CHAMBER OF MINES OF SOUTH AFRICA

EXAMINATION PAPER

SUBJECT: ROCK MACHANICS CERTIFICATE PART 1: THEORY **SUBJECT CODE:** COMRMC1 **EXAMINATION DATE:** OCTOBER 2012 **TIME:**3 Hours	**EXAMINER:** JA MARITZ **MODERATOR:** M HANDLEY **TOTAL MARKS:** 100 **PASS MARK:** 60%

NUMBER OF PAGES:18 (*including Cover and Formulae Sheets*)

SPECIAL REQUIREMENTS:

1. **Answer Questions 1 to 5.**
2. **Answer EITHER Question 6 or Question 7. <u>If both 6 and 7 are answered, NO MARKS WILL BE GIVEN TO EITHER ONE.</u>**
3. Remove Question 1 from the paper and submit with your answer book. Remember to write your ID Number on the space provided.
4. **Question 1 will be marked negative. <u>Wrong answer will be allocated a -1 mark and a correct answer +1</u>**.
5. Start each question on a new page.
6. References other than those provided are not permitted.
7. Hand-held electronic calculators may be used.
8. Write your **examination 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.

9. **<u>Write in ink on the RIGHT HAND SIDE of the paper only (only the right hand pages will be marked).</u>**
10. Show all calculations on which your answers are based.
11. Illustrate your answers by sketches or diagrams wherever possible.
12. In answering these questions, full advantage should be taken wherever necessary of your practical experience as well as of the data given.
13. Answers must be given to an accuracy that is typical of practical conditions.

QUESTION 1 – MULTI CHOICE (SUBMIT WITH EXAM BOOK) (10)

ID:			
1.1 For the trigonometry notations, which of the following would be positive in the fourth Quadrant?	Sin	A	
	Cos	B	X
	Tan	C	
1.2 Permanent deformation will not occur in which region along a Stress vs. Strain curve?	Elastic	A	X
	Plastic	B	
	Strain hardening	C	
	Strain softening	D	
1.3 A 100 kN force is acting on 2 surfaces. The first surface is square with sides 10cm and the second circular with radius 5cm. Which one experiences the highest stress?	Square surface	A	
	Circular surface	B	X
1.4 15 MPa expressed as Pa	15×10^{-3} Pa	A	
	1500×10^{3} Pa	B	
	1.5×10^{6} Pa	C	X
	150×10^{4} Pa	D	
1.5 Which failure model is presented by $\mathbf{F_s = C_o + \mu F_n}$	Griffith	A	
	Coulomb	B	X
	Hoek-Brown	C	
	Stacey	D	
1.6 Which of the following does not influence joint strength?	Joint roughness	A	
	Water	B	
	Joint length	C	X
	Joint friction angle	D	
1.7 At 1500 m below surface, which theory would result in the highest horizontal stress?	Heim's Rule	A	X
	Rigid Confinement	B	
	Hooke's Law	C	
	Young's Modulus	D	
1.8 What is measured by the acoustic emission (AE) method	P wave velocity	A	
	Sound waves	B	X
	In-situ stress	C	
	Radiation	D	
1.9 As the volume of the sample increases, the strength …	Decrease linearly	A	
	Decrease exponentially	B	X
	Increase linearly	C	
	Increase exponentially	D	
1.10 The MRMR value was 72. After adjustments of 90% (weathering), 70% (joint orientation), 100% (mining induced stresses) and 94% (blasting), the adjusted MRMR is	75.6	A	
	27.3	B	
	121.6	C	
	42.6	D	X

QUESTION 2 – STRESS AND STRAIN (20)

2.1 A 0-60-120 strain rosette was used to determine the in-situ stresses around a particular excavation. If the recorded strains are ε_0=2.8x10^{-4},ε_{60}= 1.2x10^{-4} and ε_{120}=1.8x10^{-4}, use the following equations to...

