UNISA university of south africa

EXAMINATION PAPER

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

NUMBER OF PAGES:23 (*including Cover and Formulae Sheets*)

SPECIAL REQUIREMENTS:

1. **Answer Questions 1 to 4.**
2. **Answer Question 5.1 & 5.2 and either 5.3 or 5.4. If both 5.3 and 5.4 are answered, NO MARKS WILL BE GIVEN TO EITHER ONE.**
3. Start each question on a new page.
4. References other than those provided are not permitted.
5. Hand-held electronic calculators may be used.
6. 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.

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

QUESTION 1 – STRESS AND STRAIN (20)

$$\text{Stress Tensor} = \begin{bmatrix} 10 & 5 \\ 5 & 20 \end{bmatrix}$$

1.1 Determine the principle stress and orientation of the above given stress condition [4]

$$C = \frac{20 + 10}{2} = 15$$

$$R = \frac{1}{2}\sqrt{(\sigma_x - \sigma_y)^2 + 4 \times \tau_{xy}^2}$$

$$R = \frac{1}{2}\sqrt{(10 - 20)^2 + 4 \times 5^2}$$

$$R = 7.07$$

Thus;

$$\sigma_{y2} = \frac{1}{2}(\sigma_x + \sigma_y) \pm \frac{1}{2}\sqrt{(\sigma_x - \sigma_y)^2 + 4 \times \tau_{xy}^2}$$

$$\sigma_{y2} = 15 \pm 7.07$$

$$\sigma_1 = 22.07$$

$$\sigma_2 = 7.92$$

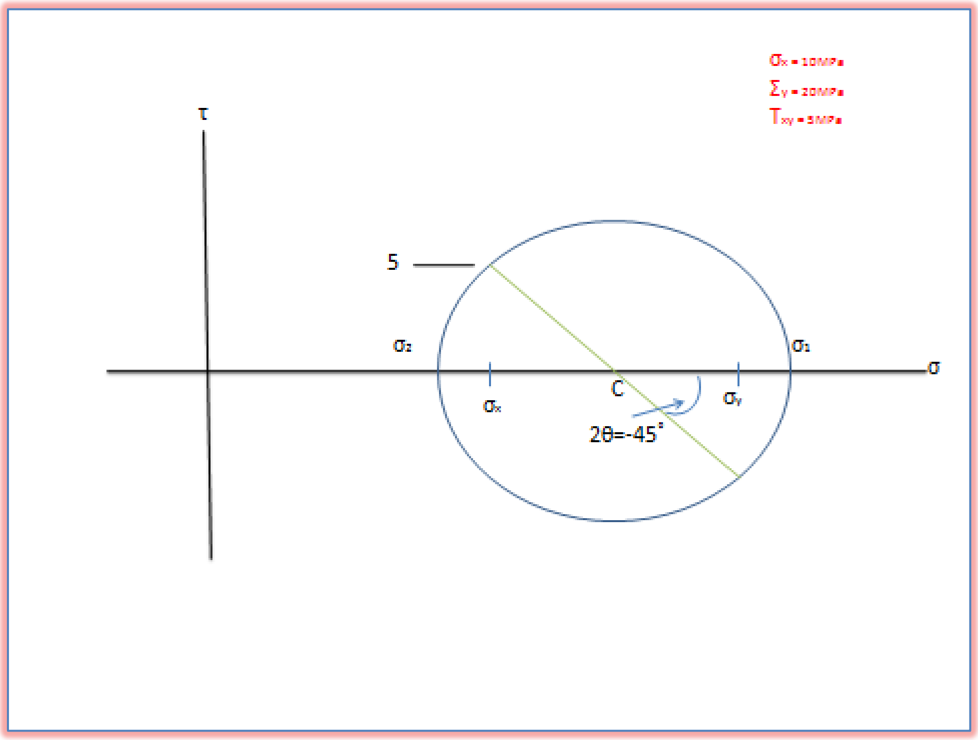
$$tan2\theta = \frac{2\tau_{xy}}{(\sigma_x - \sigma_y)}$$

