National Exams May 2019

18-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 my use only one of two approved calculators candidates are permitted however, to bring to the examination room **ONE** aid sheet 8.5" X 11" hand-written on **both** sides containing notes and formulae.

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

Value

20 Marks **Question #1**

At a depth of 400 m, a 4 m diameter circular tunnel is driven in rock having a unit weight of 26 kN/m^3 and uniaxial compressive and tensile strengths of 60.0 MPa and 3.0 MPa, respectively. Will the strength of the rock on the tunnel boundary be reached if:

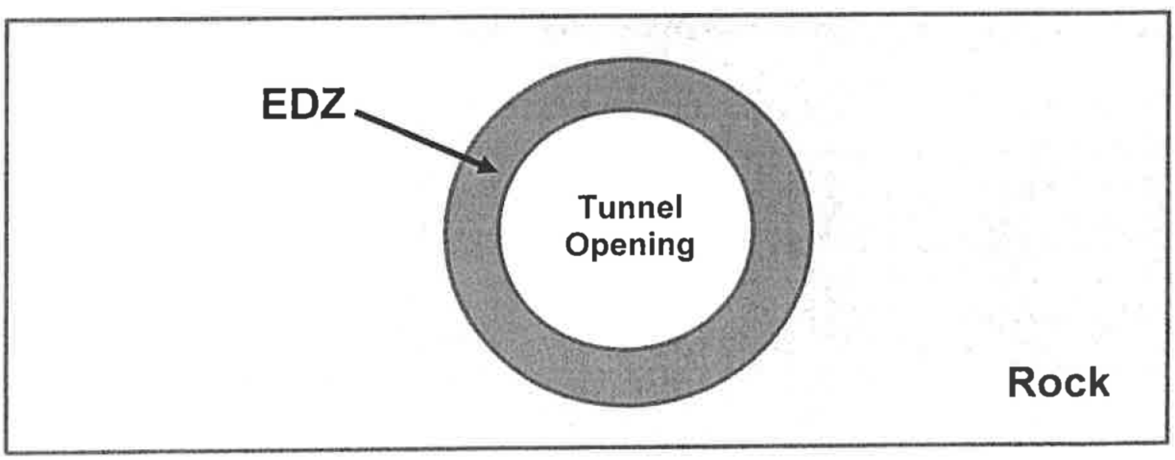
5 Marks (a) $k = 0.3$, and

5 Marks (b) $k = 2.5$?

10 Marks A second tunnel, of 6 m diameter, is subsequently driven parallel to and at the same centre line level as the first, such that the centre line spacing of the two tunnels is 10 m. Comment on the stability of the tunnels for the field stresses given by (a) and (b) above. (Hint: Use Kirsch Solution)

20 Marks **Question #2**

A circular tunnel is being excavated in a blocky rock mass by drilling and blasting. There is an Excavation Disturbed Zone (EDZ) around the excavated tunnel (defined on the basis of a blast-disturbed zone where there are loosened blocks which can fall into the tunnel under the action of gravity) which extends 0.75 m into the rock from the excavation surface. What support pressure4 is required at the crown to stabilize the loose blocks of the EDZ given that the unit weight of the rock, γ, is 25 kN/m^3?



Value

20 Marks **Question #3**

Estimate both, RMR and Q for the scenarios described below:

10 Marks a. A granite rock mass containing 3 joint sets, average RQD is 88%, average joint spacing is 0.24 m,joint surfaces are generally stepped and rough, tightly closed and unweathered with occasional strains observed. The excavation surfaces are wet but not dripping, average rock material uniaxial compressive strength (UCS) is 160 MPa. The tunnel is excavated to 150 m below the ground where no abnormal in situ stress is expected.

10 Marks b. A sandstone rock mass, fractured by 2 joint sets plus random fractures, average RQD is 70%,average joint spacing is 0.11 m, joint surfaces are slightly rough, highly weathered with stains and weathered surface but no clay found on surface. The joints are generally in contact with apertures generally less than 1 mm. The average UCS is 85 MPa. The tunnel is to be excavated at 80 m below the ground level and the groundwater table is 10 m below the ground surface.

20 Marks **Question #4**

A circular drift, 6.1 meters in diameter, is to be driven horizontally through rock in which a hydrostatic stress field exists. The uniform stress magnitude prior to development is measured to approximate 55.2 MPa. Core sample testing has indicated that the rock exhibits an unconfined compressive strength of 104.8 MPa and an internal friction angle (φ) of 30°.

