National Exams December 2015

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.

9. There are a total of 17 pages for this exam.

# Marking Scheme

## (only 4 will be marked)

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

Value

**20 Marks** **Question #1**

One of the biggest challenges of rock mechanics is to assign 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 of 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 #2**

An investigation has been proposed to transform an old underground limestone mine into an underground storage facility. The mine utilized the room and pillar method with rectangular pillars. The clear spacing between the pillars is 6 m. The pillars are 7 m square and the excavation is at a depth of 80 m. Examination of the pillars shows that the limestone is horizontally bedded with moderate spacing and gentle undulations. The bedding planes are smooth with slightly weathered surfaces and no visible aperture. Conditions within the quarry are dry. A point load test of the pillar rock yielded an estimated uniaxial compressive strength of 100 MPa; Triaxial testing of the pillar rock demonstrated that the rock failed when the axial stress in the sample was 110 MPa and the confining pressure was 4 MPa. The unit weight of limestone is 28 kN/m$^3$. The ratio of horizontal to average vertical stress is 0.075 at the centre of each pillar. Answer:

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:

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

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 #3**

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 reinfoce 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.

**20 Marks** **Question #4**

The figure below shows a cross-section of a rock slop that has a horizontal upper surface. During excavation of this slope, a fracture plane AD, dipping at 30°, was discovered, and soon after excavation a vertical tension crack CD formed that intersected the fracture plane to form the kinematically feasible block ABCD. Upon investigation, it was found that the shear strength parameters of the fracture plane were c =20 kPa and $\varphi = 30°$.

10 Marks a. Develop an equation for the factor of the block against sliding on the plane AD for the case where the depth of water in the tension crack is an unknown value '*d*'. The unit weights of rock and water may be taken to be constant with magnitudes 25 kN/m$^3$ and 10 kN/m$^3$, respectively. Explicitly state all of the simplifying assumptions.

5 Marks b. The slope was excavated during mid-summer when the general ground conditions were dry. What was the factor of safety of the slope at this time?

5 Marks c. After a period of heavy rain in the following winter, the slope failed. Does the computed factor of safety for these circumstances indicate that this would occur? Explain,

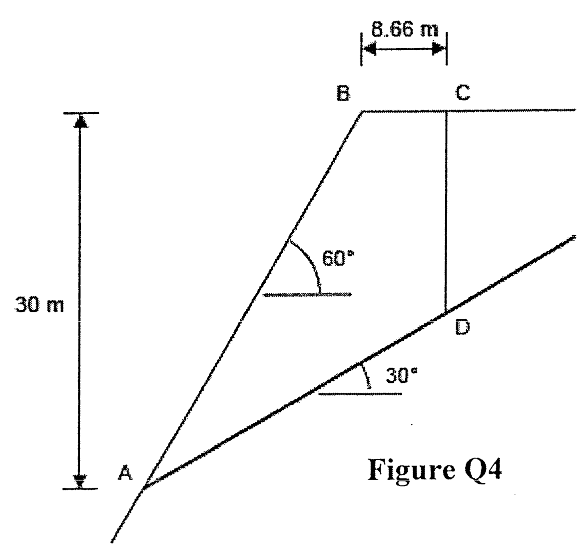



**Figure Q4**

Value

**20 Marks** **Question #5**

An underground tunnel 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 | 9.1* |
| 221.4 | 10.1* |
| 211.3 | 9.4* |
| 203.3 | 8.9* |
| 205.5 | 9.3* |
| *$I_s$ 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 13° to the horizontal and joints repeat approximately every 1.4 m; surfaces of this family of

joints are slightly rough/weathered and continuous, with separation distance between the joint surfaces ranging between 1.0-1.3 mm.

- Joint #2 strikes 45° to long axis of planned excavation, dips 20° and repeats at intervals of approximately 0.3m; 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.

