Monitoring-While-Drilling for Investigating Critical Rock and Rock Mass Properties for Blast Design and Underground Support

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1 Abstract

The aim of this thesis is to investigate critical rock and rock mass properties for modern blast- and underground support design and identify potential relations to parameters recorded in conventional Monitoring While Drilling (MWD) applications. This main goal is supported by a couple of research questions in order to come to a sound conclusion. For a structured approach, first a literature review will be done. In this chapter the theory behind the research questions will be discussed and preliminary results are obtained. This will be followed by an analysis chapter accompanied by interviews with experts from the industry and university. Here, the earlier found results are assessed and analyzed in order to answer the research questions and eventually the main objective. This ultimately led to the following major results. Monitoring While Drilling (MWD) is a proven technique that records instantaneous on-drill parameters which can be used to supply contextual information for in-situ, down hole conditions, such as: changes in geology, the presence of pre-existing fractures or voids and dynamic alterations. Where for the design of underground support Rock Mass Classification systems are often used, this is not the case for the underground blast designs. The critical parameters that determine such a design are practically the same for both designs however. For the determination of an underground blast- or support design the in-situ geological conditions play the most important role. These conditions of the rock mass are the Uniaxial Compressive Strength (UCS) and the characteristics of discontinuities, such as the conditions of the joints and joint alteration. While MWD data can identify certain geological conditions, these do not really match the critical parameters used in both designs. Therefore correlations between the MWD data and the desired parameters could be beneficial. While it is possible to construct such correlations, the validation of them heavily depends on various other in-situ or measurement induced parameters. When the influence of these parameters is investigated and determined it should be possible to make a sound conclusion on the usability of these correlations.

Contents

2 Importance of research

The mining industry is nowadays under great pressure. Plummeting market prices, stricter regulations regarding the environment and increasing scarcity of ''easy'' deposits are some of the culprits. To turn the tides there is a need for new, innovative techniques to reduce costs and increase production on mine sites. This can be achieved by different means, one of them being the concept of "Real-Time Mining". This concept promotes the change in paradigm from discontinuous intermittent process monitoring to a continuous process and quality management system in highly selective mining operations. Real-Time Mining will develop a real-time process-feedback control loop linking online data acquired during extraction at the mining face rapidly with a sequential up-datable resource model associated with real-time optimization of long-term planning, short-term sequencing and producing control decisions. Investigating critical rock- and rock mass properties for underground blast- and support designs and identifying potential relations to parameters recorded in monitoring while drilling applications is one of many integrated parts of the Real-Time Mining project. The impact of the project is expected on the environment through a reduction in CO_2-emissions, increased energy efficiency and production of zero waste by maximizing process efficiency and resource utilization. Currently economically marginal deposits or difficult to access deposits will become industrial viable. This will result in a sustainable increase in the competitiveness of the European raw material extraction through a reduced dependency on raw material from non-EU sources *(TU-Delft CiTG, Horizon 2020 Project Real-Time Mining).*

3 Scope and objectives

The main objective of this thesis is to: Investigate critical rock and rock mass properties for modern blast- and underground support design and identify potential relations to parameters recorded in monitoring while drilling (MWD) applications. This main question will be supported by four research questions:

- What is the state of the art approach for a blast design and dimensioning of underground support in underground mining?
- Which rock properties and rock mass properties are involved?
- What are the 'essential parameters to produce a basic Rock Mass Classification with usable value (focused on blast design and underground support)'?
- To what extent can these essential properties be obtained by sensors? What is the state of the art in measuring these essential rock properties on mining equipment?

First, the theory behind these research questions will be discussed in the Literature Review chapter. The general principles of a blast and support design will be treated as well as some profound classification systems. Besides that, a first insight on the concept of monitoring while drilling, including its data acquisition will be given. This is done to give an introduction on the matter of these subjects and increase or refresh the knowledge about them. The literature investigation will already lead to some general, preliminary conclusions and results. These results are then discussed in the next chapter; Analysis and Discussions.

In this chapter the emphasis lies on discussing the found results and see if it is possible to answer the earlier raised questions. The parameters used to determine a blast or support design will be assessed on importance; which are the critical parameters/ rock mass properties? Are there major differences between a blast or support design when comparing those critical parameters? Of course, it is of equal importance to look at what the possibilities are from a MWD point of view. In order to answer the main objective, relations between MWD data and critical rock properties are determined and assessed on their viability.

The combination of the two main chapters, Literature investigation and Analysis and discussions, should lead to answers on the research questions and eventually the main question of the thesis. This will lead to conclusions and recommendations, which are valued very important since there is still lots of research going on regarding this subject.

4 Introduction

Monitoring While Drilling (MWD) is a proven technique which originated from the petroleum industry and is now widely used in the mining scene. The technique is used for the recording of instantaneous on-drill parameters while the drill is operating. In the mining industry, such information can be used for modeling in-situ geological conditions. This is of value as it can supplement and improve the existing mine models and decrease the need for costly and labor intensive exploration drill core sampling and geophysical logging.

In underground mining the blast- and support designs are the most important factors in the development process. There are several methods introduced to determine such a design, where one of them is the use of Rock Mass Classification Systems. In such a system various, mostly geological parameters, are assessed and rated. The combination of those ratings results in the rock mass being ranked. From this rank certain assumptions on the rock mass can be made, and these can be used as guidelines for a design. This paper will look into the possibility of determining those parameters from the MWD data.

To come to an answer regarding this question, lots of different aspect will be reviewed. The most important parameters concerning the development of an underground support- or blast design will be determined and discussed. But also the possibilities of Monitoring While Drilling itself will be brought to light. When this is made clear, it might be possible to make correlations between the MWD data and the key parameters. When these correlations are reviewed and validated it is possible to make statements about the usability of MWD data in the process of designing underground support- and blast designs.

5 Literature investigation

In this paper the main focus lies on the geological properties that are of influence concerning the development of an underground blast or support design. The goal is to derive geological properties from MWD data and from there evaluate if it might be possible to use them for a blast or support design. Therefore the actual design aspects will not be discussed in full detail, but merely the principals. From there it’s easier to understand the basics of what comes to play in determining a blast or support design and this will help better understand the importance of the different geological parameters being used.

This literature investigation chapter serves to improve the knowledge on the different fields concerning the main goal. So, general enlightenments will be given on the underground blast and support designs, the rock mass classification systems that are being used and the concept of monitoring while drilling.

5.1 Underground Blast design

Besides the geological parameters, a good blast design depends on lots of other variables as well. Targeted production, availability of drilling equipment and explosives, desired tunnel dimensions and safety restrictions are just some of them. The single most important factor however, is the geological condition of the rock mass *(REVEY Associates, 2005).* These conditions are so important because lots of other blasting parameters such as powder factor, blasthole dimensions and type of explosives that are used are based on the geological conditions. For example, one can imagine that very weak, or heavily fractured rocks require less explosives than very strong, intact rocks.
Therefore the whole process begins with determining those conditions. Traditionally this is done with costly and labor intensive exploration drill core sampling or geophysical logging. From the acquired data the rock and rock mass properties and geological conditions are determined, and accordingly the blasting parameters are selected *(Mining Engineering Handbook, 2011)*. With these results in mind, it is already possible to determine a basic blast design.

First step in the design process itself would be the design of the drilling pattern. This pattern ensures the distribution of the explosive in the rock and desired blasting result. Several factors must be taken into account when designing the drilling pattern. These are stated below. Since every mining and construction site has its own characteristics, the drilling patterns will show great variation *(Rock Excavation Handbook, 1999).*

The tunnel or drift face can be roughly divided into four sections;

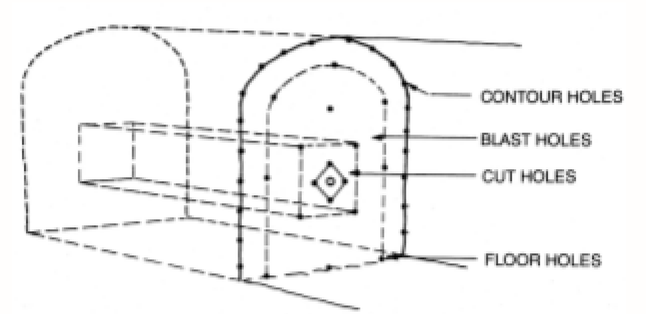


Figure 1: Schematic drill hole sections

The definitive drilling pattern design in tunneling and drifting is based on the following factors:

- Tunnel dimensions
- Tunnel geometry
- Hole size
- Final quality requirements
- Geological and rock mechanical conditions
- Explosives availability and means of detonation
- Expected water leaks
- Vibration restrictions
- Drilling equipment

Depending on site conditions, all or some of the above factors are considered important enough to determine the tunnel drilling pattern. Construction sites typically have several variations of drilling patterns to take into account the changing conditions in each tunnel. Drifting in mines is carried out with 5 to 10 drilling patterns for different tunnel sizes and the pattern is finalized at the drilling site. The big difference between bench blasting and tunnel blasting is that tunnels have only one free surface available when blasting starts. This restricts round length, and the volume of rock that can be blasted at one time *(Geology Field Manual, 2001).*

5.2 Underground support

Rock support is the term widely used to describe the procedures and materials used to improve the stability and maintain the load bearing capacity of rock near the boundaries of an underground excavation. The primary objective of a support system is to mobilize and conserve the inherent strength of the rock mass so that it becomes self-supporting. Rock support generally combines the effects of reinforcement, by such elements as dowels, tensioned rock bolts and cables, and support, with shotcrete, mesh and steel sets which carry loads from individual rock blocks isolated by structural discontinuities or zones of loosened rock *(Practical Rock Engineering, 2009).*

In modern day mining applications, three main engineering methods are available for the selection of an appropriate ground support strategy. These methods vary from analytically analyzing the ground situation to observing the conditions and selecting an appropriate design. Empirical design falls in between these two design methods as it relies on previously registered cases and ′′rules of thumb′′ developed throughout mining history. This method is efficient, commonly used but also less precise than analytical solutions. The main empirical ground support design methods are based on the use of

various rock mass classification systems *(Support of underground excavations in hard rock, 2000).* Some of the most used classification systems are the Rock Quality Designation (RQD), the Rock Mass Rating (RMR) and the Rock Quality index or Q-system. Other empirical methods, which are based on case studies, exist for example for determining the appropriate lengths of rock bolts *(Foundations of Engineering Geology, 2009).* However this may seem like a great way to determine the desired support, the methods based on those classification systems should be treated with caution since the classification of a rock mass via a classification system may be fairly arbitrary and unprecise. On the other hand it gives a very good idea about the magnitude of required support and can therefore be used as a guideline for a final design.
It may be clear now that the development of an underground support design depends on lots of different factors and parameters. To make initial planning easier, rock mass classification systems are widely used to determine the outlines of the level of required support. To see exactly how these classification systems are used, see the chapter ''Use of Rock Mass Classification Systems''. In this chapter the most used and respected classifications systems are described and explained, as well as the usage of the geological parameters.

