CHAMBER OF MINES OF SOUTH AFRICA

EXAMINATION PAPER

SUBJECT: ROCK MECHANICS CERTIFICATE PART 1: THEORY **SUBJECT CODE:** COMRMC-1 **EXAMINATION DATE:** OCTOBER 2015 **TIME:** 3 HOURS	**EXAMINER:** J WALLS **MODERATOR:** H YILMAZ **TOTAL MARKS:** 100 **PASS MARK:** 60

NUMBER OF PAGES:16 (*including Cover*)

THIS IS NOT AN OPENBOOK EXAMINATION – ONLY REFERENCES PROVIDED ARE ALLOWED

SPECIAL REQUIREMENTS:

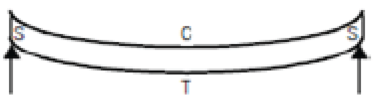
1. Answer **all questions**. Answer the questions **legibly** in English.
2. Write your **ID Number** on the outside cover of each book used and on any graph paper or other loose sheets handed in.

   NB: Your name **must not** appear on any answer book or loose sheets.
3. Show all calculations **and check calculations on which the answers are based.**
4. Hand-held electronic calculators may be used for calculations. Reference notes may not be programmed into calculators.
5. Write **legibly** in ink on the **right hand page** only – **left hand pages will not be marked**.
6. Illustrate your answers by means of sketches or diagrams wherever possible.
7. **Final answers** must be given to an accuracy which is typical of practical conditions. However be careful not to use too few decimal places during your calculations, as rounding errors may result in incorrect answers.

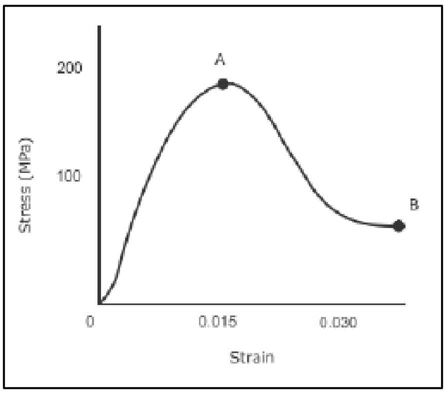
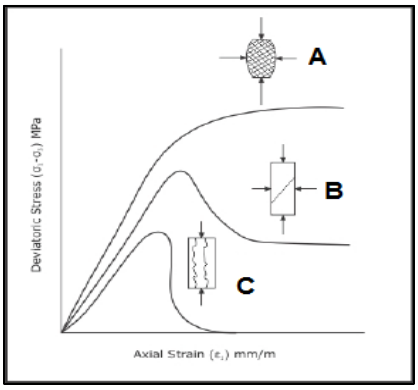
   NB: Ensure that the correct units of measure (SI unit) are recorded as marks will be deducted from answers if the incorrect unit is used (even if the calculated value is correct).
8. In answering the questions, full advantage should be taken of your practical experience as well as data given.
9. Please note that you are not allowed to contact your examiner or moderator regarding this examination.
10. Cell phones are **NOT** allowed in the examination room.

QUESTION 1 – MULTIPLE CHOICE (25)

An answer sheet has been provided at the end of the question paper. Complete the question using the answer sheet and submit together with the answer booklet. Each question represents 1 mark (correct) or 0 marks (incorrect). There is only one correct answer for each question.

No.	Question	Answer choice	
1.1	Express 300 000 N in kN	A	3×10^1 MN
		B	30 kN
		C	300 MN
		D	3×10^2 kN
1.2	In which area of the stress-strain curve is Young's modulus defined?	A	strain hardening
		B	peak stress
		C	elastic deformation
		D	plastic strain
1.3	In which Cartesian quadrants is the “cosine” trigonometric function positive?	A	third and fourth
		B	first and second
		C	third and second
		D	first and fourth
1.4	The Hoek-Brown failure criterion is best applied to one of the following conditions:	A	Swelling of weathered rock
		B	Brittle failure of intact rock
		C	Shear failure of jointed rock
		D	Creep of intact rock
1.5	What is measured by the ultrasonic waves method?	A	Seismic attenuation
		B	Sound wave velocity
		C	Intact rock strength
		D	In-situ stress
1.6	Which of the following does not influence joint strength?	A	Joint spacing
		B	Joint length
		C	Joint wall condition
		D	Joint water content
1.7	RQD = 78; Jn = 6; Jr = 1.5; Ja = 2.0; Jw = 1.0; SRF = 2.5. What is the Q-value?	A	0.3
		B	6.9
		C	3.9
		D	14.2
1.8	 Name the following beam	A	Freely supported beam
		B	Cantilever beam
		C	Built-in beam
		D	None of the above

