CHAMBER OF MINES OF SOUTH AFRICA

EXAMINATION PAPER

SUBJECT: ROCK MACHANICS CERTIFICATE PART 1: THEORY **SUBJECT CODE:** COMRMC1 **EXAMINATION DATE:** May 2014 **TIME:**3 Hours	**EXAMINER:** JA MARITZ **MODERATOR:** M HANDLEY **TOTAL MARKS:** 100 **PASS MARK:** 60%

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

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 unit 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.

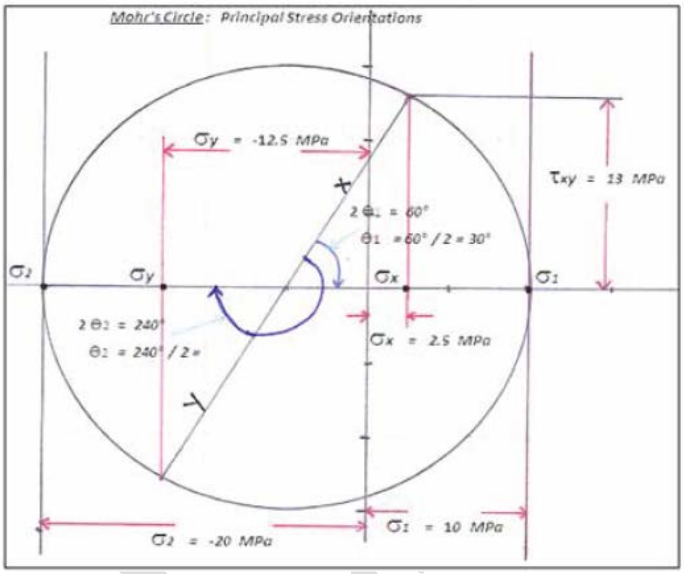
QUESTION 1 – STRESS AND STRAIN

1.1.

By using the Mohr circle, find the magnitude and directions of the principle stresses for the following state of stress:

$$\begin{bmatrix} 5 & 26 & 0 \\ 26 & -25 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

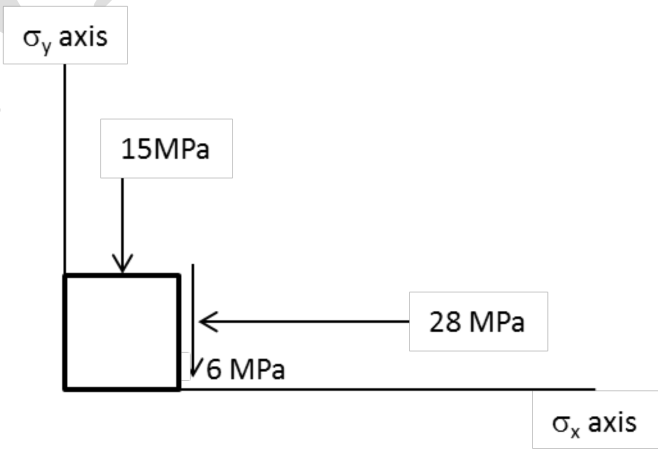
(5)



σ_1 = 20 MPa, σ_2 = -40 MPa
Major principle stress measured θ_1 = 30° from x axis
Minor principle stress measured θ_2 = 120° from x axis

1.2. G

iven stress state below,



1.2.1. Calculate the stress magnitudes on a plane rotated 40° clockwise to the give scenario. (5)

$\sigma'_{xx} = \sigma_{xx}\cos^2\theta + 2\tau_{xy}\sin\theta\cos\theta + \sigma_{yy}\sin^2\theta$	28cos^{2}40+2(6)sin40cos40+15sin^{2}40	28.54
$\sigma'_{yy} = \sigma_{xx}\sin^2\theta - 2\tau_{xy}\sin\theta\cos\theta + \sigma_{yy}\cos^2\theta$	28sin^{2}40-2(6)sin40cos40+15cos^{2}40	14.46
$\tau'_{xy} = \frac{1}{2}(\sigma_{yy} - \sigma_{xx})\sin 2\theta + \tau_{xy}\cos 2\theta$	0.5(15-28)sin2(40)+6cos2(40)	-5.36