5.3 Use of Rock Mass Classification Systems

Rock mass classification (RMC) systems are used for various engineering design and stability analysis. These systems are based on empirical relations between rock mass parameters and engineering applications, such as tunnels, slopes, and foundations. From these relations advice can be given on, for example the type of support needed in specific conditions. These suggestments are mostly considered very basic and not sufficient for final design criteria. But, since the information required for the use of those classification systems is pretty easily obtained, the results are considered well valued and can represent a framework of the final design. So, in general, rock mass classification systems are used for a feasibility study or during a pre-design, but it is not uncommon that they are as well used in the final design.

Since the development of the first RMC system back in 1946, numerous new ones have been developed and adjusted. Nowadays there are RMC systems for various purposes, such as slope mass rating, slope stability probability classification and rock mass rating. In this paper the main focus lies on parameters that play an important role concerning the determination of blast and underground support designs. Therefore we will have a closer look at the three most used classification systems concerning those designs. These systems are the Rock Mass Rating (RMR) by *Bieniawski,* in combination with its adjusted variant Mining Rock Mass Rating (MRMR) by *Laubscher,* the Q system by *Barton et al* and the Geological Strength Index (GSI) by *Hoek and Brown.*

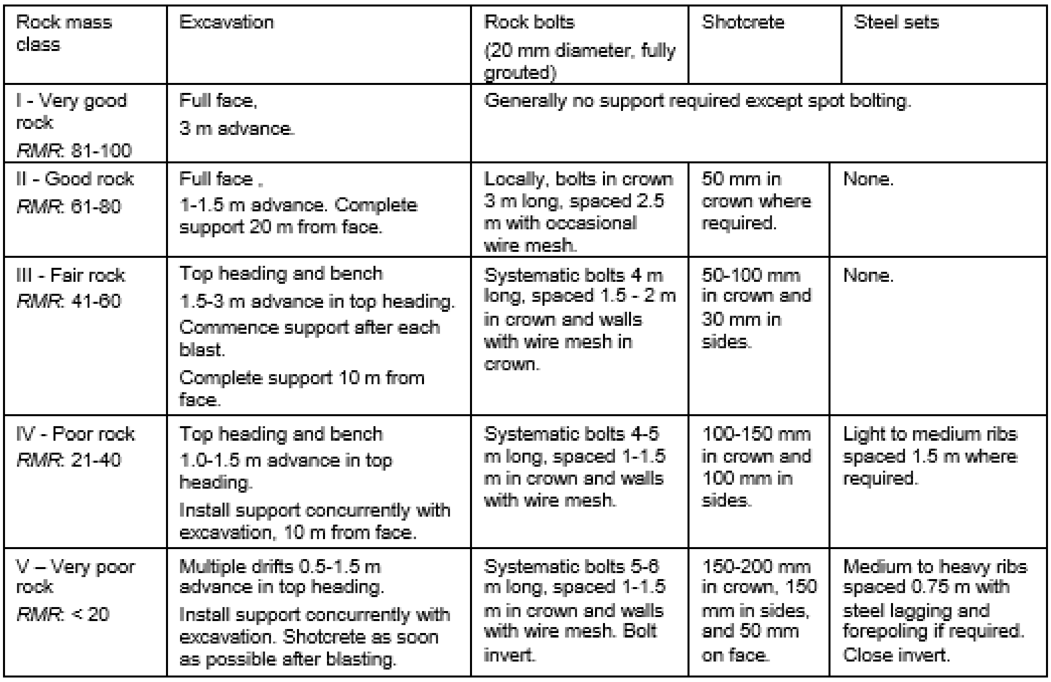
5.3.1 Rock Mass Rating and Mining Rock Mass Rating

Bieniawski (1976) published the details of a rock mass classification system called the Geomechanics Classification or the Rock Mass Rating (RMR) system. Over the years, this system has been successively refined as more case records have been examined and the reader should be aware that Bieniawski has made significant changes in the ratings assigned to different parameters. The following six parameters are used to classify a rock mass using the RMR system:

- Uniaxial compressive strength of rock material (UCS)
- Rock Quality Designation (RQD)

- Spacing of discontinuities
- Condition of discontinuities
- Groundwater conditions
- Orientation of discontinuities

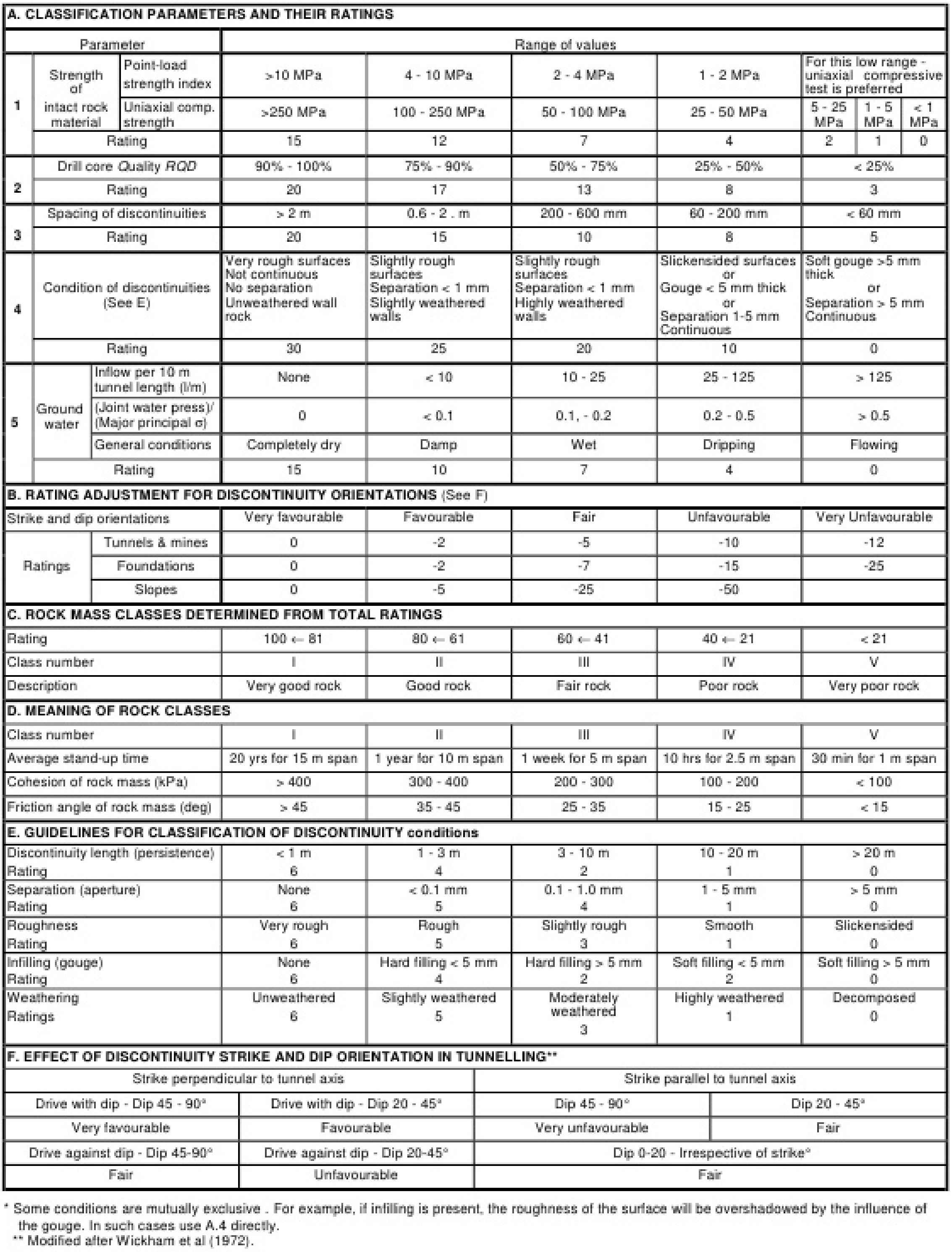
Each parameter is weighted according to its importance, and is assigned a maximum rating so that the total of all the parameters is 100. This weighting was reviewed at regular intervals in the development of the system and is now accepted as being as accurate as possible. The values of each of these parameters are determined from the rock mass and via the Rock Mass Rating table given their rating. The combinations of those six ratings gives a ‘’score’’ between 1 and 100. From this score, the rock mass can be divided into 5 classes ranging from very poor rock for RMR<20 to very good rock for RMR 81-100. Then, from these classes, basic guidelines for excavation and support can be given.



Rock mass class	Excavation	Rock bolts (20 mm diameter, fully grouted)	Shotcrete	Steel sets
I - Very good rock *RMR*: 81-100	Full face, 3 m advance.	Generally no support required except spot bolting.		
II - Good rock *RMR*: 61-80	Full face , 1-1.5 m advance. Complete support 20 m from face.	Locally, bolts in crown 3 m long, spaced 2.5 m with occasional wire mesh.	50 mm in crown where required.	None.
III - Fair rock *RMR*: 41-60	Top heading and bench 1.5-3 m advance in top heading. Commence support after each blast. Complete 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.
IV - 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 100 mm in sides.	Light to medium ribs spaced 1.5 m where required.
V – Very poor rock *RMR*: < 20	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 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.

Figure 2: Guidelines for excavation and support of 10m span rock tunnels in accordance with the RMR system. After Bieniawski1 1989.

It should be noted that Figure 2 has not had a major revision since 1973. In many mining and civil engineering applications, steel fiber reinforced shotcrete may be considered in place of wire mesh and shotcrete.



