CHAMBER OF MINES OF SOUTH AFRICA

EXAMINATION PAPER

SUBJECT:	EXAMINER:
ROCK MECHANICS CERTIFICATE PART 1: THEORY	J WALLS
SUBJECT CODE: COMRMC-1	**MODERATOR:** H YILMAZ
EXAMINATION DATE: 10 MAY 2016	**TOTAL MARKS:** 100
TIME: 14:30 -17:30	**PASS MARK:** 60

NUMBER OF PAGES:16 (*including Cover*)

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

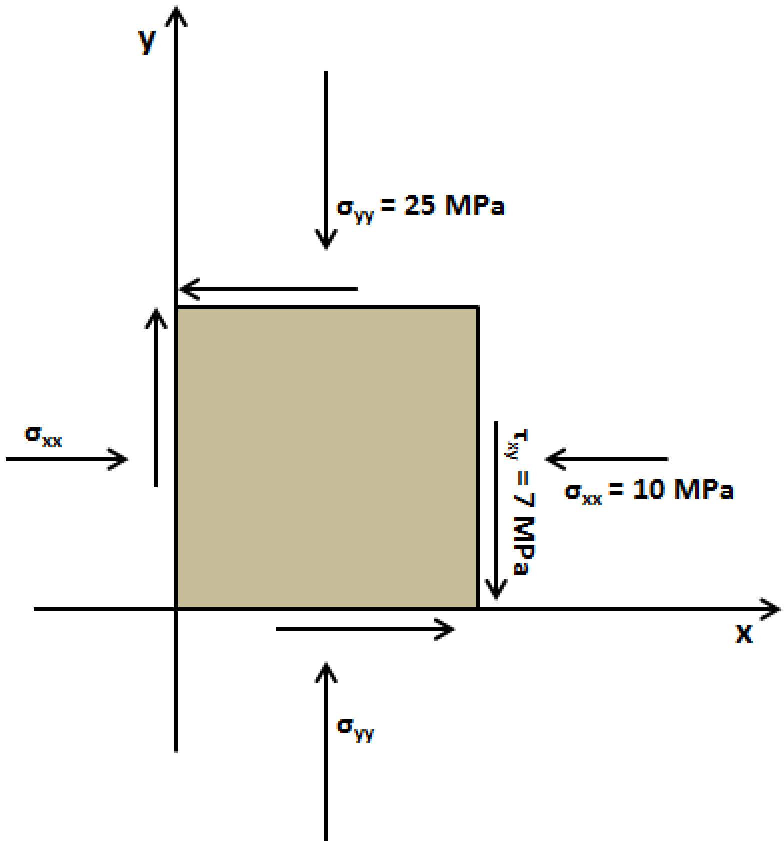
SPECIAL REQUIREMENTS:

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 – STRESS AND STRAIN (25)



1.1. Use the information provided in the body diagram to calculate the magnitudes of the principal normal and maximum shear stresses. [5]

1.2. Determine the orientations of the principal stresses with respect to the x-axis. [4]

1.3. Plot the stress state shown in the body diagram using a Mohr circle representation. [5]

1.4. Using the Mohr circle diagram, determine the normal and shear stress components for a plane rotated 35° anticlockwise from the direction of σ_{xx}. [5]

1.5. If the body diagram above represents a plane stress condition, discuss the behaviour of the surface element in the third dimension (z). Under what conditions would you expect this to occur? [3]

1.6. If the Mohr-Coulomb failure equation for the specimen is given by

$$\tau = 30 + \sigma_n \tan(35)$$

discuss whether failure would occur on a plane orientated normal to the major principal stress direction. [3]

QUESTION 2 – CONSTITUTIVE BEHAVIOUR (20)

2.1. With the aid of idealised strain-time and strain_rate-time curves, discuss and illustrate the phenomenon of time-dependant strain. [5]

2.2. A rock specimen has a modulus of elasticity of 60 GPa and a Poisson's ratio of 0.2. Determine σ_x and σ_y if $\varepsilon_x = 0.4\text{x}10^{-3}$ and $\varepsilon_y = 1.1\text{x}10^{-3}$. [4]

2.3. "Strong" and "weak" rock may be either "stiff" or "soft". Use a simple sketch to illustrate how a "soft" rock sample can be stronger than a "stiff" sample. [2]

2.4. If the applied stress in a pure elastic material is released, what will happen to the strain in the material? [1]

2.5. If you are given the Young's modulus and Poisson' ratio for a material, name and define with the use of a formula a third elastic constant that you will be able to determine. [3]

