OPG'S DEEP GEOLOGIC **REPOSITORY** FOR LOW & INTERMEDIATE LEVEL WASTE

Supporting Technical Report

Geomechanical Modeling

May 2008

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OPG's Deep Geologic Repository for Low and Intermediate Level Waste Conceptual Design Study

Supporting Technical Report GEOMECHANICAL MODELING

May 2008

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Table of Contents

1.	Introduction1								
2.	Obje	ectives of the Modeling1							
3.	Inpu	It Information and Assumptions1							
4.	Methodology3								
	4.1	Software3							
	4.2	Rock Mass Constitutive Behaviour							
	4.3	Intact Rock and Rock Mass Parameters6							
5.	Mod	lel Development							
	5.1	Pillar Factor of Safety from Numerical Analysis8							
	5.2	Pillar Damage Assessment9							
6.	Mod	leling Results							
	6.1	Pre-Closure (100 year) Model Development10							
	6.2	Model Zone Size Selection10							
	6.3	Explicit Modeling of Bedding Planes11							
	6.4	Room Excavation Sequence							
	6.5	Pre-Closure (100 year) Model - Pillar Response over Range of Geomechanical Conditions							
	6.6	Pre-Closure (100 year) Model - Impact of Rock Dowels on Results							
7.	Con	clusions							
8.	Refe	erences							

APPENDICES

Appendix A	 Basis for Assumed Rock Mass Classification
Appendix B1	 Multi-Pillar Analysis
Appendix B2	 Single Pillar Analysis - Wide Range of Parameters
Appendix C	 Single Pillar Analysis - Selected Range of Parameters





1. Introduction

Ontario Power Generation (OPG) intends to construct a Deep Geologic Repository (DGR) at a depth of approximately 680 metres beneath the Bruce Site located near Kincardine, Ontario. The facility would safely dispose of Low and Intermediate Level Waste (LLW and ILW respectively) from OPG nuclear operations in emplacement rooms in a geologically stable environment.

This supporting technical report summarises the results of geomechanical numerical modeling performed to address the stability of the emplacement rooms and pillars under the full range of credible geomechanical conditions for the anticipated service life of 100 years (pre-closure case).

2. Objectives of the Modeling

The primary objective of this modeling exercise was to predict the geomechanical behaviour and response of the rock mass pillar due to emplacement room excavation. The results of these analyses support the establishment of minimum safe rock pillar widths between DGR emplacement rooms appropriate to the range of credible geomechanical conditions.

Since the site-specific geotechnical conditions are not yet fully established for the repository site, the modeling has been carried out for a number of sets of rock mass conditions that are considered representative of the range of credible rock properties at the site. Each set of analyses provides predictions of rock mass behaviour in response to excavation for different pillar widths.

The rock pillar safety factor from the numerical analysis and estimates of the extent of rock damage caused by creating an emplacement room opening that disturbs the initial stress state in the rock mass have been numerically predicted. A sensitivity analysis has thereby been performed to determine the key parameters that have the most significant effect on the pillar requirements.

3. Input Information and Assumptions

The modeling has required the following inputs and assumptions:

- The main emplacement rooms and ancillary access and support tunnels of the DGR will be constructed in the Cobourg limestone formation that is located at a depth that is approximately between 660 m and 687 m below grade surface (bgs).
- For the purposes of the numerical analyses, this formation has been characterised from a geomechanical perspective to be sub-horizontally bedded with medium to massive bedding thickness. Aspects of Rock Mass Rating (RMR) classification (Bieniawski, 1989) and Geologic Strength Index (GSI) classification (Hoek and Brown, 1997) assessments including bedding plane and joint discontinuity features that have been assumed for the analyses are described in Appendix A.



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- The repository emplacement rooms will be constructed as rib and pillar rooms meaning that rooms will be constructed parallel to each other with a long, continuous and uniform width pillar between them. Emplacement rooms will be arrayed in panels with their length-to-span aspect ratio greater than 10.
- Room shape will be rectangular due to sub-horizontal bedding planes (see Figure 3-1). Limited size corner rounding or chamfers (necessary due to construction methods) will occur but will not affect geomechanical behaviour.
- Room sizes analyses have been performed using room sizes from previous studies 8.1 m wide and 7.5 m high for the low-level waste emplacement rooms, as the base case for design.
- Only minimal rock reinforcement will be provided within emplacement rooms (shotcrete and rock dowels) that is designed to prevent fallout of loosened and failed material from the roof and upper walls for the safety of workers and to avoid damage to waste packages in the preclosure phase. Correspondingly, no structural reinforcement of pillars or the roof has been considered in the model.
- The modeling has been conducted for horizontal to vertical in-situ stresses ratios (K₀) ranging from 1.0 to 2.5. The minor horizontal in-situ stress has been kept at the same value as the vertical stress. The orientation of the highest horizontal stress has been assumed to be perpendicular to the room length.



Figure 3-1 – Typical Emplacement Room Shape and Layout



4. Methodology

4.1 Software

The models were analyzed using finite difference software developed by Itasca Consulting Group (FLAC). FLAC Version 5.0 has been used for the two-dimensional numerical models described herein. The software is produced by Itasca Inc. of Minnesota and the programs are based on explicit finite difference method, specifically developed for modeling geotechnical problems. These programs can simulate the behaviour of media consisting of soil, rock or other materials that may undergo plastic flow when their yield limits are reached. Materials are represented by zones (elements) that are configured in a grid created by the user. Each zone behaves according to a user-prescribed linear or nonlinear constitutive behaviour (stress/strain law) in response to the applied forces or boundary restraints, with ground water/pore pressure effects included in the model. Explicit discontinuities, as well as distinct structural elements, can be modeled within the grid.

4.2 Rock Mass Constitutive Behaviour

The behaviour of a rock mass is controlled by the stress redistribution that occurs after excavation relative to the geomechanical (strength) properties of the discontinuities (joints) and the intact rock between them. According to Hoek-Brown (1997), a discontinuous rock mass can be numerically modeled as a continuum by modifying intact rock material properties to account for the presence and condition of joints and other discontinuities. Comparison of the magnitude and difference of major and minor principal stresses (denoted σ_1 and σ_3 respectively) after excavation induced stress redistribution relative to a failure criterion based on rock strength parameters is used to assess the behaviour of the rock mass (elastic or plastic failure). Reference is made to Hoek-Brown (1997) for more details. An example of the Hoek-Brown failure criterion is shown in Figure 4-1.

An elasto-plastic constitutive behaviour for the rock mass modeled as a continuum has been adopted for the study by using a modified or compound Hoek-Brown failure criterion. The compound failure criterion recognises the brittle behaviour recommended by Martin et al (1999) for low confinement stresses and reverts to the standard Hoek-Brown failure line at higher confining stresses. Figure 4-2 shows the resulting compound failure envelope and Figure 4-3 shows the stress ranges governed by each failure criterion. The resulting composite failure curve varies only slightly from the simple Hoek-Brown failure envelope. Therefore, this composite curve has been used for single pillar assessment. No post-peak strain softening has been modeled at this stage of investigation.

Rock Lab 1.0 version 1.031 developed by RocScience was used to obtain the Hoek Brown parameters, m_b , s and a, from the assumed intact rock unconfined compressive strength (UCS) and rock mass characterisation values (RMR and GSI). A sensitivity study comparing results for single pillar models using explicitly modeled bedding planes and implicitly modeled bedding was also performed.







Figure 4-1 – Hoek-Brown Failure Criteria at Peak Resistance



Figure 4-2 – Composite Failure Criteria







Figure 4-3 – Zones of Failure Envelope Criteria





4.3 Intact Rock and Rock Mass Parameters

The credible range of possible geomechanical properties has been summarised by Lam et al (2007) and the analysed range of geomechanical parameters is presented in Table 4-1, Table 4-2, and Table 4-3 are felt to reflect that range.

Parameter		Least Favourable	Selected Range	Most Favourable
	Friction Angle	20	30	40
	Cohesion (MPa)	0	0.3	0.6
Rodding Joint	Tensile Strength (MPa)	0	0.3	0.6
Parameters	Normal Stiffness K _n (GPa/m)	175	250	325
	Shear Stiffness K _s (GPa/m)	7	10	15
Horizontal Joint	spacing (m)	0.3	1	2

Table 4-1: Bedding Plane Parameters

Parameter	Lower Bound	Expected	Upper Bound
In situ horizontal pressure coefficient, K_0	1.0	1.5	2.5
In situ vertical stress, σ_{v} (MPa) (at 660m below grade)	17.2	17.2	17.2
Unit Weight of Rock (MN/m ³)	0.026	0.026	0.026

Table 4-2: Rock Stress Conditions





Parameter	Least Favourable	Low End	of Select	ed Range	Middle of Selected Range "Expected" with GSI 69			High	Most Favourable		
UCS Intact Rock (MPa)	25		48		60				140		
Rock Quality (Geological Strength Index or GSI) ¹	66	55	69	80	55	69	80	55	69	80	80
Modulus of elasticity of intact rock (GPa)	16	37	37	37	47	47	47	56	56	56	66
Modulus of elasticity of rock mass ² (GPa)	10	15	27	33	19	33	41	23	40	49	58
Poisson's ratio	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Hoek-Brown Parameter m _i	9	9	9	9	9	9	9	9	9	9	9
Hoek-Brown Parameter m _b	2.67	1.80	2.97	4.41	1.80	2.97	4.41	1.80	2.97	4.41	4.41
Hoek-Brown Parameter s	0.023	0.007	0.032	0.108	0.007	0.032	0.108	0.007	0.032	0.108	0.108
Hoek-Brown Parameter a	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Tested for Modeling issues						Yes					
K_o range considered	1.0, 1.5, 2.5	1.5	1.5	1.5	1.5	1.0, 1.5, 2.5	1.5	1.5	1.5	1.5	1.0, 1.5, 2.5

Table 4-3: Range of Considered Rock Parameters



5. Model Development

5.1 Pillar Factor of Safety from Numerical Analysis

Typically, the level of safety (often denoted factor of safety) of pillars in mining applications is assessed by comparing pillar capacity determined using empirical relations relative to the average vertical stresses in a pillar calculated on the basis of overburden pressures and pillar tributary widths. While this has served the mining industry well, empirical assessments of pillar capacity are often based on unknown definitions of failure, in-situ stress conditions and rock mass characteristics. Further, average stress levels do not provide an indication of the localised damage that may occur at free surfaces and areas of stress concentration.

To consider these behavioural characteristics, numerical modeling is used as it is capable of calculating the state of stress throughout the entire rock mass (i.e. stress distribution across the pillar) and compares that stress state to constitutive failure criteria at each calculation location. Consequently, the level of stress relative to rock capacity will vary across the pillar.

For each of the geomechanical conditions and for various pillar widths, the stress state across a horizontal section through the pillar (typically at the pillar mid-height) was assessed and used to quantitatively express the level of pillar stability. From each element along the investigated section of the pillar, the stresses were extracted and the individual zone Factor of Safety was assessed as the ratio of the differences between the principal stresses at failure σ_{1f} for the measured σ_3 and the actual differences between the measured principal stresses, as shown in Figure 5-1.



Figure 5-1 – Factor of Safety Calculation





The Safety Factor calculated by this method will always be ≥ 1.0 . If the measured σ_3 approaches the value of σ_1 the Safety Factor will be approaching infinity. In order to limit the possibility that a few zones across the pillar with σ_1 close to σ_3 would distort the results, an artificial limit of FS ≤ 20 for any zone has been set. To obtain the total pillar Safety Factor, the individual zone Safety Factors are then added and averaged. To make a distinction between the Safety Factor calculated from numerical analysis and empirical or otherwise obtained Safety Factors, the factor obtained from the numerical analysis is referred to as Numerical Analysis Factor of Safety (NAFS).

5.2 Pillar Damage Assessment

An additional pillar acceptance criterion has been established based on the extent of plasticised zone as a proportion of the original pillar width:

- Type A has the plastic zone equal to 0% to 10% of the pillar width
- Type B has the plastic zone equal to 10% to 28% of the pillar width
- Type C has the plastic zone equal to 28% to 50% of the pillar width
- Type D has the plastic zone equal to 50% to 78% of the pillar width
- Type E has the plastic zone equal to 78% to 100% of the pillar width

The numerical modeling results were used to assess the magnitude of pillar damage.

Pillar rating	Pillar condition	Appearance	DGR Category
ł	No indication of stress induced fracturing Intact pillar		Not Used
2	Spalling on pillar corners, minor spalling of pillar walls Fractures oriented sub-parallel to walls and are short relative to pillar height		Α
3	Increased corner spalling Fractures on pillar walls more numerous and continuous Fractures oriented sub-parallel to pillar walls and lengths are less than pillar height		В
4	Continuous sub-parallel open fractures along pillar walls. Early development of diagonal fractures (start of hourglassing) Fracture lengths are greater than half of pillar height)XXC	С
5	Continuous sub-parallel open fractures along pillar walls Well developed diagonal fractures (classic hourglassing) Fracture lengths are greater than half the pillar height		D
6	Failed pillar, may have minimal residual load carrying capacity and be providing local support to the stope back. Extreme hourglassed shape or major blocks fallen out	OR JK	Е

Table 13.2 Doe Run pillar condition rating system (after Roberts et al., 1998)

Figure 5-2 – Pillar Condition Rating System for Sedimentary Rock (Brady et al, 1985)



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6. Modeling Results

6.1 **Pre-Closure (100 year) Model Development**

During model development, modeling simplifications were sought with the objective of reducing computing time to allow more alternative parametric models to be analysed. Various aspects of the modeling tasks were investigated. These included:

- The effect of mesh size on result accuracy and on computing time
- The effect of explicitly modeling horizontal bedding planes compared with a implicit allowance for such bedding planes by appropriately degrading the geotechnical properties used in the model
- The effect of progressive incremental expansion of the facility compared with all adjacent rooms being excavated concurrently

The 2-D models were run for the range of geotechnical properties shown in Section 3 and a range of pillar widths from 8 to 28 m.