A. CLASSIFICATION PARAMETERS AND THEIR RATINGS

	Parameter		Range of values						
1	Strength of intact rock material	Point-load strength index	>10 MPa	4 - 10 MPa	2 - 4 MPa	1 - 2 MPa	For this low range - uniaxial compressive test is preferred		
		Uniaxial comp. 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	3		
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 discontinuities (See E)		Very rough surfaces Not continuous No separation Unweathered wall rock	Slightly rough surfaces Separation < 1 mm Slightly weathered walls	Slightly rough surfaces Separation < 1 mm Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge >5 mm thick or Separation > 5 mm Continuous		
	Rating		30	25	20	10	0		
5	Ground water	Inflow per 10 m tunnel length (l/m)	None	< 10	10 - 25	25 - 125	> 125		
		(Joint water press)/(Major principal σ)	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		

B. RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS (See F)

Strike and dip orientations		Very favourable	Favourable	Fair	Unfavourable	Very Unfavourable
Ratings	Tunnels & mines	0	-2	-5	-10	-12
	Foundations	0	-2	-7	-15	-25
	Slopes	0	-5	-25	-50	

C. ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS

Rating	100 ← 81	80 ← 61	60 ← 41	40 ← 21	< 21
Class number	I	II	III	IV	V
Description	Very good rock	Good rock	Fair rock	Poor rock	Very poor rock

D. MEANING OF ROCK CLASSES

Class number	I	II	III	IV	V
Average stand-up time	20 yrs for 15 m span	1 year for 10 m span	1 week for 5 m span	10 hrs for 2.5 m span	30 min for 1 m span
Cohesion of rock mass (kPa)	> 400	300 - 400	200 - 300	100 - 200	< 100
Friction angle of rock mass (deg)	> 45	35 - 45	25 - 35	15 - 25	< 15

E. GUIDELINES FOR CLASSIFICATION OF DISCONTINUITY conditions

Discontinuity length (persistence) Rating	< 1 m 6	1 - 3 m 4	3 - 10 m 2	10 - 20 m 1	> 20 m 0
Separation (aperture) Rating	None 6	< 0.1 mm 5	0.1 - 1.0 mm 4	1 - 5 mm 1	> 5 mm 0
Roughness Rating	Very rough 6	Rough 5	Slightly rough 3	Smooth 1	Slickensided 0
Infilling (gouge) Rating	None 6	Hard filling < 5 mm 4	Hard filling > 5 mm 2	Soft filling < 5 mm 2	Soft filling > 5 mm 0
Weathering Ratings	Unweathered 6	Slightly weathered 5	Moderately weathered 3	Highly weathered 1	Decomposed 0

F. EFFECT OF DISCONTINUITY STRIKE AND DIP ORIENTATION IN TUNNELLING**

Strike perpendicular to tunnel axis		Strike parallel to tunnel axis	
Drive with dip - Dip 45 - 90°	Drive with dip - Dip 20 - 45°	Dip 45 - 90°	Dip 20 - 45°
Very favourable	Favourable	Very unfavourable	Fair
Drive against dip - Dip 45-90°	Drive against dip - Dip 20-45°	Dip 0-20 - Irrespective of strike°	
Fair	Unfavourable	Fair	

* Some conditions are mutually exclusive . For example, if infilling is present, the roughness of the surface will be overshadowed by the influence of the gouge. In such cases use A.4 directly.

** Modified after Wickham et al (1972).

Figure 3: Rock Mass Rating System. Bieniawski, 1989.

5.3.2 MRMR

The Rock Mass rating system was originally based upon case histories form civil engineering. Consequently, the mining industry tended to regard the classification as somewhat conservative and several modifications have been proposed in order to make the classification more relevant to mining applications. *Laubscher (1977, 1984), Laubscher and Taylor (1976)* and *Laubscher and Page (1990)* have described a Modified Rock Mass Rating system for mining.

This MRMR system takes the basic RMR value and adjusts it to account for in situ and induced stressed, stress changes and the effects of blasting and weathering. These adjustments percentages are empirical, having been based on numerous observations in the field. The adjustment procedure requires that the engineer assess the proposed mining activity in terms of its effect on the rock mass. For example, poor blasting influences the stability of a drift or pit slope but has no influence on the cavability of the rock mass. Adjustments must recognize the life of the excavation and the time-dependent behavior of the rock mass:

Parameter	*Possible adjustment, %*
Weathering	30-100
Orientation	63-100
Induced stresses	60-120
Blasting	80-100

Although the percentages are empirical, the adjustment principle has proved sound and, as such, it forces the designer to allow for these important factors.

5.3.3 Q system

On the basis of an evaluation of a large number of case histories of underground excavations, *Barton et al (1974)* of the Norwegian Geotechnical Institute proposed a Tunneling Quality Index (Q-system) for the determination of rock mass characteristics and tunnel support requirements. Similar to the RMR system, the Q-rating is developed by assigning values to six parameters. The combined numerical value of these parameters vary on a logarithmic scale from 0.001 to a maximum of 1000. The Q-system is defined by:

$$Q = \frac{RQD}{J_n} * \frac{J_r}{J_a} * \frac{J_w}{SRF}$$

Where

RQD = rock quality designation

J_n = joint set number (related to the number of discontinuity sets)

J_r = joint roughness number (related to the roughness of the discontinuity surfaces)

J_a = joint alteration number (related to the degree of alteration or weathering of the discontinuity surfaces

J_w = joint water reduction number (relates to pressures and inflow rates of water within the discontinuities)

SRF = stress reduction factor (related to the presence of shear zones, stress concentrations and squeezing and swelling rocks).

In explaining the meaning of the parameters used to determine the value of Q, *Barton et al (1974)* offer the following comments:

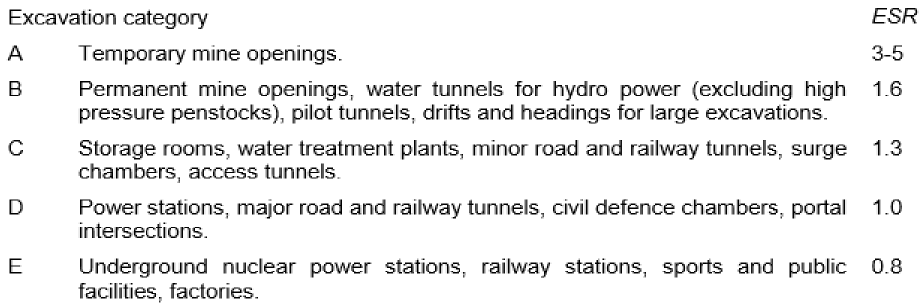
The first quotient (RQD/J_n), representing the structure of the rock mass, is a crude measure of the block or particle size. Basically, Q increases with increasing RQD and decreasing number of discontinuity sets.

The second quotient (J_r/J_a) represents the roughness and frictional characteristics of the joint walls or filling materials. So, the quotient increases with increasing discontinuity roughness and decreasing discontinuity surface alteration.

The third quotient (J_w/SRF) consists of two stress parameters. It is an 'environmental factor' incorporating water pressures and flows, the presence of shear zones, squeezing and swelling rocks and the in situ stress state. The quotient increases with decreasing water pressure or flow rate, and also with favorable rock mass strength to in situ stress ratios.

In relating the value of the index Q to the stability and support requirements of underground excavations*, Barton et al (1974)* defined an additional parameter which they called the Equivalent Dimension, De, of the excavation. This dimension is obtained by dividing the span, diameter or wall height of the excavation by a quantity called Excavation Support Ratio, ESR. Hence:

The value of ESR is related to the intended use of the excavation and to the degree of security which is demanded of the support system installed to maintain the stability of the excavation. *Barton et al (1974)* suggest the following values:



Excavation category		*ESR*
A	Temporary mine openings.	3-5
B	Permanent mine openings, water tunnels for hydro power (excluding high pressure penstocks), pilot tunnels, drifts and headings for large excavations.	1.6
C	Storage rooms, water treatment plants, minor road and railway tunnels, surge chambers, access tunnels.	1.3
D	Power stations, major road and railway tunnels, civil defence chambers, portal intersections.	1.0
E	Underground nuclear power stations, railway stations, sports and public facilities, factories.	0.8

Figure 4: Excavation category related to ESR

When both the De and Q value are plotted, an idea of the support that is required can be given, see Figure 5. It is important to notice that the majority of the case histories are derived from hard, jointed rocks. From weak rocks with few or no joints there are only few examples, and evaluation of support in such types of rocks, other methods should be considered to be used in addition to the Q-system for support design. It is important to combine application of the Q-system with deformation measurements and numerical simulations in squeezing rock or very weak rock (Q<1). This is a significant part of the total index. The Q-system classification table itself can be found in the appendix since it is quite large.

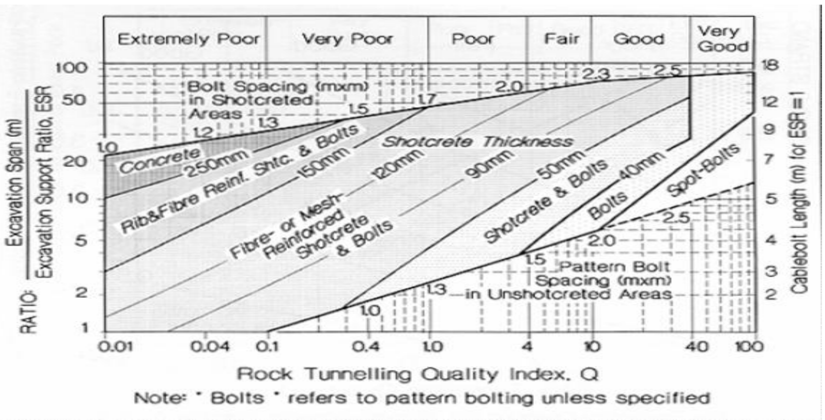


Figure 5: Support type based on Q and De

5.3.4 Geological Strength Index (GSI)

This classification system, which was first developed in 1994 by *Hoek et al*, differs from the two systems described earlier. After some years of using the RMR system it was found that it is very difficult to apply to rock masses that are of very poor quality, since the RQD in most of the weak rocks is essentially zero. Therefore it became necessary to consider an alternative classification system. The required system would place greater emphasis on basic geological observations of rock mass characteristics; reflect the material, its structure, and its geological history; and would be developed specifically for the estimation of rock mass properties rather than for tunnel reinforcement and support. The index and its use for the Hoek-Brown failure criterion was further developed by *Hoek (1995)* and presented in *Hoek et al. (1995)* and *Hoek and Brown (1997).* From then on, GSI has been continuously improved so it can nowadays include poor-quality rock masses.

The big difference between the other classification systems is that the index is based on an assessment of the lithology, structure, and condition of discontinuity surfaces in the rock mass, and it is estimated from visual examination of the rock mass exposed in outcrops, in surface excavations and in tunnel faces and borehole cores. The GSI, by combining the two fundamental parameters of the geological process, the blockiness of the mass and the conditions of discontinuities, respects the main geological constraints that govern a formation. It is thus a geologically sound index that is simple to apply in the field. However, it is therefore of limited use concerning the scope of this thesis, where the emphasis lies on classification systems which are based on measured values instead of geologists' opinions.

