Optimising Geotechnical Logging to Accurately Represent the Geotechnical Environment

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ABSTRACT

Typically, large volumes of data are collected during geotechnical investigations for mining projects but rarely is this done in a comprehensive manner that enables all aspects of the geotechnical environment to be evaluated.

A geotechnical core logging process has been developed to record mechanical and structural properties of the rock mass. The method enables data for a wide range of rock properties and geotechnically significant major structures to be collected including rock strength, joint surface condition, fracture frequency and fracture orientation. The logging method is unique in that sufficient data is collected to enable the independent determination of all the major rock mass classification systems including rock mass rating (RMR), (Bieniawski 1976, 1989; Laubscher, 1990) Norwegian Geotechnical Institute (NGI) tunnelling quality index (Q) (Barton, Lien and Lunde, 1974) and geological strength index (GSI) (Hoek, Kaiser and Bawden, 1995).

The logging system has been specifically developed to allow better and more precise appreciation of rock mass and structural conditions across the project area thereby optimising the use and application of the available geotechnical data and improving confidence in the outcomes of geotechnical investigations.

This paper describes the core logging process with case examples showing how the logged data can be used for underground and open pit mine design.

INTRODUCTION

Large volumes of geotechnical data are often collected during the life of a mining project but this data is rarely ever effectively and comprehensively collected to represent the rock mass conditions across the project. The purpose of geotechnical core logging is to get an appreciation of the rock conditions and apply these understandings to mine design.

There are many different forms of geotechnical core logging data collection that range from established methods through to project/outcome specific templates developed ‘in-house’. The format and legend for logging that is presented in this paper has evolved with development of the mining rock mass model (Seymour, Dempers and Jenkins, 2007; Jenkins, Dempers and Seymour, 2009). It differs from other logging schemes in that it is designed to help highlight rock mass variability and in particular those regions or conditions in the rock mass that are likely to be problematic for design purposes.

The core logging method developed requires the core to be grouped into logging intervals that are unique geotechnical domains or designs regions within a particular rock type. Most of the logged parameters and definitions have been used in other logging and rating schemes. However, it is the dedicated use of the logging technique and it’s refinement through creating mining rock mass models for a wide variety of different projects that make this a rigorous, robust and unique method. It has been used with equal success in many different environments and for both open pit and underground projects. The geotechnical domains are determined by grouping together rock which displays similar geotechnical characteristics and which will behave uniformly in an excavation. This domain logging allows the variability of rock mass conditions within and across individual lithological/geological/structural units to be identified more readily than fixed interval methods with logging per metre or per drill run.

As such, a domain can be many metres in length or less than one metre and is determined from significant lithological boundaries which are then further subdivided according to geological structure, weathering, hydrogeology, veining and alteration within those major lithological boundaries.

After the rock has been grouped into geotechnical domains, each relevant parameter required for geotechnical evaluation is then logged within a particular geotechnical domain. Selected parameters include rock strength, discontinuity condition, rock quality designation (RQD), discontinuity count per fracture angle and discontinuity orientation. The

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logging scheme ensures that sufficient data is collected within each domain to enable the independent determination of all the major rock mass classification systems including rock mass rating (RMR), Bieniawski or Laubscher, NGI tunnelling quality index (Q) and geological strength index (GSI).

Examples of domaining are shown in Figure 1 to Figure 2.

GEOTECHNICAL LOGGING PARAMETERS

Geotechnical logging parameters capture all relevant information for the major rock classification systems. The following parameters are recorded within each geotechnical domain:

- hole identification and from and to interval for the geotechnical domain interval logged,
- rock type,
- weathering,
- estimated rock strength,
- 'core 10', the total length of all core pieces >10 cm,
- matrix and structure type including faults, intense fracturing, sheared rock, discing,
- number of joint sets,
- number of fractures per fracture angle grouping,
- joint roughness (micro and macro),
- fracture infill, infill type and thickness,
- joint wall alteration, and
- comments.

A completed logging sheet is shown in Figure 3. Hole identification, From and To columns and comments column entries require no further explanation but definition of the other logged parameters is provided as follows.

Geotechnical interval

The geotechnical interval is the length of drill core which has been grouped into a geotechnical domain measured in metres down the borehole. The geotechnical domain can extend over many metres. Geotechnical intervals should reflect rock mass domains at the engineering scale and not small variations within these. Exceptions are ore zones; significant structural zones, faults or shears or very weak zones that need to be highlighted in the log. Where these features occur in reasonably close proximity they can be grouped into a single logged interval.

Rock type

This is usually the predominant rock type within a particular geotechnical domain, rather than slight variation within the domain.

Weathering

The degree of weathering to which the rock has been exposed rated on a scale of one to five as follows:

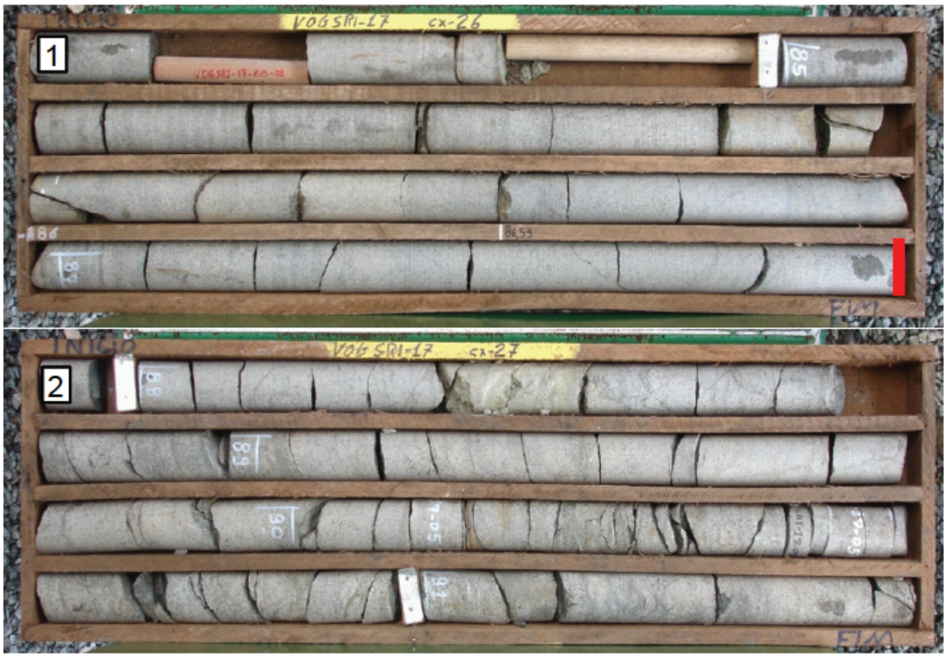

FIG 1 - Example showing domain separation based on strength and RQD: 1 = strength of four and 100 per cent RQD; and 2 = strength of 2.5 and RQD much <100 per cent.

FIG 2 - Example showing domain separation based on RQD: 1 and 3 = 100 per cent RQD; and 2 = RQD <100 per cent.

Hole-id	From	To	Rock Type	Weath (1-5)	QSI (1-5)	RQD (m)	Matrix Struct Type	No.Sets	Fract 0-30	Micro (1-9) 0-30	Macro (1-5) 0-30	Infill (1-9) 0-30	Infill type	Infill Thick	JWA (1-3)	Fract 0-90	Micro (1-9) 0-90	Macro (1-5) 0-90	Infill (1-9) 0-90	Infill type	Infill Thick	JWA (1-3)	Comments
MWRD142	50.0	65.0	tuff	3.5	2.5	2.10		3.5								250	3	2	5	iox/cly		1	NQ core ~3.0m loss mech broken/crushed i/p fol/lay i/p
MWRD142	65.0	65.7	tuff	3	3	0.50		2.5	7	7	2	5	iox/cly		1								fol/lay
MWRD142	65.7	66.5	tuff	2.5	3	0.60		2.5	6	5	2	5	iox/cly		1								fol/lay
MWRD142	66.5	69.6	tuff	2.5	2.5	1.30		3	45	3	2	5	iox/cly		1								
MWRD142	69.6	71.8	tuff	3.5	1.5	0.01	m3	4.5	100	5	2	5	iox/cly		1								fol/lay ~ 0.4m loss mech broken/crushed i/p
MWRD142	71.8	73.2	tuff	2.5	2.5	1.00		2.5	18	5	2	5	iox/cly		1								fol/lay
MWRD142	73.2	81.5	tuff	2	3	4.90		2.5	80	2	2	4	iox/cly		1								fol/lay
MWRD142	81.5	83.2	tuff	2.5	2	0.40		3.5	50	4	2	5	iox/cly		1								fol/lay mech broken i/p
MWRD142	83.2	86.2	tuff	2.5	2.5	1.60		2.5	28	2	2	6			1								fol/lay
MWRD142	86.2	86.5	tuff	3	1	0.01	m2	4.5								250	4	2	5	iox/cly		1	sheared
MWRD142	86.5	88.0	tuff	2.5	2.5	0.90		2.5	14	7	2	6			1								fol/lay
MWRD142	88.0	88.1	tuff	3.5	1	0.01	m3	4.5	100	5	2	5	iox/cly		1								
MWRD142	88.1	90.5	tuff	2.5	2.5	1.00		2.5	38	4	2	5	iox/cly		1								fol/lay i/p
MWRD142	90.5	91.2	tuff	2.5	1.5	0.01	m3	4.5	100	5	2	5	iox/cly	1	1								~0.1m loss
MWRD142	91.2	92.7	tuff	2	3	1.30		2.5	13	5	2	5	iox		1								fol/lay
MWRD142	92.7	93.5	tuff	2	2.5	0.20		2.5	13	8	2	5	iox		1								highly fol/lay
MWRD142	93.5	95.5	tuff	2	3	2.00		2.5	6	5	2	5	iox		1								highly fol/lay
MWRD142	95.5	95.6	tuff	2	1	0.01	m2	4.5	50	4	2	4	cly	2	1								sheared
MWRD142	95.6	97.3	tuff	2	3	1.40		2.5	11	4	2	5	iox		1								fol/lay
MWRD142	97.3	98.4	tuff	2	0.5	0.01	m2	5								250	1	2	3	cly	5	1	fol/lay/sheared ~0 2m loss
MWRD142	98.4	98.8	tuff	2	1.5	0.01		2.5	12	1	2	4	iox/cly		1								fol/lay
MWRD142	98.8	99.7	tuff	2	3	0.80		2.5	8	4	2	6			1								fol/lay
MWRD142	99.7	101.2	?mafic tuff	2	2	0.30	m2	3.5	75	4	2	5	iox/cly		1								fol/lay/sheared core split from 101 0 m
MWRD142	101.2	101.8	?mafic tuff/?dol	2	1	0.01	m2	4.5	100	1	2	5	iox/cly		1								sheared ~0.3m loss ? Dol contact zone Jw zone split
MWRD142	101.8	102.6	?dol	1.5	2	0.30		2.5	10	6	2	7	iox		1								split
MWRD142	102.6	104.8	chlor hem	1	3	2.10		2.5	5	8	2	5	iox/cly		1								split
MWRD142	104.8	106.6	chlor tuff	1	1	0.10	m2	4.5	100	1	2	5	chlor		1								split micro-fractured sheared ~0.4m loss
MWRD142	106.6	112.6	hem/chlor hem	1	3	5.70		2.5	18	8	2	5	cly		1								split
MWRD142	112.6	113.7	chlor/hem tuff	1	1	0.01	m2	4.5	100	7	2	5	cly/chlor		1								split micro-fractured ~0.2m loss
MWRD142	113.7	115.6	hem/chlor hem	1	3	1.80		2.5	5	8	2	8			1								split micro-fractured i/p
MWRD142	115.6	117.8	chlor tuff	1	1	0.01	m2	4.5	100	1	2	6	chlor		1								split micro-fractured ~1.0m loss
MWRD142	117.8	121.4	tuff	1	3	3.50		2.5	8	2	2	5	iox		1								split to 119 0m ~massive Jw zone
MWRD142	121.4	121.7	tuff	2	2.5	0.10		2.5	6	5	2	5	iox	1	1								~massive Jw zone
MWRD142	121.7	122.0	tuff	2.5	1.5	0.01	m3	4.5	50	2	2	5	iox	2	1								Jw zone
MWRD142	122.0	123.1	tuff	2	2.5	0.20		2.5	12	5	2	5	iox		1								~massive Jw zone
MWRD142	123.1	129.5	tuff	1	3	6.10		2.5	26	2	2	5	iox	1	1								127.1m: 1X 10mm cly/fault gouge infilled