6.2 Model Zone Size Selection

Figure 6-1 shows the sensitivity of the Numerical Analysis Factor of Safety, calculated for a single pillar model, to the grid element size in the model. It can be reasonably assumed that a smaller size element model would provide more accurate results.

From Figure 6-1 it can be seen that while there is a trend to obtain somewhat higher values of the NAFS for larger elements, the difference is relatively small; from 1.20 for the grid size of 0.05 m through 1.25 for the element size of 0.25 m up to 1.29 for a 0.5 m grid. It should be noted that the model with the grid size of 0.05 m is 25 times larger compared to a 0.25 m grid model with a corresponding increase in computational time. Therefore, a grid element size of 0.25 m has been chosen as the best balance between accuracy and computational time.







6.3 Explicit Modeling of Bedding Planes

Figure 6-2 assesses the effect of modeling the bedding planes explicitly and selects a modifier for the rock quality to produce similar results and thereby implicitly allow for the presence of the bedding planes. Figure 6-2 shows the comparison between the pillar NAFS results for a model with the rock with GSI of 69 with explicitly modelled bedding planes, and the results for a model with GSI of 67 without explicit bedding planes, and shows that the results are similar. It can be concluded that, considering the accuracy of the material properties of the rock that will be measured and known, the differences between the explicit and implicit modeling of bedding planes will not have significant impact on the overall accuracy of the predictions obtained from the analytical models. Therefore, implicit bedding plane modeling was used with a GSI reduction of 2 to allow for the bedding planes.



Figure 6-2 – Numerical Analysis Factor of Safety Variation with Element Size and Bedding Modeling

6.4 Room Excavation Sequence

An assessment of the impact of room excavation sequence was made to determine how the successive excavation of rooms would alter the stress state in the initial or exterior pillars in the emplacement room panels. This assessment was performed to determine if the modeling of a single symmetrical pillar (see Figure 6-3) that represents an infinite number of parallel rooms (and is significantly less computationally intensive) provides similar results to discrete modeling of the actual number of rooms in a panel (see Figure 6-4).

Figure 6-4 and Table 6-1 show how the pillar model-calculated Numerical Analysis Factor of Safety changes with the number of sequentially excavated rooms. If a single pillar is created (2 rooms are excavated), the NAFS of the pillar will be 1.83, based on the expected rock properties used in this calibration model. When subsequent rooms are excavated in the same model, the NAFS for the first pillar will start decreasing gradually to about 1.74. After about 6 – 7 rooms have been created there is no further decrease in the Numerical Analysis Factor of Safety value of the first pillar.





The single pillar 2-D model represents one of an infinite number of pillars and would therefore be expected to predict the lowest safety factor. The single pillar model that has been used in all the analysis is therefore conservative.



Figure 6-3 – Example of Single Rib Pillar Model Showing Vertical Stresses



Figure 6-4 – Vertical Stresses in a Multiple Room Model

0.5m Zone size w/ Bedding Joint; Pillar Width = 15m, K_0 = 1.5 Expected												
No. of Excavated	Pillar #											
Vaults	1	2	3	4	5	6						
1	2.00											
2	1.83											
3	1.81	1.79	1.84									
4	1.77		1.80	1.84								
5	1.76	1.75	1.77	1.80	1.83							
6	1.75	1.74	1.76	1.78	1.79	1.83						

Table 6-1 – Decrease of NAFS With Increasing Number of Rooms



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6.5 Pre-Closure (100 year) Model - Pillar Response over Range of Geomechanical Conditions

This group of results is with reference to the "Least Favourable", "Expected" and "Most Favourable" rock property assumptions as shown in Table 4-3.



Figure 6-5 – Numerical Analysis Factor of Safety of Pillars for the Wide Range Rock Properties (7.5 m x 8.1 m Room Size, K0z = 1.0)

Figure 6-5 shows the results of the analyses for the least favourable, expected and most favourable parameters shown on presented graphically. As expected, the Numerical Analysis Factor of Safety of a pillar increases with rock strength and the pillar width. Conversely, for the same NAFS the pillar width can be decreased if the rock strength increases.

The effect of higher K_0 values is quite apparent for wider pillars. It is apparent that as the pillar gets wider a portion of the high pre-excavation initial horizontal stress stays locked in the pillar and provides lateral confinement for the pillar core. For very large pillars and for $K_0 >> 1.0$ this may lead to a reversal of the principal stresses in the pillar when the horizontal stress may become larger than the vertical stress, as shown in Figure 6-6 below where the distribution of factors of safety across a wide pillar is presented showing σ_3 to be orientated horizontally near the edge of the pillar and vertically near the centre of the pillar. For narrower pillars this effect is small, however.

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Figure 6-6 – Wide Pillar Local NAFS across a Wide Pillar With Varying K_0

Within the range of pillar widths that can be expected for this facility, with the range shown as the shaded area on Figure 6-5, the effect of K_0 on the results is relatively small as indicated by the adjacency of the curves for the various K_0 values within this zone.

For this reason, when the selected narrower range of rock properties was considered as probable on the site, and the large number of analysis cases for the parameters shown on Table 4-1, only K_0 equal to 1.5 was used in the analyses. The results of these analyses are shown below in Figure 6-7.







Numerical Analysis Factor of Safety of Pillars 8.0m x 7.5m Vaults, K_{0x}=1.5, K_{0x}=1.0

Figure 6-7 – NAFS Results for the Selected Range of Rock Properties

The typical results for the extent of pillar damage are shown in figures, Figure 6-8 to Figure 6-12 below. The purple colour shown on the stress plots identifies the zone of the pillar that is yielding, the green zone identifies the portion that has yielded in the past. The total pillar damaged zone as quantified as the percentage of the pillar width is the sum of both of these zones.



Figure 6-8 – Pillar Model UCS = 48, GSI = 55, Pillar Width = 12.0m, NAFS = 1.0 Damage Category E, Plasticity zone 100% of the pillar width







Figure 6-9 – Pillar Model UCS = 48, GSI = 55, Pillar Width = 14.0m, NAFS = 1.1 Damage Category E, Plasticity zone 78% of the pillar width



Figure 6-10 – Pillar Model UCS = 60, GSI = 69, Pillar Width = 12.0m, NAFS = 1.4 Damage Category D, Plasticity zone 57% of the pillar width



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Figure 6-11 – Pillar Model UCS = 60, GSI = 69, Pillar Width = 16.0m, NAFS = 2.1 Damage Category C, Plasticity zone 39% of the pillar width



Figure 6-12 – Pillar Model UCS = 60, GSI = 69, Pillar Width = 20.0m, NAFS = 3.3 Damage Category B, Plasticity zone 26% of the pillar width

The conclusions that can be made from the single pillar models are as follows:

It appears that for a constant room size, that varying the width of the pillar has little influence on the size of the plasticised (damaged) zone. Figure 6-13 shows a comparison of the depth of the damaged zones for 12, 16 and 20 m wide pillars with identical rock properties. It can be seen that when the pillar widths increases by 66%, the depth of damaged zone decreases by less than 25%.

Figure 6-14 shows the depth of damage in relation to the strength of the rock, (i.e. its UCS). It can be seen that there is a near linear dependence between the UCS and the depth of the damaged zone. Therefore, it is apparent that the depth of the damaged zone is chiefly controlled by the rock strength and that the influence the pillar width is much less significant.



Table 6-2, Table 6-3 and Table 6-4 present the Numerical Analysis Factors of Safety and the pillar Damage Levels for all the analyses. The results of the individual pillar analyses are presented in Appendix B2 for the "wide range of rock properties" defined as the least favourable, expected and most favourable properties and in Appendix C for the "selected range of rock properties" defined as the more limited range of rock strength values selected for more detailed study with a distribution of GSI values.



Figure 6-13 – Pillar Model UCS = 60, GSI = 69, Width = 12, 16, 20 m, Depth of Damage.



Figure 6-14 – Pillar Model UCS = 48, 60, 72 GSI = 69, Width = 16 m, Depth of Damage



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Rock Properties K ₀ = 1.5		UCS intact rock (MPa)	Rock Mass Quality (GSI)	Values	Pillar 8.0m	Pillar 12.0m	Pillar 14.0m	Pillar 15.0m	Pillar 16.0m	Pillar 18.0m	Pillar 20.0m	Pillar 22.0m	Pillar 24.0m	Pillar 28.0m	Pillar 40.0m
Least Fa	avourable	25	66	NAFS				1.0		1.20		1.58		2.45	7.60
Louotin		20		Damage				E		D		D		N/A	N/A
			55	NAFS		1.00	1.12		1.31	1.54	1.82				
				Damage		E	E		D	D	С				
Low End of S	elected Range	48	69	NAFS		1.23	1.50		1.82	2.20	2.68				
К		40	00	Damage		D	D		С	С	С				
			80	NAFS		1.54	1.90		2.35	2.90	3.58				
				Damage		D	С		С	С	С				
	"Expected" with GSI 69	60	55	NAFS		1.08	1.26		1.50	1.82	2.21				
				Damage		Е	D		D	С	С				
Middle of			69	NAFS		1.38	1.68	1.87	2.09	2.62	3.28	4.41			
Range				Damage		D	С	С	С	С	В	N/A			
rtange			80	NAFS		1.67	2.11		2.67	3.38	4.29				
				Damage		D	С		С	С	В				
				NAFS		1.16	1.39		1.78	2.26	2.84				
			55	Damage		D	D		С	С	В				
High End	of Selected	70	00	NAFS		1.45	1.88		2.45	3.16	4.04				
Ra	inge	72	69	Damage		D	С		С	В	В				
, i i i i i i i i i i i i i i i i i i i				NAFS		1.78	2.36		3.12	4.03	5.18				
			80	Damage		С	С		В	В	В				
		1.10		NAFS	1.43	2.84		4.48		6.70					
Most Fa	avourable	140	80	Damage	А	А		А		N/A					

Note: N/A = not evaluated.

Table 6-2 – NAFS and the Level of Damage for Analyzed Cases $K_o = 1.50$







Rock Properties K ₀ = 1.0	UCS intact rock (MPa)	Rock Mass Quality (GSI)	Values	Pillar 8.0 m	Pillar 12.0m	Pillar 15 0m	Pillar 18.0m	Pillar 22.0m	Pillar 28.0m
Least Favourable	25	66	NAFS			1.00	1.22	1.59	2.26
	25	00	Damage			E	D	D	N/A
Expected	Expected 60 60	60	NAFS		1.38	1.81	2.32	3.15	
Expected	00	09	Damage		D	С	С	N/A	
Maat Eavourable 140 80	NAFS	1.43	2.42	3.63	4.90				
	140	80	Damage	А	Α	Α	N/A		

Table 6-3 – NAFS and the Level of Damage for Analyzed Cases $K_o = 1.00$

Rock Properties $K_0 = 2.5$	UCS intact rock (MPa)	Rock Mass Quality (GSI)	Values	Pillar 8.0 m	Pillar 12.0m	Pillar 15 0m	Pillar 18.0m	Pillar 22.0m	Pillar 24.0m
Loget Equation	25	66	NAFS			1.00	1.15	1.46	1.66
Least Favourable	20	00	Damage			E	D	С	N/A
Exported	60	60	NAFS		1.29	1.79	2.73	5.12	
Expected	Expected 60	69	Damage		D	С	В	N/A	
Most Eavourable	140	00	NAFS	1.44	3.42	6.11	12.90		
WOST FAVOURABLE	140	00	Damage	А	А	А	N/A		

Table 6-4 – NAFS and the Level of Damage for Analyzed Cases $K_o = 2.50$

6.6 Pre-Closure (100 year) Model - Impact of Rock Dowels on Results

In order to assess the possible effect of rock dowel reinforcing of the repository room roof on the pillar behaviour, an additional single pillar model analysis was performed. For this analysis the parameters of UCS 60, GSI 69 and K_0 equal to 1.50 for were selected for the rock mass properties. The modelled pillar width was 16m. The assumed roof reinforcing consists of 25 mm diameter dowels with the yield strength of 400 MPa, prestressed to 50% of their yield strength and placed on a 1.5 x 1.5 m grid. The dowels are 5 m long to ensure that they are well anchored into the undamaged zone of the rock.