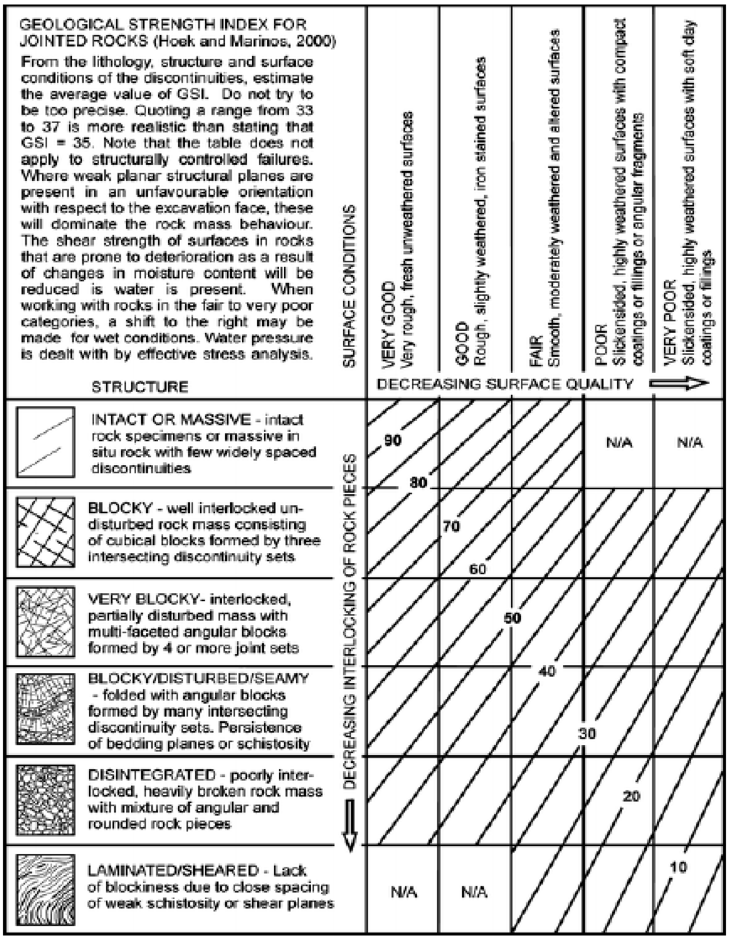


Figure 6: Geological Strength Index

Once a GSI value is determined, this number is entered into a set of empirically developed equations to estimate the rock mass properties that can then be used as input into some form of numerical analysis or closed-form solution. The index is used in conjunction with appropriate values for the unconfined compressive strength (UCS) of the intact rock, and the petrographic constant to calculate the mechanical properties of a rock mass, in particular the compressive strength of the rock mass and its deformation modulus *Hoek and Brown (1997)*.

The GSI system has considerable potential for use in rock engineering because it permits many characteristics of a rock mass to be quantified and thereby enhancing geological logic and reducing engineering uncertainty *Hoek and Brown (1997)*. Its use allows the influence of variables, which make up a rock mas, to be assessed and thus the behavior of rock masses to be explained more clearly. One of the advantages of the GSI is that the geological reasoning it embodies allows adjustments of its ratings to cover a wide range of rock masses and conditions, but it also allows us to understand the limits of its application.

5.4 Monitoring while drilling

Monitoring or Measurement While Drilling (MWD), also known as Logging While Drilling (LWD) in the oil and gas industry, is a relatively new technique in the mining business and is on the rise since the last 2 decades. Its aim is to obtain data during drilling from which rock properties can be determined and rock mass characterizations can be made in a real time basis. The most important feature of MWD is that it achieves such information more quickly and cheaply and in some cases more accurately in a real time basis than alternative approaches such as core tests and geophysical logging. This can increase the efficiency of operations and improve the reliability of short range planning since decisions affecting the efficiency of mining depend on the real time access to operations, geological information and other data *(Jorge Martin, 2007)*.

MWD parameters can be classified as measured parameters which are measured by the system automatically during drilling and calculated parameters which will be calculated from the other MWD parameters. Measured parameters can be divided into two groups. Independent Parameters which are controlled by the drill operator such as Rotary Speed or Thrust Force, and Dependent Parameters, which are related to changes in the geological situation such as Penetration Rate and Torque. The calculated parameters such as the Specific Energy are a combination of other MWD parameters and are usually used as indicator of strength of the rock mass *(minigandblasting.worldpress.com)*.

The most commonly monitored variables (and their most commonly used units) are listed below *(Gonzales, 2007)*.

- Depth (m)
- Time (s)
- Penetration Rate (m/s)
- Rotary Speed (RPM)
- Pull-down Force (N)
- Torque (Nm)
- Flushing Medium Pressure (kPa)

So, concerning the determination of geological conditions, the Dependent and Calculated Parameters are the most important.

5.4.1 Dependent parameters

- Rate of Penetration (m/s or cm/min or m/min): The rate of penetration is the rate of advance of the drill bit through the rock. The geological and geotechnical properties of the rock mass influence the rate of penetration. Therefore rate of penetration is an important parameter in MWD to locate the boundary between different rock types. This rate increases in soft rocks and fractured zones and decreases in hard rock conditions. However, the rate of penetration can also be affected by other, independent parameters. The weight exerted on the bit, rotary speed and bit age for example, will directly influence the rate of penetration. Therefore it is of utmost importance to keep these parameters as constant as possible during drilling to obtain reliable data.
- Torque (Nm): The torque is the rotation force applied to the rotating bit. The amount of torque required to rotate the drill bit is dependent on the rock properties, but also on other independent parameters such as the weight exerted on the bit and the drill bit design for example. Again, to obtain reliable data it is crucial that those parameters are kept as constant as possible.
- Flushing Medium Pressure (kPa): The flushing medium (water or slurry) is used to transport the cutting from the hole and this resolves in a certain pressure. This pressure can change when for instance a joint or void is encountered. This empty space needs to fill up with the medium first, resulting in an instant drop of flushing medium pressure which will then slowly rise back again to normal level as the void fills up. Therefore the medium pressure can be very useful to detect joints, fractured zones and voids.

5.4.2 Calculated parameters

- Specific Energy: Back in 1965 *Teale* first introduced the concept of specific energy (SE) as the energy required to excavate a unit volume of rock. Based on his investigations, it was apparent that calculated SE was seen to be highly dependent on the nature of the rock mass. For tricone rock drilling, the energy developed at the bit-rock interface is a function of the applied thrust (pulldown) and torque due to rotation. Where thrust is F (N), torque T (Nm), rotation speed N (rpm), the area of bit A (m^2) and the penetration rate P (m/min), the SE is calculated (in Pa) by the following equation:

$$SE = \frac{F}{A} + \frac{2\pi}{A} * \frac{NT}{P}$$

As shown, SE has the same units as the rock strength i.e. Pascals or Pa. therefore it can be concluded that calculated SE values can provide a reflection of the rock strength. It has also been shown that calculated SE is affected by variation in rock properties (intact strength & degree and extent of fractures), drill efficiency and bit wear.

5.5 Summary

This chapter serves as a small summary for the results found in the Literature investigation chapter. In table 1, the different parameters that are used in both the blast and support design are shown for comparison.

Parameters that are important concerning an underground blast design	**Parameters that are important concerning an underground support design**
Required tunnel dimensions	Required safety factor
Required tunnel geometry	Excavation support ratio (ESR)
Blast hole size/ powder factor	Desired roof span
Final quality requirements	Support material availability
Geological and rock mechanical conditions	Geological and rock mechanical conditions
Explosives availability and means of detonation	Expected water leaks
Expected water leaks	Rules and legislations
Vibration restrictions	
Drilling equipment availability	
Targeted production	
Rules and legislations	

Table 1: Comparison of important parameters between blast- and support design.

It is clear that the determination of both designs is subjective to all or a selection of the mentioned parameters. However, when these parameters are analyzed more precisely to determine what lies at the foundation of such a parameter, there appear to be some distinct correlations between the two sorts of designs. Besides the safety requirements and rules and legislations, most of the other parameters are in some way dependent on one other parameter; the geological and rock mechanical conditions.

In table 2, the parameters that are used in the different classification systems are listed. This way it is easy to see which are more common than others and how the parameters are nowadays determined.

Parameters used in the RMR	**Parameters used in the MRMR**	**Parameters used in the Q-system**	**Parameters used in the GSI**
Uniaxial Compressive Strength of rock material (UCS)	Uniaxial Compressive Strength of rock material (UCS)	Stress reduction factor (SRF)	Lithology
Rock Quality Designation (RQD)	Rock Quality Designation (RQD)	Rock Quality Designation (RQD)	Structure of discontinuities
Spacing of discontinuities	Spacing of discontinuities	Joint set number	Surface condition of discontinuities
Condition of discontinuities	Condition of discontinuities	Joint roughness number	
Orientation of discontinuities	Orientation of discontinuities	Joint alteration number	
Groundwater conditions	Groundwater conditions	Joint water reduction number	
	Adjustments for; Weathering, Orientation, Induced stresses, Blasting		

Table 2: Comparison of parameters between different classification systems

The colors indicate how each parameter can be determined; blue for visual, green for measured and yellow for a combination of the two.

Note that the GSI works a bit different than the other classification systems. It is much less elaborate than the others and solely relies on visual observation. However, as one can see, there are some clear resemblances between the different classification systems. Factors that are present throughout different systems are the RQD and the various joint/ discontinuity characteristics. Besides that, most parameters are nowadays obtained visually, with in some cases the possibility to also use measurements.

In table 3, the different variables that are measured with MWD are shown including their type. This may be used to determine if certain parameters are useful for the determination of geological conditions or not.

Variables measured with MWD	**Type of variable**
Depth	Independent
Time	Independent
Penetration Rate	Dependent
Rotary Speed	Independent
Pull-down Force	Dependent
Torque	Dependent
Flushing Medium Pressure	Dependent
Specific Energy	Calculated / Dependent

Table 3: List of variables measured with MWD including their type

The independent variables are not affected by external conditions whereas the dependent parameters are. This means that the dependent parameters can be possibly used to determine certain differences in the subsurface.

6 Analysis and Discussion

In the literature investigation chapter it was made clear what rock mass classification systems are, which parameters they use and to what extent they are used in determining an underground support or blast design. Besides that, the concept of monitoring while drilling and the kind of parameters that are possible to record were discussed. The goal of this research chapter is to see if it is possible to link those parameters and see if it might be possible to construct an underground blast or support design based on the information which is gathered during monitoring while drilling. If it is possible to construct such correlations, these have to be validated and it will be discussed if they might be useful or not.

Therefore it is important to first determine which parameters are the most important when it comes to developing an underground blast- or support design. Once this is determined it is equally important to have a look at the parameters from the MWD concept. If one wants to construct a design based on MWD data, it has to be possible that at least the key parameters that are necessary can be obtained from such data. That is where correlations have to be made between the MWD data on one hand and the critical rock- or rock mass parameters on the other hand. Next, it is up to see if these correlations would really be possible and/ or practical and, if they can be used worldwide or not. When these key questions have been answered it should be possible to give an answer to the main question with more confidence and certainty. In the prospect of this, it is important to keep in mind that this concept is relatively new to the mining industry and there are still many parts left unexplored and uninvestigated, making it in some cases difficult to make confident statements.

6.1 Gradation in importance of rock- and rock mass properties and MWD parameters

Now we know which parameters are used in rock mass classification systems and which are measured using monitoring while drilling it might be possible to make a gradation of those parameters based on importance. From some of the rock mass classification systems, for example the RMR, one can see that the parameters are being weighted on their importance and influence in the system. With the weights of all parameters combined a final score for a rock mass can be determined. This suggests that some parameters are valued more important than others, and it would be easy to assume that these parameters should be given priority. This is of course not completely true since all parameters are necessary to determine a viable classification. It is clear however, that with a more accurate determination of the parameters that have the greatest influence, the overall outcome becomes more accurate as well.