No.	Question		Answer choice
1.9	Determine the magnitude of the principal stresses for the given stress matrix with x-axis horizontal and y-axis vertical: $\begin{pmatrix} 35 & 15 \\ 15 & 22 \end{pmatrix}$	**A**	σ_1 = 36.07 MPa; σ_2 = 12.15 MPa
		B	σ_1 = 44.84 MPa; σ_2 = 12.15 MPa
		C	σ_1 = 36.07 MPa; σ_2 = 44.84 MPa
		D	σ_1 = 12.15 MPa; σ_2 = 44.84 MPa
1.10	A negative shear stress . . .	**A**	Causes a clockwise rotation in a body diagram
		B	Is plotted above the normal stress axis in the Mohr circle
		C	Is plotted at the minimum intersection with the normal stress axis in the Mohr circle
		D	Is plotted below the normal stress axis in the Mohr circle
1.11	Rocks that experience large amounts of plastic deformation before rupture can be classified as . . .	**A**	Brittle
		B	Visco-elastic
		C	Ductile
		D	Elastic
1.12	Which failure model is presented by $\tau^2 = 4T_o(\sigma_n + T_o)$	**A**	Stacey
		B	Hoek-Brown
		C	Coulomb
		D	Griffith
1.13	At 1 200 m below surface, which theory would result in the highest horizontal stress?	**A**	Young's modulus
		B	Heim's rule
		C	Hooke's law
		D	Rigid confinement
1.14	Around a circular excavation, where the major applied stress is vertical and no internal pressure is applied, the normal stress σ_{rr} at the periphery of the excavation is equal to . . .	**A**	zero
		B	maximum
		C	$2\sigma_v$
		D	σ_v
1.15	In the Mohr-Coulomb failure relationship, the coefficient of friction is represented by . . .	**A**	μ
		B	τ
		C	ρ
		D	ν
1.16	In the Mohr-Coulomb failure relationship, how does an increase in joint water pressure affect the shear strength of a failure surface?	**A**	Decreases cohesion
		B	Decreases friction
		C	Decreases shear strength
		D	All of the above

No.	Question	Answer choice	
1.17	Using the Hoek-Brown relationship, calculate the peak strength of a sample if m = 15, s = 1.0, UCS = 200 MPa and confinement is 20 MPa.	**A**	265 MPa
		B	161 Mpa
		C	6 325 MPa
		D	336 MPa
1.18	Plastic deformation . . .	**A**	Is reversible
		B	Is permanent
		C	Contains visible fractures
		D	Is elastic
1.19	What behaviour is represented by the segment AB in the test graph? 	**A**	Strain softening
		B	Elasto-plastic
		C	Strain hardening
		D	Non-linear elastic
1.20	A "plane strain" analysis can be related to which of the following set of conditions . . .	**A**	$\sigma_{xx} \neq 0, \sigma_{yy} \neq 0, \sigma_{zz} \neq 0, \varepsilon_{zz} \neq 0$
		B	$\sigma_{xx} \neq 0, \sigma_{yy} \neq 0, \sigma_{zz} = 0, \varepsilon_{zz} \neq 0$
		C	$\sigma_{xx} \neq 0, \sigma_{yy} \neq 0, \sigma_{zz} \neq 0, \varepsilon_{zz} = 0$
		D	$\sigma_{xx} = 0, \sigma_{yy} = 0, \sigma_{zz} \neq 0, \varepsilon_{zz} = 0$
1.21	Uni-axial loading can be described as . . .	**A**	$\sigma_1 \neq 0, \sigma_2 = 0, \sigma_3 = 0$
		B	$\sigma_1 \neq 0, \sigma_2 \neq 0, \sigma_3 = 0$
		C	$\sigma_1 \neq 0, \sigma_2 \neq 0, \sigma_3 \neq 0$
		D	None of the above
1.22	Provide the correct set of annotations for the stress strain curves at increasing confinement 	**A**	A = shear fracture; B = axial splitting; C = multiple shear fractures
		B	A = multiple shear fractures; B = axial splitting; C = fracture
		C	A = multiple shear fractures; B = shear fracture; C = axial splitting
		D	None of the above

No.	Question		Answer choice
1.23	Define Poisson's ratio	**A**	Ratio between strains in two mutually perpendicular directions
		B	Ratio of axial strain to transverse strain
		C	Shortening parallel to σ_1 in relation to corresponding elongation in σ_3 direction
		D	None of the above
1.24	In Barton's equation to estimate the peak strength of joints, an increase in normal stress applied to the discontinuity surface, results in . . .	**A**	An increase in joint shear strength
		B	A decrease in joint shear strength
		C	A combined increasing and decreasing effect on joint shear strength
		D	None of the above
1.25	Which of the following GSI ranges could refer to blocky/disturbed/seamy rock that has altered discontinuity surface quality?	**A**	50-60
		B	30-40
		C	75-85
		D	15-25

QUESTION 2 – STRESS AND STRAIN (20)

2.1 0.3 m long gauge lengths on a flat rock surface were used to measure deformation. The following measurements were recorded:

0.3003 m along the datum line (x-axis),

0.2997 m along the line at 60° from the datum line, and

0.3006 m along the line at 120° from the datum line.

2.1.1 Determine the magnitude and direction of the principal strains. [8]

2.1.2 Using the results in 2.1.1, determine the principal stresses, given E = 60 GPa and v = 0.25. [2]

Assume a horizontal x-axis (+ to the right) and a vertical y-axis (+ upwards). The z-axis increases into the rockmass and is orientated along the borehole axis. Data has been corrected for borehole end-effect.