$$tan2\theta = \frac{10}{-10} = -1$$

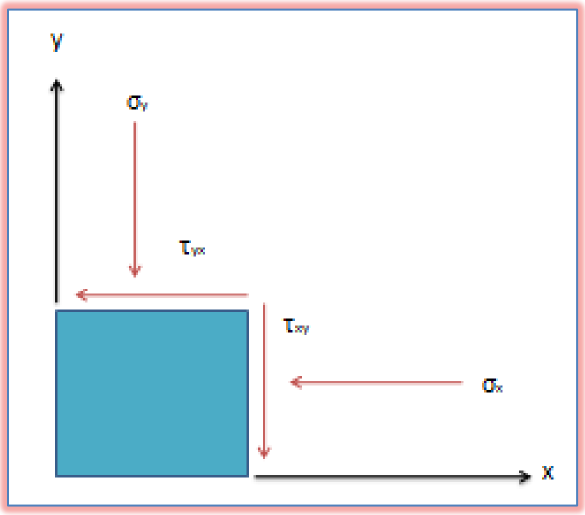
$$2\theta = -45^\circ$$

$$\theta = -22.5^\circ \; or \; 67.5^\circ$$

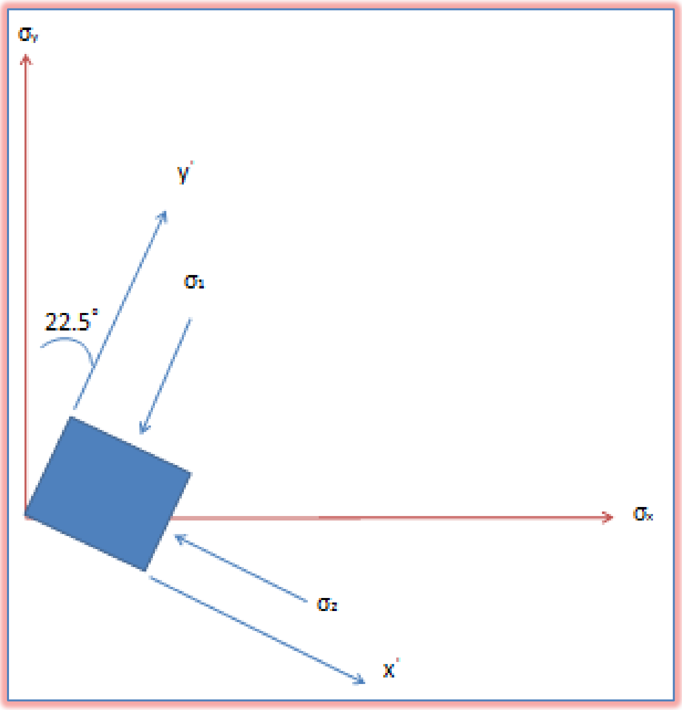
1.2 Confirm the principle stress and orientation by means of the Mohr-circle [3]



1.3 Draw the free body diagram of the given stress tensor [4]



1.4 Draw the free body diagram at the principle stress state with the orientation calculated in Question 1.1 [6]



1.5 By using the stress transformation equations, (σ_{nn}, σ_{mm}, τ_{nm}), prove that the stresses calculated given your orientation are indeed principle stresses. [3]

To prove $\tau_{nm} = 0$,
Then;

$$\tau_{nm} = \frac{1}{2}(\sigma_{yy} - \sigma_{xx})sin2\theta + \tau_{xy}cos2\theta$$
$$\theta = -22.5^{\circ}$$

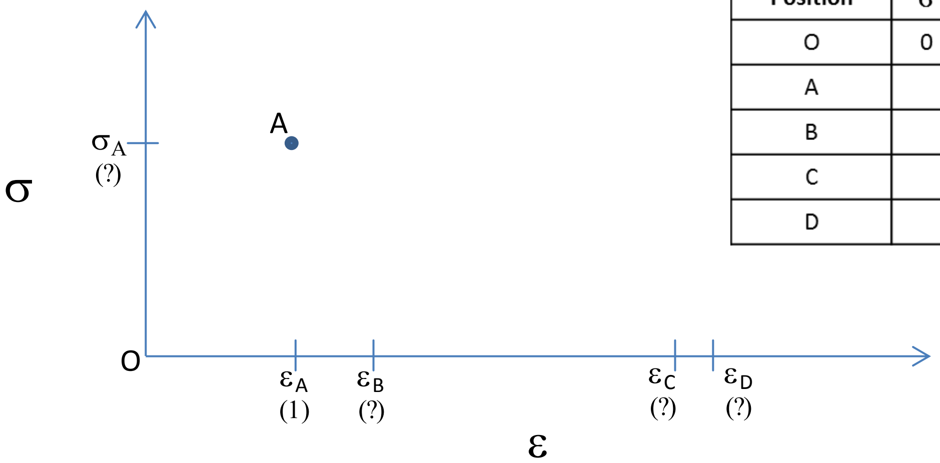
Therefore;