2 Marks a. What will be the cohesive strength of this rock?

3 Marks b. Assuming that a linear Mohr-Coulomb failure locus exists, at what level of axial stress will this rock material fail if it were to be confined at a stress level of 31.2 MPa?

2 Marks c. What will be the Factor of Safety against failure for the rock which exists about the drift surface? Illustrate the conditions of surface stress and safety conditions using a Mohr-Coulomb stress diagram;

5 Marks d. Determine the magnitude of internal stress that must be applied onto the drift wall surface to just induce stability at the drift wall surface;

8 Marks e. A 15 cm thick concrete lining will be placed against the drift wall surface, and a grout will be injected between the rock surface and the concrete liner. The grouting pressure that will be exerted will be equal to the calculated level of rock stress which was determined in part d. The concrete liner exhibits and unconfined compressive strength of 34.5 MPa. Sketch the pressure conditions which will act upon the concrete liner and determine the factor of safety condition that will exist at the liner's most critical point.

Value

20 Marks **Question #5**

10 Marks

a. Explain how the presence of water and ground acceleration, induced by either blasting or seismic events, can affect the stability of open pit wall structures. For each of the two influences (i.e. exposure togroundwarer and ground vibration), present two difference cases and show by illustrative example how wall stability can be i) determimentally affected and ii) beneficially affected (or remain unchanged).

10 Marks

b. Describe the major functions of ground support media used to reinforce underground mine excavations. Provide examples of typical reinforcement media and differentiate between support methods that have been adopted to i) reinforce the structural capabilities of near-excavation rock zones and ii) provide purely surface support enhancements for underground excavations. Use sketches in order to illustrate your answer.

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:

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

Point Load Test

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

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

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

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

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

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

$U_r = \varepsilon_r r_i$

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

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

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.
** Modified after Wickham et al (1972).