The analysis showed that the dowels have very little effect on the extent of the plastic zone in the roof and no effect on the pillar behaviour. The likely reason is that the stress changes in the rock from the in-situ pre-excavation stress to post-excavation stress state are very high. The dowels can provide only a rough equivalent of less then 0.1 MPa of a confining pressure to the rock with the assumed size and spacing. This compares to the in-situ stresses that are in the order of 20 MPa. Therefore, the dowels are useful for providing support for possible rock wedges/slabs fall outs as well as holding the damaged rock in place, where it provides confinement to the load carrying portion of the pillar. However, the dowels would have small effect on the extent of damaged rock zone itself.



This exercise was carried out solely for the purpose of assessing the influence of doweling on the extent of the plasticity zones. For the true assessment of doweling requirements a more refined methodology should be employed that models the timing of the rock dowel installation after the excavation and after some degree of stress relaxation following excavation, and not with the rock dowels installed prior to excavation as assumed here. The parameters modeled are:

- Rock-Dowels: 25 mm diameter x 5000 mm Full dowel length bond, 1.5 m x 1.5 m spacing
- UCS = 60, GSI = 69, Pillar Width = 16.0 m

Figures, Figure 6-15 to Figure 6-20, show the comparisons of results with and without roof rock dowels.

Left Picture: Without Rock Dowels



Right Picture: <u>With</u> Rock Dowels



Figure 6-15 – Comparison of Vertical Stresses between Doweled and Undoweled Roofs

Left Picture: Without Rock Dowels

Right Picture: <u>With</u> Rock Dowels







Left Picture: <u>Without</u> Rock Dowels









Left Picture: <u>Without</u> Rock Dowels Right Picture: <u>With</u> Rock Dowels





Left Picture: Without Rock Dowels



Right Picture: With Rock Dowels



Figure 6-19 – Maximum Principal Stress Trajectories (MPa)



Right Picture: With Rock Dowels



Left Picture: <u>Without</u> Rock Dowels



7. Conclusions

The numerical analyses have provided important input into the pillar width recommendation by analysing a wide range of possible rock property scenarios with a range of possible pillar widths.

The analyses included modified failure envelopes that recognised the brittle behaviour of the rock at low levels of confinement. The zones of plasticity around the openings were clearly shown and for wide pillars were shown to vary only marginally with adjustment to the pillar width. The plastic zones were found to vary significantly with changes in rock strength.

At the pillar widths presently under study, it has been shown that changing K_0 within its potential range has an insignificant effect on the results and therefore the variation in the value of horizontal stresses between the major and minor axes is similarly not significant. This means that there is no impact to the room design from a particular orientation of the room axis and therefore the rooms can be orientated to suit the facility operation without detriment to the room design.

The introduction of roof doweling, that will obviously be required, was investigated and shown to have an insignificant influence on the prediction of zones of plasticity around the openings.

In future phases of the project, it will be appropriate to rerun the analyses with updated room geometry as well as rock properties obtained from the site geotechnical investigation. At that point it may be more appropriate to incorporate explicit modeling of the bedding planes.



8. References

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Lam, T., Martin, D. and McCreath, D., "Characterising the Geomechanics Properties of Sedimentary Rocks for the DGR Excavations", Canadian Geotechnical Society 2007 Conference, Ottawa 2007.

Martin C.D., Kaiser P.K., McCreath D.R., Hoek Brown Parameters for Predicting the Depth of Brittle Failure around Tunnels, Canadian Geotechnical Journal 36 136-151, 1999.



Appendix A

Basis for Assumed Rock Mass Classification





>10 MPa

>250 MPa

15

90% - 100%

20

>2 m

20

Very rough surfaces.

Not continuous.

A. CLASSIFICATION PARAMETERS AND THEIR RATINGS

Point-load strength

Parameter

index

Uniaxial

Rating

Drill core Quality RQD

Rating

Spacing of discontinuities

Rating

comp.strength

Strength of

intact rock

material

1

2

3

such cases use A.4 directly ** Modified after Wickham et al (1972)

323874DGR-RPT-GMR109-Rev00 – Appendix A	
PR 323874 - Page 2 of 12	Im

4	Conditio	on of discontinuities (See E)	No separation. Unweathered wall rock	Slightly weathered walls	s Highly weathered walls	Gouge Sepai C	e < 5 mm thick or ration 1-5 mm ontinuous	Separation > 5 mm Continuous	
		Rating	30	25	20		10	0	
		Inflow per 10 m tunnel length (l/m)	None	< 10	10 - 25		25 -125	> 125	
5	Ground water	(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	
		Rating	15	10	7		4	0	
B. R	RATING A	ADJUSTMENT FOR DISC	ONTINUITY ORIENTATI	ONS (See F)					
Strik	ke and dip	p orientations	Very Favourable	Favourable	Fair	Un	favourable	Very unfavourable	
		Tunnels & mines	0	-2	-5		-10	-12	
R	atings	Foundations	0	-2	-7		-15	-25	
		Slopes	0	-5	-25		-50		
C. R	ROCK MA	ASS CLASSES DETERMI	NED FROM TOTAL RAT	INGS					
Rati	ng		100 - 81	80 - 61	60 - 41		40 - 21	< 21	
Clas	ss numbe	er	I	ll		IV		V	
Des	cription		Very good rock	Good rock	Fair rock	F	Poor rock	Very poor rock	
D. N	IEANING	OF ROCK CLASSES							
Clas	ss numbe	er		ll			IV	V	
Ave	rage stan	nd-up time	20 years for 15 m span	1year for 10 m span	1 week for 5 m span	for 5 m span 10 hrs for 2.5 m span		30 mins for 1 m span	
Coh	esion of I	rock mass (MPa)	>400	300 - 400	200 - 300	1	100 - 200	<100	
Frict	tion angle	e of rock mass (deg)	> 45	35 - 45	25 - 35		15 - 25	< 15	
E. G	UIDELIN	NES FOR CLASSIFICATION	ON OF DISCONTINUITY	CONDITIONS					
Disc	continuity	length persistence	< 1 m	1 -3 m	3 -10 m	1	10 - 20 m	> 20 m	
		Rating	6	4	2		1	0	
Sep	aration (a	aperture)	None	< 0.1 mm	0.1 -1.0 mm		1 - 5 mm	> 5 mm	
		Rating	6	5	4		1	0	
Rou	ghness		Very rough	Rough	Slightly rough		Smooth	Slickensided	
		Rating	6	4	3		1	0	
Infill	ing (goug	ge)	None	Hard filling < 5 mm	Hard filling > 5 mm	Soft f	filling < 5 mm	Soft filling > 5mm	
		Rating	5	4	2		2	0	
Wea	athering		Unweathered	Slightly weathered	Moderately weathered	High	ly weathered	Decomposed	
		Rating	6	5	3		1	0	
F. E	FFECT	OF DISCONTINUITY STR	IKE AND DIP ORIENTAT	ION IN TUNNELLING**					
		Strike perpen	dicular to tunnel axis		Stril	ke paralle	el to tunnel axis		
	Drive	with dip - Dip 45 to 90	Drive with dip	o - Dip 20 - 45	Dip 45 - 90		D	9 ip 20 - 45	
		Very favourable	Favou	urable	Very favourable			Fair	
	Drive a	igainst dip - Dip 45 to 90	Drive against d	lip - Dip 20 - 45	Dip 0 to	o 20 - Irre	espective of strike	e*	
		Fair	Unfavo	ourable		F	air		

4-10 MPa

100 - 250 MPa

12

75% - 90%

17

0.6 - 2 m

15

Slightly rough surfaces

Separation < 1 mm.

Rock Mass Rating System (RMR) (After Bieniawski 1989) **OPG Geologic Repository - Least Favourable Values**

1-2 MPa

25 - 50 MPa

4

25% - 50%

8

60 - 200 mm

8

Slickensided surfaces

or

Range of values

2-4 MPa

50 - 100 MPa

7

50% - 75%

13

200 - 600 mm

10

Slightly rough surfaces

Separation < 1 mm.

RMR 71

GSI 66



For this low range

test is preferred

5 - 25

MPa

2

thick

uniaxial compressive

1 - 5

MPa

1

<25%

3

< 60 mm

5

Soft gouge > 5 mm

<1

MPa

0 4

20

15

15

0

0

4

3

4

6

Hatch Mott MacDonald

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

Ro	k Mass	Rating System (RM	IR) (After Bieniawski	1989) O	PG Geologic Reposi	tory - Low End Low	/ Quality Values	
4. C	LASSIFIC	ATION PARAMETERS	AND THEIR RATINGS					
	F	Parameter			Range of values	-		
	Strenath o	Point-load strength index	>10 MPa	4-10 MPa	2-4 MPa	1-2 MPa	For this low range - uniaxial compressive test is preferred	
1	intact rock material	Uniaxial comp.strength	>250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5-25 1-5 <1 MPa MPa 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	
2	Spaci	ng of discontinuities	>2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm	< 60 mm	
3		Rating	20	15	10	8	5	
4	Condition	of discontinuities (See E)	Very rough surfaces. Not continuous. No separation. Unweathered wall rock	Slightly rough surfaces Separation < 1 mm. Slightly weathered wa	 Slightly rough surfaces. Separation < 1 mm. Highly weathered walls 	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge > 5 mm thick c Separation > 5 mm Continuous	
		Rating	30	25	20	10	0	
	lr Cround	nflow per 10 m tunnel ength (l/m)	None	< 10	10 - 25	25 -125	> 125	
5	water (I	Joint water press)/ Major principal stress)	0	< 0.1	0.1 - 0.2	0.2 - 0.5	> 0.5	
	G	General conditions	Completely dry	Damp	Wet	Dripping	Flowing	
		Rating	15	10	7	4	0	
3. R	ATING AD	JUSTMENT FOR DISC	ONTINUITY ORIENTATIO	ONS (See F)				
Strik	e and dip o	prientations	Very Favourable	Favourable	Fair	Unfavourable	Very unfavourable	
		Tunnels & mines	0	-2	-5	-10	-12	
R	atings	Foundations	0	-2	-7	-15	-25	
		Slopes	0	-5	-25	-50		
C. R	OCK MAS	S CLASSES DETERMI	NED FROM TOTAL RAT	INGS	1	1	1	
Rati	ng		100 - 81	80 - 61	60 - 41	40 - 21	< 21	
Clas	s number			ll Orandarada		IV De se re els	V	
Des	cription		Very good Tock	GOOD TOCK	Fair rock	POOLIOCK	very poor rock	
D. IV		OF ROCK CLASSES				11/	V	
Clas	s number		20 years for 15 m apap	II 1yoor for 10 m apor		10 bro for 2.5 m open	V 20 mins for 1 m span	
Aver	age stand-	-up time		300 - 400	200 - 300	100 - 200		
Erict	ion angle c	of rock mass (dea)	> 45	35 - 45	200 - 300	15 - 25	< 15	
FG		S FOR CLASSIFICATIO		CONDITIONS	20 00			
Disc	ontinuity le	andth persistence		1-3 m	3 -10 m	10 - 20 m	> 20 m	
0100	oritinaty io	Rating	6	4	2	1	0	
Sep	aration (ap	erture)	None	< 0.1 mm	0.1 -1.0 mm	1 - 5 mm	> 5 mm	
		Rating	6	5	4	1	0	
Rou	ghness	-	Very rough	Rough	Slightly rough	Smooth	Slickensided	
		Rating	6	4	3	1	0	
Infilli	ng (gouge))	None	Hard filling < 5 mm	Hard filling > 5 mm	Soft filling < 5 mm	Soft filling > 5mm	
		Rating	5	4	2	2	0	
Wea	thering		Unweathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed	
		Rating	6	5	3	1	0	
F. E	FFECT OF	DISCONTINUITY STR	IKE AND DIP ORIENTAT	ION IN TUNNELLING*	*			
		Strike perpen	dicular to tunnel axis		Stril	ke parallel to tunnel axis		
	Drive w	rith dip - Dip 45 to 90	Drive with dip	- Dip 20 - 45	Dip 45 - 90]	Dip 20 - 45	
		ery tavourable	Favou		Very favourable	00 I	⊦aır	
	Drive aga	ainst dip - Dip 45 to 90	Drive against d	ip - Dip 20 - 45	Dip 0 to	∠u - Irrespective of strik	e	