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

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

Assume an axis where X is horizontal (+ to the right) and Y vertical (+ upwards)

All data has been corrected for borehole end-effect

2.1.1 Calculate the magnitude and direction of the principle strains. [5]

ε_1 = 2.9 x 10^{-4} @ -11°
ε_2 = 1.0 x 10^{-4} @ 79°

2.1.2 Given a Young's Modulus of 70 GPa, determine the magnitude of the principle stresses from the strain values obtained in 2.1 above. [2]

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

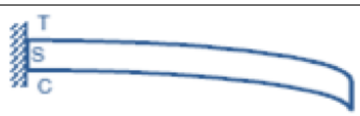
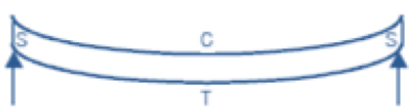
σ_1 = 22.3 MPa
σ_2 = 11.5 MPa

2.1.3 Calculate the normal and shear stresses acting on a 71° dipping fault if the calculated conditions [5]

Angle is 71°, hence the rotation will be θ = 30°

σ_{nn} = 16.8 MPa
σ_{mm} = 10.2 MPa
τ_{nm} = -5.6 MPa

2.2 Name **and** sketch the commonly known three (3) beams as encountered by Rock Engineers in the underground environment [6]

Build-in	Cantilever	Freely supported
		

2.3 In all three beams, the stress (tensile and compressive) and maximum deflection are driven by the length and thickness of the beam. Comment on the increase in both these parameters (tensile and compressive stress) given a doubling on the length from 2m to 4m of a cantilever beam. Also comment on in the influence this would have on the management of the local stability [2]

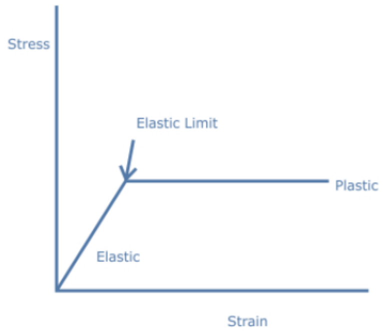
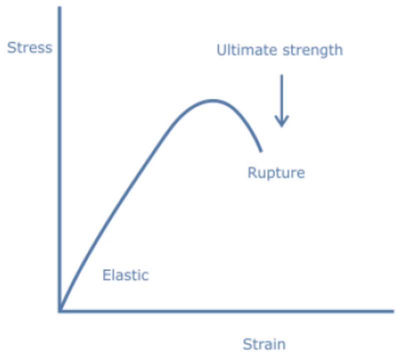
Stress $= F(\frac{\gamma L^2}{t})$

Deflection $= F(\frac{\gamma L^4}{Et^2})$

A doubling in the length will increase both parameters. Higher deflection would result in higher tension on bolts (more bolts or stronger bolts required). Higher stresses could result in the beam actually crushing or shearing the mass.

QUESTION 3 – CONSTITUTION RELATIONSHIPS (20)

3.1 Sketch and discuss the difference between Ductile and Brittle behaviour. [6]

Ductile	Brittle
 (2)	 (2)
Large amounts of plastic deformation before rupturing (1)	Elastic behaviour followed by rupturing (1)

3.2 Tests were conducted on the in-situ stress at a working place as listed below. Assuming a **plane stress** condition on the XY plane, calculate the normal strains on this plane. [3]

σ_{xx} = 60 MPa
σ_{yy} = 42 MPa
σ_{zz} = 32 MPa
E = 55 GPa
υ = 0.2

For PLANE STRESS in XY assume $\sigma_{zz} = 0$ (1)

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

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

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

$\varepsilon_{xx} = 9.382 \times 10^{-4}$ (½)
$\varepsilon_{yy} = 5.455 \times 10^{-4}$ (½)
$\varepsilon_{zz} = -3.709 \times 10^{-4}$ (1)

3.3 Define the following: [5]

3.3.1 Strain energy. (2)

Strain energy is the work done (1) in deforming (1) a body.

