National Exams December 2014

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 OPEN BOOK EXAM. Candidates my use only one of two approved calculators candidates are permitted.

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) 10 marks

   (b) 5 marks

   (c) 5 marks

2. **20 marks total**

3. **20 marks total**

   20 marks total answer

4. **20 marks total**

   (a) 10 marks

   (b) 10 marks

5. **20 marks total**

   (a) 10 marks

   (b) 10 marks

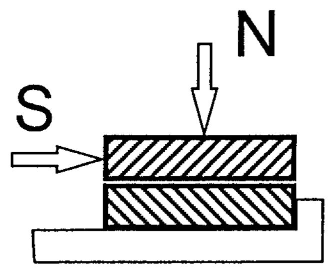
Value

20 Marks **Question #1**

Samples of a typical rock joint were tested in a square shear box of 160 mm x 160 mm dimensions, and the following data were collected:

No.	F_N	F_{Speak}	F_{Sult}
#1	1.3 kN	2.5 kN	0.8 kN
#2	5.0 kN	8.2 kN	3.1 kN
#3	10 kN	13.6 kN	5.6 kN
#4	20 kN	20.5 kN	10.0 kN
#5	30 kN	25.1 kN	13.6 kN
#6	40 kN	30.7 kN	16.9 kN

F_N = Normal force
F_{Speak} = Peak shear force
F_{Sult} = Ultimate shear force



10 marks a. Plot yield criteria for peak and ultimate strength on a Mohr diagram, noting that values in the Table are given in terms of force. Assume a Patton bilinear model (two straight lines), and fit the two parts of the Patton plot by hand, define the c' and ϕ' of each part, and specify the approximate transition normal stress. Why does the ultimate yield criterion (in general) not show bilinearity?

5 marks b. Assuming that joints in all orientations exist, and that the principal total stresses are σ_1 = 3 MPa and σ_3 = 1.2 MPa, what pore pressure is required to just exceed the <u>peak</u> shearing criterion on the most critically oriented joint? (Use a Mohr-Coulomb construction). At this instant, what are the effective normal stresses and the shear stresses on the joint plane?

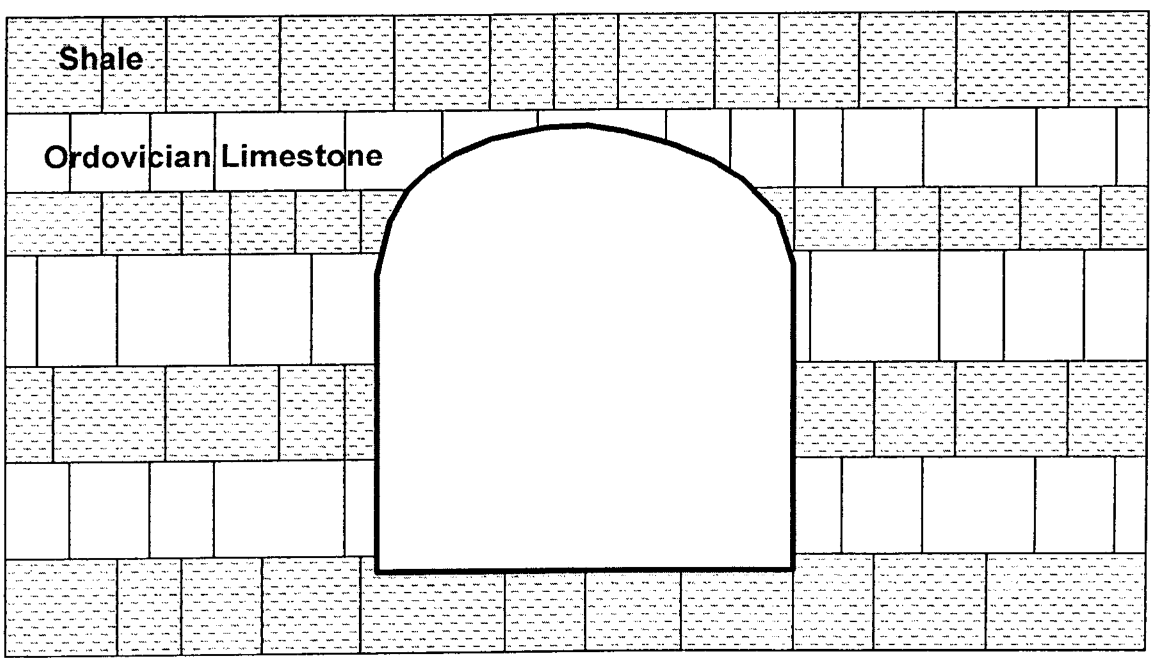
5 marks c. These tests were done on small specimens (0.0256 m^2). Discuss the issue of <u>scale</u>, as it relates to lab testing and field behaviour for rough joints.

