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 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
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: $S_1$ (cohesion) = 10 MPa and $\phi = 45^\circ$. 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.

Question #2

Design of an Open Pit Excavation. 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°). An orthogonal view of the pit face and joint intersection conditions is presented below in Figure Q2.

![Figure Q2. Open face pit](image)

Joint system (A) dips at an angle ($\beta$), such that ($\beta < 90^\circ$). 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 (i.e.- 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 (i.e.- $C = 0$).

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).
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

\[
Q = \frac{RQD}{J_n} \frac{J_r}{J_d} \frac{J_w}{SRF}
\]

where \( RQD \) is the Rock Quality Designation
\( J_n \) is the joint set number
\( J_r \) is the joint roughness number
\( J_d \) 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

\[
l_{550} = L / D^2
\]

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

\[
S_c = 24 \ (l_{564}) \text{ KPa}
\]

Where, \( S_c = \) unconfined compressive strength (kPa)
\( l_{564} = \) index values for 5.4 cm diameter core specimens (kN/cm²)

Mohr-Coulomb Failure Criterion

\[
\Psi = 45^\circ + \varphi/2
\]

\[
S_T = C / \tan \varphi
\]

\[
\frac{(\sigma_1 + \sigma_3)}{(\sigma_3 + S_T)} = \tan^2 \Psi
\]

\[
\sigma_1 = \sigma_3 \tan^2 \Psi + 2C \tan \Psi = \sigma_3 \tan^2 \Psi + S_c
\]

Where, \( C = \) cohesion
\( \Psi = \) angle of failure plane in triaxial sample from horizontal
\( S_T = \) tensile strength
\( S_c = \) unconfined compressive strength
Mining

\[ \sigma_v = \frac{\text{load}}{Y^2} \]

\[ \sigma_n = \frac{\text{load}}{X^2} \]

\[ \frac{\sigma_p}{\sigma_v} = \frac{A_T}{A_p} \]

Where, \( A_p = \) Post mining area
\( A_T = \) Tributary Area

\[ \sigma_p = \frac{\sigma_v}{(1 - r)} \]

Where, \( r = \) extraction ratio = \( \frac{(A_T - A_p)}{A_T} \)

Kirsch Equations

\[ \sigma_{rr} = \sigma/2 \{ (1+k)(1-a^2/r^2) - (1-k)(1+4a^2/r^2 + 3a^4/r^4)\cos2\theta \} \]

\[ \sigma_{\theta\theta} = \sigma/2 \{ (1+k)(1+a^2/r^2) + (1-k)(1 + 3a^4/r^4)\cos2\theta \} \]

\[ \sigma_{r\theta} = \sigma/2 \{ (1-k)(1 + 2a^2/r^2 - 3a^4/r^4)\sin2\theta \} \]

\[ U_l = \{ \mu r/E \} \cdot \{(\sigma_1 + \sigma_3) + 2(\sigma_1, \sigma_3)\cos2\theta \} \]

Where, \( \mu = \) Poisson's Ratio
Thick Wall Cylinder Stress formulae

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

\[ P_i = \frac{(2P_o - S_c)}{(\tan^2 \Psi + 1)} \]

\[ \varepsilon_r = \frac{1}{E} (\sigma_r - \mu \sigma_t) = \frac{U_r}{r_i} \]

\[ U_r = c_r r_i \]

\[ U_r = \frac{\mu(2P_o r_i)}{E} \]

\[ \sigma_t = \frac{2(r_o^2 P_o)}{(r_o^2 - r_i^2)} \]

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range of values</th>
<th>For the few ranges - unusual compressive strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength of intact rock</td>
<td>&gt;100 MPa</td>
<td>4 - 10 MPa</td>
</tr>
<tr>
<td>Joint roughness</td>
<td>&lt;100 MPa</td>
<td>100 - 200 MPa</td>
</tr>
<tr>
<td>Spacing of discontinuities</td>
<td>&gt;2 m</td>
<td>0.5 - 2 m</td>
</tr>
<tr>
<td>Conditions of discontinuities</td>
<td>Completely dry</td>
<td>Damp</td>
</tr>
</tbody>
</table>

#### B. Rating Adjustment for Discontinuity Orientations (See F)

<table>
<thead>
<tr>
<th>Strike and dip orientation</th>
<th>Very favourable</th>
<th>Favourable</th>
<th>Fair</th>
<th>Unfavourable</th>
<th>Very Unfavourable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnels &amp; shafts</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Foundations</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Slopes</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

#### C. Rock Mass Classes Determined from Total Ratings

<table>
<thead>
<tr>
<th>Ranges</th>
<th>Class number 1</th>
<th>Class number 2</th>
<th>Class number 3</th>
<th>Class number 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IV</td>
<td>VI</td>
<td>V</td>
<td>V</td>
</tr>
</tbody>
</table>