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

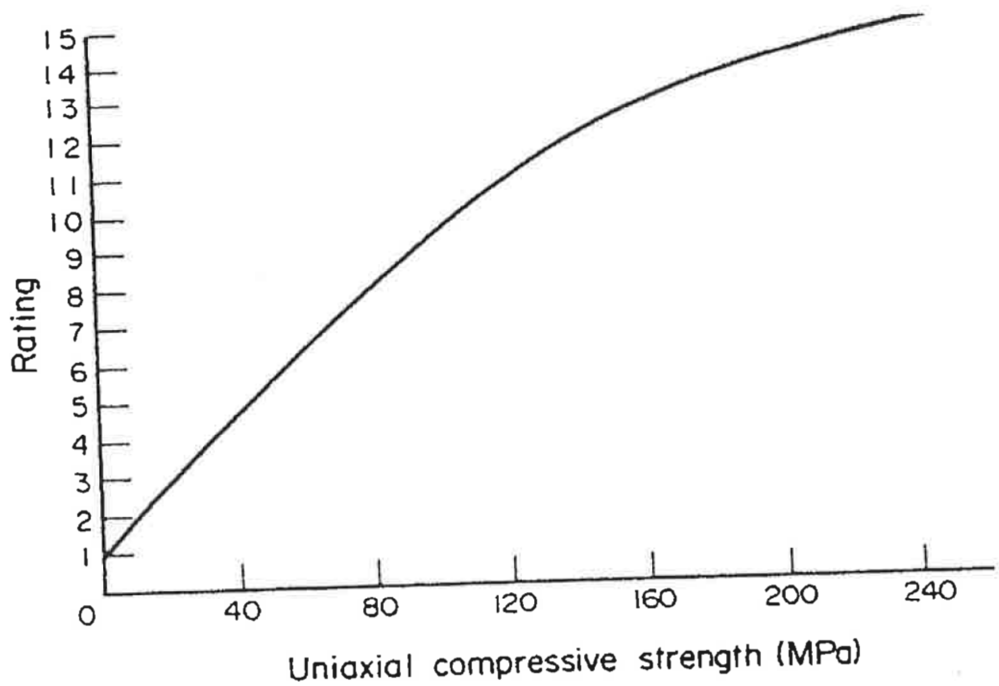


Figure 1. RMR Rating System for the strength of intact rock material

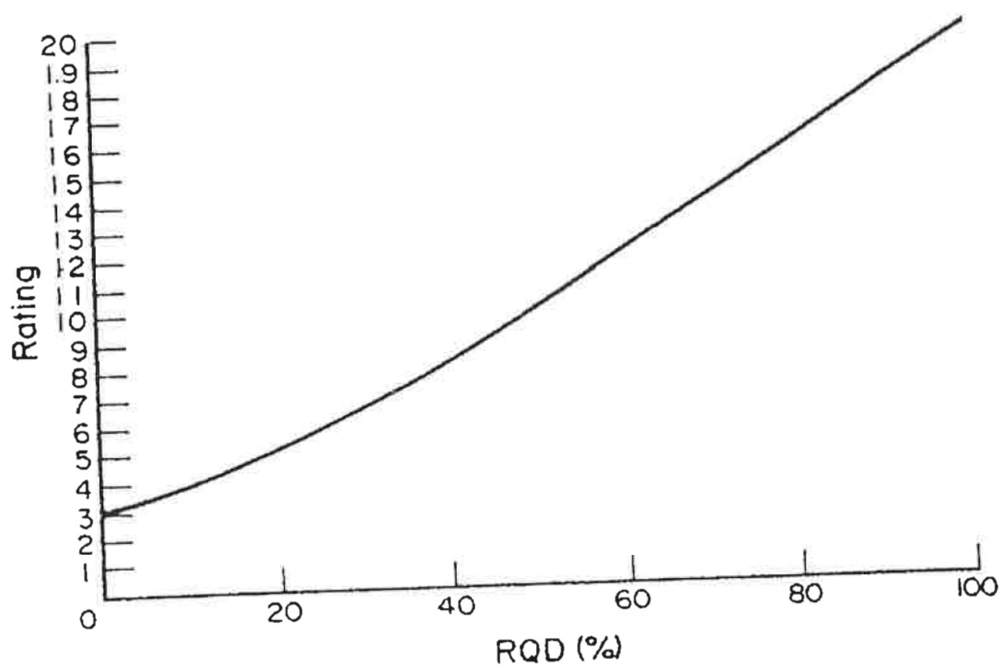


Figure 2. The RMR Rating system: ratings for RQD

