National Exams December 2017

04-Geol-A5, Rock Mechanics

3 hours duration

NOTES:

1. If doubt exists as to the interpretation of any question, the candidate is urged to submit with the answer paper, a clear statement of any assumptions made.

2. This is a CLOSED BOOK EXAM. Candidates may use only one of two approved calculators. Candidates are permitted however, to bring to the examination room two sheets containing rock mechanics formulae and notes.

3. Questions have equal value. The grade for each question is given. It is suggested that the candidate proportion time based on the allocated value.

4. All questions require an answer in analytical and/or essay format. Clarity and organization of the written answer and any figures or sketches are important.

5. The examination has an overall value of 80 Marks: each question will be marked out of 20 marks as per the marking scheme provided.

6. **ANSWER ONLY 4 of the 5 questions that are provided. Only the first 4 questions that appear in the answer book will be marked.**

7. Selected equations, graphs and tables are given at the end of the exam paper. These may (or may not) be of assistance for some questions. Indicate the question number corresponding to any graphs or tables used at the back of the exam question sheets.

8. Hand in the exam booklet and the question booklet at the end of the exam.

Marking Scheme

(only 4 will be marked)

1. **20 marks total**
2. **20 marks total**
    - (a) 10 marks
    - (b) 10 marks
3. **20 marks total**
    - (a) 5 marks
    - (b) 5 marks
    - (c) 2.5 marks
    - (d) 2.5 marks
    - (e) 5 marks
4. **20 marks total**
    - (a) 8 marks
    - (b) 2 marks
    - (c) 8 marks
    - (d) 2 marks
5. **20 marks total**
    - (a) 5 marks
    - (b) 5 marks
    - (c) 5 marks
    - (d) 5 marks

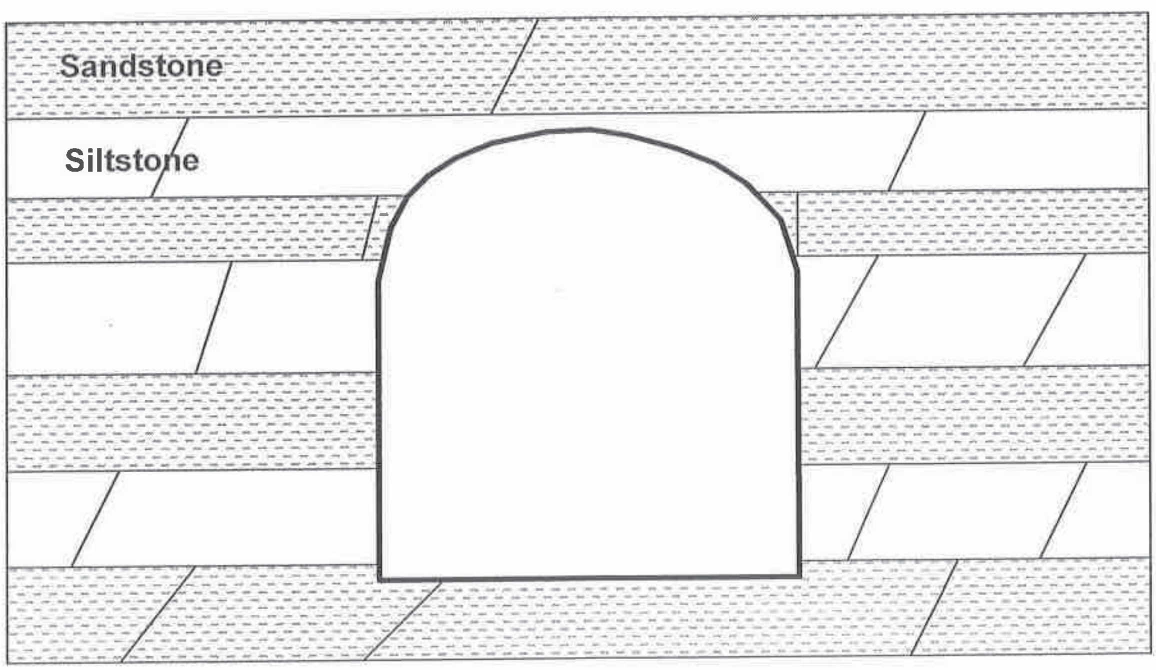
Value

20 Marks **Question #1**

Historically, a risk-based approach with an emphasis on uncertainty is utilized within the realm of Rock Mechanics. It is a difficult issue to deal with, and because of this, past case histories, personal experience, and careful integration of the main factors in Geomechanical Design is required.