2.2 Illustrate the strain gauge configuration in 2.1 and comment on the principal of measuring strain using an electrical resistance gauge (do not discuss the overcoring method). [3]

2.3 Define strain energy with the correct SI unit. [2]

2.4 Using the results in 2.1, calculate the strain energy density stored in the rock mass at this point. [3]

BONUS QUESTION

2.5 In-situ stress measurements were taken around a geological feature which was associated with seismic activity. Use the given 3D state of stress and directional cosines to determine the rotated normal stress components in all three directions. [6]

$$\text{Stress matrix} \begin{bmatrix} 12 & 1 & 2 \\ 1 & 8 & -1 \\ 2 & -1 & 5 \end{bmatrix} \text{MPa}$$

$$\text{Directional cosine} \begin{bmatrix} 0.9603 & 0.1571 & 0.2307 \\ -0.0740 & 0.9403 & -0.3323 \\ -0.2691 & 0.3020 & 0.9145 \end{bmatrix}$$

QUESTION 3 – ROCK STRENGTH (15)

Quartzite specimens are tested for triaxial compressive strength and the following Mohr-Coulomb equation is derived from the test results:

$$\tau = 25 + \sigma_n \tan 40^o$$

3.1. Plot the Mohr-Coulomb failure line [4]

3.2. Determine graphically if the following stress states would cause failure:

Confinement (MPa)	Major stress (MPa)
5	90
19	200
100	250

[9]

3.3. Explain the reason for your decision on failure in (3.2.) [2]

QUESTION 4 – STRESS IN ROCK AND ROCKMASSES (25)

A circular shaft 6 m in diameter will be bored from surface to 1 200 m below surface. The k-ratio at the maximum depth in the y-direction is $k_y = 1.4$ and in the x-direction is $k_x = 0.8$. The x- and y-directions are mutually perpendicular on the horizontal plane and the z-direction is vertical. The average host rock density is 2.9×10^3 kg.m^{-3}, UCS = 130 MPa and the rock mass condition is generally good (Q = 15).

4.1 Discuss the parameters that comprise the Hoek-Brown failure criterion and name two limitations to this theory. [4]

4.2 Calculate the m and s parameter values using the relations:

$$m = 10\, x\, e^{\frac{(RMR-100)}{14}} \quad and \quad s = e^{\frac{(RMR-100)}{9}}$$

[2]

4.3 Calculate the radial and tangential stresses in the shaft sidewall in the x-direction, as shown in the table. Draw a sketch to illustrate the scenario. Present your results in a table.

Depth into the sidewall, x-direction (m)	σ_{rr}	$\sigma_{\theta\theta}$
0.00		
0.50		
1.50		
2.00		

[14]

4.4 Using the parameters and results obtained in 4.2 and 4.3, estimate the depth of failure that might occur in the side-wall in the x-direction, based on the Hoek-Brown failure criterion (assume that the radial and tangential stresses are also principal stresses). Present your results in a table. [4]

4.5 What is the minimum length tendon that you would recommend to install to manage the zone of failure around the excavation? [1]

QUESTION 5 – ROCK TESTING (15)

5.1 Explain Heim's law [2]

5.2 The virgin or primitive state of stress is a function of several influencing components. Discuss. [4]

5.3 Briefly outline in a table the principles and applications of the following three methods of stress measurement:

- Strain cells
- Acoustic emission
- Jacking (flat jack)

. [9]

TOTAL MARKS: [100]

$$\sigma_{nn} = \sigma_{xx}\cos^2\theta + 2\tau_{xy}\sin\theta\cos\theta + \sigma_{yy}\sin^2\theta \quad \sigma'_{xx} = \sigma_{xx}\cos^2\theta + 2\tau_{xy}\sin\theta\cos\theta + \sigma_{yy}\sin^2\theta$$

$$\sigma_{mm} = \sigma_{xx}\sin^2\theta - 2\tau_{xy}\sin\theta\cos\theta + \sigma_{yy}\cos^2\theta \quad \sigma'_{yy} = \sigma_{xx}\sin^2\theta - 2\tau_{xy}\sin\theta\cos\theta + \sigma_{yy}\cos^2\theta$$

$$\tau_{nm} = \frac{1}{2}(\sigma_{yy} - \sigma_{xx})\sin 2\theta + \tau_{xy}\cos 2\theta \qquad \tau'_{xy} = \frac{1}{2}(\sigma_{yy} - \sigma_{xx})\sin 2\theta + \tau_{xy}\cos 2\theta$$

$$\tan 2\theta = \frac{2\tau_{xy}}{\sigma_{xx} - \sigma_{yy}} \quad \sigma_1 + \sigma_2 = \sigma_{xx} + \sigma_{yy}$$

$$\sigma_1 = \frac{1}{2}(\sigma_{xx} + \sigma_{yy}) + \frac{1}{2}\sqrt{(\sigma_{xx} - \sigma_{yy})^2 + 4\tau_{xy}^2} \quad \sigma'_{xx} + \sigma'_{yy} = \sigma_{xx} + \sigma_{yy}$$

$$\sigma_2 = \frac{1}{2}(\sigma_{xx} + \sigma_{yy}) - \frac{1}{2}\sqrt{(\sigma_{xx} - \sigma_{yy})^2 + 4\tau_{xy}^2} \quad \tau_{\max} = \frac{1}{2}\sqrt{(\sigma_{xx} - \sigma_{yy})^2 + 4\tau_{xy}^2}$$

