A QUANTITATIVE CORRELATION BETWEEN THE MINING ROCK MASS RATING AND IN-SITU ROCK MASS RATING CLASSIFICATION SYSTEMS

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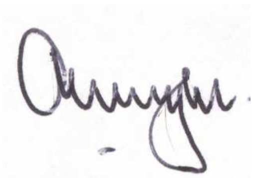
CANDIDATES DECLARATION

I declare that this research report is my own, unaided work. It is being submitted for the degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.



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ABSTRACT

The three most common rock mass classification systems in use in the South African mining industry today are Bieniawski's (1976) Geomechanics or RMR System, Barton *et al.'s* (1974) Q-System and Laubscher's (1990) MRMR System respectively. Of these three systems, only the MRMR Classification System was developed specifically for mining applications, namely caving operations. In response to the increased use of the MRMR Classification System in the mining industry, and concerns that the MRMR System does not adequately address the role played by discontinuities, veins and cemented joints in a jointed rock mass, Laubscher and Jakubec introduced the In-Situ Rock Mass Rating System (IRMR) in the year 2000. A quantitative comparison of the MRMR and IRMR Classification Systems has been undertaken to determine a correlation between the two classification systems, the results of which indicate that there is not a major difference between the resultant rock mass rating values derived from the two Classification Systems. Therefore, although the IRMR System is more applicable to a jointed rock mass than the MRMR System, the MRMR System should not be regarded as redundant, as it still has a role to play as a mine design tool.

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1 INTRODUCTION

Following the discovery of economically viable gold and diamond deposits in the 1870's, and platinum in 1924, the mining industry has, and continues to be, one of the primary economic drivers of the South African economy. Until approximately thirty years ago, exploitable mineral reserves were mined at shallow depths with the resultant perception in the industry, and among investors, that mining activities did not constitute a high instability risk, and that, consequently, the associated human and economic consequences were relatively low. However, as the shallow mineral reserves were mined out, deep level mining, to depths of some 3000m, became the norm in the Johannesburg area. This increase in mining depth resulted in a change in the mining industry's, and investors', perceptions of the risk of mining-induced instability. In order to address the increased risk of mining-induced instability, methods of quantifying the quality of the in-situ rock mass were adopted within the South African mining industry, with rock mass classification now forming an integral part of pre-feasibility, feasibility and bankable feasibility mining geotechnical investigations.

In this research report the author will carry out a quantitative correlation between one of the three main classification systems in use today, namely Laubscher's (1990) Mining Rock Mass Rating (MRMR) System, and Jakubec and Laubscher's (2000) In-Situ Rock Mass Rating (IRMR) System. The latter was introduced to address concerns pertaining to the applicability of the MRMR System to the role of fractures / veins and cemented joints in a jointed rock mass, to assess the effect of the newly introduced IRMR parameters on the resultant rock mass rating values.

1.1 Background to Rock Mass Classification

Prior to the adoption of rock mass classification systems within the mining industry, rock mass classification systems, in one form or another, have formed an integral part of civil engineering, specifically in the design and construction of tunnels It follows therefore, that initially, the development of rock mass classification systems was driven by the civil engineering industry, with a number of systems being develop by *inter alia*, Terzaghi (1946), Lauffer (1958), Deere (1967), Wickham *et al.* (1972), Bieniawski (1973) and Barton et al. (1974). While these classification systems represented significant advances as design tools, the majority of the earlier systems have fallen into disuse, or have been incorporated into other classification systems, e.g. Deere's (1967) Rock Quality Designation System and Bieniawski's (1976) Geomechanics or RMR System, while those that survived were considered to be only of limited value to the mining industry, due to fundamental differences between tunnel and mine design.

Laubscher developed the first rock mass classification system designed specifically for caving operations in 1975, which was subsequently modified by Laubscher and Taylor in 1976 (Edelbro, 2003). The new classification system, termed the Mine Rock Mass Rating (MRMR) System, represented a quantum leap in the development of rock mass classification systems for use in the mining industry, and is one of the three main classification systems in use today, the others being the Geomechanics or RMR System and the Q-System. However, concerns have been raised over the last ten years with respect to the MRMR System not adequately addressing the role of fractures / veins and cemented joints in a jointed rock mass (Jakubec and Laubscher, 2000). In order to address these concerns, Jakubec and Laubscher (2000) introduced a modified MRMR Classification System, termed the In-Situ Rock Mass Rating (IRMR) System.

1.2 Objectives of the Study

The three most common rock mass classification systems currently in use in South Africa are the Geomechanics or RMR System, the Q-System and the Mining Rock Mass Rating System respectively. Due to their common usage within the mining industry, a number of statistical correlations have been developed by a number of authors to relate the resultant rock mass rating values derived from the Geomechanics or RMR System and the Q-System to each other. Given that rock mass classification data are not always available in a format that may immediately be applied to a specific mining engineering problem, the ability to rapidly and easily derive, for example, equivalent RMR values from Q- values is a very useful design tool. Furthermore, the availability of correlation equations between classification systems facilitates a rapid means of verifying resultant rock mass rating values, without necessitating the re-calculation of the values.

With the introduction of the IRMR Classification System in 2000, it is the opinion of the author that a requirement exists for the derivation of a correlation coefficient between the Mining Rock Mass Rating and the In-Situ Rock Mass Rating Classification Systems using statistical software packages. The primary objectives of this research report are, therefore, three-fold, namely:

- The derivation of a correlation equation between MRMR and IRMR Classification Systems.
- The quantification of the effect of the newly incorporated IRMR adjustments for water, fractures, veins and cemented discontinuities on rock mass rating values.
- The evaluation of the two classification systems under various geological settings, i.e. sedimentary, metamorphic and igneous.

It is the opinion of the author that an acceptable correlation between the MRMR and IRMR Classification Systems is achievable as:

- The two classification systems share a common origin, with the IRMR Classification System representing a modification of the MRMR Classification System.
- Correlations have been established between other rock mass classification systems, e.g. the Q-System and the Geomechanics System.

1.3 Study Methodology

This research report takes the form of a statistical correlation of the MRMR and IRMR Classification Systems, using statistical software packages, in which two discrete data sets have been evaluated, namely:

- A parametric database, i.e. a database in which a quantity is fixed for the case in question, but may vary in other cases.
- A geotechnical database compiled by the author from the in-pit mapping of a number of open pit mining operations in Southern Africa.

The parametric database was used to carry out an initial qualitative analysis of the individual parameters, common to both classification systems, used in in-pit geotechnical face mapping, namely:

- Intact Rock Strength (IRS).
- Fracture Frequency (FF).
- Joint Spacing (J_s).
- The micro and macro Joint Condition (J_c).
- Water.

This facilitated an unbiased quantification of the effect of the newly introduced IRMR adjustments on the individual parameters as well as on the resultant rock mass rating values, i.e. the qualification of differences in resultant rock mass rating values due to the application of the respective classification systems. The qualitative parametric comparison was followed by a statistical correlation of the geotechnical database, which facilitated:

- The statistical evaluation of the two classification systems under various geological settings, i.e. sedimentary, metamorphic and igneous.
- The correlation between the MRMR and IRMR Classification Systems.

1.4 Structure of the Research Report

Chapter 1 of the research report presents an introduction to the research topic, a statement by the author as to why the research was carried out, succinct backgrounds to rock mass classification and the study objectives and methodology respectively.

Chapter 2 presents a critical literature review of the research topic, dealing specifically with: the nature of rocks and rock masses, the philosophy of quantitative classification systems, the implementation of quantitative classification systems by the mining industry and the evolution of rock mass classification systems.

In Chapter 3 the parametric and geotechnical data bases are presented. Furthermore, the logic behind the compilation of the parametric data base and the assimilation of the geotechnical data base is presented.

An interpretation and discussion of both the qualitative and quantitative analysis results is presented in Chapter 4, specifically in terms of the effect on the resultant MRMR and IRMR values of increasing and decreasing individual parametric data base parameters, a qualitative comparison of the MRMR and IRMR geotechnical data bases as well as a statistical analysis of the MRMR and IRMR data bases.

Chapter 5 presents the conclusions that the author derived from the research project in terms of the effect of increasing and decreasing individual parametric data base parameters on the resultant MRMR and IRMR values, the results of the MRMR and IRMR statistical analyses, the derivation of a correlation coefficient between the two classification systems and the advantages of applying the respective classification systems in the quantification of a rock mass.

The benefit of additional research on this topic is presented as recommendations in Chapter 6.

The research report reference and bibliography lists are presented as Sections 7 and 8 respectively.

2 LITERATURE REVIEW

Having presented a succinct introduction to the research report topic in Chapter 1, in terms of the background to rock mass classification, the study objectives and study methodology, a critical literature review of the research topic, specifically in terms of the nature of rocks and rock masses, the philosophy, implementation and evolution of quantitative rock mass classification systems, is presented in this Chapter.

2.1 The Nature of Rocks and Rock Masses

Natural rock represents one of the most difficult materials with which to work as:

- Rock is a natural geological material.
- Rock is a unique material.
- Rock is subject to aging.
- Rock can be either flexible or rigid.
- Rock is influenced by stress and strain.
- Rock is influenced by fluids.
- Rock has a memory.

From an engineering perspective Piteau (1970) defined a rock mass as “a discontinuous medium made up of partitioned solid bodies or aggregates of blocks, more or less separated by planes of weakness, which generally fit together tightly, with water and soft and / or hard infilling materials present or absent in the spaces between the blocks”. Attewell and Farmer (1976) stated that rock occurs in its natural state as a flawed, inhomogeneous, anisotropic and discontinuous material, capable of only minor geotechnical modification. Piteau (1970) also stated that, given the universal presence of structural discontinuities in rock, their over-riding importance in rock slope stability cannot be overemphasised, as slope stability is determined principally by the structural discontinuities in the rock mass and not by the strength of the intact rock. This notwithstanding, he also realised the importance of understanding of the properties of the materials constituting the rock mass, as pit slopes are seldom developed in a single lithological unit. Attewell and Farmer (1976) concur with this assessment stating that “design in rock requires some initial knowledge of the mechanical properties of the intact rock, although in slope design a detailed knowledge of the presence and effect of discontinuities in the massive rock is required”.

Open pit mine slopes consist of an assemblage of rock units, which may be of diverse geological origin, with inherently different engineering properties in terms of in-situ strength, structural composition, texture, fabric bonding strength and macro- and micro-structure inherited from their mode of formation, or subsequently developed during their respective depositional histories. Consequently, a rock mass could represent a complex association of several lithological units whose mechanical behaviour is likely to differ significantly from that of the individual lithological units. However, as a mine design necessitates working with numbers, all rock masses need to be classified quantitatively (Jakubec and Laubscher, 2000). Hutchinson and Diederichs (1996) are of the opinion that, potentially, one of the most complex tasks that may be assigned to a geotechnical practitioner is the determination of representative mechanical properties of a rock mass.

Difficulties associated with quantitatively classifying a rock mass include:

- The difficulty in testing rock specimens on a scale that is representative of the rock mass behaviour, as well as the natural variability of any rock mass (EM 1110-1-2908, 1994).
- The reliance on a certain degree of engineering judgement and interpretation, by either the engineering geologist or geotechnical engineer, in classifying a rock mass (Jakubec and Laubscher, 2000).

This notwithstanding, representative geotechnical data are required by the geotechnical engineer to facilitate engineering design in, or on, naturally occurring rock. Data must reflect two aspects of the rock's reaction to applied forces (Attewell and Farmer, 1976), namely:

- The mechanical behaviour of the intact rock material.
- The mechanical behaviour of the massive rock modified by the presence of joints, fissures, bedding planes, faults and other structural discontinuities.

In an attempt to facilitate the assimilation of relevant geotechnical parameters from a rock mass, a number of empirical techniques have been developed over the years by numerous researchers. The principal aim of these techniques was to quantify the relative integrity of a rock mass, and thereafter, to estimate its mechanical properties (Hutchinson and Diederichs, 1996). This aim was achieved with varying degrees of success by respective researchers. These empirical techniques have become referred to as rock mass classification systems.

2.2 The Philosophy of Quantitative Classification Systems

Classification of a rock mass does not directly measure mechanical properties such as deformation modulus (Edelbro, 2003). This notwithstanding, rock mass classification systems form the basis of the empirical design approach, which is popular due to its simplicity and ability to manage uncertainties, and is widely utilised in rock engineering (Singh and Goel, 1999). Used correctly, rock mass classifications constitute a powerful design tool and may, at times, provide the only practical basis for design. Quantitative rock mass classification systems have been successfully used in many countries including Canada, Chile, the Philippines, Austria, Europe, India, South Africa, Australia and America (Laubscher, 1990), primarily due to the following reasons (Singh and Goel, 1999):

- Rock mass classification systems provide enhanced communication between geologists, engineers, designers and contractors.
- Engineers' observations, experience and judgement are correlated and consolidated more effectively by a quantitative classification system.
- Engineers have a preference for numbers rather than qualitative descriptions; therefore a quantitative classification system has considerable application in the overall assessment of rock quality.
- The classification approach helps in the organisation of knowledge.

While empirical rock mass classification systems constitute a powerful design tool, cognisance must be taken of the fact that no single classification system is valid for the assessment of all rock parameters, and consequently, experience forms the basis for the estimation of rock parameters (Singh and Goel, 1999).

2.3 Implementation of Quantitative Classification Systems by the Mining Industry

Over the years rock mass classification systems have provided a very versatile and practical mine design tool, their usefulness and applicability not being diminished by the recent advent of sophisticated design procedures and computational software packages. As a result, the mining industry came to accept that the application of rock mass classification systems facilitates a rapid and reliable method of obtaining estimates of rock mass stability and underground support requirements, despite geological features rarely conforming to an ideal pattern of numerical classification (Jakubec and Laubscher, 2000). Unfortunately, their ease of use has resulted in classification systems being abused by rock engineering practitioners (Stacey, 2002), which has, over time, led the mining fraternity to become concerned as to their actual appropriateness and usefulness as a mine design tool.

While the concerns raised by the mining fraternity may or may not be justifiable, Jakubec and Laubscher (2000) are of the opinion that these concerns are based on the misconception that rock mass classification is a form of rigorous analysis, which it is not. This being accepted, rock mass classification should not just be regarded as a crude method of initial assessment, as rock mass classifications still have an important role to play in the mining industry. This is borne out by the fact that many of the computational programmes designed to replace rock mass classifications are partly, or wholly dependent, on these same classification systems for the provision of input data into the analytical programmes.

The future role of rock mass classification in the mining industry is best expressed by Laubscher and Jakubec (2000) who state that: “rock mass classification should be recognised as an irreplaceable practical engineering tool which could, and should, be used in conjunction with other tools during the entire stage of mine life”.

2.4 The Evolution of Rock Mass Classification Systems

In one form or another, rock mass classification systems have formed an integral part of civil engineering, specifically in the design and construction of tunnels, since Ritter attempted to formalise an empirical approach to tunnel design in 1879 (Hoek, 1998). Similarly, miners have long been utilising a crude form of rock mass classification, where rock was described as being hard rock, crumbly bad rock, squeezing ground and black mud (http:/www.ursaeng.com).

A review of geotechnical literature indicates that many formal rock mass classification systems have been proposed and developed since 1946. However, some of the problems associated with the development of a satisfactory rock mass classification system which were identified by Bieniawski (1973), included:

- Classification systems were impractical.
- Classification systems tended to be based entirely on rock characteristics.
- Practical classification systems that did not include information on rock mass properties and which, therefore, could only be applied to one type of rock structure.
- Classification systems were too general to facilitate an objective evaluation of rock quality.
- Classification systems did not provide quantitative information on the properties of rock masses.
- Classification systems emphasised the characteristics of discontinuities, but disregarded the properties of intact rock material.

These problems aside, twelve classification systems, developed between 1946 and 2002, may be used to illustrate the evolution of rock mass classification systems. Each of the twelve classification systems represents a step forward in the quest to develop a satisfactory rock mass classification system.

2.4.1 The Rock Load Height Classification (Terzaghi, 1946)

In 1946 Terzaghi published the earliest reference on the use of rock mass classification for the design of tunnel support. Descriptive in nature, Terzaghi’s classification system focused on the characteristics that dominate rock mass behaviour where gravity constitutes the dominant driving force. Terzaghi’s Rock Load Height Classification System comprised seven rock mass descriptors, namely:

- Intact rock
- Stratified Rock
- Moderately Jointed Rock
- Blocky and Seamy Rock
- Crushed but Chemically Intact Rock
- Squeezing Rock
- Swelling Rock

Bieniawski (1973) stated that, while dominant in the USA for 25 years, and excellent for the purpose for which it was proposed, the Rock Load Height Classification System is not applicable to modern tunnelling methods using shotcrete and rockbolts, the system only being applicable to tunnels with steel supports. Furthermore, Cecil (1970) considered Terzaghi's rock mass classification system, which makes no provision for obtaining quantitative data on the properties of rock masses, too general to permit an objective evaluation of rock mass quality.

2.4.2 The Stand-Up Time Classification System (Lauffer, 1958)

Another tunnelling-based classification system, the Stand-Up Time Classification System proposed that the stand-up time for an unsupported span is related to the quality of the rock mass in which the span is excavated, where an unsupported span is defined as the distance between the face and the nearest support. This system is applicable in soft (shale, phyllite and mudstone) and highly broken rock where stability problems are associated with squeezing and swelling, and the concept of stand-up time is related to the size of excavation, i.e. the larger the excavation, the greater the reduction in time available prior to failure. However, in hard rock excavations stability is not time dependant, therefore the change in the stress field becomes the primary stability factor, and not the stand-up time.

The Stand-Up Time Classification System has subsequently been modified (Pacher *et al*, 1974) and now forms part of the general tunnelling approach known as the New Austrian Tunnelling Method.

Bieniawski (1973) considered the Stand-Up Time Classification System to be a considerable step forward in tunnelling as it introduced the concept of an active unsupported rock span and the concept of stand-up time, both of which are very relevant parameters for the determination of the type and quantity of support required in tunnels. However, he was of the opinion that the primary disadvantage of the classification system was the difficulty associated with establishing the active unsupported rock span and stand-up time parameters.

2.4.3 The Rock Quality Designation Index (Deere *et al*, 1967)

In 1967 Deere *et al.* developed the Rock Quality Designation index to provide a quantitative estimate of rock mass quality from drill core logs. The Rock Quality Designation (RQD) is defined as the percentage of intact core pieces longer than 100mm in the total length of core and is, therefore, a measure of the degree of fracturing (EM 1110-1-2908, 1994). Requirements for applying the Rock Quality Designation index method included: the diameter of the core not being less than 54,7mm in diameter (NX-size) and use of double-tube core barrel drilling. In current use, the RQD is a standard geotechnical core logging parameter and provides a rapid and inexpensive index value of rock quality in highly weathered, soft, fractured, sheared and jointed rock masses (Edelbro, 2003). Simplistically, it is a measurement of the percentage "good" rock. Given that only intact core is considered, weathering is accounted for indirectly (EM 1110-1-2908, 1994). The correct measurement of drill cores, and subsequent calculation of RQD, is presented in Figure 2.1

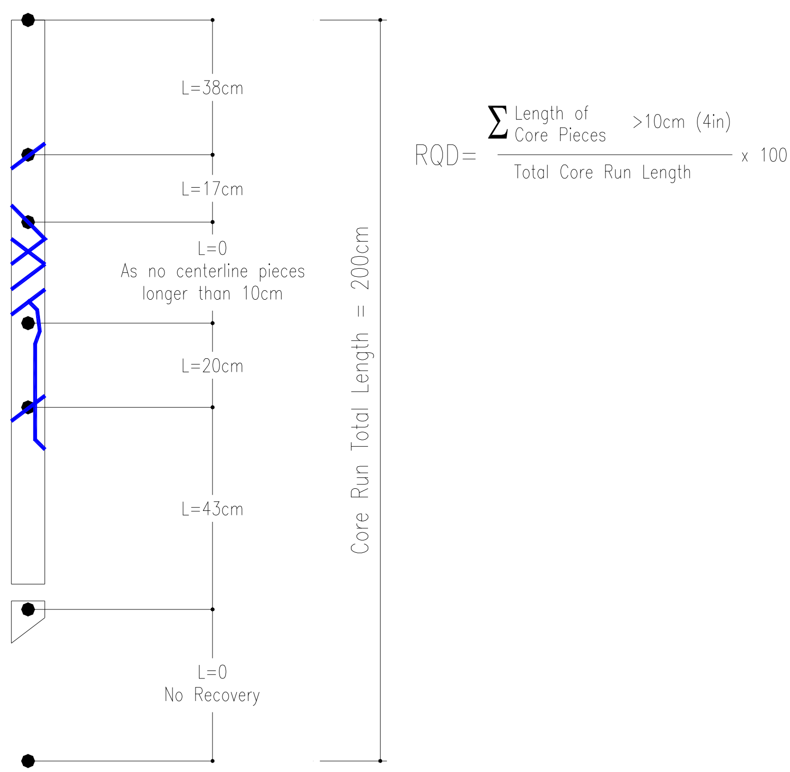

Figure 2.1: Measurement and Calculation of RQD (after Deere, 1989)

In deriving the RQD index, only intact core that has broken along the boundaries of naturally occurring discontinuities is considered. Artificial breaks, i.e. drill breaks and breaks arising from the handling of the drill cores are ignored. This is to prevent an underestimation of the in-situ RQD index and, consequently, of the rock mass quality. The relationship between the RQD index and the quality of a rock mass proposed by Deere is presented in Table 2.1.

Table 2.1: The Relationship between RQD and Rock Mass Quality

Rock Quality Designation (%)	Rock Mass Quality
<25	Very Poor
25 < 50	Poor
50 < 75	Fair
75 < 90	Good
90 < 100	Excellent

The RQD value has become recognised internationally as an indicator of rock mass conditions, and is used as an input parameter for both the Geomechanics and Q-System Classification Systems respectively. In practical applications, the major advantage of the RQD index is that it provides a rapid and quantitative indication of zones of poor, fair and good rock. However, a primary drawback of the RQD index value is that a high RQD index value may not always reflect high quality rock (Milne *et al*, 1989). This is best illustrated by an example of stiff to very stiff, intact, clay recovered from a borehole that may have an RQD index value of 90% to 100%. Accordingly, Milne *et al* (1989) consider the principal drawbacks of the RQD classification system to be:

- Its insensitivity to the direction of measurement.
- Its insensitivity to changes of joint spacing, if the joint spacing exceeds 1m.

Although Bieniawski (1973) considered Deere's Rock Quality Designation index to represent a very practical and simple approach to rock mass classification, with considerable potential in relating the RQD index value to the estimation of rock mass deformability, he regarded the fact that the RQD index value disregarded the influence of joint orientations, continuity and infill material to be a major disadvantage of the classification system.

2.4.4 Descriptive Rock Classification for Rock Mechanics Purposes (Patching and Coates, 1968)

This classification system represented a modification of the Coates (1964) and Coates and Parsons (1966) classification of rock (Edelbro, 2003). Classification is considered in two stages, namely the actual rock substance and the rock mass (Patching and Coates, 1968). The classification system contained five categories, to facilitate the sub-division of rocks into different classes, of which three related to the rock substance and two related to the rock mass. The rock classification categories are presented as Table 2.2.

Table 2.2: Rock Classification Categories

Rock Substance	**1. Geological Name of the Rock**
	2.Uniaxial Compressive Strength of the Rock Substance
	(a) Very low (<27.5MPa)
	(b) Low (27.5 – 55 MPa)
	(c) Medium (55 – 110 MPa)
	(d) High (110 – 220 MPa)
	(e) Very High (>220 MPa)
	3. Pre-failure Deformation of Rock Substance
	(a) Elastic
	(b) Yielding
Rock Mass	**4. Gross Homogeneity of Formation**
	(a) Massive
	(b) Layered
	5. Continuity of the Rock Substance in the Formation
	(a) Solid (joint spacing > 1.8m)
	(b) Blocky (joint spacing 0.9 - 1.8m)
	(c) Slabby (joint spacing 0.08 – 0.9)
	(d) Broken (joint spacing <0.08)

The aim of Patching and Coates (1968) was to provide a classification system with sufficient categories to facilitate the identification of rocks exhibiting either similar, or different, engineering behaviour without the classification system being too complicated. Patching and Coates (1968) believed that their classification system was adequate for the general classification of rocks, but recognised that "for certain special problems" the classification system would be inadequate, especially in terms of the classification system being able "to indicate the mechanical behaviour of the rock in a real situation".

2.4.5 The Rock Structure Rating (Wickham *et al*, 1972)

The majority of the case histories used to develop this classification system were from relatively small tunnels supported by steel nets (Milne *et al.*, 1998). This notwithstanding, the Rock Structure Rating (RSR) system introduced the concept of rating parameters to produce a numerical value of rock quality. The Rock Structure Rating (RSR) is defined by the equation:

$$RSR = A + B + C \qquad (1)$$

Where:

A = the geology parameter

B = the geometry parameter

C = the effect of groundwater inflow and joint condition

The geology parameter (A) accounts for the intrinsic geological structures based on:

- The origin of the rock (sedimentary, igneous, metamorphic).
- The hardness of the rock (decomposed, soft, medium, hard).
- The fabric of the rock mass (massive, slightly folded / faulted, moderately folded / faulted, intensely folded / faulted).

The geometry parameter (B) accounts for the effect of the discontinuity pattern based on the direction of a tunnel, on the basis of:

- Joint spacing.
- Strike and dip of joints (orientation).
- Direction of tunnel advance.

The effect of groundwater seepage and joint condition (parameter C) is taken into account on the basis of:

- The quality of the rock mass as derived from the combination of parameters A and B.
- The joint condition (poor, fair, bad).
- The amount of inflow into a tunnel (gallons per minute per 1000 feet of tunnel).

The parameter rating values are evaluated using tables, developed by Wickham *et al.* (1972), to calculate the resultant RSR value out of a maximum of 100. The tables used to evaluate the parameters are presented as Tables 2.3, 2.4 and 2.5 respectively.

Table 2.3: Rock Structure Rating - Parameter A

	Basic Rock Type							
	Hard	**Medium**	**Soft**	**Decomposed**	**Geological Structure**			
					Massive	**Slightly Folded or Faulted**	**Moderately Folded or Faulted**	**Intensively Folded or Faulted**
Igneous	1	2	3	4				
Metamorphic	1	2	3	4				
Sedimentary	2	3	4	4				
Type 1					30	22	15	9
Type 2					27	20	13	8
Type 3					24	18	12	7
Type 4					19	15	10	6

Table 2.4: Rock Structure Rating - Parameter B

Average Joint Spacing	Strike Perpendicular to Dip					Strike Parallel to Axis		
	Direction of Drive					Direction of Drive		
	Both		With Dip	Against Dip		Either Direction		
	Dip of Prominent Joints[(a)]					Dip of Prominent Joints		
	Flat	Dipping	Vertical	Dipping	Vertical	Flat	Dipping	Vertical
1. Very closely jointed, <2 in	9	11	13	10	12	9	9	7
2. Closely jointed, 2-6 in	13	16	19	15	17	14	14	11
3. Moderately jointed, 6-12 in	23	24	28	19	22	23	23	19
4. Moderate to blocky, 1-2ft	30	32	36	25	28	30	28	24
5. Blocky to massive, 2-4 ft	36	38	40	33	35	36	24	28
6. Massive, >4 ft	40	43	45	37	40	40	38	34

(a) Dip: flat: 0˚-20˚, dipping: 20˚-50˚ and vertical: 50˚-90˚

Table 2.5: Rock Structure Rating - Parameter C

Anticipated Water Inflow gpm/1000 ft of Tunnel	Sum of Parameters A + B					
	13 - 44			45 - 75		
	Joint Condition[(b)]					
	Good	Fair	Poor	Good	Fair	Poor
None	22	18	12	25	22	18
Slight, <200gpm	19	15	9	23	19	14
Moderate, 200-1000 gpm	15	22	7	21	16	12
Heavy, >1000 gpm	10	8	6	18	14	10

(b) Joint condition: good = tight or cemented; fair = slightly weathered or altered; poor = severely weathered, altered or open.

2.4.6 Geomechanics or Rock Mass Rating System (Bieniawski, 1973, 1976, 1989)

The Geomechanics, or Rock Mass Rating System was initially developed at the South African Council of Scientific and Industrial Research (CSIR) (Singh *et al*., 1999), based on experience gained in shallow tunnels excavated in sedimentary rocks. In proposing his engineering classification of jointed rock masses, Bieniawski (1973) stated that any rock mass classification system should satisfy five basic requirements, namely:

- A classification system should be based on inherent rock properties that are measurable and can be determined rapidly in the field.
- A classification system should be useful in practical design.
- The terminology used in the classification system should be widely acceptable.
- A classification system should be general enough so that the same rock could possess the same classification, regardless of how it was being used.
- The observations and tests required for the purpose of classification should be simple, rapid and relevant.

Bieniawski was of the opinion that none of the classification systems that had been proposed up to 1973 fully satisfied these five basic requirements. In his opinion, the two primary limitations of the classification systems available at the time were:

- A number of the classifications were based wholly on the rock mass characteristics, and as such, were impractical.
- Those classification systems that were practical did not include information on rock mass properties, and could therefore, only be applied to a single type of rock structure.

Like the majority of rock mass classification systems before it, the Geomechanics or Rock Mass Rating (RMR) system, hereafter referred to as the RMR System, was initially developed for use in tunnelling in the civil engineering industry. The RMR System was an attempt to develop an extensive classification system, capable of fulfilling the majority of practical requirements, by combining the best features from the respective classification systems available, and which could promote effective communication between the geologist and the engineer.
Bieniawski (1973) expounded these sentiments on rock mass classification by stating that:

- A rock mass classification system should divide a rock mass into zones of similar behaviour.
- A rock mass classification system should provide a good basis for understanding the characteristics of a rock mass.
- A rock mass classification system should facilitate the planning and design of structures in rock by yielding quantitative data required for the solution of practical engineering problems.
- A rock mass classification system should provide a common basis for effective communication between all people involved with geomechanical problems.

In deciding which parameters should be used in a rock mass classification system of a jointed rock mass, Bieniawski (1973) concluded that since the design of engineering structures in rock necessitates prior site exploration, the prerequisite geotechnical parameters for the classification of a rock mass should be obtained from data made available during a site investigation. Typically, this would include:

- A structural geological profile, i.e. the lithological units with depth, together with a description of the rock condition, e.g. weathering.
- The properties of the intact rock, e.g. the uniaxial compressive strength and modulus of elasticity.
- The Rock Quality Designation (RQD) or fracture frequency.
- The joint pattern, i.e. strike, dip and joint spacing, continuity, separation and gouge.
- The groundwater conditions.

Consequently, the classification system proposed by Bieniawski (1973) included the following parameters:

- The Rock Quality Designation (RQD)

  Although the RQD ignores the influence of joint orientation, continuity and gouge material, it provides an indication of the in-situ quality of a rock mass. Furthermore, there is a direct correlation between the RQD index value and fracture frequency recorded from the geotechnical logging of drill cores.

- The Degree of Weathering

  Five classes of weathering are considered by Bieniawski (1973), including:

  - Unweathered, i.e. no visible signs of weathering; rock fresh and crystals bright; slight staining associated with some discontinuity surfaces.
  - Slightly weathered, i.e. penetrative weathering associated with open discontinuities; slight weathering of rock material; discolouration of discontinuities up to 10mm from discontinuity surface.
  - Moderately weathered, i.e. majority of rock mass slightly discoloured; rock material not friable (poorly cemented sedimentary rocks the exception); discontinuities stained and / or filled with altered material.
  - Highly weathered, i.e. material friable with weathering extending throughout the rock mass; rock lacks lustre; all material is discoloured (except quartz), material can be excavated by pick.
  - Completely weathered, i.e. rock mass is completely discoloured, decomposed and friable; only fragments of the original rock fabric and texture is preserved; material has the appearance of a soil.

- The Uniaxial Compressive Strength (UCS) of Intact Rock

  Five classes, based on a modified Deere classification, are considered, namely:

  - Very low strength (1-25MPa).
  - Low strength (25 - 50MPa).
  - Medium strength (50 - 100MPa).
  - High strength (100 - 200MPa).
  - Very high strength (>200MPa).

- The Spacing of Discontinuities

  There is a direct strength reduction effect due to the presence of discontinuities within a rock mass (Attewell and Farmer, 1976), while joint spacing controls the degree of strength reduction.

The RMR System (1973) considers five classes of joint spacing, based on a modified classification by Deere, namely:

- Very wide spacing (>3m).
- Wide spacing (1-3m).
- Moderately close spacing (0,3-1m).
- Close spacing (50-300mm).
- Very close spacing (<50mm).

- The Strike and Dip Orientations of Discontinuities

  While the stability of rock slopes varies with the inclination of discontinuity surfaces (Hoek and Bray, 1977), discontinuities impart a condition of strength anisotropy to a rock mass (Piteau, 1970).

- Joint Separation

  A practical criterion for the quantitative description of a rock mass, as closely spaced joints result in the formation of smaller block sizes increasing the potential for internal shifting and rotation of the rock mass during deformation thereby reducing stability (Hutchinson and Diederichs, 1996).

- Joint Continuity

  There is a higher probability that persistent joints will combine with other structures to form large free blocks of rock, than there is with short joints (Hutchinson and Diederichs, 1996).

- Groundwater inflow

  Groundwater can have a destabilising effect on a rock mass through the erosion and weakening of joint surfaces and / or infillings (Hutchinson and Diederichs, 1996). Changes in moisture content can result in very high swelling pressures (Piteau, 1970) and increased pore water pressure reduces the frictional resistance to slip occurring along fractures which further destabilises a rock mass (Hutchinson and Diederichs, 1996).

Bieniawski (1973) stated that while each of the eight parameters contributed to the behaviour of a jointed rock mass, not all of the parameters were of equal importance. Consequently, each parameter was assigned a weighted numerical rating according to its relative importance where higher rating values were associated with better geotechnical conditions. The relative importance of the parameters was based on the results of a study of the relative importance of individual parameters carried out by Wickham, Tiedmann and Skinner in 1972. To facilitate the classification of a rock mass, Bieniawski (1973) also sub-divided the rock mass into five classes, which he considered sufficient to provide acceptably clear distinctions between different qualities of rock material.

A summary of the relative importance of Bieniawski's individual parameters, and the five rock mass classes, is presented in Table 2.6.

Table 2.6: Summary of Relative Importance of Individual Parameters (after Bieniawski, 1973)

Parameter	**Class**				
	1	**2**	**3**	**4**	**5**
Rock Quality Designation	16	14	12	7	3
Weathering	9	7	5	3	1
Intact Rock Strength	10	5	2	1	0
Joint Spacing	30	25	20	10	5
Joint Separation	5	5	4	3	1
Joint Continuity	5	5	3	0	0
Groundwater	10	10	8	5	2
Strike and Dip Orientations: Tunnels	15	13	10	5	3
Strike and Dip Orientations: Foundations	15	13	10	0	-10
Total Rating	**90-100**	**70-90**	**50-70**	**25-50**	**<25**
Class Description	**Very Good Rock**	**Good Rock**	**Fair Rock**	**Poor Rock**	**Very Poor Rock**

A feature of the classification system is that the relative percentages change as the rock mass quality deteriorates. Furthermore, different rating values are assigned to strike and dip orientations for tunnels and foundations, as the importance of this parameter is a function of the structure being designed. No rating values for rock slopes were included in the 1973 RMR System.

In applying the RMR System, the rock mass must be sub-divided into geotechnical zones, i.e. areas, or zones, of a rock mass that are bounded by major structural features, changes in lithology, significant changes in discontinuity spacing, or characteristics. The rock mass is classified according to the parameters in Table 2.6, with the individual parameter ratings being summed to produce the total RMR rating value, which then establishes the rock mass class. The original (1973) RMR System has subsequently been refined and changes made in 1974, 1975, 1976, 1979 and 1989 respectively. It is, therefore, important to state which version of the classification system is used when quoting RMR values. The changes to the classification entailed, *inter alia:*

- The reduction of classification parameters from eight to six.
- The adjustment of ratings and reduction of recommended support requirements.
- The modification of class boundaries to even multiples of 20.
- The adoption of the ISRM (1978) rock mass description (Singh and Goel, 1999).

These changes reflected a better understanding of the importance of the respective parameters, and were based on additional case histories. These changes have facilitated the application of the RMR System to the preliminary design of rock slopes and foundations, as well as for the estimation of the in-situ modulus of deformation and rock mass strength. Specific changes to the RMR System are presented as Table 2.7.