20 Marks **Question #2**

Time and again, an emphasis has been placed on the issue of uncertainty in 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 subway tunnel in horizontally bedded and jointed Ordovician limestones and non-swelling but plastic shales, 30 m under the city of Toronto, 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.

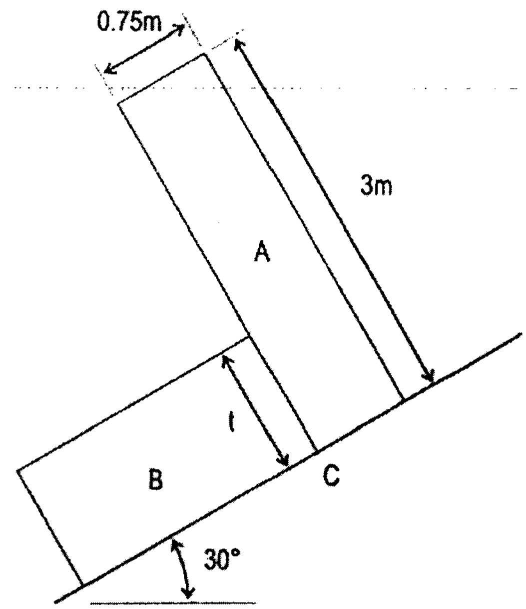
- Uncertainty in material parameters
- Probability of various "events" happening over the construction life
- Uncertainty in initial state in the ground and only scattered site investigation drillholes are available to you (one centreline drillhole per 100 metres length)
- Use of geophysical techniques to reduce uncertainty
- Adequacy of rock mechanics design in large openings
- Construction sequencing to reduce uncertainty
- Rock support strategies and their use



20 Marks **Question #3**

The system of rock blocks shown in the sketch below is to be used in the verification procedure of a computer code for analysing progressive failure of rock slopes, and for this, a manually derived solution is required.

The system is in limiting equilibrium with block A tending to topple about the corner C, while block B is on the point of sliding downhill. The shear resistance on all surfaces *is* purely frictional with $\varphi = 35^{O}$. Given that B is twice as heavy as A, determine the thickness 't' of block B. Also show that there is no tendency for block A to slip at the corner C.



20 Marks **Question #4**

A servo-controlled compression test has been conducted on a weak soapstone such that the specimen length remained unchanged throughout: as the axial stress, σ_a, was increased, so the confining pressure, *p*, was increased so that no net axial strain resulted. A plot of axial stress (vertical axis) against confining pressure (horizontal axis) gave an initial straight line passing through the origin. At a critical confining pressure of $p = 85$ MPa (when $\sigma_a = 39.1$ MPa), the slope of the σ_a - p plot suddenly changed to 29^{O} and remained constant for the remainder of the test. This change in slope may be taken to represent the onset of yield. As such:

10 Marks a. Determine an elastic constant from the slope of the initial portion of the σ_a - p curve.

10 Marks b. Assuming that the Mohr-Coulomb criterion is applicable, determine σ_a, c and φ for the rock.

20 Marks **Question #5**

If a rock mass contains more than one fracture set, one can apply the single plane of weakness theory to each set, and superimpose the results to find a lowest-bound envelope of strength. As such,

10 Marks

a. Plot the 2-D variation in strength for a rock mass containing two orthogonal sets of fractures, A and B, the strengths of which are C_A = 100 kPa, $\varphi_A = 20°$ and $C_B = 0°$, $\varphi_B = 35°$ when the minor principal stress has the value 10 MPa. The intact rock strength is given by $\sigma_1 = 75 + 5.29\,\sigma_3$.