$$\sigma_{nn} = \sigma_1\cos^2\theta + \sigma_2\sin^2\theta \quad \tau_{\max} = \frac{1}{2}(\sigma_1 - \sigma_2)$$

$$\sigma_{mm} = \sigma_1\sin^2\theta + \sigma_2\cos^2\theta$$

$$\sigma_{nn} = \frac{1}{2}(\sigma_1 + \sigma_2) + \frac{1}{2}(\sigma_1 - \sigma_2)\cos 2\theta \qquad \tau_{nm} = -\frac{1}{2}(\sigma_1 - \sigma_2)\sin 2\theta$$

$$\sigma_{mm} = \frac{1}{2}(\sigma_1 + \sigma_2) - \frac{1}{2}(\sigma_1 - \sigma_2)\cos 2\theta$$

$$\gamma_{xy} = \gamma_{yx} = 2\varepsilon_{xy} = 2\varepsilon_{yx}, \quad \gamma_{yz} = \gamma_{zy} = 2\varepsilon_{yz} = 2\varepsilon_{zy}, \quad \gamma_{zx} = \gamma_{xz} = 2\varepsilon_{zx} = 2\varepsilon_{xz}$$

$$\varepsilon_n = \varepsilon_{xx}\cos^2\theta + \gamma_{xy}\sin\theta\cos\theta + \varepsilon_{yy}\sin^2\theta \quad \varepsilon'_{xx} = \varepsilon_{xx}\cos^2\theta + \gamma_{xy}\sin\theta\cos\theta + \varepsilon_{yy}\sin^2\theta$$

$$\gamma_{nm} = (\varepsilon_{yy} - \varepsilon_{xx})\sin 2\theta + \gamma_{xy}\cos 2\theta \quad \varepsilon'_{yy} = \varepsilon_{xx}\sin^2\theta - \gamma_{xy}\sin\theta\cos\theta + \varepsilon_{yy}\cos^2\theta$$

$$\tan 2\theta = \frac{\gamma_{xy}}{\varepsilon_{xx} - \varepsilon_{yy}} \quad \varepsilon_1 + \varepsilon_2 = \varepsilon_{xx} + \varepsilon_{yy} \quad \gamma'_{xy} = (\varepsilon_{yy} - \varepsilon_{xx})\sin 2\theta + \gamma_{xy}\cos 2\theta$$

$$\varepsilon_1 = \frac{1}{2}(\varepsilon_{xx} + \varepsilon_{yy}) + \frac{1}{2}\sqrt{(\varepsilon_{xx} - \varepsilon_{yy})^2 + \gamma_{xy}^2} \quad \varepsilon'_{xx} + \varepsilon'_{yy} = \varepsilon_{xx} + \varepsilon_{yy}$$

$$\varepsilon_2 = \frac{1}{2}(\varepsilon_{xx} + \varepsilon_{yy}) - \frac{1}{2}\sqrt{(\varepsilon_{xx} - \varepsilon_{yy})^2 + \gamma_{xy}^2} \quad \gamma_{\max} = \sqrt{(\varepsilon_{xx} - \varepsilon_{yy})^2 + \gamma_{xy}^2}$$

$$\varepsilon_n = \varepsilon_1\cos^2\theta + \varepsilon_2\sin^2\theta \quad \gamma_{\max} = (\varepsilon_1 - \varepsilon_2)$$

$$\varepsilon_n = \frac{1}{2}(\varepsilon_1 + \varepsilon_2) + \frac{1}{2}(\varepsilon_1 - \varepsilon_2)\cos 2\theta \quad \varepsilon = \frac{\delta\ell}{\ell_o}$$

$$\gamma_{nm} = -(\varepsilon_1 - \varepsilon_2)\sin 2\theta$$

$$\sigma_{rr} = \sigma_{xx}\cos^2\theta + 2\tau_{xy}\sin\theta\cos\theta + \sigma_{yy}\sin^2\theta \quad \varepsilon_{rr} = \varepsilon_{xx}\cos^2\theta + \gamma_{xy}\sin\theta\cos\theta + \varepsilon_{yy}\sin^2\theta$$

$$\sigma_{\theta\theta} = \sigma_{xx}\sin^2\theta - 2\tau_{xy}\sin\theta\cos\theta + \sigma_{yy}\cos^2\theta \quad \varepsilon_{\theta\theta} = \varepsilon_{xx}\sin^2\theta - \gamma_{xy}\sin\theta\cos\theta + \varepsilon_{yy}\cos^2\theta$$

$$\tau_{r\theta} = \frac{1}{2}(\sigma_{yy} - \sigma_{xx})\sin 2\theta + \tau_{xy}\cos 2\theta \quad \gamma_{r\theta\theta} = (\varepsilon_{yy} - \varepsilon_{xx})\sin 2\theta + \gamma_{xy}\cos 2\theta$$

$$w = \frac{1}{2}(\sigma_1\varepsilon_1 + \sigma_2\varepsilon_2 + \sigma_3\varepsilon_3) \quad w = \frac{1}{2}(\sigma_{xx}\varepsilon_{xx} + \sigma_{yy}\varepsilon_{yy} + \sigma_{zz}\varepsilon_{zz} + \tau_{xy}\gamma_{xy} + \tau_{yz}\gamma_{yz} + \tau_{zx}\gamma_{zx})$$

