National Exams May 2016

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 my 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**
3. **20 marks total**
   (a) 10 marks
   (b) 10 marks
4. **20 marks total**
   (a) 5 marks
   (b) 5 marks
   (c) 5 marks
   (d) 5 marks
5. **20 marks total**

Value

20 Marks **Question #1**

Within a fault zone, the state of stress on a fault plane is determined to be $\sigma = 40$ MPa and $\tau = 40$ MPa. The strength properties of the rock are: S_i (cohesion) = 10 MPa and $\phi = 45^o$. Determine if the fault is in danger of slipping (i.e. failing)? If the answer is no, how much build-up of pore pressure will be necessary in order for the fault to become unstable? Show explicitly how you came to your conclusions.

20 Marks **Question #2**

<u>Design of an Open Pit Excavation</u>. A simplified three-dimensional (3D) wedge system has been identified, and comprises two families of joints that repeat regularly with depth. The open pit excavation is designed such that the pit face will be vertical (dip = 90^o). An orthogonal view of the pit face and joint intersection conditions is presented below in Figure Q2.

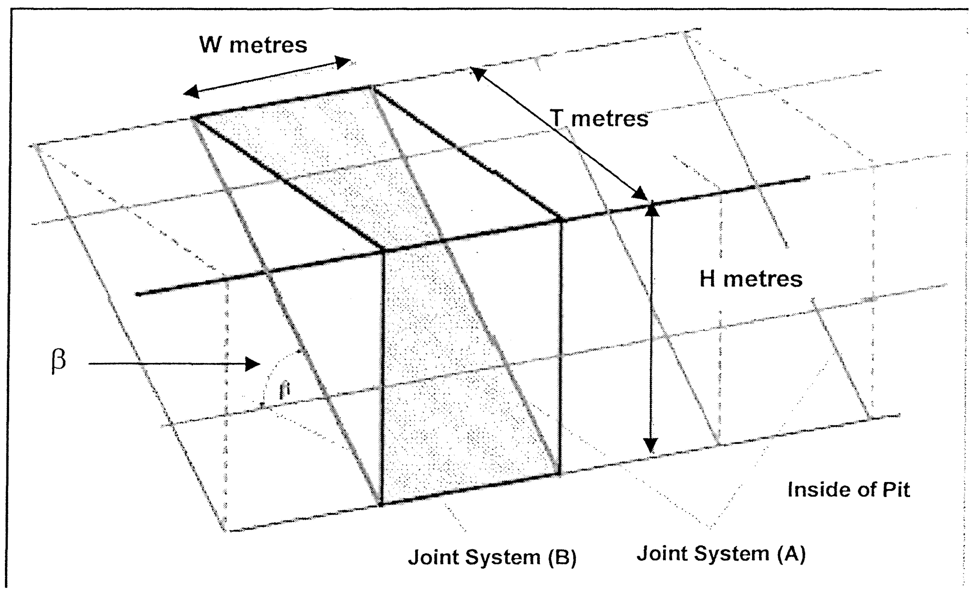


Figure Q2. Open face pit

Joint system (A) dips at an angle (β), such that ($\beta < 90^o$). The joint strike is parallel to the pit face and the dip is into the pit. These joints are regular and repeat with depth. Joint system (B) strikes perpendicular to the strike of the pit face (ie.- strikes into the pit) and has a vertical dip. The (B) joints repeat regularly along the pit face and a distance interval equal to (W) metres reflects a measure of the (B) joint spacing. No cohesion is generated by the (B) system of joints (ie.- C = 0).

Requirement: For the information provided above, derive an equation for Factor of Safety which relates the geometry of the block wedge to the excavation depth (H).

Value

20 Marks **Question #3**

A challenge associated with rock mechanics is to assign material properties and strength parameters to rocks and rock masses in order to evaluate the quality and expected behaviour of a rockmass in situ. To this end, multiple researchers and practitioners have developed empirical methods in order to quantify the relative integrity of a rockmass with a view to estimating the mechanical properties for excavation and support design. As such:

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

10 Marks b. List the strengths and limitations of each of the classification 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 #4**

Answer the following questions as fully as possible (use diagrams, equations and relevant examples as appropriate):

5 Marks a. What is the difference between stress-controlled instability mechanisms of failure and material property / strength mechanisms of failure;

5 Marks b. Discuss the zone of influence around a tunnel excavation in rock and how to determine the extent of the damaged zone; Be sure to include in the answer how stresses are propagated around an opening;

5 Marks c. Cite the major failure criterion that are used in Rock Mechanics; how does one determine the capacity of the rock?

