CHAMBER OF MINES OF SOUTH AFRICA

EXAMINATION PAPER

SUBJECT: ROCK MECHANICS CERTIFICATE PART 1: THEORY **SUBJECT CODE:** COMRMC1 **EXAMINATION DATE:** MAY 2013 **TIME:**3 Hours	**EXAMINER:** JA MARITZ **MODERATOR:** DF MALAN **TOTAL MARKS:** 100 **PASS MARK:** 60%

NUMBER OF PAGES:15 (*including Cover and Formulae Sheets*)

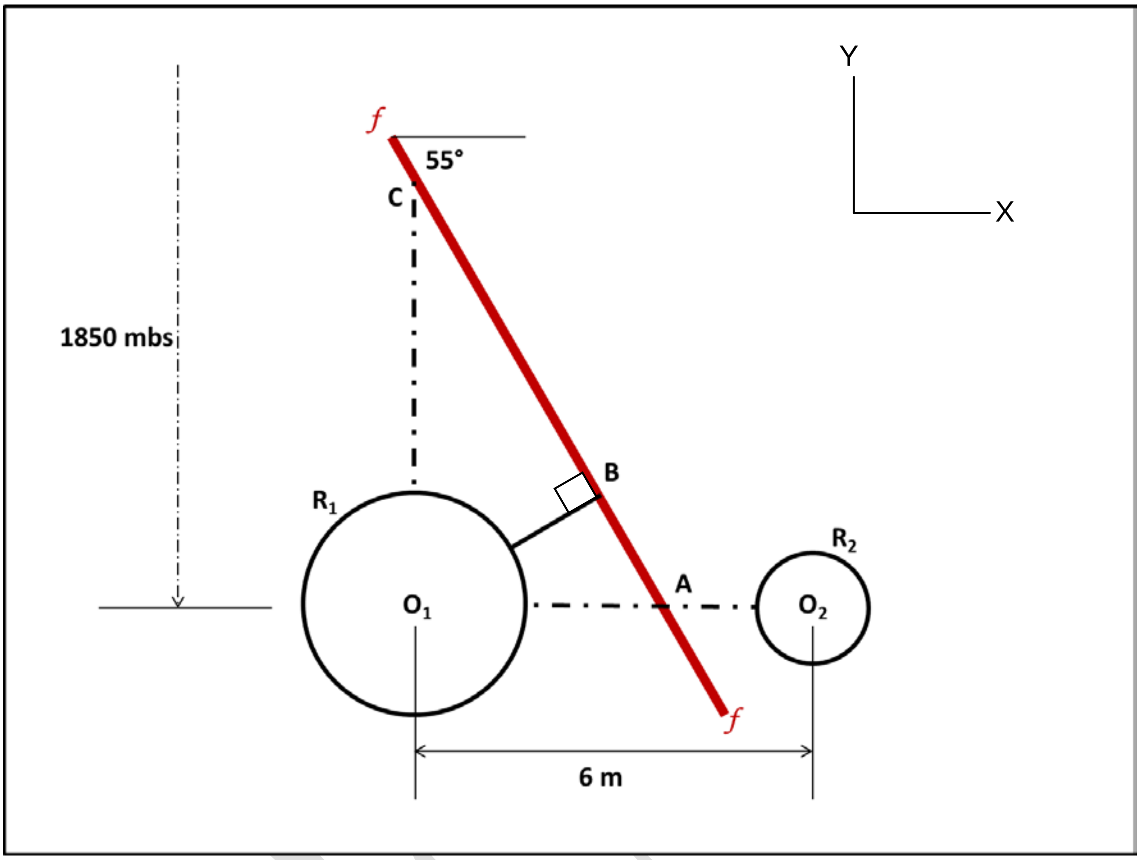
SPECIAL REQUIREMENTS:

1. **Answer All Questions.**
2. **Values given in question are not necessary answers calculated in previous questions.**
3. All Questions are based on the given mining scenario.
4. Start each question on a new page.
5. References other than those provided are not permitted.
6. Hand-held electronic calculators may be used.
7. 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.