$$Q = wV$$

$$\varepsilon_{1,2} = \frac{(\varepsilon_0 + \varepsilon_{90})}{2} \pm \frac{\sqrt{\left[\left(\varepsilon_0^2 - \varepsilon_{90}^2\right) + (2\varepsilon_{45} + \varepsilon_0 - \varepsilon_{90})^2\right]}}{2}$$

$$\tan 2\theta = \frac{(2\varepsilon_{45} - \varepsilon_0 - \varepsilon_{90})}{(\varepsilon_0 - \varepsilon_{90})}$$

$$\varepsilon_{1,2} = \frac{(\varepsilon_0 + \varepsilon_{60} + \varepsilon_{120})}{3} \pm \left(\frac{2}{3}\right) \sqrt{\left[\varepsilon_0^2 + \varepsilon_{60}^2 + \varepsilon_{120}^2 - (\varepsilon_0\varepsilon_{60} + \varepsilon_{60}\varepsilon_{120} + \varepsilon_{120}\varepsilon_0)\right]}$$

$$\tan 2\theta = \left(\sqrt{3}\right) \frac{(\varepsilon_{60} - \varepsilon_{120})}{(2\varepsilon_0 - \varepsilon_{60} - \varepsilon_{120})}$$

$$\sigma'_{xx} = \sigma_{xx}\lambda_{xx}^2 + \sigma_{yy}\lambda_{xy}^2 + \sigma_{zz}\lambda_{xz}^2 + 2\tau_{xy}\lambda_{xx}\lambda_{xy} + 2\tau_{yz}\lambda_{xy}\lambda_{xz} + 2\tau_{zx}\lambda_{xz}\lambda_{xx}$$

$$\sigma'_{yy} = \sigma_{xx}\lambda_{yx}^2 + \sigma_{yy}\lambda_{yy}^2 + \sigma_{zz}\lambda_{yz}^2 + 2\tau_{xy}\lambda_{yx}\lambda_{yy} + 2\tau_{yz}\lambda_{yy}\lambda_{yz} + 2\tau_{zx}\lambda_{yz}\lambda_{yx}$$

$$\sigma'_{zz} = \sigma_{xx}\lambda_{zx}^2 + \sigma_{yy}\lambda_{zy}^2 + \sigma_{zz}\lambda_{zz}^2 + 2\tau_{xy}\lambda_{zx}\lambda_{zy} + 2\tau_{yz}\lambda_{zy}\lambda_{zz} + 2\tau_{zx}\lambda_{zz}\lambda_{zx}$$

$$\varepsilon_{xx} = \frac{1}{E}\left\{\sigma_{xx} - \nu(\sigma_{yy} + \sigma_{zz})\right\} \quad \gamma_{xy} = \frac{1}{G}\tau_{xy} \quad \varepsilon_{xy} = \frac{1}{2G}\tau_{xy} \quad G = \frac{E}{2(1+\nu)}$$

$$\varepsilon_{yy} = \frac{1}{E}\left\{\sigma_{yy} - \nu(\sigma_{xx} + \sigma_{zz})\right\} \quad \gamma_{yz} = \frac{1}{G}\tau_{yz} \quad \varepsilon_{yz} = \frac{1}{2G}\tau_{yz} \quad K = \frac{E}{3(1 - 2\nu)}$$

$$\varepsilon_{zz} = \frac{1}{E}\left\{\sigma_{zz} - \nu(\sigma_{xx} + \sigma_{yy})\right\} \quad \gamma_{zx} = \frac{1}{G}\tau_{zx} \quad \varepsilon_{zx} = \frac{1}{2G}\tau_{zx}$$

$$\sigma_{xx} = \lambda\Delta + 2G\varepsilon_{xx} \quad \tau_{xy} = G\gamma_{xy} \quad \tau_{xy} = 2G\varepsilon_{xy} \quad \Delta = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}$$

$$\sigma_{yy} = \lambda\Delta + 2G\varepsilon_{yy} \quad \tau_{yz} = G\gamma_{yz} \quad \tau_{yz} = 2G\varepsilon_{yz} \quad \lambda = \frac{E\nu}{(1+\nu)(1-2\nu)}$$

$$\sigma_{zz} = \lambda\Delta + 2G\varepsilon_{zz} \quad \tau_{zx} = G\gamma_{zx} \quad \tau_{zx} = 2G\varepsilon_{zx}$$

$$\sigma_{zz} = 0 \quad \varepsilon_{zz} = -\frac{\nu}{E}(\sigma_{xx} + \sigma_{yy})$$

$$\varepsilon_{xx} = \frac{1}{E}(\sigma_{xx} - \nu\sigma_{yy}) \quad \gamma_{xy} = \frac{1}{G}\tau_{xy} \quad \sigma_{xx} = \frac{E}{1-\nu^2}(\varepsilon_{xx} + \nu\varepsilon_{yy}) \quad \tau_{xy} = G\gamma_{xy}$$

