National Exams May 2012
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 one of two approved calculators. Candidates are permitted, however, to bring to the examination room two sheets containing rock mechanics formulae and notes.
3. FIVE (5) questions constitute a complete exam paper. The first five questions as they appear in the answer book will be marked.
4. Each question is of equal value.
5. Some equations, graphs and tables are given at the end of the exam paper. These may 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.
6. Hand in the exam booklet and the questions booklet at the end of the exam.

1. A circular tunnel is excavated at a depth of 300m in rock having a unit weight of 0.027 MN/m3. The in-situ stress ratio, K, is estimated to be 0.3.

a. Using the Kirsch solution, determine the maximum and minimum boundary stresses around the excavation and the location of these points.

(10 marks)

b. If the rock mass has a uniaxial compressive strength of 15.5 MPa and a tensile strength of zero, determine the angular extent of compressive failure at the boundary of the excavation.

(7 marks)

d. If the same stress condition were present in a rock mass with twice the value for Young's Modulus, state what this would do to the magnitude of induced compressive stress at the opening boundary.

(3 marks)

2a. Discuss in detail at least 3 index tests used in the characterization of intact rock. State the advantages and disadvantage of using index tests.

(10 marks)

2b. Compare and contrast the Rock Mass Rating and Q rock mass classification systems.

(10 marks)

3a. Based on the following data, estimate Young's Modulus. The rock fails at a UCS of 65 MPa. The sample is 8cm long.

Stress	Deformation
10 MPa	0.2 mm
20 MPa	0.33 mm
30 MPa	0.42 mm
40 MPa	0.51 mm
50 MPa	0.62 mm
60 MPa	0.77 mm

What stress range did you base the modulus on? What three mechanisms are contributing the observed load / deformation data?

(5 marks)

Use the graph paper as necessary.

10 MM/CM

3b. A horizontally bedded sandstone has an intact modulus of elasticity of 60 GPa. The bedding has a spacing of 0.3 metres and the bedding planes are infilled with 1 mm of clay. With a 10 MPa stress increase, the clay layer thickness decreases to 0.4 mm. What is the overall vertical modulus of elasticity for the rock mass corresponding to a vertical stress increase of 10 MPa.

(5 marks)

3c. Three samples of the same size are being loaded on a stiff testing machine. The three samples are placed on the machine together and tested simultaneously. Sample A has a Young's Modulus of 75 GPa and a maximum strength of 210 MPa. Samples B and C have a modulus of 25 GPa and a maximum strength of 65 MPa. Assume the samples have no residual strength after failure. The samples are 10cm long with a diameter of 5 cm. A force of 0.29MN is exerted by the stiff testing machine. Give two possible stresses being carried by the 3 samples. Ignore any deformation of the loading platens.

(10 marks)

4a. Consider a 5 metre wide tunnel constructed in a north / south direction in a jointed rock mass. Three joint sets are present, two sub vertical joint sets striking north-south and east-west, both with a 1.0m spacing, and a sub-horizontal set with a 0.2m spacing. The tunnel back is horizontal. Based on a voussoir stability analysis, what is the maximum possible downward movement of the blocks in the back before failure? Make a labelled sketch showing this.

(5 marks)

4b. An 8 metre wide tunnel is being driven in the north / south direction. The following are the orientations of 2 joint sets present in the rock mass. Orientations are given as strike and dip.

J.S. A	000/45 W
J.S. B	180/45 E

Wedge failures have been observed in the 8 metre wide tunnel. 4 metre long cable bolts have been installed at a 2.0 metre ring spacing. 4 cables per ring were installed – support started 1m from the walls of the tunnel. The cable bolts have a breaking strength of 30 tonnes and a bond strength of 10 tonnes / metre. No plates have been installed. What is the factor of safety for wedge failure after installing the cable bolts?

(7 marks)

4c. A drift was driven and was found to be stable at a width (span) of 10 metres. Cables were installed for support. The same number of cables were installed for a section of the drift that was increased in width to 13 metres. At a 13 metre width, a wedge failure across the total drift span occurred, breaking the installed cable support (a factor of safety of 1.0 can be assumed for this geometry). What is the factor of safety for the 10 metre wide drift against failure along the same joint sets. Assume zero cohesion on the joint surfaces and assume potential failure across the total drift width.