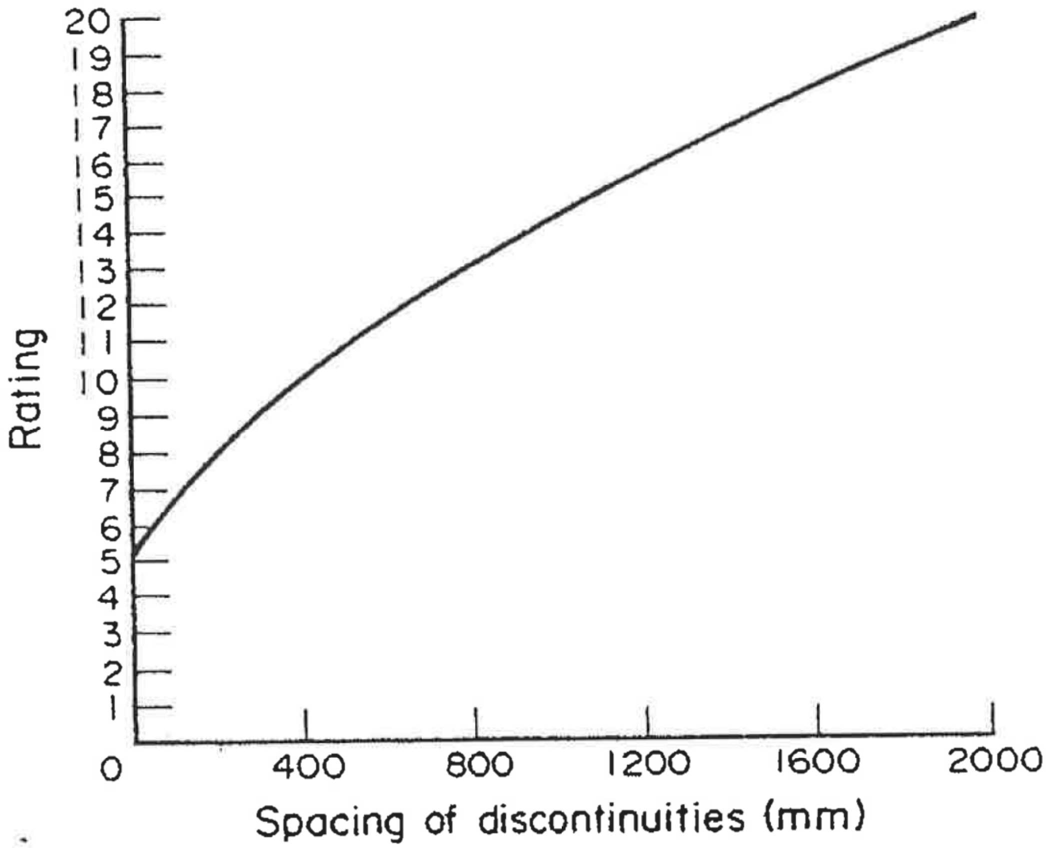


Figure 3. The RMR Rating system: ratings for Discontinuity Spacing

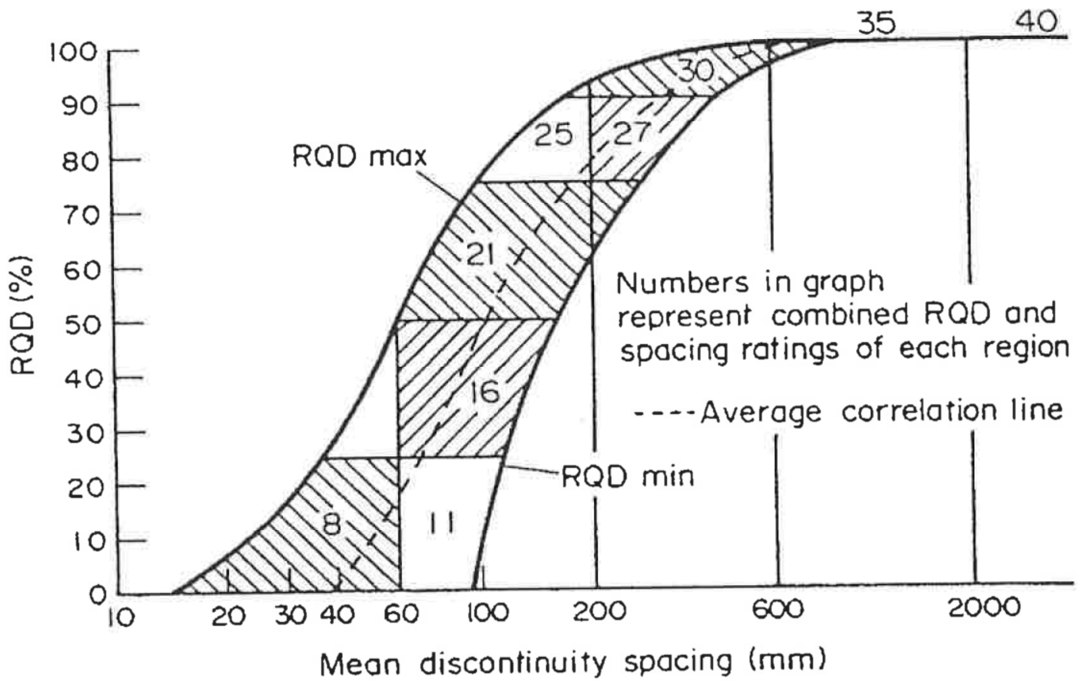


Figure 4. The RMR Rating system: Chart for correlation between RQD and Discontinuity Spacing