5 Marks d. In an active pillar mine, how can one determine the optimum pillar width and spacing in order to ensure a stable and economical mining operation?

Value

20 Marks **Question #5**

At a depth of 700 m, a 9.5 m diameter circular tunnel is driven in rock. The rock has the following properties:

Unit weight = 25 kN/m^3

Uniaxial Compressive Strength = 70 MPa

Tensile Strength 2.8 MPa

Use the Kirsch solution to determine when the strength on the tunnel boundary be exceeded. Will it be exceeded when the stress ratio (k) is:

a. k = 0.3; or

b. k = 2.0?

Discuss your results and show your calculations fully.

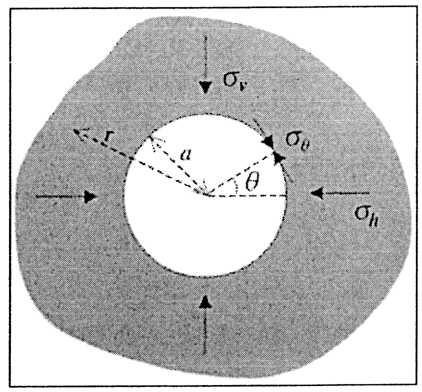


Figure Q5

Reference Section

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

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

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

$S_T = C / \tan \varphi$

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

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

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

Mining

σ_v = load / Y^2