** Modified after Wickham et al (1972)

RMR 60



Roc	k Mass	Rating System (RN	R) (After Bieniawski	1989) OP	G Geologic Reposit	ory - Low End Med	l Quality Values	
4. C	LASSIFIC	ATION PARAMETERS	AND THEIR RATINGS					
	F	Parameter			Range of values			
	Strength o	Point-load strength index	>10 MPa	4-10 MPa	2-4 MPa	1-2 MPa	For this low range - uniaxial compressive test is preferred	
1	intact rock material	Uniaxial comp.strength	>250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5-25 1-5 <1 MPa MPa MPa	
Ī		Rating	15	12	7	4	2 1 0	
~	Drill	core Quality RQD	90% - 100%	75% - 90%	50% - 75%	25% - 50%	<25%	
- [Rating	20	17	13	8	3	
2	Spacir	ng of discontinuities	>2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm	< 60 mm	
3		Rating	20	15	10	8	5	
4	Condition	of discontinuities (See E)	Very rough surfaces. Not continuous. No separation. Unweathered wall rock	Slightly rough surfaces. Separation < 1 mm. Slightly weathered walls	Slightly rough surfaces. Separation < 1 mm. Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge > 5 mm thick c Separation > 5 mm Continuous	
Ī		Rating	30	25	20	10	0	
	lr Grand le	nflow per 10 m tunnel ength (l/m)	None	< 10	10 - 25	25 -125	> 125	
5	water (1	Joint water press)/ Major principal stress)	0	< 0.1	0.1 - 0.2	0.2 - 0.5	> 0.5	
ļ	G	General conditions	Completely dry	Damp	Wet	Dripping	Flowing	
		Rating	15	10	7	4	0	
3. R	ATING AD	JUSTMENT FOR DISC	ONTINUITY ORIENTATIO	ONS (See F)				
Strik	e and dip o	prientations	Very Favourable	Favourable	Fair	Unfavourable	Very unfavourable	
		Tunnels & mines	0	-2	-5	-10	-12	
Ra	atings	Foundations	0	-2	-7	-15	-25	
_		Slopes	0	-5	-25	-50		
). R	OCK MAS	S CLASSES DETERM	NED FROM TOTAL RAT	NGS				
Ratir	ng		100 - 81	80 - 61	60 - 41	40 - 21	< 21	
Jlas	s number		l Voru good rook	II Cood rook	III Esiansela	IV Boor rook	V Voruppor rock	
			Very good fock	GOOUTOCK	Fair rock	FOULTOCK	very poor rock	
). IVI	EANING	JF RUCK CLASSES		11		11/	V	
		up time	20 years for 15 m span	1vear for 10 m span	1 wook for 5 m span	10 brs for 2.5 m span	30 mins for 1 m span	
:ohe	age startu-	ck mass (MPa)	>400	300 - 400	200 - 300	100 - 200	<100	
rict	ion angle c	of rock mass (deg)	> 45	35 - 45	25 - 35	15 - 25	< 15	
. G	UIDELINE	S FOR CLASSIFICATI	ON OF DISCONTINUITY	CONDITIONS			•	
isc	ontinuity le	ength persistence	< 1 m	1 -3 m	3 -10 m	10 - 20 m	> 20 m	
		Rating	6	4	2	1	0	
Sepa	aration (ap	erture)	None	< 0.1 mm	0.1 -1.0 mm	1 - 5 mm	> 5 mm	
		Rating	6	5	4	1	0	
Rou	ghness		Very rough	Rough	Slightly rough	Smooth	Slickensided	
		Rating	6	4	3	1	0	
nfilli	ng (gouge))	None	Hard filling < 5 mm	Hard filling > 5 mm	Soft filling < 5 mm	Soft filling > 5mm	
		Rating	5	4	2	2	0	
Vea	thering	Poting	Unweathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed	
	EFECT OF				3	1	U U	
. El					04-11	o porollol to turnel ent-		
	Drivow	Strike perpen		- Dip 20 - 45	Dip 45 00		Nin 20 - 45	
		erv favourable	Favou	rable	Very favourable		Fair	
_	Drive and	ainst dip - Din 45 to 90	Drive against di	ip - Dip 20 - 45	Din 0 tr	20 - Irrespective of strike	e*	
	Dine age	Fair	Linfavo		ט קים	Fair	•	

** Modified after Wickham et al (1972)

RMR 74

Consulting Engineers

HATCH"





Rock M	/lass R	ating System (RM	R) (After Bieniawski	1989) OP	G Geologic Reposit	ory - Low End High	n Quality Values	
A. CLAS	SIFICA	TION PARAMETERS	AND THEIR RATINGS					
	Pa	arameter			Range of values			
. Strei	ength of	Point-load strength index	>10 MPa	4-10 MPa	2-4 MPa	1-2 MPa	For this low range - uniaxial compressive test is preferred	
1 intac mate	ct rock erial	Uniaxial comp.strength	>250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5-25 1-5 <1 MPa MPa MPa	
		Rating	15	12	7	4	2 1 0	
2	Drill co	ore Quality RQD	90% - 100%	75% - 90%	50% - 75%	25% - 50%	<25%	
2		Rating	20	17	13	8	3	
3	Spacing	g of discontinuities	>2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm	< 60 mm	
J		Rating	20	15	10	8	5	
Con 4	ndition o	f discontinuities (See E)	Very rough surfaces. Not continuous. No separation. Unweathered wall rock	Slightly rough surfaces. Separation < 1 mm. Slightly weathered walls	Slightly rough surfaces. Separation < 1 mm. Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge > 5 mm thick c Separation > 5 mm Continuous	
		Rating	30	25	20	10	0	
0	Infl Ien	low per 10 m tunnel igth (l/m)	None	< 10	10 - 25	25 -125	> 125	
5 wat	ater (Ma	pint water press)/ ajor principal stress)	0	< 0.1	0.1 - 0.2	0.2 - 0.5	> 0.5	
	Ge	eneral conditions	Completely dry	Damp	Wet	Dripping	Flowing	
		Rating	15	10	7	4	0	
. RATIN	ng adj	USTMENT FOR DISC	ONTINUITY ORIENTATIO	ONS (See F)	_		-	
trike an	nd dip or	ientations	Very Favourable	Favourable	Fair	Unfavourable	Very unfavourable	
		Tunnels & mines	0	-2	-5	-10	-12	
Rating	gs	Foundations	0	-2	-7	-15	-25	
		Slopes	0	-5	-25	-50		
ROCK	K MASS	CLASSES DETERMI	NED FROM TOTAL RAT		a a <i>i</i> i	10.01		
ating			100 - 81	80 - 61	60 - 41	40 - 21	< 21	
ass nui	imper		Verv good rock	Good rock	III Fair rock	Poor rock	Very poor rock	
			Very good Toek	COOCHOCK	Fail TOCK	1 OUT TOOK	Very poor lock	
	und Or	ROCK CLASSES		Ш	ш	IV	V	
verane -	stand-u	n time	20 years for 15 m span	1vear for 10 m span	1 week for 5 m span	10 hrs for 2.5 m span	30 mins for 1 m span	
ohesion	n of rock	(mass (MPa)	>400	300 - 400	200 - 300	100 - 200	<100	
riction a	angle of	rock mass (deg)	> 45	35 - 45	25 - 35	15 - 25	< 15	
. GUIDE	ELINES	FOR CLASSIFICATIO	ON OF DISCONTINUITY	CONDITIONS	•			
iscontin	nuity len	gth persistence	< 1 m	1 -3 m	3 -10 m	10 - 20 m	> 20 m	
	F	Rating	6	4	2	1	0	
eparatic	on (aper	rture)	None	< 0.1 mm	0.1 -1.0 mm	1 - 5 mm	> 5 mm	
	F	Rating	6	5	4	1	0	
loughne	ess		Very rough	Rough	Slightly rough	Smooth	Slickensided	
	F	Rating	6	4	3	1	0	
ntilling (g	gouge)	D-41	None	Hard filling < 5 mm	Hard filling > 5 mm	Soft filling < 5 mm	Soft filling > 5mm	
1004	F	kating	5	4	2 Madaratah	2	0 Decertation	
eatheri	ing r	Rating	Unweathered	Slightly weathered	vioderately weathered	Higniy weathered		
FFFF					5	I	, v	
21120	51 51 1	Strike nernen	dicular to tunnel avis		Ctril	e narallel to tunnel avia		
П	Drive with	h dip - Dip 45 to 90	Drive with din	- Dip 20 - 45	Dip 45 - 90		lip 20 - 45	
	Ver	y favourable	Favou	Irable	Very favourable		Fair	
Driv	ive agair	nst dip - Dip 45 to 90	Drive against d	ip - Dip 20 - 45	Dip 0 to	20 - Irrespective of strike	9*	
	0.1	Fair	Unfavo	urable		Fair		

** Modified after Wickham et al (1972)





A. CL	ASSIFIC	CATION PARAMETERS	AND THEIR RATINGS					
		Parameter			Range of values			
	Strength	Point-load strength index	>10 MPa	4-10 MPa	2-4 MPa	1-2 MPa	For this low range - uniaxial compressive test is preferred	
1 n	ntact roc naterial	k Uniaxial comp.strength	>250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5-25 1-5 <1 MPa MPa MPa	
Г		Rating	15	12	7	4	2 1 0	
2	Dril	I core Quality RQD	90% - 100%	75% - 90%	50% - 75%	25% - 50%	<25%	
ΈΓ		Rating	20	17	13	8	3	
	Spac	ing of discontinuities	>2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm	< 60 mm	
° Г		Rating	20	15	10	8	5	
4	Conditior	n of discontinuities (See E)	Very rough surfaces. Slightly ro		Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge > 5 mn thick Separation > 5 mn Continuous		
		Rating	30	25	20	10	0	
Ţ		Inflow per 10 m tunnel length (I/m)	None	< 10	10 - 25	25 -125	> 125	
5	water ((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	
		Rating	15	10	7	4	0	
RA	ATING A	DJUSTMENT FOR DISC	ONTINUITY ORIENTATIO	ONS (See F)				
rike	and dip	orientations	Very Favourable	Favourable	Fair	Unfavourable	Very unfavourable	
		Tunnels & mines	0	-2	-5	-10	-12	
Rat	tings	Foundations	0	-2	-7	-15	-25	
		Slopes	0	-5	-25	-50		
RC	OCK MA	SS CLASSES DETERMI	NED FROM TOTAL RAT	NGS				
ating	g		100 - 81	80 - 61	60 - 41	40 - 21	< 21	
ass	number		I		III	IV	V	
esci	ription		Very good rock	Good rock	Fair rock	Poor rock	Very poor rock	
ME	EANING	OF ROCK CLASSES					-	
ass	number		I	11	III	IV	V	
/era	ige stand	d-up time	20 years for 15 m span	1year for 10 m span	1 week for 5 m span	10 hrs for 2.5 m span	30 mins for 1 m spa	
ohe	sion of ro	ock mass (MPa)	>400	300 - 400	200 - 300	100 - 200	<100	
ictic	on angle	of rock mass (deg)	> 45	35 - 45	25 - 35	15 - 25	< 15	
GL	JUELIN	ES FOR CLASSIFICATIO			0.40	10.00		
SCO	ntinuity l	ength persistence	< 1 m	1-3 m	3 -10 m	10 - 20 m	> 20 m	
		Rating	6	4	2	1	0	
pa	iation (ap	Poting	inone	< U.1 MM	0.1 -1.0 mm	1 - 5 MM	> 5 mm	
200	hnosa	Rauny	0 Vorv rough	Э Роцар	4 Slightly rough	I Smooth	U Slickopaidad	
Jugi	111000	Rating	¢ery rougin 6	A Nough		1		
fillin	ומ (מסוומי		None	Hard filling < 5 mm	Hard filling > 5 mm	Soft filling < 5 mm	Soft filling > 5mm	
	.g (gouge	Rating	5	4	2	2	0	
eat	herina		Unweathered	Slightly weathered	Moderately weathered	- Highly weathered	Decomposed	
	9	Rating	6	5	3	1	0	
EF	FECT O	F DISCONTINUITY STR	IKE AND DIP ORIENTAT	ION IN TUNNELLING**				
	-	Strike perpen	dicular to tunnel axis		Stril	e parallel to tunnel axis		
	Drive v	with dip - Dip 45 to 90	Drive with dip	- Dip 20 - 45	Dip 45 - 90	C	9 ip 20 - 45	
	N	/ery favourable	Favou	rable	Very favourable		Fair	
_	Drive ag	ainst dip - Dip 45 to 90	Drive against d	ip - Dip 20 - 45	Dip 0 to	20 - Irrespective of strike	e*	
	- C	Fair	Unfavo	urable	•	Fair		

Rock Mass Rating System (RMR) (After Bieniawski 1989)

OPG Geologic Repository - Expected Low Qual Values

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

** Modified after Wickham et al (1972)





GSI 55



Rock Mass Rating System (RMR) (After Bieniawski 1989)