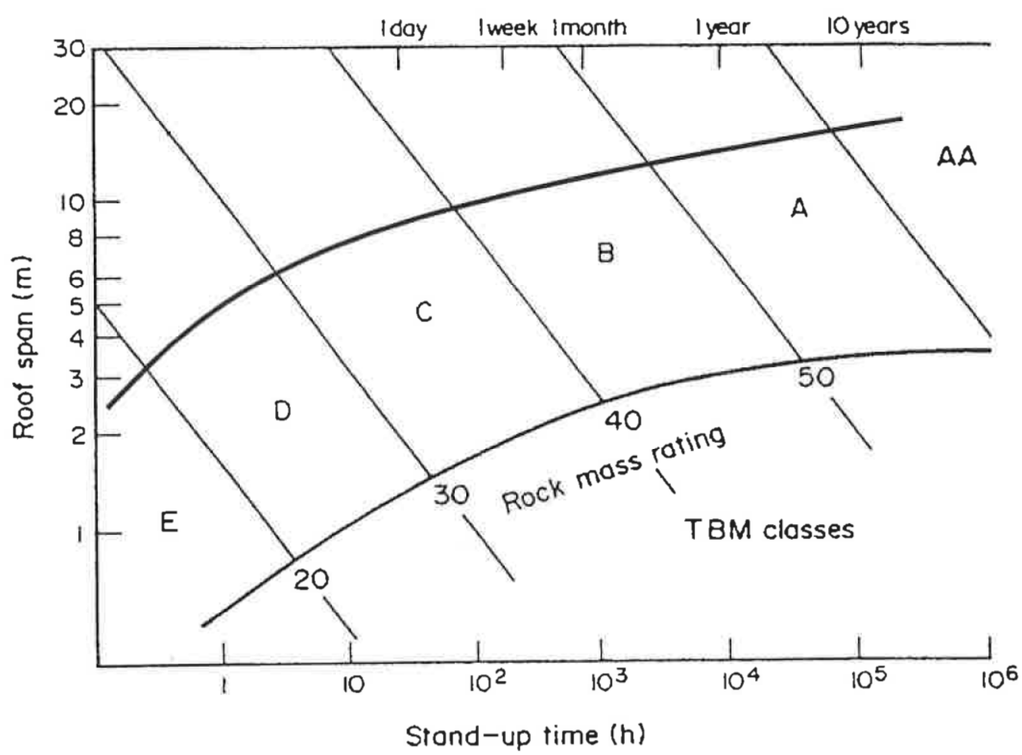
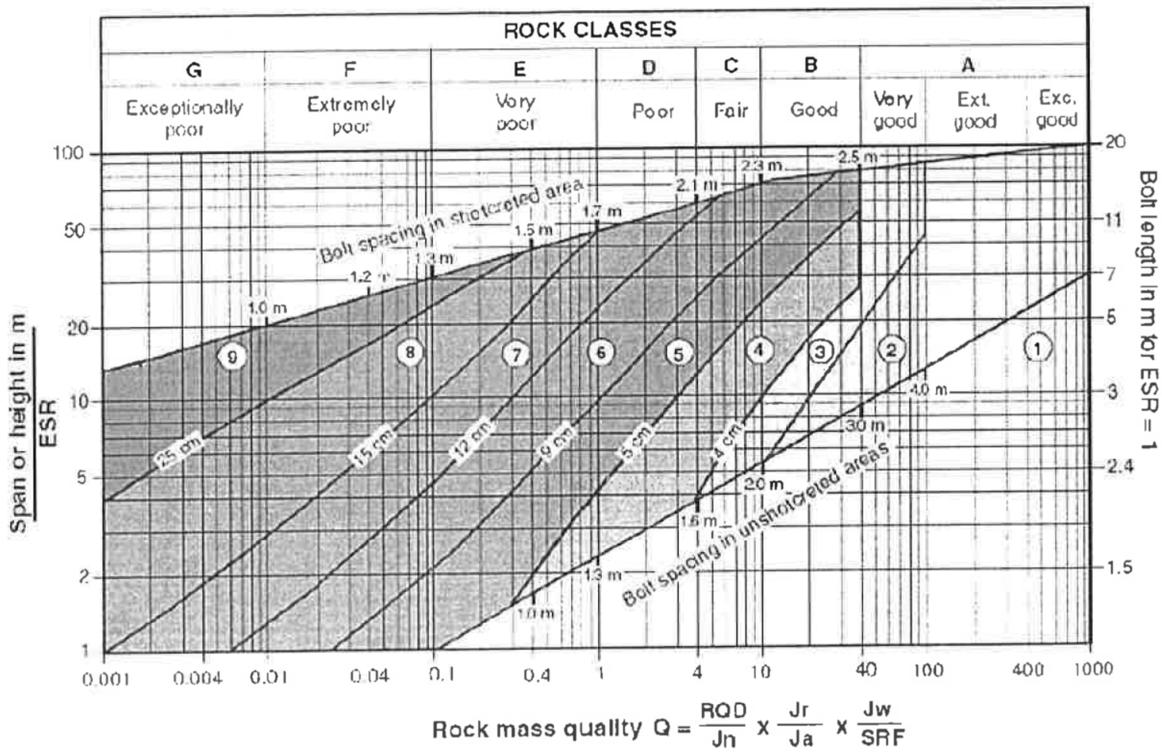


Figure 5. Modified Lauffer diagram depicting boundaries of rock mass classes for TBM applications (after Lauffer 1988).



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).