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

GIVEN MINING SCENARIO



A fault is dipping at 55° and traverse the rock mass between to circular excavations which are 6 m apart (measured centre-to-centre). These excavations form part of an intense ventilation arrangement needed to supply air to the workings 1850 m below surface. The main tunnel (O_1) is 4 m in diameter with the secondary tunnel (O_2) being 2 m in diameter. Drilling a <u>horizontal hole</u> in the sidewalls of O_1 depicted the fault position as being 2 m into the sidewall.

Given:

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

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

m_i	25
Relative Density	2.8
RMR	68
E	65 GPa
v	0.27
$UCS_{\text{fault material}}$	55 MPa
$\phi_{\text{fault plane}}$	26°
$C_{o\ \text{fault plane}}$	1.5 MPa
k-ratio	0.5

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

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

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

QUESTION 1 – STRESS IN ROCK & ROCKMASSES (20)

1.1. Determine the stress state for the polar coordinates at points A, B and C for the given mining scenario by using the Kirch equations assuming only the development of the main tunnel. (10)

	θ	Distance in Sidewall	R	r	$\sigma_{\theta\theta}$	σ_{rr}	$\tau_{r\theta}$
A	0	2	2	4.00	62.73	26.20	0.00
B	35	1.27	2	3.27	58.54	24.19	15.86
C	90	3.71	2	5.71	29.51	40.48	0.00

1.2. Considering the secondary tunnel together with the main tunnel, what would be the stress state at point A? (4)

Stress state at A as result of main tunnel induced stress + secondary tunnel induced stress + virgin stress.

	$\sigma_{\theta\theta}$	σ_{rr}	$\tau_{r\theta}$
Virgin A	50.82	25.41	0.00
Induced M	11.91	0.79	0.00
Induced S	11.91	0.79	0.00
Total at A	74.64	27.00	0.00

1.3. What would be the expected virgin stress levels at the 1850 mbs when calculated with:

1.3.1. Heim's rule (2)

σ_v = 50.82 MPa; σ_h = 50.82 MPa

1.3.2. Rigid confinement theory (2)

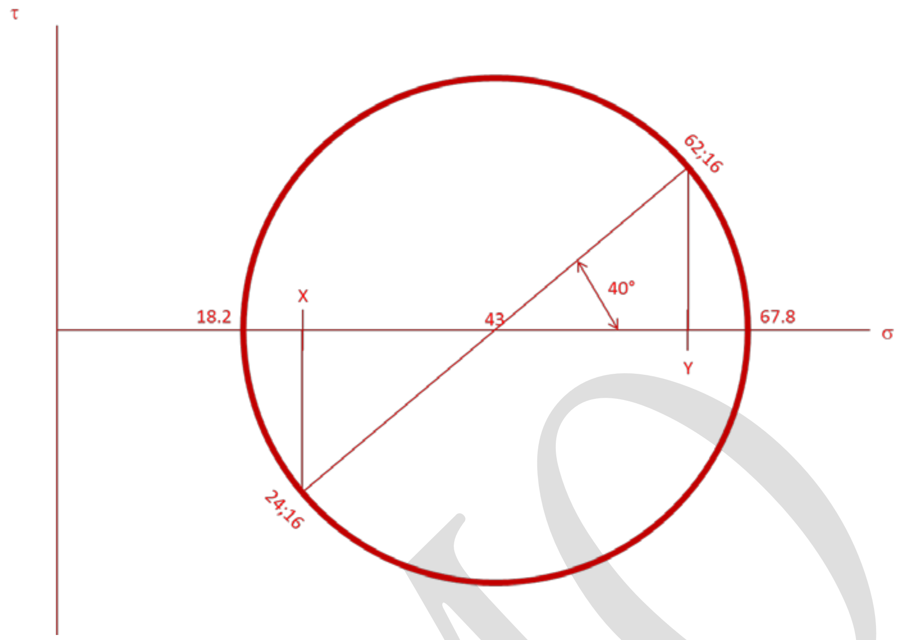
σ_v = 50.82 MPa; $\sigma_h = (v/1-v)*\sigma_v$ = 18.79 MPa