For the case of a horseshoe-shaped highway tunnel in horizontally bedded and jointed siltstone and sandstone layers with 210 m of overburden, develop a pre-construction design strategy and a program during construction to cope with uncertainty. The following issues should be addressed, using diagrams, point-form, etc. The development of small flow charts may assist you in clarifying your answer, as design is largely a structured decision-making endeavour.

- i Uncertainty in material parameters;
- ii Probability of various "events" happening over the construction life;
- iii Uncertainty in initial state in the ground and only scattered site investigation drillholes are available to you (one centreline drillhole per 100 metres length);
- iv Use of geophysical techniques to reduce uncertainty;
- v Adequacy of rock mechanics design in large openings;
- vi Construction sequencing to reduce uncertainty;
- vii Rock support strategies and their use; and,
- viii Any other factors to consider.



20 Marks **Question #2**

A design Engineer is faced with the challenge of assigning material properties and strength parameters to rocks and rock masses with a view to evaluating the quality and expected behaviour of a rockmass in the field. In order to address such issues, numerous researchers have developed empirical methods in order to quantify the relative integrity of a rockmass in order to estimate the mechanical properties for excavation and support design. As such:

10 Marks a. List and Define each of the most credible and commonly used empirical classification systems used within the rock mechanics field by practicing Rock Engineers;

10 Marks b. Cite the strengths and limitations of each of the systems / schemes.

The use of diagrams, equations, and figures are encouraged in order to describe each of the cited classification schemes / systems.

20 Marks **Question #3**

A mine in limestone is being designed utilizing a pillar method with rectangular pillars. The clear spacing between the pillars is 8 m. The pillars are 9 m square and the excavation is at a depth of 100 m. Conditions within the mine are dry. The bedding planes are smooth with slightly weathered surfaces and no visible aperture. Examination of the pillars shows that the limestone is horizontally bedded with moderate spacing and gentle undulations. A point load test of the pillar rock yielded an estimated uniaxial compressive strength of 120 MPa; Triaxial testing of the pillar rock demonstrated that the rock failed when the axial stress in the sample was 140 MPa and the confining pressure was 6 MPa. The unit weight of limestone is 26.5 kN/m^3. The ratio of horizontal to average vertical stress is 0.09 at the centre of each pillar. Provide the answers to the following:

5 Marks a. Estimate the Rock Mass Rating (RMR) for the pillars;

5 Marks b. Determine the Hoek-Brown Strength Parameters m and s for the rock mass using the following equations:

$$m = m_i exp\left(\frac{RMR - 100}{28}\right) \text{ and } s = \left(\frac{RMR - 100}{9}\right)$$

2.5 Marks *c.* Determine the maximum vertical stress the pillars can sustain at their faces;

2.5 Marks *d.* Determine the maximum vertical stress the pillars can sustain at their centres;

5 Marks *e.* Use the tributary area theory in order to estimate the average vertical stress in the pillar and hence determine the factor of safety of the pillars;

$$\frac{\sigma_1}{\sigma_c} = \frac{\sigma_3}{\sigma_c} + \sqrt{m\frac{\sigma_3}{\sigma_c} + s}$$

Value

20 Marks **Question #4**

The following triaxial compression strength test results were obtained as the result of a series of laboratory trials on core specimens recovered from a rock excavation for tunnelling. .

Confining Stress (MPa)	Failure Axial Stress (MPa)
16.7	159.3
13.1	154.5
25.1	198.0
9.8	140.1
20.1	168.0

8 Marks
a. Based on the information provided, determine the Mohr-Coulomb parameters which can be estimated to establish the limiting compression failure locus for this rock. These parameters should include strength variables as well as orientation conditions (i.e. internal angle of friction and failure angle values);

2 Marks
b. From the results of part a, what problems appear to be evident from the data that has been given?

8 Marks
c. Using the Mohr-Coulomb empirical equation relating principal stresses at failure, determine the minimum axial stresses that would need to be applied during triaxial failure tests to induce shear failure when confining stresses equivalent to 5, 15, 22.5 MPa are also applied;

2 Marks
d. How could one verify the accuracy of the results in part c?

Value

20 Marks **Question #5**

An underground mine is planned to be excavated in rock. This excavation is to be developed initially on the basis of diamond drill core data retrieved by remote drilling, as no site development currently has taken place. Based upon information which is provided:

5 Marks a. Determine the RQD for the core shown;

5 Marks b. Determine the RMR for the rock mass at the proposed development site;

5 Marks c. Determine the limiting excavation dimensions (maximum and minimum);

5 Marks d. Determine the unsupported stand-up times for these excavation dimensions and the range of rock reinforcement that would be necessary for the excavation (over the dimension ranges selected).