#### D. Meaning of Rock Classes

<table>
<thead>
<tr>
<th>Class number</th>
<th>Description</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Very good rock</td>
<td>I</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Good rock</td>
<td>II</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fair rock</td>
<td>III</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Poor rock</td>
<td>IV</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Very poor rock</td>
<td>V</td>
<td></td>
</tr>
</tbody>
</table>

#### E. Guidelines for Classification of Discontinuity Conditions

<table>
<thead>
<tr>
<th>Discontinuity length (perpendicular)</th>
<th>&lt;1 m</th>
<th>1 - 3 m</th>
<th>3 - 10 m</th>
<th>10 - 20 m</th>
<th>&gt;20 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacing (parallel)</td>
<td>None</td>
<td>&lt;0.1 m</td>
<td>0.1 - 0.5 m</td>
<td>0.5 - 1 m</td>
<td>&gt;1 m</td>
</tr>
<tr>
<td>Roughness</td>
<td>Very rough</td>
<td>Rough</td>
<td>Slightly rough</td>
<td>Rough</td>
<td>Slightly rough</td>
</tr>
<tr>
<td>Filling (width)</td>
<td>None</td>
<td>Hand filling &lt; 5 mm</td>
<td>Hand filling &gt; 5 mm</td>
<td>Short filling &gt; 5 mm</td>
<td>Full filling</td>
</tr>
<tr>
<td>Weathering</td>
<td>Unweathered</td>
<td>Slightly weathered</td>
<td>Moderately weathered</td>
<td>Highly weathered</td>
<td>Decayed</td>
</tr>
</tbody>
</table>

#### F. Effect of Discontinuity Strike and Dip Orientation in Tunneled Rock**

<table>
<thead>
<tr>
<th>Strike perpendicular to tunnel axis</th>
<th>Strike parallel to tunnel axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive with dip: Dip 45 - 60°</td>
<td>Drive with dip: Dip 20 - 45°</td>
</tr>
<tr>
<td>Drive against dip: Dip 45 - 60°</td>
<td>Drive against dip: Dip 0° - 20°</td>
</tr>
</tbody>
</table>

*Some conditions are not mutually exclusive. For example, if infilling is present, the roughness of the surface will be overruled by the influence of the gauge. In such cases, use A.4 directly.

**Modified after Winkler 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).

<table>
<thead>
<tr>
<th>Rock mass class</th>
<th>Excavation</th>
<th>Rock bolts (20 mm diameter, fully grouted)</th>
<th>Shotcrete</th>
<th>Steel sets</th>
</tr>
</thead>
<tbody>
<tr>
<td>I - Very good rock</td>
<td>Full face, 3 m advance</td>
<td>Generally no support required except spot bolting.</td>
<td>None.</td>
<td></td>
</tr>
<tr>
<td>RMR: 81-100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II - Good rock</td>
<td>Full face, 1-1.5 m advance, Complete support 20 m from face.</td>
<td>Locally, bolts in crown 3 m long, spaced 2.5 m with occasional wire mesh</td>
<td>50 mm in crown where required.</td>
<td></td>
</tr>
<tr>
<td>RMR: 61-60</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>III - Fair rock</td>
<td>Top heading and bench 1.5-3 m advance in top heading. Commence support after each blast. Complete support 10 m from face.</td>
<td>Systematic bolts 4 m long, spaced 1.5 - 2 m in crown and walls with wire mesh in crown.</td>
<td>None.</td>
<td></td>
</tr>
<tr>
<td>RMR: 41-60</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV - Poor rock</td>
<td>Top heading and bench 1.0-1.5 m advance in top heading. Install support concurrently with excavation. Complete support 10 m from face.</td>
<td>Systematic bolts 4-8 m long, spaced 1-1.5 m in crown and walls with wire mesh.</td>
<td>100-150 mm in crown and 100 mm in sides.</td>
<td></td>
</tr>
<tr>
<td>RMR: 21-40</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V - Very poor rock</td>
<td>Multiple drifts 0.5-1.5 m advance in top heading. Install support concurrently with excavation. Shotcrete as soon as possible after blasting.</td>
<td>Systematic bolts 5-6 m long, spaced 1-1.5 m in crown and walls with wire mesh. Bolt invert.</td>
<td>150-200 mm in crown, 150 mm in sides, and 50 mm on face.</td>
<td></td>
</tr>
<tr>
<td>RMR: &lt; 20</td>
<td></td>
<td></td>
<td>Medium to heavy ribs spaced 0.75 m with steel lagging and forepoling if required. Close invert.</td>
<td></td>
</tr>
</tbody>
</table>
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).
Figure 6. Estimated support categories based on the tunnelling quality index $Q$ (After Grimstad and Barton, 1993, reproduced from Palmstrom and Broch, 2005).