In this chapter the parameters that are used in classification systems will be discussed and they are ranked on importance concerning rock mass classification. The same will be done with the parameters that are measured with monitoring while drilling. This ranking depends on various factors such as sensitivity to external factors, amount of occurrence in different classification systems and obtainability.

6.1.1 Parameters used in rock mass classification systems

RMR and MRMR

From the chapter about classification systems in the literature investigation we learned that the RMR is based on the following parameters:

- Uniaxial compressive strength of rock material
- Rock Quality Designation (RQD)
- Spacing of discontinuities
- Condition of discontinuities
- Groundwater conditions
- Orientation of discontinuities

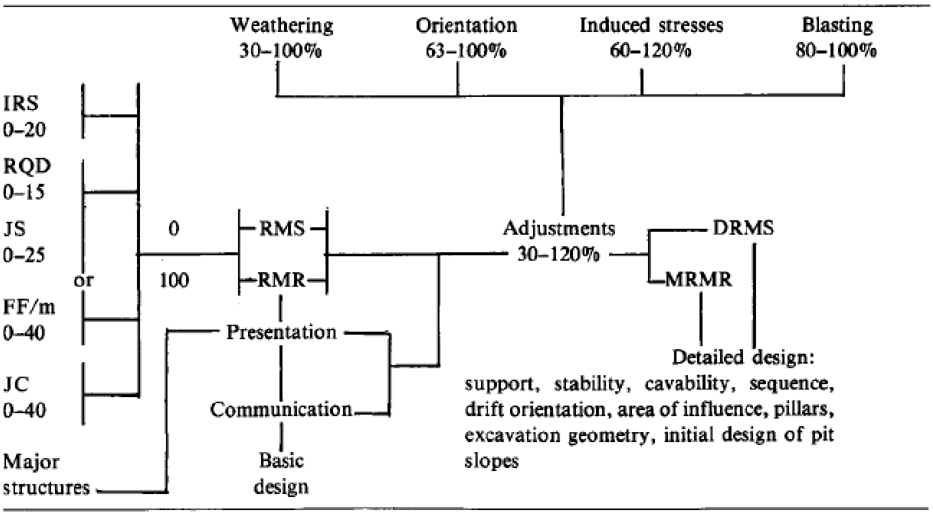


Figure 7: MRMR scheme

In Figure 7 a visualization is given on how the RMR and also the MRMR are determined and which weights are given to which parameters. As one can see from the chart, the RMR classification system does not work with these parameters itself but with abbreviations called IRS, RQD+JS or FF/M, and JC which are comprised of the parameters listed above. Therefore it may be useful to list the abbreviations in a table with the parameters out of which they are composed (figure 8).

Terms used in RMR system	**Rock mass parameters used**
Intact Rock Strength (IRS)	Uniaxial compressive strength of rock material
Rock Quality Designation (RQD)	Rock Quality Designation
Joint Spacing (JS)	Spacing of discontinuities + amount of joint sets
Fracture Frequency per meter (FF/M)	Spacing of discontinuities + orientation of discontinuities
Joint Condition (JC)	Condition of discontinuities + groundwater conditions + orientation of discontinuities

Figure 8: RMR terms and their Rock Mass parameters

The only parameter which does not clearly represent a rock mass property is the RQD. In the chart one can see that it is possible to choose between the combined values of RQD and JS or for the value FF/m when a RMR is determined. The description of RQD as given and designed by *Deere, 1965*, is; “RQD is the sum of the length (between natural joints) of all core pieces more than 10 cm long (or core diameter * 2) as a percentage of the total core length’’. Therefore the determining parameters are the spacing of the discontinuities and the orientation of the discontinuities. It is important to note that both FF/m and the combination of RQD and JS are valid to determine a RMR rating, but the RQD and JS combination is valued as a more detailed technique *(Laubscher, 1990).*

When a RMR is determined it is also possible to determine the MRMR. This, more accurate classification for in situ regimes, can then be used for more detailed designs for support, stability, pit slopes, etc. To come to a MRMR four adjustment criteria are accounted for and valued, giving them a rating in percentages between preset boundaries (Figure 9). Then the earlier obtained RMR value is multiplied with this factor to result in the final MRMR rating. The adjustments have already shortly been discussed in the chapter on classification systems and are listed below.

MRMR adjustments	**Possible adjustment in percentages**
Weathering	30-100
Orientation	63-100
Induced stresses	60-120
Blasting	80-100

Figure 9: MRMR adjustments

From this table it may be clear that the amount of adjustment to evolve an RMR to an MRMR rating can be substantial, with a total possible adjustment of 30-120%. Besides the significant possible difference, there is a possibility that the MRMR ends up higher than the RMR due to induced stress conditions which can improve the cohesion of the rock mass. The weathering and induced stresses can have the greatest effect on the final rating, and have the greatest possible diversion, with an internal difference of 70% and 60% respectively. Therefore these adjustments are thought to be the ones with the greatest possible influence on final results.

However, it is too easy to conclude that higher possible scores or percentages can be automatically linked to a more dominant influence on the total outcome. This has different reasons, for example, the extreme values of a large range might rarely be encountered, where, for an adjustment or parameter with a lower range the variation in the outcome might be much higher, resulting in a different perception of the overall influence.

So, let's take the weathering and blasting adjustments from the MRMR for example. Weathering has a possible adjustment of 30-100 and blasting of 80-100 causing a tendency to choose for weathering as a more dominant factor since the possible outcome has a much wider range. If in reality however, 95 out of a 100 cases for weathering get an adjustment in the range of 90-100% and only a few lie around the 30% adjustment, this gives a completely different view. So, the range only gives a boundary of values which are possible, but says nothing about the probability of which values can be determined. This also applies to the parameters in the RMR system of course, since they too have differences in ''boundary values''. To give a more accurate image of the importance of such factors it is therefore necessary to do some investigation on the spread of the outcomes for each factor or adjustment.

Besides this important note there are more factors to be reckoned with when one wants to make statements about an order of importance. Think about the interconnectivity of the rock mass parameters for example. It is easy to imagine that groundwater conditions and the number of discontinuities can have an effect on the condition of the discontinuities for example. These are all different rock mass parameters and are given a separate value in the classification systems, but can very much influence each other, making it hard to say which parameter is of greater importance over the others. It is therefore important to investigate if there are such connections between parameters, and if this is the case, what the magnitude of the influence between them is.

Q-system

As was described in the literature investigation the Q-system is determined by the following rock mass parameters:

RQD = rock quality designation
J_n = joint set number (related to the number of discontinuity sets)
J_r = joint roughness number (related to the roughness of the discontinuity surfaces)
J_a = joint alteration number (related to the degree of alteration or weathering of the discontinuity surfaces
J_w = joint water reduction number (relates to pressures and inflow rates of water within the discontinuities)
SRF = stress reduction factor (related to the presence of shear zones, stress concentrations and squeezing and swelling rocks).

All of these parameters speak for themselves except the SRF. In general, SRF describes the relation between stress and rock strength around an underground opening. The effects can usually be observed in an underground opening, however, some time may pass before the stress phenomena are visible. Both stress and strength of the rock mass can be measured, and SRF can then be calculated from the relation between the rock uniaxial compressive strength and the major principal stress. During the planning phase of an underground excavation, SRF can be estimated from the overburden and topographic features of general experiences from the same geological and geographical region *(Using the Q-system, NGI).*

The actual determination process of the SRF and the other parameters in the Q-system is a much more elaborate, detailed process which can be found in the paper of the NGI, *Using the Q-system*. It might be useful however to see what the possible values of the factors are and see if they have great differences from each other. These values are taken from the appendix of the earlier mentioned paper and are listed below in Figure 10.

Parameters of the Q-system	**Value range**
RQD	0 – 100 (in percentages)
Joint set number	0.5 - 20
Joint roughness number	0.5 - 4
Joint alteration number	0.75 - 20
Joint water reduction number	0.05 - 1
SRF	2.5 - 400

Figure 10: Parameters of the Q-system and their range

It is clear that there are huge differences in possible values, and the same questions and remarks that were made on the parameters of the RMR system can be applied to those of the Q-system, making it therefore very hard to make conclusions about the importance of individual parameters. Besides those remarks, it may be clear from the descriptions of the parameters or from the paper *"Using the Q-system"* that most of those parameters cannot be calculated but have to be assessed and scored by an engineering geologist. The GSI index goes even further, it solely relies on observations and there is no real use of numbers or values. This makes it obviously hard to do an assessment of a rock mass with MWD data, as it cannot measure parameters that are based on experts' insight.

General

So, in a small summary, these are the reasons why it is difficult to make a gradation of the parameters based on importance:

- The spread of the possible outcome of a parameter is more important than its range. However, the range is known and the spread is not.
- Interconnectivity between separate parameters. If one parameters influences the other it is of course of greater importance.

With these constraints and unknowns in mind, it might be arbitrary to use the range of possible values to try and make a rating comparing the importance of the parameters. What is possible however, is to base this rating on other factors. For example, it might be possible to assess the rating based on the occurrence of the parameters; how often are they used in other classification systems. Or to classify them based on opinions from engineers who often work with these classification systems and their parameters. The results of this approach may not be really scientific but might give an insight in the matter.

If one compares the (M)RMR and Q-system on parameters being used, some clear correlations can be seen. First, one can see that the RQD and UCS is used in both systems. The RQD is clearly indicated but the UCS is in the Q-system a part of the SRF, so in combination with in situ stress. Besides those two parameters, both systems rely for a great part on different characteristics of discontinuities. In fact, the RQD can also be described as a combination of the spacing and orientation of discontinuities as said earlier. From this comparison it may be clear that the characteristics of discontinuities play a very, if not the most important role in the classification of a rock mass via those systems. So, to conclude, besides the characteristics of discontinuities, the UCS is also proven an important parameter, occurring in both systems.

As an additional source of information for this thesis some interviews were held with professors from the TU-Delft who have lots of experience on these subjects. Besides staff members, also engineers who work in the related industry were questioned. The choice to interview both professors as well as in field engineers is deliberately made. It gives the opinions of professionals from two points of view; a more research driven, investigative opinion and a more practical, from a company's point of view opinion. This mix gives a good view on what is possible and what is practical, both of which are ought to be equally important. The results of these questionnaires led to the same sort of conclusions which were made earlier.

To start with, it is very difficult if not impossible to quantify a parameter on importance based on the values it might represent. Then, when looking for other ways to determine the most dominant parameters, it is said that the geological properties of the rock are the single most important factor. Within geological properties think of the sort of rock (hard, medium or soft rock), which could be assessed with the UCS, and the different discontinuity conditions. These parameters are valued so important not just because they are used in the two earlier mentioned classification systems, but mostly because these parameters influence almost every other parameter used to determine a blast or support design. This results in the summary displayed in table 4.