Given:

Core Recovery Data: As illustrated in **Figure Q5** in the accompanying core box sketch (total length of core recovered = 3.0 m).

Core Strength Data:

Unconfined Compressive Strength (S_c)(MPa)	Point Load Index (I_{s54})(MPa)
206.2	9.2*
221.4	10.2*
211.3	9.5*
203.3	8.8*
205.5	9.4*
*I_s values and linked UCS values for calibration (i.e. first 5 pairs of data in table)	9.7
	8.9
	9.1
	10.1
	9.3
	9.7
	9.0
	8.9
	9.9
	9.7

Joint Conditions:

- Two joint families identified:
- Join #1 strikes parallel to long axis of planned excavation, dips at 12° to the horizontal and joints repeat approximately every 2.5 m; surfaces of this family of

joints are slightly rough/weathered and continuous, with separation distance between the joint surfaces ranging between 1.0-1.5mm.

- Joint #2 strikes 45° to long axis of planned excavation, dips 15° and repeats at intervals of approximately 0.25 m; surface of these joints are very rough and discontinuous with separation between surfaces being << 0.1 mm.

Stress / Water Conditions:

- Maximum ground stress components are expected to be horizontally directed, of magnitude less than 1.5 times vertical stress component, and uniformly distributed horizontally at the site of excavation; minimal water flow (<5L/min at low pressure) from the rock is anticipated.

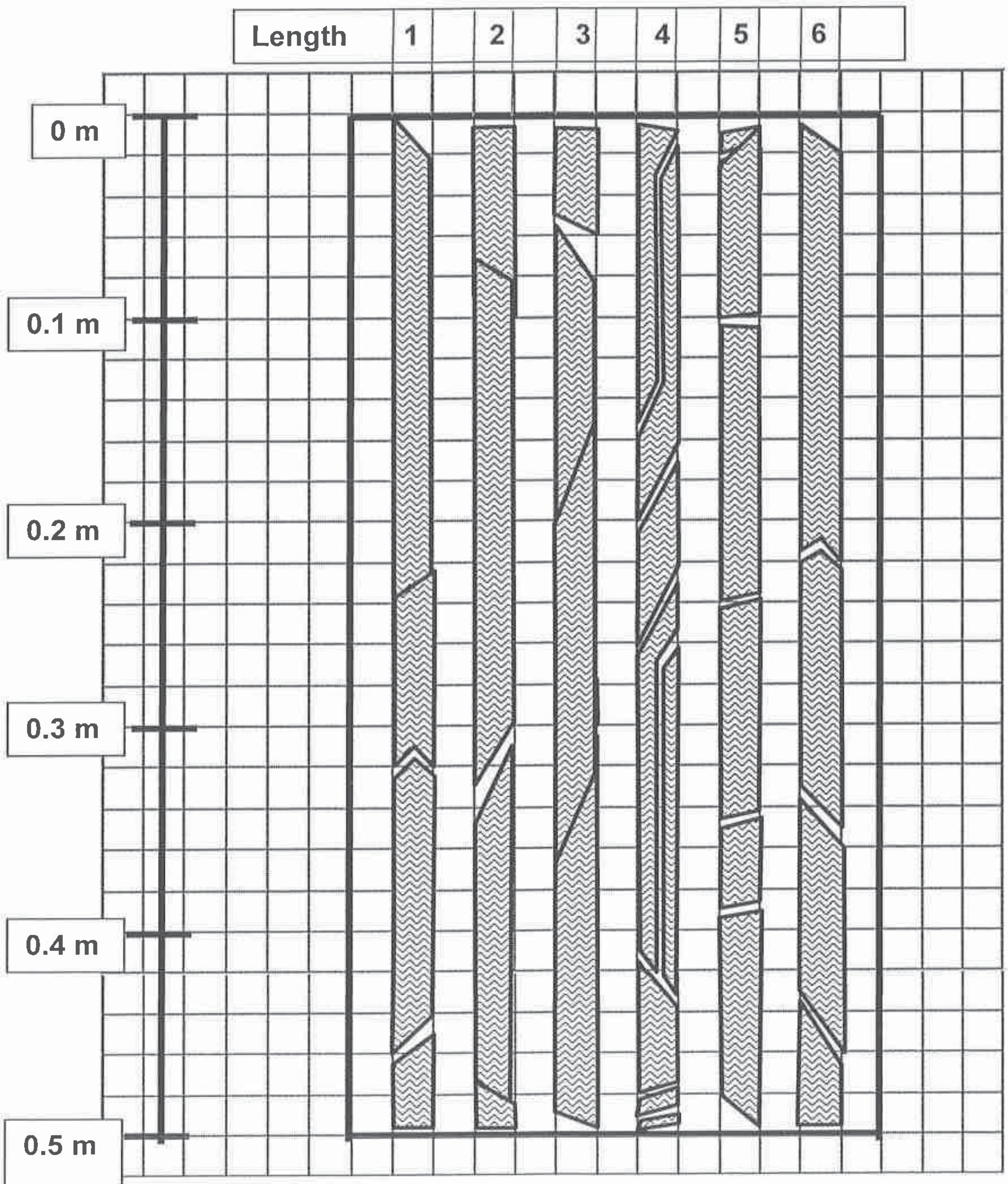


Figure Q5. Core Recovery View (3.0 metre length of core).