1.2.2. Calculate the principle stresses and orientation for the give scenario. (4)

$\tan 2\theta = \frac{2\tau_{xy}}{\sigma_{xx} - \sigma_{yy}}$ $\quad \sigma_1 + \sigma_2 = \sigma_{xx} + \sigma_{yy}$	2θ = 2(6)/[28-15]	42.71 132.71
$\sigma_1 = \frac{1}{2}(\sigma_{xx} + \sigma_{yy}) + \frac{1}{2}\sqrt{(\sigma_{xx} - \sigma_{yy})^2 + 4\tau_{xy}^2}$	0.5(28+15)+0.5√([28-15]^2+4(6)^2)	30.35
$\sigma_2 = \frac{1}{2}(\sigma_{xx} + \sigma_{yy}) - \frac{1}{2}\sqrt{(\sigma_{xx} - \sigma_{yy})^2 + 4\tau_{xy}^2}$	0.5(28+15)-0.5√([28-15]^2+4(6)^2)	12.65

1.3.

The deflection on a cantilever beam is given by $\delta = \frac{3\gamma L^4}{2Et^2}$. By use of a sketch, explain the indicate the position of maximum deflection, compressive and tensile stress and calculate the maximum strain you would exert on a 1.5m roofbolt given the following parameters:

Density	1800 kg/m^3
Thickness	0.8 m
Beam length	2.0 m
Young's Modulus	5 GPa

(6)

δ = 1.32 (10)$^{-4}$ m
ε = Δl/l = 0.088 (10)$^{-3}$

[20]

QUESTION 2 – CONSTITUTIVE BEHAVIOUR

2.1. What is the significance of the following matrix? Explain what is meant by this special stress condition

$$\begin{bmatrix} \tau_{11} & 0 & \tau_{13} \\ 0 & 0 & 0 \\ \tau_{31} & 0 & \tau_{33} \end{bmatrix} \qquad (3)$$

Plane stress condition
A plane stress state exists when all the stress components with respect to one plane in the solid are zero

2.2. Name and explain the three Elastic Parameters of a rock sample and provide the equation linking these three. (7)

E = Young modulus: The "stiffness" of rocksample, relates normal stress to normal strain
v = Poissons Ratio: ration of lateral to axial strain
G = Modulus of rigidity: Relates shear stress to shear strain

$$G = \frac{E}{2(1+v)}$$

2.3. Given the following strain matrix, Young's modulus = 55 GPa and Poisson's ration = 0.28, calculate the principle stresses:

$$\begin{bmatrix} 2.5(10)^{-3} & 0 & 0 \\ 0 & 1.6(10)^{-3} & 0 \\ 0 & 0 & 1.4(10)^{-3} \end{bmatrix} \qquad (5)$$

σ_1 = 257.8 MPa

σ_2 = 219.1 MPa

σ_3 = 210.5 MPa

2.4. On the attached sheet, find the Strain vs Strain graph of a particular rock sample (Base sample). Determine the secant Young's Modulus for the sample at 4 millistrain. Various other samples had been tested of which you are required to draw the given results on the graph. ***Remember to write your ID on the loose paper and submit the plot together with your script.***