Table 2.7: Summary of Modifications to the RMR System

Year of Revision	Specific Revisions
1974	A joint condition parameter was added.
	A strike and dip orientation parameter was added.
	The weight of the RQD parameter was increased from 16 to 20.
	The strike and dip orientation parameter for tunnels was removed.
	The joint separation and continuity parameter was removed.
	The weathering parameter was removed.
1975	The initial joint condition parameter weighting of 15 was increased to 30.
	The weighting of the rock strength parameter was increased from 10 to 15.
	The strike and dip orientation parameter was removed.
	A strike and dip orientation parameter for tunnels was added back, but reduced from 3-15 to 0-12.
1976	The joint condition parameter was increased from 15 to 25.
	The concept of rock mass classes was introduced, each class being sub-divided into classes at intervals of 20.
1989	The weighting of the discontinuity spacing parameter was decreased to 20.
	The weighting of the ground water parameter was increased to 15.
	The weighting of joints parameter was increased back to 30.
	The condition of the discontinuities was further quantified to facilitate a less subjective evaluation of discontinuity condition.
	The assessment of sub-horizontal joints was modified from "unfavourable" to "fair" to account for the effect on stability of tunnel backs. The weighting of the joint orientation parameter has remained unchanged.

The modifications to the RMR system are summarised in Table 2.8. The current RMR System (1989) is presented as Table 2.9.

Table 2.8: Summary of Modifications to the RMR System (after Milne *et al*, 1998)

Parameter	Time Span				
	1973	1974	1975	1976	1989
Rock Strength	10	10	15	15	15
RQD	16	20	20	20	20
Discontinuity Spacing	30	30	30	30	20
Separation of Joints	5	-	-	-	-
Continuity of Joints	5	-	-	-	-
Weathering	9	-	-	-	-
Condition of Joints	-	15	30	25	30
Ground Water	10	10	10	10	15
Strike and Dip Orientation	-	15	-	-	-
Strike and Dip Orientation for Tunnels	3-45	-	0-12	0-12	0-12

Apart from the RMR System evolving over time, several authors modified the basic RMR System for specific applications (Hutchinson and Diederichs, 1996), including:

- Mining applications: Laubscher (1977, 1993) and Kendorski *et al* (1983).
- Coal mining: Ghose and Raju (1981), Newman (1981), Unal (1983), Venkateswarlu (1986) and Sheorey (1993).
- Slope stability: Romana (1985).
- The RMR value was linked to the original Hoek-Brown equation as part of the development of the Hoek-Brown failure criterion (Hoek and Brown, 1980).

The principal advantage of the RMR System is its ease of use, while the principal disadvantages of the system include:

- The system has been found to be unreliable in very poor rock masses (Singh and Goel, 1999).
- The classification system is insensitive to minor variations in rock mass quality.
- The classification system is regarded as being too conservative by the mining industry.

Table 2.9: The 1989 RMR Classification System

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	1-2MPa	For this low range- uniaxial compressive test is preferred		
		Uniaxial Compressive 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		>2m	0.6m-2m	200-600mm	60-200mm	<60mm		
	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 <1mm; Slightly weathered walls	Slightly rough surfaces; Separation <1mm; Highly weathered walls	Slickensided surfaces or Gouge <5mm thick or Separation 1-5mm; Continuous	Soft gouge >5mm thick or Separation >5mm; Continuous		
	Rating		30	25	20	10	0		
5	Groundwater	Inflow / 10m tunnel length (l/m)	None	<10	10-25	25-125	>125		
		(Joint water press.) / (Major principal stress)	0	<0.1	0.1-0.2	0.2-0.5	>0.5		
		General Conditions	Completely Dry	Damp	Wet	Dripping	Flowing		
	Ratings		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 and Mines	0	-2	-5	-10	-12
	Foundations	0	-2	-7	-15	-25
	Slopes	0	-5	-25	-50	-

Table 2.9 (cont.): The 1989 RMR Classification System

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	20yrs for 15m span	1yr for 10m span	1 week for 5m span	10hrs for 2.5m span	30min for 1m span
Cohesion of Rock Mass (kPa)	>400	300-400	200-300	100-200	<100
Friction Angle of Rock Mass (˚)	>45	35-45	25-35	15-25	<15
E. GUIDELINES FOR CLASSIFICATION OF DISCONTINUITY CONDITIONS					
Discontinuity Length (Persistence)	<1m	1-3m	3-10m	10-20m	>20m
Rating	6	4	2	1	0
Separation (Aperture)	None	<0.1mm	0.1-1.0mm	1-5mm	>5mm
Rating	6	5	4	1	0
Roughness	Very Rough	Rough	Slightly Rough	Smooth	Slickensided
Rating	6	5	3	1	O
Infilling (Gouge)	None	Hard Filing <5mm	Hard Filling >5mm	Soft Filling <5mm	Soft Filling >5mm
Rating	6	4	2	2	0
Weathering	Unweathered	Slightly Weathered	Moderately Weathered	Highly Weathered	Decomposed
Rating	6	5	3	1	0

F. EFFECT OF DISCONTINUITY STRIKE AND DIP ORIENTATION IN TUNNELING			
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	

2.4.7 Norwegian Geotechnical Institute's Q-System (Barton *et al*, 1974)

The Norwegian Geotechnical Institute (NGI) Q-System, originally based on approximately 200 case histories of tunnels and caverns (Singh and Goel, 1999), was specifically developed by Barton, Lien and Lunde (1974) to facilitate the design of tunnel support systems. A summary of the original database used in the development of the classification system is presented in Table 2.10.

Table 2.10: Summary of Original Q-System Database (after Hutchinson and Diederichs, 1996)

Excavation Type	No. of Case Histories
Temporary mine openings	2
Permanent mine openings, low pressure water tunnels, pilot tunnels, drifts and headings for large openings	83
Storage caverns, water treatment plants, minor road and railway tunnels, surge chambers, access tunnels	25
Power stations, major road and railway tunnels, civil defence chambers, portals, intersections	79
Underground nuclear power stations, railway stations, sports and public facilities, factories	2

The Norwegian Geotechnical Institute (NGI) Q-System, hereafter referred to as the Q-System, uses six parameters to determine the quality of a rock mass. The rock mass rating is calculated from the equation:

$$Q = RQD/Jn \times Jr/Ja \times Jw/SRF \qquad (2)$$

Where:
RQD is the Rock Quality Designation.
J_n is the Joint Set number (number of discontinuities).
J_r is the Joint Roughness number (roughness of the most unfavourable discontinuity).
J_a is the Joint Alteration number (degree of alteration or filling along the weakest discontinuity).
J_w is the Joint Water Reduction factor (water inflow into excavation).
SRF is the Stress Reduction Factor (in-situ stress condition).

The Q-System does not explicitly take the strength of the rock mass into account; rather it is implicitly taken into consideration in the derivation of the SRF. SRF is derived from the equation:

$$SRF = UCS/\sigma' \qquad (3)$$

Where:
UCS is the Unconfined Compressive Strength
σ' is the major principal stress
Given Equation 3, the Q index value can be described by three quotients, namely:

- RQD/J_n
- J_r/J_a
- J_w/SRF

According to Barton *et al* (1974), the quotient RQD/J_n represents the rock mass structure, and is a crude measure of the block size. The second quotient J_r/J_a represents the roughness and frictional characteristics of joint walls or gouge materials, and is a crude reflection of the inter-block shear strength. J_r/J_a is weighted to favour rough, unaltered joint surfaces in direct contact with each other. Such surfaces will be expected to be close to peak strength, dilate strongly when sheared and consequently be favourable to tunnel stability. The third quotient J_w/SRF is a complicated empirical factor comprising two stress parameters, and is a crude measure of the active stress conditions. The SRF can be considered to represent the total stress parameter and is a measure of:

- The loosening load in excavations through shear zones and clay-rich rocks.
- Rock stress in competent rock.
- Squeezing loads in incompetent plastic rock masses.

Water pressure is represented by the parameter J_{w}, which has a negative impact on the shear strength of joints through the reduction in effective normal stress, which may result in softening and out-wash of clay-filled joints. To date, it has not been possible to combine the total stress and water pressure parameters in terms of inter-block effective stress as a high effective normal stress value may relate to less stable conditions than a low value, despite a higher shear strength.

The most notable exclusion from the Q-System is an allowance for joint orientation. Barton *et al* (1974) are of the opinion that joint orientation is not as important as initially expected. This may be due to the fact that many of the excavations for which the system was originally developed can be, and normally are, aligned such that the effects of unfavourably orientated discontinuities are avoided. However, this cannot be the primary reason, as the orientation of tunnels, which comprise a significant percentage of the case histories, cannot be adjusted in a similar manner. It would, therefore, appear that Barton *et al* (1974) are of the opinion that the joint set number (J_n), joint roughness (J_r) and joint alteration (J_a) are more important than the joint orientation in so much as the joint number parameter determines the degree of freedom for block movement, and the frictional and dilatational characteristics can vary more than the down-dip gravitational component of unfavourably orientated joint sets.

The resultant Q index value varies on a logarithmic scale from 0.001 to 1.000, with the rock mass quality being divided into nine classes. A summary of the nine classes is presented as Table 2.11.

Table 2.11: Summary of Q-System Classification (after Barton *et al*, 1990)

Q Index Value	Rock Mass Class
0.0001 - 0.01	Exceptionally Poor
0.01 - 0.1	Extremely Poor
0.1 - 1	Very Poor
1 - 4	Poor
4 - 10	Fair
10 - 40	Good
40 - 100	Very Good
100 - 400	Extremely Good
400 - 1000	Exceptionally Good

Both the Q and RMR Systems consider three principal rock mass properties:

- Intact rock strength (included in the derivation of SRF in the Q-System).
- The frictional properties of discontinuities.
- The geometry of intact blocks of rock as defined by the discontinuities.

The influence of these properties on the values derived from the Q- and RMR Systems is shown in Table 2.12.

Table 2.12: The Influence of Rock Mass Properties on the Q- and RMR Systems (after Milne, 1988)

Principal Rock Properties	Q System	RMR System (1976)
Range in Values	**0.001 to 1000**	**8 to 100**
Strength as % of Total Range	19%	16%
Block Size as % of Total Range	44%	54%
Discontinuity as % of Total Range	39%	27%

Although a high degree of similarity exists between the weightings assigned to the three basic rock properties, the two systems are not directly related as the assessment of rock strength and stress differs significantly for the two systems. However, Bieniawski (1976) derived a correlation between the two systems:

$$RMR = 9 \ln Q + 44 \quad (4)$$

Although equation (4) is the most popular equation linking the two systems, Barton (1995) also derived a correlation between the two systems:

$$RMR = 15 \log Q + 50 \quad (5)$$

These two correlations are, however, not unique as a number of authors have also derived similar correlations for specific applications. A summary of correlations reflecting differing overall intact rock and discontinuity properties and discontinuity spicing is presented in Table 2.13.

Table 2.13: Summary of Q- and RMR System Correlations (after Milne et al, 1989)

Correlation	**Source**	**Application**
RMR = 13.5 logQ + 43	New Zealand	Tunnels
RMR = 12.5 logQ + 55.2	Spain	Tunnels
RMR = 5 lnQ + 60.8	South Africa	Tunnels
RMR = 43.89 – 9.9 lnQ	Spain	Soft Rock Mining
RMR = 10.5 ln Q + 41.8	Spain	Soft Rock Mining
RMR = 12.11 log Q + 50.81	Canada	Hard Rock Mining
RMR = 8.7 ln Q + 38	Canada	Tunnels, Sedimentary Rock
RMR = 10 ln Q + 39	Canada	Hard Rock Mining

The original Q-System has been updated several times and is now based on 1050 case histories. In 2002, Barton published a technical paper entitled "Some New Q-Value Correlations to Assist in Site Characterisation and Tunnel Design", which introduced a number of changes to the respective Q-System parameters. The amended Q-value parameters are presented in Table 2.14.

Table 2.14: Summary of Amended Q-System Parameters (after Barton, 2002)

Joint Set Number	**Description**	J_n
A	**Massive, no or few joints**	0.5-1
B	One joint set.	2
C	One joint set plus random joints.	3
D	Two joint sets.	4
E	Two joint sets plus random joints.	6
F	Three joint sets.	9
G	Three joint sets plus random joints.	12
H	Four or more joint sets, random, heavily jointed, "sugar-cube", etc.	15
J	Crushed rock, earthlike.	20
Joint Roughness Number	**Description**	J_r
(a)	*Rock-wall contact, and (b) rock-wall contact before 10cm shear.*	
A	Discontinuous joints.	4
B	Rough or irregular, undulating.	3
C	Smooth, undulating.	2
D	Slickensided, undulating.	1.5
E	Rough or irregular, planar.	1.5

Table 2.14 (cont.): Summary of Amended Q-System Parameters (after Barton, 2002)

Joint Roughness Number	Description	J_r	
F	Smooth, planar.	1.0	
G	Slickensided, planar.	0.5	
(b)	*No rock-wall contact when sheared.*		
H	Zone containing clay minerals thick enough to prevent rock-wall contact.	1.0	
J	Sandy, gravely or crushed rock zone thick enough to prevent rock-wall contact.	1.0	
Joint Alteration Number	**Description**	**$Ø_r$ (Deg)**	**J_a**
(a)	*Rock-wall contact (no mineral fillings, only coatings).*		
A	Tightly healed, hard, non-softening, impermeable filling, i.e. quartz or epidote.	-	0.75
B	Unaltered joint walls, surface staining only.	25-35	1.0
C	Slightly altered joint walls, non-softening mineral coatings, sandy particles, clay-free disintegrated rock, etc.	25-30	2.0
D	Silty- or sandy-clay coatings, small clay fraction (non-softening).	20-25	3.0
E	Softening or low friction clay mineral coatings, i.e. kaolinite or mica. Also chlorite, talc, gypsum, graphite, etc., and small quantities of swelling clays.	8-16	4.0
(b)	*Rock-wall contact before 10cm shear(thin mineral fillings).*		
F	Sandy particles, clay-free disintegrated rock, etc.	25-30	4.0
G	Strongly overconsolidated non-softening clay mineral fillings (continuous, butb<5mm thickness).	16-24	6.0
H	Medium or low over-consolidation, softening, clay mineral fillings (continuous but <5mm thickness).	12-16	8.0
J	Swelling-clay fillings, i.e. montmorillonite (continuous, but <5mm thickness). Value of J_a depends on % of swelling clay-size particles, and access to water, etc.	6-12	8-12
(c)	*No rock-wall contact when sheared (thick mineral filling).*		
KLM	Zones or bands of disintegrated or crushed rock and clay (see G, H, J for description of clay condition).	6-24	6, 8 or 8-12
N	Zones or bands of silty- or sandy-clay, small clay fraction (non-softening).	-	5.0
OPR	Thick, continuous zones or bands of clay (see G, H, J for description of clay condition).	6-24	10,13 or 13-20
Joint Water Reduction Factor	**Description**	**Approx. Water Pressure (kg/cm^2)**	**J_w**
A	Dry excavations or minor inflow, i.e. <5l/min locally.	<1	1.0
B	Medium inflow or pressure, occasional outwash of joint fillings.	1-2.5	0.66
C	Large inflow or high pressure in competent rock with unfilled joints.	2.5-10	0.5
D	Large inflow or high pressure, considerable outwash of joint fillings.	2.5-10	0.33

Table 2.14 (cont.): Summary of Amended Q-System Parameters (after Barton, 2002)

Joint Water Reduction Factor	**Description**	**Approx. Water Pressure (kg/cm^2)**		**J_w**
E	Exceptionally high inflow or water pressure at blasting, decaying with time.	>10		0.2-0.1
F	Exceptionally high inflow or water pressure continuing without noticeable decay.	>10		0.1-0.05
Stress Reduction Factor	**Description**	**SRF**		
(a)	*Weakness zones interesting 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		
B	Single weakness zones containing clay or chemically disintegrated rock (depth of excavation ≤50m).	5		
C	Single weakness zones containing clay or chemically disintegrated rock (depth of excavation <50m).	2.5		
D	Multiple shear zones in competent rock (clay-free), loose surrounding rock (any depth).	7.5		
E	Single shear zones in competent rock (clay-free), (depth of excavation ≤50m).	5.0		
F	Single shear zones in competent rock (clay-free), (depth of excavation >0m).	2.5		
G	Loose, open joints, heavily lointed or “sugar cube”, etc. (any depth).	5.0		
		σ_c/σ_1	σ_θ/σ_c	SRF
(b)	*Competent rock, rock stress problems.*			
H	Low stress, near surface, open joints.	>200	<0.01	2.5
J	Medium stress, favourable stress condition.	200-10	0.01-0.3	1
K	High stress, very tight structure. Usually favourable to stability, may be unfavourable for wall stability.	10-5	0.3-0.4	0.5-2
L	Moderate slabbing after >1hr in massive rock.	5-3	0.5-0.65	5-50
M	Slabbing and rock burst after a few minutes in massive rock.	3-2	0.65-1	50-200
N	Heavy rock burst (strain-burst) and immediate dynamic deformations in massive rock.	<2	>1	200-400
		σ_θ/σ_c	SRF	
(c)	*Squeezing rock: plastic flow of incompetent rock under the influence of high rock pressure.*			
O	Mild squeezing rock pressure.	1-5	5-10	
P	Heavy squeezing rock pressure.	>5	10-20	
		SRF		
(d)	*Swelling rock: chemical swelling activity depending on presence of water.*			
R	Mild swelling rock pressure.	5-10		
S	Heavy swelling rock pressure.	10-15		

The applicability and effectiveness of the Q-System is borne out by the fact that, apart from a modification to the SRF parameter in 1994 and the 2002 modifications, the original parameters of the classification system remain unaltered (Singh and Goel, 1999). According to Milne *et al* (1998), the advantages of the Q-System are:

- It is sensitive to minor variations in rock mass properties.
- The descriptors are rigorous with less room for subjectivity.

The primary limitations of the Q-System include:

- Inexperienced users experiencing difficulty with the J_n parameter, i.e. the number of joint sets in a rock mass. This is especially true in widely jointed rock masses, with an overestimation of the number of joint sets in a rock mass resulting in an underestimation of the Q index (Milne *et al*, 1998).
- The SRF parameter, which is regarded as the most contentious parameter. Kaiser *et al* (1986) are of the opinion that the SRF should not be included in the rock mass classification, with the detrimental effects of high stress being assessed separately (Singh and Goel, 1999).

2.4.8 Mining Rock Mass Rating (MRMR) Classification System (Laubscher, 1990)

According to Milne *et al* (1998), one of the fundamental differences between tunnel and mine design approaches to rock mass classification is the large variation in the engineered openings in mining applications. In tunnels the orientation depth and stress conditions are usually constant over significant distances, unlike mining where none of these properties can be assumed to be constant. To facilitate the development of an appropriate rock mass classification system for the mining industry, specifically caving operations, Laubscher met with Bieniawski in 1973 to discuss the development of his RMR Classification System. While agreeing with the basic concept of the RMR classification system, Laubscher was of the opinion that it was too inflexible for mining applications. In order to make the classification system more applicable to the mining environment, Laubscher (1975) and Laubscher and Taylor (1976) developed adjustments to account for different mining applications. These were then applied to in-situ ratings derived from the RMR Classification System (Laubscher and Jakubec, 2000). The resultant classification system became known as the Modified Rock Mass Rating System. As with other classification systems, modifications were made to the rating values based on experience gained from practical applications of the system and as the relative importance of the respective adjustments became apparent. These modifications led to the development of Laubscher's completely independent Mine Rock Mass Rating (MRMR) System in 1976.

Application of the Mining Rock Mass Rating System (MRMR) involves assigning in-situ ratings to a rock mass based on measurable geological parameters (Laubscher, 1990). The geological parameters are weighed according to their relative importance, with a maximum possible total rating of 100. Rating values between 0 and 100 cover five rock mass classes comprising ratings of 20 per class, ranging from very poor to very good, which are a reflection of the relative strengths of the rock masses (Laubscher, 1990). Each rock mass class is further sub-divided into a division A and B. Geological parameters that must be assessed include:

- Intact Rock Strength (IRS)

  IRS refers to the Uniaxial Compressive Strength (UCS) of intact rock between discontinuities. To account for zones of intercalated strong and weak rock that can affect the IRS of a rock mass, an average strength value is used on the basis that a weaker rock will have a greater influence on the average value than a stronger rock (Laubscher, 1990). An empirical chart of the non-linear relationship has been developed by Laubscher (Refer to Figure 2.3) to facilitate the determination of an IRS value in those instances where the rock mass comprises intercalated strong and weak zones.

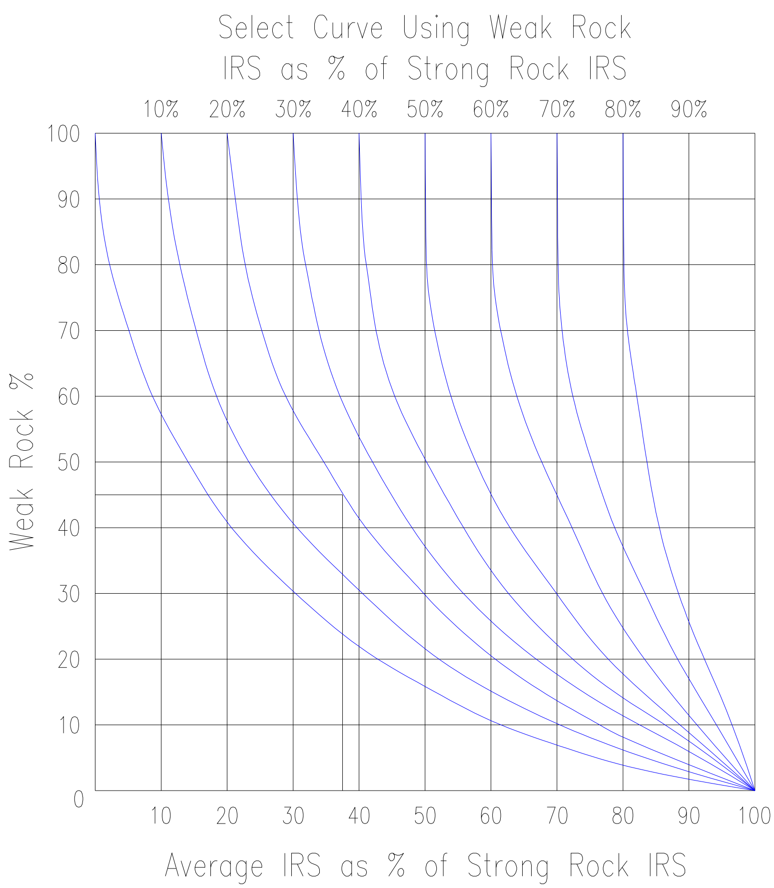

Figure 2.2: Determination of Average IRS in Intercalated Strong and Weak Rock Zones (after Laubscher, 1990)

The IRS is rated between 0 and 20, catering for in-situ rock strengths of 0 MPa to in excess of 185 MPa. An upper limit of 185 MPa is used as, according to Laubscher (1990), IRS values in excess of 185 MPa have an insignificant impact on the strength of a jointed rock mass.

- Joint / Fracture Spacing

  Joint spacing is the measurement of all discontinuities and partings, excluding cemented discontinuities, which are assessed separately in the determination of the IRS. Based on the premise that a block of rock will be defined by three joint sets, with additional joints only serving to modify the shape of the block, a maximum of three joint sets is considered in the MRMR classification system (Laubscher, 1990). If more than three joint sets are developed, the three closest-spaced joints are used (Laubscher, 1990). The rating value for one-, two- or three-joint sets is read off a chart design chart as presented in Figure 2.3. Joint spacing can be assessed by two different techniques:

  - The separate measurement of both the RQD and Joint spacing (Js) parameters with maximum possible ratings of 15 and 25 respectively. RQD should be calculated on cores that are not less than 42mm diameter (BXM) (Laubscher, 1990). A minimum core length of 100mm is required to calculate RQD, for if BXM core is drilled perpendicular to discontinuities spaced at 90mm the RQD resultant value is zero. However, if the borehole is inclined at 40º, the spacing between the same fractures is 137mm, which equates to an RQD of 100%. By only considering core of 100mm or more, the core cylinder would only be 91mm at an angle of 40º, which equates to zero RQD. The RQD is calculated using the equation:

    RQD (%) = Total Lengths of Core >100mm/Length of Run x100 (6)

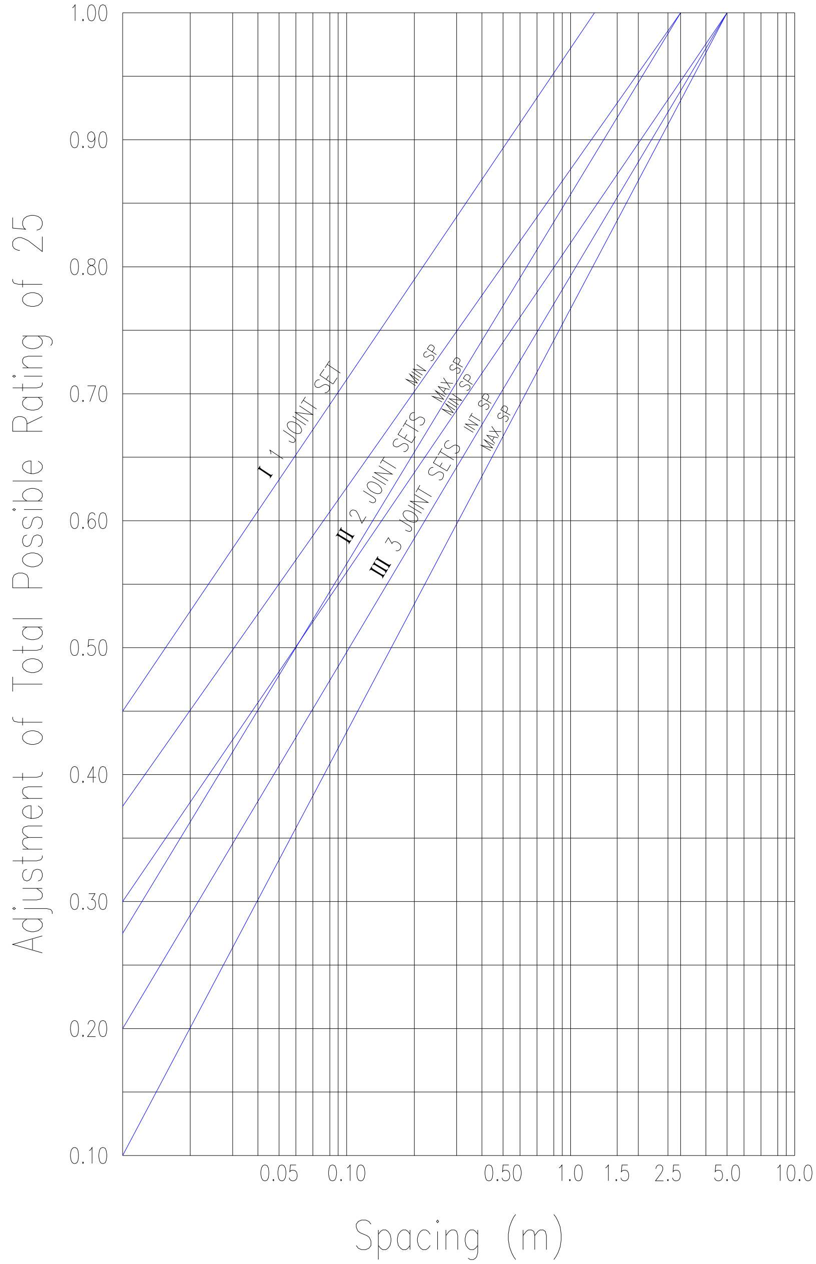

Figure 2.3: Assessment of Joint Spacing Rating Values (Laubscher, 1990)

- The measurement of all discontinuities to facilitate the determination of the fracture frequency per metre (FF/m) with a maximum rating of 40. The type of joint system being sampled, i.e. one-, two- or three-joint system, needs to be established as for the same fracture frequency, a one-joint rock mass is stronger than a two-joint rock mass, which is stronger than a three-joint rock mass. Fracture frequency does not recognise core recovery (Laubscher, 1990), consequently the fracture frequency per metre must be increased to reflect any core loss. The adjustment requires dividing the fracture frequency per metre by the core recovery and multiplying the quotient by 100 (Laubscher, 1990).

- Joint condition / Water

  Joint condition is an assessment of the frictional properties of joints based on expression, surface properties, alteration zones, filling and water (Laubscher, 1990). The maximum possible rating for joint condition is 40. Use is made of Table 2.15 to assign rating values for joint condition. Section A represents the large-scale joint expression, section B represents the small-scale joint expression, based on the joint profiles in Figure 2.4, section C represents the joint wall alteration and section D represents the joint gouge material. To account for the differing joint condition for each joint set, a weighted average rating value is used (Laubscher, 1990).

Table 2.15: Joint Condition Assessment

Parameter	**Accumulative % Adjustment of Possible Rating of 40**				
	Description	**Dry**	**Moist**	**Mod. Pressure (25-125l/m)**	**High Pressure (>125l/m)**
A: Large-Scale Joint Expression	Multi wavy directional	100	100	95	90
	Uni	95	90	85	80
	Curved	85	80	75	70
	Slight undulation	80	75	70	65
	Straight	75	70	65	60
B: Small-Scale Joint Expression	Rough stepped/Irregular	95	90	85	80
	Smooth stepped	90	85	80	75
	Slickensided stepped	85	80	75	70
	Rough undulating	80	75	70	65
	Smooth undulating	75	70	65	60
	Slickensided undulating	70	65	60	55
	Rough planar	65	60	55	50
	Smooth planar	60	55	50	45
	Polished	55	50	45	40
C: Joint wall alteration weaker than wall rock and only if it is weaker than the filling		75	70	65	60
D: Joint Filling	Non-softening and sheared material – Coarse	90	85	80	75
	- Medium	85	80	75	70
	- Fine	80	75	70	65
	Softening sheared material - Coarse	70	65	60	55
	- Medium	60	55	50	45
	- Fine	50	45	40	35
	Gouge thickness < amplitude of irregularities	45	40	35	30
	Gouge thickness > amplitude of irregularities	30	20	15	10

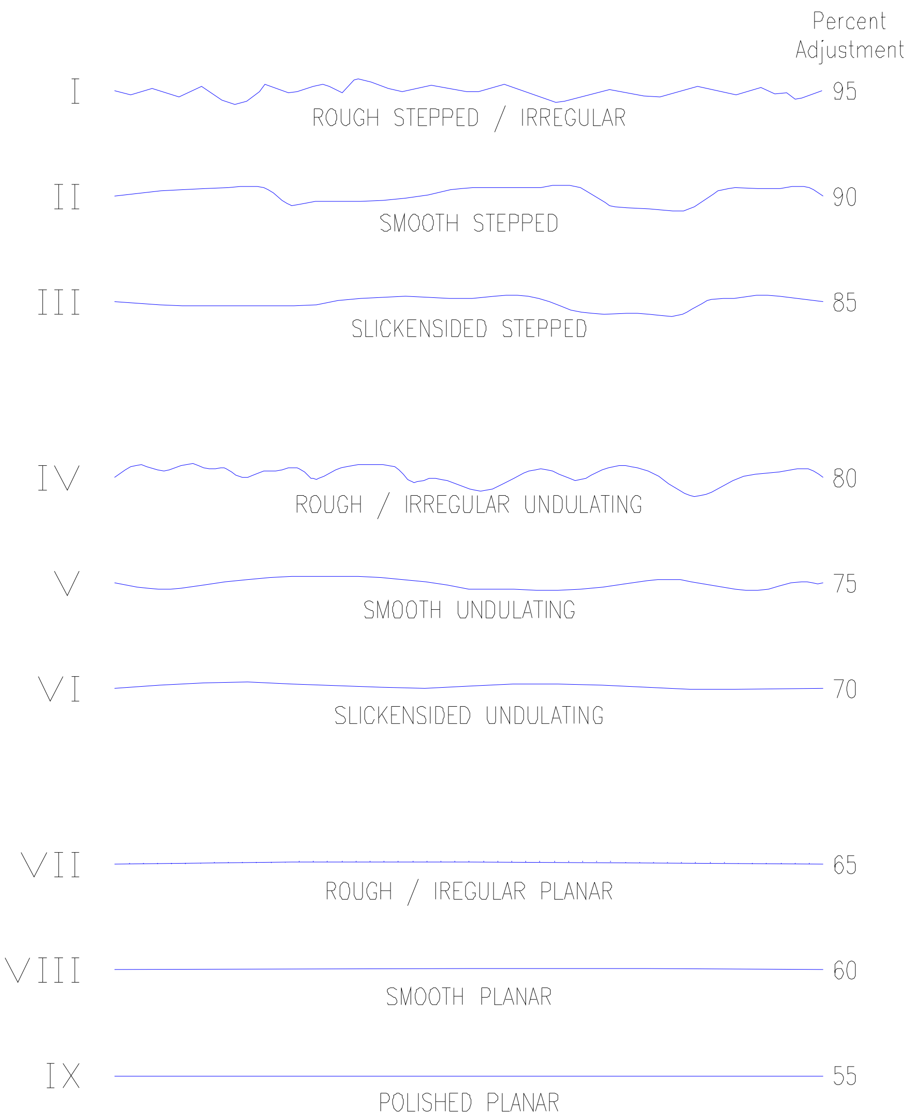

Figure 2.4: Joint Roughness Profiles (Laubscher, 1990)

To facilitate an assessment of the effect of the mining environment on the exposed rock mass, the basic RMR rating values are adjusted to account for four factors to determine the adjusted RMR value, or MRMR value. These adjustment percentages are empirical and are based on numerous field observations (Laubscher, 1990). The adjustments need to take into account the effect of the proposed mining activities on the in-situ rock mass. Mining activities that need to be considered include:

- Weathering
  The susceptibility of certain rock types to rapid weathering, e.g. kimberlite and Karoo shale, needs to be considered. According to Laubscher (1990), weathering affects three of the RMR parameters, namely IRS, RQD or (FF/m) and joint condition. Chemical weathering can

significantly decrease the rock strength; increased fracturing can result in a decrease in the RQD value, while alteration of the host rock and gouge material affects the joint condition. Weathering adjustments are applied over a period of six months to four years. A summary of applicable weathering adjustments are presented as Table 2.16.

Table 2.16: Weathering Adjustments

Description	Potential Weathering and % Adjustments				
	6months	1 year	2 years	3 years	4+ years
Fresh	100	100	100	100	100
Slightly	88	90	92	94	96
Moderately	82	84	86	88	90
Highly	70	72	74	76	78
Completely	54	56	58	60	62
Residual Soil	30	32	34	36	38

- Mining-induced stresses

  The re-distribution of regional stress fields, due to mining activities, results in mining-induced stresses. Stress adjustments cater for the magnitude and orientation of the principal stress (Jakubec and Laubscher, 2000). Spalling, crushing of pillars and the plastic flow of soft zones can all be caused by the maximum principal stress (Jakubec and Laubscher, 2000).

  Stress adjustments range from 60% to 120% reflecting poor and good confinement conditions respectively (Laubscher, 1990), with application of the adjustment factor being based largely on engineering judgement. A graphic depiction of mining induced stress is presented as Figure 2.5.

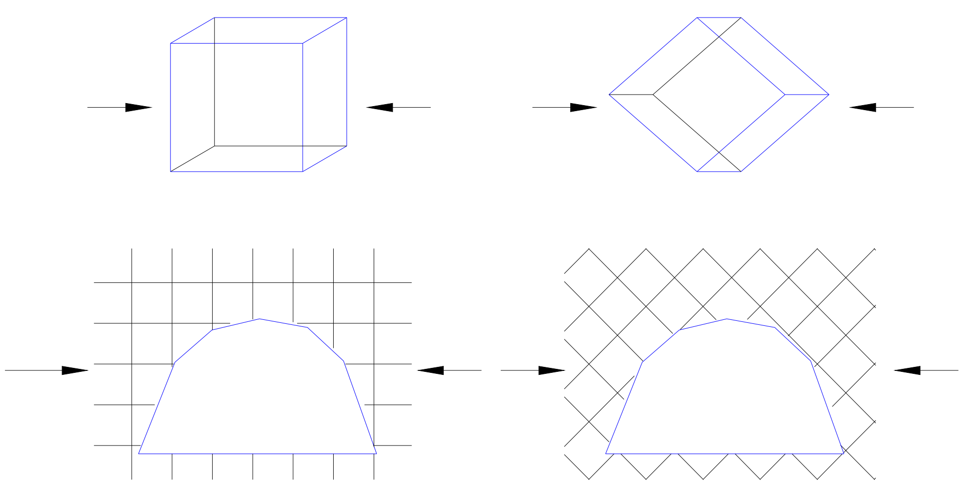

Figure 2.5: Illustration of Adjustments for Stress (Jakubec and Laubscher, 2000)

- Joint orientation

  According to Laubscher (1990), the behaviour of a rock mass is a function of the size, shape and orientation of an excavation. Furthermore, the stability of an excavation is significantly affected by the attitude of the discontinuities, and whether or not the bases of the blocks formed by the discontinuities are exposed (Refer to Figure 2.6). The joint orientation adjustment is, therefore, a function of the joint orientations with respect to the vertical axis of the block (Stacey, 2005). The percentage adjustments applicable to joint orientation are presented as Table 2.17.