Equations

$$RQD = 115 - 3.3\,J_v,$$

Where, J_v is the sum of the number of joints per unit length for all joint (discontinuity) sets known as the volumetric joint count

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

where RQD is the Rock Quality Designation
J_n is the joint set number
J_r is the joint roughness number
J_a is the joint alteration number
J_w is the joint water reduction factor
SRF is the stress reduction factor

Resolved Normal Stress:

$$\sigma_\theta = \frac{(\sigma_x+\sigma_y)}{2} + \frac{\{(\sigma_x-\sigma_y)(cos2\theta)\}}{2} + \tau_{xy}(sin2\theta)$$

Resolved Shear Stress:

$$\tau_\theta = \frac{\{(\sigma_y-\sigma_x)(sin2\theta)\}}{2} + \tau_{xy}(cos2\theta)$$

<u>Point Load Test</u>

$$I_{s50} = L / D^2$$

Where, L = failure compressive loading force applied (kN);
D = specimen core diameter

$$S_c = 24\ (I_{s54})\ \text{KPa}$$

Where, S_c = unconfined compressive strength (kPa)
(I_{s54}) = index values for 5.4 cm diameter core specimens (kN/cm^2)

Mohr Coulomb Failure Criterion

$\Psi = 45^o + \varphi/2$

$S_T = C / \tan \varphi$

$(\sigma_1 + \sigma_3) / (\sigma_3 + S_T) = \tan^2 \Psi$

$\sigma_1 = \sigma_3 \tan^2 \Psi + 2C \tan \Psi = \sigma_3 \tan^2 \Psi + S_c$

Where, C = cohesion
Ψ = angle of failure plane in triaxial sample from horizontal
S_T = tensile strength
S_c = unconfined compressive strength

Mining

$\sigma_v = \text{load} / Y^2$

$\sigma_p = \text{load} / X^2$

$$\frac{\sigma_p}{\sigma_v} = \frac{A_T}{A_P}$$

Where, A_p = Post mining area
A_T = Tributary Area

$$\sigma_p = \frac{\sigma_v}{(1-r)}$$

Where, r = extraction ratio = $(A_T - A_P) / A_T$

Kirsch Equations

$$\sigma_{rr} = \sigma/2 \{(1+k)(1-a^2/r^2) - (1-k)(1-4a^2/r^2 + 3a^4/r^4)\cos 2\theta\}$$

$$\sigma_{\theta\theta} = \sigma/2\{(1+k)(1+a^2/r^2) + (1-k)(1 + 3a^4/r^4)\cos 2\theta\}$$

$$\sigma_{r\theta} = \sigma/2\{(1-k)(1 + 2a^2/r^2 - 3a^4/r^4)\sin 2\theta\}$$

$$U_r = \{\mu\, r_i/E\} \bullet \{(\sigma_1 + \sigma_3) + 2(\sigma_1 - \sigma_3)\cos 2\theta$$

Where, μ = Poisson's Ratio

Thick Wall Cylinder Stress formulae

$(2P_o\text{-}P_i)=(P_i)\tan^2\Psi + S_c$

$P_i = (2P_o - S_c) / (\tan^2\Psi + 1)$

$\varepsilon_r = 1/E\ (\sigma_r - \mu\ \sigma_t) = U_r / r_i$

$U_r = \varepsilon_r\, r_i$

$U_r = \{\mu(2P_o\, r_i)\} / E$

$\sigma_t = 2(r_o^2 P_o) / (r_o^2 - r_i^2)$

Where, P_o = pre-mining hydrostatic pressure at $r = r_o$

P_i = internal pressure applied against opening surface at $r = r_i$

σ_r = radially oriented post-mining stress components, uniform for all angular directions but varying by distance away from the excavation surface.

r_i = inside radius of circular opening in rock or liner\

r_o = outside radius of installed liner or radial distance to boundary of rock media if the opening is unlined

μ = Poisson's Ratio

U_r = inward radial displacement

Tables

Table 1. Rock Mass Rating System (After Bieniawski 1989).