(8 marks)

5. Consider an east / west striking road cut dipping 65° to the north. The road cut is 35 metres high. Joints were mapped along a 300 metre traverse and laboratory shear strength tests were conducted on samples of each joint surface. The rock is a competent andesite. A tension crack was observed 5 metres from the slope crest. The following joint orientations and friction values were estimated:

	Dip/Dip Dir.	Lab friction value
Joint Set A	30/280	35°
Joint Set B	50/040	33°
Joint Set C	03/087	27°
Joint Set D	40/355	45°

a. Sketch a free hand stereonet and show the great circles representing the joint sets and the road cut. (2 Marks)

b. List joint combinations which form possible wedge failures. (2 Marks)

c. Assess the slope stability against planar failure for dry conditions, assuming the tension crack is full of water. Make a realistic assumption on joint cohesion. (8 Marks)

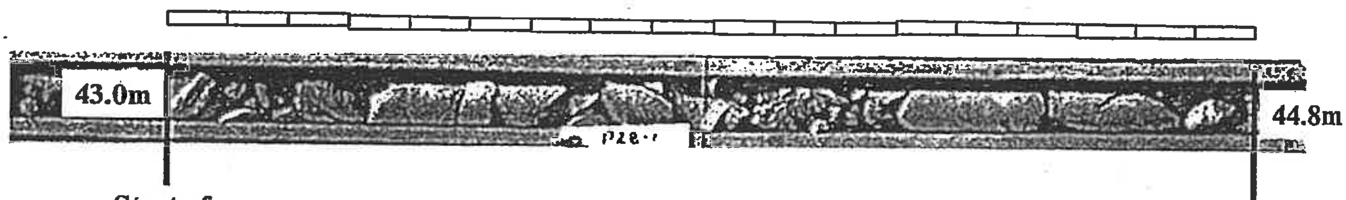
d. List additional information which should be collected to improve this stability analysis? (3 Marks)

e. List any remedial measures you would recommend for this slope. (3 Marks)

6. The following rock mass properties have been estimated from rock exposures, lab testing of intact samples and core logging. A typical example of the core is shown in the accompanying photograph.

- UCSLab = 70 MPa
- Young's ModulusLab = 80 GPa
- Joint Properties
  - JRC (10 cm scale) = 7
  - Joint surfaces are wavy
  - Sericite coating on joints, joint surfaces can be dented with a fingernail

Scale showing 10cm increments



Start of run

End of run

Estimate the following values and give any required assumptions:

6a. RQD (3 marks)

6b. Q (6 marks)

6c. RMR_{76} and RMR_{89} (6 marks)

6d. Young's Modulus E for the rock mass (2 marks)

6e. ϕ and c for the rock mass (3 marks)

7. A room and pillar mining method has been conducted. The opening width is 5m and the pillar width is 10 metres. The pillars are square with a height of 10m. The room and pillar mining area is horizontal at a depth of 230 metres. This room and pillar geometry results in a pillar confining stress of 3MPa. The pillars are consist of a granite with a specific gravity of 2.7, an unconfined compressive strength of 150 MPa, a Q (NGI) classification value of 5 and an RMR_{76} of 58

a. Estimate the vertical stress in the pillars based on tributary theory. Clearly state any required assumptions.

(10 marks)

b. Estimate a factor of safety for the pillar based on m & s failure criteria. The mi value for this rock is approximately 17. An equation relating the rock mass condition and m & s values are attached.

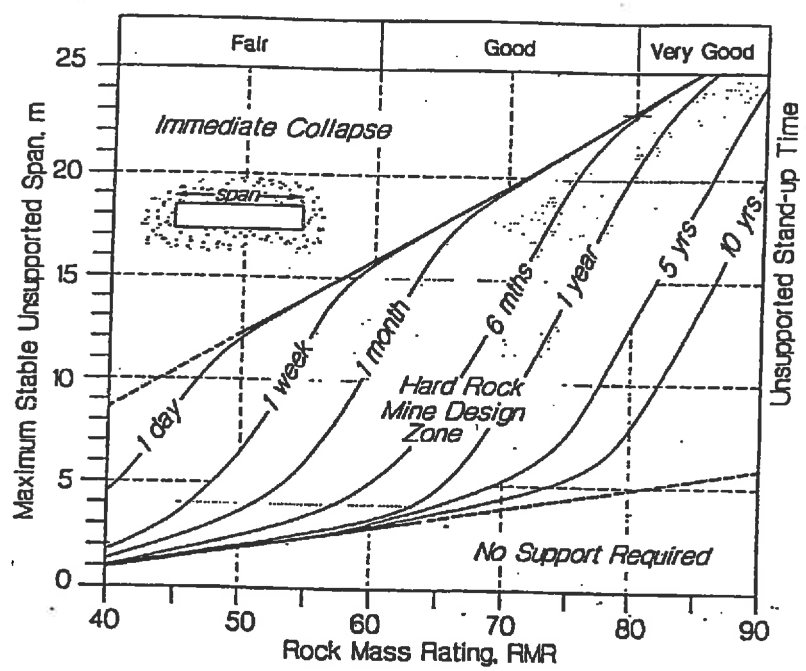
(5 marks)