2.4.1. Secant Young's Modulus at 4 millistrain. (1)

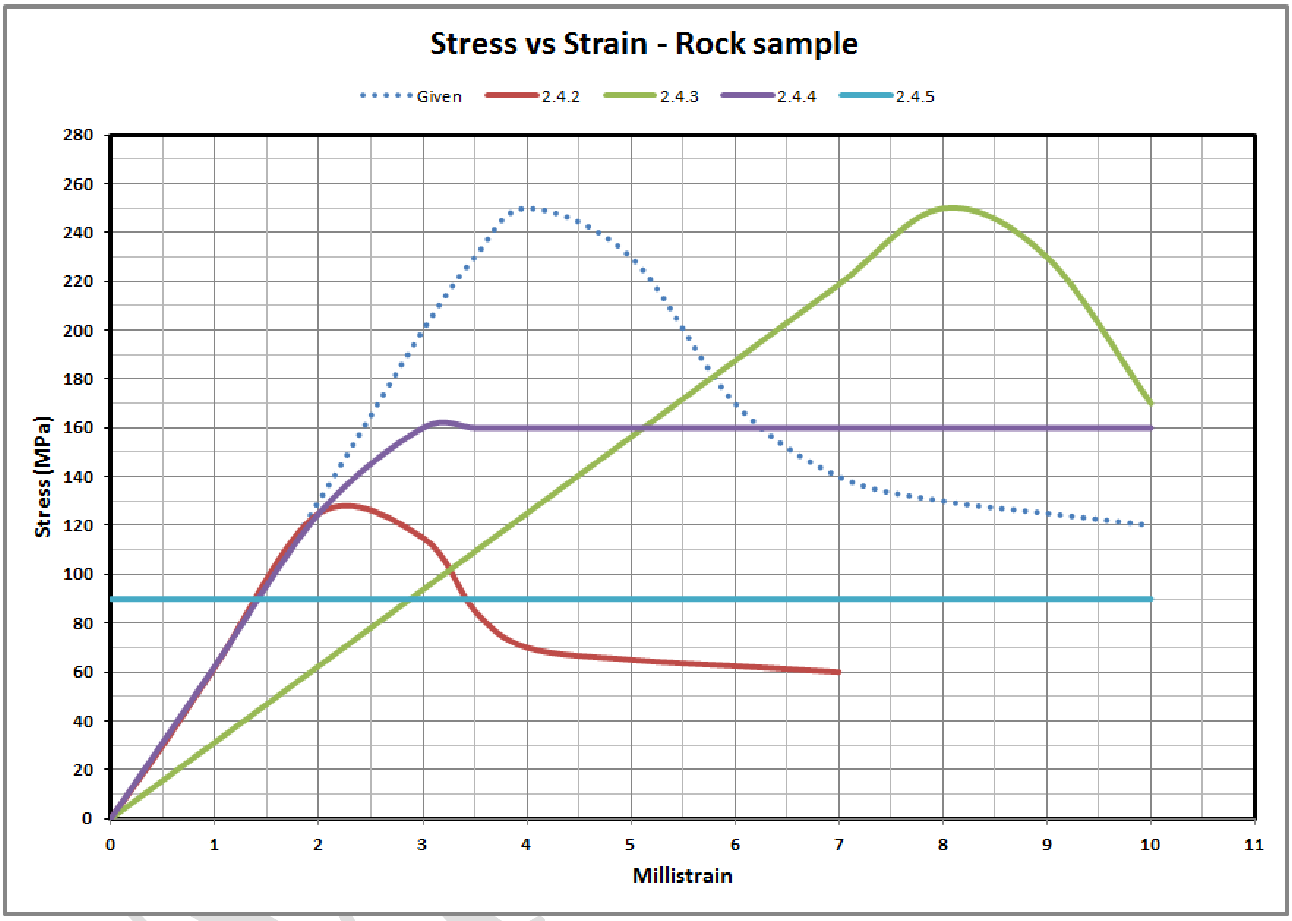
E = 62.5 GPa

2.4.2. A sample which has the same Young's Modulus and post failure characteristics, yet a 50% UCS compared to the Base (1)

2.4.3. 50% of the Base sample Young's modulus (1)

2.4.4. Same Young's Modulus as the Base sample, yet shows elasto-platic behaviour at 160 MPa (1)

2.4.5. A sample showing perfectly plastic behaviour at 90 MPa (1)



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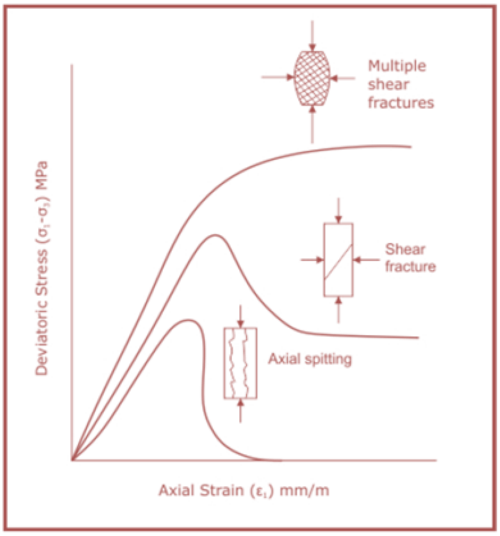
QUESTION 3 – ROCK & JOINT STRENGTHS

3.1. B

y means of a sketch, explain the change in post failure behaviour of a rock sample with increasing confinement pressure (6)



3.2. J

oint strength is described by Barton’s equation

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

According to this, discuss the 4 parameters that influence the strength of joints.