A. CLASSIFICATION PARAMETERS AND THEIR RATINGS

	Parameter		Range of values				
1	Strength of intact rock material	Point-load strength index	>10 MPa	4 - 10 MPa	2 - 4 MPa	1 - 2 MPa	For this low range - uniaxial compressive test is preferred
		Uniaxial comp. strength	>250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5 - 25 MPa / 1 - 5 MPa / < 1 MPa
	Rating		15	12	7	4	2 / 1 / 0
2	Drill core Quality *RQD*		90% - 100%	75% - 90%	50% - 75%	25% - 50%	< 25%
	Rating		20	17	13	8	3
3	Spacing of discontinuities		> 2 m	0.6 - 2 . m	200 - 600 mm	60 - 200 mm	< 60 mm
	Rating		20	15	10	8	5
4	Condition of discontinuities (See E)		Very rough surfaces Not continuous No separation Unweathered wall rock	Slightly rough surfaces Separation < 1 mm Slightly weathered walls	Slightly rough surfaces Separation < 1 mm Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge >5 mm thick or Separation > 5 mm Continuous
	Rating		30	25	20	10	0
5	Groundwater	Inflow per 10 m tunnel length (l/m)	None	< 10	10 - 25	25 - 125	> 125
		(Joint water press)/ (Major principal σ)	0	< 0.1	0.1, - 0.2	0.2 - 0.5	> 0.5
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing
	Rating		15	10	7	4	0

B. RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS (See F)

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

C. ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS

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

D. MEANING OF ROCK CLASSES

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

E. GUIDELINES FOR CLASSIFICATION OF DISCONTINUITY conditions

Discontinuity length (persistence)	< 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	5	3	1	0
Infilling (gouge)	None	Hard filling < 5 mm	Hard filling > 5 mm	Soft filling < 5 mm	Soft filling > 5 mm
Rating	6	4	2	2	0
Weathering	Unweathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed
Ratings	6	5	3	1	0

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

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

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

Table 2. Guidelines for excavation and support of 10 m span rock tunnels in accordance with the *RMR* system (After Bieniawski 1989).