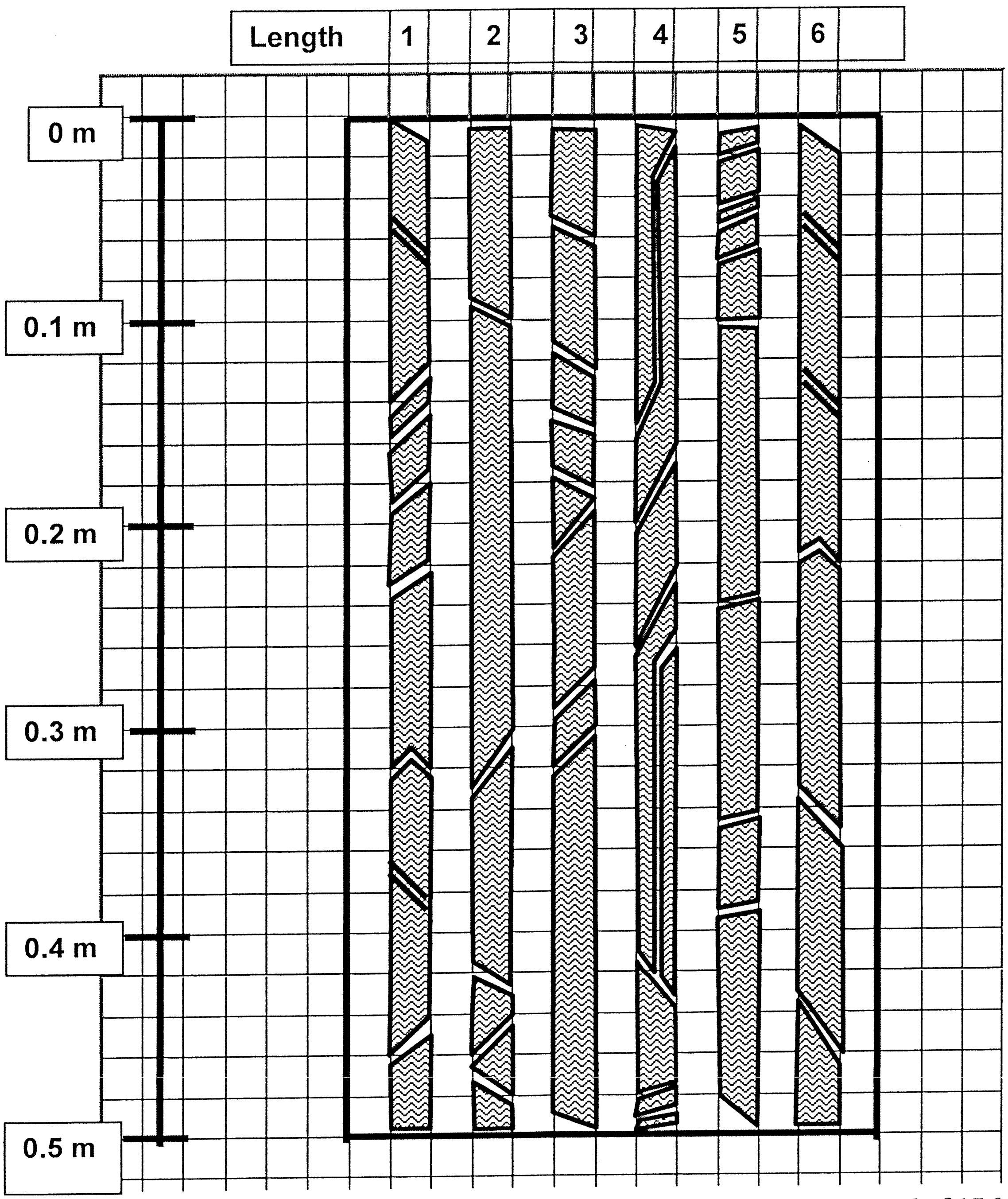



**Figure Q5**. Core Recovery View (3.0 metre length of core).

## 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:

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

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
$\Psi$ = angle of failure plane in triaxial sample from horizontal
$S_T$ = tensile strength
$S_c$ = unconfined compressive strength

Mining

$\sigma_v$ = load / $Y^2$

$\sigma_p$ = 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, $\mu$ = Poisson's Ratio