3.3.2 Dilation. (1)

Dilation is defined as the quotient of the change in volume to the original volume of a body submitted to stress. (Volumetric strain)

3.3.3 Dilatation. (1)

Referred to when the radial strain deviates from linearity close to and after the peak strength point of a sample under stress.

3.3.4 Creep. (1)

Creep is the tendency of a solid material to slowly move or deform permanently under the influence of stress. It occurs as a result of long term exposure to high levels of stress that are below the yield strength of the material.

3.4 A 2t granite block (Relative density of 2.9) is subjected to the following stress environment. (***σ_1 = 82 MPa, σ_2 = 41 MPa, σ_3 = 39 MPa***). Assuming a Young's Modulus of 70 GPa and υ of 0.25, calculate the strain energy within the block. [6]

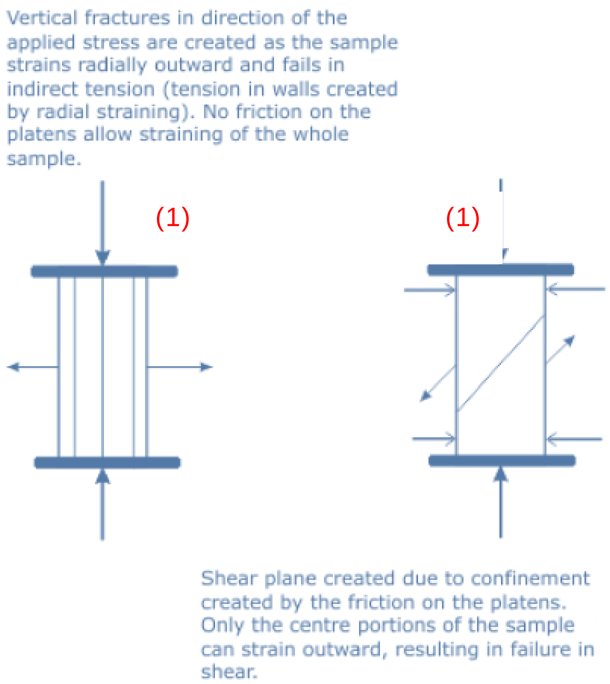
$$\varepsilon_{xx} = \frac{1}{E}\{\sigma_{xx} - \nu(\sigma_{yy} + \sigma_{zz})\}$$
$$\varepsilon_{yy} = \frac{1}{E}\{\sigma_{yy} - \nu(\sigma_{xx} + \sigma_{zz})\}$$
$$\varepsilon_{zz} = \frac{1}{E}\{\sigma_{zz} - \nu(\sigma_{xx} + \sigma_{yy})\}$$

Volume = 2/2.9 = 0.690 m^3 (1)
$\sigma = \varepsilon E$, hence
$\varepsilon_1 = 0.89 \times 10^{-3}$ (1)
$\varepsilon_2 = 0.15 \times 10^{-3}$ (1)
$\varepsilon_3 = 0.19 \times 10^{-3}$ (1)

W = ½ ($\sigma_1\varepsilon_1 + \sigma_2\varepsilon_2 + \sigma_3\varepsilon_3$) = 41 761 J/$m^3$ (1)
Q = Vol x W = 28.8 kJ (1)

QUESTION 4 – ROCK PROPERTIES (20)