$$\varepsilon_{yy} = \frac{1}{E}(\sigma_{yy} - \nu\sigma_{xx}) \quad \sigma_{yy} = \frac{E}{1-\nu^2}(\varepsilon_{yy} + \nu\varepsilon_{xx})$$

$$\varepsilon_{zz} = 0 \quad \sigma_{zz} = \nu(\sigma_{xx} + \sigma_{yy})$$

$$\varepsilon_{xx} = \frac{1}{E}\left\{(1-\nu^2)\sigma_{xx} - \nu(1+\nu)\sigma_{yy}\right\}$$

$$\varepsilon_{yy} = \frac{1}{E}\left\{(1-\nu^2)\sigma_{yy} - \nu(1+\nu)\sigma_{xx}\right\}$$

$$q = \rho g H \quad \sigma_v = q \quad \sigma_h = kq$$

$$\sigma_{rr} = \frac{1}{2}q(1+k)\left(1 - \frac{R^2}{r^2}\right) - \frac{1}{2}q(1-k)\left(1 - \frac{4R^2}{r^2} + \frac{3R^4}{r^4}\right)\cos 2\theta$$

$$\sigma_{\theta\theta} = \frac{1}{2}q(1+k)\left(1 + \frac{R^2}{r^2}\right) + \frac{1}{2}q(1-k)\left(1 + \frac{3R^4}{r^4}\right)\cos 2\theta$$

$$\tau_{r\theta} = \frac{1}{2}q(1-k)\left(1 + \frac{2R^2}{r^2} - \frac{3R^4}{r^4}\right)\sin 2\theta$$

$$\sigma_{rr} = q\left(1 - \frac{R^2}{r^2}\right) \quad \sigma_{\theta\theta} = q\left(1 + \frac{R^2}{r^2}\right) \quad \tau_{r\theta} = 0 \quad \sigma_{zz} = 2\nu q$$

$$u = \frac{(1+\nu)}{E}q\left\{(1-2\nu)r + \frac{R^2}{r}\right\} \quad v = 0$$

$$s_z = \frac{2(1-\nu)q}{G}\sqrt{\ell^2 - x^2} \qquad \ell_c = \frac{s_m G}{2(1-\nu)q}$$

$$\ell < \ell_c \quad ERR = \frac{\Delta U_m}{\Delta A} = \frac{\pi(1-\nu)\ell q^2}{2G} \qquad \ell = \ell_c \quad ERR = \frac{\Delta U_m}{\Delta A} = \frac{\pi}{4} s_m q$$

$$\ell > \ell_c \quad ERR = \frac{\Delta U_m}{\Delta A} = \frac{\pi}{4} s_m q \left(\frac{1-(1-\ell_c/\ell)^{1,27}}{\ell_c/\ell} \right) \qquad \ell \to \infty \quad ERR = \frac{\Delta U_m}{\Delta A} = s_m q$$

$$\tau = c + \mu\sigma \qquad \mu = \tan\phi \qquad \sigma_1 = \sigma_c + \tan\psi\,\sigma_3$$

$$\tan\psi = \frac{1+\sin\phi}{1-\sin\phi} \qquad \sigma_c = \frac{2c\cos\phi}{1-\sin\phi} \qquad \phi = \operatorname{asin}\left(\frac{\tan\psi - 1}{\tan\psi + 1}\right) \qquad c = \frac{\sigma_c}{2\sqrt{\tan\psi}}$$

$$Q = \frac{RQD}{J_n}\frac{J_r}{J_a}\frac{J_w}{SRF} \qquad RMR = 9\log_e Q + 44$$

$$\sigma_1 = \sigma_3 + \sigma_{ci}\left(m_b\frac{\sigma_3}{\sigma_{ci}} + s\right)^a \qquad \sigma_1 = \sigma_3 + \sigma_{ci}\sqrt{m_i\frac{\sigma_3}{\sigma_{ci}} + 1}$$

$$GSI > 25 \quad GSI = RMR_{76} \qquad GSI = RMR_{89} - 5$$

$$GSI < 25 \quad Q' = \frac{\mathrm{RQD}}{\mathrm{J_n}}\frac{J_r}{J_a} \qquad GSI = 9\log_e Q' + 44$$

$$m_b = m_i \exp\left(\frac{GSI-100}{28}\right)$$

$$GSI > 25 \quad s = \exp\left(\frac{GSI-100}{9}\right) \qquad a = \frac{1}{2} \qquad \sigma_1 = \sigma_3 + \sigma_{ci}\sqrt{m_b\frac{\sigma_3}{\sigma_{ci}} + s}$$

$$\sigma_{tm} = \frac{\sigma_{ci}}{2}\left(m_b - \sqrt{m_b^2 + 4s}\right) \qquad \sigma_{cm} = \sigma_{ci}\sqrt{s}$$

$$GSI < 25 \quad s = 0 \qquad a = 0.65 - \frac{GSI}{200} \qquad \sigma_1 = \sigma_3 + \sigma_{ci}\left(m_b\frac{\sigma_3}{\sigma_{ci}}\right)^{0,65-\frac{GSI}{200}}$$

$$\sigma_{tm} = 0 \qquad \sigma_{cm} = 0$$

$$\sigma_{ci} > 100\ \mathrm{MPa} \qquad \mathrm{E_m\,(GPa)} = 10^{\left(\frac{\mathrm{GSI-10}}{40}\right)}$$