1.3.3. Kirch equations (2)

Taken at 50 m into sidewall $\sigma_v = \sigma_{\theta\theta}$ =50.87 MPa; $\sigma_h = \sigma_{rr}$ = 25.43 MPa

QUESTION 2 – STRESS AND STRAIN (20)

2.1. Given the stress state at point B is represented by the matrix $\begin{bmatrix} 24 & 16 \\ 16 & 62 \end{bmatrix}$ MPa (X direction horizontal to the right and Y direction vertical up); determine the magnitude and direction of the principle stress conditions acting on the fault plane using Mohr's circle. (12)



2.2. Plot the schematic Mohr circles for the following conditions

2.2.1. Pure shear (2)

2.2.2. Uniaxial tension (2)

2.2.3. Hydrostatic stress field (2)

2.2.4. Uniaxial compression (2)

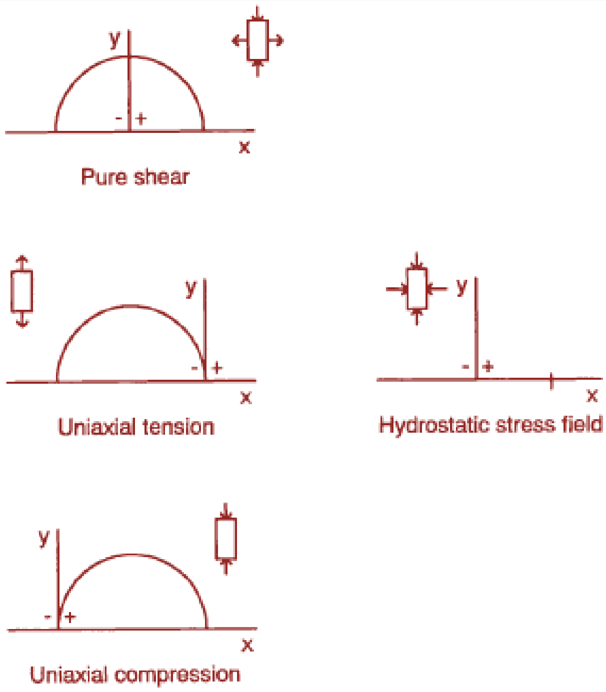


Figure 85 **Location of the Mohr stress circle in four common situations. y is the shear stress axis and x the principal stress axis; + denoting pressure and - tension**

QUESTION 3 – CONSTITUTION RELATIONSHIPS (20)