c. What confinement is required in order to ensure that the factor of safety exceeds 2.0. How can this be achieved in practice.

(5 marks)

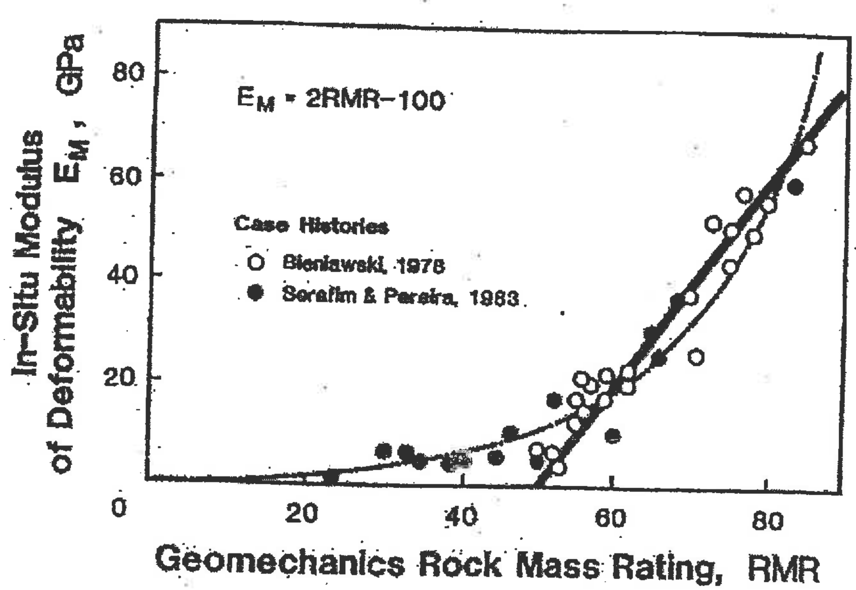
Supporting Graphs, Equations and Figures