Table 2.17: Joint Orientation Adjustments

No. of Joints Defining the Block	No. of Faces Inclined Away from the Vertical				
	70%	75%	80%	85%	90%
3	3		2		
4	4	3		2	
5	5	4	3	2	1
6	6	5	4	3	2,1

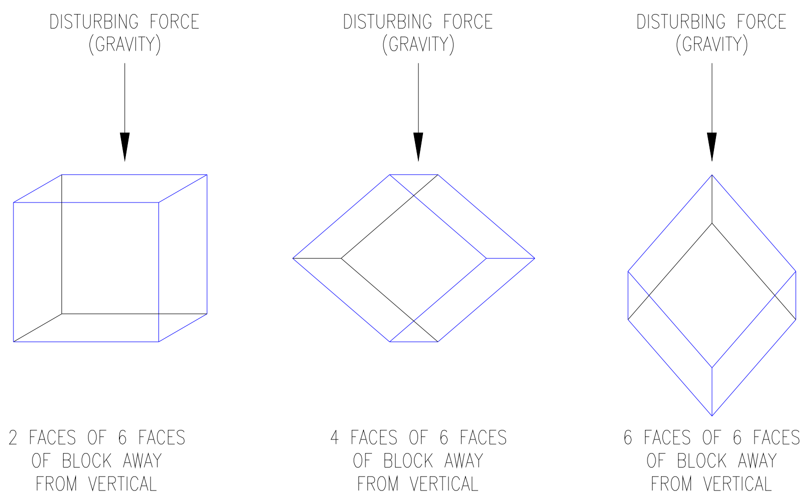

Figure 2.6 : Illustration of Joint Orientation Adjustments (Jakubec and Laubscher, 2000)

- Effect of Blasting

  Blasting creates new fractures, loosens the rock mass and causes movement along existing joints (Laubscher, 1990). Four excavation techniques are considered in applying adjustments to blasting:

  - Boring
  - Smooth wall blasting
  - Good conventional blasting
  - Poor blasting

The adjustments for blasting are presented in Table 2.18.

Table 2.18: Blasting Adjustments

Technique	Adjustment (%)
Boring	100
Smooth-Wall Blasting	97
Good Conventional Blasting	94
Poor Blasting	80

The above adjustments are cumulative, being applied as multipliers to the RMR rating value. Laubscher (1990) states that, in applying the adjustment factors, cognisance must be taken of the life of mine / excavation and the time-dependant behaviour of the rock mass.

2.4.9 The Ramamurthy and Arora Classification (Ramamurthy and Arora, 1993)

Ramamurthy and Arora proposed a classification for intact and jointed rock based on its compressive strength and modulus value in an unconfined state (Edelbro, 2003). In developing the classification system, laboratory tests were conducted on sandstone and granite samples. The classification is based on the modulus ratio (M_{rj}) of a linear stress-strain condition, represented by the equation:

$$M_r = E_{tj} / \sigma_{cj} = 1/\varepsilon \qquad (7)$$

Where:

Subscript j refers to jointed rock and subscript i refers to intact rock.

E_{tj} is the tangent modulus at 50% of the failure stress.

To estimate the rock strength and modulus ratio, the joint factor J_f , representing the weakness of the rock mass due to the presence of joint systems, needs to be calculated. The strength and modulus classification of intact and jointed rock masses, after Ramamurthy and Arora (1993) are presented as Tables 2.19 and 2.20 respectively.

Table 2.19: Strength Classification of Intact and Jointed Rock

Class	Description	Compressive Strength (MPa)
A	Very high strength	> 250
B	High strength	100 - 250
C	Moderate strength	50 - 100
D	Medium strength	25 -50
E	Low strength	5 - 25
F	Very low strength	< 5

Table 2.20: Modulus Ratio Classification of Intact and Jointed Rock

Class	Description	Compressive Strength (MPa)
A	Very high modulus ratio	> 500
B	High modulus ratio	200 - 500
C	Medium modulus ratio	100 - 200
D	Low modulus ratio	50 - 100
E	Very low modulus ratio	< 50

The rock mass is classified using a combination of letters from the two Tables, e.g. a classification of CD would represent a rock having a moderate compressive strength (50 - 100MPa) and a low modulus ratio (50 - 100).

2.4.10 The Geological Strength Index (Hoek *et al*, 1995)

The Geological Strength Index (GSI) was introduced to complement the generalised Hoek-Brown rock failure criterion, and as a way to estimate the parameters s, a and m_b in the criterion (Edelbro, 2003). The GSI system is a simple visual method of quantifying a rock mass under different geological conditions. The system comprises a chart with a description of a range of rock mass structures, together with a sketch of the representative structure on the vertical axis and descriptions of a range of joint surface conditions on the horizontal axis. The correlation of an appropriate rock mass description and joint surface description for a specific rock mass determines the GSI value. The primary advantage of the GSI system is that it facilitates the rapid classification of a rock mass. However, due to the generalised nature of the system, a range of GSI values should be reported rather than a single value. The GSI chart is presented as Figure 2.7.

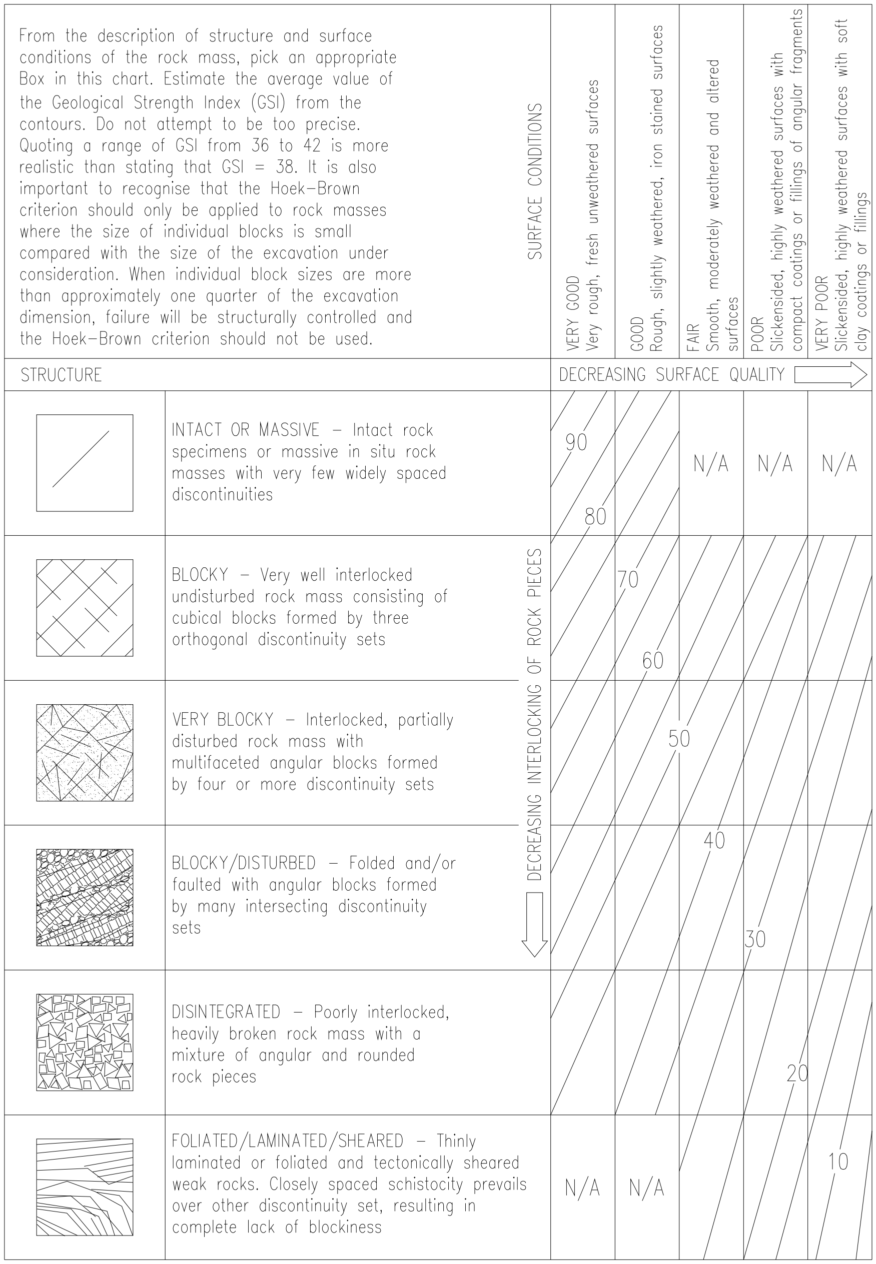

Figure 2.7: The Geological Strength Index Chart (Cai *et al*, 2004)

According to Cai *et al* (2004), the GSI system is the only rock mass classification system that is directly correlated to the Mohr-Coulomb, Hoek-Brown and rock mass modulus engineering parameters. However, as the application of the GSI system is limited by its subjective nature, a quantitative approach, utilising block volume and joint condition factors as quantitative parameters has been developed by Cai *et al* (2004). The proposed revised GSI chart is presented as Figure 2.8.

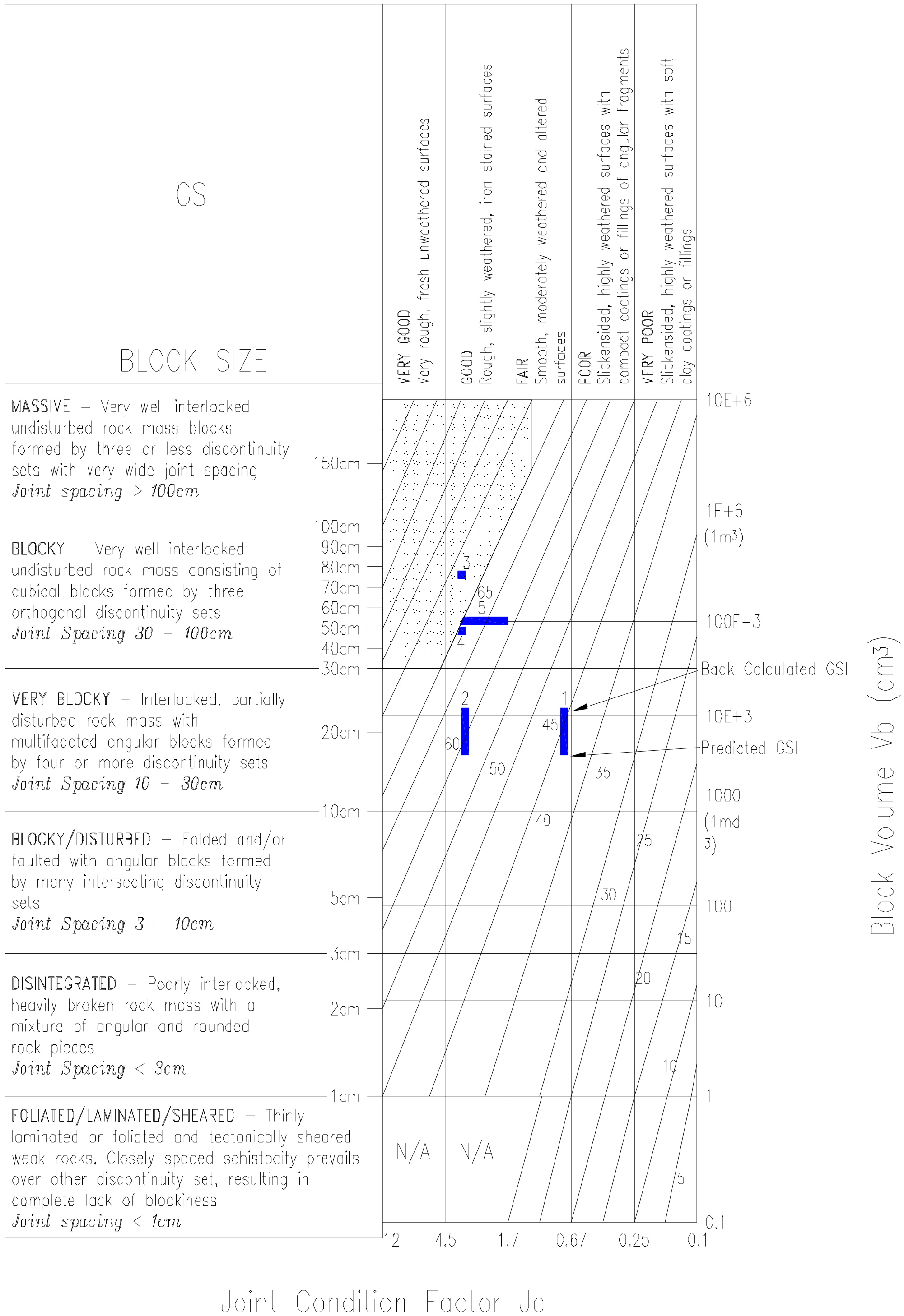

Figure 2.8: Revised GSI Chart (after Cai *et al*, 2004)

It may be noted that in the revised GSI Chart, the descriptive block size has been supplemented with the quantitative block volume (V_b) and the descriptive joint condition has been supplemented with the quantitative joint condition factor (J_C). Furthermore, additional structure categories, namely a massive category for large block volumes and moderately jointed rock and a foliated / laminated / sheared category for very small volumes of rock or highly fractured rock, have been added.

The revised GSI system has been applied to the Kannagawa pumped hydropower project in Japan (Cai *et al*, 2004), where the site is characterised by conglomerate, sandstone and mudstone. In applying the system use was made of laboratory strength tests and field mapping data. Results from the application of the system indicated that the strength and deformation parameters estimated from the GSI system correlated very well with those obtained from in-situ tests.

2.4.11 The In-Situ Rock Mass Rating (IRMR) Classification System (Laubscher and Jakubec, 2000)

According to Laubscher and Jakubec (2000), the competency of a jointed rock mass is a function of the nature, orientation and continuity of discontinuities in a rock mass. In applying the MRMR Classification System, concerns have been raised as to the potential effect of fractures, veins and cemented discontinuities on the quality of the rock mass. In 2000, Laubscher and Jakubec modified the MRMR Classification System to account for these concerns. The resultant classification system was termed the In-Situ Rock Mass Rating (IRMR) System. Laubscher and Jakubec (2000) define fractures, veins and cemented discontinuities as follows:

- Fractures and Veins:

  Low continuities of fractures and veins can occur within a rock block. The hardness number defines the fill material, with open fractures having a hardness of 1.

- Cemented Discontinuities:

  A structural feature that has continuity with the walls cemented with minerals of different cementing strength. In high stress environments, cemented joints can influence the rock mass strength, consequently, the frequency and hardness of the cementing material must be recorded.

  In determining the IRMR value, two input parameters are considered, namely:

- The Rock Block Strength (RBS) Rating

  Testing of the core, using either field techniques or laboratory testing, yields the Unconfined Compressive Strength (UCS) of the rock mass and the appropriate Intact Rock Strength (IRS) rating value is assigned to the rock mass. The corrected IRS is then determined by estimating the percentage of weak rock in the rock block. To facilitate the determination of the corrected IRS value, the estimated percentage of weak rock is located on the y-axis of a nomogram (Refer to Figure 2.9), and a horizontal line is drawn to intersect the curve representing the strength of the weak rock. A vertical line is then drawn to intersect the x-axis and the average IRS as a percentage of strong rock, which equates to the corrected IRS value, is read off.

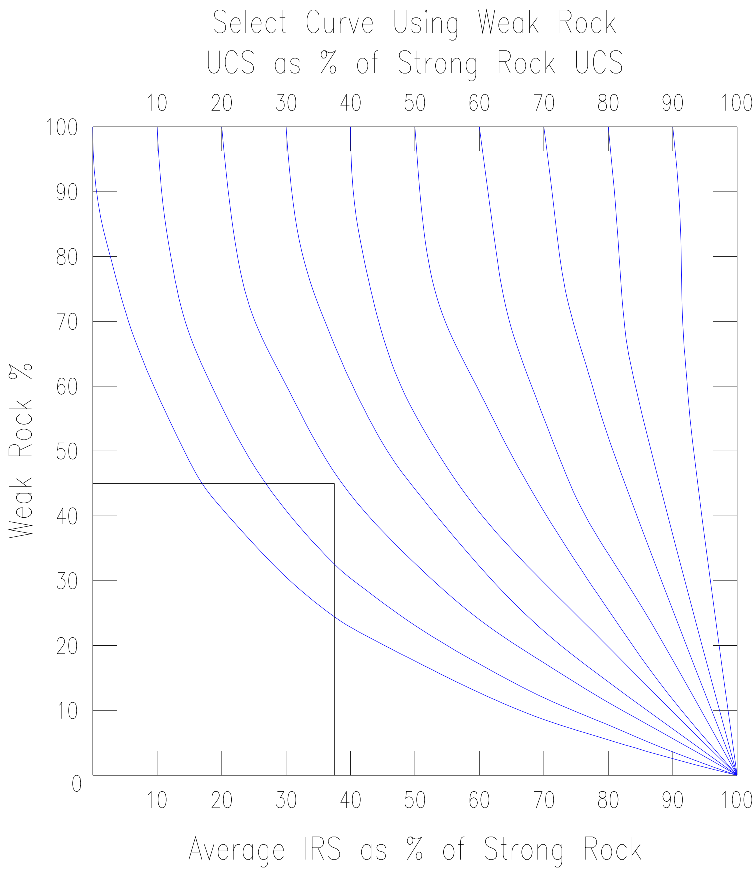

Figure 2.9: IRMR Corrected Value Nomogram (Laubscher and Jakubec, 2000)

If the rock block is devoid of fractures or veins, a factor of 0.8 is applied to adjust for the small- to large-scale specimen effect (Laubscher and Jakubec, 2000). In those instances where fractures and veins are developed, use is made of the Moh's hardness number to define the frictional properties of the infill material. A maximum hardness of 5 is used, as values in excess of 5 are unlikely to be significant (Laubscher and Jakubec, 2000). In applying the adjustment, it is to be noted that the infill material must be weaker than the host rock. In adjusting for infilled fractures and veins, the inverse of the hardness index (Refer to Table 2.21) is multiplied by the fracture/vein frequency per metre to derive a number reflecting the relative weakness between different rock masses (Laubscher and Jakubec, 2000).

Table 2.21: IRMR Moh's Hardness Scale

Infill Material	**Talc, Molybd.**	**Gypsum, Chlorite**	**Calcite, Anhydrite**	**Fluorite, Chalcopy.**	**Apatite**
Strength	1	2	3	4	5
Inverse	1.00	0.50	0.33	0.25	0.20

By applying the resultant value to Figure 2.10, the percentage IRS adjustment value is determined. The RBS rating value is obtained from Figure 2.11.

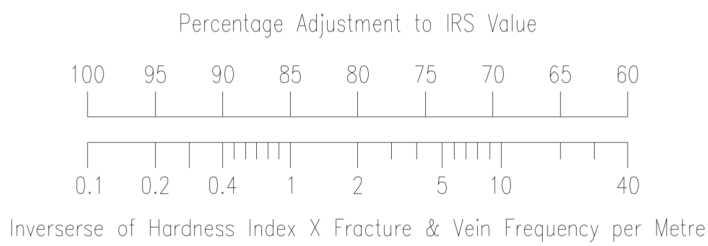

Figure 2.10: IRMR Nomogram of IRS Adjustments, Hardness Index and Vein Frequency (Laubscher and Jakubec, 2000)

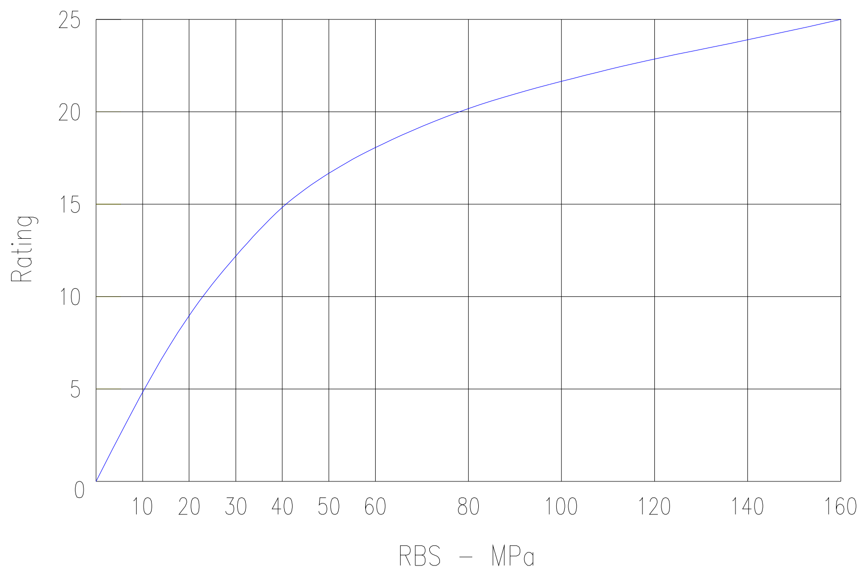

Figure 2.11: IRMR Rock Block Strength Rating Value Graph (Laubscher and Jakubec, 2000)

As small changes are significant in determining the RBS rating value, the slope of the curve in Figure 2.11 is steeper for lower RBS values.

- The Overall Joint Rating

  Unlike the MRMR Classification System, the IRMR Classification System does not allow the use of two discrete methods pertaining to discontinuity spacing, i.e. the product of the RQD and joint spacing, or alternatively, the fracture frequency, to calculate the RMR value. In calculating the RMR value, the IRMR Classification System considers two types of joints and joint conditions, namely:

- Open Joints

  The fracture / vein frequency and joint condition parameters are an integral part of the RBS calculation. As these parameters cannot be considered twice in the RMR calculation, the joint spacing rating has been reduced from 40 to 35 (Refer to Figure 2.12) and only refers to open joints (Laubscher and Jakubec, 2000).

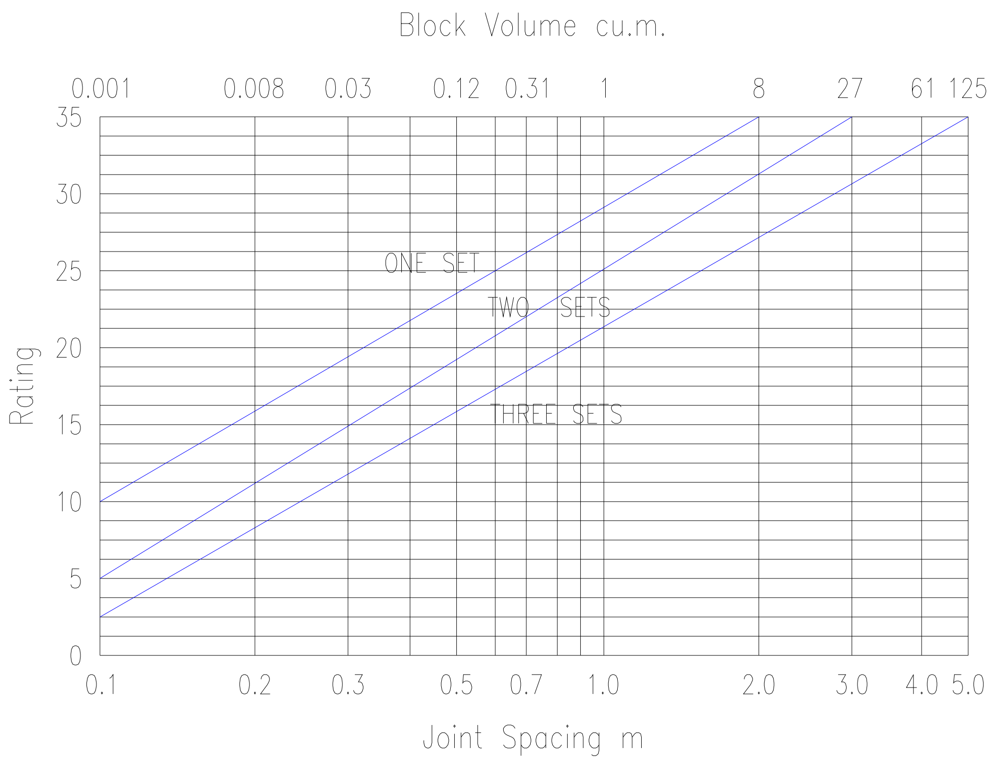

Figure 2.12: IRMR Joint Spacing Rating Values (Laubscher and Jakubec, 2000)

- Cemented Joints

  The strength of a rock mass will be affected by cemented joints, if the strength of the cementing material is less than the strength of the host rock. When cemented joints form discrete joint sets, use is made of Figure 2.13 to down rate the joint spacing rating value.

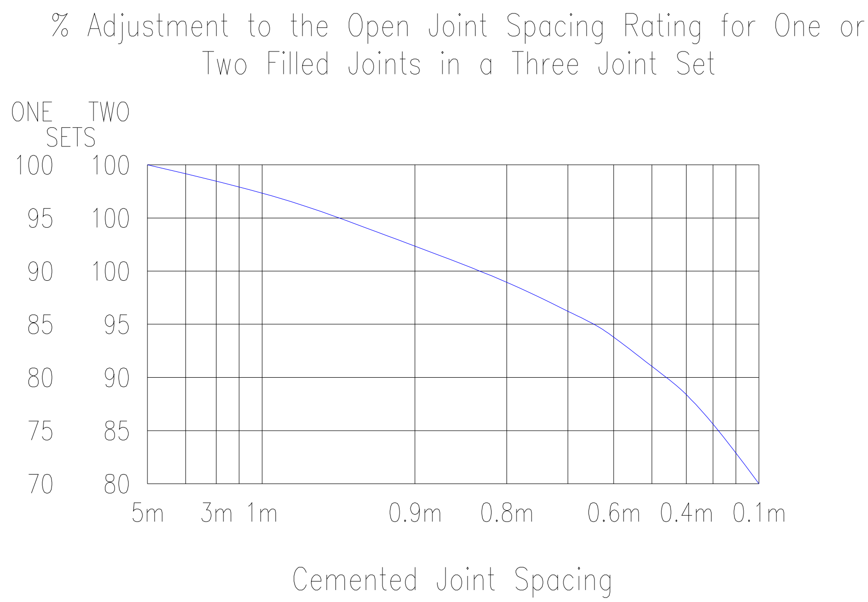

Figure 2.13: IRMR Graph for Down Rating Cemented Joint Rating Values (Laubscher and Jakubec, 2000)

The slope of the curve shown in Figure 2.13 represents an adjustment to account for the significant influence of closer joint spacing on the joint spacing parameter.

- Single Joints

  The joint condition rating remains unchanged in the IRMR Classification System; however, the joint condition adjustments have been altered to those in Table 2.22.

Table 2.22: IRMR Joint Condition Ratings and Adjustments

A. Large-Scale Joint Expression	**Adjustment % of 40**
Wavy - multidirectional	100
Wavy - unidirectional	95
Curved	90
Straight, slight undulation	85
B. Small-scale Joint Expression (200mm x 200mm)	
Rough stepped / irregular	95
Smooth stepped	90
Slickensided stepped	85
Rough undulating	80
Smooth undulating	75
Slickensided undulating	70
Rough planar	65
Smooth planar	60
Polished	55
C. Joint wall alteration weaker than sidewall and filling	75

Table 2.22 (cont.): IRMR Joint Condition Ratings and Adjustments

D. Gouge	
Thickness < amplitudes	60
Thickness > amplitudes	30
E. Cemented/filled joints-cement weaker than wall rock. The percentage in the column is the adjustment to obtain the cemented filled-joint condition rating	
Hardness	**Adjustment**
5	95%
4	90%
3	85%
2	80%
1	75%

- Multiple Joints

  Average joint condition ratings are used in calculating the RMR value. Use is made of Figure 2.14 to obtain realistic average joint condition rating values, as a weighted average joint condition can give incorrect results when the rating value of one set is high.

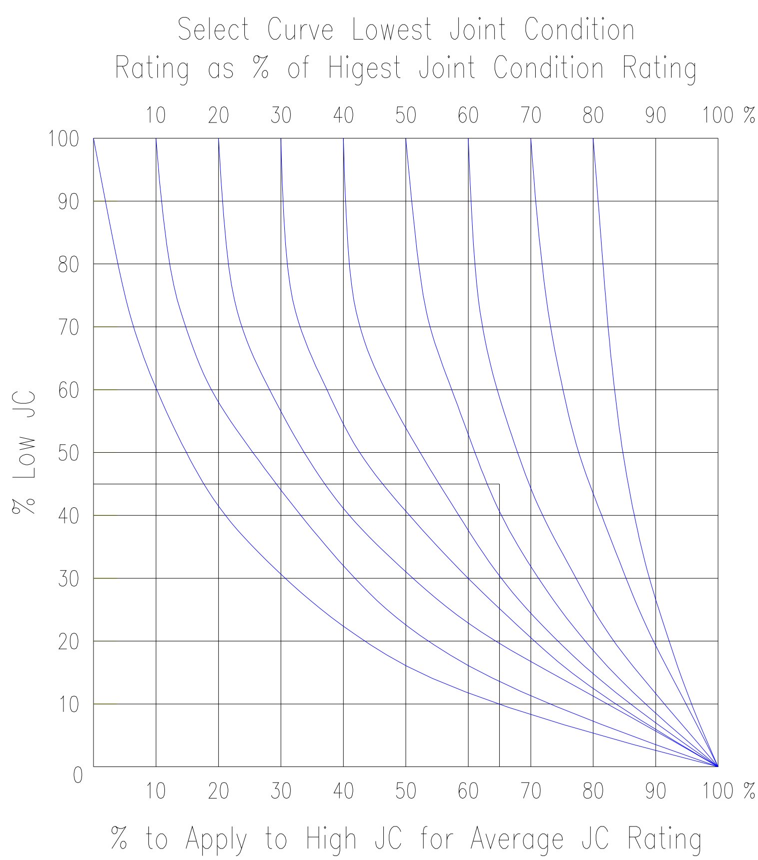

Figure 2.14: IRMR Joint Condition Rating Chart (Laubscher and Jakubec, 2000)

The RMR value equals the sum of the RBS and the Overall Joint Rating.

As with the RMR Classification System, the IRMR Classification System takes into account the effect of the proposed mining activities on the in-situ rock mass to adjust the RMR value to a realistic number for a particular mining situation (Laubscher and Jakubec, 2000). The same four adjustments as used in the MRMR Classification System, namely weathering, joint orientation, mining-induced stress and blasting, are used in the IRMR Classification System, as well as a new adjustment for water and / or ice.

- Weathering Adjustment

  The weathering adjustment is used to make allowance for the anticipated reduction in rock mass strength due to the weathering that alters the exposed rock surfaces and joint infill material. It does not, however, take the existing weathered state of the rock mass into consideration, as this is taken into account by the IRS in calculating the RMR value. Proposed weathering adjustment factors for the IRMR Classification System are presented in Table 2.23.

Table 2.23: IRMR Weathering Adjustment Factors (after Laubscher and Jakubec, 2000)

Rock Mass Description	**Potential Weathering and Percentage Adjustments**				
	6 Months	**1 Year**	**2 Years**	**3 Years**	**4 Years or More**
Fresh	100	100	100	100	100
Slightly Weathered	88	90	92	94	96
Moderately Weathered	82	84	86	88	90
Highly Weathered	70	72	74	76	78
Completely Weathered	54	56	58	60	62
Residual Soil	30	32	34	36	38

- Joint Orientation Adjustment

  The joint orientation adjustment, which is a function of the joint orientations with respect to the vertical axis of the block, is used to take into consideration the attitude of the discontinuities, and whether or not the bases of the blocks formed by the discontinuities are exposed. The dip, number of joints and their frictional properties determine the magnitude of the joint orientation adjustment value. Proposed joint orientation adjustment factors for the IRMR Classification System, which have been revised to account for the effect of low-friction surfaces as defined by the joint condition, are presented in Table 2.24.

Table 2.24: IRMR Joint Orientation Adjustments (after Laubscher and Jakubec, 2000)

No. of Joints Defining Rock Block	No. of Faces Inclined From Vertical	Percentage Orientation adjustment for Ranges in Joint Condition		
		0 - 15	16 - 30	31 - 40
3	3	70	80	95
	2	80	90	95
4	4	70	80	90
	3	75	80	95
	2	85	90	95
5	5	70	75	80
	4	75	80	85
	3	80	85	90
	2	85	90	95
	1	90	95	-

- Mining-Induced Stress Adjustment

  Stress adjustments range from 60% to 120%, reflecting poor and good confinement conditions respectively Laubscher (1990). Examples of stress adjustments would be an adjustment of 70% for low angle stresses that result in shear failure, an adjustment of 120% for compressive stress that inhibits failure and a 60% adjustment for high stresses resulting in failure (Refer to Figure 2.5). Typically, application of the stress adjustment factor is based largely on engineering judgement.

- Blasting Adjustment

  The blasting adjustment is used to account for the creation of new fractures, and the opening of existing fractures, which decreases the strength of the rock mass. The blasting adjustments presented in Table 2.25 are the same as those for the MRMR Classification System, which are presented in Table 2.18.

Table 2.25: IRMR Blasting Adjustments (after Laubscher and Jakubec, 2000)

Excavation Technique	Adjustment
Boring	100
Smooth-wall blasting	97
Good conventional blasting	94
Poor blasting	80

- Water / Ice Adjustment

  A water / ice adjustment has been added to the IRMR Classification System due to its effect on reducing the frictional properties and effective stress of a rock mass. Furthermore, ice may temporarily increase the rock mass strength, but this usually decreases over time due to ice creep (Laubscher and Jakubec, 2000). The proposed water / ice adjustments are presented in Table 2.26.

Table 2.26: IRMR Water/Ice Adjustments (after Laubscher and Jakubec, 2000)

Water Condition		
Moist	**Moderate Pressure: 1-5 MPa; 25-125 l/m**	**High Pressure: >5MPa; >125 l/m**
95% - 90%	90% - 80%	80% - 70%

The above adjustments are cumulative, being applied as multipliers to the RMR rating value.

2.5 Literature Review Findings

A review of the current literature indicates that correlations have been derived for two of the three most common classification systems currently in use. Although not directly related, RMR values and Q-values have been derived by a number of authors, including both Bieniawski (1976) and Barton (1995). However, despite the fact that the IRMR Classification System was introduced some six years ago and that the MRMR and IRMR Classification Systems share a common origin, the author was unable to source literature on the correlation between the MRMR and IRMR Classification Systems during the literature review.

Given the fact that the IRMR Classification System was introduced to address perceived short-comings in the MRMR Classification System, the application of this system by geotechnical practitioners will increase and may eventually replace the MRMR Classification System in certain applications. A review of current literature indicates that, at present, no studies have been carried out on the derivation of a correlation between the MRMR and IRMR Classification Systems. Consequently, it is the opinion of the author that there is a requirement for such a study and, therefore, this requirement will be addressed in the following chapters of this dissertation.

The parametric and geotechnical data bases, together with an explanation of logic behind the compilation of the parametric data base and the assimilation of the geotechnical data base, are presented in Chapter 3. Thereafter, the results of the parametric and geotechnical data base analyses are presented in Chapter 4.

3 PARAMETRIC AND GEOTECHNICAL DATABASES

Chapter 2 has dealt with the nature of rocks and rock masses and the philosophy, implementation and evolution of rock mass classification systems that are, or were, in use by the mining industry. In Chapter 3, the research report addresses the concept of the parametric data base and the approach taken in analysing the effect of individual parameters on the resultant MRMR and IRMR values. Furthermore, a succinct overview of the geotechnical data base, together with an explanation of the analysis methodology, is presented.

3.1 Scope of Study

Subsequent to its introduction in South Africa in 2000, the author has been unable to source literature pertaining to case studies on the application of the IRMR Classification System. Consequently, the scope of this study will comprise a quantitative assessment of the IRMR Classification System, based on geotechnical data assimilated by the author from the in-pit mapping of a number of mining operations in South Africa and Zimbabwe respectively and the subsequent derivation of a correlation between the MRMR and IRMR Classification Systems. The Scope of the Study comprised both a qualitative and a quantitative analysis, the details of which are presented in Sections 3.1.1 and 3.1.2 respectively.

3.1.1 Qualitative Analysis

A parametric database was developed for both the MRMR and IRMR Classification Systems. This was done to facilitate an initial assessment of the effect of increasing and decreasing individual MRMR and IRMR parameters on the resultant rock mass rating values. Parameters that were assessed included:

- The Intact Rock Strength (IRS).
- The Rock Quality Designation (RQD).
- The Joint Spacing (J_s).
- The micro and macro Joint Condition (J_c).
- Water.

It is to be noted that parametric rock mass rating values were derived for both wet and dry conditions. This was done to facilitate an assessment of the effect of water on the resultant rock mass rating values.