10 Marks

b. How would this strength variation change if the minor principal stress were reduced to zero?

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:

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

Resolved Shear Stress:

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

<u>Point Load Test</u>

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

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

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

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

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

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

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	

... 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

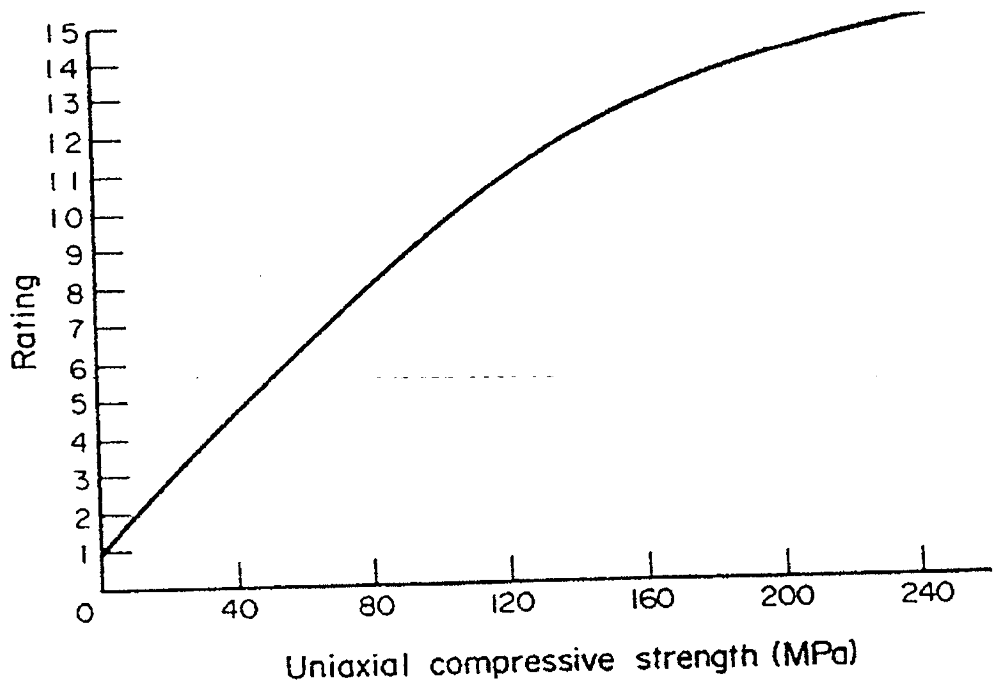