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

Figures

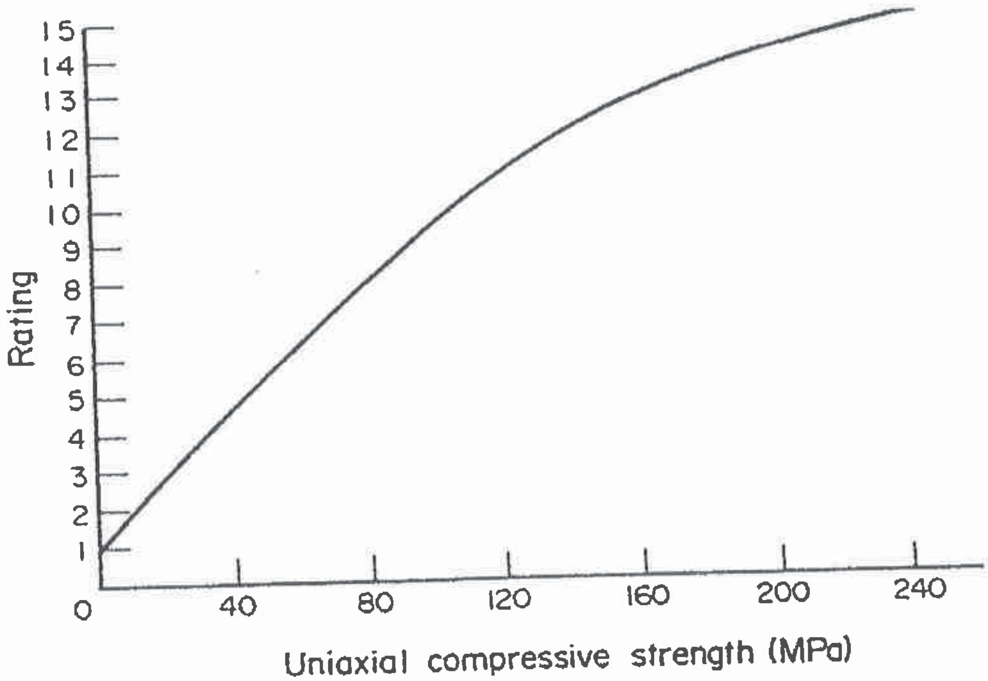


Figure 1. RMR Rating System for the strength of intact rock material

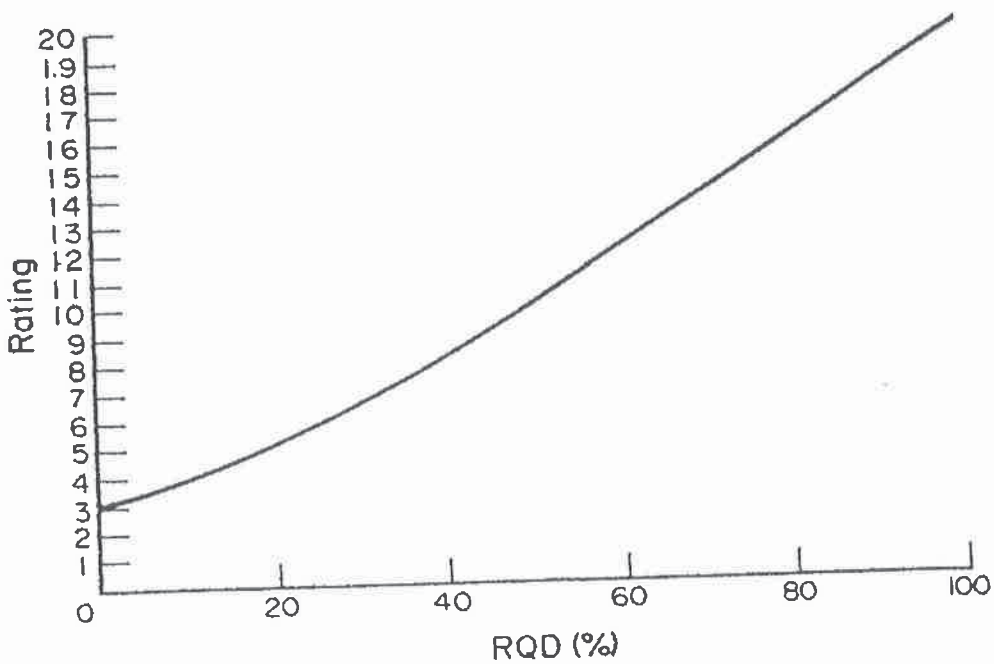


Figure 2. The RMR Rating system: ratings for RQD