3.1.2 Quantitative Analysis

The quantitative analysis was carried out on a geotechnical database comprising 72 rock mass rating values, derived for various lithological units from the in-pit mapping of three open pit mining operations in South Africa and Zimbabwe respectively. All geotechnical data considered in the quantitative assessment were obtained using direct field measurements. Given the size of the exposures of engineering interest, the number of discontinuities was too numerous to achieve a 100% coverage. Consequently, only representative samples of the field conditions were obtained for analysis and interpretation. Use was made of the window face mapping technique to obtain representative discontinuity samples, which involves recording the orientations of all accessible discontinuities within a specified horizontal distance of a predetermined design section line. In all instances, the discontinuity data used in this research project was recorded from a 50m wide zone spanning predetermined design section lines at each of the respective sites, i.e. a 25m wide zone on either side of the design section line. During the geotechnical in-pit face mapping, the following geotechnical parameters were recorded to facilitate the calculation of rock mass rating values:

- Rock type (Lithology).
- Joint orientation (Dip and Dip Direction).
- Intact Rock Strength (using accepted field techniques).
- Joint condition (Infill Thickness and Consistency, Joint Macro- and Micro-Expression).
- Joint Spacing / Fracture frequency.
- Water condition.

3.2 The Parametric Database

A parametric database was compiled of both MRMR and IRMR data to facilitate an initial assessment of the effect of the individual parameters, i.e. Intact Rock Strength (IRS), Fracture Frequency (FF), Joint Spacing (J_s), the micro and macro Joint Condition (J_c) and Water, on the resultant rock mass rating values obtained from both classification systems.

In compiling the parametric database a medium hard rock having a RQD value of 96% and comprising three joint sets was assumed. The macro-joint expression was assumed to be straight, while the micro-joint expression was assumed to be rough undulating and devoid of gouge. Furthermore, a value of 1 was assumed for all mining adjustments, i.e. weathering, joint orientation, induced stress and blasting respectively. An RQD of approximately 96% was calculated using the following equation (Edelbro, 2003):

$$RQD = 115 - 3.3J_v \qquad (8)$$

Where:

J_v = the volumetric joint count, i.e. the sum of the number of joints per unit length for all joint sets in a clay-free rock mass

A summary of the MRMR and IRMR Classification System parametric databases is presented as Tables 3.1 and 3.2 respectively.

Table 3.1: The MRMR Parametric Database

Intact Rock Strength (MPa)	Joint Spacing (m)			RQD (%)			Joint Surface Condition			
	J1	J2	J3	Jv	3.3Jv	Total	Micro	Macro	Infill	Wall Alteration
125	1.20	0.60	0.30	5.83	19.25	95.7	Rough Undulating (0.8)	Straight (0.75)	None (1.0)	None (1.0)

Table 3.2: The IRMR Parametric Database

IRS		Jointing								
		Infill Type/ Hardness	Joints/ m	Open			Single		Cemented	Multiple
% Strong Rock	Corrected IRS (MPa)			J1	J2	J3	Macro	Micro	No. of Cemented Joints	No. of Multiple Joints
100	125	0	1	1.2	0.6	0.3	0.85	0.80	NA	NA

The approach taken in analysing the effect of the individual parameters on the resultant MRMR and IRMR values was to initially increase and decrease the individual MRMR parameter values by 16%, with the maximum and minimum values not exceeding the maximum and minimum permissible parameter rating values. The value of 16% was chosen as this equates to the percentage difference in Intact Rock Strength (IRS) sub-divisions using Laubscher's (1990) MRMR Classification System. This was followed by further analysis where the individual parameter values were increased by 50%, with the maximum and minimum values not exceeding the maximum and minimum permissible parameter rating values. This series of analyses was carried out to assess the effect of both small and large adjustments on the resultant MRMR value.

3.3 The Geotechnical Database

The geotechnical database comprises 72 rock mass rating values that were derived for various lithological units from in-pit mapping of four open pit mining operations in South Africa and Zimbabwe respectively. The MRMR and IRMR geotechnical databases are presented as Appendices A and B respectively. A breakdown of the data source and geological setting of the geotechnical data is presented as Table 3.3.

Table 3.3: Breakdown of Geotechnical Database

Data Source	Geological Setting
Colleen Bawn Limestone Quarry, Zimbabwe	Sedimentary and Igneous
Kalgold Mine, NW Province, South Africa	Sedimentary, metamorphic and Igneous
Marikana Mine, NW Province, South Africa	Igneous

Rock mass rating values were calculated for each of the three open pit mining operations using both Laubscher's (1990) Mining Rock Mass Rating Classification (MRMR) System and Laubscher and Jakubec's (2000) In-Situ Rock Mass Rating Classification (IRMR) System. This facilitated a quantitative assessment of the effect of the newly introduced adjustments on the resultant rock mass rating values, the statistical evaluation of the two classification systems under various geological settings and the derivation of a mathematical correlation between the MRMR and IRMR Classification Systems.

3.3.1 Analysis Methodology

Use was made of statistical techniques in the quantitative analysis of the MRMR and IRMR Classification Systems. The advantage of using statistics in the quantitative analysis is the ability to draw conclusions about the nature of the rock mass classification data obtained from the two classification systems, based on the limited information in the respective samples, as:

- Statistical inferences are subject to smaller errors than other methods.
- Statistical inferences are subject to a specified measure of error allowing a statement to be made regarding the magnitude of error.

Two software packages were used in the quantitative analysis of the MRMR and IRMR Classification Systems, namely Excel and Axum® 5.

- The Excel Software Package

  Use was made of the Excel graphic package to display data in the form of 2-D histograms, line graphs and scatter graphs respectively. The construction of histograms facilitates the visual representation of the distributional characteristics of a quantitative data set, with each bar representing an individual category and the height of each bar representing the category frequency. The width of the respective bars has no meaning. The construction of line graphs facilitates a visual comparison of how closely the distribution of the one data set approximates the other data set. The construction of a scatter graph facilitates the visualisation of the relationship between two variables x and y in a set of bivariate data, i.e. pairs of measurements (x,y) made on a set of observations.

- The Axum Software Package

  Axum® 5 is a technical graphing and data analysis package which facilitates the construction of a variety of 2-D and 3-D graph types, as well as basic and advanced statistical analyses. The Axum® 5 software facilitates the calculation of descriptive statistics, a frequency distribution, correlation matrix or perform an Analysis of Variance (ANOVA) on a data set. Other functions include linear and non-linear curve fitting and multivariate regression analysis.

4 INTERPRETATION OF QUALITATIVE AND QUANTITATIVE ANALYSES

Chapter 3 presented the parametric and geotechnical data bases used in the research report. In Chapter 4 the interpretation and discussion of both the qualitative and quantitative analysis results is presented.

4.1 MRMR Parametric Analysis

The results of increasing and decreasing the individual MRMR parameters by 16% are summarised as Tables 4.1 and 4.2 respectively. Cognisance is to be taken of the fact that only those individual parameter values that do not exceed the maximum or minimum parameter rating values are reported. Furthermore, the results are reported to one decimal point to illustrate the changes, which may be subtle, in the individual parameter rating values. The results are depicted graphically in Figure 4.1. The detailed MRMR parametric analysis results are presented as Appendix C.

Table 4.1: Parametric Results for a 16% Increase in Individual MRMR Parameter Rating Values

Parameters Increased	Initial MRMR Value	Resultant MRMR Value	Difference in MRMR Value	Percentage Difference in MRMR Value (%)	Rock Quality Class	Rock Quality Description
IRS	61.8	63.8	2.0	3.2	Class 2B	Good
J1 Joint Spacing/RQD	61.8	62.1	0.3	0.0	Class 2B	Good
J2 Joint Spacing/RQD	61.8	62.2	0.4	0.0	Class 2B	Good
J3 Joint Spacing/RQD	61.8	63.0	1.1	1.8	Class 2B	Good
Micro Joint Condition	61.8	71.7	9. 9	6.3	Class 2A	Good
Macro Joint Condition	61.8	65.7	3.9	6.3	Class 2A	Good
Stress Adjustment	61.8	65.6	3.8	16.0	Class 2A	Good

Analysis of the MRMR parametric results, in terms of increasing the individual parameters by 16%, indicates the following:

- The effect of a 16% increase in the seven parameter values does not elevate the resultant MRMR value into a higher class, i.e. the rock mass remains classified as a “Good” rock.
- A 16% increase in the IRS, J2 and J3 joint spacing and macro joint condition parameters has a nominal effect on the resultant MRMR value.

- A 16% increase in the micro joint condition parameter results in the highest increase in the resultant MRMR value, i.e. 10 points, and elevates the MRMR value into a higher sub-class classification, i.e. from a Class 2B rock mass to a Class 2A rock mass.
- The effect of a 16% increase in the induced stress adjustment is nominal.

Table 4.2: Parametric Results for a 16% Decrease in Individual MRMR Parameter Rating Values

Parameters Decreased	Initial MRMR Value	Resultant MRMR Value	Difference in MRMR Value	Percentage Difference in MRMR Value (%)	Resultant Rock Quality Class	Resultant Rock Quality Description
IRS	61.8	59.8	2.0	3.4	Class 3A	Fair
J1 Joint Spacing/RQD	61.8	61. 6	0.2	0.0	Class 2B	Good
J2 Joint Spacing/RQD	61.8	61.5	0.3	0.0	Class 2B	Good
J3 Joint Spacing/RQD	61.8	61.2	0.6	0.9	Class 2B	Good
Micro Joint Condition	61.8	57.9	3.9	6.3	Class 3A	Fair
Infill	61.8	58.0	3.8	6.2	Class 3A	Fair
Wall Alteration	61.8	58.0	3.8	6.2	Class 3A	Fair
Weathering Adjustment	61.8	51.9	9.9	16.0	Class 3A	Fair
Orientation Adjustment	61.8	51.9	9.9	16.0	Class 3A	Fair
Stress Adjustment	61.8	51.9	9.9	16.0	Class 3A	Fair
Blasting Adjustment	61.8	51.9	9.9	16.0	Class 3A	Fair
Moisture	61.8	58.8	3.0	4.9	Class 3A	Fair

Analysis of the MRMR parametric results, in terms of decreasing the individual parameters by 16%, indicates the following:

- A 16% decrease in the individual parameter values results in the majority of the resultant MRMR value falling into a lower class, i.e. from “Good” rock to “Fair” rock.
- The exceptions are the J1, J2 and J3 joint spacing parameter values, as a 16% decrease in these parameter values only results in a nominal change in the resultant MRMR values.
- Decreasing the IRS, J1, J2 and J3 joint spacing parameters has a nominal effect on the resultant MRMR value.
- The greatest decrease in resultant MRMR values is associated with a decrease in the adjustment parameters; the resultant MRMR values decreasing by some 10 points.

- The effect of decreasing the moisture adjustment parameter has a nominal effect on the resultant MRMR value, i.e. decreasing the weathering, joint orientation, induced stress and blasting adjustment parameters has a greater effect on the resultant MRMR value.

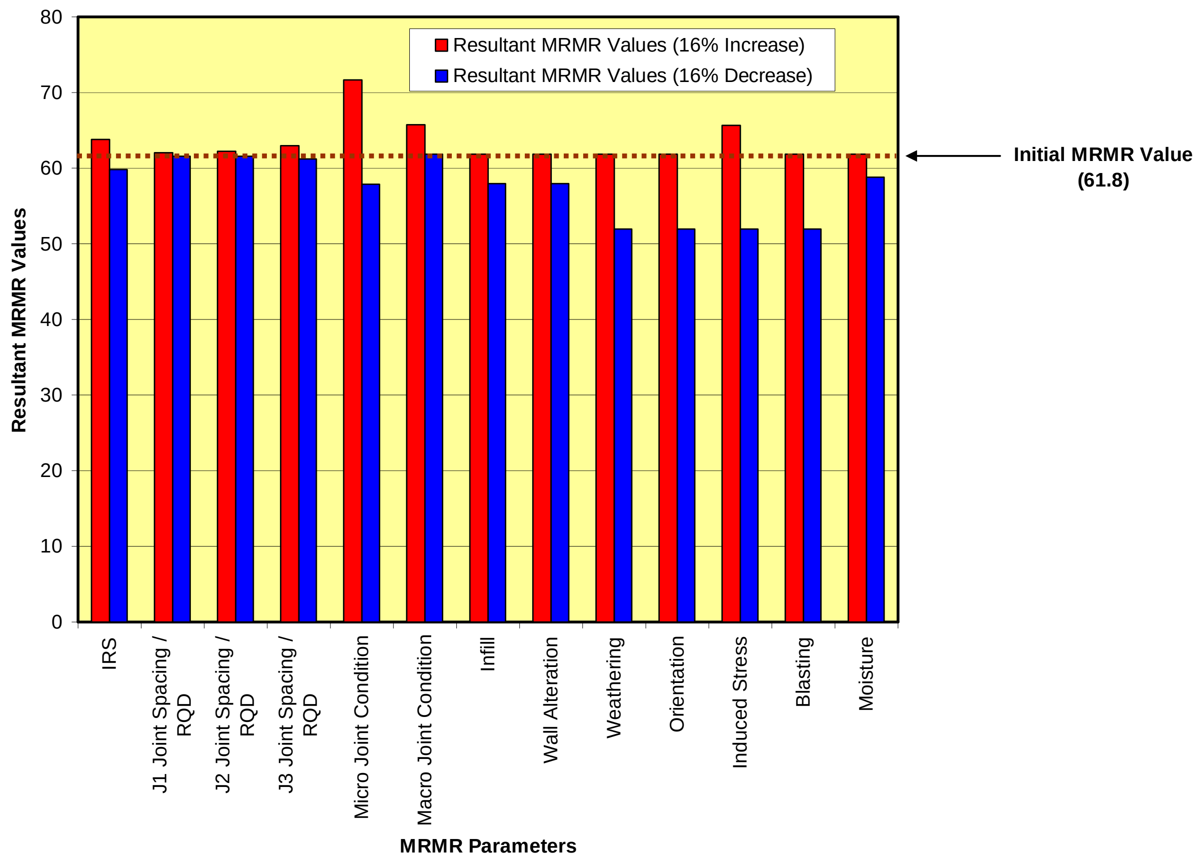

Figure 4.1: Histogram of Resultant MRMR Values for a 16% Increase and Decrease in Individual Parameter Values

The results of increasing and decreasing the individual MRMR parameters by 50% are summarised as Tables 4.3 and 4.4 respectively. Cognisance is to be taken of the fact that only those individual parameter values that do not exceed the maximum or minimum parameter rating values are reported. Furthermore, the results are reported to one decimal point to illustrate the changes, which may be subtle, in the individual parameter rating values. The results are depicted graphically in Figure 4.2. The detailed MRMR parametric analysis results are presented as Appendix C.

Table 4.3: Parametric Results for a 50% Increase in Individual MRMR Parameter Rating Values

Parameters Increased	Initial MRMR Value	Resultant MRMR Value	Difference in MRMR Value	Percentage Difference in MRMR Value (%)	Resultant Rock Quality Class	Resultant Rock Quality Description
IRS	61.8	67.8	6.0	9.7	Class 2B	Good
J1 Joint Spacing/RQD	61.8	64.1	2.2	3.6	Class 2B	Good
J2 Joint Spacing/RQD	61.8	63.8	2.0	3.2	Class 2B	Good
J3 Joint Spacing/RQD	61.8	63.8	2.0	3.2	Class 2B	Good
Macro Joint Condition	61.8	69.8	8.00	12.9	Class 2B	Good
Micro Joint Condition	61.8	67.8	6.0	9.7	Class 2B	Good
Stress Adjustment	61.8	92.7	30.9	50.0	Class 1A	Very Good

Analysis of the MRMR parametric results, in terms of increasing the individual parameters by 50%, indicates the following:

- A 50% increase in the individual parameter values does not elevate the resultant MRMR values into a higher class.
- A 50% increase has the greatest effect on the macro-joint condition parameter; the resultant MRMR value being elevated to within 0.7 points of a Class 2A rock.
- The greatest increase in resultant MRMR value is associated with the stress adjustment parameter, with a 31 point increase, which elevates the MRMR value to a higher class.
- A 50% increase in the six MRMR parameter values has a nominal effect on the resultant MRMR values.

Table 4.4: Parametric Results for a 50% Decrease in Individual MRMR Parameter Rating Values

Parameters Decreased	Initial MREMR Value	Resultant MRMR Value	Difference in MRMR Value	Percentage Difference in MRMR Value (%)	Resultant Rock Quality Class	Resultant Rock Quality Description
IRS	61.8	53.8	8.0	12.9	Class 3A	Fair
J1 Joint Spacing/RQD	61.8	60. 5	1.4	2.2	Class 3A/Class 2B	Good/Fair
J2 Joint Spacing/RQD	61.8	60.7	1.1	1.8	Class 2B	Good
J3 Joint Spacing/RQD	61.8	60.5	1.3	2.1	Class 3A/Class 2B	Good/Fair
Micro Joint Condition	61.8	49.8	12.0	19.4	Class 3B	Fair
Infill	61.8	49.8	12.0	19.4	Class 3B	Fair
Weathering	61.8	30.9	30.9	50.0	Class 4A	Poor
Orientation	61.8	30.9	39.9	54.4	Class 4A	Poor
Stress Adjustment	61.8	30.9	33.2	51.8	Class 4A	Poor
Blasting	61.8	30.9	22.9	42.6	Class 4A	Poor

Analysis of the MRMR parametric results, pertaining to decreasing the individual parameters by 50%, indicates the following:

- A 50% decrease in the individual parameter values results in the majority of the resultant MRMR values falling into lower classes of rock.
- The exception is the J2 joint spacing parameter; resultant MRMR value remains classified as a Class 2B rock.
- A 50% decrease in the joint spacing parameter values has the least effect on the resultant MRMR values, i.e. the resultant MRMR is decreased by a maximum of 1.4 points.
- The most significant effect on the resultant MRMR values is by decreasing the adjustment parameter values by 50%. The resultant MRMR values fall by two classes resulting in a classification of “Poor” rock.

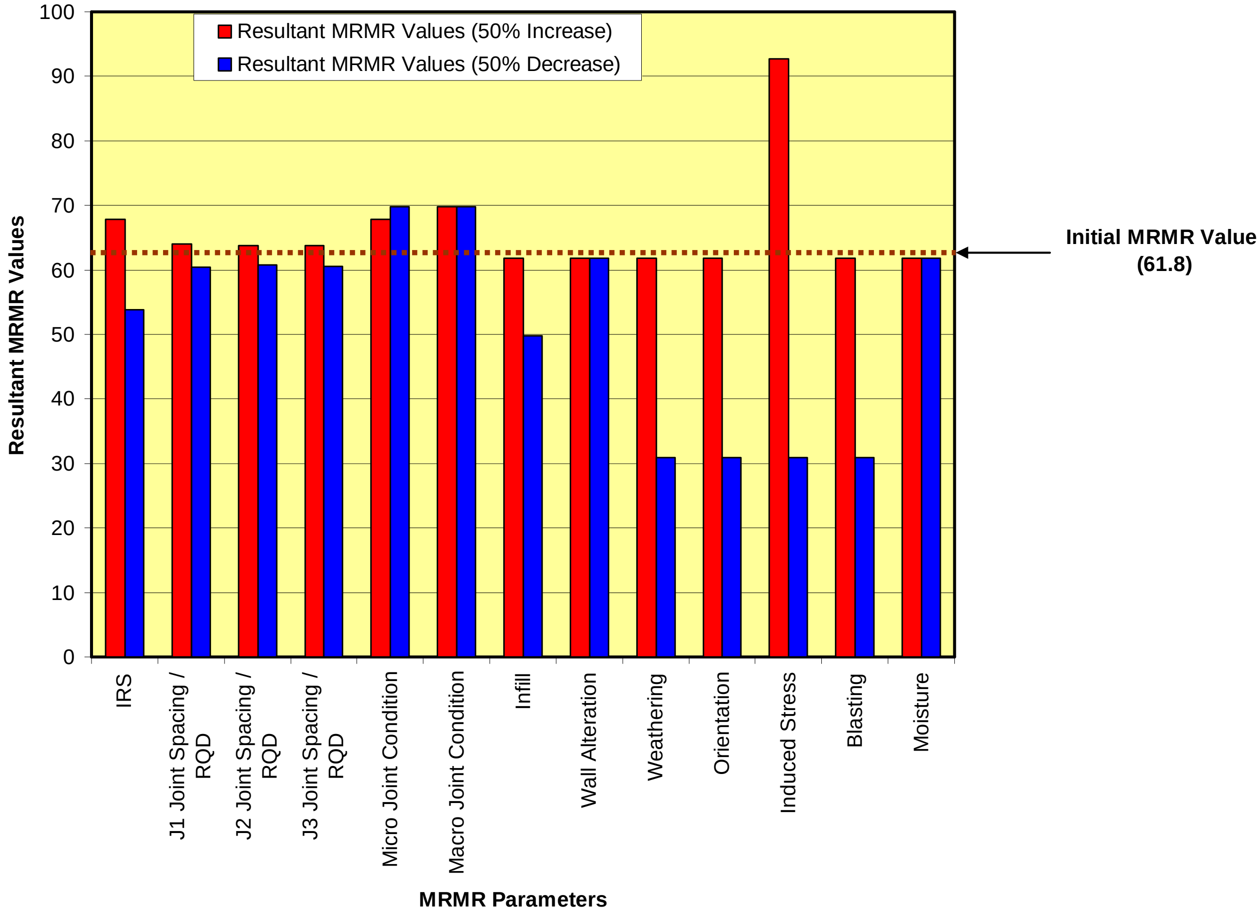

Figure 4.2: Histogram of Resultant MRMR Values for a 50% Increase and Decrease in Individual Parameter Values

4.1.1 Discussion of MRMR Parametric Data Base Analysis Results

A summary of the MRMR parametric analysis results for a 16% and 50% increase in individual parameter values is presented as Table 4.4, which indicates that, typically, a 16% increase in individual parameter values results in a percentage increase in the resultant MRMR value of 6% or less, the difference in resultant MRMR values being 4 points or less. The individual parameter ratings which had the greatest effect on the resultant MRMR value were the IRS (3%), micro- (6%) and macro-joint condition (6%) parameters respectively. Increasing the induced stress adjustment parameter by 16% has the greatest effect on the resultant MRMR value, which is increased by 10 points.

Similarly, a 16% decrease in individual parameter values results in a percentage decrease in the resultant MRMR value of 6% or less, the difference in resultant MRMR values being 4 points or less. The highest percentage decreases are associated with the IRS (3%) and micro-joint condition (6%) parameters respectively, with the resultant MRMR values falling into lower classification classes and sub-classes respectively. In terms of decreasing the adjustment parameters, the resultant

MRMR values are lowered by between 33 and 40 points. However, the effect of decreasing the effect of moisture adjustment value only reduces the resultant MRMR value by 3 points.

A 50% increase in individual parameter values results in a 13% percentage difference in the resultant MRMR value, equating to a numerical difference of 8 points or less. As with a 16% increase, the individual parameters that have the greatest effect on the resultant MRMR values are the IRS (10%), micro- (10%) and macro-joint condition (13%) parameter values respectively. In terms of increasing the adjustment parameters, a 50% increase in the induced stress adjustment parameter increases resultant MRMR value by 31 points.

A 50% decrease in individual parameter values results in a difference in resultant MRMR values of 20 points or less, with the IRS (13%) and micro-joint condition parameter (19%) values having the greatest effect on the resultant MRMR values. Decreasing the adjustment parameters applied to the rock mass rating results in a percentage difference in the resultant MRMR value of between 23% and 40%.

4.2 IRMR Parametric Analysis

The results of increasing and decreasing the IRMR parametric data base by 16% are presented as Tables 4.5 and 4.6 respectively. The detailed IRMR parametric analysis results are presented as Appendix D. The results are depicted graphically in Figure 4.3.

Table 4.5: Parametric Results for a 16% Increase in Individual IRMR Parameter Rating Values

Parameter	Initial IRMR Rating Value	Resultant IRMR Rating Value	Numerical Difference in IRMR Value	Percentage Difference in IRMR Value	Resultant Rock Quality Class	Resultant Rock Quality Description
Rock Block Strength	66.4	66.9	0.5	0.8	Class 2B	Good
J1 Open Joint Spacing	66.4	66.7	0.3	0.5	Class 2B	Good
J2 Open Joint Spacing	66.4	66.7	0.3	0.5	Class 2B	Good
J3 Open Joint Spacing	66.4	66.7	0.3	0.5	Class 2B	Good
Macro Single Joint Condition	66.4	70.8	4.5	6.8	Class 2A	Good

Table 4.5 (cont.): Parametric Results for a 16% Increase in Individual IRMR Parameter Rating Values

Parameter	Initial IRMR Rating Value	Resultant IRMR Rating Value	Numerical Difference in IRMR Value	Percentage Difference in IRMR Value	Resultant Rock Quality Class	Resultant Rock Quality Description
Micro Single Joint Condition	66.4	70.8	4.4	6.7	Class 2A	Good
Macro Multiple Joint Condition	66.4	70.3	3.9	6.0	Class 2B/2A	Good
Micro Multiple Joint Condition	66.4	70.3	3.9	5.9	Class 2B/2A	Good
Stress Adjustment	66.4	77.0	10.6	16.0	Class 2A	Good

Analysis of the IRMR parametric results, in terms of increasing the individual parameters by 16%, indicates the following:

- A 16% increase in the individual IRMR parameter values does not significantly affect the majority of the resultant IRMR values.
- Exceptions are the macro and micro single joint condition parameter values; a 16% increase elevating the resultant IRMR values into a higher sub-class classification.
- Increasing the micro and macro single / multiple joint condition parameter values results in the highest increase in the resultant IRMR values.
- A 16% increase in the stress adjustment parameter value has the greatest single effect on the resultant IRMR value.

Table 4.6: Parametric Results for a 16% Decrease in Individual IRMR Parameter Rating Values

Parameter	Initial IRMR Rating Value	Resultant IRMR Rating Value	Numerical Difference in IRMR Value	Percentage Difference in IRMR Value	Resultant Rock Quality Class	Resultant Rock Quality Description
Rock Block Strength	66.4	64.87	1.50	2.30	Class 2B	Good
Percentage Strong / Weak Rock	66.4	63.87	2.50	3.80	Class 2B	Good
J1 Open Joint Spacing	66.4	65.70	0.70	1.00	Class 2B	Good
J2 Open Joint Spacing	66.4	65.70	0.70	1.00	Class 2B	Good
J3 Open Joint Spacing	66.4	65.70	1.00	1.50	Class 2B	Good
Macro Single Joint Condition	66.4	61.89	4.50	6.80	Class 2B	Good

Table 4.6 (cont.): Parametric Results for a 16% Decrease in Individual IRMR Parameter Rating Values

Parameter	Initial IRMR Rating Value	Resultant IRMR Rating Value	Numerical Difference in IRMR Value	Percentage Difference in IRMR Value	Resultant Rock Quality Class	Resultant Rock Quality Description
Micro Single Joint Condition	66.4	61.95	1.90	2.90	Class 2B	Good
Wall Alteration Single Joint Condition	66.4	62.01	4.70	7.10	Class 2B	Good
Gouge Single Joint Condition	66.4	59.57	6.80	10.20	Class 3A	Fair
Effect of Multiple Joint	66.4	65.84	0.50	0.80	Class 2B	Good
Macro Multiple Joint Condition	66.4	62.36	5.00	7.50	Class 2B	Good
Micro Multiple Joint Condition	66.4	61.42	5.00	7.50	Class 2B	Good
Wall Alteration Multiple Joint Condition	66.4	61.48	4.90	7.40	Class 2B	Good
Gouge Multiple Joint Condition	66.4	59.04	7.30	11.00	Class 3A	Fair
Cemented/Filled Multiple Joints	66.4	61.48	2.40	3.70	Class 2B	Good
Weathering Adjustment	66.4	55.75	10.62	16.00	Class 3A	Fair
Orientation Adjustment	66.4	55.75	10.62	16.00	Class 3A	Fair
Stress Adjustment	66.4	55.75	10.62	16.00	Class 3A	Fair
Blasting Adjustment	66.4	55.75	10.62	16.00	Class 3A	Fair
Water/Ice Adjustment	66.4	63.05	3.30	5.00	Class 2B	Good

Analysis of the IRMR parametric results, in terms of decreasing the individual parameters by 16%, indicates the following:

- A 16% decrease in the individual IRMR parameter values does not significantly affect the majority of the resultant IRMR values.
- Exceptions are the gouge rating parameter values for single / multiple joint conditions in that a 16% decrease in these parameters reduces the resultant IRMR value by 7 points, which results in a drop from a “Good” rock classification to a “Fair” rock classification.
- A 16% decrease in the adjustment parameter values reduces the majority of the resultant IRMR value by 11 points, causing the majority of the resultant IRMR values to fall into a lower classification class.

- The exception is the water / ice adjustment which only reduces the resultant IRMR value by 3 points, i.e. the effect on the resultant IRMR value is nominal.

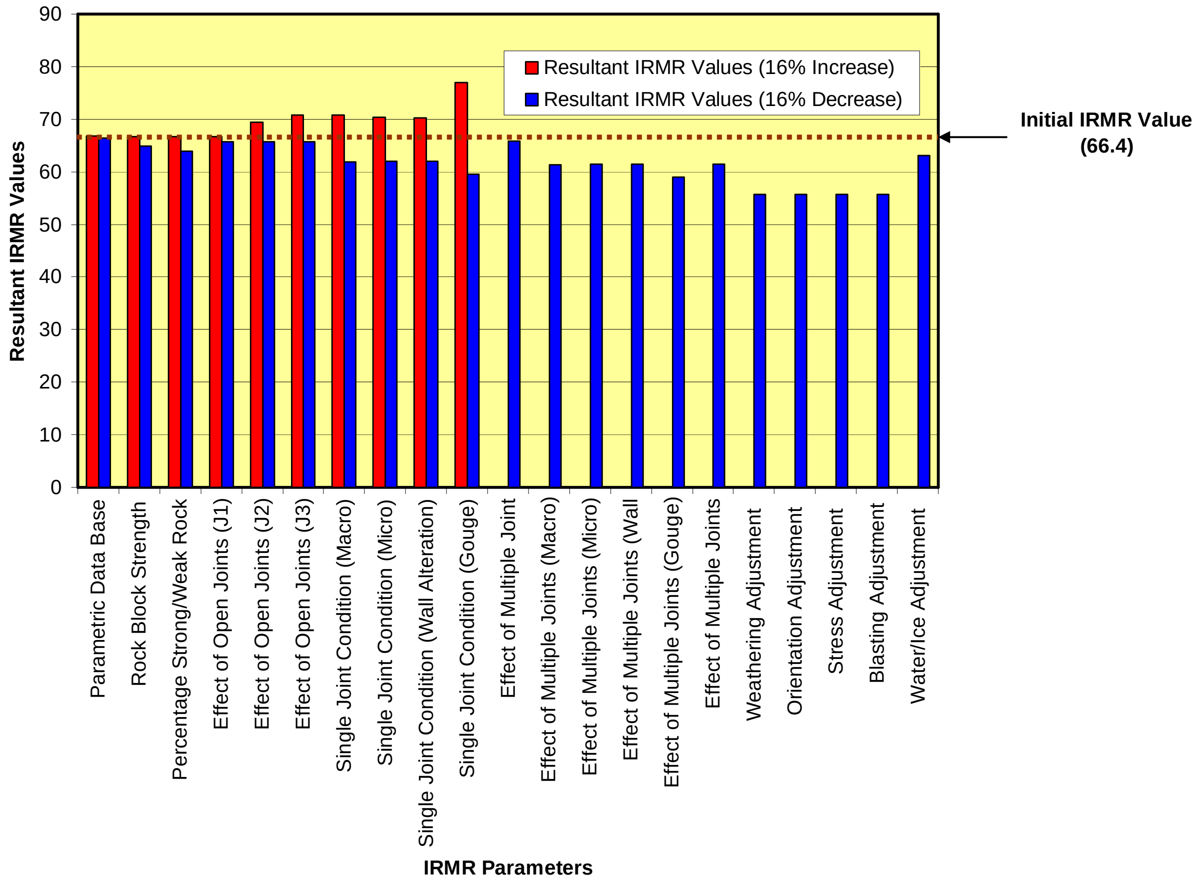

Figure 4.3: Histogram of Resultant IRMR Values for a 16% Increase and Decrease in Individual Parameter Values

The results of IRMR parametric analysis, where the individual parameters were increased and decreased by 50%, are presented as Tables 4.7 and 4.8 respectively. The detailed IRMR parametric analysis results are presented as Appendix D. The results are depicted graphically in Figure 4.4.

Table 4.7: Parametric Results for a 50% Increase in Individual IRMR Parameter Rating Values

Parameter	Initial IRMR Rating Value	Resultant IRMR Rating Value	Numerical Difference in IRMR Value	Percentage Difference in IRMR Value	Resultant Rock Quality Class	Resultant Rock Quality Description
Rock Block Strength	66.4	69.37	3	4.5	Class 2B	Good
Effect of Open Joints (J1)	66.4	67.53	1.20	1.90	Class 2B	Good
Effect of Open Joints (J2)	66.4	67.37	1.00	1.50	Class 2B	Good
Effect of Open Joints (J3)	66.4	67.37	1.00	1.50	Class 2B	Good
Effect of Multiple Joints (Macro)	66.4	71.17	4.80	7.20	Class 2A	Good
Single Joint Condition (Macro)	66.4	71.17	4.80	7.20	Class 2A	Good
Single Joint Condition (Micro)	66.4	71.47	5.10	7.70	Class 2A	Good
Effect of Multiple Joints (Macro)	66.4	71.17	4.80	7.20	Class 2A	Good
Effect of Multiple Joints (Micro)	66.4	73.17	6.80	10.20	Class 2A	Good
Stress Adjustment	66.4	99.55	33.20	50.00	Class 1A	Very Good

Analysis of the IRMR parametric results, in terms of increasing the individual parameters by 50%, indicates the following:

- A 50% increase in the IRMR parameter values does not significantly affect the majority of the resultant IRMR values.
- A 50% increase in the macro- and micro-joint condition parameter rating values, for single and multiple joints elevates the resultant IRMR values into a higher sub-class classification.
- A 50% increase in the stress adjustment parameter value significantly affects the resultant IRMR value, i.e. the resultant IRMR value is elevated into a higher classification class.

Table 4.8: Parametric Results for a 50% Decrease in Individual IRMR Parameter Rating Values

Parameter	Initial IRMR Rating Value	Resultant IRMR Rating Value	Numerical Difference in IRMR Value	Percentage Difference in IRMR Value	Resultant Rock Quality Class	Resultant Rock Quality Description
Rock Block Strength	66.4	61.9	4.5	6.8	Class 2B	Good
Percentage Strong/Weak Rock	66.4	62.9	3.5	5.3	Class 2B	Good
Effect of Open Joints (J1)	66.4	64.7	1.7	2.5	Class 2B	Good
Effect of Open Joints (J2)	66.4	64.4	2.0	3.0	Class 2B	Good
Effect of Open Joints (J3)	66.4	64.4	2.0	3.0	Class 2B	Good
Single Joint Condition (Macro)	66.4	66.4	0.0	0.0	Class 2B	Good
Single Joint Condition (Micro)	66.4	57.9	8.5	12.8	Class 3A	Fair
Single Joint Condition (Wall Alteration)	66.4	59.6	6.8	10.2	Class 3A	Fair
Single Joint Condition (Gouge)	66.4	52.8	13.6	20.5	Class 3A	Fair
Effect of Multiple Joint	66.4	65.7	0.7	1.1	Class 2B	Good
Effect of Multiple Joints (Macro)	66.4	66.4	0.0	0.0	Class 2B	Good
Effect of Multiple Joints (Micro)	66.4	57.9	8.5	12.8	Class 3A	Fair
Effect of Multiple Joints (Wall Alteration)	66.4	59.6	6.8	10.2	Class 3A	Fair
Effect of Multiple Joints (Gouge)	66.4	52.7	13.6	20.5	Class 3A	Fair
Effect of Multiple Joints (Cemented/Filled Joints)	66.4	59.6	3.3	5.2	Class 3A	Fair
Weathering Adjustment	66.4	33.2	33.2	50.0	Class 4A	Poor
Orientation Adjustment	66.4	33.2	33.2	50.0	Class 4A	Poor
Stress Adjustment	66.4	33.2	13.3	20.0	Class 4A	Poor
Blasting Adjustment	66.4	33.2	13.3	20.0	Class 4A	Poor
Water/Ice Adjustment	66.4	46.5	19.9	30.0	Class 3B	Fair

Analysis of the IRMR parametric results, in terms of decreasing the individual parameters by 50%, indicates the following:

- A 50% decrease in the IRMR parameter values does not significantly affect the majority (53%) of the resultant IRMR values.
- A 50% decrease in the single and multiple joint micro-joint condition parameter rating values reduce the resultant IRMR values such that they fall into a lower classification class.
- A 50% decrease in the majority of the adjustment parameter values significantly reduces the resultant IRMR values, i.e. the resultant IRMR values fall two classification classes to “Poor” rock.