FIG 3 - Typical rock mass log (note 30° - 60° and 60° - 90° log not shown).

1. unweathered,
2. slightly weathered,
3. moderately weathered,
4. highly weathered, and
5. completely weathered.

Quality strength index

The quality strength index (QSI) reflects the average? estimated rock strength within a geotechnical domain. The logged QSI range is from extremely weak (0.5) to extremely strong (five). RMR ratings and equivalent uniaxial compressive strengths (UCS) for possible logged values are shown in Table 1. Various published field estimates for UCS can be used to help determine these ratings, for example Hoek, Kaiser and Bawden (1995).

Rock quality designation

Rock quality designation (RQD) is the percentage of the drilled length of a geotechnical domain which has recovered core lengths of 10 cm or greater. 'Core 10' is the total length of core which is greater than 10 cm within a geotechnical domain which is measured and recorded in the log. RQD is later calculated according to the following:

$$\text{RQD}\,\% \frac{\text{Total length of core} > 10\text{ cm}}{\text{Length of geotechnical domain}} \times 100$$

Matrix and structure codes

Matrix and structure codes are additional descriptors used to help highlight conditions of geotechnical significance. As such, they are not recorded for every logged interval but are used sparingly for exceptional circumstances. The matrix codes most commonly used are:

- M1 – fault (discrete),
- M2 – shear zone,
- M3 – intense fracturing,
- M4 – intense mineralisation (usually ore),
- M5 – deformable material,
- M6 – discing (record metres in the comments column), and
- M7 – vuggy.

Additional project specific matrix codes may be employed where appropriate to indicate specific types of pervasive alteration, veining or other unique geotechnical features within the rock mass.

Joint sets

This is the number of joint sets present within a geotechnical domain. The Q classification rating number associated with the logged number of joint sets is given in Table 2. Logged values are generally 2.5 or greater if the logged intervals reflect geotechnical domains at the engineering scale. That is, at the scale of a tunnel wall or batter slope, rather than of intact rock blocks between joints.

Fractures per interval

This is the counted number of fractures per fracture angle grouping, or 'bin' within the logged interval. Fracture angle bins

TABLE 1

Quality strength index.

Description	Logged value	RMR[†] rating	Equivalent UCS (MPa)	UCS range (MPa)
Extremely weak	0.5	1	1	<1
Very weak	1.0	1	4	1 - 5
Weak	2.0	3	25	5 - 25
Moderately strong	2.5	6	64	25 - 65
Strong	3.0	10	100	66 - 105
Strong to very strong	3.5	13	134	106 - 140
Very strong	4.0	15	154	141 - 160
Very hard to extremely strong	4.5	17	174	161 - 185
Extremely strong	5.0	18	185	>185

[†] IRS strength rating for RMR after Laubscher (1990).

TABLE 2

Logged number of joint sets and Jn rating.

Description	Logged values	Q joint set number rating (Jn)
Massive or few joints	0.5	1
One joint set	1.0	2
One joint set plus random joints(s)	1.5	3
Two joint sets	2.0	4
Two joint sets plus random joints(s)	2.5	6
Three joint sets	3.0	9
Three joint sets plus random joints(s)	3.5	12
Four or more joint sets, random, heavily jointed	4.0	15
Crushed rock, earth-like	5.0	20

are 0° - 30°, 30° - 60° and 60° - 90° with 0° being parallel to the core axis.

Only obvious pre-existing structures that are continuous planes of weakness right through the core stick should be counted. These include core breaks that are obviously joints, foliation/bedding, faults, shears or veins. Annealed structures that are not weaknesses or have not broken continuously through the core are not counted. Also not counted are drilling breaks or core handling induced breaks, such as at the end of the core run or core box row, unless these are obviously along natural weaknesses. Breaks along foliation should all be counted. Foliations that are cleanly broken through the core by the time it is logged are weak enough to be (for example) potential wedge forming planes of weakness in a tunnel or stope wall.