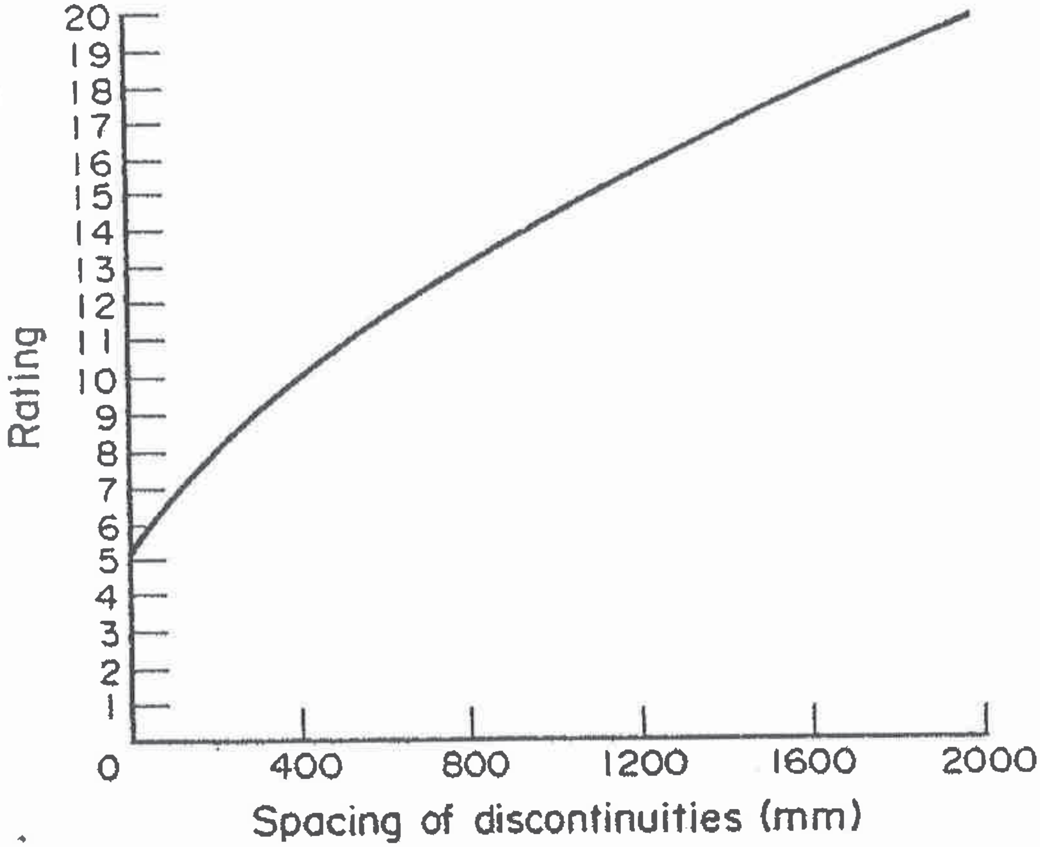


Figure 3. The RMR Rating system: ratings for Discontinuity Spacing

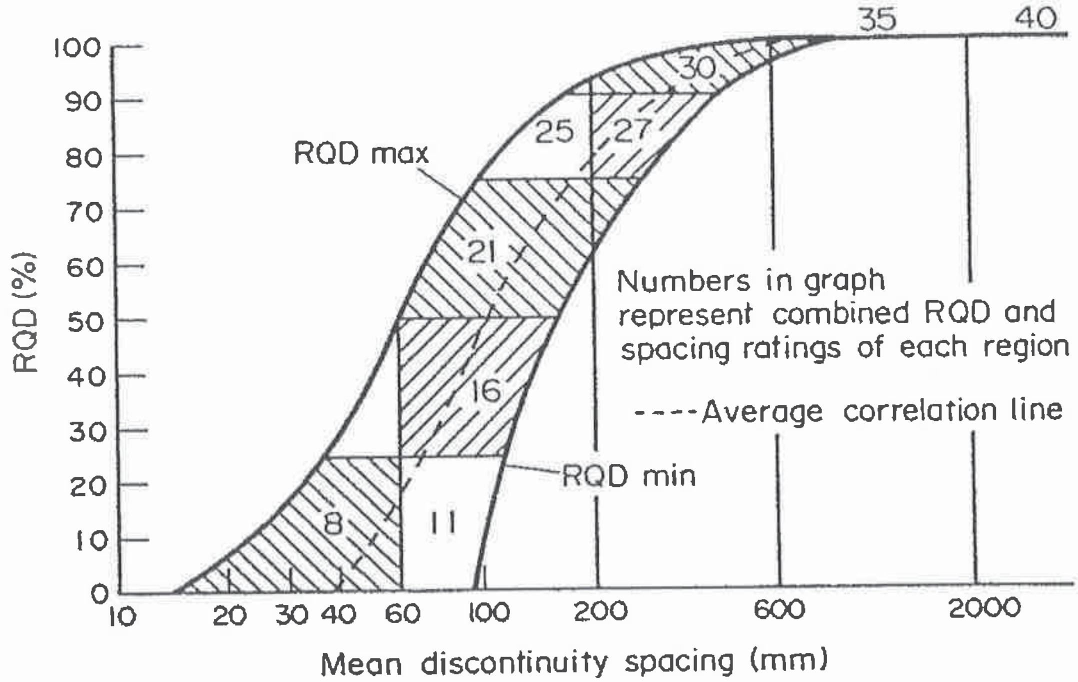


Figure 4. The RMR Rating system: Chart for correlation between RQD and Discontinuity Spacing