Critical parameters concerning rock mass classification systems	**Reasons they are thought to be critical**
Uniaxial Compressive Strength (UCS), is part of RQD value	• Is used in multiple classification systems • Is easy to obtain • Is assessed via measurements instead of observations • Is a key indicator for rock type • Has a (great) influence on other (rock mass classification) parameters
Different characteristics of discontinuities. (spacing, condition, alteration, orientation)	• Are used in multiple classification systems (sometimes in a slightly different way) • Are easy to obtain • Have (great) influence on other (rock mass classification) parameters
Water conditions	• Can have enormous influence on other (rock mass classification) parameters • Used in multiple classification systems

Table 4: Summary of critical parameters concerning rock mass classification systems

6.1.2 Parameters possible to obtain from monitoring while drilling

Besides the parameters which are used in the classification systems, it is, while keeping the main question of this thesis in mind, equally important to look at the parameters which are possible to be obtained with MWD. The most commonly monitored variables (and their most commonly used units) are listed below *(Gonzales, 2007).* These were earlier mentioned and described in the literature review.

- Depth (m)
- Time (s)
- Penetration Rate (m/s)
- Rotary Speed (RPM)
- Pull-down Force (N)
- Torque (Nm)
- Flushing Medium Pressure (kPa)
- Core recovery (good results possible with Sonic Drilling)

As was earlier stated, the dependent and calculated parameters are the most important when one wants to determine geological conditions. From, for example Specific Energy, one can determine the rock strength or UCS and with the help of the Flushing Medium Pressure voids can be detected. These measurements can then help to assess a rock mass rating, but cannot be used solely to determine a rock mass rating, therefore additional information has to be acquired. In the following paragraphs the problems faced when correlating MWD data with geological properties will be explained. The most useful feature of MWD data however, would be the core recovery. From the core recovery lots of important geological conditions can be precisely determined such as the amount of fractures, condition of discontinuities etc. This can give a clear and true representation of the subsurface when the cores are assessed correctly.

6.1.3 Differences when comparing blast and support design

In the parts above the importance of the parameters that are used in the classification systems and the parameters that are possible to measure with MWD were discussed. However, when one wants to determine a blast or support design, the importance of parameters might not be the same for the two. This is caused by the fact that the classification systems that are described are mostly used in the determination of a support design, and not a blast design. Of course, the classification of a rock mass via those systems can still be very beneficial when one wants to make a blast design, but it is not as widely worked out as with the support designs. So, for the support design one can say that the gradation of importance of the parameters used in the classification systems is more or less the same as for an underground support design. For the blast design this comparison does clearly not apply and therefore raises the question; what kind of parameters are most important concerning a blast design?

The parameters used for the determination of a blast design were shortly discussed in the literature investigation on the blast design part. There, the importance of geological parameters, targeted production, availability of drilling equipment and types of explosives were some of the mentioned variables which are important to a good blast design. These statements are backed up by the interviewed professors and engineers from the field. Besides those parameters also the Blastability Index (Lily's is the most used) and the Excavatability are widely used factors. Here, the Blastability Index (BI) is use for the description of the ease of blasting, and is also related to rock fragmentation or powder factor (IJEIT, 2015). The Excavatability is a measure of how easy it is to remove earth materials and is used to determine appropriate excavation methods. It is a function of the geotechnical properties of the material (strength or density), and mass characteristics, in particular mechanical discontinuities *(British Geological Survey)*. Without going into full detail on the BI or Excavatability, it may be clear that these parameters, which are more elaborately determined than the others, primarily rely on the geological conditions of the rock mass.

From here, preliminary conclusions on the kind and importance of the parameters used for blast designs can be made. It is clear that yet again the geological parameters play a very important role in this. This can be observed by the fact that almost every other factor which has a possible influence on the blast design also is dependent on the geological conditions. As stated above, the Blastability Index, which is used to determine the powder factor, is based on the geological conditions of the rock mass. But also the type of explosives has a relation with the geological conditions. A hard, solid rock, needs different explosives than a very weak, heavily jointed rock for example. This illustrates that the geological conditions, and the characteristics of discontinuities in particular, in combination with the UCS of the rock mass are the most important factors when concerning a blast design.

So, in general, there are some minor differences when comparing the parameters of a blast and a support design. Each design relies on some specific factors or parameters, but on the other hand there are lots of similarities as well. A clear and very important similarity is that the main focus in both designs lies on the geological conditions of the rock mass. Not only because the rock mass characteristics itself are high valued parameters, but also because a lot of other parameters are dependent on the characteristics. These characteristics include the rock type, discontinuity characteristics and water conditions for example. Besides those characteristics, which are determined somewhat arbitrary, the UCS or uniaxial compressive strength, is considered a key parameter in both designs. Compared to the earlier mentioned characteristics, the UCS has the advantage that it can be determined very accurately.

From this it is possible to conclude that there are no major differences between a support design and a blast design concerning the **critical parameters.** Therefore the critical parameters which were linked to the support design and stated at page 23 can also be applied to a blast design.

6.2 Relations between MWD data and critical rock- and rock mass properties

In the previous chapters the critical rock- and rock mass properties when concerning an underground support or blast design were discussed. Besides that, the key parameters which are measured with the MWD technique have been indicated. Concerning the main question of this paper, its goal is to see if there are potential relations between the MWD data the critical rock- and rock mass parameters. Now that both the critical properties or key parameters used in blast and support designs and the parameters from MWD have been made clear, it might be possible to see if there are relations between them, and if so, what their potential might be.

So far, one has learned that the most important parameters are roughly the same when comparing a support with a blast design. The highest valued parameters are the geological conditions of the rock mass, with the characteristics of discontinuities in particular, and the UCS of the rock mass. Therefore, the main focus will lie on finding correlations between the MWD parameters and those characteristics. First, the MWD parameters which are thought to be the most promising will be linked to critical rock- and rock mass properties. After that the relation between the MWD data and their resulting geological parameters will be discussed. In this chapter it is checked if those found relations are valid under changing circumstances and if they can be used worldwide.

6.2.1 Linking MWD data with geological parameters and identify relations

From the previous parts one has learned that there are a few promising parameters which are possible to record with MWD. These parameters are the Rate of Penetration, Torque, Flushing Medium Pressure and the Specific Energy. The first three of those parameters can directly give information about the geological properties, whereas the Specific Energy is calculated with the use of some (other) MWD parameters. Some of these parameters on their own are not very useful to determine underground conditions. However, due to the combination of them that *Teale (1965)* invented they can be of use. This is a great example of how it is possible to use different parameters in combination to come to a better understanding of the subsurface.

Rate of Penetration and Torque

The parameters Rate of Penetration and Torque are, when independent MWD parameters such as weight on the bit and rotary speed are constant, influenced by the geological and geotechnical properties of the rock mass. These parameters change with changes in rock strength or zones with fractures. Therefore the ROP and Torque might be an indicator for the UCS of a rock mass for instance. However, one major difficulty is then already immediately revealed. Where the UCS of a rock mass is classically determined from a piece of rock in between fractured zones, it is from the MWD data not possible to see in such detail in what conditions it is recording. For clarification, it might be useful to illustrate this with an example;

Assume there are two different rock types, the first a soft to medium rock with little to no fractures, and the second a strong rock with lots of fractures. When the UCS is determined from a piece of rock taken from the mass the two will most likely show significant differences in rock strength, giving the strong rock the highest score. If in the same rocks the ROP and Torque are measured, the results are probably more likely to show a resemblance instead of significant differences, since with this technique the fractures will also play a very important role on the outcome. It therefore might be dangerous to make assumptions solely based on the results of ROP or Torque regarding UCS, at least not until such complications have been thoroughly investigated. What could be an option is to underpin these results with simple and fast tests that can be done by an experienced person on site. *Deere and Miller (1966)* have shown that rock strength can be estimated with a Schmidt hammer and a specific gravity test with enough reliability to make an adequate strength characterization. Then, these results can be compared and from there it would be possible to assess the usability of the found results.

Flushing Medium Pressure

The flushing medium transports cuttings from the hole, resulting in a certain pressure. Normally this pressure is kept at a constant level, but when for instance a large void is encountered, this level will drop instantly. This void will eventually fill up with the flushing medium, resulting in a gradationally increase in pressure until the base level is reached again. The flushing medium pressure is therefore not really useful to determine quantified geological parameters but can be used to detect large joints, fractured zones and voids. This technique may, on the other hand, bring some complications. First the flushing medium pressure will always show variations during drilling, even when no voids or fractures are encountered. This makes it hard to determine which ‘’spikes’’ in the data actually represent voids or fractures and which don’t. Besides that, this technique is only useful for relatively large fractures or voids. One can imagine that small fractures probably don’t show up in the results, or are discarded as normal fluctuations. It is therefore difficult to assess the usage of this factor, most likely it can be used as additional information or to back up results obtained from other investigation methods.

Specific Energy
As explained earlier the specific energy is a calculated parameter. This means that multiple parameters which are obtained with MWD are built into a simple formula. This results in the specific energy, which represents the energy required to excavate a unit of rock. Based on the investigation of Teale and others, it was apparent that the calculated SE was seen to be highly dependent on the nature of the rock mass. It is therefore assumed that it can provide a reflection of the rock strength. But, as was already suggested with the ROP and Torque, the SE is also affected by variation in rock properties such as intact strength and degree and extend of fractures. It is therefore, just as with the ROP and Torque, probably not possible to determine the UCS without the use of other techniques.

Here follows a small summary showing in table 5 the links between certain MWD parameters and geological conditions. Table 6 shows the problems that are possibly encountered when the geological conditions were to be determined from the MWD data.

MWD parameters	**Geological conditions**
Rate of Penetration	*Unconfined Compressional Strength (UCS) and ‘’nature of rock mass’’*
Torque	*Unconfined Compressional Strength (UCS) and ‘’nature of rock mass’’*
Flushing Medium Pressure	*Voids or fractures*
Specific Energy	*Unconfined Compressional Strength (UCS) and ‘’nature of rock mass’’*

Table 5: Link between MWD parameters and geological conditions

Sort of problem	**MWD parameter it is applicable to**
Difficulties in ‘’correctly’’ assessing the UCS. Traditionally done in a non-fractured zone, but impossible to establish such a zone from a log	*Rate of Penetration, Torque and Specific Energy*
Natural variations in recording or ‘’noise’’	*All parameters*
Correlating the right results or ‘’spikes’’ with conditions.	*All parameters*
Accuracy	*All parameters, especially important if it is desired to obtain discontinuities since they can be very small.*
Measurements are not only affected by one single geological condition	*Rate of Penetration, Torque and Specific Energy*

Table 6: List of problems which might be encountered and their corresponding MWD parameters

6.3 Validation check on found relations

What comes forth from these possible relations is that most of the parameters are thought to be possible to link to the UCS of the rock mass. Besides the link with the UCS, also a connection between the flushing medium pressure and fractures or voids was found. As already described, both of these relations show various implications. On top of the ones mentioned above there are some other constraints which have to be taken into account when one wants to assess the viability of these relations.