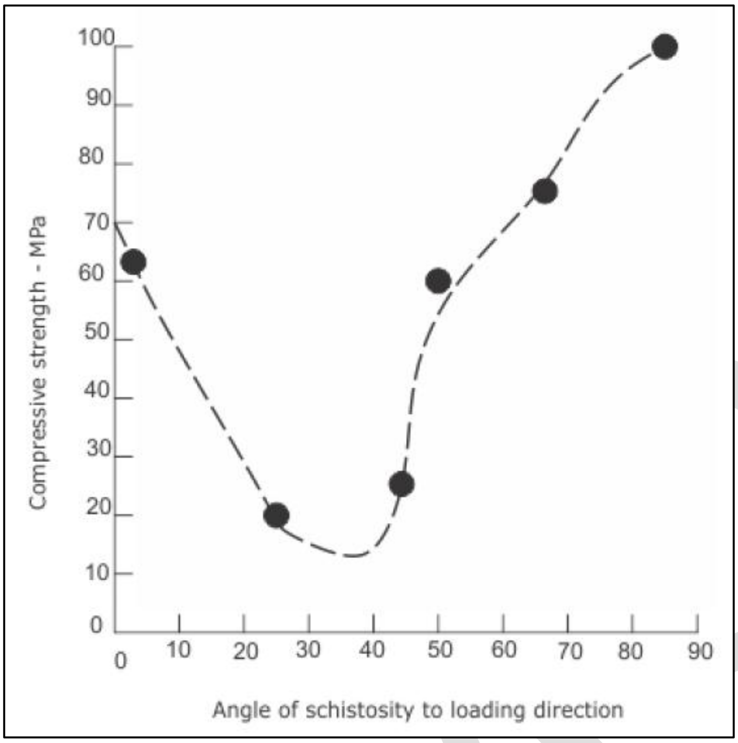
4.1 When a rock sample is subjected to uniaxial compression, failure could occur. Describe and explain the possible modes of failure. [8]



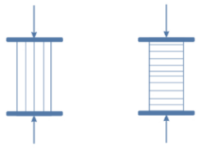
Indirect tension (1): If the platens are lubricated, confinement on the ends of the sample is nullified and the sample is allowed to radially strain along the whole length (1). Under these conditions, a specimen splits axially and near vertical fractures is formed (1). The 'extension' fractures relates to the fracturing seen on tunnel sidewalls, pillars and abutments in stress environments

Shear (1): When **confinement** (1)of the sample ends, one or more inclined 'shear' fractures(1) planes are created and the sample fails by shear along these planes.

4.2 If presented with the following graph, write a short paragraph, including pictures, on how you would explain this to the rookie Geologist helping you with testing of samples for their compressive strength. [2]



As the angle between the direction of the force and the lamination tend to 0 or 90° the strength increases (1). At 45°, the sample will be at its weakest (1).



4.3 You are preparing to setup a numerical model in order to test stability of a geological discontinuity in close proximity of a current high grade stoping face. What failure criteria (include formulae) would you base your findings on and what parameters (calculated values) would you retrieve from the model? (4)

For geological features, the Mohr-Coulomb (1) would be applicable $\tau = C_o + \mu\sigma_n$ (1). Use σ_n (1) to determine maximum shear allowed on contact. Use τ (1) from model to compare against criteria for stability

4.4 The feature as modelled in 4.3 was found to have water present. How would this effect the strength? (2)

Confinement or normal stress clamping the joint, increasing the friction, is reduced (1).

Assist in lubricating the joint surface (1).

4.5 Five cylindrical samples of rock are tested in compression in a rock testing machine under tri-axial loading conditions with the results presented below.

Confining stress (MPa)	*Peak strength (MPa)*
0	200

Confining stress (MPa)	*Peak strength (MPa)*
5	228
10	264
15	300
20	315

If one of the samples had Hoek-Brown m and s values of 15 and 1.0 respectively, what would the peak strength be if the confinement were 20 MPa? Comment on the comparison with the test results? (4)

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

$= 20 + \sqrt{15 \times 200 \times 20 + 1 \times 200^2}$ (1)

$= 336\ MPa$ (1)

336 vs 315 MPa. Value is slightly higher (1). Slight overestimation of intact rock strength (1).