3.1. Draw the Stress vs. Strain graphs comparing brittle and ductile rock formations. (4)

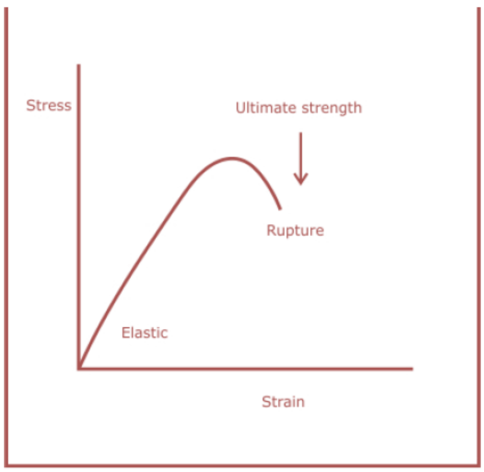


Figure 2: Brittle rock deformation

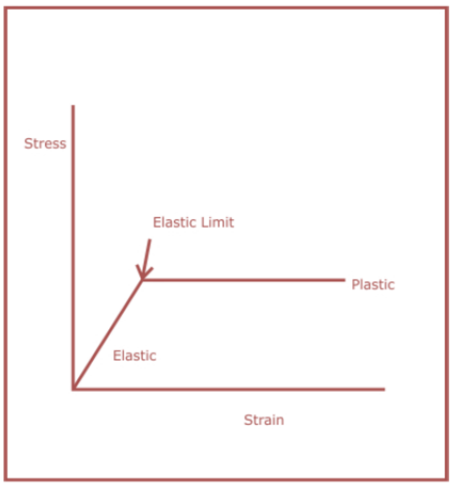


Figure 3: Ductile rock deformation

3.2. What is the major difference between brittle and ductile rocks (1)

The post failure behaviour

3.3. In the given scenario, what strain would a rock sample experience when a force of 100 kN is applied to a 34 mm diameter sample. (3)

$A = \pi d^2/4 = 0.908 \times 10^{-3}\ m^2$
$\sigma = F/A = 110.1$ MPa
$\varepsilon = \sigma/E = 1.69 \times 10^{-3}$

3.4. In which section along the Strain vs. Strain graph may one assume the Hooke's Law to be a valid? (1)

Elastic portion

3.5. Assuming the following stress matrix, $\begin{bmatrix} 45 & 5 \\ 5 & 80 \end{bmatrix}$ MPa at an arbitrary location in the rock mass within the mining scenario, calculate all strain components by using the 2D representation of Hooke's Law and Modulus of Rigidity formulae. (5)

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

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

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

G = 25.59 GPa

$\sigma_{zz}=0$,

$\varepsilon_{xx} = 1/(65\ 000)*(45-0.27*80) = 0.0004$

$\varepsilon_{yy} = 1/(65\ 000)*(80-0.27*45) = 0.0010$

$\gamma_{xy} = 5x(10)^6 / 26.77x(10)^9 = 0.0002$

$$\begin{bmatrix} \varepsilon_{xx} & \gamma_{xy} \\ \gamma_{yx} & \varepsilon_{yy} \end{bmatrix} = \begin{bmatrix} 0.0003 & 0.0002 \\ 0.0002 & 0.0010 \end{bmatrix}$$

3.6. Define strain energy (1)

Strain energy is the work done in deforming a body.

3.6.1. Based on your answers calculated in Question 3.5, calculate the amount of strain energy density stored in the rock mass at this point (3)

$$w = \frac{1}{2}(\sigma_{xx}\varepsilon_{xx} + \sigma_{yy}\varepsilon_{yy} + \sigma_{zz}\varepsilon_{zz} + \tau_{xy}\gamma_{xy} + \tau_{yz}\gamma_{yz} + \tau_{zx}\gamma_{zx})$$

, Hence W = 47.25 kJ

3.7. Define creep (2)

Creep is the tendency of a solid material to slowly move or deform permanently under the influence of stresses.

QUESTION 4 – ROCK PROPERTIES (20)

4.1. When stability of a rock mass is tested, a specific failure criterion is used to base the assessment on. Name and discuss which criterion you would consider when the following conditions in the mining scenario are assessed: (10)

4.1.1. Assessment of fault plane stability.

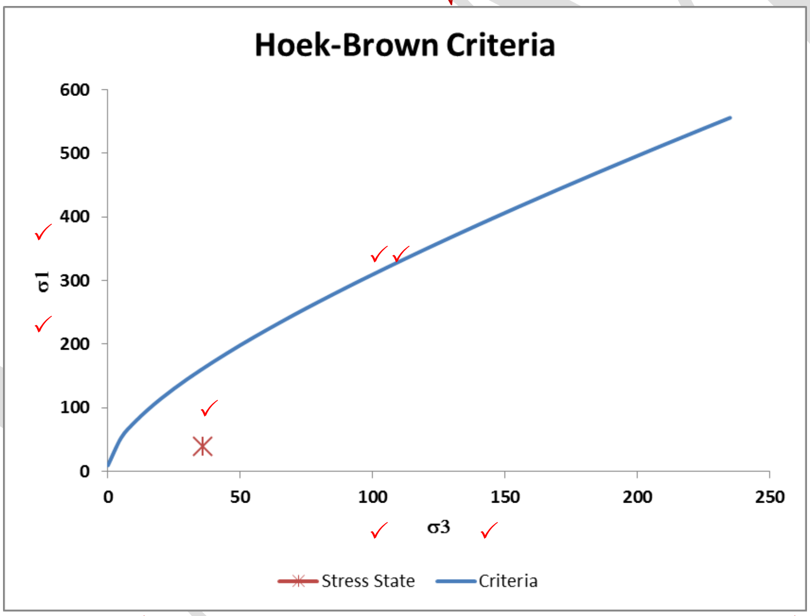
Mohr-Coulomb - $\tau = \mu\sigma_n + C_0$
Discussion 3 marks