(8)

σ_n	Stress normal to the joint	MPa	Higher normal stress will increase joint strength as it clamps the joint together, but can reduce shear strength if the (JCS/σn) ratio approaches or reduces below 1 (Log of ratio becomes zero at a ratio of 1 and negative at below 1, indicating reduction in strength when σn exceeds JCS)
JRC	Joint roughness coefficient	Degrees, but effectively dimensionless	Higher JRC will increase joint strength as a rougher surface increases friction angle and therefore shear strength.
JCS	Jointwall compressive strength,	MPa	Higher JCS will require a much higher σnto fail the asperities on the joint and allow slip, therefore higher JCS gives higher joint strength.
$ø_r$	Residual friction angle	Degrees	Joint angle after failure and suggests that higher residual friction angle would indicate higher final joint strength.

____

3.3. W

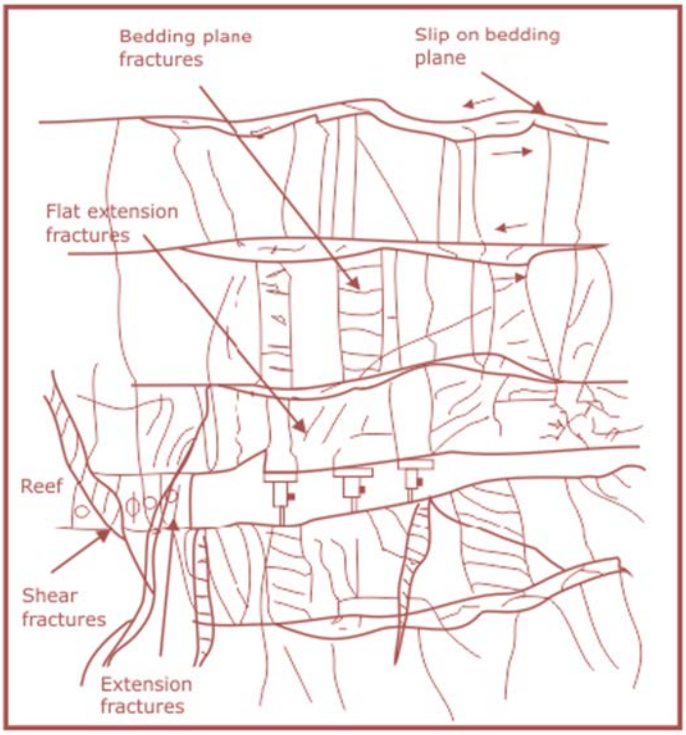
hat is the major difference between a JOINT and a FRACTURE (2)

Joint – Natural discontinuity generally not parallel to lithological variations

Fracture – Separation of material in two or more pieces under the action of stress

3.4. S

ketch and indicate the three general fractures one would find around an underground excavation. (4)



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QUESTION 4 – STRESS IN ROCK AND ROCKMASSES

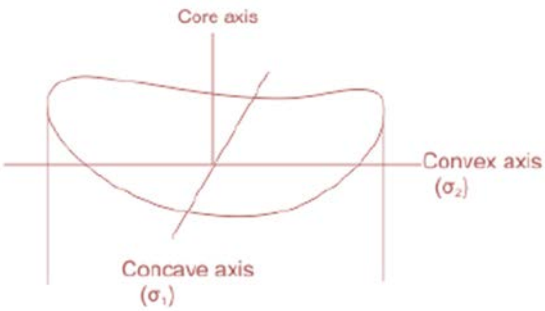
4.1. N

ame the two common pre-mining stress (primitive stress) models and the k-ratios assumed for each case (4)

Heim's rule: Lithostatic stress model – k = **1**
Rigid Confinement model – k = **v/(1-v)**