$$\sigma_{ci} < 100\ \mathrm{MPa} \qquad \mathrm{E_m\,(GPa)} = \sqrt{\frac{\sigma_{\mathrm{ci}}\,(MPa)}{100(MPa)}}\,10^{\left(\frac{\mathrm{GSI-10}}{40}\right)}$$

$$\tau = \sigma_n \tan\left[\phi_a + JRC\log_{10}\left(\frac{JCS}{\sigma_n}\right)\right]$$

$$\tau_{strength} = \sigma_n \tan\left[JRC\log_{10}\left(\frac{JCS}{\sigma_n}\right) + \varphi_\gamma\right]$$

$$q = 0.025H \quad MPa \quad H[m] \qquad \sigma_v = \rho g h \qquad \sigma_h = k\sigma_v$$

$$e = 1 - \frac{w^2}{C^2} \qquad C = w + B \qquad r = \frac{h}{M}\left(1 - \frac{w^2}{C^2}\right) \qquad h_e = h\left(1 - \frac{w^2}{C^2}\right) \qquad h_e = he$$

$$\sigma_p = \frac{q}{1-e} \qquad \sigma_p = 0.025H\,\frac{(w+B)^2}{w^2} \quad MPa \qquad R = \frac{w}{h}$$

$R < 5$

$$\sigma_s = 7.2\,\frac{w^{0.46}}{h^{0.66}} \quad MPa \qquad Fs = \frac{\sigma_s}{\sigma_p} \qquad Fs = 288\,\frac{w^{2.46}}{Hh^{0.66}(w+B)^2}$$

$R \geq 5$

$$\sigma_s = 7.2\,\frac{R_o^{0.5933}}{V^{0.0667}}\left\{\frac{0.5933}{\varepsilon}\left[\left(\frac{R}{R_o}\right)^{\varepsilon} - 1\right] + 1\right\} \quad MPa$$

$$V = w^2 h \qquad R_o = 5 \qquad \varepsilon = 2.5$$

$$\sigma_s = \frac{0.07942}{(w^2 h)^{0.0667}}\left(R^{2.5} + 179.65\right) \quad MPa$$

$$Fs = \frac{\sigma_s}{\sigma_p} \qquad Fs = \frac{3.1768 w^{1.8666}}{H(w+B)^2 h^{0.0667}}\left\{\left(\frac{w}{h}\right)^{2.5} + 179.65\right\}$$

$$e = 1 - \frac{w_1 w_2}{C_1 C_2} \qquad w_e = \frac{4w_1 w_2}{2w_1 + 2w_2}$$

$$\sigma_p = 0.025H\,\frac{C_1 C_2}{w_1 w_2} \quad MPa$$

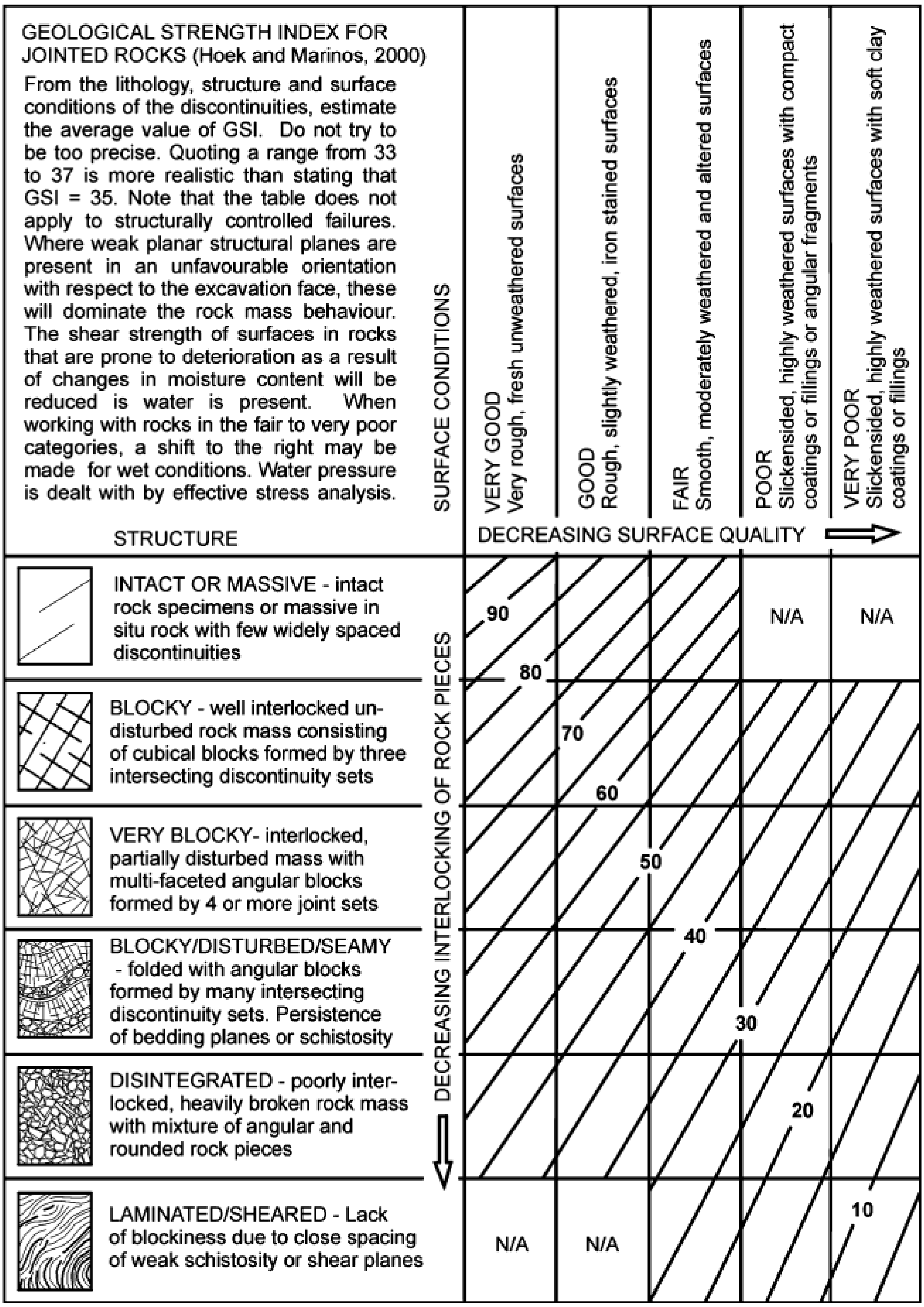
$$R = \frac{E}{4(1-\nu^2)}\,\frac{s_m}{(\sigma_{cr} - q)} \qquad R = 0.28\,\frac{s_m}{\varepsilon_{cr}}$$