$$\tau_{nm} = \frac{1}{2}(20 - 10)sin2(-22.5^{\circ}) + 5cos2(-22.5^{\circ})$$
$$\tau_{nm} = -3.54 + 3.54$$

$$\tau_{nm} = 0 \; and \; hence \; principle \; stresses \; @ -22.5^{\circ}/67.5^{\circ}$$

QUESTION 2 – CONSTITUTIVE RELATIONSHIPS (20)

2.1 A test was conducted on an imaginary rock type. The observations are discussed. Complete a Stress vs. Strain graph based on the example below, tabulating your reference points as shown and name the behaviour for each region. [10]



Position	σ	ε
O	0	0
A		1
B		
C		
D		

Region	Behaviour
OA	
AB	Strain Hardening
BC	
CD	
D	

- The stress at Point A (σ_A) is determined when a Young's Modules of 70 MPa is applied.
- $\varepsilon_B = 1.5\varepsilon_A$, $\varepsilon_C = 2\varepsilon_B$, $\varepsilon_D = \varepsilon_C + 0.25\varepsilon_A$
- Region AB is a strain hardening region with E half (½) of Region OA.
- σ_C has the same value as σ_B
- Region CD indicates a drop in stress values with an increase in strain. The stress value at Point D is 80% of the peak value.

Position	σ	e
O	0	0
A	70	1
B	105	1.5
C	105	3
D	56	3.25
Region	**Behaviour**	
OA	Elastic	
AB	Strain Hardening	
BC	Plastic	
CD	Strain Softening	
D	Failure	

2.2 Assume a force of 100kN acts on the end-surface of a piece of core with original diameter of 34mm and length 68mm. If the core sample decreases in length to 63mm and increase in diameter to 35mm, determine the modulus of elasticity of the material and Poisson's ratio. [6]

To calculate E, the stress acting on a sample and the axial strain are required:

The radius r of the core

= ½ x diameter = 17mm (or 0.017m).

The area on which the force works

$= \pi r^2$

$= 3.14 \times (0.017)^2$

$= 3.14\ (0.000289)\,m^2$

$= 0.000907\,m^2$

Stress = Force / Area

= 100kN/0.000907m²

= 110.253 MPa

Axial strain (ε_a) = (change in dimension/original dimension)

= (Δ Length / original length)

= (68mm-63mm)/68mm

= 0.0735

E = Stress / Axial strain

= 110.253MPa / 0.0735

= 1.5 GPa.

When a linearly elastic body is loaded uniaxially, it will also strain in the direction perpendicular to the applied stress.
This relationship is given by the equation shown below, giving the Poisson's ratio (ratio between the strains in the two mutually perpendicular directions) even under uniaxial stress.

$V = \left|\frac{\varepsilon_t}{\varepsilon_a}\right|$ where v= Poissons ratio, ε_t = Transverse strain (perpendicular to applied stress), and ε_a = Axial strain (in direction of applied stress).

$V = \frac{\varepsilon_t}{\varepsilon_a}$ = (0.00025)/(0.0005)

= 0.5

2.3 If you are given the Young's Modulus and Poisson's Ratio, name and define the third elastic constant which you would be able to calculate. [4]

G = Modulus of Rigidity
Relates to shear stress and shear strain.