A. CLASSIFICATION PARAMETERS AND THEIR RATINGS

323874DGR-RPT-GMR109-Rev00 – Appendix A	
PR 323874 - Page 7 of 12	ļ

** Modified after Wickham et al (1972)

					0		
	Strength	Point-load strength index	>10 MPa	4-10 MPa	2-4 MPa	1-2 MPa	For this low range - uniaxial compressive test is preferred
	ntact roc naterial	k Uniaxial comp.strength	>250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5-25 1-5 <1 MPa MPa MPa
ľ		Rating	15	12	7	4	2 1 0
T	Dril	I core Quality RQD	90% - 100%	75% - 90%	50% - 75%	25% - 50%	<25%
ſ		Rating	20	17	13	8	3
T	Spac	ing of discontinuities	>2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm	< 60 mm
ľ		Rating	20	15	10	8	5
	Conditior	n of discontinuities (See E)	Very rough surfaces. Not continuous. No separation. Unweathered wall rock	Slightly rough surfaces. Separation < 1 mm. Slightly weathered walls	Slightly rough surfaces. Separation < 1 mm. Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge > 5 mm thick c Separation > 5 mm Continuous
ŀ		Rating	30	25	20	10	0
I		Inflow per 10 m tunnel length (I/m)	None	< 10	10 - 25	25 -125	> 125
	Ground water	(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	
		Rating	15	10	7	4	0
٢.	ATING A	DJUSTMENT FOR DISC	ONTINUITY ORIENTATIO	DNS (See F)			
k	and dip	orientations	Very Favourable	Favourable	Fair	Unfavourable	Very unfavourable
		Tunnels & mines	0	-2	-5	-10	-12
a	tings	Foundations	0	-2	-7	-15	-25
	ľ	Slopes	0	-5	-25	-50	
		SS CLASSES DETERMI	NED FROM TOTAL RATI	NGS			
Z							
۲ ir	g		100 - 81	80 - 61	60 - 41	40 - 21	< 21
ir s	g s number		100 - 81 I	80 - 61 II	60 - 41 III	40 - 21 IV	< 21 V
ir s	g number ription		100 - 81 I Very good rock	80 - 61 II Good rock	60 - 41 III Fair rock	40 - 21 IV Poor rock	< 21 V Very poor rock
ir s: s:	g number ription EANING	OF ROCK CLASSES	100 - 81 I Very good rock	80 - 61 II Good rock	60 - 41 III Fair rock	40 - 21 IV Poor rock	< 21 V Very poor rock
ir s S	g number ription EANING	OF ROCK CLASSES	100 - 81 I Very good rock I	80 - 61 II Good rock	60 - 41 III Fair rock III	40 - 21 IV Poor rock IV	< 21 V Very poor rock
R ir s S S	g ription EANING number	OF ROCK CLASSES	100 - 81 I Very good rock I 20 years for 15 m span	80 - 61 II Good rock II 1year for 10 m span	60 - 41 III Fair rock III 1 week for 5 m span	40 - 21 IV Poor rock IV 10 hrs for 2.5 m span	< 21 V Very poor rock V 30 mins for 1 m spar
r s s s s s	g ription EANING age stand sion of ro	OF ROCK CLASSES	100 - 81 I Very good rock I 20 years for 15 m span >400	80 - 61 II Good rock II 1year for 10 m span 300 - 400	60 - 41 III Fair rock III 1 week for 5 m span 200 - 300	40 - 21 IV Poor rock IV 10 hrs for 2.5 m span 100 - 200	<pre>< 21 V Very poor rock V 30 mins for 1 m span <100</pre>
	g ription EANING age stand sion of roon angle	OF ROCK CLASSES J-up time ock mass (MPa) of rock mass (deq)	100 - 81 I Very good rock I 20 years for 15 m span >400 > 45	80 - 61 II Good rock II 1year for 10 m span 300 - 400 35 - 45	60 - 41 III Fair rock III 1 week for 5 m span 200 - 300 25 - 35	40 - 21 IV Poor rock IV 10 hrs for 2.5 m span 100 - 200 15 - 25	< 21 V Very poor rock 30 mins for 1 m spar <100 < 15
ir so so so so so so so so so so so so so	g s number ription EANING s number age stand sion of ro on angle	OF ROCK CLASSES 	100 - 81 I Very good rock 20 years for 15 m span >400 > 45 DN OF DISCONTINUITY	80 - 61 II Good rock II 1year for 10 m span 300 - 400 35 - 45 CONDITIONS	60 - 41 III Fair rock III 1 week for 5 m span 200 - 300 25 - 35	40 - 21 IV Poor rock IV 10 hrs for 2.5 m span 100 - 200 15 - 25	< 21 V Very poor rock V 30 mins for 1 m spart <100
R ir s s s s r s r s r	g s number ription EANING s number age stanc sion of ro on angle UIDELINI	OF ROCK CLASSES 	100 - 81 I Very good rock I 20 years for 15 m span >400 > 45 DN OF DISCONTINUITY (80 - 61 II Good rock II 1year for 10 m span 300 - 400 35 - 45 CONDITIONS 1 -3 m	60 - 41 III Fair rock III 1 week for 5 m span 200 - 300 25 - 35 3 - 10 m	40 - 21 IV Poor rock IV 10 hrs for 2.5 m span 100 - 200 15 - 25	< 21 V Very poor rock V 30 mins for 1 m spar <100 < 15 > 20 m
	g ription EANING age stance sion of re on angle JIDELINI	OF ROCK CLASSES 	100 - 81 I Very good rock I 20 years for 15 m span >400 > 45 DN OF DISCONTINUITY (<1 m 6	80 - 61 II Good rock II 1year for 10 m span 300 - 400 35 - 45 CONDITIONS 1 -3 m 4	60 - 41 III Fair rock III 1 week for 5 m span 200 - 300 25 - 35 3 -10 m 2	40 - 21 IV Poor rock IV 10 hrs for 2.5 m span 100 - 200 15 - 25 10 - 20 m 1	< 21 V Very poor rock 30 mins for 1 m spar <100 <15 > 20 m 0
	g ription EANING number age stance sion of re on angle JIDELINI pontinuity I	OF ROCK CLASSES d-up time bock mass (MPa) of rock mass (deg) ES FOR CLASSIFICATIO ength persistence Rating perfure)	100 - 81 I Very good rock I 20 years for 15 m span >400 > 45 DN OF DISCONTINUITY (<1 m 6 None	80 - 61 II Good rock II 1year for 10 m span 300 - 400 35 - 45 CONDITIONS 1 -3 m 4 < 0.1 mm	60 - 41 III Fair rock III 1 week for 5 m span 200 - 300 25 - 35 3 -10 m 2 0,1 - 1 0 mm	40 - 21 IV Poor rock IV 10 hrs for 2.5 m span 100 - 200 15 - 25 10 - 20 m 1 1 - 5 mm	<pre>< 21 V Very poor rock V 30 mins for 1 m spar <100 <15 >20 m 0 </pre>
ir s s s c u s s r n e t t i	g a number ription EANING age stance sion of ro on angle UIDELINI entinuity I	OF ROCK CLASSES d-up time bock mass (MPa) of rock mass (deg) ES FOR CLASSIFICATIO ength persistence Rating perture) Rating	100 - 81 I Very good rock I 20 years for 15 m span >400 > 45 DN OF DISCONTINUITY (<1 m 6 None 6	80 - 61 II Good rock II 1year for 10 m span 300 - 400 35 - 45 CONDITIONS 1 -3 m 4 < 0.1 mm 5	60 - 41 III Fair rock III 1 week for 5 m span 200 - 300 25 - 35 3 -10 m 2 0.1 -1.0 mm 4	40 - 21 IV Poor rock IV 10 hrs for 2.5 m span 100 - 200 15 - 25 10 - 20 m 1 - 5 mm 1 - 5 mm	<pre>< 21 V Very poor rock V 30 mins for 1 m spar <100 <15 >20 m 0 >5 mm 0</pre>
R irr s: so or so	g a number ription EANING age stand sion of ro on angle JIDELINI ontinuity I ration (ap	OF ROCK CLASSES d-up time bock mass (MPa) of rock mass (deg) ES FOR CLASSIFICATIO ength persistence Rating perture) Rating	100 - 81 I Very good rock I 20 years for 15 m span >400 > 45 DN OF DISCONTINUITY (<1 m 6 None 6 Very rough	80 - 61 II Good rock II 1year for 10 m span 300 - 400 35 - 45 CONDITIONS 1 -3 m 4 < 0.1 mm 5 Rough	60 - 41 III Fair rock III 1 week for 5 m span 200 - 300 25 - 35 3 -10 m 2 0.1 -1.0 mm 4 Slightly rough	40 - 21 IV Poor rock IV 10 hrs for 2.5 m span 100 - 200 15 - 25 10 - 20 m 1 - 5 mm 1 Smooth	< 21 V Very poor rock 30 mins for 1 m spar <100 < 15 > 20 m 0 > 5 mm 0 Slickensided
	g s number ription EANING s number age stanc sion of rc on angle JIDELINI ontinuity I ration (ap	OF ROCK CLASSES d-up time bock mass (MPa) of rock mass (deg) ES FOR CLASSIFICATIO ength persistence Rating perture) Rating Rating	100 - 81 I Very good rock I 20 years for 15 m span >400 > 45 DN OF DISCONTINUITY (<1 m 6 None 6 Very rough 6	80 - 61 II Good rock II 1year for 10 m span 300 - 400 35 - 45 CONDITIONS 1 -3 m 4 < 0.1 mm 5 Rough 4	60 - 41 III Fair rock III 1 week for 5 m span 200 - 300 25 - 35 3 -10 m 2 0.1 -1.0 mm 4 Slightly rough 3	40 - 21 IV Poor rock IV 10 hrs for 2.5 m span 100 - 200 15 - 25 10 - 20 m 1 - 5 mm 1 Smooth 1	< 21 V Very poor rock V 30 mins for 1 m spar <100
	g s number ription EANING s number age stanc sion of rc on angle JIDELINI ontinuity I ration (ap	OF ROCK CLASSES d-up time ock mass (MPa) of rock mass (deg) ES FOR CLASSIFICATIO ength persistence Rating perture) Rating Rating e)	100 - 81 I Very good rock I 20 years for 15 m span >400 > 45 DN OF DISCONTINUITY (<1 m 6 None 6 Very rough 6 None	80 - 61 II Good rock II 1year for 10 m span 300 - 400 35 - 45 CONDITIONS 1 -3 m 4 < 0.1 mm 5 Rough 4 Hard filling < 5 mm	60 - 41 III Fair rock III 1 week for 5 m span 200 - 300 25 - 35 3 -10 m 2 0.1 -1.0 mm 4 Slightly rough 3 Hard filling > 5 mm	40 - 21 IV Poor rock IV 10 hrs for 2.5 m span 100 - 200 15 - 25 10 - 20 m 1 1 - 5 mm 1 Smooth 1 Soft filling < 5 mm	< 21 V Very poor rock V 30 mins for 1 m spar <100
	g s number ription EANING age stanc sion of ro on angle JIDELINI pation (ap hness	OF ROCK CLASSES d-up time ock mass (MPa) of rock mass (deg) ES FOR CLASSIFICATIO ength persistence Rating perture) Rating Rating e) Rating e) Rating	100 - 81 I Very good rock I 20 years for 15 m span >400 > 45 DN OF DISCONTINUITY (< 1 m 6 None 6 Very rough 6 None 5	80 - 61 II Good rock II 1year for 10 m span 300 - 400 35 - 45 CONDITIONS 1 -3 m 4 < 0.1 mm 5 Rough 4 Hard filling < 5 mm 4	60 - 41 III Fair rock III 1 week for 5 m span 200 - 300 25 - 35 3 -10 m 2 0.1 -1.0 mm 4 Slightly rough 3 Hard filling > 5 mm 2	40 - 21 IV Poor rock IV 10 hrs for 2.5 m span 100 - 200 15 - 25 10 - 20 m 1 - 5 mm 1 - 5 mm 1 Smooth 1 Smooth 1 Soft filling < 5 mm 2	< 21 V Very poor rock V 30 mins for 1 m spar <100
	g s number ription EANING EANING age stance sion of ro on angle JIDELINI nation (ap hness ag (gouge hering	OF ROCK CLASSES d-up time bock mass (MPa) of rock mass (deg) ES FOR CLASSIFICATIO ength persistence Rating perture) Rating e) Rating e) Rating	100 - 81 I Very good rock I 20 years for 15 m span >400 > 45 DN OF DISCONTINUITY (< 1 m 6 None 6 Very rough 6 None 5 Unweathered	80 - 61 II Good rock II 1year for 10 m span 300 - 400 35 - 45 CONDITIONS 1 -3 m 4 < 0.1 mm 5 Rough 4 Hard filling < 5 mm 4 Slightly weathered	60 - 41 III Fair rock III 1 week for 5 m span 200 - 300 25 - 35 3 -10 m 2 0.1 -1.0 mm 4 Slightly rough 3 Hard filling > 5 mm 2 Moderately weathered	40 - 21 IV Poor rock IV 10 hrs for 2.5 m span 100 - 200 15 - 25 10 - 20 m 1 1 - 5 mm 1 Smooth 1 Soft filling < 5 mm 2 Highly weathered	< 21 V Very poor rock V 30 mins for 1 m spar <100
	g s number ription EANING a number age stances sion of rc on angle JIDELINI pontinuity I ration (ap hness ag (gouge hering	OF ROCK CLASSES d-up time bock mass (MPa) of rock mass (deg) ES FOR CLASSIFICATIC ength persistence Rating perture) Rating a) Rating Rating Rating Rating Rating Rating	100 - 81 I Very good rock I 20 years for 15 m span >400 > 45 DN OF DISCONTINUITY (< 1 m 6 None 6 Very rough 6 None 5 Unweathered 6	80 - 61 II Good rock II 1year for 10 m span 300 - 400 35 - 45 CONDITIONS 1 -3 m 4 < 0.1 mm 5 Rough 4 Hard filling < 5 mm 4 Slightly weathered 5	60 - 41 III Fair rock III 1 week for 5 m span 200 - 300 25 - 35 3 -10 m 2 0.1 -1.0 mm 4 Slightly rough 3 Hard filling > 5 mm 2 Moderately weathered 3	40 - 21 IV Poor rock IV 10 hrs for 2.5 m span 100 - 200 15 - 25 10 - 20 m 1 1 - 5 mm 1 Smooth 1 Soft filling < 5 mm 2 Highly weathered 1	< 21 V Very poor rock V 30 mins for 1 m spar <100
	g s number ription EANING s number age stand ge stand sion of rc on angle JIDELINI pontinuity I ration (ap hness ag (gouge hering FECT O	OF ROCK CLASSES d-up time ock mass (MPa) of rock mass (deg) ES FOR CLASSIFICATIO ength persistence Rating perture) Rating Rating e) Rating F DISCONTINUITY STR	100 - 81 I Very good rock I 20 years for 15 m span >400 > 45 DN OF DISCONTINUITY (< 1 m 6 None 6 Very rough 6 None 5 Unweathered 6 KE AND DIP ORIENTAT	80 - 61 II Good rock II 1year for 10 m span 300 - 400 35 - 45 CONDITIONS 1 -3 m 4 < 0.1 mm 5 Rough 4 Hard filling < 5 mm 4 Slightly weathered 5 ON IN TUNNELLING**	60 - 41 III Fair rock III 1 week for 5 m span 200 - 300 25 - 35 3 -10 m 2 0.1 -1.0 mm 4 Slightly rough 3 Hard filling > 5 mm 2 Moderately weathered 3	40 - 21 IV Poor rock IV 10 hrs for 2.5 m span 100 - 200 15 - 25 10 - 20 m 1 1 - 5 mm 1 Smooth 1 Soft filling < 5 mm 2 Highly weathered 1	< 21 V Very poor rock V 30 mins for 1 m spar <100
	g s number ription EANING s number age stand sion of rc on angle JIDELINI ontinuity I ration (ap hness ag (gouge hering	OF ROCK CLASSES d-up time ock mass (MPa) of rock mass (deg) ES FOR CLASSIFICATIO ength persistence Rating perture) Rating Rating Bating F DISCONTINUITY STR	100 - 81 I Very good rock I 20 years for 15 m span >400 > 45 DN OF DISCONTINUITY (< 1 m 6 None 6 Very rough 6 None 5 Unweathered 6 KE AND DIP ORIENTAT dicular to tunnel axis	80 - 61 II Good rock II 1year for 10 m span 300 - 400 35 - 45 CONDITIONS 1 -3 m 4 < 0.1 mm 5 Rough 4 Hard filling < 5 mm 4 Slightly weathered 5 ON IN TUNNELLING**	60 - 41 III Fair rock III 1 week for 5 m span 200 - 300 25 - 35 3 -10 m 2 0.1 -1.0 mm 4 Slightly rough 3 Hard filling > 5 mm 2 Moderately weathered 3 Strik	40 - 21 IV Poor rock IV 10 hrs for 2.5 m span 100 - 200 15 - 25 10 - 20 m 1 - 5 mm 1 Smooth 1 Soft filling < 5 mm 2 Highly weathered 1 se parallel to tunnel axis	< 21 V Very poor rock V 30 mins for 1 m spar <100 < 15 > 20 m 0 > 5 mm 0 Slickensided 0 Soft filling > 5mm 0 Decomposed 0
	g s number ription EANING s number age stances sion of ric on angle JIDELINI ontinuity I ration (ag hness bg (gouge hering FECT O	OF ROCK CLASSES d-up time bock mass (MPa) of rock mass (deg) ES FOR CLASSIFICATIO ength persistence Rating perture) Rating Rating F DISCONTINUITY STRI Strike perpend with din - Din 45 to 90	100 - 81 I Very good rock 1 20 years for 15 m span >400 > 45 DN OF DISCONTINUITY of a state of a st	80 - 61 II Good rock II 1year for 10 m span 300 - 400 35 - 45 CONDITIONS 1 -3 m 4 < 0.1 mm 5 Rough 4 Hard filling < 5 mm 4 Slightly weathered 5 ON IN TUNNELLING**	60 - 41 III Fair rock III 1 week for 5 m span 200 - 300 25 - 35 3 -10 m 2 0.1 -1.0 mm 4 Slightly rough 3 Hard filling > 5 mm 2 Moderately weathered 3 Strik Dip 45 - 90	40 - 21 IV Poor rock IV 10 hrs for 2.5 m span 100 - 200 15 - 25 10 - 20 m 1 1 - 5 mm 1 Smooth 1 Soft filling < 5 mm 2 Highly weathered 1 se parallel to tunnel axis	< 21 V Very poor rock V 30 mins for 1 m spar <100 < 15 > 20 m 0 > 5 mm 0 Slickensided 0 Soft filling > 5mm 0 Decomposed 0
	g s number ription EANING s number s number s number sion of rc on angle JIDELINI ontinuity I ration (ap hness hering FECT O Drive v	OF ROCK CLASSES d-up time cock mass (MPa) of rock mass (deg) ES FOR CLASSIFICATIC length persistence Rating Perture) Rating Rating F DISCONTINUITY STRI Strike perpend with dip - Dip 45 to 90 (perture)	100 - 81 I Very good rock 1 20 years for 15 m span >400 > 45 DN OF DISCONTINUITY < 1 m	80 - 61 II Good rock II 1year for 10 m span 300 - 400 35 - 45 CONDITIONS 1 -3 m 4 < 0.1 mm 5 Rough 4 Hard filling < 5 mm 4 Slightly weathered 5 ON IN TUNNELLING** - Dip 20 - 45 rable	60 - 41 III Fair rock III 1 week for 5 m span 200 - 300 25 - 35 3 -10 m 2 0.1 -1.0 mm 4 Slightly rough 3 Hard filling > 5 mm 2 Moderately weathered 3 Strik Dip 45 - 90 Very favourable	40 - 21 IV Poor rock IV 10 hrs for 2.5 m span 100 - 200 15 - 25 10 - 20 m 1 1 - 5 mm 1 Smooth 1 Soft filling < 5 mm 2 Highly weathered 1 se parallel to tunnel axis	<pre>< 21 V Very poor rock V 30 mins for 1 m spar <100 <15 >20 m 0 >5 mm 0 Slickensided 0 Soft filling > 5mm 0 Decomposed 0 bip 20 - 45 Fair</pre>
	g s number ription EANING s number sion of rc on angle JIDELINI ontinuity I ration (ap hness hering FECT O	OF ROCK CLASSES d-up time cock mass (MPa) of rock mass (deg) ES FOR CLASSIFICATIC length persistence Rating Rating Rating F DISCONTINUITY STRI Strike perpend with dip - Dip 45 to 90 //ery favourable	100 - 81 I Very good rock I 20 years for 15 m span >400 > 45 DN OF DISCONTINUITY (< 1 m	80 - 61 II Good rock Il 1year for 10 m span 300 - 400 35 - 45 CONDITIONS 1 -3 m 4 < 0.1 mm	60 - 41 III Fair rock III 1 week for 5 m span 200 - 300 25 - 35 3 -10 m 2 0.1 -1.0 mm 4 Slightly rough 3 Hard filling > 5 mm 2 Moderately weathered 3 Strik Dip 45 - 90 Very favourable Dip 0 for 0	40 - 21 IV Poor rock IV 10 hrs for 2.5 m span 100 - 200 15 - 25 10 - 20 m 1 1 - 5 mm 1 Smooth 1 Smooth 1 Soft filling < 5 mm 2 Highly weathered 1 te parallel to tunnel axis	< 21 V Very poor rock V 30 mins for 1 m spar <100