4.2. B

y means of a sketch, indicate how discing of core from exploration drilling can give an indication of the principle stresses (2)



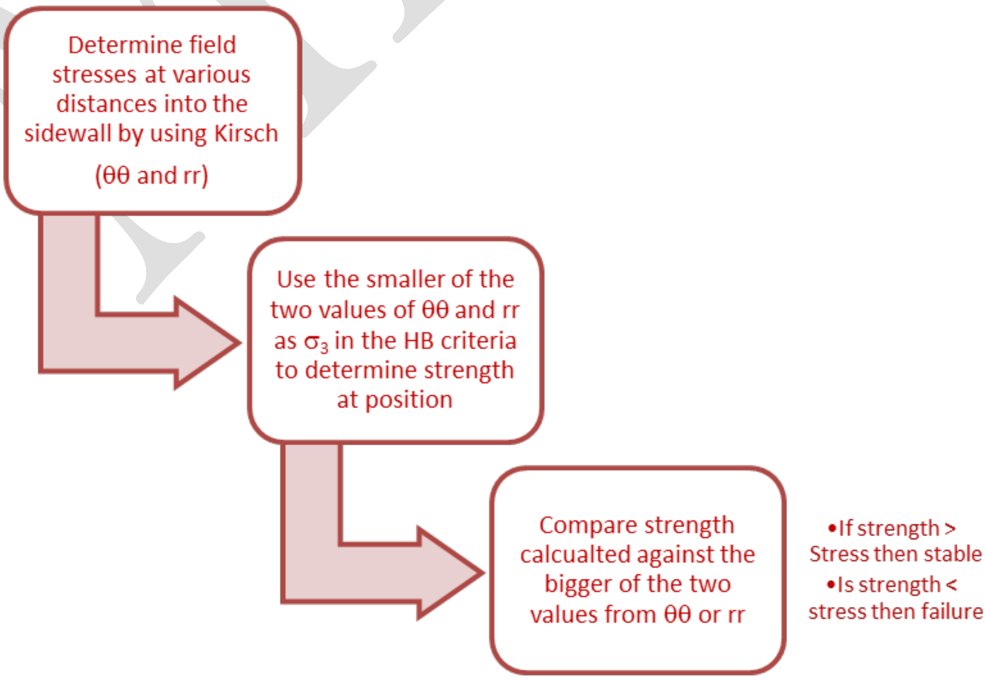
4.3. When using the flat jack method to measure in-situ stress levels, what would be the typical stress range where this test is applicable and at what orientation does it measure stress? (2)

Stress range 0.3 – 3.5 MPa
Measure 90° to the jack

4.4. Explain the Kaiser Effect and what is the significance of this point when measuring in-situ stress levels. (2)

Change in slope during Acoustic Emission testing
Maximum stress the sample was exposed to in the underground environment

4.5. Explain by means of a flow diagram how you would go about in determining the depth of fracturing into the sidewall for a circular excavation by using the Kirsch set of equations and a failure criteria (name the criteria)



(6)

4.6. When using the Kirsch set of equations to solve problems in a 2D space, what stresses are calculated? Field, Mining Induced or Virgin stresses (1)

Field stresses

4.7. At what angle would the rock mass experience the maximum induced shear stress? (1)

45°

4.8. At what angle would the radial stresses be 0 MPa on the skin of the excavation? (1)

Any angle

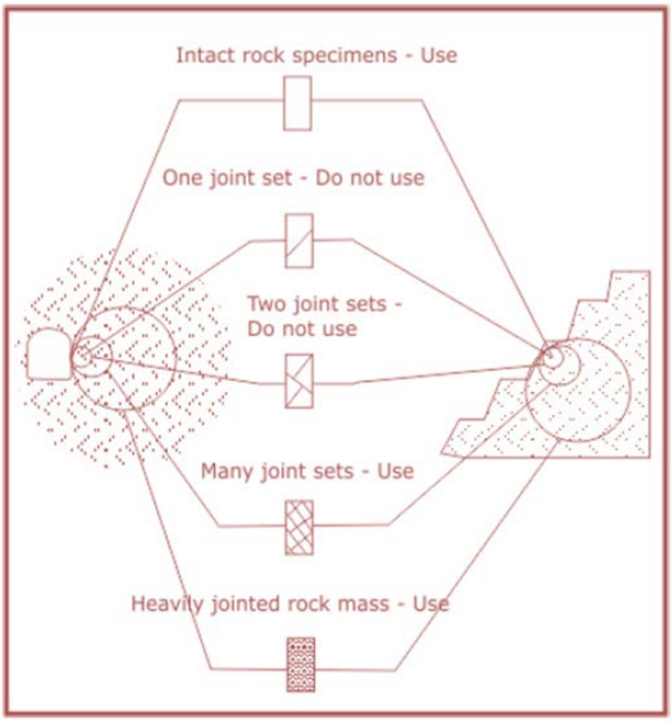
4.9. How would you use the Kirsch equations to determine the Virgin stresses in the rock mass? (1)