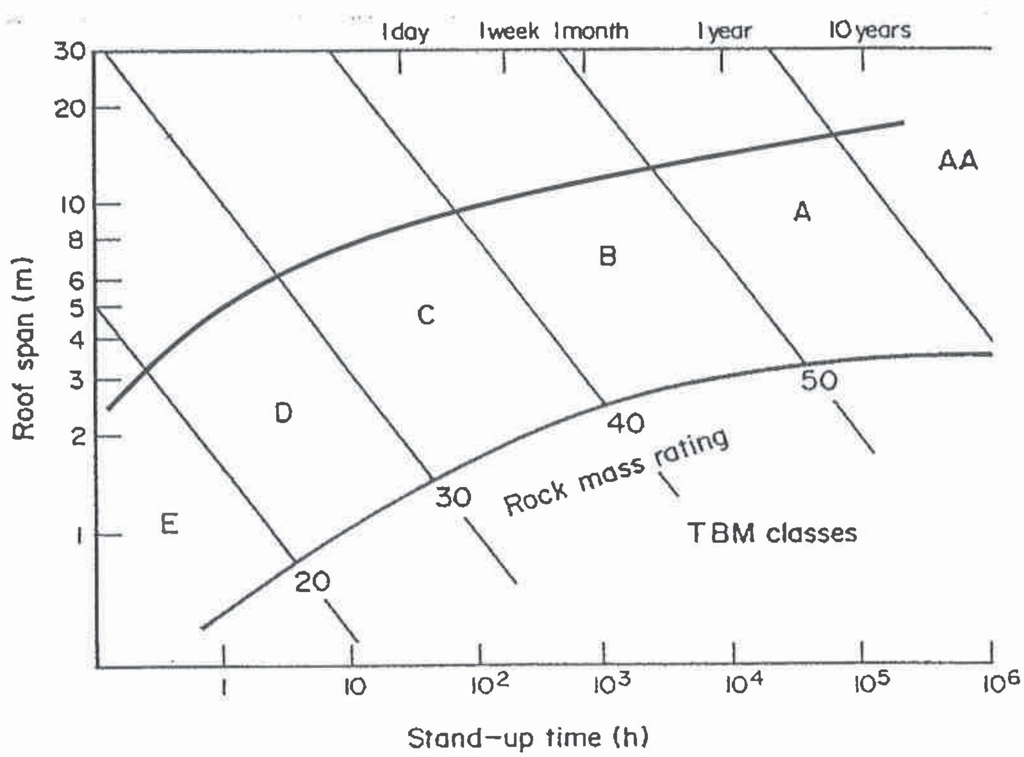
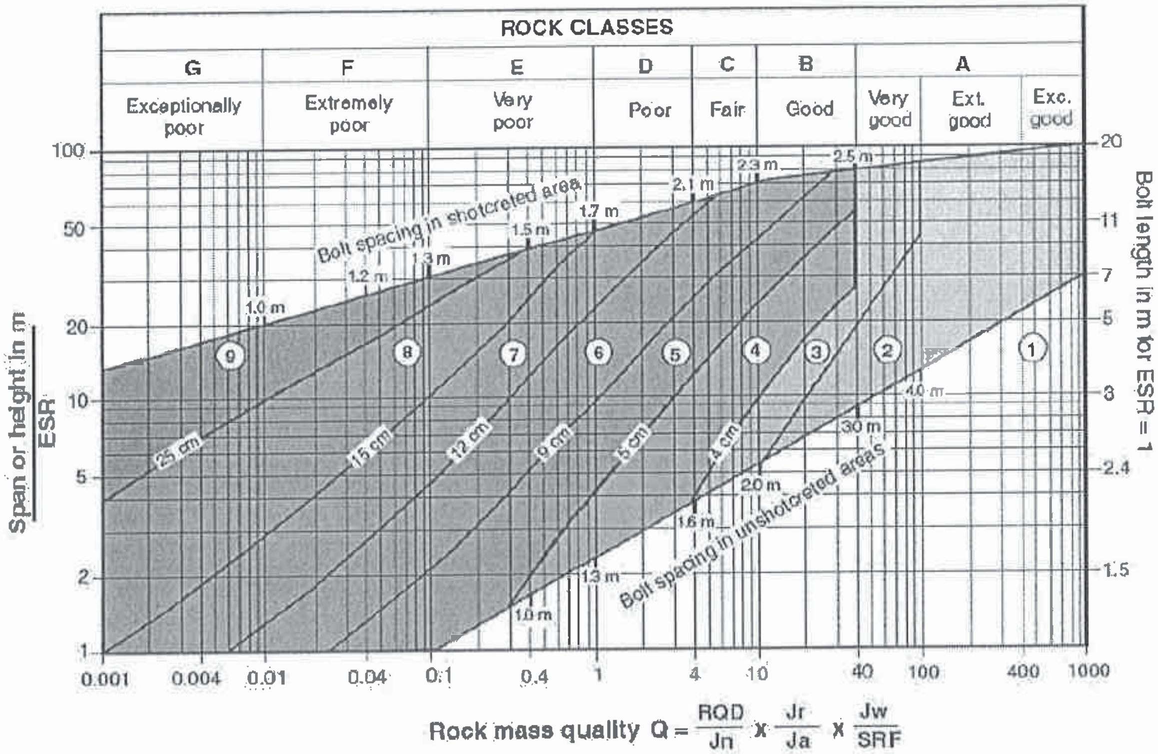


Figure 5. Modified Lauffer diagram depicting boundaries of rock mass classes for TBM applications (after Lauffer 1988).



REINFORCEMENT CATEGORIES:

1) Unsupported
2) Spot bolting
3) Systematic bolting
4) Systematic bolting, (and unreinforced shotcrete, 4 - 10 cm)
5) Fibre reinforced shotcrete and bolting, 5 - 9 cm
6) Fibre reinforced shotcrete and bolting, 9 - 12 cm
7) Fibre reinforced shotcrete and bolting, 12 - 15 cm
8) Fibre reinforced shotcrete, > 15 cm, reinforced ribs of shotcrete and bolting
9) Cast concrete lining

Figure 6. Estimated support categories based on the tunnelling quality index *Q* (After Grimstad and Barton, 1993, reproduced from Palmstrom and Broch, 2006).