<u>Thick Wall Cylinder Stress formulae</u>

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

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

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

$U_r = \varepsilon_r r_i$

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

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

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

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

$\sigma_r$ = 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

$\mu$ = 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<br>Not continuous<br>No separation<br>Unweathered wall rock | Slightly rough surfaces<br>Separation < 1 mm<br>Slightly weathered walls | Slightly rough surfaces<br>Separation < 1 mm<br>Highly weathered walls | Slickensided surfaces<br>or Gouge < 5 mm thick<br>or Separation 1-5 mm<br>Continuous | Soft gouge >5 mm thick<br>or Separation > 5 mm<br>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)<br>Rating | < 1 m<br>6 | 1 - 3 m<br>4 | 3 - 10 m<br>2 | 10 - 20 m<br>1 | > 20 m<br>0 |
| Separation (aperture)<br>Rating | None<br>6 | < 0.1 mm<br>5 | 0.1 - 1.0 mm<br>4 | 1 - 5 mm<br>1 | > 5 mm<br>0 |
| Roughness<br>Rating | Very rough<br>6 | Rough<br>5 | Slightly rough<br>3 | Smooth<br>1 | Slickensided<br>0 |
| Infilling (gouge)<br>Rating | None<br>6 | Hard filling < 5 mm<br>4 | Hard filling > 5 mm<br>2 | Soft filling < 5 mm<br>2 | Soft filling > 5 mm<br>0 |
| Weathering<br>Ratings | Unweathered<br>6 | Slightly weathered<br>5 | Moderately weathered<br>3 | Highly weathered<br>1 | Decomposed<br>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