Calculate the field stress at a far enough distance (greater than 5D)

[20]

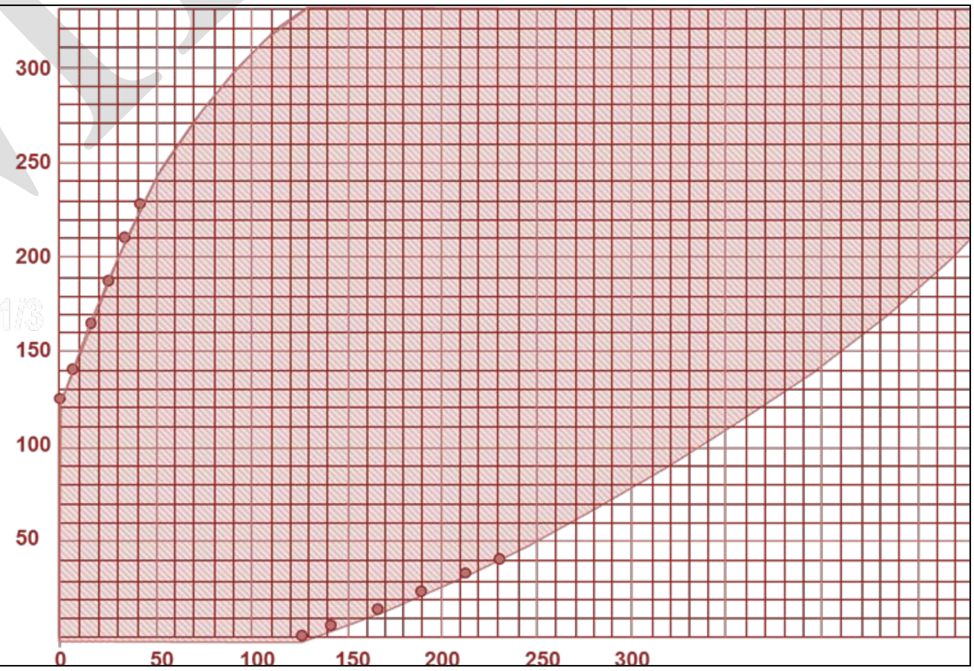
QUESTION 5 – ROCKMASS PROPERTIES & CLASSIFICATION

5.1. By means of a sketch, indicate the applicability of the Hoek-Brown failure criterion to different rock mass conditions (5)



5.2. Applying the Hoek-Brown criteria to a highly fractured rockmass, plot the failure envelope based on the following test results. The S and M values are 0.5 and 3.5 respectively with an UCS of 165 MPa. Tabulate your data points for confining stresses ranging from 0 MPa to 40 MPa at 8 MPa increments. (8)

σ_3 (MPa)	σ_1 (MPa)
0	**116.67**
8	**143.03**
16	**167.17**
24	**189.75**
32	**211.14**



40	**231.61**	

5.3. I

n the above question, would $\begin{bmatrix}20 & 0\\ 0 & 250\end{bmatrix}$ be stable? (1)

NO

5.4. N

ame and 6 parameters that are used in the Q-index (Barton's classification system) (6)