In areas of highly fractured ground where fractures cannot be easily counted, a fourth fracture angle bin (0° - 90°) is used and, one of three fracture count numbers are entered into the 0 - 90° fracture angle bin, depending on the intensity of fracturing:

- 1000 – highly fractured and broken rock that does not display any joint surfaces (all fragments 'corn flake' sized or less),
- 500 – ground is fractured and broken to a lesser degree and may contain some joint surfaces (average fragment is approximately 'match-box' to 'corn flake' sized), and
- 250 – ground is fractured and broken and may contain some joint surfaces (average fragment is larger than 'match-box' sized).

Examples of some 0° - 90° fracture bin zones are shown in Figure 4. Note that a matrix code (as discussed previously under Matrix and Structure codes) should always be recorded where a 250, 500 or 1000 fracture count has been used.

The RMR ratings for relevant fracture frequencies and numbers of joint sets is presented in Table 3. Note that for assignment of fracture frequency to the 0 - 90° bin logged values (250, 500 or 1000) more appropriate numbers of joints, based on the interval length, are used for rating calculation purposes.

Fracture characteristics

Fracture characteristics are logged for each fracture angle bin. Fracture characteristics comprise a fracture count, macro and micro-roughness, infill condition and type and joint wall alteration (JWA). These descriptors (excluding macro-roughness) represent fracture surface characteristics at the scale of the core specimen. Macro-roughness describes

TABLE 3

Fracture frequency, after Laubscher (1990).

Average joints per metre	RMR rating – 2 joint sets	RMR rating – 3 joint sets
0.10	40	40
0.15	40	40
0.20	40	38
0.25	38	36
0.30	36	34
0.50	34	31
0.80	31	28
1.00	28	26
1.50	26	24
2.00	24	21
3.00	21	18
5.00	18	15
7.00	15	12
10.00	12	10
15.00	10	7
20.00	7	5
30.00	5	2
40.00	2	0

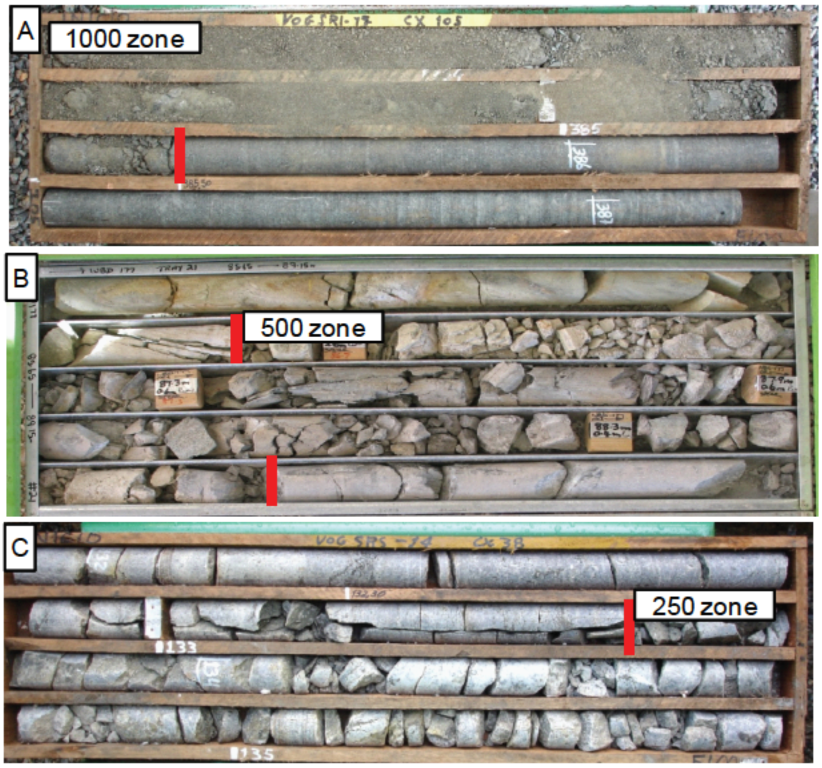

FIG 4 - Examples of 0° - 90° zones where matrix code of M3 applies.

the large-scale joint surface characteristics at the scale of exposure (several metres). For logging purposes and unless the specific joint condition is known, a macro-roughness default descriptor of 'undulating' (logged value of two) is applied.

When recording joint infill characteristics, slight traces of infill material (not continuous over the fracture surface) that do not influence the shear strength/cohesion of the structure, are for geotechnical purposes not considered as infill and the structure is recorded as 'clean'. Fracture infill and alteration codes are based on the Q Index and RMR classification systems.

Joint wall alteration is logged according to the effect of alteration on the wall rock of the joint as per Table 8.

Relevant logged values for each joint characteristic are shown in Table 4 to Table 8 and where appropriate, equivalent classification ratings are also provided.