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

QUESTION 3 – ROCK STRENGTH (20)

3.1 Discuss the parameters used in the Hoek-Brown failure criterion and name 2 limitations to this theory. [4]

$$\sigma_1 = \sigma_3 + \sqrt{m\sigma_c\sigma_3 + s\sigma_c^2}$$
$$\sigma_1 = Major$$
$$\sigma_3 = Minor$$
$$\sigma_c = UCS$$
$$m, s = Rock\ Property\ constants$$
$$m = Rock\ type$$
$$s = fracture/weathering$$

Limitations include (only 2 required) Isotropic/empirical/overstate downgrading ("m", "s")/over-estimate high confinements

3.2 The quality of a rock mass is described by its Q rating of 22.5. The m and s values in the Hoek and Brown failure criterion can be calculated from the following:

$$m = 10 \times e^{\frac{(RMR-100)}{14}} \text{ and } s = e^{\frac{(RMR-100)}{6}}$$

A circular tunnel with diameter 5m is bored horizontally within this rock mass at a mining depth of 400m, under virgin stress conditions. Assume that the rock mass overburden has an average density of 2600kg/m^3, a UCS of 70 MPa and that the k-ratio in this area is 1. Answer the following questions:

3.2.1 Using the Kirsch equations, calculate and complete a table for radial and tangential stresses in the bored tunnel sidewall at the following distances into the sidewall of the tunnel: [5]

q = 10.2 MPa

Depth into sidewall	$\sigma_{\phi\phi}$	σ_{rr}
0.00	**20.40**	**0.00**
0.15	**19.28**	**1.12**
0.30	**18.34**	**2.07**
0.45	**17.53**	**2.88**

3.2.2 Estimate the depth of failure that might occur in the sidewall, based on the Hoek and Brown failure criterion, assuming that the radial and tangential stresses are also principal stresses. Clearly indicate how decisions were made. [11]

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

$$m = 1.35 \quad s = 0.01$$

Distance in Sidewall	Tangential	H&B Strenght	Failure Y/N
0	20.40	6.8	Y
0.15	19.28	13.5	Y
0.3	18.34	17.6	Y
0.45	17.53	20.7	N

QUESTION 4 – ROCKMASS PROPERTIES (20)

4.1 When applying geomechanics classification systems to classify rock masses name and discuss only 5 of the various parameters you would require as part of your Rock Engineering Data Requirements (input parameters for classification methods). [10]

Based on the Q-rating system.

- the geology (change in rock type)
- the joint sets (total number of joints, their spacing and number of joint sets) and fracturing
- the joint conditions
- the presence of veining, shearing fault/weakness zones
- the strength of the rock
- the state of weathering

4.2 An exploration borehole was logged to capture geotechnical information. The core and logging is presented below. Define RQD and determine the qaulity based on the core recovery. [3]

Core: **1050**
Recovered Core: **1050**
>100: **840**
RQD: **80%**

4.3 A 15m wide workshop for an underground mine is to be excavated in quartzite at a depth of 2500m below surface. Two sets of rough, planar and unaltered joints traverse the workshop. Laboratory tests on core samples of intact rock provide an average uni-axial compressive strength of 210MPa. The principle stress directions are approximately vertical and horizontal and the magnitude of the horizontal principle stress is approximately 0.5 times that of the vertical principle stress. The rock mass is moist but there is no evidence of flowing water. RQD values obtained from core logging were calculated as 90%. Determine the Q Index rating for the rock mass exposed in the excavation. [7]

Determining input values for the Q value calculation.

The numerical value of RQD is used directly in the calculation of Q andthe value of 90% will be used :

RQD = 90

From Figure 13 part 2 (See Connection 51) follows that, for two joint sets, the joint set number is

$J_n = 4$

For rough or irregular joints which are undulating, Figure 13 part 3 (See Connection 51) gives a joint roughness number of

$J_r = 1.5$

Figure 13 part 4 (See Connection 51) gives the joint alteration number-for unaltered joint walls with surface staining only as

$J_a = 1.0$

Figure 13 part 5 (See Connection 51) shows that for an excavation with minor water inflow, the joint water reduction factor is

$J_w = 1.0$

For a depth below surface of 2500 m the overburden stress is approximately 66MPa(2700kg/m³) yielding a major vertical principal stress σ_1 = 66MPa. Since the uni-axial compressive strength of thequartzite is given as210MPa, this gives a ratio of σ_c/σ_1 of 3.18.