- The exception is a 50% decrease in the adjustment for water / ice, which is not as significant as for the other adjustments; the resultant IRMR value falling by only one classification class to "Fair" rock.

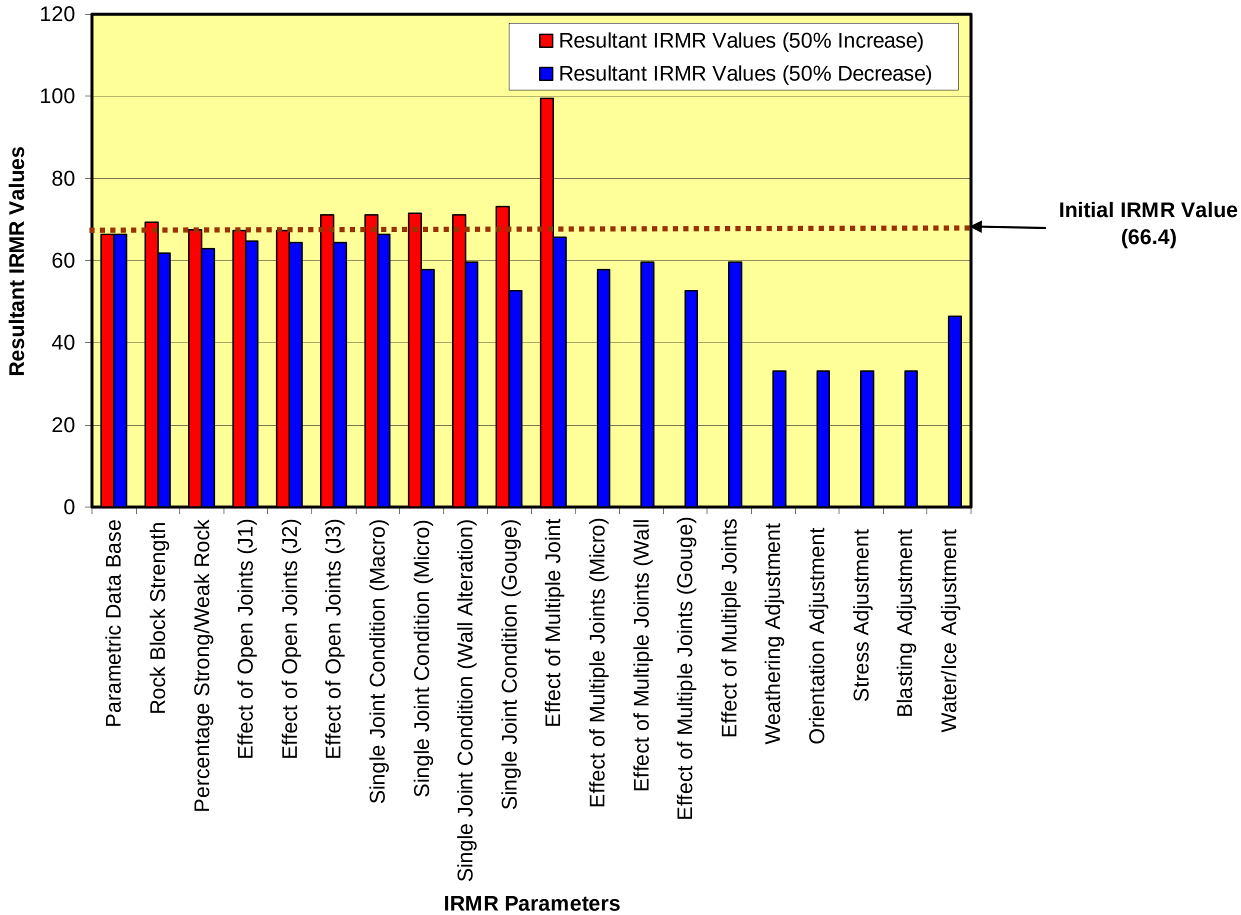

Figure 4.4: Histogram of Resultant IRMR Values for a 50% Increase and Decrease in Individual Parameter Values

4.1.2 Discussion of IRMR Parametric Data Base Analysis Results

A 16% increase in individual parameter values results in a percentage increase in the resultant IRMR value of 7% or less, the difference in resultant IRMR values being 4 points or less. The individual parameter rating values having the greatest effect on the resultant IRMR value are the micro- and macro-joint condition parameters for single and multiple joints, which results in a 4% difference in the resultant IRMR values. Increasing the induced stress adjustment parameter results in an 11 point increase in the resultant IRMR value.

A 16% decrease in individual parameter values results in a percentage decrease in the resultant IRMR value of 11% or less, the difference in resultant IRMR values being 7 points or less. The highest percentage decrease is associated with the effect of gouge on single and multiple joint surfaces, followed by the micro- and macro-joint condition parameter rating values for single and multiple joints. Decreasing the gouge parameter rating value for single and multiple joints, results in a percentage decrease of 10% and 11% in the resultant IRMR values respectively. Decreasing the adjustment parameters by 16%, results in a numerical difference of 11 points in the resultant IRMR values. The effect of moisture on the resultant IRMR is less marked, only a 5% difference in the resultant IRMR value being noted.

A 50% increase in individual parameter values results in a 10% percentage or less difference in the resultant IRMR value, which equates to a numerical difference of 7 points or less. As with a 16% increase, the individual parameters that have the greatest affect on the resultant IRMR values are the micro- and macro-joint condition parameter values for single and multiple joints. Increasing the rating values of these parameters, results in a 7% to 10% difference in the resultant IRMR values. A 50% increase in the induced stress adjustment parameter results in a 33 point numerical difference in the resultant IRMR value.

A 50% decrease in individual parameter values results in a percentage decrease in the resultant IRMR value of 21% or less. The highest percentage decrease is associated with the effect of gouge on single and multiple joint surfaces, followed by the micro-joint condition and the wall alteration parameter rating values for single and multiple joints respectively. Decreasing the gouge parameter rating value for single and multiple joints, results in a percentage decrease of 20% and 11% in the resultant IRMR values respectively. Decreasing the macro parameter rating value for single and multiple joints, results in a percentage decrease of 13% in the resultant IRMR values. Decreasing the wall alteration parameter rating value, results in a percentage decrease of 10% in the resultant IRMR value.

4.3 Qualitative Comparison of MRMR and IRMR Data Sets

Prior to undertaking a quantitative assessment of the MRMR and IRMR data sets, a qualitative comparison was carried out by plotting the respective data sets on a line graph. The primary objective of the qualitative comparison was two-fold, namely:

- To gain an appreciation of how closely the resultant rock mass rating values obtained using the two classification systems approximate one another.
- To identify significant differences in resultant rock mass rating values through use of the two classification systems.

Line graphs depicting the resultant rock mass rating values for sedimentary, igneous and metamorphic rocks are presented as Figures 4.5, 4.6 and 4.7 respectively. A line graph representing the entire MRMR and IRMR data sets is presented as Figure 4.8. The MRMR and IRMR classification data for sedimentary, igneous and metamorphic rocks are appended as Appendices E, F and G respectively. The combined MRMR and IRMR classification data are presented as Appendix H.

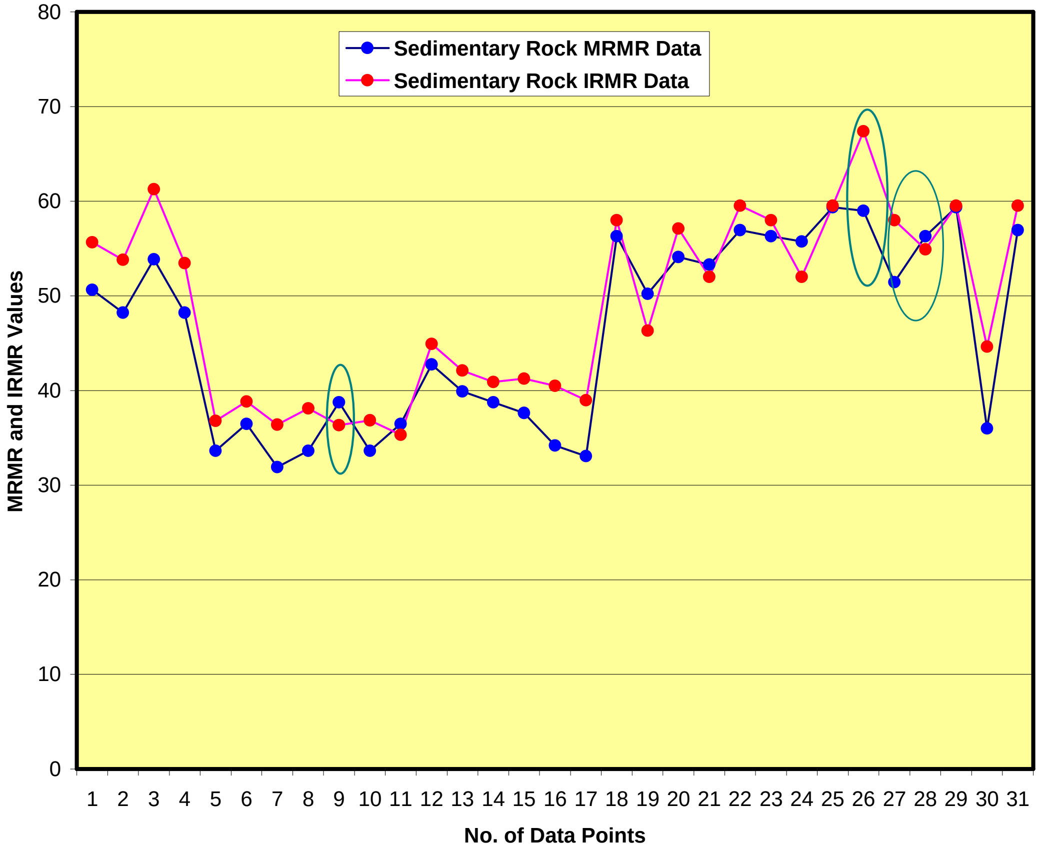

Figure 4.5: Line Graph Comparing Sedimentary Rock MRMR and IRMR Data

From Figure 4.5 it is noted that, although the individual sedimentary rock IRMR values are generally higher than the resultant MRMR values, the trends of the individual sedimentary rock line graphs, for the two classification systems, closely approximate one another. These notwithstanding, localised differences do occur where the MRMR value exceeds the corresponding IRMR value, or the IRMR value exceeds the corresponding MRMR value. Three such instances are noted, and indicated, where:

- In the first instance, the MRMR value (data point 9) represents a localised spike in the MRMR values that is not reflected in the trend of the IRMR values, which in this portion of the graph, reflects a general downward trend in IRMR values.
- In the second instance, the reverse occurs, with the IRMR value (data point 26) representing a localised spike (IRMR = 67), which is not reflected in the more uniformly distributed MRMR values.

- In the third instance, the MRMR value (data point 27) represents a localised dip (MRMR = 51), which is not manifest to the same degree in the IRMR value (IRMR = 55).

These differences may be attributed to the resultant IRMR values being characterised by a degree of regularity, while the MRMR values are more irregular.

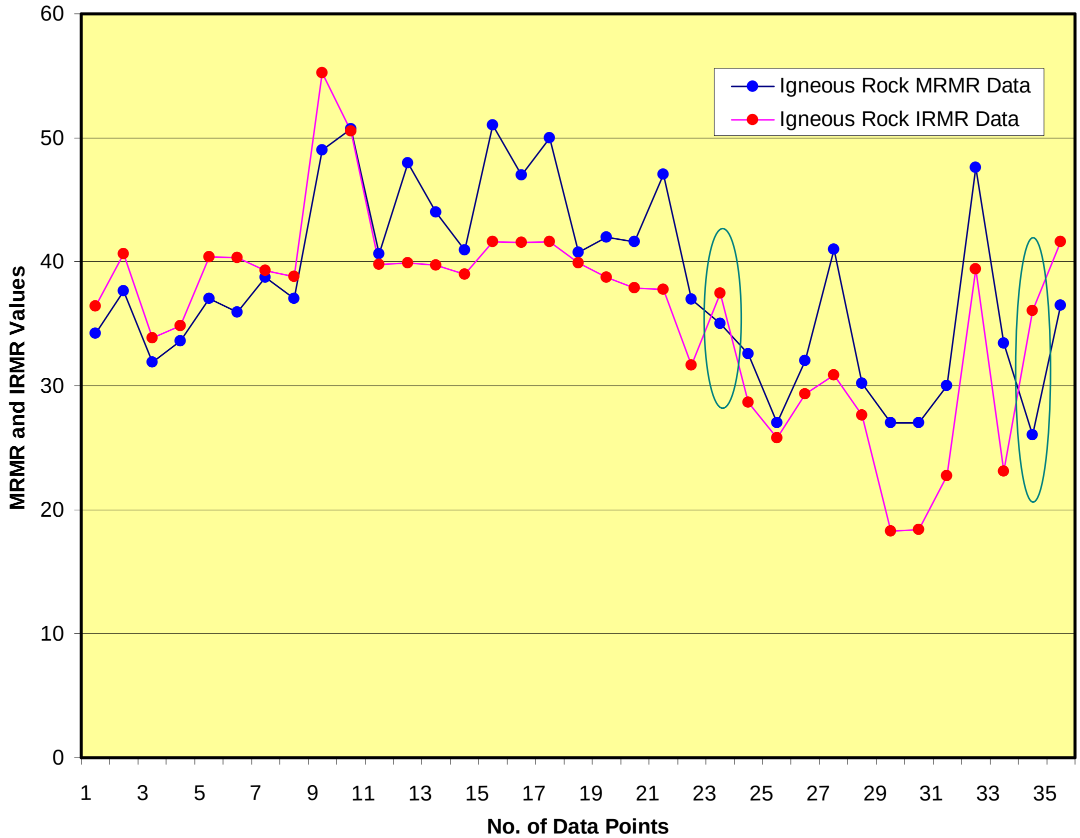

Figure 4.6: Line Graph Comparing Igneous Rock MRMR and IRMR Data

Figure 4.6 indicates that, while the trend of the individual igneous rock line graphs, for the two classification systems, approximate one another, it is not as close an approximation as for the sedimentary rock data. Initially, up to data point 9, the IRMR values are higher than the corresponding MRMR values. However, from data point 9 to data point 33, the resultant MRMR values are generally significantly higher than the corresponding IRMR values; this trend being reversed for data points 34 and 35 respectively. As was the case with respect to the sedimentary rock, localised differences, where the MRMR value increases and the corresponding IRMR decreases, and vice versa, do occur. Two such instances are noted, and indicated, where:

- In the first instance, there is a localised peak in the generally downward trend in IRMR values (data point 23), which is not reflected in the MRMR data.

- In the second instance, there is a localised peak in the generally downward trend in IRMR values (data point 34), which is not reflected in the MRMR data.

The irregularity of the trend in the resultant MRMR values, responsible for the localised differences in resultant MRMR and IRMR values, is well illustrated in Figure 4.6.

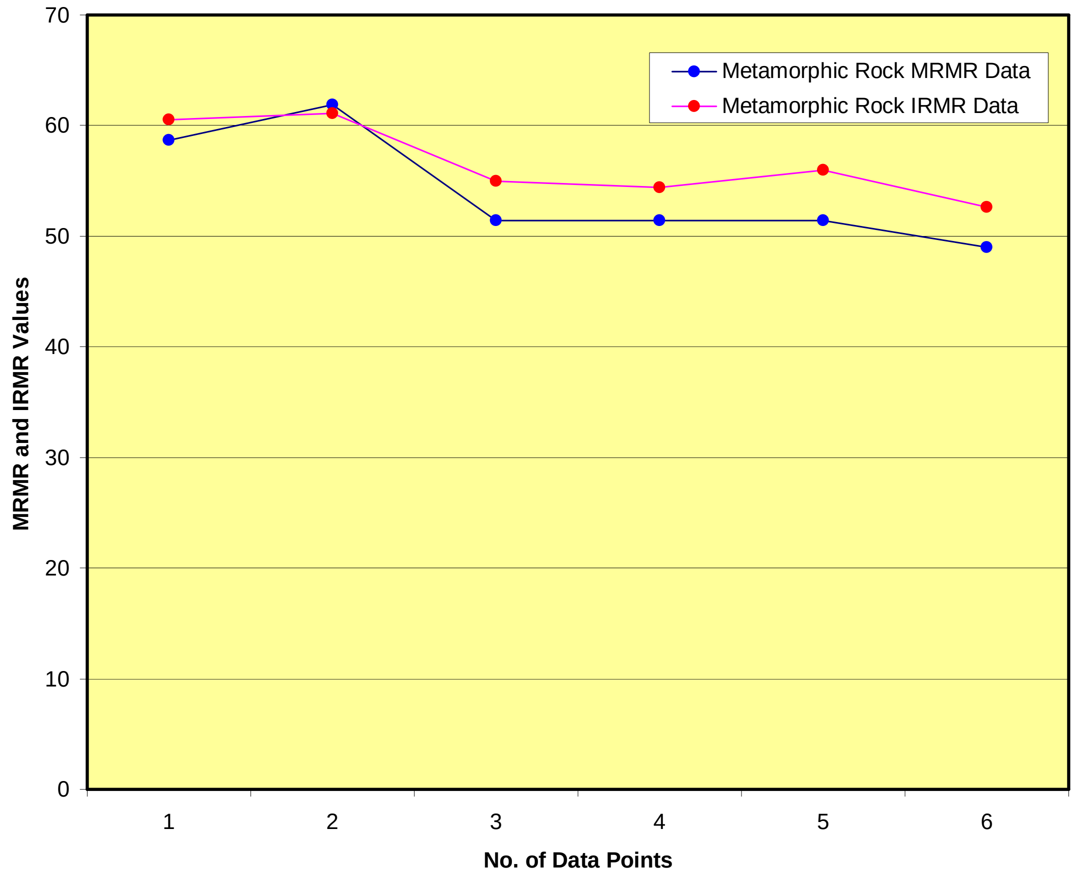

Figure 4.7: Line Graph Comparing Metamorphic Rock MRMR and IRMR Data

Figure 4.7 indicates that as with the sedimentary rock data, the individual sedimentary rock IRMR values are generally higher than the resultant MRMR values. This notwithstanding, for the most part, the trend of the resultant metamorphic rock MRMR and IRMR values closely approximate one another.

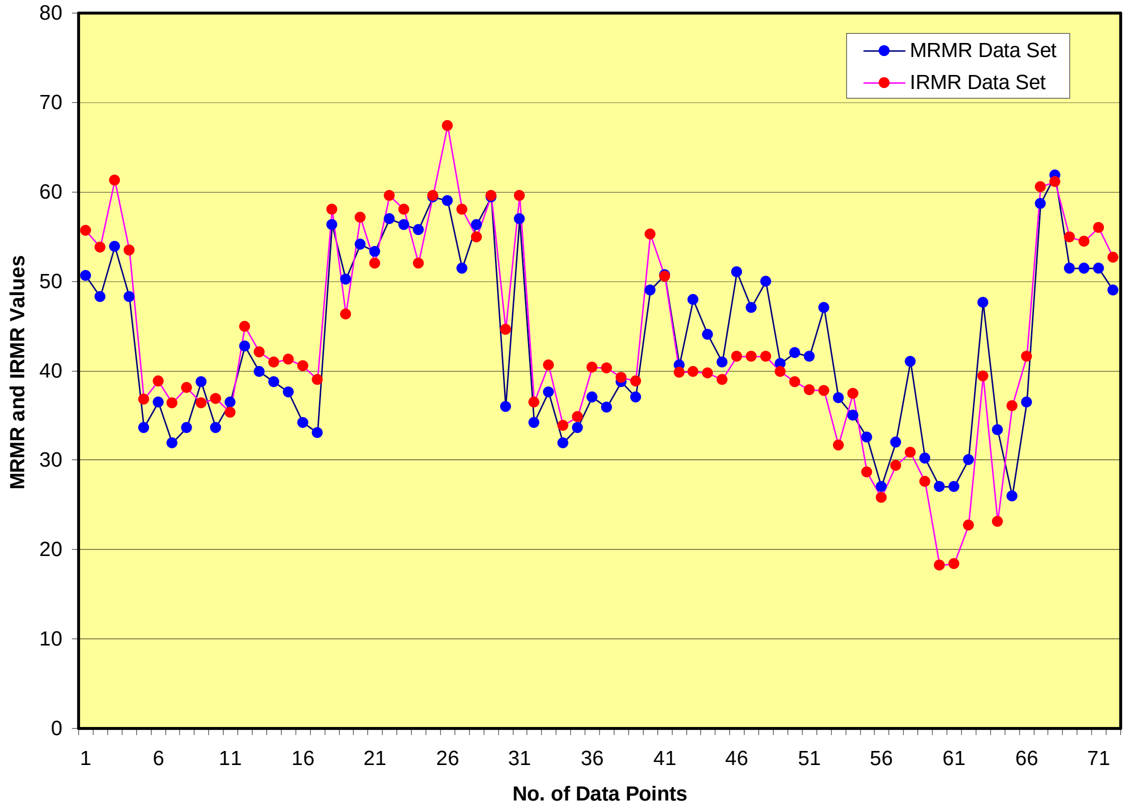

Figure 4.8: Line Graph Comparing the MRMR and IRMR Data Sets

A qualitative comparison of the entire MRMR and IRMR data sets indicates that, generally, the IRMR data set closely approximates the MRMR data set.

4.4 Statistical Analysis of the MRMR and IRMR Database

The MRMR and IRMR classification systems have been statistically evaluated under various geological settings, namely sedimentary, metamorphic and igneous, with respect to frequency distributions, measures of central tendency, measures of variability and measures of relationship respectively. The aim of this additional analysis was to obtain a MRMR / IRMR mathematical correlation, based on a larger data set, to facilitate the determination of equivalent MRMR or IRMR rock mass rating values. The statistical analysis data in terms of the sedimentary, igneous and metamorphic rock is presented as Appendices I, J and K respectively. The statistical analysis data pertaining to the combined MRMR and IRMR data sets is presented as Appendix L.

In applying statistics to the data sets, the raw data have been arranged into usable and understandable formats, namely distributions and graphs, in order to:

- Facilitate a preliminary interpretation of results.
- Facilitate additional statistical analysis.

- Facilitate a preliminary test of assumptions regarding the nature of the data upon which further statistical procedures are to be based (Mendenhall, 1993).

4.4.1 Sedimentary Rock

- Frequency Distribution

A frequency distribution is the assignment of scale values, or numbers, to observations. Frequency distributions may be classified into three types of distributions, namely:

- Listed Data

Listed data constitutes the simplest form of frequency distribution in which the range of scale, i.e. the difference between the highest and lowest value, is 20 or less and no scale value occurs more than once (Fallik and Brown, 1983).

- Ungrouped Frequency Distributions

Ungrouped frequency distributions are an extension of listed data, where the range of scale is 20 or less, but at least one scale value occurs more than once.

- Grouped Frequency Distributions

Grouped frequency distributions are an extension of ungrouped frequency distributions, where the range of scale values is greater than 20, but there is more than one case for some scale value (Fallik and Brown, 1983).

The frequency distribution graphs for sedimentary rocks, classified according to the MRMR and IRMR Classification Systems, are presented as Figures 4.9 and 4.10 respectively.

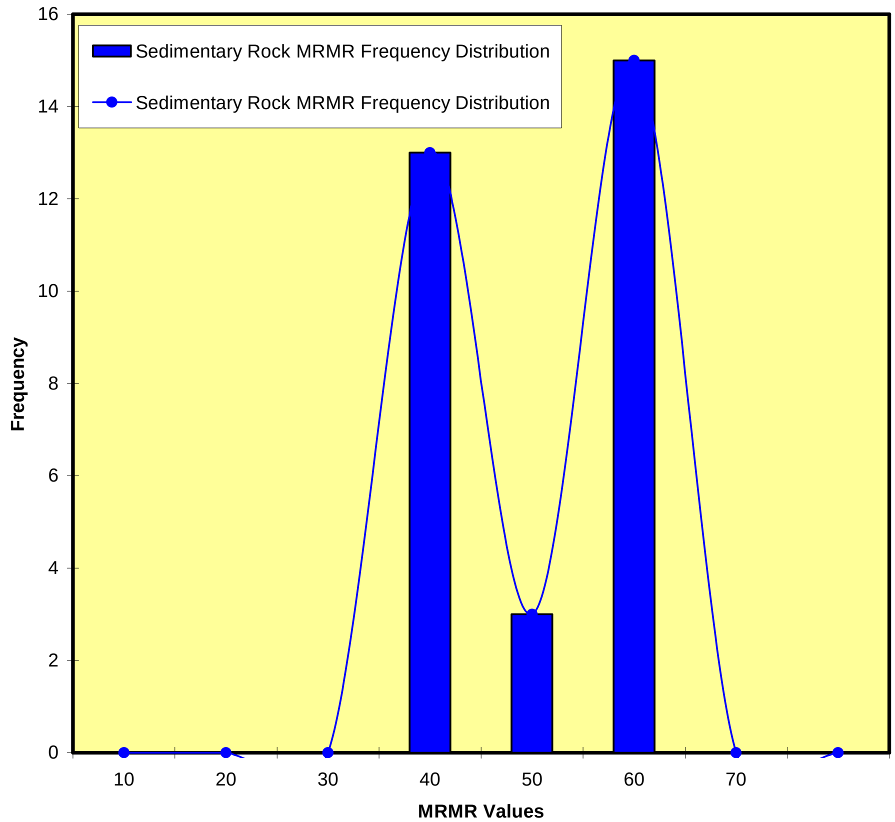

Figure 4.9: Sedimentary Rock MRMR Frequency Distribution

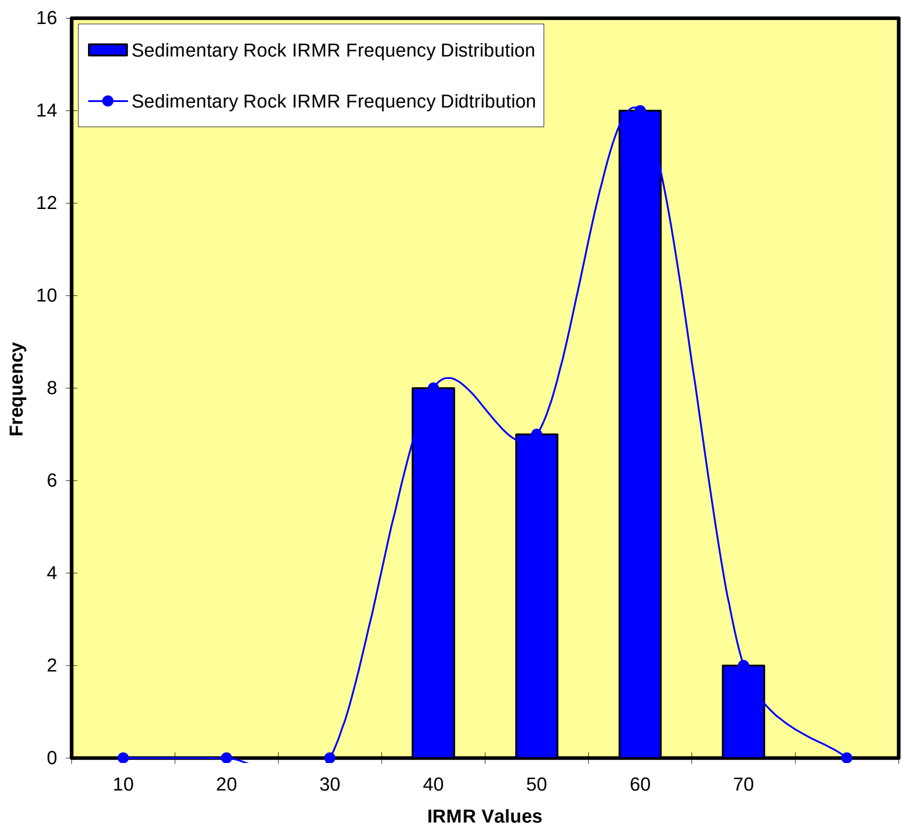

Figure 4.10: Sedimentary Rock IRMR Frequency Distribution

The MRMR and IRMR sedimentary rock data constitute a grouped frequency distribution, i.e. the range of scale exceeds 20, and there is more than a single case for some scale values. Frequency distributions may have a single peak (unimodal) or multiple peaks (bimodal etc.), referred to as the modality of the distribution, where the mode of a distribution refers to the scale value having the highest frequency, or number of cases. For sedimentary rock, both frequency distributions are bimodal with kurtosis values of -1.7 (MRMR) and -1.5 (IRMR) respectively. The bimodal frequency distribution may be attributed to the sedimentary rock mass rating values having two scale values that have the highest frequencies, namely 40 to 60. The kurtosis value refers to the degree of peaking of the frequency distribution, indicating the extent to which the frequencies are closely grouped or thinly spread throughout the scale values (Fallik and Brown, 1983).

- Measures of Central Tendency

  Measures of central tendency refer to the notion of averages (Fallik and Brown, 1983). Averages are used to represent the typical scale of values in a distribution. Three measures of central tendency include:

- The Mode

  The mode is that scale value which is represented by the greatest number of cases, i.e. has the highest frequency. The primary value of the mode is in identifying the most common scale value (Fallik and Brown, 1983).

- The Median

  The median is an example of a percentile point, i.e. a scale value below which a specified percentage of cases fall, and divides a distribution into two parts, with a certain percentage of cases falling below the percentile point and the rest falling above. The median does not, however, take into account how far above or below the percentile point the cases fall. Typically, the median falls halfway between the mean and mode of a frequency distribution (Fallik and Brown, 1983).

- The Arithmetic Mean

  The arithmetic mean is the most frequently used measure of central tendency, and for listed data, equates to the sum of the scale values divided by the number of values. In computing the arithmetic mean for ungrouped or grouped data, each scale value (X_i) is multiplied by its associate frequency (f_i). The products ($X_i f_i$) are added together, and the result divided by the number of cases (N) (Fallik and Brown, 1983). The mean value should not be used when analysing highly skewed distributions, or when the data set contains outliers. In these instances, use should be made of the median value.

  A summary of the measures of central tendency is presented as Table 4.9.

Table 4.9: MRMR and IRMR Sedimentary Rock Measures of Central Tendency

Measures of Central Tendency	MRMR Values	IRMR Values
Mode	33.6	59.5
Median	48.0	53.0
Mean	45.9	50.3
95% Confidence Interval	2.6	3.1

From Table 4.9 it is noted that in terms of the MRMR data the mean < median > mode, which indicates a tendency towards a negatively skewed frequency distribution, i.e. a preponderance of high MRMR values and isolated low values (Fallik and Brown, 1983). In terms of the IRMR data, the mean < median < mode, which is indicative of a negatively skewed frequency distribution, i.e. a preponderance of high MRMR values and isolated low values (Fallik and Brown, 1983). The skew of a distribution represents the extent to which it departs from symmetry throughout the range of scales. The tails of a distribution are important as they represent the low and high ends of the scale value distribution (Fallik and Brown, 1983). Computation of the sedimentary rock skewness gives values of -0.11 (MRMR) and 0.03 (IRMR) respectively, indicating that the MRMR values are more skewed than the IRMR values.

- Measures of Variability

While useful, averages only address one aspect of the total distribution of scale values. While distributions may have the same average, they may differ from each other in other ways. The variability of a distribution is the extent to which scale values differ from each other, i.e. the spread along the total distribution of possible scale values (Fallik and Brown, 1983). The degree of variability exhibited by a distribution is independent of the mean of that distribution. Measures of variability include:

- The Range

Range equates to the highest numbered category minus the lowest numbered category, and is the simplest, and potentially, the most misleading of all measures of variability (Fallik and Brown, 1983). The greater the range value, the more variable the distribution. It is to be noted that two distributions may have the same range, even though their distributions differ significantly. This is due to the range being a function of only the highest and lowest values in a distribution; all intermediate values and their frequency differences being ignored. Generally, an inaccurate index of variability is obtained using the range when the distribution is highly skewed, or contains a value that is significantly higher or lower the other distribution values.

- Variance and Standard Deviation

The variance and standard deviation provide an index number summarising all the scale values in a distribution (Fallik and Brown, 1983). The average deviation is obtained by computing the mean value of the distribution which is then subtracted from the raw scale value. By adding the squared deviations, the sum of squares is obtained, which when divided by the sum of the number of cases, gives the variance. The standard deviation is the square root of the variance. Commonly, the variance and standard deviation are used to provide an indication of how well, or poorly, measures of central tendency represent the distribution of scale values. Generally, the greater the variability, the less representative the measure of central tendency. Standard deviations may be compared through conversion of the standard deviations into coefficients of variation.

A summary of the sedimentary rock measures of variability is presented as Table 4.10.

Table 4.10: MRMR and IRMR Sedimentary Rock Measures of Variability

Measures of Variability	MRMR Values	IRMR Values
Range	27.0	32.0
Variance	98.2	89.0
Standard Deviation	9.9	9.4

From Table 4.10 it is noted that the MRMR values have a lower range, but a higher variance and standard deviation than the IRMR values, i.e. the sedimentary rock MRMR values are more variable than the sedimentary rock IRMR values.

- Measures of Relationship

Although a comparison of measures of central tendency and variability gives an indication of the degree of similarity between the overall qualities of each distribution, no indication is given of the variability between individual scale values within each distribution. This is achieved through use of a scatter plot, to obtain a visual representation of the relationship between individual ranks for both distributions. The closer the points on the scatter plot approximate a straight line, the greater he relationship between the distributions. A regression line is a line connecting points from a distribution, used to predict one set of values from another set of values, described mathematically by the equation:

$$Yi = bX_i + a \qquad (9)$$

Where:
b = the slope of the regression line
a = the intercept of the line
X_i = unit change in X

In order to obtain an indication of the degree of similarity between the individual ranks of the sedimentary rock MRMR and IRMR distributions, a scatter plot of the MRMR and IRMR values was constructed, and is presented as Figure 4.11. It is to be noted that, in constructing Figure 4.11, the MRMR values constitute the independent variables (x-axis), while the IRMR values constitute the dependant variables (y-axis). To ascertain the relative dispersion between the two data sets, the covariance and correlation coefficient (ρ) were calculated. The covariance and correlation coefficient for the MRMR and IRMR sedimentary rock data sets are presented in Table 4.11.

Table 4.11: MRMR and IRMR Sedimentary Rock Covariance and Correlation Coefficient Values

Measures of Relationship	Values
Covariance	86.62
Correlation Coefficient	0.97

The correlation coefficient indicates a very good correlation between the MRMR and IRMR sedimentary rock data sets.

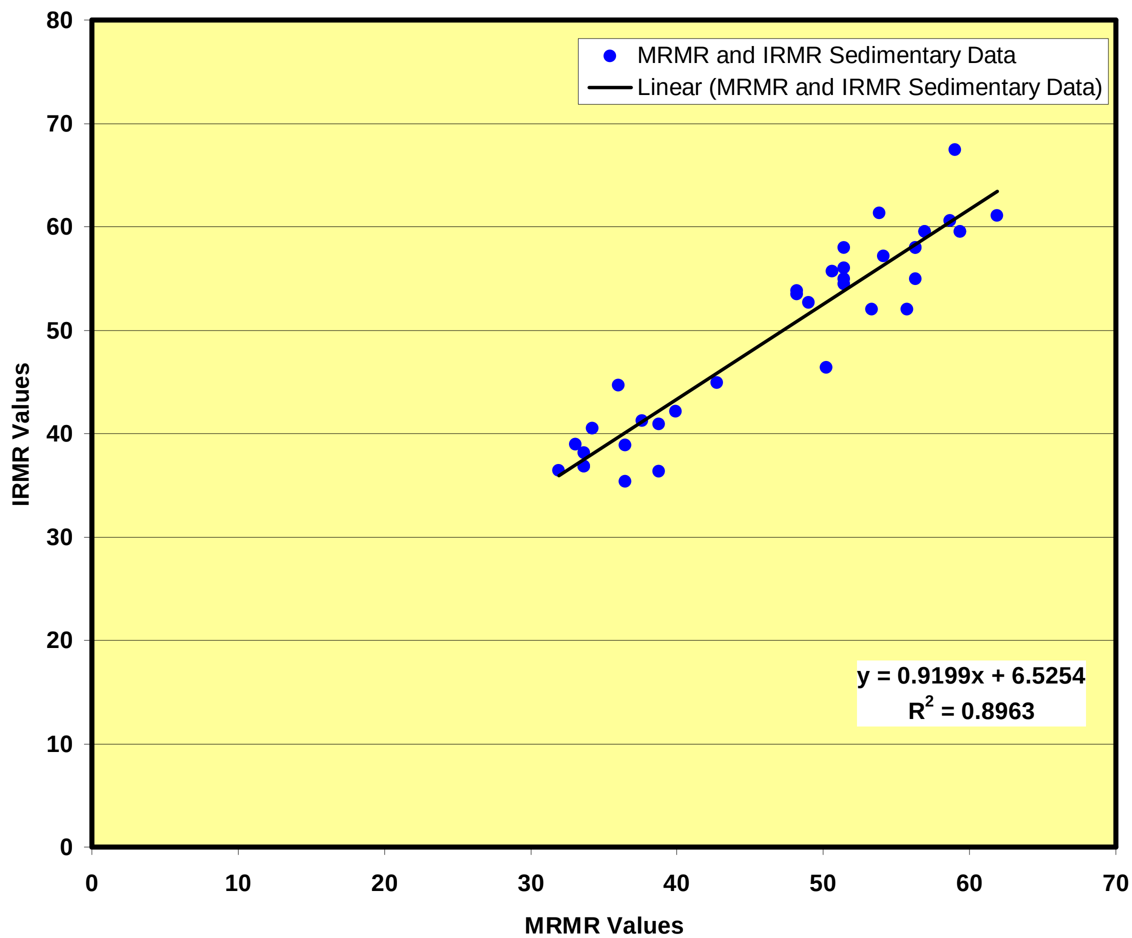

Figure 4.11: Scatter Graph of Sedimentary Rock MRMR and IRMR Values

In interpreting Figure 4.11, it is noted that a direct linear relationship exists between the MRMR and IRMR data sets. The R^2 value for the linear trend line indicates an imperfect, yet significant, correlation between the MRMR and IRMR data sets.