INTERPRETATION OF GEOTECHNICAL LOGGING

The raw logging data can be used to calculate various geotechnical parameters and rock mass rating values, for example RMR (Laubscher, 1990), rock tunnel quality index, Q (Barton, Lien and Lunde, 1974) and GSI (Hoek, Kaiser and Bawden, 1995). RMR is calculated as follows:

$$RMR = FF + IRS + Jc$$

where:

Input parameter	**Rating range**	
Intact rock strength (IRS):	0 - 20	(Table 1)
Fracture frequency per joint set (FF):	0 - 40	(Table 3)
Joint condition (Jc):	0 - 40 (40 × micro × macro × infill × JWA from Tables 4,5, 6 and 8)	

Q is calculated as follows:

$$Q = RQD\%/Jn \times Jr/Ja \times Jw/SRF$$

where:

RQD = rock quality designation
Jn = joint set number (Table 2)
Jr = joint roughness number (Table 4)
Ja = joint alteration number (Table 6)
J_w = joint water reduction factor, assumed to be 1 (0.1 - 1)
SRF = stress reduction factor (0.5 - 20)

Based on the quantitative approach (Cai *et al* 2004), GSI can be determined from block size (joint spacing) and the joint condition factor defined as follows:

$$Jc = Jw \times Js/Ja$$

where:

Jw = large-scale waviness determined from logged macro joint roughness (Table 5)
Js = small scale smoothness determined from logged micro joint roughness (Table 4)
Ja = joint alteration determined from logged infill condition (Table 6)

The rock mass can be classified according to GSI as shown in Figure 5.

TABLE 4

Micro joint roughness.

Description	Logged value	RMR rating (moderate water)	RMR rating (dry)	Q joint roughness rating (Jr)	GSI rating (Js)	JRC
Polished or slickensided and planar	1	0.45	0.55	0.5	0.5	0.5
Smooth and planar	2	0.50	0.60	1.0	1.0	1.0
Rough and planar	3	0.55	0.65	1.5	1.0	2.0
Slickensided undulating	4	0.60	0.70	1.5	1.5	3.0
Smooth undulating	5	0.65	0.75	2.0	1.5	4.0
Rough undulating	6	0.70	0.80	3.0	2.0	5.0
Slickensided stepped	7	0.75	0.85	3.0	2.0	6.0
Smooth stepped	8	0.80	0.90	3.0	3.0	7.0
Rough stepped	9	0.85	0.95	3.0	3.0	8.0

TABLE 5

Macro joint roughness.

Description	Logged value	RMR rating (moderate water)	RMR rating (dry)	GSI rating (Jw)
Planar	1	0.65	0.75	1.0
Undulating	2	0.75	0.80	1.5
Curved	3	0.75	0.85	2.0
Irregular, unidirectional	4	0.85	0.95	2.5
Irregular multi-directional	5	0.95	1.00	3.0

TABLE 6

Joint infill condition.

Description	Logged value	RMR rating (moderate water)	RMR rating (dry)	Q joint alteration rating (Ja)	GSI rating (Ja)
Gouge >amplitude[†]	1	0.15	0.30	12	12
Gouge <amplitude[†]	2	0.35	0.45	8	6
Soft sheared – fine	3	0.40	0.50	4	4
Soft sheared – medium	4	0.50	0.60	4	4
Soft sheared – coarse	5	0.60	0.70	4	4
Non-softening – fine	6	0.70	0.80	3	3
Non-softening – medium	7	0.75	0.85	3	2
Non-softening – coarse	8	0.80	0.90	2	1
Clean/surface staining	9	0.90	1.00	1	1

[†] Gouge thickness greater or less than the amplitude of joint surface irregularities.

TABLE 7

Infill thickness.

Description	Logged value
Clean, no infill or insignificant	0
Thickness of infill <1 mm	1
Thickness of infill <5 mm	2
Thickness of infill >5 mm	3
Sheared with no wall contact or thick zones of highly weathered material	4

TABLE 8

Joint wall alteration (JWA).

Description	Logged value	RMR rating
JWA = rock hardness	1	1.00
JWA (dry) weaker than wall rock and filling	2	0.75
JWA (wet) weaker than wall rock and filling	3	0.65

Rock mass ratings can then be used as input to develop three dimensional block models using the resource estimation routines currently available in geological software packages (Seymour, Dempers and Jenkins, 2007; Jenkins, Dempers and Seymour, 2009). The domaining methodology allows for variability of the rock mass to be identified and defined during the logging process. Realistic domaining of the geotechnical logging, as opposed to fixed interval logging, enables valid statistical ranges, averages and quartile values to be readily determined from the block models. A cross-section through a rock mass model illustrating variability with a single lithological unit is shown in Figure 6.

The models can also be interrogated based on specific geotechnical parameters. The parameters may include rock strength, shear strength and block size. Matrix codes and 0°-90° bin joint numbers are also useful for model interrogation and refinement, although these parameters are not used in any of the rating calculations. The ranges of the parameters that are routinely interrogated in the modelling process are presented in Table 9. An example of the variation in two of these critical parameters within an underground project setting is given in the circled areas of Figures 7 and 8. The rock strength is classified as very good (UCS >160 MPa) in Figure 4 but is poor to fair (Jr/Ja <2) in terms of joint shear strength (Figure 8).

CONCLUSIONS

The development of the domaining logging system has enabled the transfer of an accurate representation of the rock mass and structure to be applied to block, numerical and limit equilibrium models for rigorous analysis of both underground and open pit projects.

A benefit of this technique is that rock testing can then be based on the true rock mass domain variability, rather than just testing according to rock type. Hence, test samples are picked from the domains and major structures and joint sets identified that are relevant to the engineering structure and its scale. After testing has been completed, the domains can be calibrated against test data

The value of the domaining process has been realised in several studies where the presence of major structures, variable rock units or zones of extremely soft rock caused by alteration have been identified as domains.

The logging method is unique in that sufficient data is collected to enable the independent determination of all the major rock mass classification systems such as rock mass rating (RMR), Bieniawski or Laubscher, NGI tunnelling quality index (Q) and geological strength index (GSI).