Figure 13(part 6) shows that for competent rock with rock stress problems, this value of σc/σ1can be expected to produce mild rock burst conditions and that the value of SRF lie between 5 and 10.A value of

SRF = 6.3

A fast rating can be obtained by selecting the ratings closest to the parameter values. However, it is suggested that the user allocate proportionate ratings. Rating to be used is determined by determining the ratio of the calculated σ_c/σ_1 value to the lower value stipulated in Figure 13 (namely 2.5). This ratio provides a factor of 1.27 (Example: 3.18/2.5=1.27). Multiplication of the 1.27 factor with the lower rating from Figure 13 (namely 5) gives the allocated value of 6.3.

The process above will obviously improve the accuracy of any rock mass rating comparisons made between rock mass or areas within a rock mass. The user must determine whether this level of accuracy in an empirical method will provide the results required or whether it is unnecessary to go into such detail differences.

Using these values gives:

$$Q = \frac{RQD}{J_n} \times \frac{JR}{J_a} \times \frac{J_w}{SRF}$$

Q = (90/4)x(1.5/1)x(1/6.3)

<u>Q = 5.357</u>

QUESTION 5 – STRESSES IN ROCK AND ROCK MASSES (20)

5.1 Name and discuss four factors influencing primitive stress. *(½ mark for each factor and ½ mark for discussion)* [4]

- Weight of overburden – Gravitational
- Tectonic stress – Tectonic plate movement
- Individual geological structure
- Residual stresses – Previous tectonic activity
- Pore water pressure – Water

5.2 To be able to calculate in-situ stresses using various methods, a number of setups would be required depending of course on the method and the methods' limitations. For the following methods, comment on the number of setups you would require to determine the in-situ stress (How many setups and why?).

5.2.1 CSIRO Overcoring gauge method [2]

1 Set-up, 6 values

5.2.2 Hydraulic Fracturing methods [2]

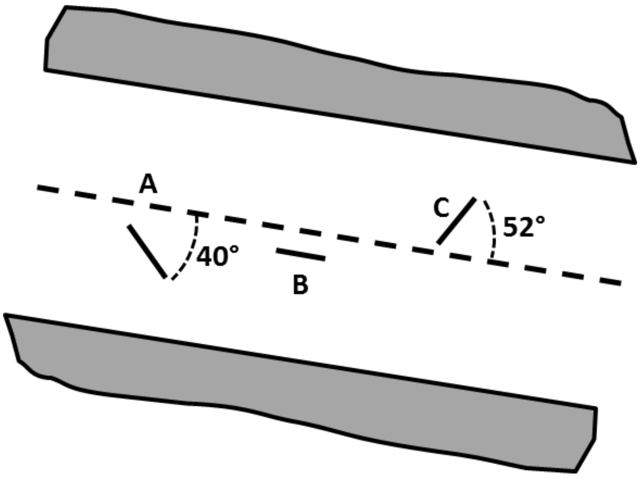
2 set-up, 4 assumptions

5.2.3 Flat Jack method [2]

6 set-ups, different orientations

ANSWER EITHER

5.3 Three flat-jack tests have been made close to each other in the wall of a long, straight tunnel, the axis of which dips at 7°. The measurement position is approximately 250m below the ground surface and it is assumed that the flat-jacks are in the same stress field. The slots for the flat-jacks were cut normal to the wall of the tunnel, and were oriented relative to the tunnel axis as shown. The cancellation pressure for each of the flat-jacks A, B and C was 7.56MPa, 6.72MPa and 7.50MPa, respectively. Compute the principal stresses and their directions. [10]



A4.4 One way of solving this problem is to use the stress transformation equations, i.e.

$$\sigma'_x = \sigma_x \cos^2\theta + \sigma_y \sin^2\theta + 2\tau_{xy} \sin\theta \cos\theta$$

where σ_x, σ_y and τ_{xy} are the global stress components, and θ is the angle between the global x axis and the direction of the stress in question.