σ_p = 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

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

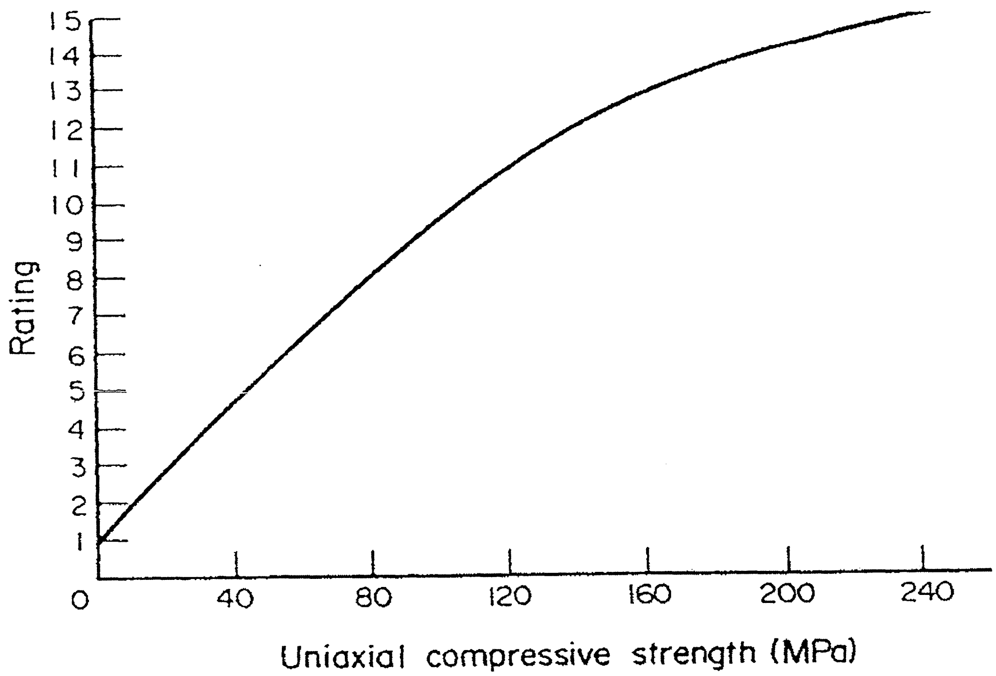


Figure 1. RMR Rating System for the strength of intact rock material

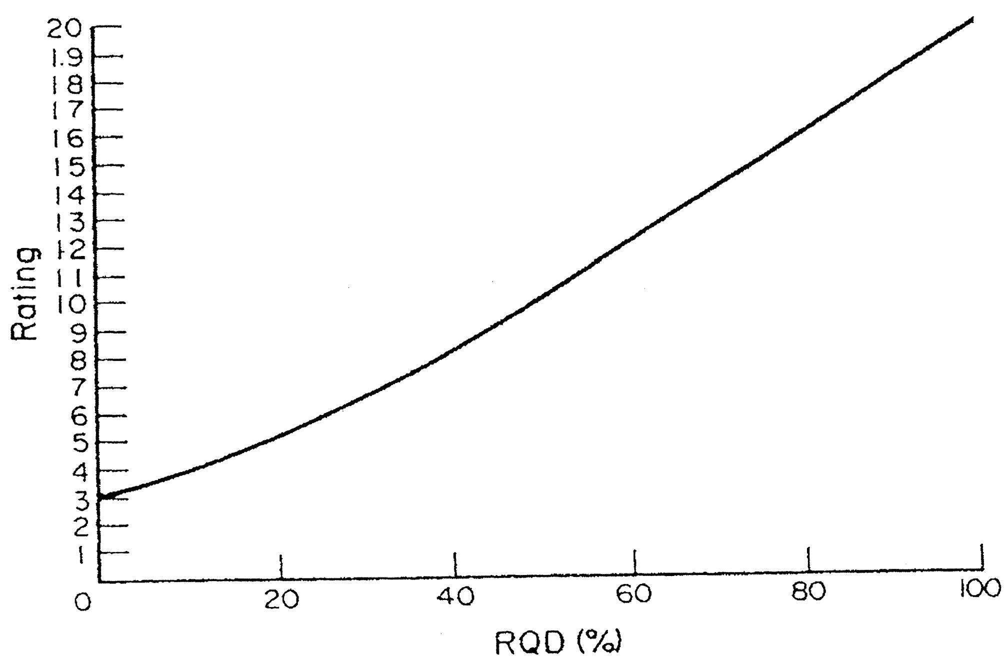


Figure 2. The RMR Rating system: ratings for RQD

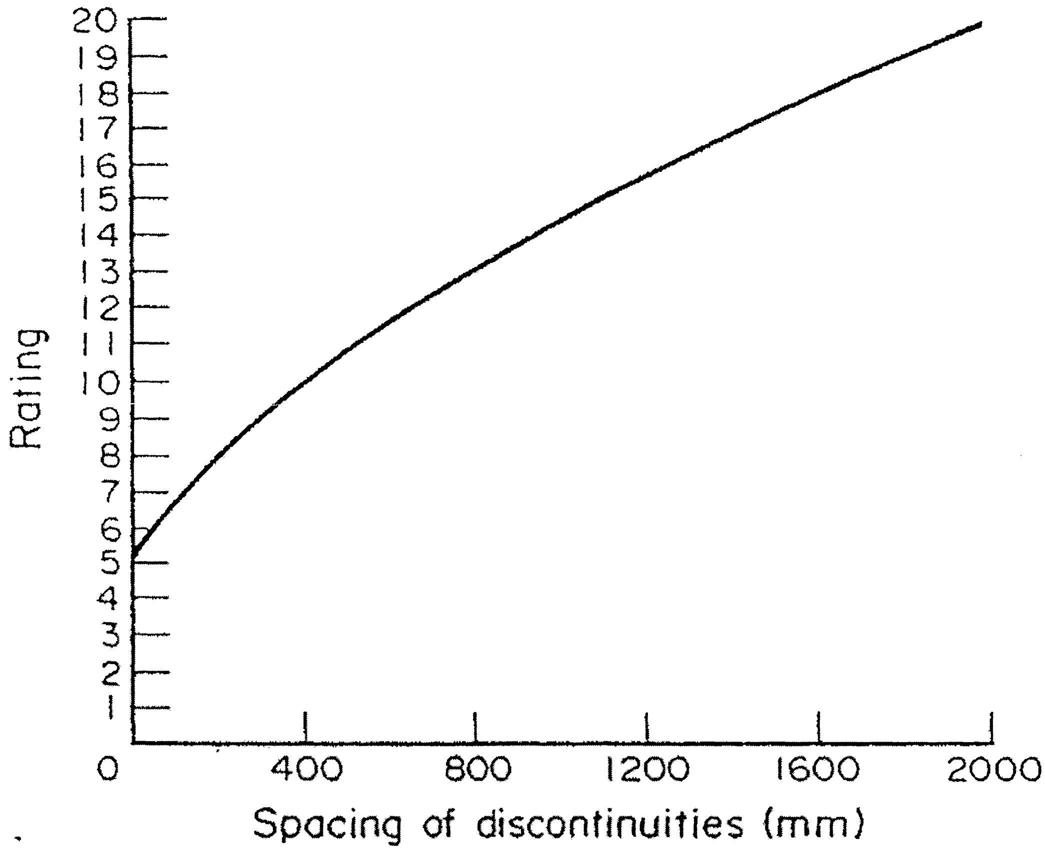


Figure 3. The RMR Rating system: ratings for Discontinuity Spacing

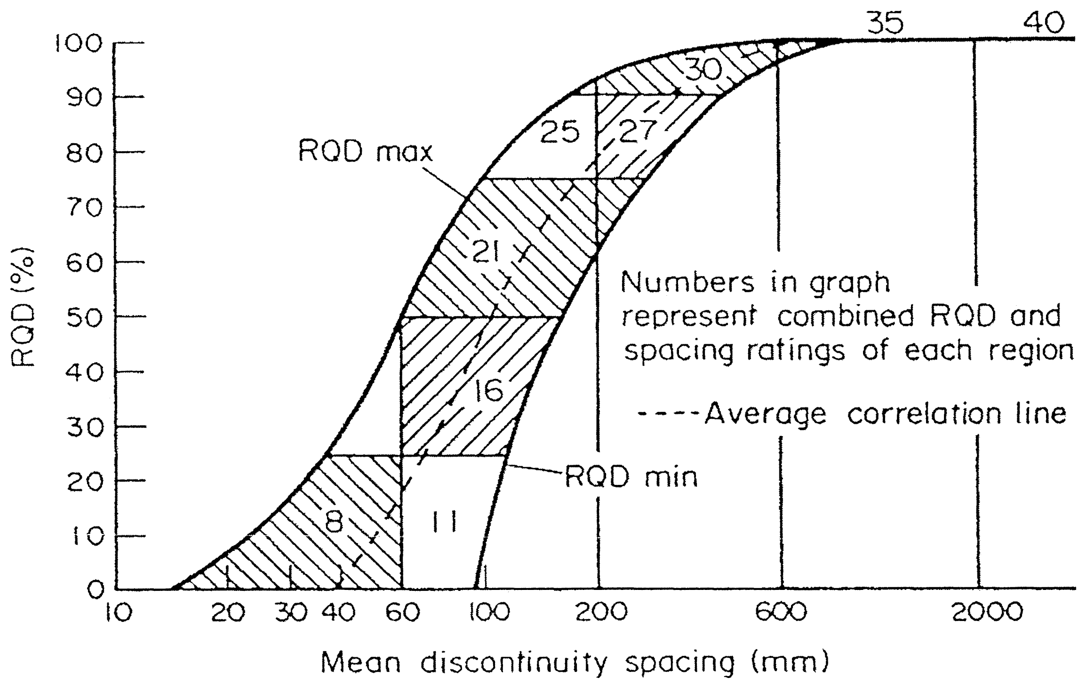


Figure 4. The RMR Rating system: Chart for correlation between RQD and Discontinuity Spacing