The method enables data for a wide range of rock properties and geotechnically significant major structures to be collected including rock strength, joint surface condition, fracture frequency and fracture orientation.

The logging system has been specifically developed to allow better and more precise appreciation of rock mass and structural conditions across the project area thereby optimising the use and application of the available geotechnical data and improving confidence in the outcomes of geotechnical investigations.

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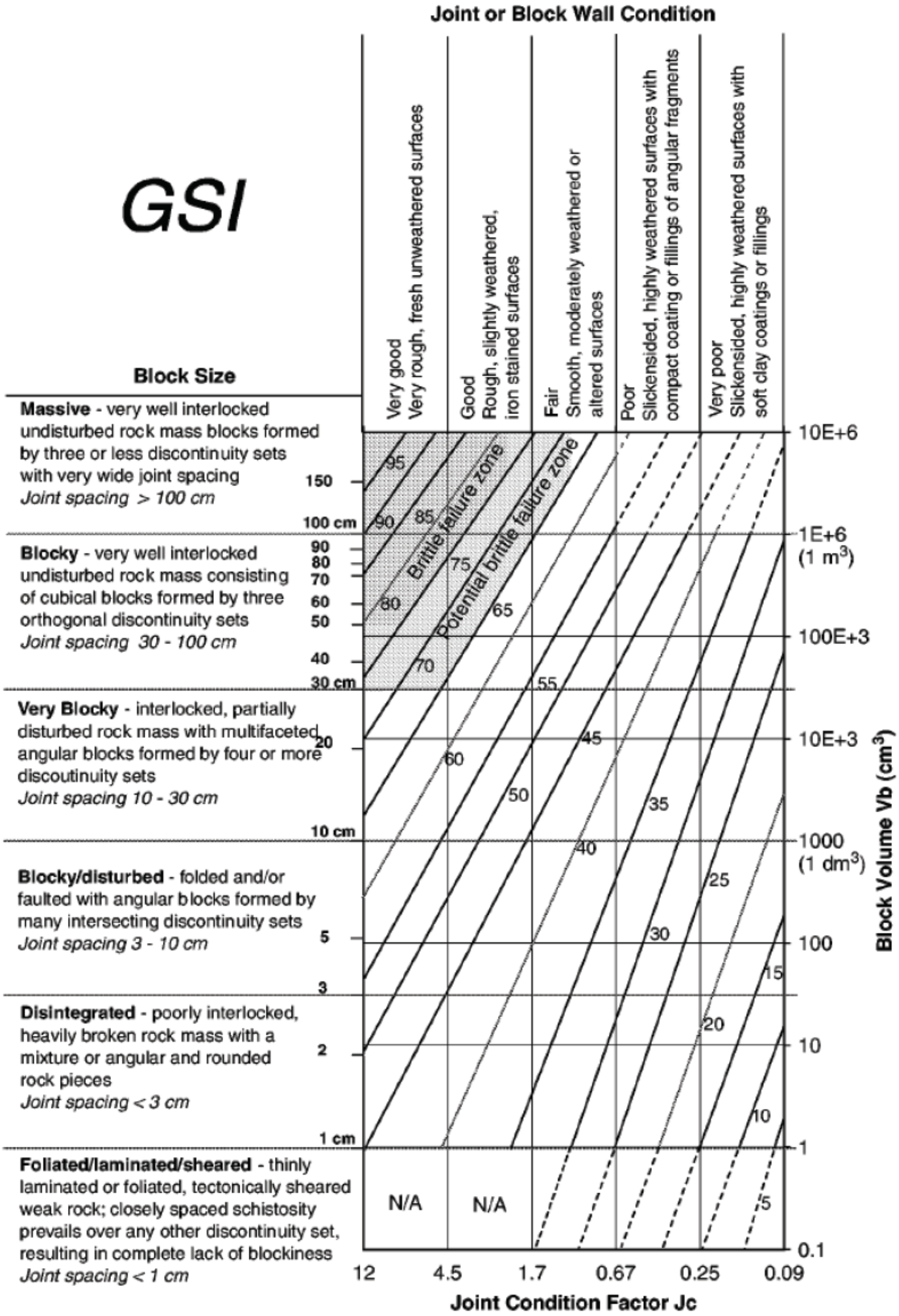