Figure 1. RMR Rating System for the strength of intact rock material

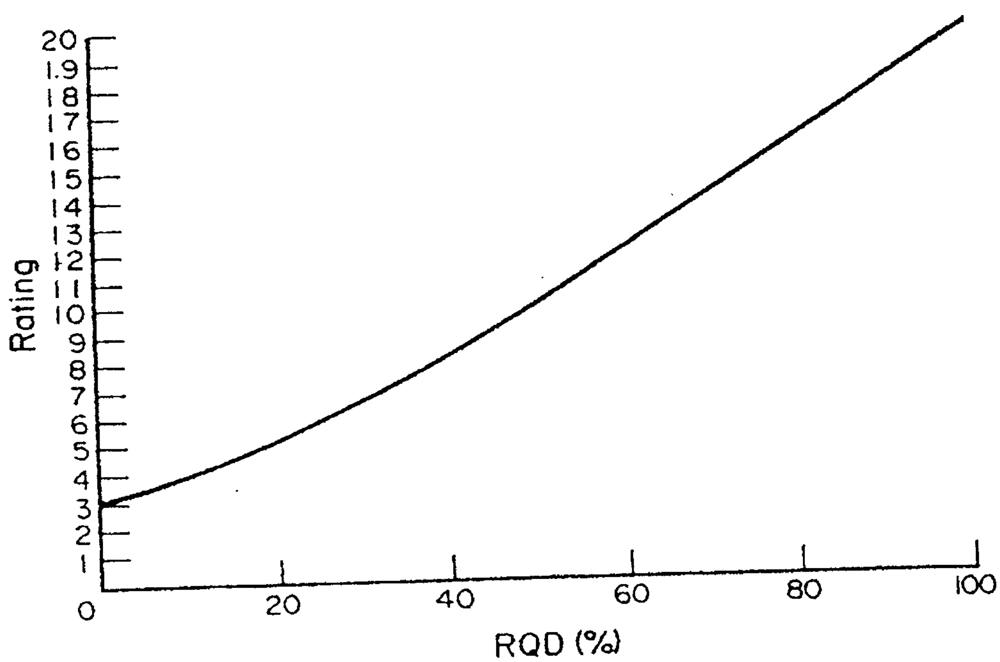


Figure 2. The RMR Rating system: ratings for RQD

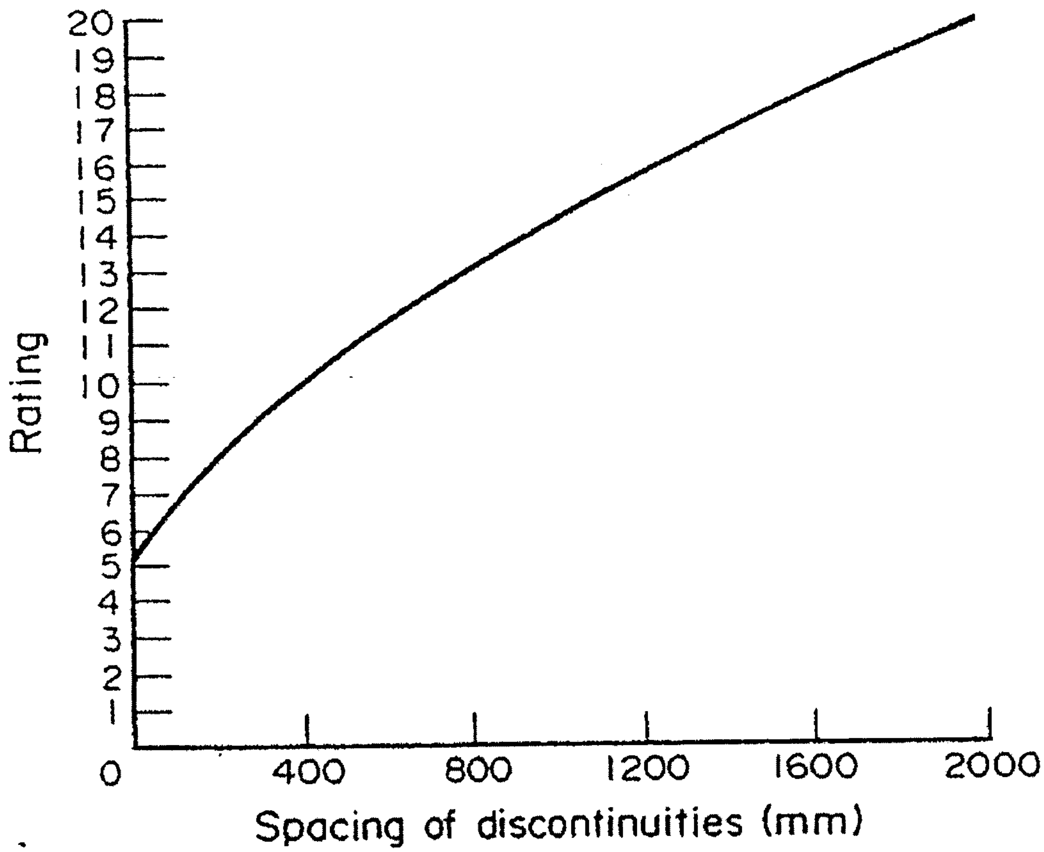


Figure 3. The RMR Rating system: ratings for Discontinuity Spacing

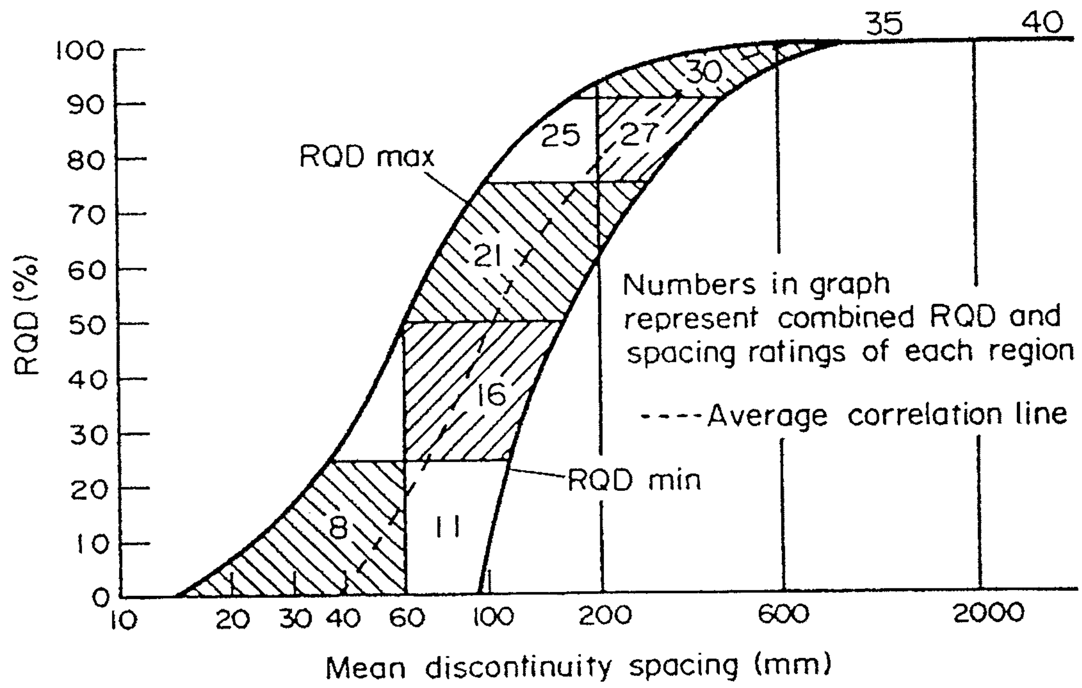


Figure 4. The RMR Rating system: Chart for correlation between RQD and Discontinuity Spacing