- Derivation of Equivalent Rock Mass Rating Values

Regression analysis indicates that equivalent IRMR sedimentary rock values may be predicted from MRMR sedimentary rock values with a high degree of confidence, by applying the following regression equation:

$$IRMR = 0.9199MRMR + 6.5254 \quad (10)$$

4.4.2 Igneous Rock

- Frequency Distribution

The frequency distribution graphs for igneous rocks classified according to the MRMR and IRMR Classification Systems are presented as Figures 4.12 and 4.13 respectively.

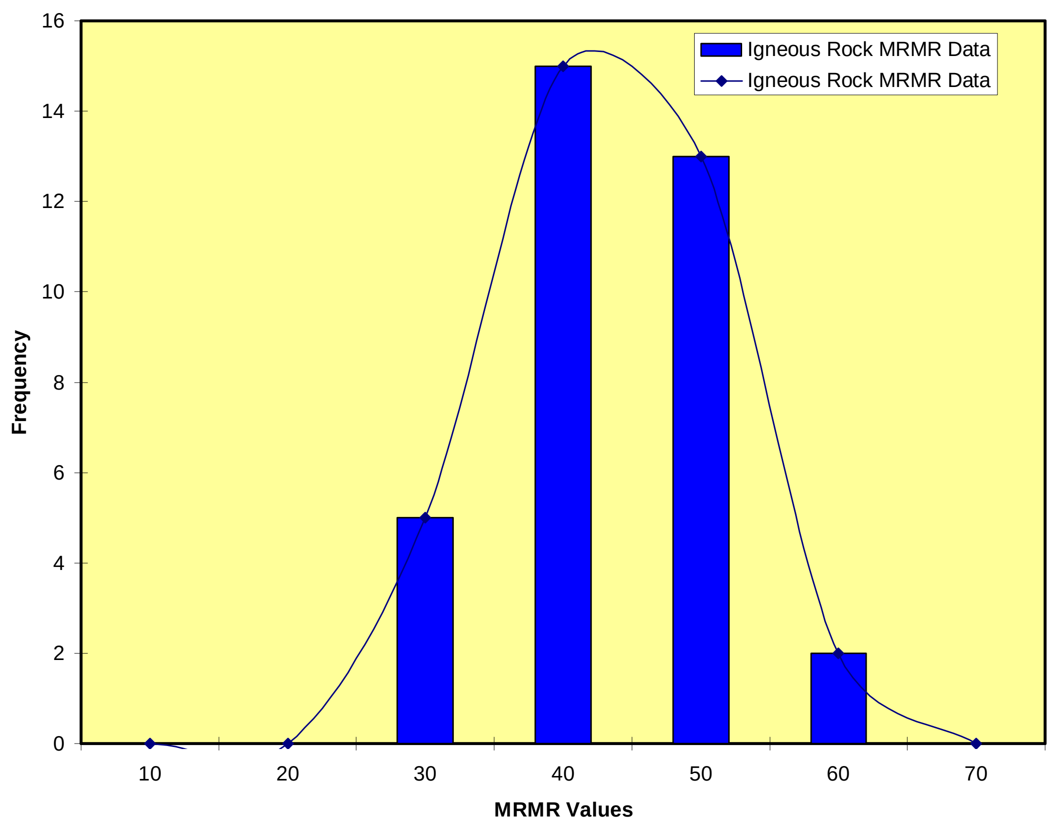

Figure 4.12: Igneous Rock MRMR Frequency Distribution

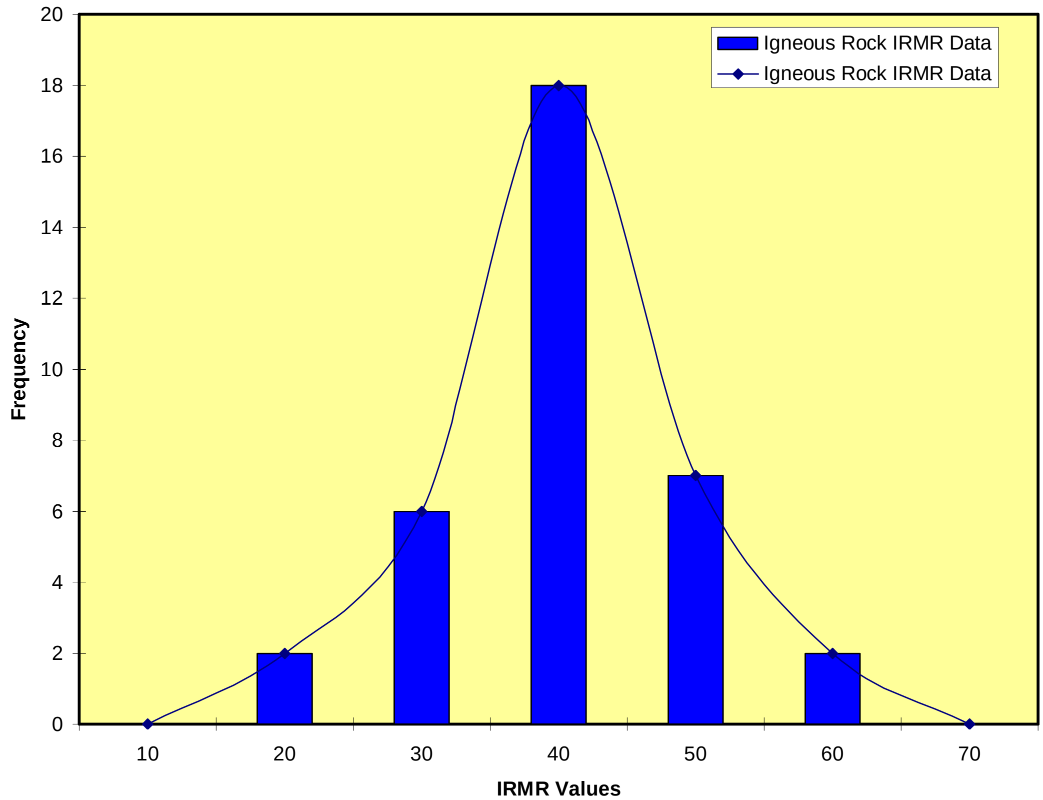

Figure 4.13: Igneous Rock IRMR Frequency Distribution

The MRMR igneous rock data constitutes a grouped frequency distribution, i.e. the range of scale exceeds 20, and there is more than a single case for some scale values. The range of scale for the IRMR igneous rock data exceeds 20, but as no single value occurs more than once, the IRMR data tends towards listed data. Both frequency distributions are unimodal and have kurtosis values of -0.9 (MRMR) and 0.7 (IRMR) respectively.

- Measures of Central Tendency

A summary of the measures of central tendency is presented as Table 4.12.

Table 4.12: MRMR and IRMR Igneous Rock Measures of Central Tendency

Measures of Central Tendency	MRMR Values	IRMR Values
Mode	27.0	-
Median	37.0	39.0
Mean	38.4	36.1
95% Confidence Interval	2.6	2.8

From Table 4.12 it is noted that, for the MRMR igneous rock data, the mean > median > mode, which is indicative of a positively skewed frequency distribution, i.e. a preponderance of low MRMR values and isolated higher values (Fallik and Brown, 1983). With respect to the IRMR igneous rock data, the mean < median which is indicative of a negatively skewed frequency distribution, i.e. a preponderance of high IRMR values and isolated low IRMR values (Fallik and Brown, 1983). Computation of the skewness results in values of 0.13 (MRMR) and -0.39 (IRMR) respectively, indicating that the degree of skewness of the igneous rock data is higher than that for the sedimentary rock data.

- Measures of Variability

A summary of the measures of variability are presented as Table 4.13.

Table 4.13: MRMR and IRMR Igneous Rock Measures of Variability

Measures of Variability	MRMR Values	IRMR Values
Range	24.0	37.0
Variance	55.1	64.7
Standard Deviation	7.4	8.0

From Table 4.13 it is noted that the MRMR Classification System has a lower range, variance and standard deviation than the IRMR Classification system, i.e. the igneous rock IRMR values are more variable than the igneous rock MRMR values.

- Measures of Relationship

In order to obtain an indication of the degree of similarity between the individual ranks of the igneous rock MRMR and IRMR distributions, a scatter plot of the MRMR and IRMR values has been constructed, and is presented as Figure 4.14. It is to be noted that, in constructing Figure 4.14, the MRMR values constitute the independent variables (x-axis), while the IRMR values constitute the dependant variables (y-axis).

In order to ascertain the relative dispersion between the two data sets, the covariance and correlation coefficient (ρ) were calculated. The covariance and correlation coefficient for the MRMR and IRMR igneous rock data sets are presented as Table 4.14.

Table 4.14: MRMR and IRMR Igneous Rock Covariance and Correlation Coefficient Values

Measures of Relationship	Values
Covariance	43.8
Correlation Coefficient	0.73

The correlation coefficient indicates a moderate to good correlation between the MRMR and IRMR igneous rock data sets.

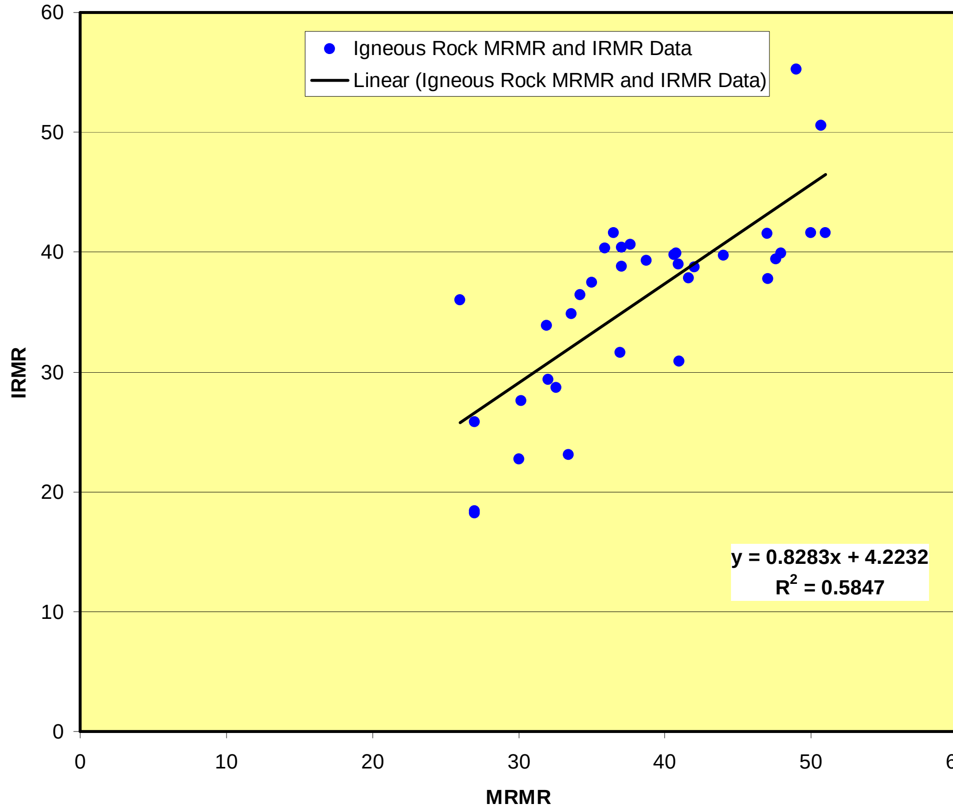

Figure 4.14: Scatter Graph of Igneous Rock MRMR and IRMR Values

In interpreting Figure 4.14, the following is noted:

- A direct linear relationship, albeit with a relatively wide scatter, exists between the MRMR and IRMR data sets.
- The R^2 value for the linear trend line indicates an imperfect, moderate correlation between the MRMR and IRMR data sets.
- Derivation of Equivalent Rock Mass Rating Values.

Regression analysis indicates that equivalent IRMR sedimentary rock values may be derived from MRMR sedimentary rock values with moderate degree of confidence, by applying the following regression equation:

$$IRMR = 0.8283MRMR + 4.2232 \quad (11)$$

4.4.3 Metamorphic Rock

- Frequency Distribution

The frequency distribution graphs for igneous rocks classified according to the MRMR and IRMR Classification Systems are presented as Figures 4.15 and 4.16 respectively.

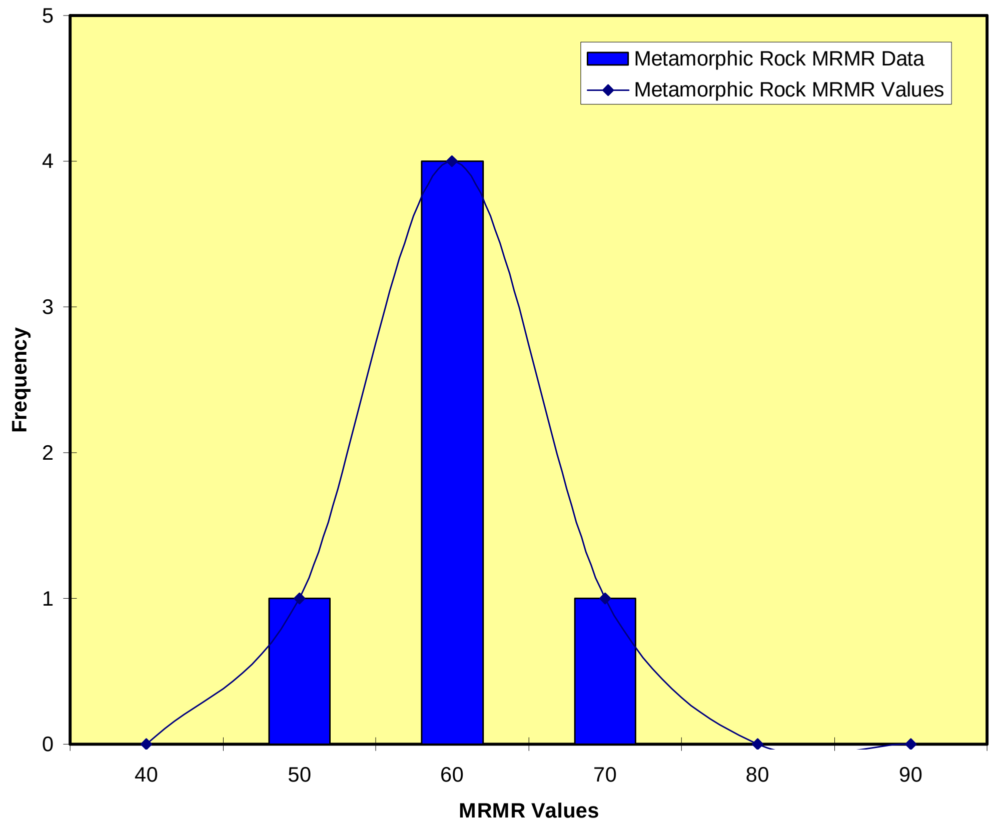

Figure 4.15: Frequency Distribution of Metamorphic Rock MRMR Values

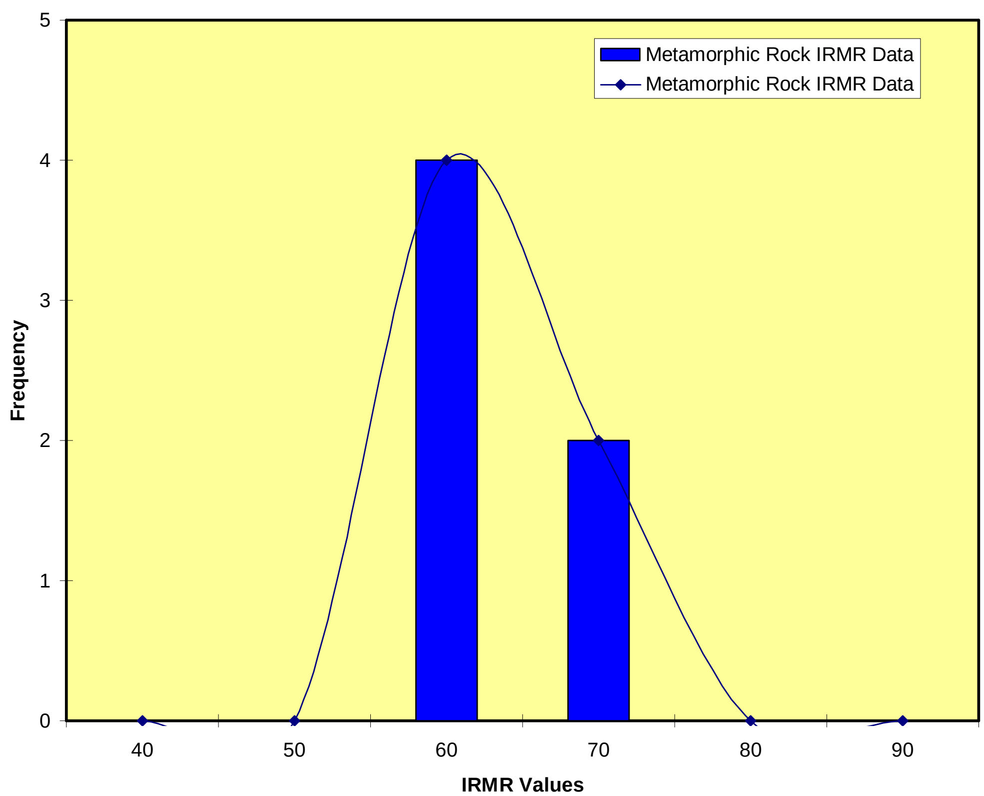

Figure 4.16: Metamorphic Rock IRMR Frequency Distribution

The MRMR metamorphic rock data constitutes an ungrouped frequency distribution. The range of scale is 20 or less, and a minimum of one value occurs more than once. The IRMR metamorphic rock data, however, constitutes listed data; the range of scale is less than 20, but no single value occurs more than once. Both frequency distributions are unimodal, with kurtosis values of -0.83 (MRMR) and -1.64 (IRMR) respectively.

- Measures of Central Tendency

A summary of the measures of central tendency is presented as Table 4.15.

Table 4.15: MRMR and IRMR Metamorphic Rock Measures of Central Tendency

Measures of Central Tendency	MRMR Values	IRMR Values
Mode	51.4	-
Median	51.0	55.5
Mean	54.0	56.7
95% Confidence Interval	5.6	3.7

In terms of the metamorphic rock MRMR data, the mean > median < mode indicating a tendency towards a positively skewed frequency distribution and a preponderance towards low MRMR values with isolated higher values (Fallik and Brown, 1983). Similarly, the IRMR data also shows a tendency towards a positively skewed frequency distribution, i.e. the mean > median. Skewness values of 0.98 (MRMR) and 0.54 (IRMR) indicate that the MRMR values are more skewed than the IRMR values. Furthermore, the degree of metamorphic rock data skewness is higher than for both the sedimentary and igneous rock data respectively.

- Measures of Variability

A summary of the measures of variability is presented as Table 4.16.

Table 4.16: MRMR and IRMR Metamorphic Rock Measures of Variability

Measures of Variability	MRMR Values	IRMR Values
Range	13.0	8.0
Variance	28.2	12.3
Standard Deviation	5.3	3.5

From Table 4.16 it is noted that the MRMR Classification System has a higher range, variance and standard deviation than the IRMR Classification system, i.e. the metamorphic rock MRMR values are more variable than the metamorphic rock IRMR values.

- Measures of Relationship

In order to obtain an indication of the degree of similarity between the individual ranks of the igneous rock MRMR and IRMR distributions, a scatter plot of the MRMR and IRMR values has been constructed, and is presented as Figure 4.17. It is to be noted that, in constructing Figure 4.17, the MRMR values constitute the independent variables (x-axis), while the IRMR values constitute the dependant variables (y-axis).

In order to ascertain the relative dispersion between the two data sets, the covariance and correlation coefficient (p) were calculated. The covariance and correlation coefficient for the MRMR and IRMR igneous rock data sets are presented in Table 4.17.

Table 4.17: MRMR and IRMR Metamorphic Rock Covariance and Correlation Coefficient Values

Measures of Relationship	Values
Covariance	14.12
Correlation Coefficient	0.76

The correlation coefficient indicates a moderate to good correlation between the MRMR and IRMR metamorphic rock data sets.

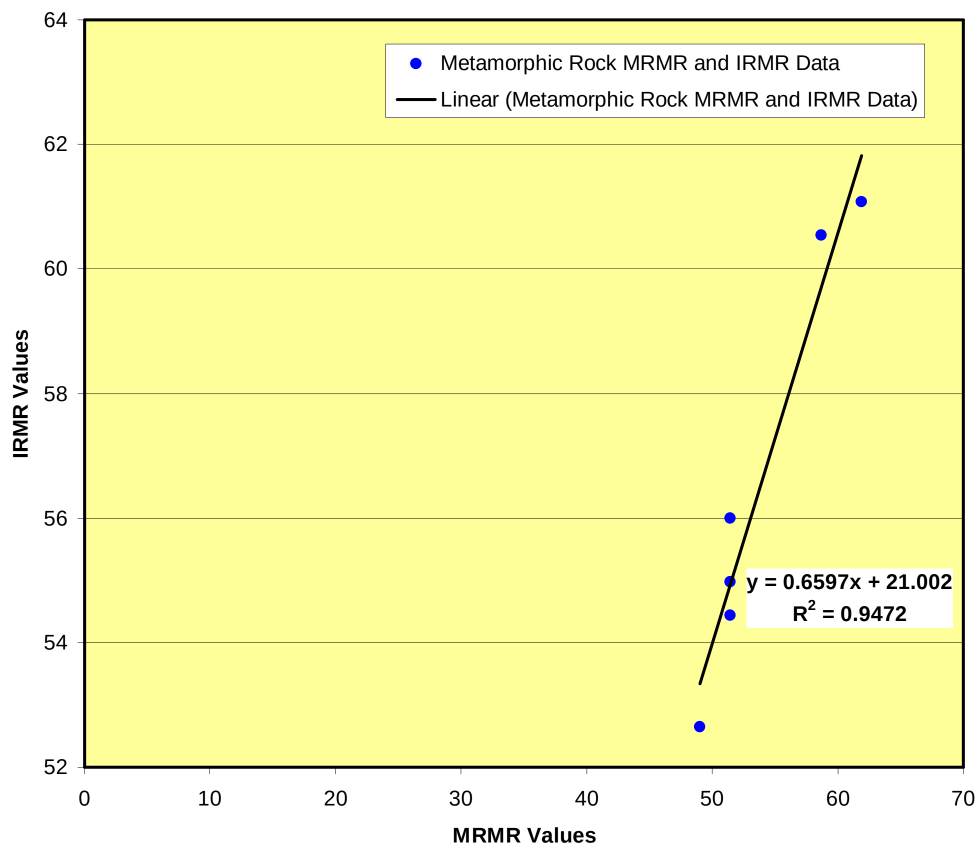

Figure 4.17: Scatter Graph of Metamorphic Rock MRMR and IRMR Values

In interpreting Figure 4.17, the following is noted:

- A direct linear relationship exists between the MRMR and IRMR data sets.
- The R^2 value for the linear trend line indicates. An imperfect, yet good, correlation between the MRMR and IRMR data sets.

- Derivation of Equivalent Rock Mass Rating Values

Regression analysis indicates that equivalent IRMR sedimentary rock values may be predicted from MRMR sedimentary rock values with a high degree of confidence, by applying the following regression equation:

$$IRMR = 0.6597MRMR + 21.002 \qquad (12)$$

4.4.4 Statistical Analysis of Combined Rock Mass Rating Data Sets

- Frequency Distribution

The frequency distribution graph for the combined data set classified according to the MRMR and IRMR Classification Systems are presented as Figures 4.18 and 4.19 respectively.

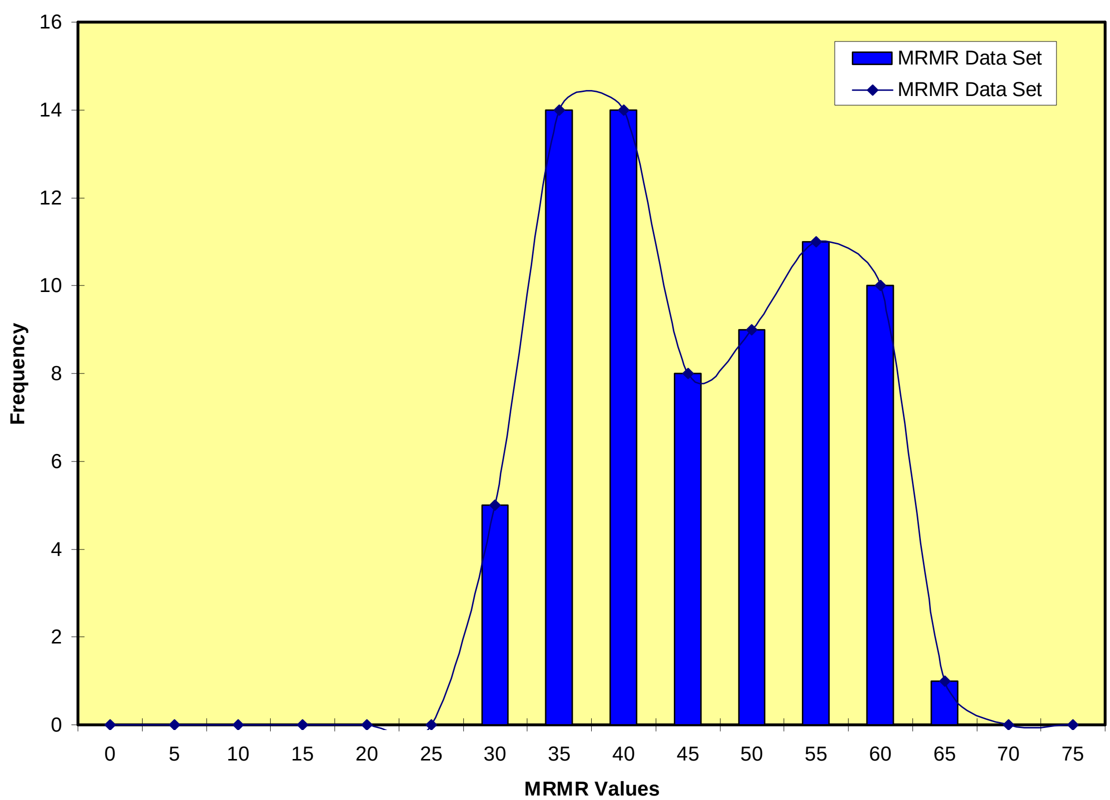

Figure 4.18: MRMR Data Set Frequency Distribution

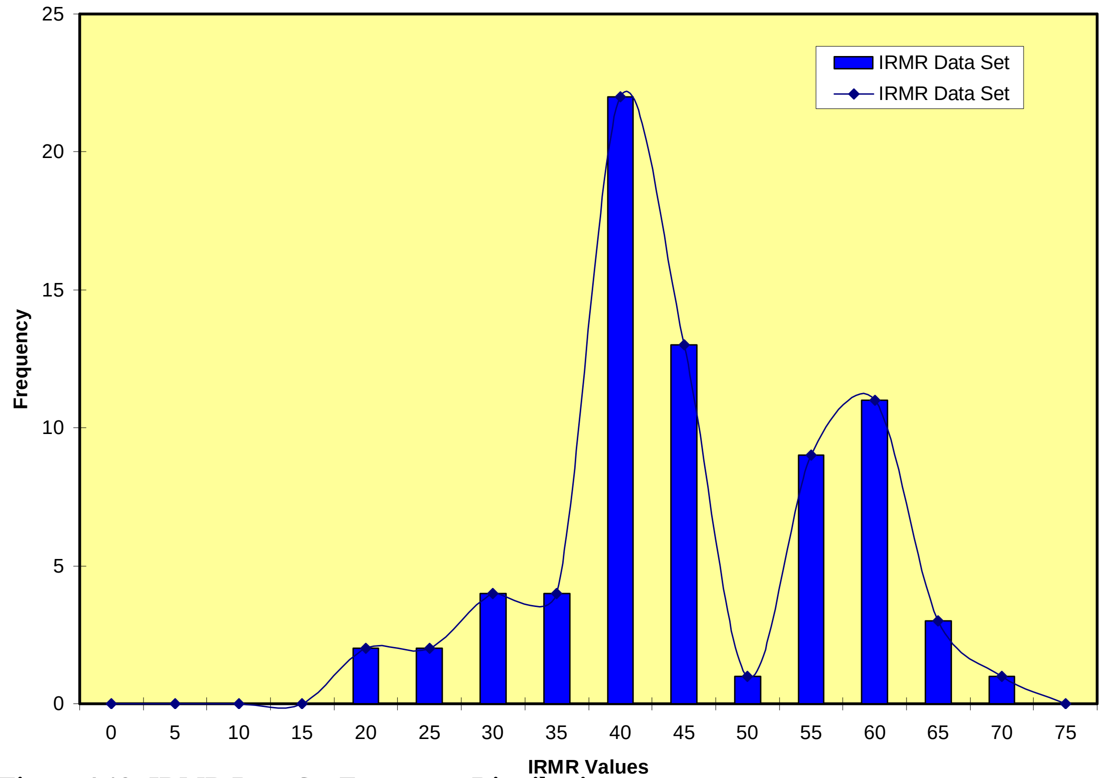

Figure 4.19: IRMR Data Set Frequency Distribution

Both the MRMR and IRMR data sets represent a grouped frequency distribution, in that the range of scale exceeds 20, there is more than a single case for some scale values. Furthermore, both frequency distributions are bimodal, and have kurtosis values of -1.2 (MRMR) and -0.5 (IRMR) respectively.

- Measures of Central Tendency

A summary of the measures of central tendency is presented as Table 4.18.

Table 4.18: MRMR and IRMR Data Sets Measures of Central Tendency

Measures of Central Tendency	MRMR Values	IRMR Values
Mode	33.6	59.5
Median	41.0	40.0
Mean	43.0	43.3
95% Confidence Interval	2.3	2.6

From Table 4.18 it is noted that, for both the MRMR and IRMR data set the mean > median > mode, indicating a positively skewed frequency distribution. This indicates a preponderance of cases at low scale values, with isolated higher scale values (Fallik and Brown, 1983). Skewness values of 0.16 (MRMR) and 0.03 (IRMR) respectively, indicate that the MRMR values are more skewed than the IRMR values.

- Measures of Variability

A summary of the measures of variability are presented as Table 4.19.

Table 4.19: MRMR and IRMR Data Set Measures of Variability

Measures of Variability	MRMR Values	IRMR Values
Range	36.0	49.0
Variance	93.4	127.1
Standard Deviation	9.7	11.3

From Table 4.19 it is noted that the IRMR Classification System has a higher range, variance and standard deviation than the MRMR Classification system, i.e. the IRMR values are more variable than the MRMR values.

- Measures of Relationship

In order to obtain an indication of the degree of similarity between the individual ranks of the combined MRMR and IRMR distributions, a scatter plot of the MRMR and IRMR values was constructed, and is presented as Figure 4.20. It is to be noted that, in constructing Figure 4.20, the MRMR values constitute the independent variables (x-axis), while the IRMR values constitute the dependant variables (y-axis).

In order to ascertain the relative dispersion between the two data sets, the covariance and correlation coefficient (p) was calculated. The covariance and correlation coefficient for the MRMR and IRMR sedimentary rock data sets are presented as Table 4.20.

Table 4.20: MRMR and IRMR Sedimentary Rock Covariance and Correlation Coefficient Values

Measures of Relationship	Values
Covariance	96.6
Correlation Coefficient	0.90

The correlation coefficient indicates a good correlation between the combined MRMR and IRMR data sets.

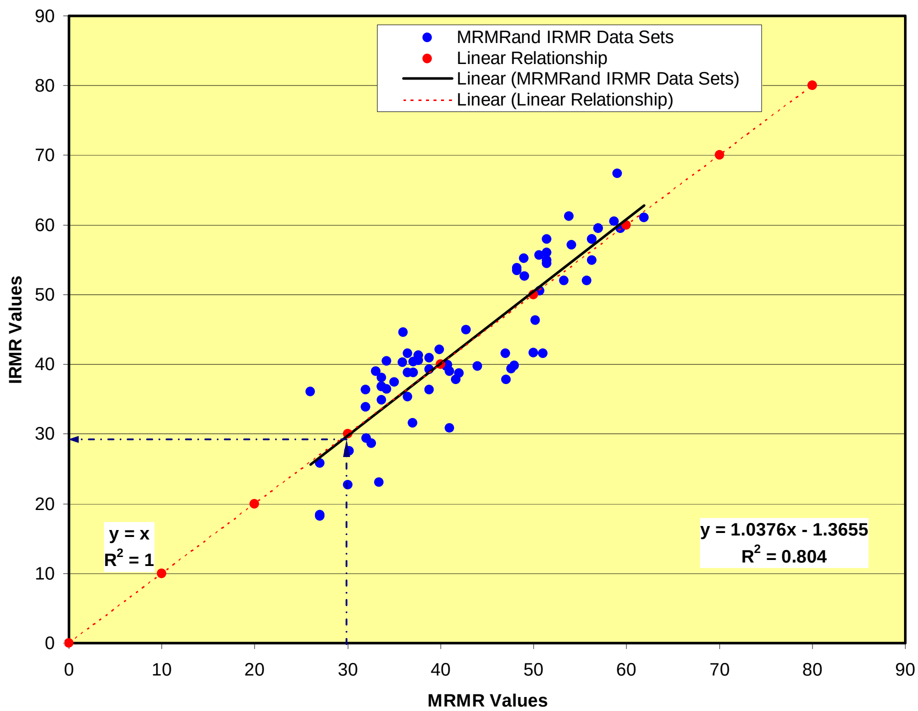

Figure 4.20: Scatter Graph of MRMR and IRMR Data Sets

In interpreting Figure 4.20, the following is noted:

- A linear, yet imperfect, relationship exists between the combined MRMR and IRMR data sets.
- The R^2 value for the linear trend line indicates an imperfect, yet good, correlation between the combined MRMR and IRMR data sets.
- Comparison of the MRMR and IRMR data set correlation with an assumed linear relationship, where $R^2 = 1$, indicates an error of ± 0.24.

- Derivation of Equivalent Rock Mass Rating Values

Regression analysis indicates that equivalent IRMR values may be predicted from MRMR values with an acceptable degree of confidence, by applying the following general regression equation:

$$IRMR = 1.0376MRMR - 1.3655 \tag{13}$$

5 CONCLUSIONS

5.1 Parametric Analysis

5.1.1 The MRMR Parametric Analysis

The results of the parametric database analyses indicate that the base-line MRMR value (61.8) is lower than the corresponding base-line IRMR value (66.4). In terms of the effect of increasing and decreasing individual parameter and adjustment values, decreasing individual MRMR parameter ratings has a greater effect on the resultant MRMR values than increasing the individual parameter ratings. With respect to the effect of specific individual parameters, the micro-joint condition parameter has the greatest individual effect on the resultant MRMR values. Apart from the micro-joint condition parameter, other parameters that significantly effect the resultant MRMR value include decreasing the IRS, infill and wall alteration parameters by 16% and the IRS, J1 joint spacing by 50% respectively.

The stress adjustment parameter is sensitive to both increases and decreases of 16% and 50% respectively, significantly impacting on the resultant MRMR value. Furthermore, the stress adjustment parameter has the most significant effect of all mining adjustments on the resultant MRMR value.