Hatch Mott MacDonald

OPG Geologic Repository - Expected Med Quality Values

RMR 74 GSI 69





Rock Mass Rating System (RMR) (After Bieniawski 1989)

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

PR 323874 - Page 8 of 12

** Modified after Wickham et al (1972)

A. C	LASSIFI	CATION PARAMETERS										
ļ.,		Parameter			Range of values		E an d i	la				
1	Strength	Point-load strength index	>10 MPa	4-10 MPa	2-4 MPa	1-2 MPa	ror this uniaxial test is p	iow ran compre referred	ge - essive I			
	intact roo material	ck Uniaxial comp.strength	>250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5 - 25 MPa	1 - 5 MPa	<1 MPa			
		Rating	15	12	7	4	2	1	0			
2	Dri	ill core Quality RQD	90% - 100%	75% - 90%	50% - 75%	25% - 50%		<25%				
-		Rating	20	17	13	8		3				
3	Spa	cing of discontinuities	>2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm	<	< 60 mm	า			
		Rating	20	15	10	8		5				
4	4 Condition of discontinuities (See E)		Very rough surfaces. Slightly rough surfaces. Not continuous. Separation < 1 mm E) Unweathered wall rock		Slightly rough surfaces. Separation < 1 mm. Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	thick o Separation > 5 mm Continuous		5 mm or 5 mm JS			
		Rating	30	25	20	10		0				
	Ground	Inflow per 10 m tunnel length (l/m)	None	< 10	10 - 25	25 -125		> 125				
5	water	(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				
		Rating	15		7	4		0				
B. R	RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS (See F)											
Strik	Strike and dip orientations		Very Favourable	Favourable	Fair	Unfavourable	very untavourable		irable			
P	Tunnels & mines Ratings Eoundations		0	-2	-5	-10	-12					
		Slopes 0		-5	-25	-50		20				
C. R	ОСК МА	SS CLASSES DETERMI	NED FROM TOTAL RAT	NGS			I					
Rati	ng		100 - 81	80 - 61	60 - 41	40 - 21		< 21				
Clas	s numbe	r	l I	11	III	IV	V					
Des	cription		Very good rock	Good rock	Fair rock	Poor rock	Very poor rock		ock			
D. N	EANING	OF ROCK CLASSES										
Clas	s numbe	r	1			IV		V				
Ave	age stan	id-up time	20 years for 15 m span	1year for 10 m span	1 week for 5 m span	10 hrs for 2.5 m span	30 min	s for 1 r	n span			
Coh	esion of r	rock mass (MPa)	>400	300 - 400	200 - 300	100 - 200		<100				
⊢rict	ion angle	e of rock mass (deg)	> 45	35 - 45	25 - 35	15 - 25		< 15				
ב.G	UIDELIN	ILS FUR CLASSIFICATIO			0.40	10 00	-	. 00 -				
UISC	ontinuity	Reting	< 1 m	1-3 M	3-10 m	10 - 20 m		> 20 m				
Sen	aration (a	naung aperture)	0 None	4 < 0.1 mm	2 0.1 -1.0 mm	1 - 5 mm		v				
Cop		Rating	6	5	4	1	· · · ·	0				
Rou	ghness		Very rough	Rough	Slightly rough	Smooth	Sli	- ckensid	ed			
	-	Rating	6	4	3	1		0				
Infilli	ng (goug	je)	None	Hard filling < 5 mm	Hard filling > 5 mm	Soft filling < 5 mm	Soft f	illing >	5mm			
		Rating	5	4	2	2		0				
Wea	thering		Unweathered	Slightly weathered	Moderately weathered	Highly weathered	De	compos	sed			
		Rating	6	5	3	1		0				
F. E	FFECT C		IKE AND DIP ORIENTAT	ION IN TUNNELLING**								
Strike perpen			dicular to tunnel axis		Strik	e parallel to tunnel axis	parallel to tunnel axis					
	Dates	with dia Dia 45 to 00	Distance container P	Din 20 45	Dia 15 00		Dip 20 - 45					
	Drive	with dip - Dip 45 to 90	Drive with dip	- Dip 20 - 45	Dip 45 - 90		10 20 - 48 Fair	5				
	Drive	with dip - Dip 45 to 90 Very favourable gainst dip - Dip 45 to 90	Drive with dip	- Dip 20 - 45 rable in - Dip 20 - 45	Dip 45 - 90 Very favourable	20 - Irrespective of strike	Fair	5				
	Drive Drive a	with dip - Dip 45 to 90 Very favourable gainst dip - Dip 45 to 90 Fair	Drive with dip Favou Drive against di	- Dip 20 - 45 rable ip - Dip 20 - 45 urable	Dip 45 - 90 Very favourable Dip 0 to	20 - Irrespective of strike Fair	Fair •*	5				