Stand-up Time Graph

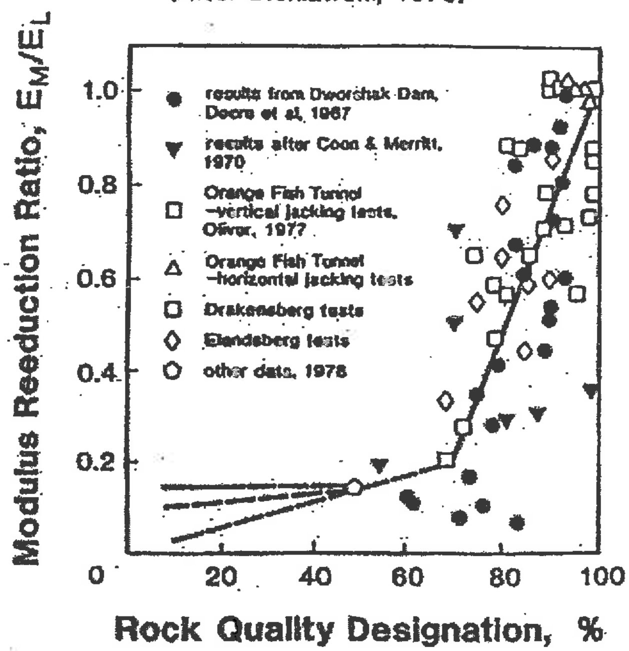


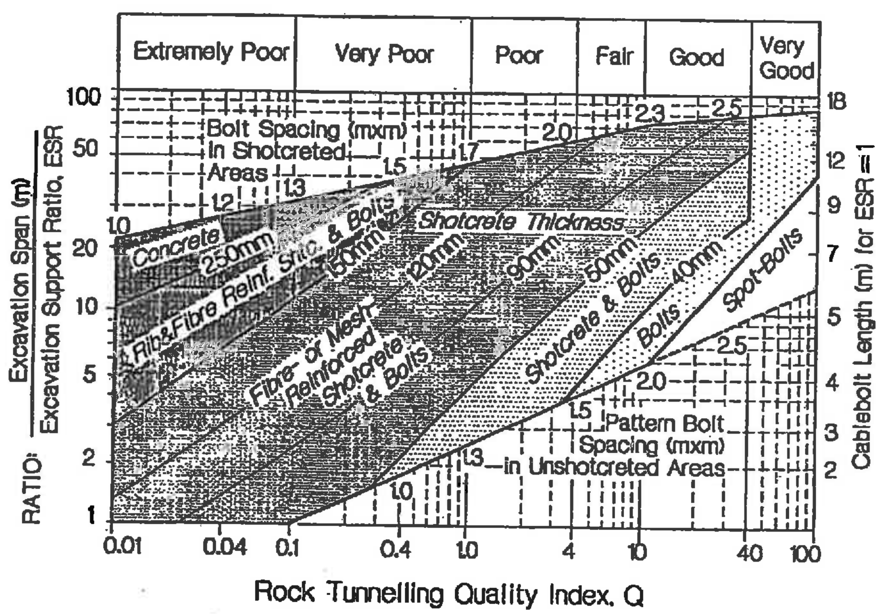
CORRELATION BETWEEN THE IN-SITU MODULUS OF DEFORMATION & THE GEOMECHANICS CLASSIFICATION ROCK MASS RATING (RMR)

(After Bieniawski, 1984)



CORRELATION BETWEEN RQD & MODULUS RATIO E_M/E_L
(After Bieniawski, 1978)





Note: " Bolts " refers to pattern bolting unless specified

RMR_{89}

A. Classification Parameters And Their Ratings

PARAMETER			RANGES 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 compressive 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		>2m	0.6 - 2 m	200 - 600 mm	60 -200 mm	<60 mm		
	Rating		20	15	10	8	5		
4	Condition of discontinuities		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	Ground water	Inflow per 10 m tunnel length	None	<10 litres/min	10-25 litres/min	5 - 125 litres/min	>125 litres/min		
		Ratio= (Joint water pressure)/ (major principal stress)	0	0.0-0.1	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 Joint Orientations

Strike and dip orientations of joints		Very favourable	Favourable	Fair	Unfavourable	Very unfavourable
Ratings	Tunnels	0	-2	-5	-10	-12
	Foundations	0	-2	-7	-15	-25
	Slopes	0	-5	-25	-50	-60

C. Rock Mass Classes Determined From Total Ratings

Rating	100-81	80-61	60-41	40-21	<20
Class No	I	II	III	IV	V
Description	Very good rock	good rock	Fair rock	Poor rock	Very poor rock

D. Meaning Of Rock Mass Classes

Class No	I	II	III	IV	V
Average stand-up time	10 years for 15m span	6 months for 8 m span	1 week for 5 m span	10 hours for 2,5 m span	30 minutes for 1 m span
Cohesion of the rock mass	>400 kPa	300-400 kPa	200-300 kPa	100-200 kPa	<100 kPa
Friction angle of the rock mass	>45	35-45	25-35	15-25	<15

E. Guidelines for Classification of Discontinuity Conditions

Parameter	Ratings				
Discontinuity length (persistence/continuity)	< 1 m	1-3m	3-10m	10-20m	>20 m
	6	4	2	1	0
Separation (aperture)	None	<0.1mm	0.1-1.0mm	1.5 mm	>5mm
	6	5	4	1	0
Roughness	Very rough	Rough	Slightly Rough	Smooth	Slickensided
	6	5	3	1	0
Infilling (gouge)	None	<5mm	>5mm	<5mm	>5mm
	6	4	2	2	0
Weathering	Unweathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed
	6	5	3	1	0

RMR_{76} Chart

Description	*MPA*	*Rating*
Very low	1-25	0-2
Low	25-50	4
Medium	50-100	7
High	100-200	12
Very high	>200	15

Description	*Inflow*	*Rating*
Dry	0	10
Moist	>25L/min	7
under moderate water pressure	25-125L/min	4
sever water problems	>125L/min	0

RQD	*Joints/m³*	*Rating*
90-100%	0-8	20
75-90%	8-12	17
50-75%	12-20	13
25-50%	20-27	8
<25%	>27	3