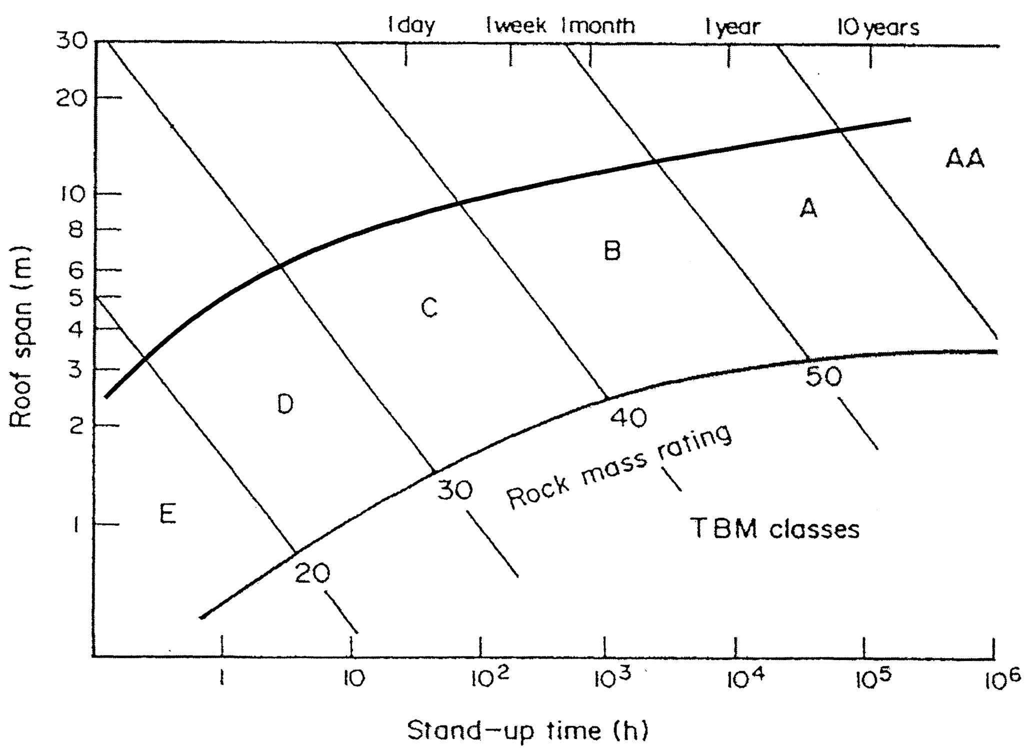
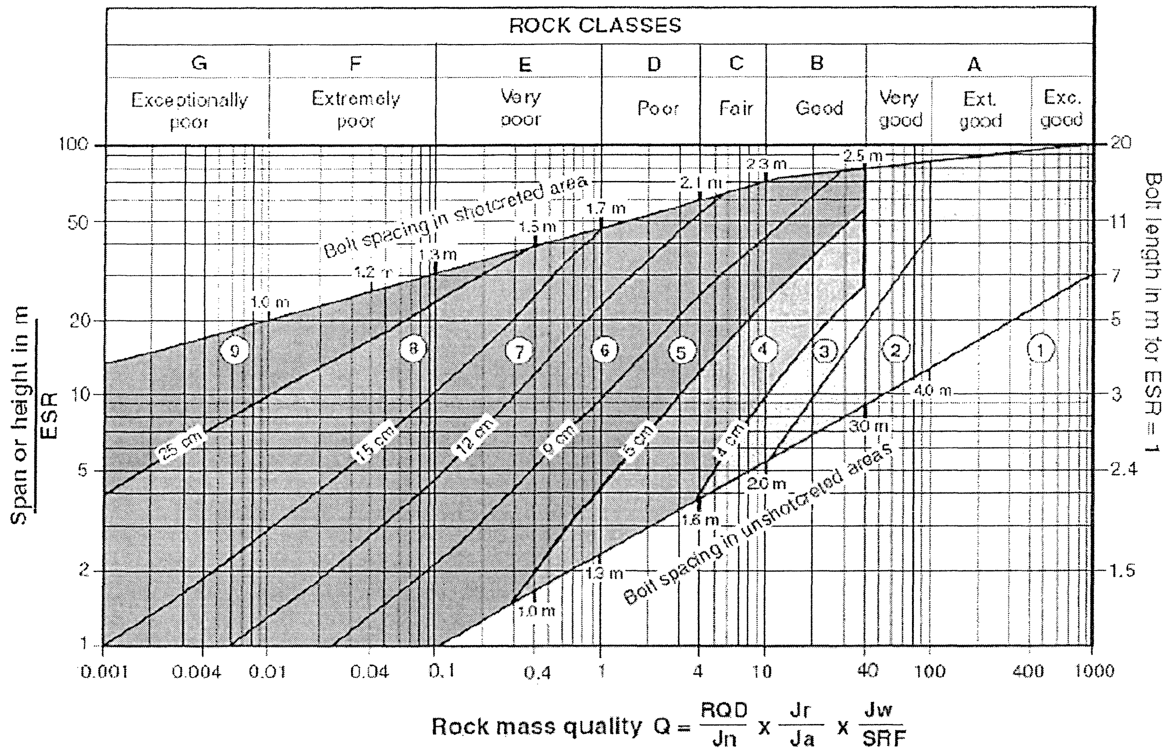


Figure 5. Modified Lauffer diagram depicting boundaries of rock mass classes for TBM applications (after Lauffer 1988).



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).