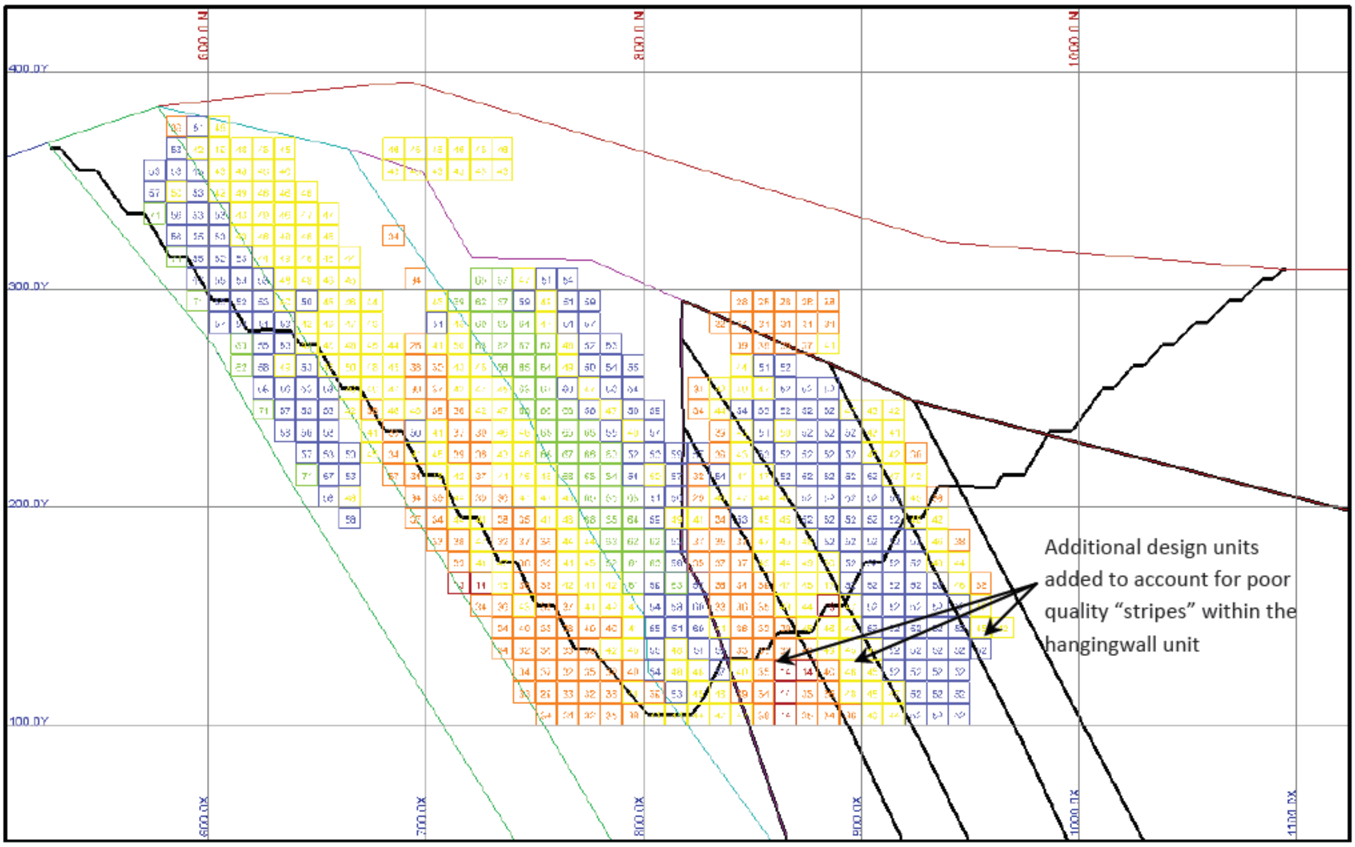
FIG 5 - Geological strength index classification chart (after Cai *et al*, 2004).

TABLE 9

Geotechnical parameters.

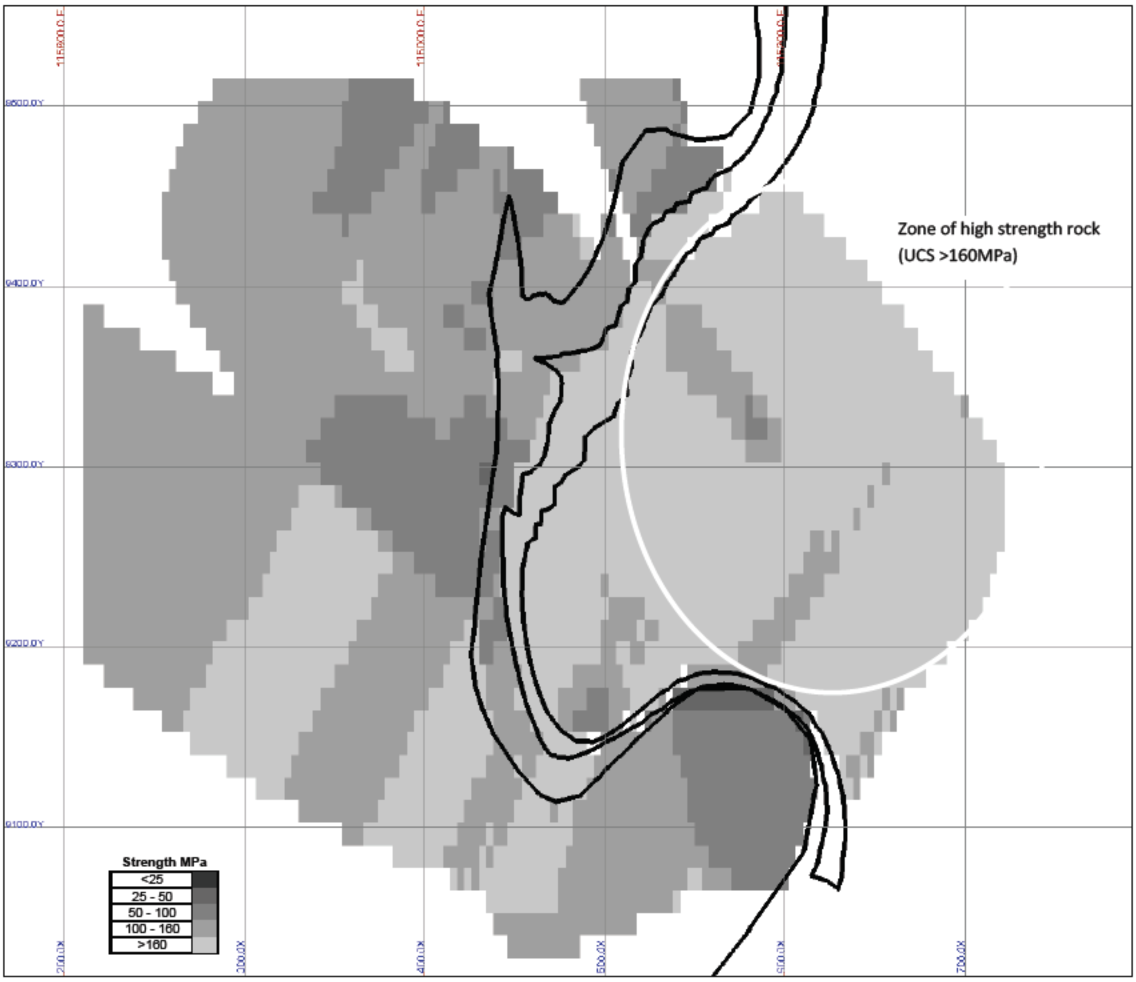
Parameter	Very poor	Poor	Fair	Good	Very good
Joint intensity (RQD/Jn)†	<4	4 - 8	8 - 15	15 - 25	>25
Joint shear strength (Jr/Ja)†	<0.5	0.5 - 0.75	0.75 - 2	2 - 3	>3
Fracture frequency (FF/m)	>15	3 - 15	1 - 3	0.3 - 1	<0.3
Rock strength (MPa)	<25	25 - 50	50 - 100	100 - 160	>160