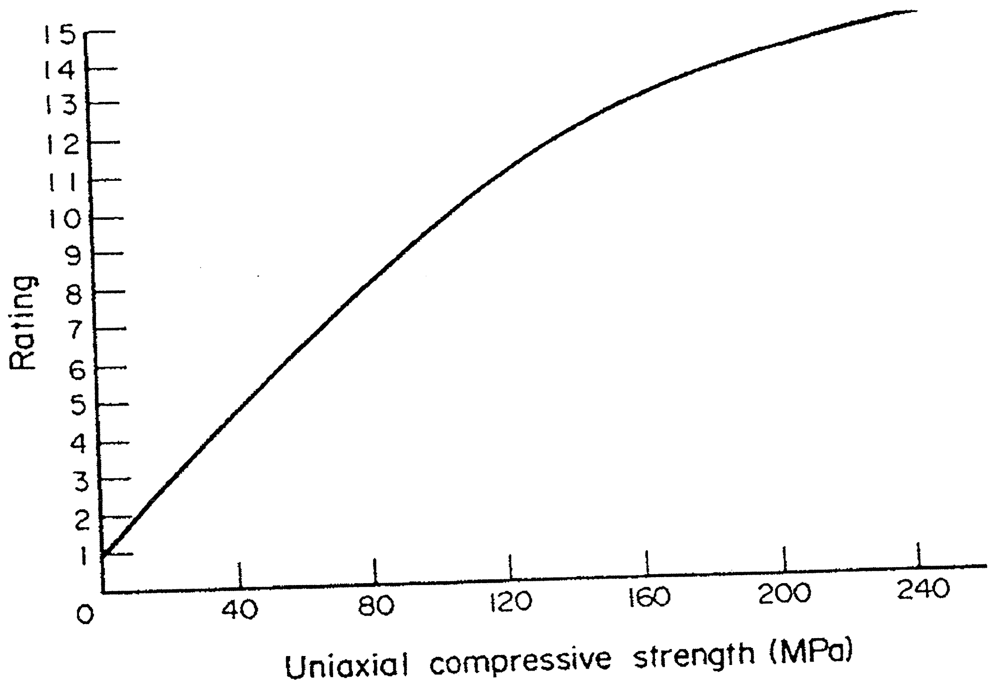



Figure 1. RMR Rating System for the strength of intact rock material

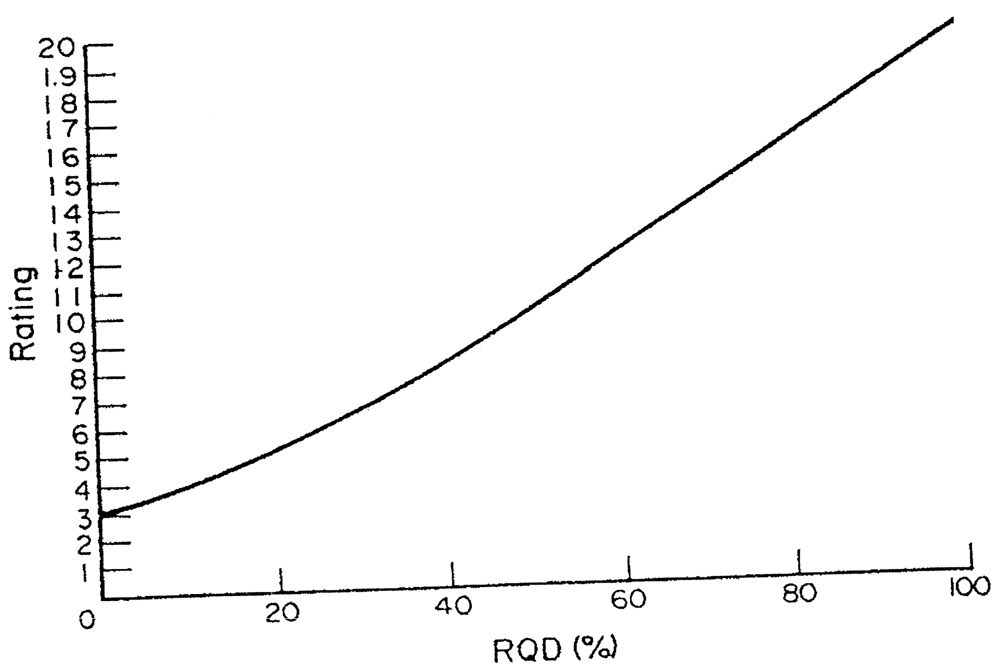


Figure 2. The RMR Rating system: ratings for RQD