Taking the x axis horizontal directed to the right, and the y axis vertical upwards, and all orientations measured anticlockwise positive from the positive x axis, we have the following dip angles:

$$\beta_{\text{tunnel}} = -7^\circ, \quad \beta_{\text{A}} = -40^\circ + \beta_{\text{tunnel}} = -47^\circ;$$

$$\beta_{\text{B}} = 0^\circ + \beta_{\text{tunnel}} = -7^\circ; \quad \beta_{\text{C}} = 52^\circ + \beta_{\text{tunnel}} = 45^\circ.$$

Finally, because each flatjack measures the normal stress component perpendicular to the flatjack, we add 90° to each of these directions to obtain the direction of the normal stress on each jack. Thus, the magnitude and direction of the normal stress on each jack is as follows:

$$\begin{array}{llll} \text{Jack A} & \sigma_A = 7.56\ \text{MPa}, & \theta_A = \beta_A + 90^\circ, & \theta_A = 43^\circ \\ \text{Jack B} & \sigma_B = 6.72\ \text{MPa}, & \theta_B = \beta_B + 90^\circ, & \theta_B = 83^\circ \\ \text{Jack C} & \sigma_C = 7.50\ \text{MPa}, & \theta_C = \beta_C + 90^\circ, & \theta_C = 135^\circ \end{array}$$

Assembling the stress transformation equation for all three jacks into matrix form gives

$$\begin{bmatrix} \sigma_A \\ \sigma_B \\ \sigma_C \end{bmatrix} = \begin{bmatrix} \cos^2\theta_A & \sin^2\theta_A & 2\sin\theta_A\cos\theta_A \\ \cos^2\theta_B & \sin^2\theta_B & 2\sin\theta_B\cos\theta_B \\ \cos^2\theta_C & \sin^2\theta_C & 2\sin\theta_C\cos\theta_C \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} \quad \text{or } \boldsymbol{\sigma}_{\text{jack}} = \mathbf{R}\boldsymbol{\sigma}_{\text{global}}$$

which, upon evaluation, yields

$$\begin{bmatrix} 7.56 \\ 6.72 \\ 7.50 \end{bmatrix} = \begin{bmatrix} 0.535 & 0.465 & 0.998 \\ 0.015 & 0.985 & 0.242 \\ 0.500 & 0.500 & -1.000 \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix}$$

Inverting this matrix equation gives $\boldsymbol{\sigma}_{\text{global}} = \mathbf{R}^{-1}\boldsymbol{\sigma}_{\text{jack}}$ and this evaluates as

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} 1.093 & -0.952 & 0.860 \\ -0.134 & 1.021 & 0.113 \\ 0.479 & 0.034 & -0.514 \end{bmatrix} \begin{bmatrix} 7.56 \\ 6.72 \\ 7.50 \end{bmatrix}$$

from which we find $\boldsymbol{\sigma}_{\text{global}} = \begin{bmatrix} 8.31 \\ 6.70 \\ 0.00 \end{bmatrix}$ MPa.

We see that σ_x and σ_y are principal stresses, because $\tau_{xy} = 0$, and the principal stresses are vertical and horizontal, which is a reasonable result. In addition, we have the horizontal stress, σ_x, greater than the vertical stress, σ_y, which is usually the case.

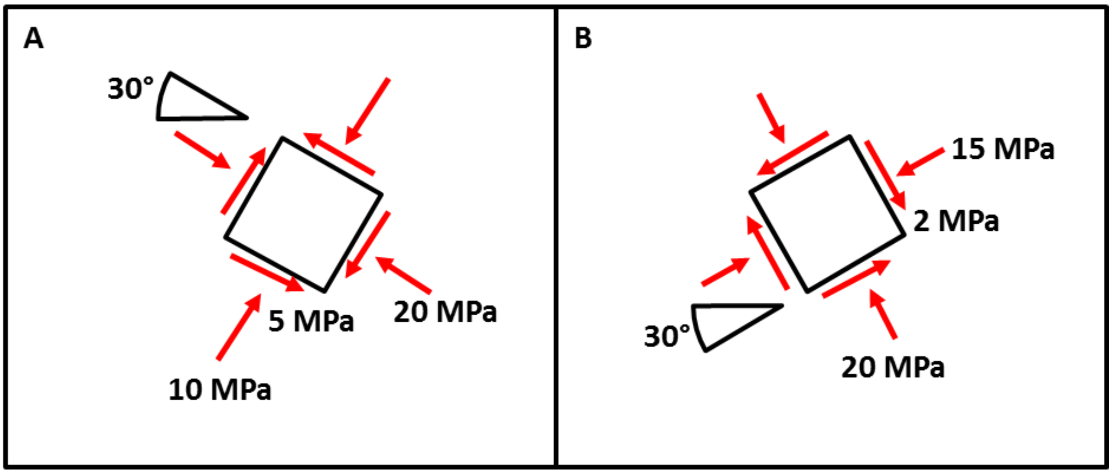
Now, to compare the vertical stress with the weight of the overburden, compute a value for the vertical stress based on the depth of the tunnel and an assumed unit weight for the rock:

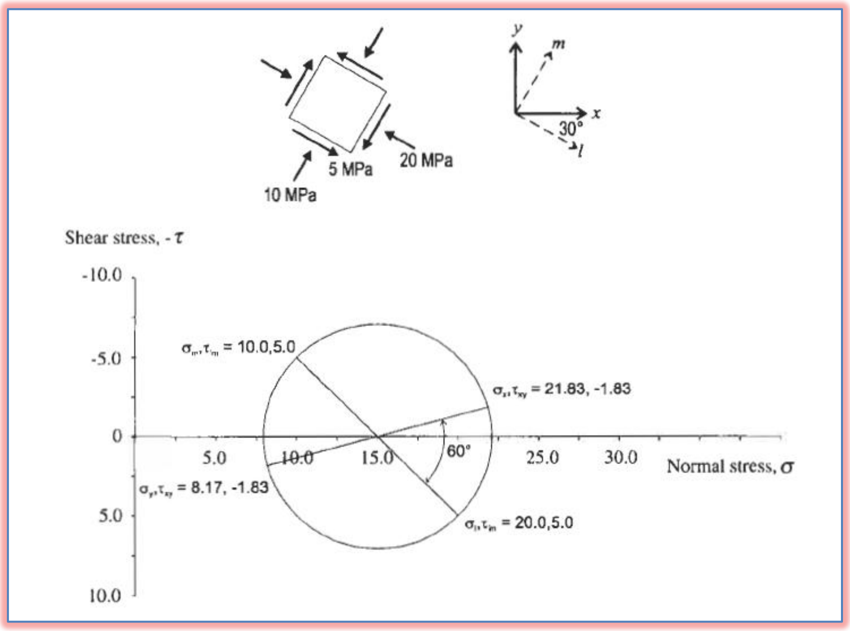
$$\gamma_{\text{rock}} = 27\ \text{kN/m}^3, \quad z = 250\ \text{m}, \quad \sigma_v = \gamma_{\text{rock}} \times z, \quad \sigma_v = 6.75\ \text{MPa}.$$

This compares well with the value for σ_y found above.

OR

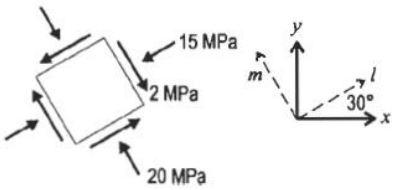
5.4 Add the following 2-D rock stress states, and find the principal stresses and directions of the resultant stress state. *HINT: Make use of the Mohr Circle* [10]

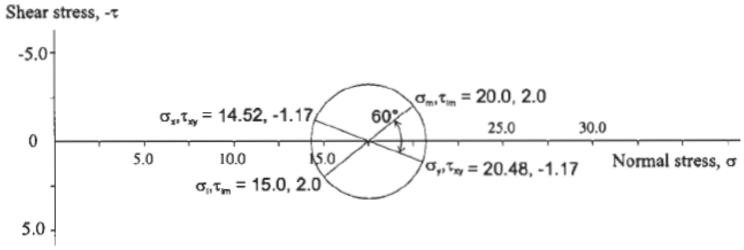




The stresses transformed to the xy axes are $\begin{bmatrix} 21.83 & -1.83 \\ -1.83 & 8.17 \end{bmatrix}$.

Draw xy and lm axes for the second stress state, and plot the corresponding Mohr circle.