RQD

Joint set number

Joint roughness

Joint alteration

Joint water

Stress reduction factor

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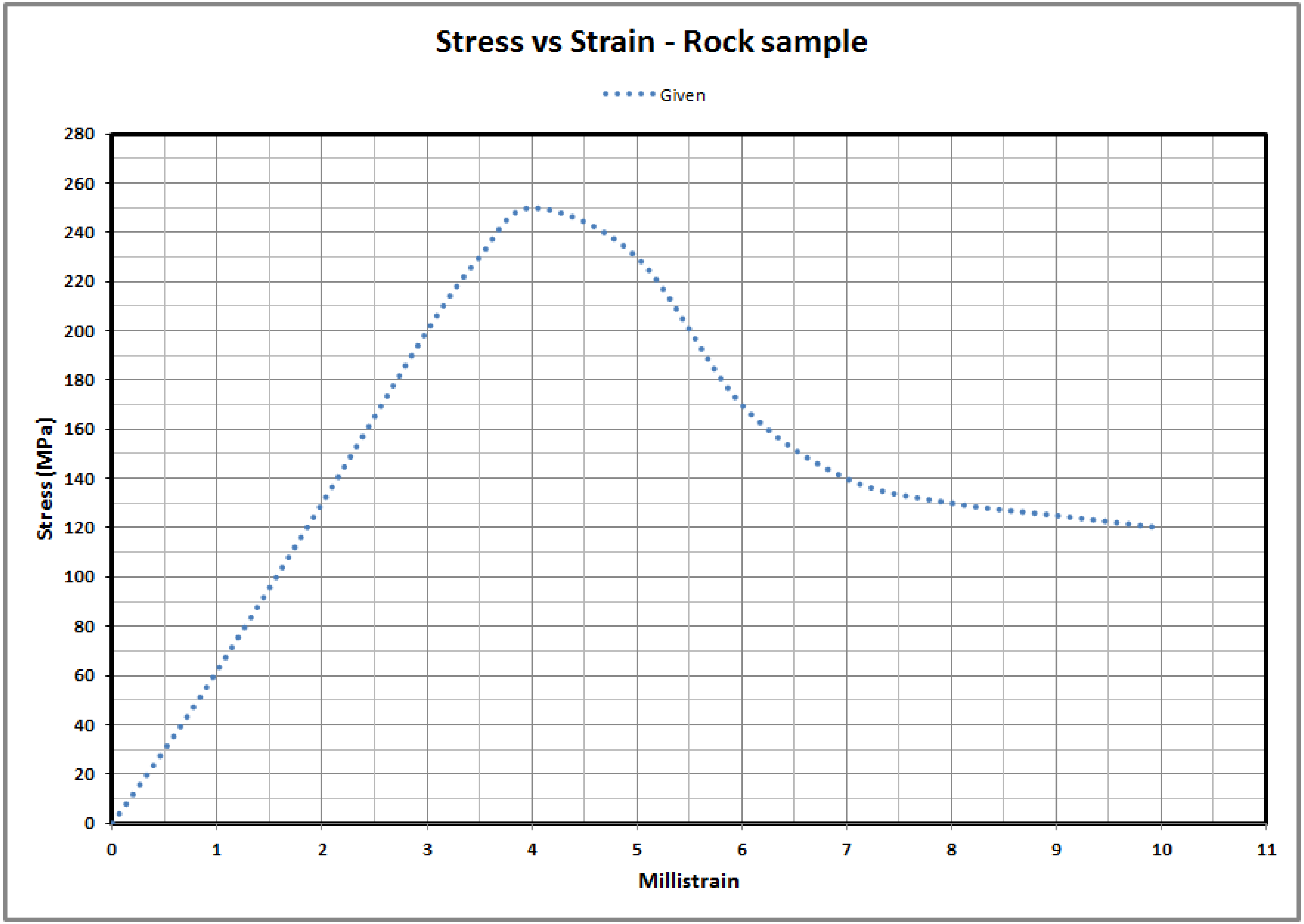
TOTAL MARKS: [100]


Stress vs Strain - Rock sample
Given
Stress (MPa)
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
11
Millistrain

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$Q = wV$$

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

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

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

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

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

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

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

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

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

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

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

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

$$q=\rho gH\quad \sigma_v=q\quad \sigma_h=kq$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$R < 5$

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

$R \geq 5$

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

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

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

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

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

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

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

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

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

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

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

$$h_e = eh$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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