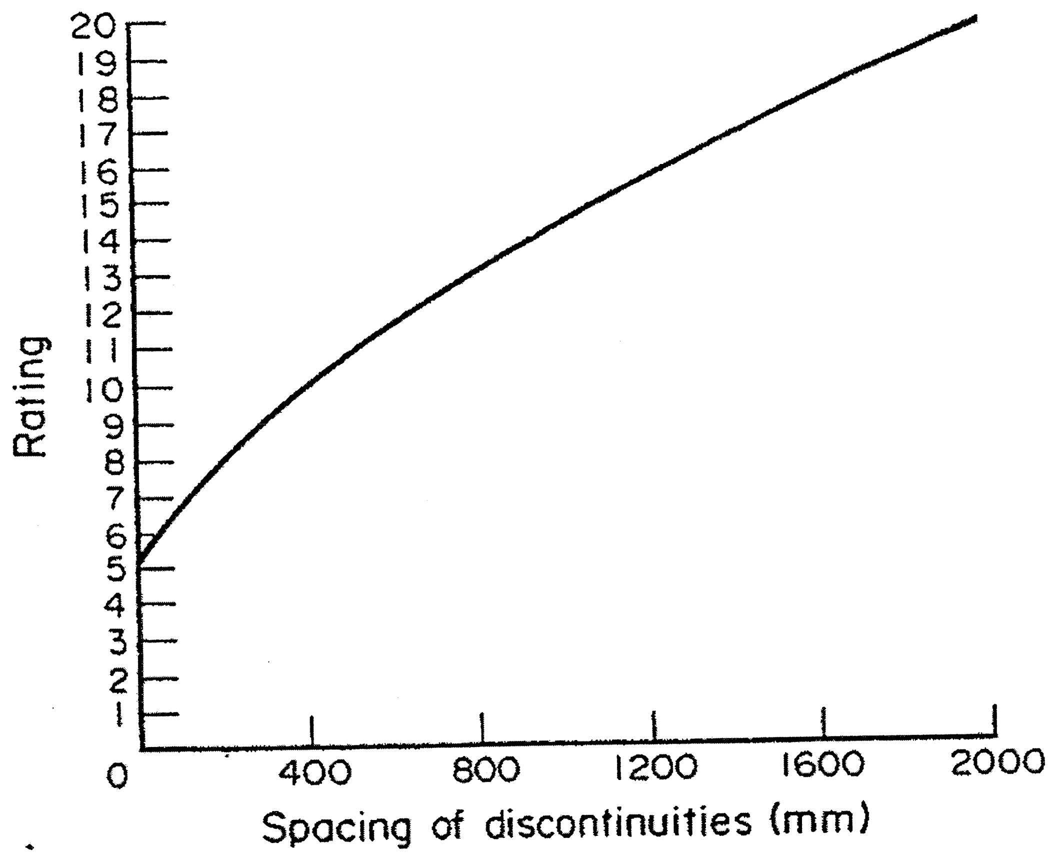



Figure 3. The RMR Rating system: ratings for Discontinuity Spacing

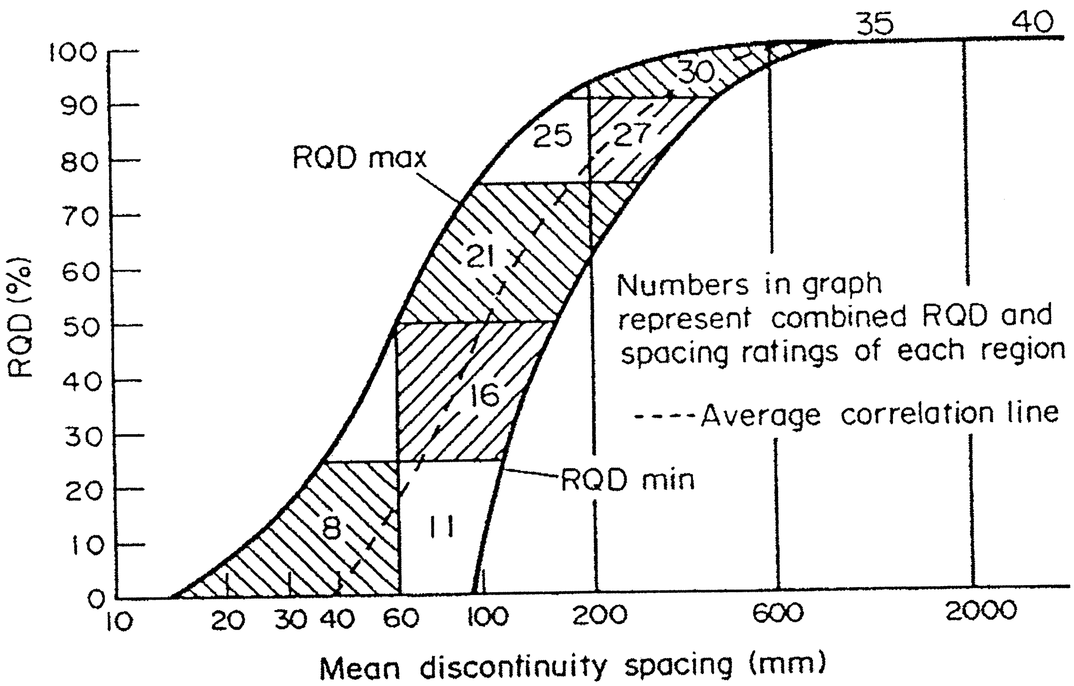



Figure 4. The RMR Rating system: Chart for correlation between RQD and Discontinuity Spacing