C Consulting Engineers



RMR GSI 80

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May 2008 Appendix A

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Roc	ck Mass F	Rating System (RM	IR) (After Bieniawski	1989) OP	G Geologic Reposit	ory - High End Lov	v Values
4. C	LASSIFICA	ATION PARAMETERS	AND THEIR RATINGS				
	P	Parameter	Range of values				
	Strength of intact rock material	Point-load strength index f	>10 MPa	4-10 MPa	2-4 MPa	1-2 MPa	For this low range - uniaxial compressive test is preferred
1		Uniaxial comp.strength	>250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5-25 1-5 <1 MPa MPa MPa
ſ		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
2	Spacing of discontinuities		>2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm	< 60 mm
J	Rating		20	15	10	8	5
4	Condition	of discontinuities (See E)	Very rough surfaces. Not continuous. No separation. Unweathered wall rock	Slightly rough surfaces. Separation < 1 mm. Slightly weathered walls	Slightly rough surfaces. Separation < 1 mm. Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge > 5 mm thick or Separation > 5 mm Continuous
ľ	Rating		30	25	20	10	0
	In Cround le	nflow per 10 m tunnel ength (I/m)	None	< 10	10 - 25	25 -125	> 125
5	water (M Ground (M Ge	loint water press)/ Major principal stress)	0	< 0.1	0.1 - 0.2	0.2 - 0.5	> 0.5
		eneral conditions	Completely dry	Damp	Wet	Dripping	Flowing
		Rating	15	10	7	4	0
3. R	ATING AD	JUSTMENT FOR DISC	ONTINUITY ORIENTATIO	ONS (See F)			-
Strike and dip orientations			Very Favourable	Favourable	Fair	Unfavourable	Very unfavourable
Tunnels & mines Ratings Foundations		Tunnels & mines	0	-2	-5	-10	-12
		Foundations	0	-2	-7	-15	-25
	Slopes		0	-5	-25	-50	
). R	OCK MAS	S CLASSES DETERMI	NED FROM TOTAL RAT	INGS			
Rating			100 - 81	80 - 61	60 - 41	40 - 21	< 21
			l Voru good rock	II Cood rook	III Fair reals	IV Boor rook	V Voruppor rock
Jeso			Very good Tock	GOOUTOCK	Fair rock	FOULTOCK	Very poor lock
). IVI		JF RUCK CLASSES	1	П		11/	V
			20 years for 15 m span	1vear for 10 m span	1 wook for 5 m opon	10 brs for 2.5 m span	30 mins for 1 m span
Cohesion of rock mass (MPa)			>400	300 - 400	200 - 300	100 - 200	<100
Friction angle of rock mass (deg)			> 45	35 - 45	25 - 35	15 - 25	< 15
. G		S FOR CLASSIFICATIO	ON OF DISCONTINUITY	CONDITIONS			
)isc	ontinuity le	nath persistence	< 1 m	1-3 m	3 -10 m	10 - 20 m	> 20 m
Rating			6	4	2	1	0
Separation (aperture)			None	< 0.1 mm	0.1 -1.0 mm	1 - 5 mm	> 5 mm
Rating			6	5	4	1	0
Roughness			Very rough	Rough	Slightly rough	Smooth	Slickensided
Rating			6	4	3	1	0
nfilling (gouge)			None	Hard filling < 5 mm	Hard filling > 5 mm	Soft filling < 5 mm	Soft filling > 5mm
Rating			5	4	2	2	0
Vea	thering		Unweathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed
		Rating	6	5	3	1	0
. El	FFECT OF	DISCONTINUITY STR	IKE AND DIP ORIENTAT	ION IN TUNNELLING**			
Strike perpendicular to tunnel axis					Strike parallel to tunnel axis		
_	Drive wi	Ith dip - Dip 45 to 90	Drive with dip - Dip 20 - 45		Dip 45 - 90 Dip 20 - 45		
	Drive ere		Favourable		Dip 0 to 20 Irrographics of strike*		
	Drive aga	Epir	Unve against dip - Dip 20 - 45				

** Modified after Wickham et al (1972)

RMR 60

С


Rock Mass Rating System (RMR) (After Bieniawski 1989) OPG Geologic Repository - High End Med Values									
A. C	LASSIFIC	CATION PARAMETERS	AND THEIR RATINGS						
		Parameter			Range of values				
	Strength of intact rock Uniaxial		>10 MPa	4-10 MPa	2-4 MPa	1-2 MPa	For this uniaxial test is pr	low ran compre referred	ge - ssive
1 intact roo material		k Uniaxial comp.strength	>250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5 - 25 MPa	1 - 5 MPa	<1 MPa
		Rating	15	12	7	4	2	1	0
2 Drill core Quality RQD		I core Quality RQD	90% - 100%	75% - 90%	50% - 75%	25% - 50%	<u> </u>	<25%	
2 Rating		Rating	20	17	13	8		3	
2 Spacing of discontinuities		cing of discontinuities	>2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm	<	60 mm	1
3 Rating		Rating	20	15	10	8	5		
Condition of discontinuities (See 4 E)		n of discontinuities (See E)	Very rough surfaces. Not continuous. No separation. Unweathered wall rock	Slightly rough surface Separation < 1 mm. Slightly weathered wa	 Slightly rough surfaces. Separation < 1 mm. Highly weathered walls 	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft go thick Separa Co	ouge > ation > ontinuou	5 mm or 5 mm JS
Rating		Rating	30	25	20	10		0	
	Inflow per 10 m tunnel Ground ength (I/m)		None	< 10	10 - 25	25 -125		> 125	
5 Ground (Joint water (Major princ		(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	ŀ	Flowing	
Rating		Rating	15	10	7	4		0	
B. F	RATING A	DJUSTMENT FOR DISC	ONTINUITY ORIENTATIO	ONS (See F)					
Strike and dip orientations		orientations	Very Favourable	Favourable	Fair	Unfavourable	Very un		rable
Tunnels & mines Ratings Foundations		Tunnels & mines	0	-2	-5	-10		-12	
		Foundations	0	-2	-7	-15		-25	
		Slopes	0	-5	-25	-50			
C. F	OCK MA	SS CLASSES DETERM	NED FROM TOTAL RAT	INGS					
Rati	ng		100 - 81	80 - 61	60 - 41	40 - 21		< 21	
Clas	ss number	•	I	11		IV	V		
Des	cription		Very good rock	Good rock	Fair rock	Poor rock	Very	/ poor r	ock
D. N	IEANING	OF ROCK CLASSES	-						
Clas	ss number	•	I	11		IV	V		
Ave	rage stand	d-up time	20 years for 15 m span	1year for 10 m spa	n 1 week for 5 m span	10 hrs for 2.5 m span	30 mins	s for 1 r	n span
Coh	esion of ro	ock mass (MPa)	>400	300 - 400	200 - 300	100 - 200		<100	
Fric	tion angle	of rock mass (deg)	> 45	35 - 45	25 - 35	15 - 25		< 15	
E. G	SUIDELIN	ES FOR CLASSIFICATI	ON OF DISCONTINUITY	CONDITIONS					
Disc	continuity I	length persistence	< 1 m	1 -3 m	3 -10 m	10 - 20 m	> 20 m		
		Rating	6	4	2	1		0	
Sep	aration (ap	perture)	None	< 0.1 mm	0.1 -1.0 mm	1 - 5 mm	+ ³	> 5 mm	
		Rating	6	5	4	1	0	0	
KOU	ignness	Dating	very rougn	Rougn	Slightly rough	Smooth	Sh	ckensid	əd
-fill	ina (anua)	Rating	None	4	Jard filling - Emm	Coft filling . Emm	Coff 6	U	
nfill	ing (gouge	e) Pating	5		i ⊓aru iiiing > 5 mm	3011 IIIIIII < 5 mm	Sont	nnng > : •	חוווכ
No	athoring	Rating	Jinweathered	4 Slightly weathered	Z Modoratoly weathered	Lighly weathered	Der		- d
v v eð	amening	Rating	6	5 Silgnuy weathered	3	1 ngniy weathered	Dec	000000	u
F. F	FFECT	F DISCONTINUITY STR	IKE AND DIP ORIENTAT		**	•	1	•	
		Strike nernen	dicular to tunnel axis		Qtril	e parallel to tunnel avie			
	Drive	with dip - Dip 45 to 90	Drive with din	- Dip 20 - 45	Din 45 - 90)in 20 - 45	5	
		/erv favourable	Favou	Irable	Very favourable		Fair		
_	Drive ac	painst dip - Dip 45 to 90	Drive against d	ip - Dip 20 - 45	Din 0 tr	20 - Irrespective of strik	e*		
Eair			Unfavo	urable	Fair				

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

** Modified after Wickham et al (1972)

RMR 74





Parameter

index

Uniaxial

Rating

Drill core Quality RQD

Rating

Spacing of discontinuities

Rating

Condition of discontinuities (See

E)

Rating nflow per 10 m tunnel

(Major principal stress)

General conditions

Rating

length (l/m) Ground (Joint water press)/

Strike and dip orientations

D. MEANING OF ROCK CLASSES

Drive with dip - Dip 45 to 90

Very favourable

Drive against dip - Dip 45 to 90

Fair

such cases use A.4 directly ** Modified after Wickham et al (1972)

Description

Class number Average stand-up time

comp.strength

Strength of

intact rock

material

1

2

3

4

5 water Point-load strength

74DGR-RPT-GMR109-Rev00 – Appendix A	/
and the second s	

Strike perpendicular to tunnel axis

Drive with dip - Dip 20 - 45

Favourable

Drive against dip - Dip 20 - 45

Unfavourable

3238 PR 323874 - Page 11 of 12

l i	II	III	IV	V
r 15 m span	1year for 10 m span	1 week for 5 m span	10 hrs for 2.5 m span	30 mins for 1 m span

Dip 45 - 90

Very favourable

Cohesion of rock mass (MPa)	>400	300 - 400	200 - 300	100 - 200	<100
Friction angle of rock mass (deg)	> 45	35 - 45	25 - 35	15 - 25	< 15
E. GUIDELINES FOR CLASSIFICATION	ON OF DISCONTINUITY	CONDITIONS			
Discontinuity length persistence	< 1 m	1 -3 m	3 -10 m	10 - 20 m	> 20 m
Rating	6	4	2	1	0
Separation (aperture)	None	< 0.1 mm	0.1 -1.0 mm	1 - 5 mm	> 5 mm
Rating	6	5	4	1	0
Roughness	Very rough	Rough	Slightly rough	Smooth	Slickensided
Rating	6	4	3	1	0
Infilling (gouge)	None	Hard filling < 5 mm	Hard filling > 5 mm	Soft filling < 5 mm	Soft filling > 5mm
Rating	5	4	2	2	0
Weathering	Unweathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed
Rating	6	5	3	1	0
F. EFFECT OF DISCONTINUITY STR	IKE AND DIP ORIENTAT	ION IN TUNNELLING**			

	Tunnels & mines	0	-2	-5	-10 -15 -50	
Ratings	Foundations	0	-2	-7		
	Slopes	0	-5	-25		
C. ROCK MA	SS CLASSES DETERMI	NED FROM TOTAL RATI	NGS			
Rating		100 - 81	80 - 61	60 - 41	40 - 21	
Class numbe			=	=	IV	
Description		Very good rock		Fair rock	Poor rock	

Rock Mass Rating System (RMR) (After Bieniawski 1989)	OPG Geologic
A. CLASSIFICATION PARAMETERS AND THEIR RATINGS	

4-10 MPa

100 - 250 MPa

12

75% - 90%

17

0.6 - 2 m

15

Slightly rough surfaces

Slightly weathered walls

25

< 10

< 0.1

Damp

10

Favourable

Separation < 1 mm.

>10 MPa

>250 MPa

15

90% - 100%

20

>2 m

20

Very rough surfaces

Unweathered wall rock

30

None

0

Completely dry

15

Very Favourable

20 years for

B. RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS (See F)

Not continuous.

No separation.

Repository - High End High Values

1-2 MPa

25 - 50 MPa

4

25% - 50%

8

60 - 200 mm

8

Slickensided surfaces

or Gouge < 5 mm thick

or

Separation 1-5 mm Continuous

10

25 -125

02-05

Dripping

4

Unfavourable

Strike parallel to tunnel axis

Dip 0 to 20 - Irrespective of strike

Fair

Range of values

2-4 MPa

50 - 100 MPa

7

50% - 75%

13

200 - 600 mm

10

Slightly rough surfaces

Highly weathered walls

20

10 - 25

0.1 - 0.2

Wet

7

Fair

Separation < 1 mm.