Description	*Distance*	*Rating*
very wide	>3m	30
wide	1-3m	25
moderately close	.3-1m	20
close	.05-.3m	10
very close	<.05m	5

Joint Description	**Rating**
• Very Rough, not continuous, no separation - hard joint wall rock	25
• Slightly rough surfaces, separation <1mm - hard joint wall rock	20
• Slightly rough surfaces, separation < 1mm - soft joint wall rock	12
• Slickensided or gouge, <5mm thick or Open 1– 5mm	6

Table 1 Ratings for the six Q-system parameters updated by Barton and Grimstad 1994).

	1: Rock Quality Designation	RQD
A	Very poor	0-25
B	Poor	25-50
C	Fair	50-75
D	Good	75-90
E	Excellent	90-100
Note: Where RQD is reported or measured as ≤ 10 (including 0), a nominal value of 10 is used to evaluate Q. RQD intervals of 5, i.e. 100, 95, 90, etc. are sufficiently accurate.		

	2. Joint Set Number	J_n
A	Massive no or few joints	0.5-1.0
B	One joint set	2
C	One joint set plus random joints	3
D	Two joint sets	4
E	Two joint sets plus random joints	6
F	Three joint sets	9
G	Three joint sets plus random joints	12
H	Four or more joint sets, random, heavily jointed, 'sugar cube', Etc.	15
J	Crushed rock, earthlike	20
Note: For intersections, Use ($3.0 \times J_n$). For portals, use ($2.0 \times J_n$).		

	3. Joint Roughness Number	J_r
a) Rock-wall contact. And b) rock-wall contact before 10 cm shear		
A	Discontinuous joints	4
B	Rough or irregular, undulating	3
C	Smooth, undulating	2
D	Slickensided, undulating	1.5
E	Rough or irregular, planar	1.5
F	Smooth, planar	1.0
G	Slickensided, planar	0.5
Note: Descriptions refer to small scale features and intermediate scale features, in that order.		
c) No rock wall contact when sheared		
H	Zone Containing clay minerals thick enough to prevent rock-wall contact	1.0
J	Sandy, gravelly or crushed zone thick enough to prevent rock wall contact	1.0
Note: i) Add 1.0 if the mean spacing of the relevant joint set is greater than 3m. ii) J_r = 0.5 can be used for planar slickensided joints having lineations, provided the lineations are oriented for minimum strength.		

	4. Joint Alteration Number	ϕ_r°	J_a
a) Rock-wall contact (no mineral fillings, only coatings)			
A	Tightly healed. Hard. Non-softening, impermeable filling. i.e. Quartz or epidote	-	0.75
B	Unaltered joint walls, surface staining only	25-35	1.0
C	Slightly altered joint walls non-softening mineral coatings, sandy particles, clay-free disintegrated rock, etc	25-30	2.0
D	Silty-, or sandy-clay coatings, small clay-fraction (nonsoftening)	20-25	3.0
E	Softening or low friction clay mineral coatings, i.e. kaolinite, mica. Also chlorite, talc, gypsum and graphite etc., and small quantities of swelling clays. (Discontinuous coatings, 1-2mm or less in thickness	8-16	4.0
b. Rock wall contact before 10 cms shear			
F	Sandy particles, clay-free disintegrated rock.	25-30	4.0
G	Strongly over-consolidated, nonsoftening clay mineral fillings (continuous, < 5mm thick)	16-24	6.0
H	Medium or low over-consolidation, softening, clay mineral fill., (continuous, <5mm thick)	12-16	8.0
J	Swelling clay fillings, i.e. montmorillonite (continuous, but < 5 mm thick). Values of J_a depend on percent of swelling clay-size particles, and access to water, etc.	6-12	8-12
c) *No rock wall contact when sheared.*			
K, L, M	Zones or bands of disintegrated Or crushed rock and clay (see G, H, J) for clay conditions)	6-24	6, 8 or 8-12
N	Zones or bands of silty- or sandy clay, small clay fraction. (non-softening)	-	5.0
O P	Thick, continuous zones or bands of clay (see G, H and for clay conditions)	6-24	10, 13 or
R			13-20

	5. Joint Water Reduction Factor	Approx. water pres. (kg/cm^2)	Jw
A	Dry excavations or minor inflow, i.e. < 5 lit/min. locally	<1	1.0
B	Medium inflow or pressure, occasional outwash of joint fillings	1-2.5	0.66
C	Large inflow or high pressure in competent rock with unfilled joints	2.5-10	0.50
D	Large inflow or high pressure considerable outwash of fillings	2.5-10	0.33
E	Exceptionally high inflow or pressure at blasting, decaying with time	>10	0.2-0.1
F	Exceptionally high inflow or pressure continuing without decay	>10	0.1-.05
Note: Factors C to F are crude estimates. Increase Jw if drainage measures are installed. Special problems caused by ice formation are not considered.			