The effect of introducing moisture on the resultant MRMR value is not as great as the effect of decreasing joint condition parameters and mining adjustments respectively.

5.1.2 The IRMR Parametric Analysis

The results of the parametric database analyses indicate that the base-line IRMR value (66.4) is higher than the corresponding value MRMR (61.8).). In terms of the effect of increasing and decreasing individual parameter and adjustment values, decreasing individual IRMR parameter rating values does not generally have a more significant effect on the resultant IRMR value than increasing the individual parameter ratings. The exception is a 16% decrease in the gouge rating value for single / multiple joints, which does significantly affect the resultant IRMR value. With respect to the effect of specific individual parameters, increasing the joint condition parameters has the greatest individual effect on the resultant MRMR values, while decreasing the micro- and macro-joint parameter condition parameter rating value by 50% also significantly affects the resultant IRMR value.

The mining adjustment parameters are sensitive to both increases and decreases and significantly impact on the resultant IRMR values. With respect to the water / ice adjustment, the resultant IRMR value is only significantly affected if the adjustment value is reduced by 50%.

5.2 Quantitative Analysis

5.2.1 Frequency Distribution

The frequency distribution analysis results indicate that the sedimentary rock MRMR and IRMR data sets have bimodal frequency distributions, while the igneous and metamorphic rock MRMR and IRMR data sets have unimodal frequency distributions. When combined, both the MRMR and IRMR data sets have a bimodal frequency distribution.

In terms of the degree of skewness, the metamorphic rock data is more skewed than either the sedimentary or igneous rock data respectively.

5.2.2 Measures of Central Tendency

The central tendency analysis results show that the mean sedimentary and metamorphic rock IRMR values are greater than the mean MRMR values, and that the mean igneous rock MRMR value is greater than the mean IRMR value. The mean combined data set MRMR value is slightly lower (43.2) than the mean IRMR value (43.5).

5.2.3 Measures of Variability

From the results of the measures of variability analyses, the following may be concluded:

- Range

  The range of the igneous rock IRMR value is 13 points higher than the MRMR range value while the metamorphic rock IRMR range value is 5 points lower than the corresponding MRMR range value. However, the sedimentary rock MRMR and IRMR range values differ by only two points; the IRMR value being higher than the MRMR value. The combined MRMR data set range is 13 points lower than the IRMR data set range.

- Variance

  The sedimentary rock MRMR and IRMR values have the highest variance values, and the lowest difference between the two sets of values. The metamorphic rock MRMR and IRMR values have the lowest variance values, and the highest difference between the two sets of values. When combined, the IRMR data set has a 33.7 point higher variance than the combined MRMR data set.

- Standard Deviation

  The sedimentary rock MRMR and IRMR values have the highest standard deviation, and the least difference (0.1 point) between the two data sets. The metamorphic rock MRMR and IRMR values have the lowest standard deviation values, and the highest difference (1.8 points) between the two data sets. The combined MRMR data set standard deviation is 1.6 points lower than the combined IRMR data set.

5.2.4 Measures of Relationship

The measures of relationship analyses indicate that there is a linear, yet imperfect, relationship between the MRMR and IRMR sedimentary and igneous rock data sets and a direct linear relationship between the metamorphic rock MRMR and IRMR data sets. In terms of the combined data sets, there is a linear, yet imperfect, relationship between the combined MRMR and IRMR data sets.

The correlation coefficient values indicate that the best correlation exists between the sedimentary rock (Correlation coefficient = 0.97) followed by metamorphic rock (Correlation coefficient = 0.76) and igneous rock (Correlation coefficient = 0.73) respectively. The combined MRMR and IRMR data bases have a correlation coefficient of 0.90.

The sedimentary, igneous, metamorphic rock and combined rock scatter plots indicate that there is a direct linear relationship between the MRMR and IRMR data bases.

5.2.5 Derivation of Equivalent Rock Mass Rating Values

The statistical analyses indicate that an almost linear relationship exists between the MRMR and IRMR data bases. Consequently, equivalent IRMR values can be derived from a MRMR data base with a high degree of confidence, in terms of sedimentary, metamorphic or igneous rock respectively, or through the application of the general equation:

$$IRMR = 1.0376MRMR - 1.3655$$

Derivation of equivalent IRMR values from MRMR values, using the above general equation, would result in the equivalent IRMR values having an error of ± 0.24.

5.2.6 Applicability of the MRMR and IRMR Systems

The results of the research report show that there is not a major difference between the resultant rock mass rating values derived from the MRMR and IRMR Classification Systems. This implies that, although the IRMR System constitutes an up-dated MRMR System that is more applicable to a jointed rock mass, the MRMR System itself has not been made redundant and still has a role to play as a mine design tool.

It is envisaged that the MRMR System will remain in common usage, with the IRMR System being applied in those situations where a more robust classification system is required to adequately quantify the quality of an intensely jointed rock mass that is characterised by a significant number of discontinuities, veins and cemented joints.

6 RECOMMENDATIONS

It is the recommendation of the author that use of the MRMR Classification System is not discontinued in favour of the IRMR Classification System; rather, the IRMR Classification System should be regarded as a supplementary classification system that can be applied to the classification of intensely jointed rock masses, where the use of a more robust classification system is warranted.

Furthermore, it is recommended that the author continually updates the geotechnical data base presented in this research report to facilitate the expansion of the current data base, which in turn, will facilitate additional statistical analyses and the possible amelioration of the correlation derived between the MRMR and IRMR Classification Systems in this study.

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Appendix A: MRMR Geotechnical Database

KALGOLD OPEN PIT GOLD MINE - MRMR CALCULATIONS											
Design Section Line	Lithology	UCS	FF/m	Jc	RMR	Mining Adjustments					
						Weathering	Orientation	Induced Stress	Blasting	Total Adjustment	MRMR
13100 N (Western Slope)	SHL	14	27	22.5	64	1	0.85	0.95	1	0.81	51
13100 S (Western Slope)	SHL	14	19.5	27.0	61	1	0.85	0.95	1	0.81	48
13300 N (Western Slope)	CARB SHL	12	26	28.5	67	1	0.85	0.95	1	0.81	54
13300 S (Western Slope)	CARB SHL	12	26	22.5	61	1	0.85	0.95	1	0.81	49
13500 N (Western Slope)	SCH	14	31	28.5	74	1	0.85	0.95	1	0.81	59
13500 S (Western Slope)	SCH / BIF	20	28	28.5	77	1	0.85	0.95	1	0.81	62
13700 N (Western Slope)	SCH	14	24	25.5	64	1	0.85	0.95	1	0.81	51
13700 S (Western Slope)	SCH	14	24	25.5	64	1	0.85	0.95	1	0.81	51
13900 N (Western Slope)	SCH	14	28	22.5	65	1	0.85	0.95	1	0.81	52
13900 S (Western Slope)	SCH	14	26	22.5	63	1	0.85	0.95	1	0.81	50
13900 N (Eastern Slope)	GW	16	29.5	22.5	68	1	0.8	0.95	0.8	0.61	41
13900 S (Eastern Slope)	GW	16	26	24.0	66	1	0.8	0.95	0.8	0.61	40
13700 N (Eastern Slope)	GW	16	32.5	27.2	76	1	0.8	0.95	0.8	0.61	46
13700 S (Eastern Slope)	GW	16	29.5	25.6	71	1	0.8	0.95	0.8	0.61	43
13900 N (Eastern Slope)	GW	10	26	24.0	60	1	0.8	0.95	0.8	0.61	36
13900 S (Eastern Slope)	GW	10	24	24.0	58	1	0.8	0.95	0.8	0.61	35
13700 N (Eastern Slope)	VC	10	29.5	25.5	65	1	0.8	0.95	0.8	0.61	40
13700 S (Eastern Slope)	VC	10	29.5	24.0	64	1	0.8	0.95	0.8	0.61	39
13700 N (Eastern Slope)	VC	10	29.5	28.5	68	1	0.8	0.95	0.8	0.61	41
13700 S (Eastern Slope)	VC	10	31	24.0	65	1	0.8	0.95	0.8	0.61	40
13500 N (Eastern Slope)	VC	10	21	24.0	55	1	0.8	0.95	0.8	0.61	33
13500 S (Eastern Slope)	VC	10	24	24.0	58	1	0.8	0.95	0.8	0.61	35
13300 N (Eastern Slope)	VC	10	19.5	30.4	60	1	0.8	0.95	0.8	0.61	36
13300 S (Eastern Slope)	VC	10	26	28.8	65	1	0.8	0.95	0.8	0.61	39
13500 S (Eastern Slope)	GW	10	24	24.0	58	1	0.8	0.95	0.8	0.61	35
13300 N (Eastern Slope)	GW	10	22.5	24.0	57	1	0.8	0.95	0.8	0.61	34
13300 S (Eastern Slope)	GW	10	26	24.0	60	1	0.8	0.95	0.8	0.61	36
13100 N (Eastern Slope)	SHL	14	21	24.0	59	1	0.8	0.95	0.8	0.61	36
13100 S (Eastern Slope)	SHL	14	22.5	27.2	64	1	0.8	0.95	0.8	0.61	39

COLLEEN BAWN LIMESTONE QUARRY - MRMR CALCULATIONS														
Zone	Lithology	Joint Condition					RMR	Adjustments					MRMR
		IRS (MPa)	Frac. Freq.	Large Scale	Small Scale	Infill		Weathering	Orientation	Induced Stress	Blasting	Total Adjustment	
Zone 1(955L)	Limestone	20	21	0.75	0.95	NA	70	1	0.9	1	0.9	0.81	56
Zone 2 (925L)	Diabase Dyke	20	15	0.75	0.85	NA	61	1	0.9	1	0.9	0.81	49
Zone 2 (935L)	Limestone	20	18	0.75	0.80	NA	62	1	0.9	1	0.9	0.81	50
Zone 3 (945L)	Diabase Dyke	20	12	0.85	0.90	NA	63	1	0.9	1	0.9	0.81	51
Zone 3 (945L)	Limestone	20	21	0.85	0.95	0.80	67	1	0.9	1	0.9	0.81	54
Zone 4 (955L)	Limestone	23	13.5	0.85	0.95	NA	66	1	0.9	1	0.9	0.81	53
Zone 4 (945L)	Limestone	20	18	0.85	0.95	NA	70	1	0.9	1	0.9	0.81	57
Zone 4 (935L)	Limestone	20	21	0.75	0.95	NA	70	1	0.9	1	0.9	0.81	56
Zone 4 (925L)	Limestone	20	16.5	0.85	0.95	NA	69	1	0.9	1	0.9	0.81	56
Zone 5 (970L)	Limestone	20	21	0.85	0.95	NA	73	1	0.9	1	0.9	0.81	59
Zone 5 (945L)	Limestone	20	21	0.85	0.95	NA	73	1	0.9	1	0.9	0.81	59
Zone 5 (925L)	Limestone	20	15	0.75	0.95	NA	64	1	0.9	1	0.9	0.81	51
Zone 6 (980L)	Greenstone	16	10	0.85	0.85	0.50	40	0.8	0.9	1	0.9	0.65	26
Zone 6 (995L)	Limestone	20	21	0.95	0.75	NA	70	1	0.9	1	0.9	0.81	56
Zone 6 (965L)	Limestone	20	21	0.85	0.95	NA	73	1	0.9	1	0.9	0.81	59
Zone 7 (965L)	Greenstone	14	10	0.85	0.95	NA	56	0.8	0.9	1	0.9	0.65	36
Zone 7 (955L)	Schist	12	18	0.75	0.55	NA	47	0.95	0.9	1	0.9	0.77	36
Zone 7 (945L)	Limestone	20	18	0.85	0.95	NA	70	1	0.9	1	0.9	0.81	57

MARIKANA OPEN PIT PLATINUM MINE - MRMR CALCULATIONS											
Pit	**UCS (Mpa)**	**RQD (%)**	**Js**	**Jc**	**RMR**	**Weathering**	**Orientation**	**Blasting**	**Induced Stress**	**Total Adjustments**	**MRMR**
B	20	10	9.05	12.80	52	1	0.98	0.8	1	0.78	41
	18	15	15.34	12.80	61	1	0.98	0.8	1	0.78	48
	20	14	9.78	12.80	57	1	0.98	0.8	1	0.78	44
C	20	10	9.42	12.80	52	1	0.98	0.8	1	0.78	41
	20	14	18.10	12.48	65	1	0.98	0.8	1	0.78	51
	20	14	12.60	12.80	59	1	0.98	0.8	1	0.78	47
	20	14	17.60	12.48	64	1	0.98	0.8	1	0.78	50
	17	14	8.54	12.48	52	1	0.98	0.8	1	0.78	41
D	16	14	12.01	12.80	55	1	0.95	0.8	1	0.76	42
	14	15	12.97	12.80	55	1	0.95	0.8	1	0.76	42
	14	14	8.98	24.96	62	1	0.95	0.8	1	0.76	47
	14	12	10.64	12.00	49	1	0.95	0.8	1	0.76	37
	8	14	12.42	12.12	47	1	0.95	0.8	1	0.76	35
	4	15	14.02	9.83	43	1	0.95	0.8	1	0.76	33
	3	12	7.94	12.80	36	1	0.95	0.8	1	0.76	27
	3	14	10.06	14.82	42	1	0.95	0.8	1	0.76	32
	6	14	10.52	23.40	54	1	0.95	0.8	1	0.76	41
	4	12	6.14	17.55	40	1	0.95	0.8	1	0.76	30
	1	12	13.43	9.59	36	1	0.95	0.8	1	0.76	27
ROM	1	12	12.66	9.45	35	1	0.95	0.8	1	0.76	27
	1	12	15.36	11.40	40	1	0.95	0.8	1	0.76	30
	17	14	7.62	24.00	63	1	0.95	0.8	1	0.76	48
	3.5	15	15.01	10.44	44	1	0.95	0.8	1	0.76	33

Appendix B: IRMR Geotechnical Database

KALGOLD OPEN PIT GOLD MINE - IRMR CALCULATIONS

Geotechnical Section Line	Lithology	IRS (see Fig 57.3)		ROCK BLOCK STRENGHT (RBS) CALCULATION								RBS Rating (Refer to Fig 57.5)	JOINT SPACING					JOINT CONDITION					OVERALL JOINT RATING	IN-SITU ROCK MASS RATING	ADJUSTMENTS						IRMR RATING
		% Strong Rock	% Weak Rock	IRS (UCS)	Homogeneous (Factor = 0.8)	Corrected RBS (Heterogeneous Conditions): Infill Type / Hardness	FF	Refer to Fig 57.4	% Adjust.	RBS (MPa) Homo	RBS (MPa) Hetero		Open Joints (see Fig 57.6) J1	J2	J3	Average Rating	Cemented Joints (see Fig 57.7)	Single Joints (see Table 57.1) Factor	Large	Small	Total	Multiple Joints (see Fig 57.8)			Weathering	Orientation	Stresses	Blasting	Water/Ice	Total	
13100N (West)	SHL	100	NA	127	0.8	0	0	0	0	102	0	23.0	14.8	22.5	25.0	21	NA	40	0.85	0.75	26	NA	46	69	1	0.85	0.95	1	1	0.81	56
13100S (West)	SHL	100	NA	127	0.8	0	0	0	0	102	0	23.0	9.0	15.0	16.0	13	NA	40	0.85	0.9	31	NA	44	67	1	0.85	0.95	1	1	0.81	54
13300N (West)	CARB SHL	100	NA	110	0.8	0	0	0	0	88	0	22.0	19.5	24.5	27.5	24	NA	40	0.95	0.8	30	NA	54	76	1	0.85	0.95	1	1	0.81	62
13300S (West)	CARB SHL	100	NA	110	0.8	0	0	0	0	88	0	22.0	12.0	22.0	23.0	19	NA	40	0.85	0.75	26	NA	45	67	1	0.85	0.95	1	1	0.81	54
13500N (West)	SCH	100	NA	133	0.8	0	0	0	0	106	0	21.5	22.0	26.0	28.0	25	NA	40	0.95	0.75	29	NA	54	75	1	0.85	0.95	1	1	0.81	61
13500S (West)	SCH/BIF	100	NA	231	0.8	0	0	0	0	185	0	25.0	18.0	22.0	27.5	23	NA	40	0.95	0.75	29	NA	51	76	1	0.85	0.95	1	1	0.81	61
13700N (West)	SCH	100	NA	133	0.8	0	0	0	0	106	0	21.5	18.0	19.0	20.0	19	NA	40	0.93	0.75	28	NA	47	68	1	0.85	0.95	1	1	0.81	55
13700S (West)	SCH	100	NA	133	0.8	0	0	0	0	106	0	21.5	15.0	18.0	22.0	18	NA	40	0.93	0.75	28	NA	46	68	1	0.85	0.95	1	1	0.81	55
13900N (West)	SCH	100	NA	133	0.8	0	0	0	0	106	0	21.5	18.0	23.0	27.0	23	NA	40	0.85	0.75	26	NA	48	70	1	0.85	0.95	1	1	0.81	56
13900S (West)	SCH	100	NA	133	0.8	0	0	0	0	106	0	21.5	12.0	18.5	25.0	19	NA	40	0.85	0.75	26	NA	44	66	1	0.85	0.95	1	1	0.81	53
13100N (East)	SHL	100	NA	127	0.8	0	0	0	0	102	0	23.0	13.0	13.5	18.5	15	NA	40	0.85	0.8	27	NA	42	65	1	0.8	0.95	0.8	1	0.61	40
13100S (East)	SHL	100	NA	127	0.8	0	0	0	0	102	0	23.0	12.5	19.0	19.5	17	NA	40	0.9	0.8	29	NA	46	69	1	0.8	0.95	0.8	1	0.61	42
13300N (East) - 1187m	VC	100	NA	91	0.8	0	0	0	0	73	0	19.0	13.0	14.5	16.0	15	NA	40	0.95	0.8	30	NA	45	64	1	0.8	0.95	0.8	1	0.61	39
13300S (East) - 1187m	VC	100	NA	91	0.8	0	0	0	0	73	0	19.0	20.0	22.5	23.0	22	NA	40	0.95	0.8	30	NA	52	71	1	0.8	0.95	0.8	1	0.61	43
13300N (East) - 1140m	GW	100	NA	155	0.8	0	0	0	0	124	0	23.0	13.0	17.0	21.0	17	NA	40	0.85	0.8	27	NA	44	67	1	0.8	0.95	0.8	1	0.61	41
13300S (East) - 1140m	GW	100	NA	155	0.8	0	0	0	0	124	0	23.0	18.5	19.5	22.5	20	NA	40	0.85	0.8	27	NA	47	70	1	0.8	0.95	0.8	1	0.61	43
13500N (East) - 1170m	VC	100	NA	91	0.8	0	0	0	0	73	0	19.0	15.0	16.0	18.0	16	NA	40	0.85	0.8	27	NA	44	63	1	0.8	0.95	0.8	1	0.61	38
13500S (East) - 1170m	VC	100	NA	91	0.8	0	0	0	0	73	0	19.0	15.0	17.5	22.0	18	NA	40	0.85	0.8	27	NA	45	64	1	0.8	0.95	0.8	1	0.61	39
13500S (East) - 1157m	GW	100	NA	155	0.8	0	0	0	0	124	0	23.0	13.5	20.0	20.0	18	NA	40	0.85	0.8	27	NA	45	68	1	0.8	0.95	0.8	1	0.61	41
13700N (East) - 1145m	GW	100	NA	155	0.8	0	0	0	0	124	0	23.0	22.5	23.5	35.0	27	NA	40	0.9	0.8	29	NA	56	79	1	0.8	0.95	0.8	1	0.61	48
13700S (East) - 1145m	GW	100	NA	155	0.8	0	0	0	0	124	0	23.0	17.0	26.5	27.5	24	NA	40	0.85	0.8	27	NA	51	74	1	0.8	0.95	0.8	1	0.61	45
13700N (East) - 1163m	VC	100	NA	91	0.8	0	0	0	0	73	0	19.0	22.0	25.0	27.5	25	NA	40	0.9	0.75	27	NA	52	71	1	0.8	0.95	0.8	1	0.61	43
13700S (East) - 1163m	VC	100	NA	91	0.8	0	0	0	0	73	0	19.0	19.5	26.5	27.5	25	NA	40	0.85	0.8	27	NA	52	71	1	0.8	0.95	0.8	1	0.61	43
13700N (East) - 1179m	VC	100	NA	91	0.8	0	0	0	0	73	0	19.0	19.5	27.0	28.5	25	NA	40	0.95	0.75	29	NA	54	73	1	0.8	0.95	0.8	1	0.61	44
13700S (East) - 1179m	VC	100	NA	91	0.8	0	0	0	0	73	0	19.0	20.5	27.0	29.0	26	NA	40	0.85	0.8	27	NA	53	72	1	0.8	0.95	0.8	1	0.61	44
13900N (East)	GW	100	NA	155	0.8	0	0	0	0	124	0	23.0	22.0	22.5	27.5	24	NA	40	0.85	0.75	26	NA	50	73	1	0.8	0.95	0.8	1	0.61	44
13900S (East)	GW	100	NA	155	0.8	0	0	0	0	124	0	23.0	21.0	22.0	23.5	22	NA	40	0.85	0.8	27	NA	49	72	1	0.8	0.95	0.8	1	0.61	44
13900N (East) - 1164m	GW	100	NA	155	0.8	0	0	0	0	124	0	23.0	17.0	19.5	26.0	21	NA	40	0.85	0.8	27	NA	48	71	1	0.8	0.95	0.8	1	0.61	43
13900S (East) - 1164m	GW	100	NA	155	0.8	0	0	0	0	124	0	23.0	16.0	16.5	22.0	18	NA	40	0.85	0.8	27	NA	45	68	1	0.8	0.95	0.8	1	0.61	42

COLLEEN BAWN LIMESTONE QUARRY - IRMR CALCULATIONS

Geotechnical Section Line	Lithology	IRS (see Fig 57.3) % Strong Rock	IRS (see Fig 57.3) % Weak Rock	RBS Calculation: IRS (UCS)	Homogeneous (Factor = 0.8)	Corrected RBS: Infill Type / Hardness	FF	Refer to Fig 57.4	% Adjust.	RBS (MPa) Homo	RBS (MPa) Hetero	RBS Rating (Refer to Fig 57.5)	Joint Spacing, Open Joints (see Fig 57.6): J1	J2	J3	Average Rating	Cemented Joints (see Fig 57.7)
Zone 1 (955L)	Limestone	100	NA	200	0.8	0	21	0	0	160	0	25.0	14.3	14.3	14.3	14	NA
Zone 2 (925L)	Diabase Dyke	100	NA	200	0.8	0	15	0	0	160	0	25.0	14.3	14.3	14.3	14	NA
Zone 2 (935L)	Limestone	100	NA	200	0.8	0	18	0	0	160	0	25.0	5.0	5.0	5.0	5	NA
Zone 3 (945L)	Diabase Dyke	100	NA	200	0.8	0	12	0	0	160	0	25.0	5.0	5.0	5.0	5	NA
Zone 3 (945L)	Limestone	100	NA	200	0.8	0.33	21	6.93	0.72	160	115.2	22.0	14.3	14.3	14.3	14	NA
Zone 4 (955L)	Limestone	100	NA	200	0.8	0	13.5	0	0	160	0	25.0	5.0	5.0	5.0	5	NA
Zone 4 (945L)	Limestone	100	NA	200	0.8	0	18	0	0	160	0	25.0	14.3	14.3	14.3	14	NA
Zone 4 (935L)	Limestone	100	NA	200	0.8	0	21	0	0	160	0	25.0	14.3	14.3	14.3	14	NA
Zone 4 (925L)	Limestone	100	NA	200	0.8	0	16.5	0	0	160	0	25.0	5.0	5.0	5.0	5	NA
Zone 5 (970L)	Limestone	100	NA	200	0.8	0	21	0	0	160	0	25.0	14.3	14.3	14.3	14	NA
Zone 5 (945L)	Limestone	100	NA	200	0.8	0	16.5	0	0	160	0	25.0	24.0	24.0	24.0	24	NA
Zone 5 (925L)	Limestone	100	NA	200	0.8	0	15	0	0	160	0	25.0	14.3	14.3	14.3	14	NA
Zone 6 (980L)	Greenstone	100	NA	135	0.8	0.5	10	5	0.74	108	79.92	20.0	5.0	5.0	5.0	5	NA
Zone 6 (995L)	Limestone	100	NA	200	0.8	0	21	0	0	160	0	25.0	14.3	14.3	14.3	14	NA
Zone 6 (965L)	Limestone	100	NA	200	0.8	0	21	0	0	160	0	25.0	14.3	14.3	14.3	14	NA
Zone 7 (965L)	Greenstone	100	NA	135	0.8	0	10	0	0	108	0	25.0	5.0	5.0	5.0	5	NA
Zone 7 (955L)	Schist	100	NA	115	0.8	0	8.5	0	0	92	0	25.0	14.3	14.3	14.3	14	NA
Zone 7 (945L)	Limestone	100	NA	200	0.8	0	18	0	0	160	0	25.0	14.3	14.3	14.3	14	NA

Geotechnical Section Line	Lithology	Joint Condition, Single Joints (see Table 57.1): Factor	Large	Small	Total	Multiple Joints (see Fig 57.8)	OVERALL JOINT RATING	IN-SITU ROCK MASS RATING	ADJUSTMENTS: Weathering	Orientation	Stresses	Blasting	Water/Ice	Total	IRMR RATING	Total Rating (RMR)	Adjustments: Weathering	Orientation	Stresses	Blasting	Total	MRMR Rating
Zone 1 (955L)	Limestone	40	0.85	0.95	32	NA	47	72	1	0.9	1	0.9	1	0.81	**58**	70	1	0.9	1	0.9	0.81	**56**
Zone 2 (925L)	Diabase Dyke	40	0.85	0.85	29	NA	43	68	1	0.9	1	0.9	1	0.81	**55**	52	1	0.9	1	0.9	0.81	**42**
Zone 2 (935L)	Limestone	40	0.85	0.8	27	NA	32	57	1	0.9	1	0.9	1	0.81	**46**	62	1	0.9	1	0.9	0.81	**50**
Zone 3 (945L)	Diabase Dyke	40	0.9	0.9	32	NA	37	62	1	0.9	1	0.9	1	0.81	**51**	63	1	0.9	1	0.9	0.81	**51**
Zone 3 (945L)	Limestone	40	0.9	0.95	34	NA	49	71	1	0.9	1	0.9	1	0.81	**57**	67	1	0.9	1	0.9	0.81	**54**
Zone 4 (955L)	Limestone	40	0.9	0.95	34	NA	39	64	1	0.9	1	0.9	1	0.81	**52**	66	1	0.9	1	0.9	0.81	**53**
Zone 4 (945L)	Limestone	40	0.9	0.95	34	NA	49	74	1	0.9	1	0.9	1	0.81	**60**	70	1	0.9	1	0.9	0.81	**57**
Zone 4 (935L)	Limestone	40	0.85	0.95	32	NA	47	72	1	0.9	1	0.9	1	0.81	**58**	70	1	0.9	1	0.9	0.81	**56**
Zone 4 (925L)	Limestone	40	0.9	0.95	34	NA	39	64	1	0.9	1	0.9	1	0.81	**52**	69	1	0.9	1	0.9	0.81	**56**
Zone 5 (970L)	Limestone	40	0.9	0.95	34	NA	49	74	1	0.9	1	0.9	1	0.81	**60**	73	1	0.9	1	0.9	0.81	**59**
Zone 5 (945L)	Limestone	40	0.9	0.95	34	NA	58	83	1	0.9	1	0.9	1	0.81	**67**	69	1	0.9	1	0.9	0.81	**56**
Zone 5 (925L)	Limestone	40	0.85	0.95	32	NA	47	72	1	0.9	1	0.9	1	0.81	**58**	64	1	0.9	1	0.9	0.81	**51**
Zone 6 (980L)	Greenstone	40	0.9	0.85	31	NA	36	56	0.8	0.9	1	0.9	1	0.65	**36**	39	0.8	0.9	1	0.9	0.65	**25**
Zone 6 (995L)	Limestone	40	0.95	0.75	29	NA	43	68	1	0.9	1	0.9	1	0.81	**55**	70	1	0.9	1	0.9	0.81	**56**
Zone 6 (965L)	Limestone	40	0.9	0.95	34	NA	49	74	1	0.9	1	0.9	1	0.81	**60**	73	1	0.9	1	0.9	0.81	**59**
Zone 7 (965L)	Greenstone	40	0.9	0.95	34	NA	39	64	0.8	0.9	1	0.9	1	0.65	**42**	56	0.8	0.9	1	0.9	0.65	**36**
Zone 7 (955L)	Schist	40	0.85	0.55	19	NA	33	58	0.95	0.9	1	0.9	1	0.77	**45**	37	0.95	0.9	1	0.9	0.77	**28**
Zone 7 (945L)	Limestone	40	0.9	0.95	34	NA	49	74	1	0.9	1	0.9	1	0.81	**60**	70	1	0.9	1	0.9	0.81	**57**

MARIKANA OPEN PIT PLATINUM MINE - IRMR CALCULATIONS

Pit	Lithology	IRS (see Fig 57.3)		ROCK BLOCK STRENGHT (RBS) CALCULATION								RBS Rating (Refer to Fig 57.5)	JOINT SPACING					JOINT CONDITION					OVERALL JOINT RATING	IN-SITU ROCK MASS RATING	ADJUSTMENTS						IRMR RATING
		% Strong Rock	% Weak Rock	IRS (UCS)	Homogeneous (Factor = 0.8)	Corrected RBS (Heterogeneous Conditions)							Open Joints (see Fig 57.6)				Cemented Joints (see Fig 57.7)	Single Joints (see Table 57.1)				Multiple Joints (see Fig 57.8)									
						Infill Type / Hardness	FF	Refer to Fig 57.4	% Adjust.	RBS (MPa)																					
										Homo	Hetero		J1	J2	J3	Average Rating		Factor	Large	Small	Total				Weathering	Orientation	Stresses	Blasting	Water/Ice	Total	
	Anorthosite	100	0	200	0.8	0.5	0.11	0.055	1	124	124	22.8	0.68	0.71	0.75	0.71	NA	40	0.85	0.8	27	NA	28	51	1	0.98	1	0.8	1	0.78	40
B	Anorthosite	100	0	175	0.8	0.5	0.1	0.05	1	124	124	22.8	0.76	0.85	0.95	0.85	NA	40	0.85	0.8	27	NA	28	51	1	0.98	1	0.8	1	0.78	40
	Anorthosite	100	0	200	0.8	0.5	0.1	0.05	1	108	108	21.8	0.66	0.77	0.77	0.73	NA	40	0.88	0.8	28	NA	29	51	1	0.98	1	0.8	1	0.78	40
	Norite	100	0	200	0.8	0.5	0.11	0.055	1	108	108	21.8	0.67	0.73	0.77	0.72	NA	40	0.85	0.8	27	NA	28	50	1	0.98	1	0.8	1	0.78	39
	Norite	100	0	200	0.8	0	1	0	1	160	160	25.0	0.77	0.94		0.86	NA	40	0.85	0.8	27	NA	28	53	1	0.98	1	0.8	1	0.78	42
C	Norite	100	0	200	0.8	0	1	0	1	160	160	25.0	1.00	0.90	0.56	0.82	NA	40	0.85	0.8	27	NA	28	53	1	0.98	1	0.8	1	0.78	42
	Anorthosite	100	0	200	0.8	0	1	0	1	160	160	25.0	0.85	0.91	0.91	0.89	NA	40	0.85	0.8	27	NA	28	53	1	0.98	1	0.8	1	0.78	42
	Anorthosite	100	0	165	0.8	0	1	0	1	132	132	23.0	0.65	0.73	0.72	0.70	NA	40	0.85	0.8	27	NA	28	51	1	0.98	1	0.8	1	0.78	40
	Anorthosite	95	5	155	0.8	0	1	0	1	124	124	22.8	1.00	1.00		1.00	NA	40	0.85	0.8	27	NA	28	51	1	0.95	1	0.8	1	0.76	39
	Anorthosite	95	5	135	0.8	0.5	0.1	0.05	1	108	108	21.8	0.76	0.75	0.91	0.81	NA	40	0.85	0.8	27	NA	28	50	1	0.95	1	0.8	1	0.76	38
	Anorthosite	95	5	135	0.8	0	1	0	1	108	108	21.8	0.67	0.67	0.80	0.71	NA	40	0.85	0.8	27	NA	28	50	1	0.95	1	0.8	1	0.76	38
	Anorthosite	95	5	135	0.8	0.5	0.1	0.05	1	108	108	21.8	0.68	0.68	0.92	0.76	NA	40	0.88	0.75	26	NA	27	49	1	0.95	1	0.8	0.85	0.65	32
	Anorthosite	10	90	75	0.8	0	1	0	1	60	60	18.0	0.74	0.73	0.92	0.80	NA	40	0.85	0.88	30	NA	31	49	1	0.95	1	0.8	0.85	0.65	31
D	Anorthosite	5	95	30	0.8	0.5	0.1	0.05	1	24	24	10.5	0.71	0.79	1.00	0.83	NA	40	0.88	0.75	26	NA	27	38	1	0.95	1	0.8	1	0.76	29
	Anorthosite	5	95	18	0.8	0	1	0	1	14	14.4	6.9	0.64	0.62	0.80	0.69	NA	40	0.88	0.8	28	NA	29	36	1	0.95	1	0.8	0.95	0.72	26
	Anorthosite	5	95	18	0.8	0	1	0	1	14	14.4	6.9	0.67	0.66	0.91	0.75	NA	40	0.88	0.88	31	NA	32	39	1	0.95	1	0.8	1	0.76	29
	Anorthosite	10	90	55	0.8	0.5	0.1	0.05	1	44	44	15.5	0.71	0.77	0.77	0.75	NA	40	0.85	0.78	27	NA	27	43	1	0.95	1	0.8	0.95	0.72	31
	Anorthosite	5	95	30	0.8	0.5	0.1	0.05	1	24	24	10.5	0.60	0.65	0.63	0.63	NA	40	0.88	0.83	29	NA	30	40	1	0.95	1	0.8	0.9	0.68	28
	Anorthosite	1	99	2.5	0.8	0.5	0.1	0.05	1	2	2	0.5	0.68	0.79	1.00	0.82	NA	40	0.88	0.72	25	NA	26	27	1	0.95	1	0.8	0.9	0.68	18
	Norite	1	99	2.5	0.8	0.5	0.1	0.05	1	2	2	0.5	0.78	0.86	0.93	0.86	NA	40	0.85	0.75	26	NA	26	27	1	0.95	1	0.8	0.9	0.68	18
ROM	Norite	1	99	2.5	0.8	0	1	0	1	2	2	0.5	0.73	0.85	0.99	0.86	NA	40	0.88	0.81	29	NA	29	30	1	0.95	1	0.8	1	0.76	23
	Norite	100	0	165	0.8	0	1	0	1	132	132	23.0	0.65	0.67	0.70	0.67	NA	40	0.88	0.8	28	NA	29	52	1	0.95	1	0.8	1	0.76	39
	Norite	1	99	2.5	0.8	0	1	0	1	2	2	0.5	0.75	0.95		0.85	NA	40	0.88	0.87	31	NA	31	32	1	0.95	1	0.8	0.95	0.72	23