For this low range

test is preferred

5 - 25

MPa

2

thick

uniaxial compressive

1 - 5

MPa

1

<25%

3

< 60 mm

5

Soft gouge > 5 mm

Separation > 5 mm

Continuous

0

> 125

> 0.5

Flowing

0

Very unfavourable

-12

-25

< 21

V

Very poor rock

<1

MPa

0 7

20

20

15

0

4

5

4

4

6

RMR 85

80



Hatch Mott MacDonald m

GSI

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

Dip 20 - 45

Fair

323874DGR-RPT-GMR109-Rev00 – Appendix A	
PR 323874 - Page 12 of 12	him

Ge	omec	chanical Modeli	ng					Ар	penc		
Ro	ck Mass	s Rating System (RM	IR) (After Bieniawski AND THEIR RATINGS	1989) OP (G Geologic Reposi	tory - Most Favoura	ıble Va	lues			
		Parameter	1		Range of values						
1	Point-load strength index		>10 MPa	4-10 MPa	2-4 MPa	1-2 MPa	For this low range - uniaxial compressive test is preferred		ige - essive d		
	intact roo material	ck Uniaxial comp.strength	>250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5 - 25 MPa	1 - 5 MPa	<1 MPa		
		Rating	15	12	7	4	2	1	0		
2	Dri	ill core Quality RQD	90% - 100%	75% - 90%	50% - 75%	25% - 50%		<25%			
4	Rating		20	17	13	8		3			
3	Spa	cing of discontinuities	>2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm		< 60 mn	n		
3		Rating	20	15	10	8		5			
4	4 Condition of discontinuities (See E)		Very rough surfaces. Not continuous. No separation. Unweathered wall rock	Slightly rough surfaces. Separation < 1 mm. Slightly weathered walls	Slightly rough surfaces. Separation < 1 mm. Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge > 5 n thick Separation > 5 n Continuous		5 mm o 5 mm us		
		Rating	30	25	20	10	0				
	Ground	Inflow per 10 m tunnel length (I/m)	None	< 10	10 - 25	25 -125	> 125				
5	water	(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			
		Rating	15	10	7	4	0				
B. F	RATING A	ADJUSTMENT FOR DISC	ONTINUITY ORIENTATIO	ONS (See F)	_						
Stril	ke and dip	o orientations	Very Favourable	Favourable	Fair	Unfavourable	Very	unfavou	urable		
		Tunnels & mines	0	-2	-5	-10		-12			
R	atings	Foundations	0	-2	-7	-15	└──	-25			
		Slopes	0	-5	-25	-50					
C. F		ASS CLASSES DETERMI	NED FROM TOTAL RAT	INGS							
Rati	ng		100 - 81	80 - 61	60 - 41	40 - 21		< 21			
Clas	ss numbe	r	l			IV		V			
Des	cription		Very good rock	Good rock	Fair rock	Poor rock	Ve	y poor r	rock		
D. N	IEANING	OF ROCK CLASSES			-						
Clas	ss numbe	r		11		IV	<u> </u>	V			
Ave	rage stan	id-up time	20 years for 15 m span	1year for 10 m span	1 week for 5 m span	10 hrs for 2.5 m span	30 mir	is for 1 r	m span		
Cohesion of rock mass (MPa)		rock mass (MPa)	>400	300 - 400	200 - 300	100 - 200	1	<100			

35 - 45

1 -3 m

4

< 0.1 mm

5

Rough

4

Hard filling < 5 mm

Slightly weathered

5

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

Hatch Mott

MacDonald

25 - 35

3 -10 m

2

0.1 -1.0 mm

4

Slightly rough

3

Hard filling > 5 mm

2

Moderately weathered

3

Dip 45 - 90

Very favourable

20

20

15

0

Soft filling > 5mm 4 6

0

5

3

< 15

> 20 m

0

> 5 mm

0

Slickensided

0

0

Decomposed

0

Dip 20 - 45

Fair

GSI 80

85

RMR



0 12

> 45

< 1 m

6

None

6

Very rough

6

None 5

Unweathered

6

Drive with dip - Dip 20 - 45

Favourable

Drive against dip - Dip 20 - 45

Unfavourable

F. EFFECT OF DISCONTINUITY STRIKE AND DIP ORIENTATION IN TUNNELLING** Strike perpendicular to tunnel axis

E. GUIDELINES FOR CLASSIFICATION OF DISCONTINUITY CONDITIONS

Friction angle of rock mass (deg)

Discontinuity length persistence

Separation (aperture)

Roughness

Weathering

Infilling (gouge)

Rating

Rating

Rating

Rating

Rating

Drive with dip - Dip 45 to 90

Very favourable

Drive against dip - Dip 45 to 90

Fair

such cases use A.4 directly ** Modified after Wickham et al (1972)

15 - 25

10 - 20 m

1

1 - 5 mm

1

Smooth

1

Soft filling < 5 mm

2

Highly weathered

1

Strike parallel to tunnel axis

Dip 0 to 20 - Irrespective of strike*

Fair

Appendix B1

Multi-Pillar Analysis (2D FLAC Analysis Results)







Expected Parameters, K₀ = 1.5, Pillar Width = 15.0m

Simultaneous Excavation

Vertical Stresses (MPa)



Plasticity Indicators

JOB TITLE : OPG Deep Repository								C 10°1)
FLAC (Version 5.00)								_ 9.000
LEGEND								_ 7.000
-4.299E+01 <y< 9.799e+01<="" td=""><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>_ 5.000</td></y<>								_ 5.000
Plasticity Indicator shear-p shear-n shear-p	0	0				0	Q	_ 3.000
								_ 1.000
								1.000
Hetch Mott MacDonald								3 000
HMM	0.100		0.500	0.700 (* 10°2)	0.900	1.100	1300	ļ





Step-by-step Excavation

Vertical Stresses (MPa)



Plasticity Indicators

IOB TITLE : OBC Deep Repository								
FLAC (Version 5.00)								_ 0.900
LEGEND								
26-may-07_0:11 step 151782 -7.667E+00 <x< 1.457e+02<br="">-4.917E+01 <y< 1.042e+02<="" td=""><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>- 0.700</td></y<></x<>								- 0.700
Boundary plot Immulumuu 0 2E 1								_ 0.500
Plasticity Indicator shear-p shear-n shear-p	0	0					\mathbf{O}	_ 0.300
								_ 0.100
								10.100
								0.300
Hatch Mott MacDonald								
	0.100	o ando	0.500	0.700 (* 10*2)	0900	1.100	1300	





Appendix B2

Single-Pillar Analysis Wide Range of Parameters (2D FLAC Analysis Results)







Least Favourable Parameters, $K_0 = 1.0$, Pillar Width = 15.0m

Vertical Stresses (MPa)

























Least Favourable Parameters, $K_0 = 1.0$, Pillar Width = 18.0m

Vertical Stresses (MPa)

























Least Favourable Parameters, $K_0 = 1.0$, Pillar Width = 22.0m

Vertical Stresses (MPa)

























Least Favourable Parameters, K₀ = 1.5, Pillar Width = 15.0m

Vertical Stresses (MPa)

























Least Favourable Parameters, K₀ = 1.5 Pillar Width = 18.0m

Vertical Stresses (MPa)

























Least Favourable Parameters, K₀ = 1.5, Pillar Width = 22.0m

Vertical Stresses (MPa)

























Least Favourable Parameters, K₀ = 2.5, Pillar Width = 15.0m

Vertical Stresses (MPa)

























Least Favourable Parameters, K₀ =2.5, Pillar Width = 18.0m

Vertical Stresses (MPa)

























Least Favourable Parameters, K₀ = 2.5, Pillar Width = 22.0m

Vertical Stresses (MPa)

























Expected Parameters, K₀ = 1.0, Pillar Width = 12.0m

Vertical Stresses (MPa)
























Expected Parameters, $K_0 = 1.0$, Pillar Width = 15.0m

Vertical Stresses (MPa)

























Expected Parameters, $K_0 = 1.0$, Pillar Width = 18.0m

Vertical Stresses (MPa)

























For Expected Parameters, $K_0 = 1.5$,

Pillar Width of 12.0m, 14.0m, 16.0m, 18.0m and 20.0m

See Appendix C







Expected Parameters, $K_0 = 2.5$, Pillar Width = 12.0m

Vertical Stresses (MPa)

























Expected Parameters, $K_0 = 2.5$, Pillar Width = 15.0m

Vertical Stresses (MPa)

























Expected Parameters, $K_0 = 2.5$, Pillar Width = 18.0m

Vertical Stresses (MPa)

























Most Favourable Parameters, $K_0 = 1.0$, Pillar Width = 8.0m

Vertical Stresses (MPa)

























Most Favourable Parameters, $K_0 = 1.0$, Pillar Width = 12.0m

Vertical Stresses (MPa)

























Most Favourable Parameters, K₀ = 1.0, Pillar Width = 15.0m

Vertical Stresses (MPa)

























Most Favourable Parameters, $K_0 = 1.5$, Pillar Width = 8.0m

Vertical Stresses (MPa)

























Most Favourable Parameters, $K_0 = 1.5$, Pillar Width = 12.0m

Vertical Stresses (MPa)

























Most Favourable Parameters, K₀ = 1.5, Pillar Width = 15.0m

Vertical Stresses (MPa)

























Most Favourable Parameters, $K_0 = 2.5$, Pillar Width = 8.0m

Vertical Stresses (MPa)


















Factor Of Safety Across The Pillar







Most Favourable Parameters, K₀ = 2.5, Pillar Width = 12.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar







Most Favourable Parameters, K₀ = 2.5, Pillar Width = 15.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar







Appendix C

Single Pillar Analysis Selected Range of Parameters (2D FLAC Analysis Results)

(K_{0x} =1.5, K_{0z} = 1.0 in all analyses)





UCS = 48, GSI = 55, Pillar Width = 12.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar





HATCH"

CN

UCS = 48, GSI = 55, Pillar Width = 14.0m

Vertical Stresses (MPa)











Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)





HATCH"

CN



Factor Of Safety Across The Pillar





HATCH"

CN

UCS = 48, GSI = 55, Pillar Width = 16.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar







UCS = 48, GSI = 55, Pillar Width = 18.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar





HATCH"

CN

UCS = 48, GSI = 55, Pillar Width = 20.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar







UCS = 48, GSI = 69, Pillar Width = 12.0m

Vertical Stresses (MPa)











Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)





HATCH"

CN



Factor Of Safety Across The Pillar







UCS = 48, GSI = 69, Pillar Width = 14.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar





HATCH"

CN

UCS = 48, GSI = 69, Pillar Width = 16.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar





HATCH"

CN

UCS = 48, GSI = 69, Pillar Width = 18.0m

Vertical Stresses (MPa)











Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)





HATCH"

CN



Factor Of Safety Across The Pillar





HATCH"

CN
UCS = 48, GSI = 69, Pillar Width = 20.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar





HATCH"

CN

UCS = 48, GSI = 80, Pillar Width = 12.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar







UCS = 48, GSI = 80, Pillar Width = 14.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar







UCS = 48, GSI = 80, Pillar Width = 16.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar





HATCH"

CN

UCS = 48, GSI = 80, Pillar Width = 18.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar





HATCH"

CN

UCS = 48, GSI = 80, Pillar Width = 20.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar





HATCH"

CN

UCS = 60, GSI = 55, Pillar Width = 12.0m

Vertical Stresses (MPa)











Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)





HATCH"

CN



Factor Of Safety Across The Pillar







UCS = 60, GSI = 55, Pillar Width = 14.0m

Vertical Stresses (MPa)











Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)





HATCH"

CN



Factor Of Safety Across The Pillar





HATCH"

CN

UCS = 60, GSI = 55, Pillar Width = 16.0m

Vertical Stresses (MPa)











Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)





HATCH"

CN



Factor Of Safety Across The Pillar







UCS = 60, GSI = 55, Pillar Width = 18.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar







UCS = 60, GSI = 55, Pillar Width = 20.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar







UCS = 60, GSI = 69, Pillar Width = 12.0m

Vertical Stresses (MPa)











Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)





HATCH"

CN



Factor Of Safety Across The Pillar






UCS = 60, GSI = 69, Pillar Width = 14.0m

Vertical Stresses (MPa)











Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)





HATCH"

CN



Factor Of Safety Across The Pillar





HATCH"

CN

UCS = 60, GSI = 69, Pillar Width = 16.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar





HATCH"

CN

UCS = 60, GSI = 69, Pillar Width = 18.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar





HATCH"

CN

UCS = 60, GSI = 69, Pillar Width = 20.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar







UCS = 60, GSI = 80, Pillar Width = 12.0m

Vertical Stresses (MPa)











Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)





HATCH"

CN



Factor Of Safety Across The Pillar





HATCH"

CN

UCS = 60, GSI = 80, Pillar Width = 14.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar







UCS = 60, GSI = 80, Pillar Width = 16.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar





HATCH"

CN

UCS = 60, GSI = 80, Pillar Width = 18.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar





HATCH"

CN

UCS = 60, GSI = 80, Pillar Width = 20.0m

Vertical Stresses (MPa)











Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)





HATCH"

CN



Factor Of Safety Across The Pillar







UCS = 72, GSI = 55, Pillar Width = 12.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar







UCS = 72, GSI = 55, Pillar Width = 14.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar







UCS = 72, GSI = 55, Pillar Width = 16.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar





HATCH"

CN
UCS = 72, GSI = 55, Pillar Width = 18.0m

Vertical Stresses (MPa)











Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)





HATCH"

CN



Factor Of Safety Across The Pillar





HATCH"

CN

UCS = 72, GSI = 55, Pillar Width = 20.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar





HATCH"

CN

UCS = 72, GSI = 69, Pillar Width = 12.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar





HATCH"

CN

UCS = 72, GSI = 69, Pillar Width = 14.0m

Vertical Stresses (MPa)

























UCS = 72, GSI = 69, Pillar Width = 16.0m

Vertical Stresses (MPa)











Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)





HATCH"

CN









UCS = 72, GSI = 69, Pillar Width = 18.0m

Vertical Stresses (MPa)











Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)





HATCH"

CN









UCS = 72, GSI = 69, Pillar Width = 20.0m

Vertical Stresses (MPa)

























UCS = 72, GSI = 80, Pillar Width = 12.0m

Vertical Stresses (MPa)



















Factor Of Safety Across The Pillar





HATCH"

CN

UCS = 72, GSI = 80, Pillar Width = 14.0m

Vertical Stresses (MPa)

























UCS = 72, GSI = 80, Pillar Width = 16.0m

Vertical Stresses (MPa)

























UCS = 72, GSI = 80, Pillar Width = 18.0m

Vertical Stresses (MPa)

























UCS = 72, GSI = 80, Pillar Width = 20.0m

Vertical Stresses (MPa)











Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)





HATCH"

CN