2.6. Define "dilation angle" and indicate where it is determined on a stress-strain graph. [3]

2.7. Using $\sin(\psi_p) = \frac{(2\,\nu_p - 1)}{(2\,\nu_p + 1)}$, calculate the dilation angle for a material with a plastic radial:axial strain ratio of 0.8. [2]

QUESTION 3 – ROCK MASS PROPERTIES (25)

3.1. Name, sketch and discuss two possible modes of failure of rock in uni-axial and tri-axial compression. [4]

3.2. Use graphical illustrations to discuss how a change in "*m*" and "*s*" in the Hoek-Brown failure criterion influences rockmass strength. [4]

3.3. Calculate the downgraded UCS value for a rockmass with σ_c = 210 MPa and GSI = 65. Discuss the implications of your result. [3]

3.4. Barton and Choubey expressed the shear strength of a rock surface using the equation

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

Provide definitions for each of the terms and describe how you would go about determining the parameters. [8]

3.5. If φ_b = 30°, JRC = 6 and JCS = 90 MPa, calculate the peak shear strength of a plane when σ_n = 2 MPa and σ_n = 25 MPa. Discuss the significance of increasing σ_n on a joint surface with few asperities. [3]

3.6. Discuss some of the essential differences between Hoek and Brown's failure criterion versus Barton and Choubey's shear strength criterion. [3]

QUESTION 4 – STRESS IN ROCK AND ROCKMASSES (15)

4.1 Simple elastic beam solutions are commonly used to evaluate underground rock mechanics stability problems. Describe, explain and illustrate the normal and shear stresses induced in the three commonly encountered types of beams in an underground environment. [6]

4.2 Discuss the principles of a "Voussoir" beam. [3]

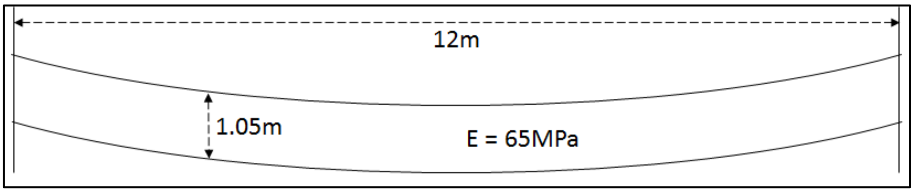
4.3 Discuss three modes of potential beam failure. [3]

4.4 Assume a reasonable value for the rock mass density, calculate the maximum deflection and maximum shear stress of a freely supported beam using the given information:

$$\delta = \frac{5}{32}\ \gamma\ \frac{L^4}{E\ t^2}$$

And

$$S = \frac{1}{2}\ \gamma\ L$$



[3]

QUESTION 5 – ROCKMASS BEHAVIOUR (ENERGY) (15)

Energy can be transmitted or stored in a rockmass as a result of several influencing factors or events.

5.1 Discuss two forms of violent energy release in mining that would result in the transmission of seismic waves. [2]

5.2 Calculate the P- and S-wave velocities for a homogeneous isotropic elastic medium with Young's modulus of 75 GPa, Poisson's ratio of 0.2 and rockmass density 2 750 kg.m^{-3}, using the relationships:

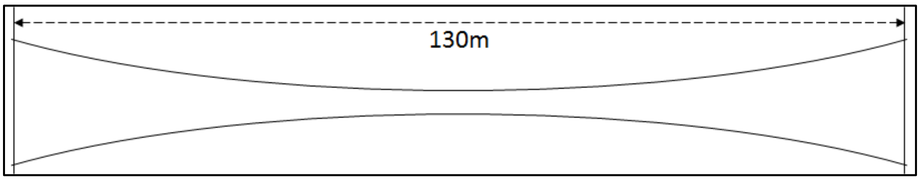
$$V_p = \sqrt{\frac{E\,(1-\nu)}{(1+\nu)*(1-2\nu)*\rho}}$$

$$V_s = \sqrt{\frac{E}{2\,(1+2\nu)\,\rho}}$$

[4]

In normal mining conditions, a steady flow of available energy is released for every incremental area mined (ERR).

5.3 Using the information provided in (5.2), calculate the ERR for an isolated stope at a depth of 1 500 m below surface with dimensions shown in the figure (assume that the stope length is less than the critical half-span).



[4]

5.4 Would you expect microseismic (acoustic emission) energy to be associated with high frequencies or low frequencies? Discuss. [2]

5.5 Discuss the rockmass properties that influence propagation of seismic or acoustic energy through the rockmass. [4]

TOTAL MARKS: [100]

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$Q = wV$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$R < 5$

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

$R \geq 5$

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

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

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

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

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

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

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

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

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

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