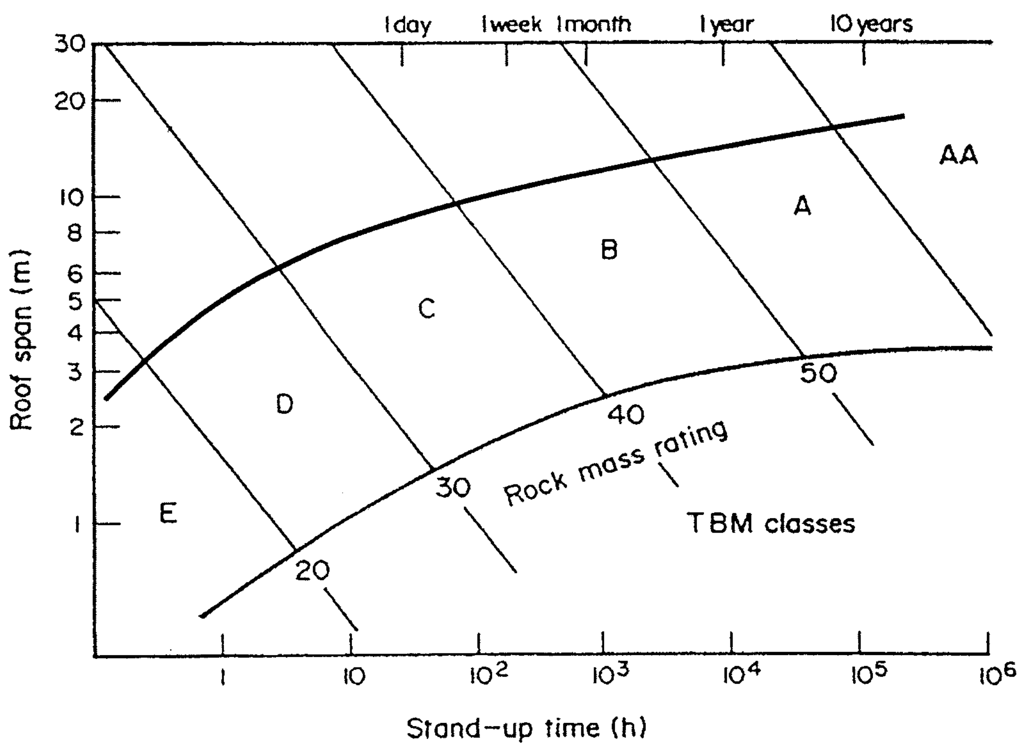
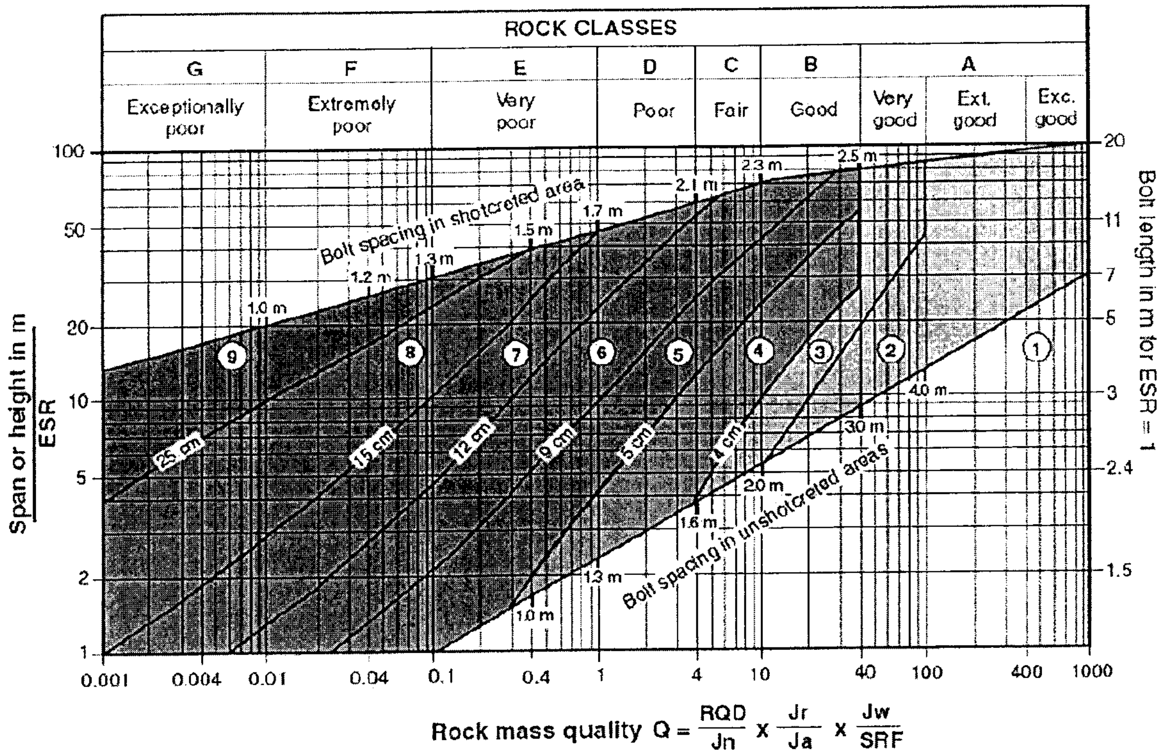


Figure 5. Modified Lauffer diagram depicting boundaries of rock mass classes for TBM applications (after Lauffer 1988).



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).