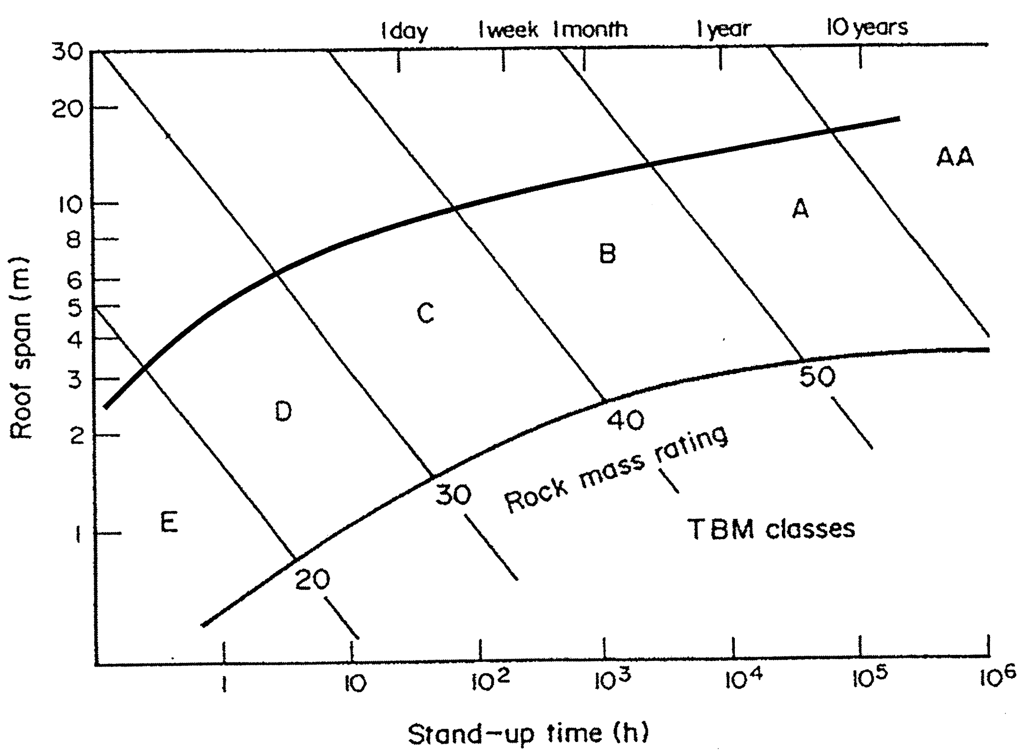
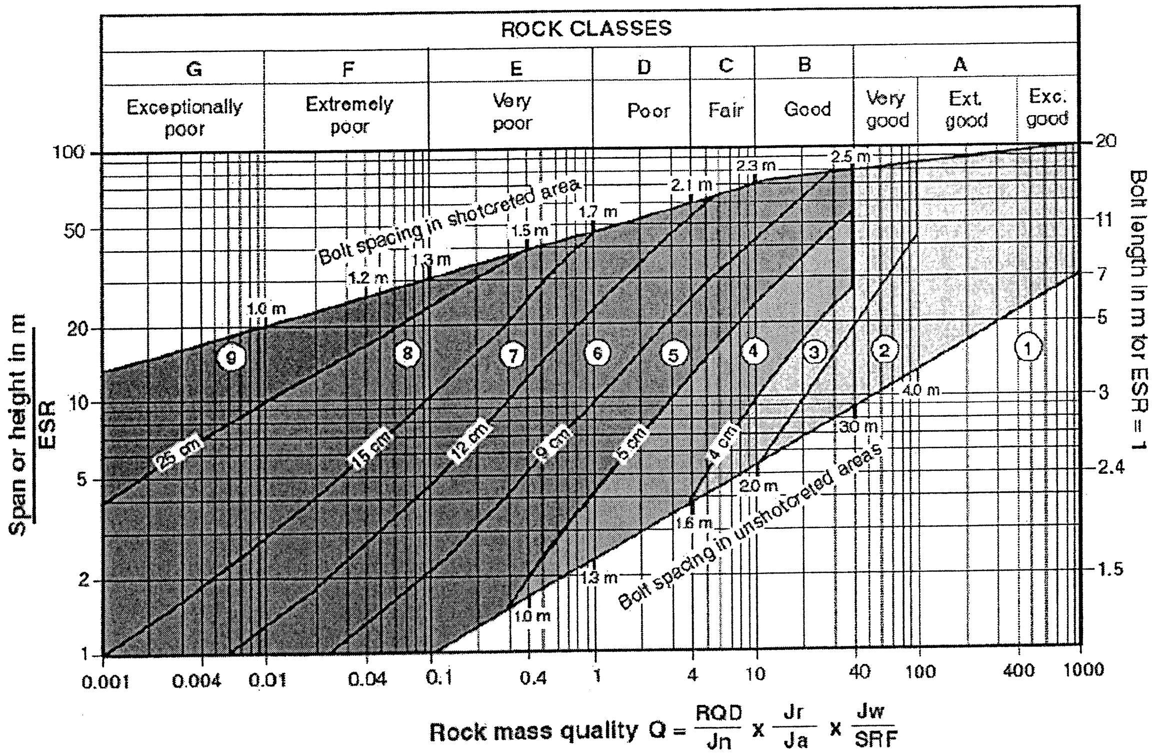



Figure 5. Modified Lauffer diagram depicting boundaries of rock mass classes for TBM applications (after Lauffer 1988).




**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).