Say that it is possible to construct a direct relation between the data from the ROP and Torque and the UCS. This relation then has to be quantified so that certain values from the data would represent certain UCS values. To make this relation usable for work it has to be possible to adapt it under any circumstances and in any place on earth. This may pose certain complications. The data used is measured underground, and then analyzed to assess a UCS value of the rock mass. Because these measurements take place underground, there is a great possibility that the results will strongly be affected by other factors than the geological characteristics of the rock mass alone. Think of differences in amount of overburden, in situ stresses and local water regimes. Because of these factors the possibility exist that the same sort of rock masses under different circumstances give completely different responses in the measurements. It is therefore very important to further investigate those relations and as well the influence of changing circumstances on the measurements.

Possible problems when constructing a correlation that can be used in multiple sites
Differences in amount of overburden, causing a variation in vertical pressure
Differences in in-situ stress regimes
Differences in local water regimes

Table 7: Problems encountered when constructing a correlation usable for multiple sites

Another possibility might be to only use these correlations on a specific site. The mentioned circumstances that can influence the measurements will most likely show little variations when only one site is regarded. These variations can then be determined from various tests and the responses from the MWD data can then be correlated accordingly with those circumstances. Then, it is possible to reflect the MWD data with other standard, proven tests, for this example a normal UCS test, to set a benchmark for that specific site. This way it might be possible to determine a site specific correlation and use this for the rest of the project, but yet again further investigation on these subjects is required.

It may be clear now that it is very difficult to properly assess the viability of possible relations and even to determine those relations in the first place. The parameters which are used in classification systems are not really reflected by the parameters possible to obtain from MWD data except for a few of them. For these parameters it has proven to be a challenge to construct trustworthy relations due to lots of other factors that can possibly influence the results. The most promising option would be to determine the relation for each site specifically with the use of comparisons with other, proven, testing methods. This may lead to some usable correlations. However, the best technique to determine the critical parameters would be via the assessment of borehole cores. This is a very sound and proven method and can identify most of the critical parameters used in the determination of a blast or support design.

7 Conclusions

It may be clear that the subject of MWD and its relations with critical rock- and rock mass parameters used for the determination of an underground blast or support design is very complex. It covers lots of different engineering subjects and also fields of study that have not been fully investigated and understood just yet. This makes it difficult to give a solid answer to the main and research questions. Here, the found results will be reflected on the research questions.

What is the state of the art approach for a blast design and dimensioning of underground support in underground mining?
From the study one can see that there are **multiple guidelines** used in the design process of an underground blast- or support design. Especially concerning the support design, a lot can be determined from the **classification systems**. This is proven a sound method since these systems are widely used in the field, mostly concerning the pre-studies. These systems rely on the input of certain parameters. To see if it is possible to obtain these parameters from MWD data it would be wise to start with the most important ones.

Which rock properties and rock mass properties are involved? + What are the 'essential parameters to produce a basic Rock Mass Classification with usable value (focused on blast design and underground support)'?
From the study it was concluded that, concerning an underground blast- or support design, the most important parameters are 1; **the characteristics of discontinuities in the rock mass** and 2; the **UCS of the rock mass**. These parameters are proven to be of the greatest importance for both of the designs, not only because they directly determine certain factors, but also because they have a great, indirect, influence on others.

To what extent can these essential properties be obtained by sensors? What is the state of the art in measuring these essential rock properties on mining equipment?
Once the key parameters concerning the designs are determined, it is equally important to have a look at what is possible to obtain from the MWD data. Then, if the parameters that are possible to measure with MWD show potential, it might be possible to determine relations between them and the required parameters used for the design. The most promising parameters measured with MWD are the **Rate of Penetration, Torque, Flushing Medium Pressure** and the calculated parameter **Specific Energy**. Where these parameters can be used to determine certain geological conditions, the difficulty lies in making correlations such that the data reflects the parameters that are necessary.

Difficulties in assessing the characteristics from the MWD data
This is proven to be the hardest part, since the single most important geological condition are the characteristics of discontinuities. These characteristics, such as joint condition and spacing, are very difficult to assess from measurements for a variety of reasons. First is **the scale of the measurements** compared to the scale of the characteristics. For example, joints and fractures of several millimeters can have significant effects on the overall conditions of the rock mass, however it is impossible to notice them on drill logs. Besides that, it is very difficult to spot the **difference between normal fluctuations in the measurements** and actual measurements of the fractures. Also, when relating measured data with for example UCS, it is very hard to tell if the read outs are purely caused by the strength of the rock, or if for example **discontinuities or other conditions affect the measurements**.

Troubles in validating the usability of the correlations + alternative
These problems in fact cause great trouble when validating the usability of such correlations, especially when such a correlation would have to be used in different sites. One can see that the **measurements from MWD can be affected by other factors than the parameter which is desired to obtain**, resulting in a false image of the true values. Besides the earlier mentioned factors that can be of influence there are others to keep in mind. Think of the **variances in overburden** causing **differences in local stress regimes, ground water conditions** and so on. What might be a ready to use alternative is the consideration of **using borehole cores to assess the critical parameters**. With only a few (at least more than 1) cores it is possible to determine lots of those critical parameters, and especially the very important characteristics of discontinuities. This process used to be very time consuming but nowadays there is software available that can automatically assess such borehole cores. With the information retrieved from the cores it might be possible to **determine site specific correlations** and to use these in the rest of the mining progress.

However some problems were encountered and new difficulties revealed, the main objective of the thesis can now be answered. *The aim of the project is to investigate critical rock and rock mass properties for modern blast – and underground support design and identify potential relations to parameters recorded in MWD applications.*
The critical properties are 1; the characteristics of discontinuities in the rock mass and 2; the UCS of the rock mass. The potential relations to MWD parameters are with the; Rate of Penetration, Torque, Flushing Medium Pressure and Specific Energy.

To conclude, it is apparent that there are some promising MWD parameters which could maybe be used to determine critical geological parameter for an underground blast or support design, however additional investigation on the matter is required. Besides that, probably the best solution would be to use a combination of information retrieving methods. This way it is possible to check the results with different techniques and are flaws more easily spotted. For this particular case it would therefore be interesting to use the MWD data in combination with borehole core assessment.

8 Recommendations

What is made clear from the conclusions of this thesis is that there are still lots of different fields regarding this subject left to investigate. With more research on these subjects it might be possible to determine other, better correlations. Also, the statements that are already made can be evaluated and checked, and maybe improved or adjusted. Therefore the recommendations for further research play a very important role regarding this subject.

To begin with, in the part about "linking MWD data with geological parameters and identify relations'' on page 26, the specific energy is mentioned as a probably useful parameter. This parameter is, in contradiction to the other MWD parameters, made up out of a combination of others. Therefore it might be beneficial to **investigate other calculated parameters**, or the possibility to construct new calculated parameters.

Regarding the other mentioned MWD parameters; ROP, Torque and Flushing Medium Pressure, it would be useful to check several things. As explained, **the sensitivity of the measurements** is important to identify for example small joints or fractures. If the sensitivity is improved, it would be possible to identify more discontinuities. The sensitivity is also somewhat related to the **natural occurring fluctuations** in the measurements; even if the sensitivity is greatly improved but the natural fluctuations remain the same, it will still be very difficult to spot the difference between noise and actual desired measurements. It would therefore be advised to check the possibility of enhancing the sensitivity but also to **analyze the ''noise''** and see how this can be filtered in some way.

Also, as mentioned in the Analysis and Discussions chapter, the measurements obtained from the MWD equipment are **affected by a variety of geological conditions**, and not only the ones who are desired to measure. This causes unreliable results when these measurements are correlated to a single geological property. Most important is therefore to investigate the **level of effect these other conditions have on the measurements** and see if it might be possible to work with some sort of correction.

Most promising option is thought to be a **site specific correlation**, eliminating all the variables that can fluctuate from place to place. This correlation can be established and checked with the use of borehole cores and simple on-site tests. This also **reduces the possibility of mistakes with measuring** because the results can be compared with a different technique to see if they are the same. To achieve this**, research on the determination of those correlations** need to be done, as well as **investigate if those other variables only fluctuate between reasonable boundaries within a single site**.