	6. Stress Reduction Factor	SRF
a) Weakness zones intersecting excavation, which may cause loosening of rock mass when tunnel is excavated.		
A	Multiple occurrences of weakness zones containing clay or chemically disintegrated rock, very loose surrounding rock (any depth)	10
B	Single weakness zones containing clay, or chemically disintegrated rock (excavation depth < 50m)	5
C	Single weakness zones containing clay, or chemically disintegrated rock (excavation depth > 50m)	2.5
D	Multiple shear zones in competent rock (clay free), loose surrounding rock (any depth)	7.5
E	Single shear zones in competent rock (clay free), (depth of excavation < 50m	5.0
F	Single shear zones in competent rock (clay free), (depth of excavation > 50m)	2.5
G	Loose open joints, heavily jointed or 'sugar cube'(any depth)	5.0
Note: Reduce these values of SRF by 25 - 50% if the relevant shear zones only influence but do not intersect the excavation.		

	b) Competent rock, rock stress problems	σ_c/σ_1	σ_θ/σ_c	SRF
H	Low stress, near surface	>200	<0.01	
J	Medium stress, favourable stress condition	200-10	0.01-0.3	1
K	High stress, very tight structure. Usually favourable to stability, maybe unfavourable to wall stability	10-5	0.3-0.4	0.5-2
L	Moderate slabbing after > 1 hour in massive rock	5-3	0.5-0.65.	5-50
M	Slabbing and rock burst after a few minutes in massive rock	3-2	0.65-1	50-200
N	Heavy rock burst (strain burst) and immediate dynamic deformations in massive rocks	<2	>1	200-400
Note: For strongly anisotropic virgin stress field (if measured): when 5 ≤ σ_1/σ_3 ≤ 10, reduce σ_c to $0.8\sigma_c$ where σ_c = unconfined compression strength, σ_1 and σ_3 are the major and minor principal stresses and σ_θ = maximum tangential stress. Few case records available where depth of crown below surface is less than span width. Suggest SRF increase from 2.5 to 5 for such cases (see H).				

	c) *Squeezing rock, plastic flow of incompetent rock under the influence of high rock pressure*	σ_θ/σ_c	SRF
O	Mild squeezing rock pressure.	1-5	5-10
P	Heavy squeezing rock pressure	>5	10-20
Note: iv) Cases of squeezing rock may occur for depth $H > 350 Q^{1/3}$ rock mass compression strength can be estimated from $q \approx 7 \gamma Q^{1/3}$ (MPa) where γ = rock density in gm/cc			

	d) *Swelling rock: chemical swelling activity depending upon presence of water)*	
R	Mild swelling rock pressure	5-10
S	Heavy swelling rock pressure	10-15

Note: J_r and J_a classification is applied to the joint set or discontinuity that is least favourable for stability both from the point of view of orientation and shear resistance (where $\tau \approx \sigma_n \tan^{-1}(J_r/J_a)$.

$$RQD = \frac{RQD}{Jn} x \frac{Jr}{Ja} x \frac{Jw}{SRF}$$

Rock Mechanics Equations:

RQD Equation

RQD = 115 – 3.3 Jv   Jv = number of joints in a cubic metre of rock

$$\frac{m}{m_i} = e^{\frac{(RMR-100)}{28}}$$

$$s = e^{\frac{(RMR-100)}{9}}$$

Kirsch Equations

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

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

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

Marking Scheme

Q1.	a) 10	b) 7	c) 3			
Q2.	a) 10	b) 10				
Q3.	a) 5	b) 5	c) 10			
Q4.	a) 5	b) 7	c) 8			
Q5.	a) 2	b 2	c) 10	d) 2	e) 2	f) 2
Q6.	a) 3	b) 6	c) 6	d) 2	e) 3	
Q7.	a) 10	b) 5	c) 5			