system can be applied from only input for the degree of jointing (block volume) when there are only few inputs available.

For special ground conditions such as swelling, squeezing and ravelling ground, the rock support should be evaluated separately for each and every case. Other features to be separately assessed are connected with project-specific requirements, such as the lifetime required and safety aspects.

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.

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