†Geotechnical parameters for joint intensity and joint shear strength after McCracken and Stacey (1989).



Additional design units added to account for poor quality "stripes" within the hangingwall unit

FIG 6 - Cross-section showing variability within individual lithological units.



Zone of high strength rock (UCS >160MPa)

FIG 7 - Block model showing rock strength.

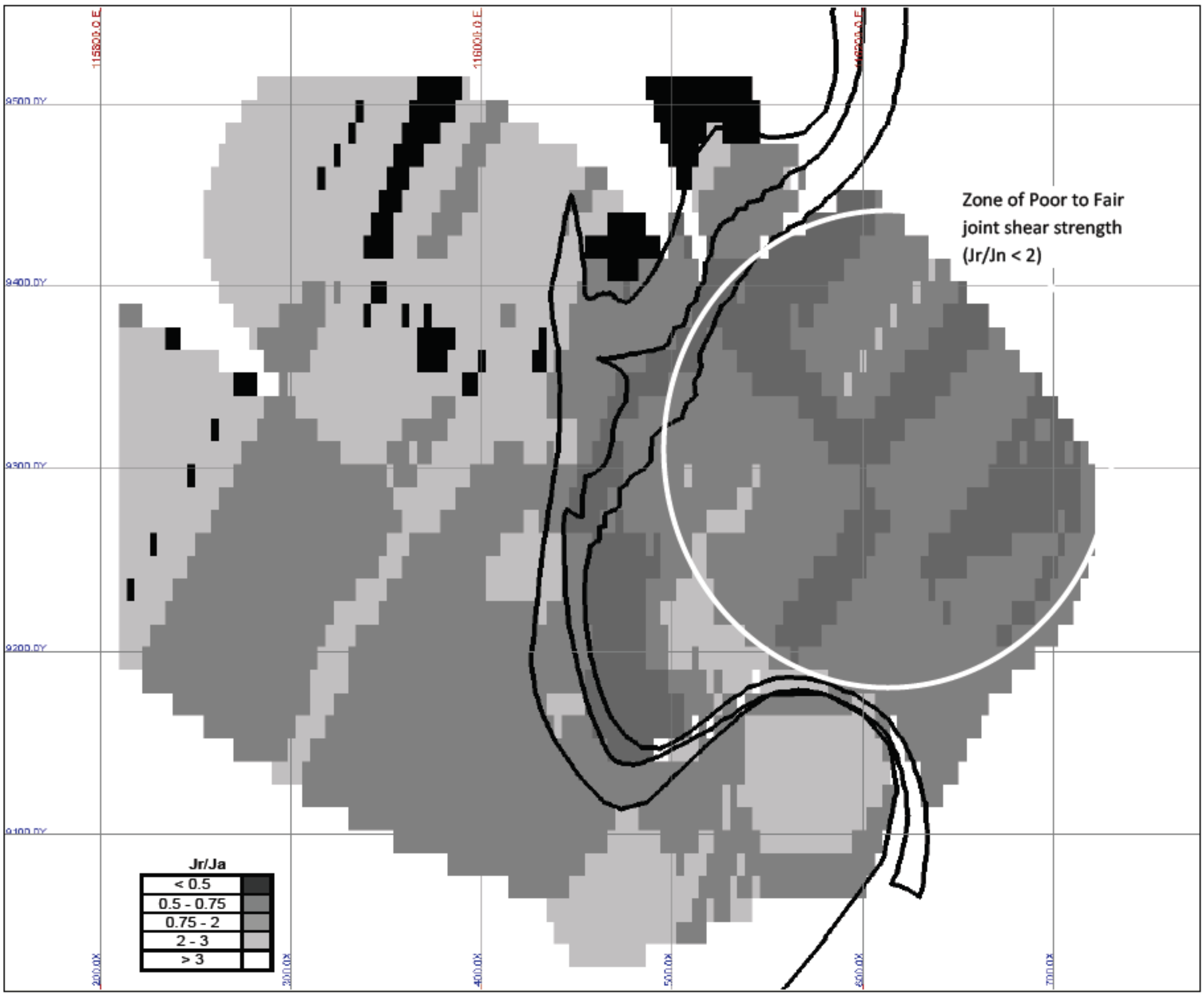


FIG 8 - Block model showing joint shear strength (Jr/Ja).

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