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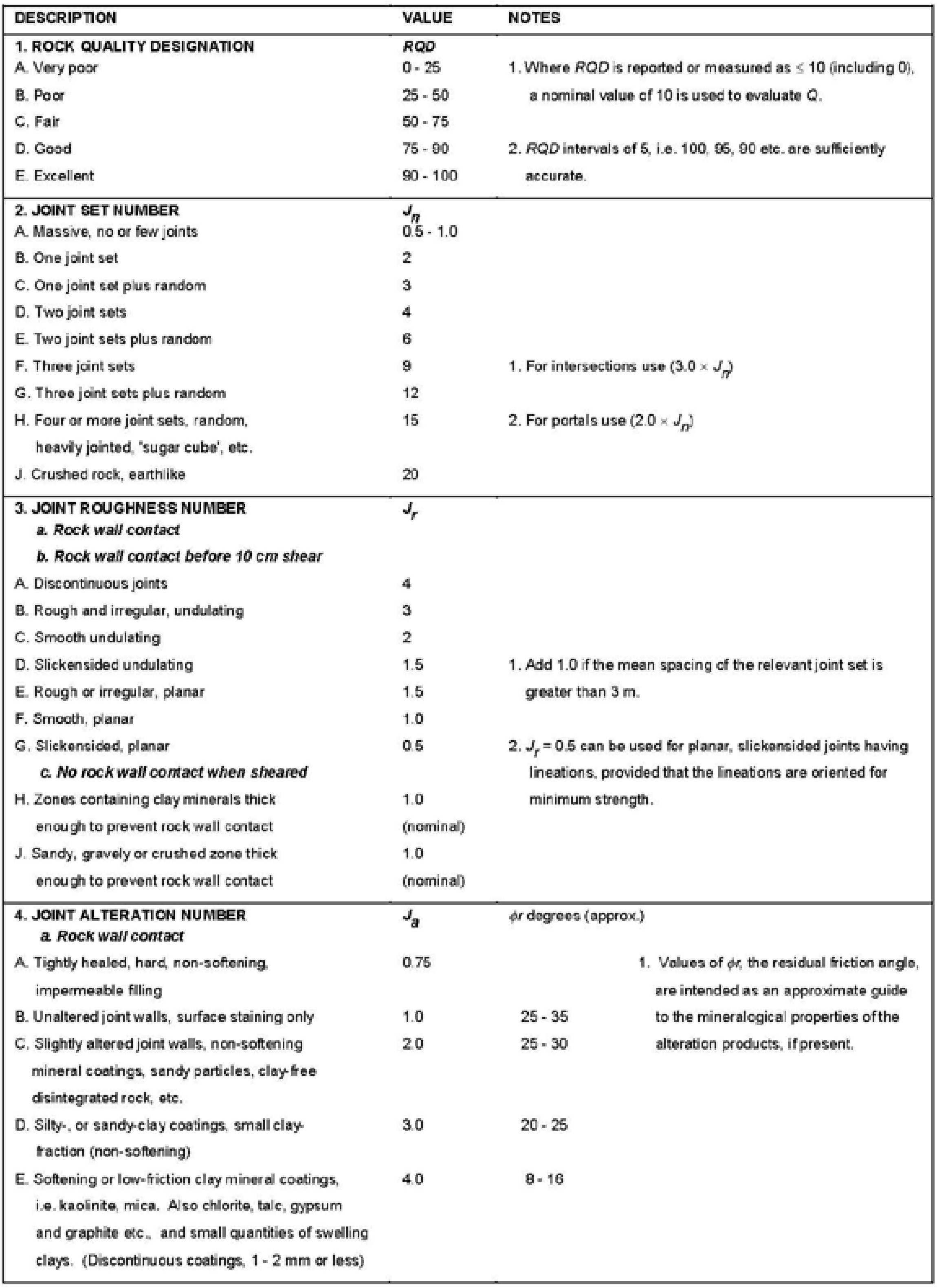
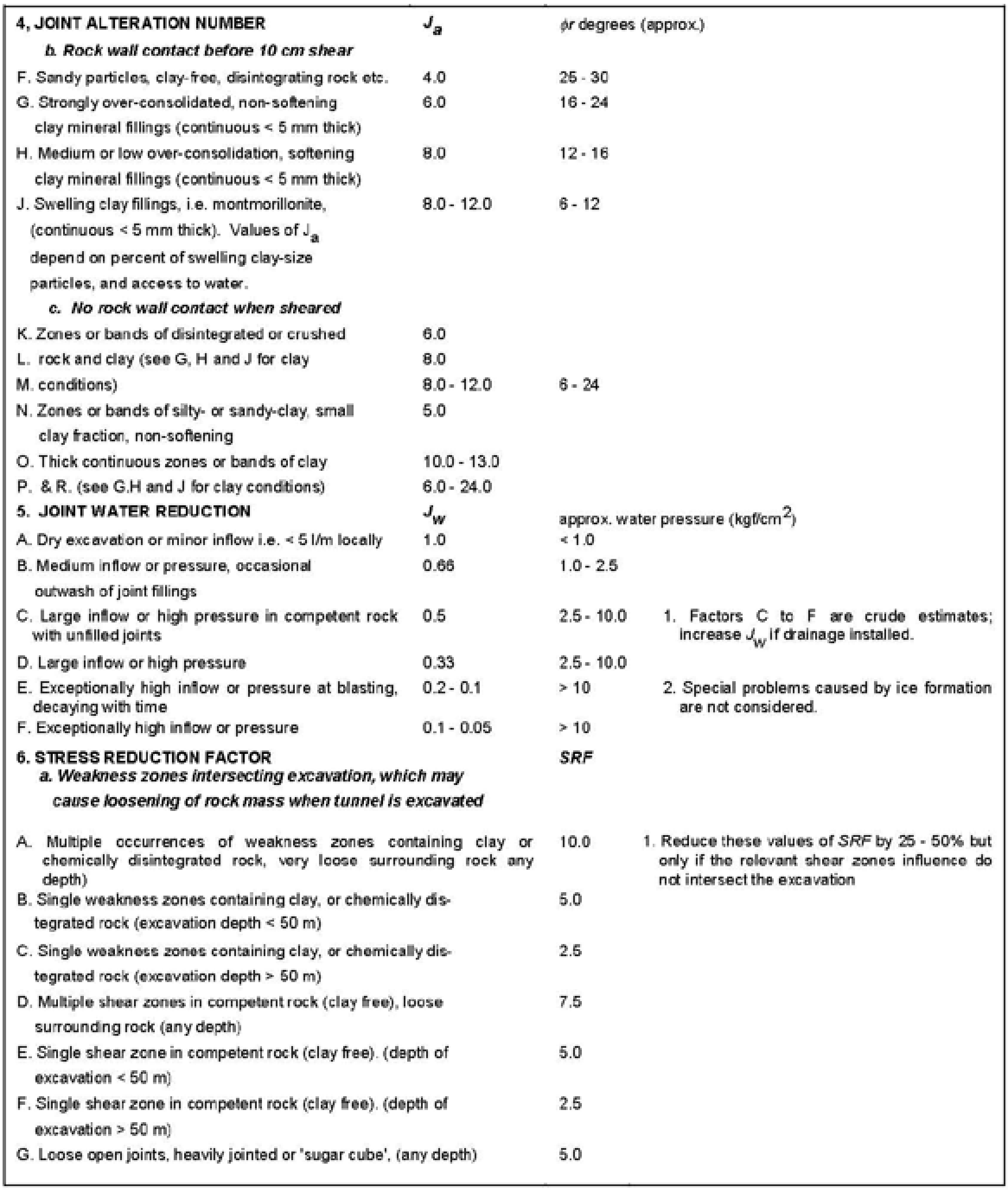
10 Appendix



DESCRIPTION	VALUE	NOTES	
1. ROCK QUALITY DESIGNATION	***RQD***		
A. Very poor	0 - 25	1. Where *RQD* is reported or measured as ≤ 10 (including 0), a nominal value of 10 is used to evaluate *Q*.	
B. Poor	25 - 50		
C. Fair	50 - 75		
D. Good	75 - 90	2. *RQD* intervals of 5, i.e. 100, 95, 90 etc. are sufficiently accurate.	
E. Excellent	90 - 100		
2. JOINT SET NUMBER	J_n		
A. Massive, no or few joints	0.5 - 1.0		
B. One joint set	2		
C. One joint set plus random	3		
D. Two joint sets	4		
E. Two joint sets plus random	6		
F. Three joint sets	9	1. For intersections use (3.0 × J_n)	
G. Three joint sets plus random	12		
H. Four or more joint sets, random, heavily jointed, 'sugar cube', etc.	15	2. For portals use (2.0 × J_n)	
J. Crushed rock, earthlike	20		
3. JOINT ROUGHNESS NUMBER	J_r		
a. Rock wall contact			
b. Rock wall contact before 10 cm shear			
A. Discontinuous joints	4		
B. Rough and irregular, undulating	3		
C. Smooth undulating	2		
D. Slickensided undulating	1.5	1. Add 1.0 if the mean spacing of the relevant joint set is greater than 3 m.	
E. Rough or irregular, planar	1.5		
F. Smooth, planar	1.0		
G. Slickensided, planar	0.5	2. J_r = 0.5 can be used for planar, slickensided joints having lineations, provided that the lineations are oriented for minimum strength.	
c. No rock wall contact when sheared			
H. Zones containing clay minerals thick enough to prevent rock wall contact	1.0 (nominal)		
J. Sandy, gravely or crushed zone thick enough to prevent rock wall contact	1.0 (nominal)		
4. JOINT ALTERATION NUMBER	J_a	ϕr degrees (approx.)	
a. Rock wall contact			
A. Tightly healed, hard, non-softening, impermeable filling	0.75		1. Values of ϕr, the residual friction angle, are intended as an approximate guide to the mineralogical properties of the alteration products, if present.
B. Unaltered joint walls, surface staining only	1.0	25 - 35	
C. Slightly altered joint walls, non-softening mineral coatings, sandy particles, clay-free disintegrated rock, etc.	2.0	25 - 30	
D. Silty-, or sandy-clay coatings, small clay-fraction (non-softening)	3.0	20 - 25	
E. Softening or low-friction clay mineral coatings, i.e. kaolinite, mica. Also chlorite, talc, gypsum and graphite etc., and small quantities of swelling clays. (Discontinuous coatings, 1 - 2 mm or less)	4.0	8 - 16	

Figure 11: Q-system classification table part 1



4, JOINT ALTERATION NUMBER	J_a	ϕr degrees (approx.)	
b. Rock wall contact before 10 cm shear			
F. Sandy particles, clay-free, disintegrating rock etc.	4.0	25 - 30	
G. Strongly over-consolidated, non-softening clay mineral fillings (continuous < 5 mm thick)	6.0	16 - 24	
H. Medium or low over-consolidation, softening clay mineral fillings (continuous < 5 mm thick)	8.0	12 - 16	
J. Swelling clay fillings, i.e. montmorillonite, (continuous < 5 mm thick). Values of J_a depend on percent of swelling clay-size particles, and access to water.	8.0 - 12.0	6 - 12	
c. No rock wall contact when sheared			
K. Zones or bands of disintegrated or crushed	6.0		
L. rock and clay (see G, H and J for clay	8.0		
M. conditions)	8.0 - 12.0	6 - 24	
N. Zones or bands of silty- or sandy-clay, small clay fraction, non-softening	5.0		
O. Thick continuous zones or bands of clay	10.0 - 13.0		
P. & R. (see G.H and J for clay conditions)	6.0 - 24.0		
5. JOINT WATER REDUCTION	J_w	approx. water pressure (kgf/cm^2)	
A. Dry excavation or minor inflow i.e. < 5 l/m locally	1.0	< 1.0	
B. Medium inflow or pressure, occasional outwash of joint fillings	0.66	1.0 - 2.5	
C. Large inflow or high pressure in competent rock with unfilled joints	0.5	2.5 - 10.0	1. Factors C to F are crude estimates; increase J_w if drainage installed.
D. Large inflow or high pressure	0.33	2.5 - 10.0	
E. Exceptionally high inflow or pressure at blasting, decaying with time	0.2 - 0.1	> 10	2. Special problems caused by ice formation are not considered.
F. Exceptionally high inflow or pressure	0.1 - 0.05	> 10	
6. STRESS REDUCTION FACTOR		***SRF***	
a. Weakness zones intersecting excavation, which may cause loosening of rock mass when tunnel is excavated			
A. Multiple occurrences of weakness zones containing clay or chemically disintegrated rock, very loose surrounding rock any depth)		10.0	1. Reduce these values of *SRF* by 25 - 50% but only if the relevant shear zones influence do not intersect the excavation
B. Single weakness zones containing clay, or chemically distegrated rock (excavation depth < 50 m)		5.0	
C. Single weakness zones containing clay, or chemically distegrated rock (excavation depth > 50 m)		2.5	
D. Multiple shear zones in competent rock (clay free), loose surrounding rock (any depth)		7.5	
E. Single shear zone in competent rock (clay free). (depth of excavation < 50 m)		5.0	
F. Single shear zone in competent rock (clay free). (depth of excavation > 50 m)		2.5	
G. Loose open joints, heavily jointed or 'sugar cube', (any depth)		5.0	

Figure 12: Q-system classification table part 2