QUESTION 5 – STRESS IN ROCK & ROCKMASSES (20)

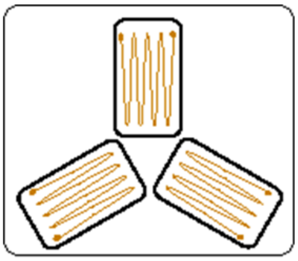
5.1 According to Heim's Rule, for a rockmass with a density of 2750 kg/m^3 at 1500 m below surface, would have a vertical stress of 41.25 MPa. Rigid Confinement would estimate the horizontal stress to be 10.31 MPa for a mass with Poisson's ratio of 0.2. How could it be that in-situ stress measurements seldom yield the same values? [3]

Heim's rule assumes visco-plastic material flow where shear stress becomes zero. Not the case in mining rockmass. (1)

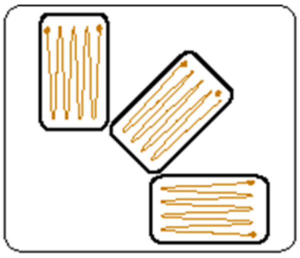
RCT assumes horizontal build-up due to Poisson's ratio only and excludes residual stress, tectonics, topography, erosion, etc. (1)

Some other attempts to calculate the stress, measurement remain the best option to determine the actual stress state. (1)

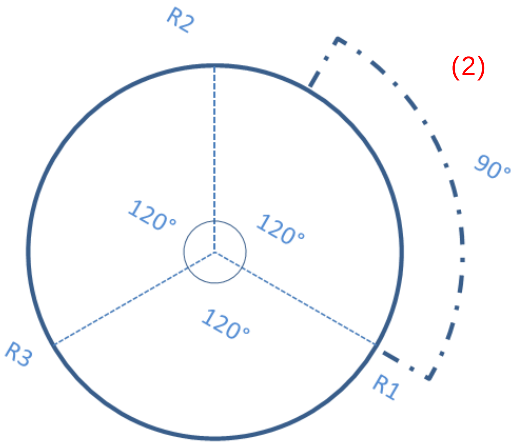
5.2 Two strain gauge rosette configurations are generally used in practice. Sketch the two configurations and comment on how the instrument is used to determine in-situ stress levels **Note: Do not comment on the method of over coring, discuss the actual working of the strain gauge.** [5]