$$v_p = \sqrt{\frac{\lambda + 2G}{\rho}} \qquad v_s = \sqrt{\frac{G}{\rho}}$$

$$ESS = |\tau| - [\sigma_n \tan(\theta) + C_0]$$

$$\sigma_1 = \sigma_3 + \sqrt{m\sigma_c\sigma_3 + s\sigma_c^2}$$

$$\tau_{strength} = \sigma_n \tan\left[JRC \log_{10}\left(\frac{JCS}{\sigma_n}\right) + \varphi_\gamma\right]$$


GEOLOGICAL STRENGTH INDEX FOR JOINTED ROCKS (Hoek and Marinos, 2000)
From the lithology, structure and surface conditions of the discontinuities, estimate the average value of GSI. Do not try to be too precise. Quoting a range from 33 to 37 is more realistic than stating that GSI = 35. Note that the table does not apply to structurally controlled failures. Where weak planar structural planes are present in an unfavourable orientation with respect to the excavation face, these will dominate the rock mass behaviour. The shear strength of surfaces in rocks that are prone to deterioration as a result of changes in moisture content will be reduced is water is present. When working with rocks in the fair to very poor categories, a shift to the right may be made for wet conditions. Water pressure is dealt with by effective stress analysis.
SURFACE CONDITIONS
VERY GOOD Very rough, fresh unweathered surfaces
GOOD Rough, slightly weathered, iron stained surfaces
FAIR Smooth, moderately weathered and altered surfaces
POOR Slickensided, highly weathered surfaces with compact coatings or fillings or angular fragments
VERY POOR Slickensided, highly weathered surfaces with soft clay coatings or fillings
STRUCTURE
DECREASING SURFACE QUALITY
INTACT OR MASSIVE - intact rock specimens or massive in situ rock with few widely spaced discontinuities
BLOCKY - well interlocked undisturbed rock mass consisting of cubical blocks formed by three intersecting discontinuity sets
VERY BLOCKY- interlocked, partially disturbed mass with multi-faceted angular blocks formed by 4 or more joint sets
BLOCKY/DISTURBED/SEAMY - folded with angular blocks formed by many intersecting discontinuity sets. Persistence of bedding planes or schistosity
DISINTEGRATED - poorly interlocked, heavily broken rock mass with mixture of angular and rounded rock pieces
LAMINATED/SHEARED - Lack of blockiness due to close spacing of weak schistosity or shear planes
DECREASING INTERLOCKING OF ROCK PIECES
90
80
70
60
50
40
30
20
10
N/A
N/A
N/A
N/A

ID NUMBER: ______________________________

SUBJECT CODE: ______________________________

DATE: ______________________________

Mark each answer with a X as shown in the example.

Question no.	Answer choice							
EXAMPLE	A		B	X	C		D	
1.1	A		B		C		D	
1.2	A		B		C		D	
1.3	A		B		C		D	
1.4	A		B		C		D	
1.5	A		B		C		D	
1.6	A		B		C		D	
1.7	A		B		C		D	
1.8	A		B		C		D	
1.9	A		B		C		D	
1.10	A		B		C		D	
1.11	A		B		C		D	
1.12	A		B		C		D	
1.13	A		B		C		D	
1.14	A		B		C		D	
1.15	A		B		C		D	
1.16	A		B		C		D	
1.17	A		B		C		D	
1.18	A		B		C		D	
1.19	A		B		C		D	
1.20	A		B		C		D	
1.21	A		B		C		D	
1.22	A		B		C		D	
1.23	A		B		C		D	
1.24	A		B		C		D	
1.25	A		B		C		D	