4.1.2. Assessment of heavily jointed rock close to the contact.

Hoek-Brown - $\sigma_1 = \sigma_3 + \sqrt{m\sigma_c\sigma_3 + s\sigma_c{}^2}$
Discussion 3 marks

4.2. Given the Hoek-Brown values for a rock mass RMR=68, while the fault material strength is 55 MPa, plot the yield curve for this infilling as well as the Point C stress state of $\begin{bmatrix} 39 & 0 \\ 0 & 36 \end{bmatrix}$ and comment whether the fault material should be stable or not. (10)

Use Hoek-Brown formula $\sigma_1 = \sigma_3 + \sigma_c\sqrt{m\frac{\sigma_3}{\sigma_c} + s}$ ✓ to plot graph and plot stress condition.



No failure ✓ is expected as the stress state plot below the graph.✓

QUESTION 5 – ROCKMASS PROPERTIES & CLASSIFICATION (20)

5.1. $\alpha = \sqrt{\frac{E(1-\nu)}{(1+\nu)(1-2\nu)\rho}}$ [m/s]

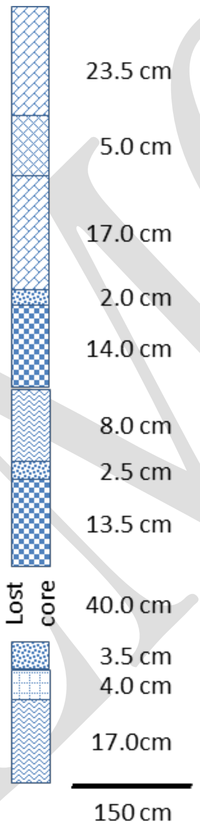
$\beta = \sqrt{\frac{E}{2(1+2\nu)\rho}}$ [m/s]

$V_p \approx 3.5 + Log_{10}Q$ [km/s]

Given the three equations showing the relationship between strength and seismic wave velocity in a rock mass, determine the Q rating of the given mining scenario and classify the rock accordingly (*Exceptionally poor to Exceptionally good*). (4)

α=5385.9m/s, hence Vp~5.3859km/s = 3.5+logQ => Q=77, Group 1: Good

5.2. Given the drill hole information as presented to the right, define and determine the following recovery values:



5.2.1. (SCR) Solid core recovery (2)

Estimating the intack rock = 1100 mm

5.2.2. (%CR) Percentage core recovery (2)

Core recovery / Total core length = 73%

5.2.3. (RQD) Rock Quality Designation as a percentage (2)

Sum of the lengths >100 mm / Total core drilled x 100 = 57%

5.3. Terms and definitions: Define each of the following

5.3.1. Coefficient of friction (2)

Constant of proportionality relating NORMAL stress and corresponding critical SHEAR stress at which sliding starts between surfaces

5.3.2. Cohesion (2)

Shear resistance at zero normal stress

5.3.3. Compressive stress (2)

Normal stress tending to shorten a body in the directions in which it acts

5.3.4. Plane strain (2)

All strain components normal to a plane are zero

5.3.5. Plane stress (2)

All stress components normal to a plane are zero

- END -

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$Q = wV$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$R < 5$

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

$R \geq 5$

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

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

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

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

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

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

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

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

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

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

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

$$h_e = eh$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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