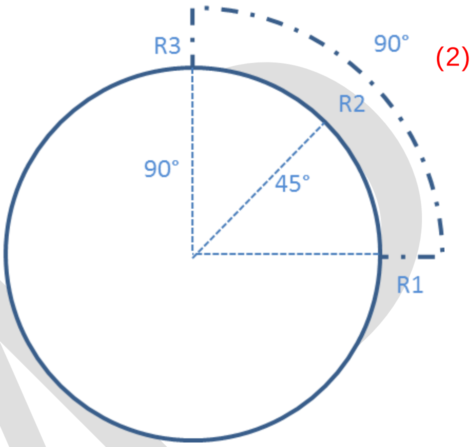


0°-60°-120° Delta Rosette



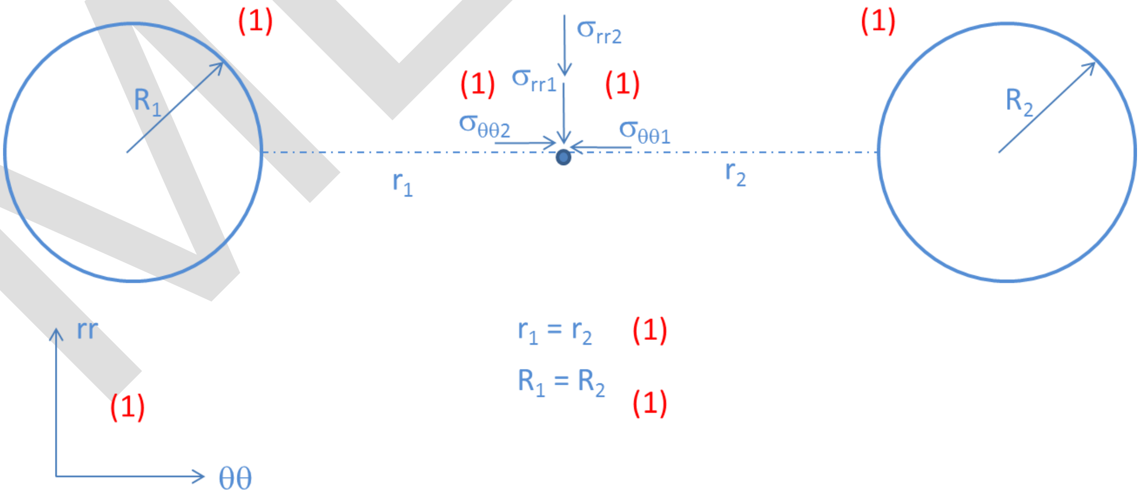
0°-45°-90° Retangular Rosette





Its principle is based on fact that the resistance of a wire increases with increasing strain and decreases with decreasing strain (1)

5.3 The Kirsch equation to determine tangential and radial stresses on a circular excavation are a popular method to estimate failure points. Provide the sketch and equation for calculating the resultant for $\sigma_{\theta\theta}$ and σ_{rr} at the centre of the middling for two identical sized horizontal bored tunnels? Assume θ=0° is horizontal. [10]



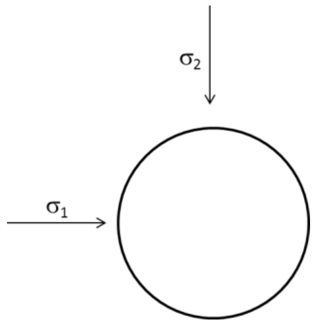
~ Resultant $\sigma_{\theta\theta}{}^{R}$ = $\sigma_{\theta\theta2}$-$\sigma_{\theta\theta1}$ (½)

Resultant $\sigma_{rr}{}^{R}$ = σ_{rr1}+σ_{rr2} (½)

Therefore $\sigma_{\theta\theta}{}^{R}$ = 0 and $\sigma_{rr}{}^{R}$ = $(q_h + q_v)(1 - t^2) + 2pt^2 + (q_h - q_v)(1 - 4t^2 + 3t^4)Cos2\theta$ (2)

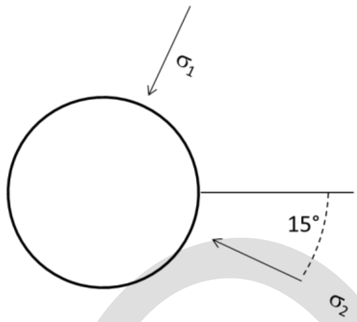
Or $\sigma_{rr}{}^{R}$ = $2(\frac{1}{2}(q_h + q_v)(1 - t^2) + pt^2 + \frac{1}{2}(q_h - q_v)(1 - 4t^2 + 3t^4)Cos2\theta)$

5.4 What would be the value of θ in the following two scenarios when used in the Kirsch equation for calculating the respective stresses in the hangingwall? [2]



a.

θ=0° (1)



b.

θ=105° (1)

QUESTION 6 – ROCKMASS PROPERTIES *(10)*

6.1 Name and briefly discuss five (5) factors that plays a role in the strength of a rock mass. [10]

Any 5 (1 each) with discussion (1 each)
Volume
Joint strength
Joint frequency
Joint length
Intact rock strength
Groundwater

QUESTION 7 – FAILURE CRITERIA *(10)*

7.1 Identify, describe and explain the limitations of the Hoek and Brown criterion. [10]

The Hoek-Brown criterion does not make any assumptions about the failure mechanisms that are responsible for the yield of rock under stress. It is a fairly general criterion that can be used for most materials ranging from soils to hard rock in most stress conditions.