Appendix C: Results of MRMR Parametric Analyses

16% Increase and Decrease in MRMR Classification System Parameters

Moisture Condition	Rock Strength (MPa)	Joint Spacing (m)			RQD (%)			Joint Surface Conditions				MRMR Calculation											RMR	Adjustments					MRMR	Difference in MRMR Value	Percentage Difference (%)
		J1	J2	J3	J_v	$3.3J_v$	Total	Micro	Macro	Infill	Wall Alter.	IRS	RQD	Joint Spacing J1	J2	J3	Total	Joint Surface Conditions Micro	Macro	Infill	Wall Alter.	Total		Weath	Orient	Stress	Blast	Total Adj			
Dry	125	1.20	0.60	0.30	5.83	19.25	95.75	Rough Undulating	Planar	Clean	None	14	14	0.79	0.72	0.69	9.8	0.80	0.75	1.00	1.00	24	62	1.00	1.00	1.00	1.00	1.00	61.81	NA	NA
Wet	125	1.20	0.60	0.30	5.83	19.25	95.75	Rough Undulating	Planar	Clean	None	14	14	0.79	0.72	0.69	9.8	**0.75**	**0.70**	1.00	1.00	21	**59**	1.00	1.00	1.00	1.00	1.00	**58.81**	3.0	4.9
Dry	**145**	1.20	0.60	0.30	5.83	19.25	95.75	Rough Undulating	Planar	Clean	None	**16**	14	0.79	0.72	0.69	9.8	0.80	0.75	1.00	1.00	24	**64**	1.00	1.00	1.00	1.00	1.00	**63.81**	2.0	3.2
Dry	**105**	1.20	0.60	0.30	5.83	19.25	95.75	Rough Undulating	Planar	Clean	None	**12**	14	0.79	0.72	0.69	9.8	0.80	0.75	1.00	1.00	24	**60**	1.00	1.00	1.00	1.00	1.00	**59.81**	2.0	3.4
Dry	125	**1.39**	0.60	0.30	**5.72**	**18.87**	**96.13**	Rough Undulating	Planar	Clean	None	14	14	**0.81**	0.72	0.69	**10.1**	0.80	0.75	1.00	1.00	24	**62**	1.00	1.00	1.00	1.00	1.00	**62.06**	**0.2**	**0.0**
Dry	125	**1.01**	0.60	0.30	**5.99**	**19.77**	**95.23**	Rough Undulating	Planar	Clean	None	14	14	**0.77**	0.72	0.69	**9.6**	0.80	0.75	1.00	1.00	24	**62**	1.00	1.00	1.00	1.00	1.00	**61.56**	**0.2**	**0.0**
Dry	125	1.20	**0.70**	0.30	**5.60**	**18.46**	**96.54**	Rough Undulating	Planar	Clean	None	14	14	0.79	**0.75**	0.69	**10.2**	0.80	0.75	1.00	1.00	24	**62**	1.00	1.00	1.00	1.00	1.00	**62.22**	**0.4**	**0.0**
Dry	125	1.20	**0.50**	0.30	**6.17**	**20.35**	**94.65**	Rough Undulating	Planar	Clean	None	14	14	0.79	**0.70**	0.69	**9.5**	0.80	0.75	1.00	1.00	24	**62**	1.00	1.00	1.00	1.00	1.00	**61.54**	**0.3**	**0.0**
Dry	125	1.20	0.60	**0.35**	**5.36**	**17.68**	**97.32**	Rough Undulating	Planar	Clean	None	14	**15**	0.79	0.72	**0.70**	**10.0**	0.80	0.75	1.00	1.00	24	**63**	1.00	1.00	1.00	1.00	1.00	**62.95**	1.1	1.8
Dry	125	1.20	0.60	**0.25**	**6.50**	**21.45**	**93.55**	Rough Undulating	Planar	Clean	None	14	14	0.79	0.72	**0.65**	**9.2**	0.80	0.75	1.00	1.00	24	**61**	1.00	1.00	1.00	1.00	1.00	**61.24**	0.6	0.9
Dry	125	1.20	0.60	0.30	5.83	19.25	95.75	Slickensided Stepped	Planar	Clean	None	14	14	0.79	0.72	0.69	9.8	**0.85**	0.75	1.00	1.00	25.5	**63**	1.00	1.00	1.00	1.00	1.00	**63.31**	1.50	2.4
Dry	125	1.20	0.60	0.30	5.83	19.25	95.75	Smooth Undulating	Planar	Clean	None	14	14	0.79	0.72	0.69	9.8	**0.75**	0.75	1.00	1.00	22.5	**60**	1.00	1.00	1.00	1.00	1.00	**60.31**	1.50	2.4
Dry	125	1.20	0.60	0.30	5.83	19.25	95.75	Rough Undulating	Uni-directional/Curved	Clean	None	14	14	0.79	0.72	0.69	9.8	0.80	**0.87**	1.00	1.00	27.84	**66**	1.00	1.00	1.00	1.00	1.00	**65.65**	3.84	6.2
Dry	125	1.20	0.60	0.30	5.83	19.25	95.75	Rough Undulating	Planar	Non-Softening Medium	None	14	14	0.79	0.72	0.69	9.8	0.80	0.75	**0.84**	1.00	20.16	**58**	1.00	1.00	1.00	1.00	1.00	**57.97**	3.84	6.2
Dry	125	1.20	0.60	0.30	5.83	19.25	95.75	Rough Undulating	Planar	Clean	Weaker than Wall Rock	14	14	0.79	0.72	0.69	9.8	0.80	0.75	1.00	**0.75**	18	**56**	1.00	1.00	1.00	1.00	1.00	**55.81**	6.00	9.7
Dry	125	1.20	0.60	0.30	5.83	19.25	95.75	Rough Undulating	Planar	Clean	None	14	14	0.79	0.72	0.69	9.8	0.80	0.75	1.00	1.00	24	**62**	**0.84**	1.00	1.00	1.00	0.84	**51.92**	9.9	16.0
Dry	125	1.20	0.60	0.30	5.83	19.25	95.75	Rough Undulating	Planar	Clean	None	14	14	0.79	0.72	0.69	9.8	0.80	0.75	1.00	1.00	24	**62**	1.00	**0.84**	1.00	1.00	0.84	**51.92**	9.9	16.0
Dry	125	1.20	0.60	0.30	5.83	19.25	95.75	Rough Undulating	Planar	Clean	None	14	14	0.79	0.72	0.69	9.8	0.80	0.75	1.00	1.00	24	**62**	1.00	1.00	**1.16**	1.00	1.16	**71.70**	9.9	16.0
Dry	125	1.20	0.60	0.30	5.83	19.25	95.75	Rough Undulating	Planar	Clean	None	14	14	0.79	0.72	0.69	9.8	0.80	0.75	1.00	1.00	24	**62**	1.00	1.00	**0.84**	1.00	0.84	**51.92**	9.9	16.0
Dry	125	1.20	0.60	0.30	5.83	19.25	95.75	Rough Undulating	Planar	Clean	None	14	14	0.79	0.72	0.69	9.8	0.80	0.75	1.00	1.00	24	**62**	1.00	1.00	1.00	**0.84**	0.84	**51.92**	9.9	16.0

50% Increase and Decrease in MRMR Classification System Parameters

Moisture Condition	Rock Strength (MPa)	Joint Spacing (m)			RQD (%)			Joint Surface Conditions				MRMR Calculation											RMR	Adjustments					MRMR	Difference in MRMR Value	Percentage Difference (%)
		J1	J2	J3	J_v	$3.3J_v$	Total	Micro	Macro	Infill	Wall Alter.	IRS	RQD	Joint Spacing J1	J2	J3	Total	Joint Surface Conditions Micro	Macro	Infill	Wall Alter.	Total		Weath	Orient	Stress	Blast	Total Adj			
Dry	125.0	1.20	0.60	0.30	5.83	19.25	95.75	Rough Undulating	Planar	Clean	None	14	14	0.79	0.72	0.69	9.8	0.80	0.75	1.00	1.00	24	62	1.00	1.00	1.00	1.00	1.00	61.81	NA	NA
Dry	**250.0**	1.20	0.60	0.30	5.83	19.25	95.75	Rough Undulating	Planar	Clean	None	**20**	14	0.79	0.72	0.69	9.8	0.80	0.75	1.00	1.00	24	**68**	1.00	1.00	1.00	1.00	1.00	**67.81**	6.0	9.7
Dry	**62.5**	1.20	0.60	0.30	5.83	19.25	95.75	Rough Undulating	Planar	Clean	None	**6**	14	0.79	0.72	0.69	9.8	0.80	0.75	1.00	1.00	24	**54**	1.00	1.00	1.00	1.00	1.00	**53.81**	8.0	12.9
Dry	125.0	**2.40**	0.60	0.30	**5.42**	**17.88**	**97.13**	Rough Undulating	Planar	Clean	None	14	**15**	**0.89**	0.72	0.69	**11.1**	0.80	0.75	1.00	1.00	24	**64**	1.00	1.00	1.00	1.00	1.00	**64.05**	2.2	3.6
Dry	125.0	**0.60**	0.60	0.30	**6.67**	**22.00**	**93.00**	Rough Undulating	Planar	Clean	None	14	14	**0.68**	0.72	0.69	**8.4**	0.80	0.75	1.00	1.00	24	**60**	1.00	1.00	1.00	1.00	1.00	**60.45**	1.4	2.2
Dry	125.0	1.20	**1.20**	0.30	**5.00**	**16.50**	**98.50**	Rough Undulating	Planar	Clean	None	14	**15**	0.79	**0.79**	0.69	**10.8**	0.80	0.75	1.00	1.00	24	**64**	1.00	1.00	1.00	1.00	1.00	**63.77**	2.0	3.2
Dry	125.0	1.20	**0.30**	0.30	**7.50**	**24.75**	**90.25**	Rough Undulating	Planar	Clean	None	14	14	0.79	**0.64**	0.69	**8.7**	0.80	0.75	1.00	1.00	24	**61**	1.00	1.00	1.00	1.00	1.00	**60.72**	1.1	1.8
Dry	125.0	1.20	0.60	**0.60**	**4.17**	**13.75**	**101.25**	Rough Undulating	Planar	Clean	None	14	**15**	0.79	0.72	**0.76**	**10.8**	0.80	0.75	1.00	1.00	24	**64**	1.00	1.00	1.00	1.00	1.00	**63.81**	2.0	3.2
Dry	125.0	1.20	0.60	**0.15**	**9.17**	**30.25**	**84.75**	Rough Undulating	Planar	Clean	None	14	14	0.79	0.72	**0.6**	**8.5**	0.80	0.75	1.00	1.00	24	**61**	1.00	1.00	1.00	1.00	1.00	**60.53**	1.3	2.1

Appendix D: Results of IRMR Parametric Analyses

16% Increase and Decrease in IRMR Classification System Parameters

IRS (see Fig 57.3): % Strong Rock	IRS (see Fig 57.3): % Weak Rock	RBS Calculation: IRS (UCS)	RBS Calculation: Corrected IRS (MPa)	RBS Calculation: Homogeneous (Factor = 0.8)	Corrected RBS (Heterogeneous Conditions): Infill Type / Hardness	Corrected RBS: No. of Joints / m	Corrected RBS: Refer to Fig 57.4	Corrected RBS: % Adjust.	Corrected RBS: Rock Block Strength (MPa)	RBS Rating (Refer to Fig 57.5)	Joint Spacing – Open Joints (see Fig 57.6): J1	Open Joints: J2	Open Joints: J3	Open Joints: JS Rating	Multiple Joints: No. of Cemented Joints	Multiple Joints: Spacing of Cemented Joints (m)	Multiple Joints: Cemented Joint Adjustments (see Fig 57.7)	Multiple Joints: Adjusted Average Rating	Multiple Joints: No. of Joints / m	Multiple Joints: JS Rating	Average JS Rating	Joint Condition – Single Joints (see Table 57.1): Factor	Single Joints: Large	Single Joints: Small	Single Joints: JC Rating	Multiple Joints (see Table 57.8): Factor	Multiple Joints: Large	Multiple Joints: Small	Multiple Joints: JC Rating	TOTAL JOINT RATING	IN-SITU ROCK MASS RATING	Adjustments: Weathering	Adjustments: Orientation	Adjustments: Stresses	Adjustments: Blasting	Adjustments: Water/Ice	Adjustments: Total	IRMR RATING	Difference in MRMR Value	Percentage Difference (%)
100	0	125	125	0.8	0	1	0	0	100	21.5	23	18.0	12	17.67	NA	NA	NA	NA	NA	NA	NA	40	0.85	0.80	27.20	NA	NA	NA	NA	44.87	66.37	1	1	1	1	1	1.00	66.37	NA	NA
100	0	125	125	0.8	0	1	0	0	100	21.5	23	18.0	12	17.67	NA	NA	NA	NA	NA	NA	NA	40	0.85	0.80	27.20	NA	NA	NA	NA	44.87	66.37	1	1	1	1	**0.94**	0.94	**62.38**	4.0	6.0
84	**16**	125	**94.0**	0.8	**Calcite / 3**	1	**0.33**	**0.92**	**69.2**	**19**	23	18.0	12	17.67	NA	NA	NA	NA	NA	NA	NA	40	0.85	0.80	27.20	NA	NA	NA	NA	44.87	**63.87**	1	1	1	1	1	1.00	**63.87**	2.5	3.8
100	0	125	125	0.8	0	1	0	0	100	21.5	**24**	18.0	12	**18.00**	NA	NA	NA	NA	NA	NA	NA	40	0.85	0.80	27.20	NA	NA	NA	NA	45.20	**66.70**	1	1	1	1	1	1.00	**66.70**	**0.3**	**0.5**
100	0	125	125	0.8	0	1	0	0	100	21.5	**21**	18.0	12	**17.00**	NA	NA	NA	NA	NA	NA	NA	40	0.85	0.80	27.20	NA	NA	NA	NA	44.20	**65.70**	1	1	1	1	1	1.00	**65.70**	0.7	1.0
100	0	125	125	0.8	0	1	0	0	100	21.5	23	**19.0**	12	**18.00**	NA	NA	NA	NA	NA	NA	NA	40	0.85	0.80	27.20	NA	NA	NA	NA	45.20	**66.70**	1	1	1	1	1	1.00	**66.70**	**0.3**	**0.5**
100	0	125	125	0.8	0	1	0	0	100	21.5	23	**16.0**	12	**17.00**	NA	NA	NA	NA	NA	NA	NA	40	0.85	0.80	27.20	NA	NA	NA	NA	44.20	**65.70**	1	1	1	1	1	1.00	**65.70**	0.7	1.0
100	0	125	125	0.8	0	1	0	0	100	21.5	23	18.0	**13**	**18.00**	NA	NA	NA	NA	NA	NA	NA	40	0.85	0.80	27.20	NA	NA	NA	NA	45.20	**66.70**	1	1	1	1	1	1.00	**66.70**	**0.3**	**0.5**
100	0	125	125	0.8	0	1	0	0	100	21.5	23	18.0	**10**	**17.00**	NA	NA	NA	NA	NA	NA	NA	40	0.85	0.80	27.20	NA	NA	NA	NA	44.20	**65.70**	1	1	1	1	1	1.00	**65.70**	1.0	1.5
100	0	125	125	0.8	0	1	0	0	100	21.5	**27**	**21.5**	**0**	**16.17**	**1**	**1**	**0.96**	**15.52**	NA	NA	NA	40	0.85	0.80	27.20	NA	NA	NA	NA	**42.72**	**64.22**	1	1	1	1	1	1.00	**64.22**	2.1	3.2
100	0	125	125	0.8	0	1	0	0	100	21.5	23	18.0	12	17.67	NA	NA	NA	NA	**5.00**	**16.0**	**16.28**	40	0.85	0.80	27.20	40	0.85	0.80	**27.2**	**43.48**	**64.98**	1	1	1	1	1	1.00	**64.98**	1.4	2.2
100	0	125	125	0.8	0	1	0	0	100	21.5	23	18.0	12	17.67	NA	NA	NA	NA	**5.00**	**16.0**	**16.28**	40	**0.99**	0.80	**31.68**	40	**0.99**	0.80	**31.68**	**47.96**	**69.46**	1	1	1	1	1	1.00	**69.46**	3.1	4.8
100	0	125	125	0.8	0	1	0	0	100	21.5	23	18.0	12	17.67	NA	NA	NA	NA	**5.00**	**16.0**	**16.28**	40	**0.99**	0.80	**31.68**	40	**0.71**	0.80	**22.72**	**39.00**	**60.50**	1	1	1	1	1	1.00	**60.50**	5.9	8.4
100	0	125	125	0.8	0	1	0	0	100	21.5	23	18.0	12	17.67	NA	NA	NA	NA	**5.00**	**16.0**	**16.28**	40	**0.99**	0.80	**31.68**	40	0.85	**0.93**	**31.62**	**47.90**	**69.40**	1	1	1	1	1	1.00	**69.40**	3.0	5.0
100	0	125	125	0.8	0	1	0	0	100	21.5	23	18.0	12	17.67	NA	NA	NA	NA	**5.00**	**16.0**	**16.28**	40	**0.99**	0.80	**31.68**	40	0.85	**0.67**	**22.78**	**39.06**	**60.56**	1	1	1	1	1	1.00	**60.56**	5.81	8.7
100	0	125	125	0.8	0	1	0	0	100	21.5	23	18.0	12	17.67	NA	NA	NA	NA	NA	NA	NA	40	0.85	0.80	27.20	NA	NA	NA	NA	44.87	66.37	**0.84**	1	1	1	1	**0.84**	**55.75**	10.62	16.0
100	0	125	125	0.8	0	1	0	0	100	21.5	23	18.0	12	17.67	NA	NA	NA	NA	NA	NA	NA	40	0.85	0.80	27.20	NA	NA	NA	NA	44.87	66.37	1	**0.84**	1	1	1	**0.84**	**55.75**	10.62	16.0
100	0	125	125	0.8	0	1	0	0	100	21.5	23	18.0	12	17.67	NA	NA	NA	NA	NA	NA	NA	40	0.85	0.80	27.20	NA	NA	NA	NA	44.87	66.37	1	1	**1.16**	1	1	**1.16**	**76.99**	10.62	16.0
100	0	125	125	0.8	0	1	0	0	100	21.5	23	18.0	12	17.67	NA	NA	NA	NA	NA	NA	NA	40	0.85	0.80	27.20	NA	NA	NA	NA	44.87	66.37	1	1	**0.84**	1	1	**0.84**	**55.75**	10.62	16.0
100	0	125	125	0.8	0	1	0	0	100	21.5	23	18.0	12	17.67	NA	NA	NA	NA	NA	NA	NA	40	0.85	0.80	27.20	NA	NA	NA	NA	44.87	66.37	1	1	1	**0.84**	1	**0.84**	**55.75**	10.62	16.0

50% Increase and Decrease in IRMR Classification System Parameters

IRS (see Fig 57.3): % Strong Rock	IRS (see Fig 57.3): % Weak Rock	RBS Calculation: IRS (UCS)	RBS Calculation: Corrected IRS (MPa)	RBS Calculation: Homogeneous (Factor = 0.8)	Corrected RBS (Heterogeneous Conditions): Infill Type / Hardness	Corrected RBS: No. of Joints / m	Corrected RBS: Refer to Fig 57.4	Corrected RBS: % Adjust.	Corrected RBS: Rock Block Strength (MPa)	RBS Rating (Refer to Fig 57.5)	Joint Spacing – Open Joints (see Fig 57.6): J1	Open Joints: J2	Open Joints: J3	Open Joints: JS Rating	Multiple Joints: No. of Cemented Joints	Multiple Joints: Spacing of Cemented Joints (m)	Multiple Joints: Cemented Joint Adjustments (see Fig 57.7)	Multiple Joints: Adjusted Average Rating	Multiple Joints: No. of Joints / m	Multiple Joints: JS Rating	Average JS Rating	Joint Condition – Single Joints (see Table 57.1): Factor	Single Joints: Large	Single Joints: Small	Single Joints: JC Rating	Multiple Joints (see Table 57.8): Factor	Multiple Joints: Large	Multiple Joints: Small	Multiple Joints: JC Rating	TOTAL JOINT RATING	IN-SITU ROCK MASS RATING	Adjustments: Weathering	Adjustments: Orientation	Adjustments: Stresses	Adjustments: Blasting	Adjustments: Water/Ice	Adjustments: Total	IRMR RATING	Difference in MRMR Value	Percentage Difference (%)
100	0	125	125	0.8	0	1	0	0	100	21.5	23	18.0	12	17.67	NA	NA	NA	NA	NA	NA	NA	40	0.85	0.80	27.20	NA	NA	NA	NA	44.87	66.37	1	1	1	1	1	1.00	66.37	NA	NA
100	0	125	125	0.8	0	1	0	0	100	21.5	23	18.0	12	17.67	NA	NA	NA	NA	NA	NA	NA	40	0.85	0.80	27.20	NA	NA	NA	NA	44.87	66.37	1	1	1	1	**0.94**	0.94	**62.38**	4.0	6.0
50	**50**	125	**87.0**	0.8	**Calcite / 3**	1	**0.33**	**0.92**	**64.0**	**18.0**	23	18.0	12	17.67	NA	NA	NA	NA	NA	NA	NA	40	0.85	0.80	27.20	NA	NA	NA	NA	44.87	**62.87**	1	1	1	1	1	1.00	**62.87**	3.5	5.3
100	0	125	125	0.8	0	1	0	0	100	21.5	**28.5**	18.0	12	**19.50**	NA	NA	NA	NA	NA	NA	NA	40	0.85	0.80	27.20	NA	NA	NA	NA	46.70	**68.20**	1	1	1	1	1	1.00	**68.20**	1.8	2.9
100	0	125	125	0.8	0	1	0	0	100	21.5	23	**23.0**	12	**19.33**	NA	NA	NA	NA	NA	NA	NA	40	0.85	0.80	27.20	NA	NA	NA	NA	46.53	**68.03**	1	1	1	1	1	1.00	**68.03**	1.7	2.5
100	0	125	125	0.8	0	1	0	0	100	21.5	23	18.0	**17**	**19.33**	NA	NA	NA	NA	NA	NA	NA	40	0.85	0.80	27.20	NA	NA	NA	NA	46.53	**68.03**	1	1	1	1	1	1.00	**68.03**	1.7	2.5
100	0	125	125	0.8	0	1	0	0	100	21.5	**27**	**21.5**	**0**	**16.17**	**2**	**0.5**	**0.92**	**14.87**	NA	NA	NA	40	0.85	0.80	27.20	NA	NA	NA	NA	**42.07**	**63.57**	1	1	1	1	1	1.00	**63.57**	2.8	4.2

Appendix E: MRMR and IRMR Classification System Sedimentary Rock Data

Rock Type	Site	Pit Location	Lithology	No. of Data points	IRMR	MRMR
SEDIMENTARY	Kalgold	13100N (West)	SHL	1	56	51
		13100S (West)	SHL	2	54	48
		13300N (West)	CARB SHL	3	61	54
		13300S (West)	CARB SHL	4	53	48
		13100N (East)	SHL	11	37	34
		13100S (East)	SHL	12	39	36
		13300N (East) - 1140m	GW	15	36	32
		13300S (East) - 1140m	GW	16	38	34
		13300S (East)	GW	17	36	39
		13500S (East) - 1157m	GW	20	37	34
		13500S (East)	GW	21	35	36
		13700N (East) - 1145m	GW	22	45	43
		13700S (East) - 1145m	GW	23	42	40
		13900N (East)	GW	28	41	39
		13900S (East)	GW	29	41	38
		13900N (East) - 1164m	GW	30	40	34
		13900S (East) - 1164m	GW	31	39	33
	Colleen Bawn	Zone 1 (955L)	Limestone	32	58	56
		Zone 2 (935L)	Limestone	34	46	50
		Zone 3 (945L)	Limestone	36	57	54
		Zone 4 (955L)	Limestone	37	52	53
		Zone 4 (945L)	Limestone	38	60	57
		Zone 4 (935L)	Limestone	39	58	56
		Zone 4 (925L)	Limestone	40	52	56
		Zone 5 (970L)	Limestone	41	60	59
		Zone 5 (945L)	Limestone	42	67	59
		Zone 5 (925L)	Limestone	43	58	51
		Zone 6 (995L)	Limestone	45	55	56
		Zone 6 (965L)	Limestone	46	60	59
		Zone 7 (955L)	Schist	48	45	36
		Zone 7 (945L)	Limestone	49	60	57

Appendix F: MRMR and IRMR Classification System Igneous Rock Data

Rock Type	Site	Pit Location	Lithology	No. of Data points	IRMR	MRMR
IGNEOUS	Kalgold	13300N (East) - 1187m	VC	13	36	34
		13300S (East) - 1187m	VC	14	41	38
		13500N (East) - 1170m	VC	18	34	32
		13500S (East) - 1170m	VC	19	35	34
		13700N (East) - 1163m	VC	24	40	37
		13700S (East) - 1163m	VC	25	40	36
		13700N (East) - 1179m	VC	26	39	39
		13700S (East) - 1179m	VC	27	39	37
	Colleen Bawn	Zone 2 (925L)	Diabase Dyke	33	55	49
		Zone 3 (945L)	Diabase Dyke	35	51	51
		Zone 6 (980L)	Greenstone	44	36	26
		Zone 7 (965L)	Greenstone	47	42	36
	Marikana	B	Anorthosite	50	40	41
			Anorthosite	51	40	48
			Anorthosite	52	40	44
		C	Norite	53	39	41
			Norite	54	42	51
			Norite	55	42	47
			Anorthosite	56	42	50
			Anorthosite	57	40	41
		D	Anorthosite	58	39	42
			Anorthosite	59	38	42
			Anorthosite	60	38	47
			Anorthosite	61	32	37
			Anorthosite	62	37	35
			Anorthosite	63	29	33
			Anorthosite	64	26	27
			Anorthosite	65	29	32
			Anorthosite	66	31	41
			Anorthosite	67	28	30
			Anorthosite	68	18	27
		ROM	Norite	69	18	27
			Norite	70	23	30
			Norite	71	39	48
			Norite	72	23	33

Appendix G: MRMR and IRMR Classification System Metamorphic Rock Data

Rock Type	Site	Pit Location	Lithology	No. of Data points	IRMR	MRMR
METAMORPHIC	Kalgold	13500N (West)	SCH	5	61	59
		13500S (West)	SCH/BIF	6	61	62
		13700N (West)	SCH	7	55	51
		13700S (West)	SCH	8	54	51
		13900N (West)	SCH	9	56	51
		13900S (West)	SCH	10	53	49

Appendix H: Complete MRMR and IRMR Classification System Rock Data Set

Lithology	No. of Data points	IRMR	MRMR
SHL	1	56	51
SHL	2	54	48
CARB SHL	3	61	54
CARB SHL	4	53	48
SHL	11	37	34
SHL	12	39	36
GW	15	36	32
GW	16	38	34
GW	17	36	39
GW	20	37	34
GW	21	35	36
GW	22	45	43
GW	23	42	40
GW	28	41	39
GW	29	41	38
GW	30	40	34
GW	31	39	33
Limestone	32	58	56
Limestone	34	46	50
Limestone	36	57	54
Limestone	37	52	53
Limestone	38	60	57
Limestone	39	58	56
Limestone	40	52	56
Limestone	41	60	59
Limestone	42	67	59
Limestone	43	58	51
Limestone	45	55	56
Limestone	46	60	59
Schist	48	45	36
Limestone	49	60	57
VC	13	36	34
VC	14	41	38
VC	18	34	32
VC	19	35	34
VC	24	40	37
VC	25	40	36
VC	26	39	39
VC	27	39	37
Diabase Dyke	33	55	49
Diabase Dyke	35	51	51
Greenstone	44	36	26
Greenstone	47	42	36
Anorthosite	50	40	41
Anorthosite	51	40	48
Anorthosite	52	40	44
Norite	53	39	41
Norite	54	42	51
Norite	55	42	47
Anorthosite	56	42	50
Anorthosite	57	40	41
Anorthosite	58	39	42
Anorthosite	59	38	42
Anorthosite	60	38	47
Anorthosite	61	32	37
Anorthosite	62	37	35
Anorthosite	63	29	33
Anorthosite	64	26	27
Anorthosite	65	29	32
Anorthosite	66	31	41
Anorthosite	67	28	30
Anorthosite	68	18	27
Norite	69	18	27
Norite	70	23	30
Norite	71	39	48
Norite	72	23	33
SCH	5	61	59
SCH/BIF	6	61	62
SCH	7	55	51
SCH	8	54	51
SCH	9	56	51
SCH	10	53	49

Appendix I: Sedimentary Rock Statistical Analysis Results

Descriptive Statistics (Axum)	MRMR Sedimentary Rock	IRMR Sedimentary Rock
Min	32.00	35.00
Max	62.00	67.00
Sum	1755.00	1858.00
Mean	45.91	50.22
Median	48.00	53.00
Variance	98.22	89.01
Std. Dev.	9.91	9.43
Std. Err.	1.30	1.55
95 Conf Int	3.18	3.15
Descriptive Statistics (Excel)	**MRMR Sedimentary Rock**	**IRMR Sedimentary Rock**
Kurtosis	-1.70	-1.47
Mode	33.63	59.54
Skewness	-0.11	0.03
Range	27.00	32.00
Covariance	86.62	
Correlation coefficient	0.97	

Rock Type	Site	Pit Location	Lithology	No. of Points	IRMR	Bin	Frequency	MRMR	No. of Data points	Bin	Frequency
SEDIMENTARY	Kalgold	13100N (West)	SHL	1	**56**	10	0	**51**	1	10	0
		13100S (West)	SHL	2	**54**	20	0	**48**	2	20	0
		13300N (West)	CARB SHL	3	**61**	30	0	**54**	3	30	0
		13300S (West)	CARB SHL	4	**53**	40	8	**48**	4	40	13
		13100N (East)	SHL	11	**37**	50	7	**34**	11	50	3
		13100S (East)	SHL	12	**39**	60	14	**36**	12	60	15
		13300N (East) - 1140m	GW	15	**36**	70	2	**32**	15	70	0
		13300S (East) - 1140m	GW	16	**38**		0	**34**	16		0
		13300S (East)	GW	17	**36**			**39**	17		
		13500S (East) - 1157m	GW	20	**37**			**34**	20		
		13500S (East)	GW	21	**35**			**36**	21		
		13700N (East) - 1145m	GW	22	**45**			**43**	22		
		13700S (East) - 1145m	GW	23	**42**			**40**	23		
		13900N (East)	GW	28	**41**			**39**	28		
		13900S (East)	GW	29	**41**			**38**	29		
		13900N (East) - 1164m	GW	30	**40**			**34**	30		
		13900S (East) - 1164m	GW	31	**39**			**33**	31		
	Colleen Bawn	Zone 1 (955L)	Limestone	32	**58**			**56**	32		
		Zone 2 (935L)	Limestone	34	**46**			**50**	34		
		Zone 3 (945L)	Limestone	36	**57**			**54**	36		
		Zone 4 (955L)	Limestone	37	**52**			**53**	37		
		Zone 4 (945L)	Limestone	38	**60**			**57**	38		
		Zone 4 (935L)	Limestone	39	**58**			**56**	39		
		Zone 4 (925L)	Limestone	40	**52**			**56**	40		
		Zone 5 (970L)	Limestone	41	**60**			**59**	41		
		Zone 5 (945L)	Limestone	42	**67**			**59**	42		
		Zone 5 (925L)	Limestone	43	**58**			**51**	43		
		Zone 6 (995L)	Limestone	45	**55**			**56**	45		
		Zone 6 (965L)	Limestone	46	**60**			**59**	46		
		Zone 7 (955L)	Schist	48	**45**			**36**	48		
		Zone 7 (945L)	Limestone	49	**60**			**57**	49		

Appendix J: Igneous Rock Statistical Analysis Results

Descriptive Statistics (Axum)	**MRMR Igneous Rock**	**IRMR Igneous Rock**
Min	26.00	18.00
Max	51.00	55.00
Sum	1343.00	1261.00
Mean	38.37	36.03
Median	37.00	39.00
Variance	55.12	64.68
Std. Dev.	7.42	8.04
Std. Err.	1.25	1.36
95 Conf Int	2.55	2.76
Descriptive Statistics (Excel)	**MRMR IgneousRock**	**IRMR Igneous Rock**
Kurtosis	-0.95	0.70
Mode	27.00	#N/A
Skewness	0.13	-0.39
Range	24.00	37.00
Covariance	43.84	
Correlation coefficient	0.73	

Rock Type	Site	Pit Location	Lithology	No. of Data points	IRMR	Bin	Frequency	MRMR	No. of Data points	Bin	Frequency
IGNEOUS	Kalgold	13300N (East) - 1187m	VC	13	**36**	10	0	**34**	13	10	0
		13300S (East) - 1187m	VC	14	**41**	20	2	**38**	14	20	0
		13500N (East) - 1170m	VC	18	**34**	30	6	**32**	18	30	5
		13500S (East) - 1170m	VC	19	**35**	40	18	**34**	19	40	15
		13700N (East) - 1163m	VC	24	**40**	50	7	**37**	24	50	13
		13700S (East) - 1163m	VC	25	**40**	60	2	**36**	25	60	2
		13700N (East) - 1179m	VC	26	**39**	70	0	**39**	26	70	0
		13700S (East) - 1179m	VC	27	**39**			**37**	27		
	Colleen Bawn	Zone 2 (925L)	Diabase Dyke	33	**55**			**49**	33		
		Zone 3 (945L)	Diabase Dyke	35	**51**			**51**	35		
		Zone 6 (980L)	Greenstone	44	**36**			**26**	44		
		Zone 7 (965L)	Greenstone	47	**42**			**36**	47		
	Marikana	B	Anorthosite	50	**40**			**41**	50		
			Anorthosite	51	**40**			**48**	51		
			Anorthosite	52	**40**			**44**	52		
		C	Norite	53	**39**			**41**	53		
			Norite	54	**42**			**51**	54		
			Norite	55	**42**			**47**	55		
			Anorthosite	56	**42**			**50**	56		
			Anorthosite	57	**40**			**41**	57		
		D	Anorthosite	58	**39**			**42**	58		
			Anorthosite	59	**38**			**42**	59		
			Anorthosite	60	**38**			**47**	60		
			Anorthosite	61	**32**			**37**	61		
			Anorthosite	62	**37**			**35**	62		
			Anorthosite	63	**29**			**33**	63		
			Anorthosite	64	**26**			**27**	64		
			Anorthosite	65	**29**			**32**	65		
			Anorthosite	66	**31**			**41**	66		
			Anorthosite	67	**28**			**30**	67		
			Anorthosite	68	**18**			**27**	68		
		ROM	Norite	69	**18**			**27**	69		
			Norite	70	**23**			**30**	70		
			Norite	71	**39**			**48**	71		
			Norite	72	**23**			**33**	72		

Appendix K: Metamorphic Rock Statistical Analysis Results

Descriptive Statistics (Axum)	MRMR Metamorphic Rock	IRMR Metamorphic Rock
Min	49.00	53.00
Max	62.00	61.00
Sum	323.00	340.00
Mean	53.83	56.67
Median	51.00	55.50
Variance	28.17	12.27
Std. Dev.	5.31	3.50
Std. Err.	2.17	1.43
95 Conf Int	5.57	3.68
Descriptive Statistics (Excel)	**MRMR Metamorphic Rock**	**IRMR Metamorphic Rock**
Kurtosis	-0.83	-1.64
Mode	51.44	#N/A
Skewness	0.98	0.54
Range	13.00	8.00
Covariance	14.12	
Correlation coefficient	0.76	

Rock Type	Site	Pit Location	Lithology	No. of Points	IRMR	Bin	Frequency	MRMR	No. of Data points	Bin	Frequency
METAMORPHIC	**Kalgold**	13500N (West)	SCH	5	61	40	0	59		40	0
		13500S (West)	SCH/BIF	6	61	50	0	62		50	1
		13700N (West)	SCH	7	55	60	4	51		60	4
		13700S (West)	SCH	8	54	70	2	51		70	1
		13900N (West)	SCH	9	56	80	0	51		80	0
		13900S (West)	SCH	10	53	90	0	49		90	0

Appendix L: MRMR and IRMR Data Set Statistical Analysis Results

Descriptive Statistics (Axum)	**MRMR**	**IRMR**
Min	26.00	18.00
Max	62.00	67.00
Sum	3098.00	3119.00
Mean	43.03	43.32
Median	41.00	40.00
Variance	93.41	127.09
Std. Dev.	9.66	11.27
Std. Err.	1.14	1.33
95 Conf Int	2.27	2.65
Descriptive Statistics (Excel)	**MRMR**	**IRMR**
Kurtosis	-1.15	-0.54
Mode	33.63	59.54
Skewness	0.16	0.03
Range	35.88	49.02
Covariance	96.56	
Correlation coefficient	0.90	

No.of Data Points	MRMR	Bin	Frequency	IRMR	Bin	Frequency
1	51	0	0	56	0	0
2	48	5	0	54	5	0
3	54	10	0	61	10	0
4	48	15	0	53	15	0
5	34	20	0	37	20	2
6	36	25	0	39	25	2
7	32	30	5	36	30	4
8	34	35	14	38	35	4
9	39	40	14	36	40	22
10	34	45	8	37	45	13
11	36	50	9	35	50	1
12	43	55	11	45	55	9
13	40	60	10	42	60	11
14	39	65	1	41	65	3
15	38	70	0	41	70	1
16	34	75	0	40	75	0
17	33		0	39		0
18	56			58		
19	50			46		
20	54			57		
21	53			52		
22	57			60		
23	56			58		
24	56			52		
25	59			60		
26	59			67		
27	51			58		
28	56			55		
29	59			60		
30	36			45		
31	57			60		
32	34			36		
33	38			41		
34	32			34		
35	34			35		
36	37			40		
37	36			40		
38	39			39		
39	37			39		
40	49			55		
41	51			51		
42	41			40		
43	48			40		
44	44			40		
45	41			39		
46	51			42		
47	47			42		
48	50			42		
49	41			40		
50	42			39		
51	42			38		
52	47			38		
53	37			32		
54	35			37		
55	33			29		
56	27			26		
57	32			29		
58	41			31		
59	30			28		
60	27			18		
61	27			18		
62	30			23		
63	48			39		
64	33			23		
65	26			36		
66	36			42		
67	59			61		
68	62			61		
69	51			55		
70	51			54		
71	51			56		
72	49			53		