The points listed below explain the limitations of the Hoek-Brown criterion:

- It is a purely empirical criterion. It ignores the effect of the intermediate principal stress on the rock strength and assumes ($\sigma_2 = \sigma_3$) and includes plain strain situations. This may result into 30-50% errors in results.
- The Hoek-Brown criteria's formula fits the laboratory low-stress regimes reasonably well, but sometimes tends to over-estimate strengths at high confining stresses. Many hard rocks show very little downward curvature at high confining stresses ($\sigma_3 > 0.5\ \sigma_c$).
- Use of the suggested (1982) tabulations of 'm' and 's' values can lead to greatly overstated 'downgrading' of the in-situ strength. Practitioners using the Hoek-Brown criterion should carry out their own back-analyses of in-situ strengths and corresponding estimates of appropriate 'm' and 's' values, wherever possible.
- Hoek and Brown have recognized that their criterion is applicable only to either
  - intact rock, or
  - in-situ rock that is transected by many closely-spaced joint sets of multiple angles or rock which is otherwise heavily and isotropically damaged. In-situ rock which is transected by, for example, just one set of joints is anisotropic and cannot be described by theHoek-Brown criterion - other techniques in which the discrete joints are directly modeled, need to be used under these

- END -

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$Q = wV$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$R < 5$

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

$R \geq 5$

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

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

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

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

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

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

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

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

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

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

$S_{m,he} = 0.39h\left(\frac{W}{H}\right)^{0.32}$ $S_{m,pf} = 0.1h_e$, H>80m $S_{m,pf} = 0.8h_e$, H<80m

$h_e = eh$

$\varepsilon_{m+} = 4.2S_m + 1.7$ $\varepsilon_{m-} = -9.1S_m - 2.8$ $T_m = 21.6S_m + 7$

$$L_c = 2T\sqrt{k + \frac{\beta}{D}} + 2(H - D)\tan\phi$$

$$\beta = \frac{1.53}{\gamma_m} - 0.8$$

$$\gamma_m = 0.025\frac{D-T}{D} + 0.03\frac{T}{D}$$

$\sigma_t = \frac{qB^2}{2t_s^{\ 2}}$ $q = \rho g(t_s + t_w)$ $\sigma = \frac{3qL^2}{t^2}$ $\eta = \frac{qL^4}{32Et^3}$ $l_a = \frac{\gamma S_b^2 t_w}{\pi d_h \tau}$

$$w_e = \frac{4A}{c}$$

$\sigma_{squat} = k\frac{R_o^b}{V^a}\left\{\frac{b}{\varepsilon}\left[\left(\frac{R}{R_o}\right)^{\varepsilon} - 1\right] + 1\right\}$ $Strength_{Squat} = \frac{0.0786}{V^{0,0667}}\left\{R^{2,5} + 181,6\right\}$

$$SF = \frac{Strength}{Load} \qquad Strength = 7.2\frac{w^{0.46}}{h^{0.66}}$$

$$SF_{CM} = SF\left(1+\frac{0,6}{w}\right)^{2,46} \qquad Load = \frac{\left[.025\left(H-T\right)+.030T\right]C_1C_2}{w_1w_2}$$

$$SF^{//} = SF\left(\frac{w-\Delta w}{w}\right)^{2,46} \qquad SF^{/} = SF\left(\frac{h}{h+\Delta h}\right)^{0,66}$$

$$e\% = \left[100\frac{h_m}{h_s}\left(1-\frac{w^2}{C^2}\right)\right]\frac{W}{W+P}$$

$$\sigma_t = \frac{qB^2}{2t_s^{\ 2}}, \quad q = \rho g(t_s + t_w) \qquad t_{sb} = \frac{Fk\rho gB^2}{2\sigma_t}$$

$$s = 1.414t_l\sqrt{\frac{\sigma_t}{Fq_c}}, \quad q_c = q_l + \frac{q_uE_l + q_lE_u}{E_l + E_u} \qquad F_b = \frac{s}{\tan\phi}\left[\frac{3\rho gkB_s}{4} - \sigma_r d_h\right]$$

$$l_a = \frac{\rho gs^2t_w + 0.05}{\pi d_h\tau_c} \qquad l_a = \frac{Ft}{\pi d_h\tau_c}, \quad w_b = \rho gkt_{sb}s^2, \quad F_t = F_b + w_b$$

$$\sigma_{ts} = \frac{4w_b}{\pi d^2}, \quad w_b = \rho gs^2t_w \qquad \sigma_s = \frac{4F_t}{\pi d_s^2}$$