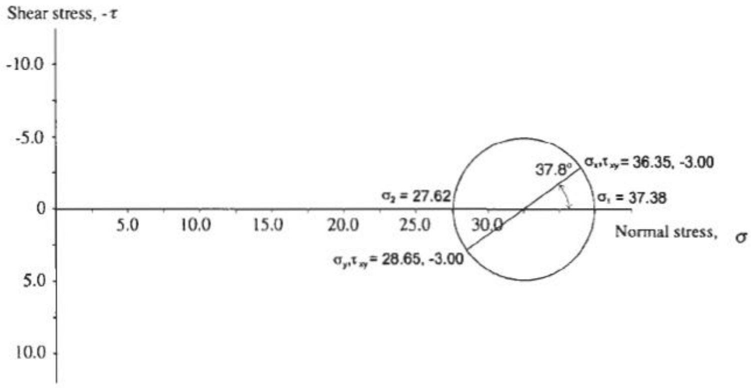


The stresses transformed to the xy axes are $\begin{bmatrix} 14.52 & -1.17 \\ -1.17 & 20.48 \end{bmatrix}$.

Adding the two xy stress states gives

$$\begin{bmatrix} 21.83 & -1.83 \\ -1.83 & 8.17 \end{bmatrix} + \begin{bmatrix} 14.52 & -1.17 \\ -1.17 & 20.48 \end{bmatrix} = \begin{bmatrix} 36.35 & -3.00 \\ -3.00 & 28.65 \end{bmatrix}.$$

Plotting the Mohr circle for the combined stress state and reading off the principal stresses and the principal directions gives the required values.



The principal stresses of the resultant stress state are $\sigma_1 = 37.38$ MPa and $\sigma_2 = 27.62$ MPa, with σ_1 being rotated 18.9° clockwise from the x-direction.

- END -

Tables for classification of the rock mass based on the Q system

1. Rock Quality Designation		**RQD**
A	Very poor	0 – 25
B	Poor	25 – 50
C	Fair	50 – 75
D	Good	75 – 90
E	Excellent	90 – 100
Note i) Where RQD is reported or measured as ≤ 10 (including 0), a nominal value of 10 is used to evaluate Q. ii) RQD intervals of 5, i.e. 100, 95, 90 etc. are sufficiently accurate		

2. Joint Set Number		**Jn**
A	Massive, no or few joints	0.5 - 1.0
B	One joint set	2
C	One joint set plus random joints	3
D	Two joint sets	4
E	Two joint sets plus random joints	6
F	Three joint sets	9
G	Three joint sets plus random joints	12
H	Four or more joint sets, random, heavily jointed, ‘sugar cube’, etc.	15
J	Crushed rock, earth like.	20
Note i) For intersections, use 3 x Jn. ii) For portals, use 2 x Jn.		

3. Joint Roughness Number		**Jr**
a) Rock wall contact, and b) rock wall contact before 10 cm shear		
A	Discontinuous joints	4
B	Rough or irregular, undulating	3
C	Smooth, undulating	2
D	Slickensided, undulating	1.5
E	Rough or irregular, planar	1.5
F	Smooth, planar	1.0
G	Slickensided, planar	0.5
Note: i) Descriptions refer to small scale features and intermediate scale features in that order		
c) No rock wall contact when sheared		
H	Zone containing clay minerals thick enough to prevent rock wall contact	1.0
J	Sandy, gravely or crushed zone thick enough to prevent rock wall contact.	1.0
Note: i) Add 1.0 if the mean spacing of the relevant joint set is greater than 3 m. ii) Jr = 0.5 can be used for planar slickensided joints having lineations, provided the lineations are orientated for minimum strength.		

4. Joint Alteration Number		**φr approx.**	**Ja**
a) Rock wall contact (no mineral filling, only coatings)			
A	Tightly healed, hard, non-softening, impermeable filling i.e. quartz or epidote.	---	0.75
B	Unaltered joint walls, surface staining only	25 - 35°	1.0
C	Slightly altered joint walls. Non-softening mineral coatings, sandy particles, clay free disintegrated rock, etc.	25 - 30°	2.0
D	Silty- or sandy-clay coatings, small clay fraction (non-softening)	20 - 25°	3.0
E	Softening or low friction clay mineral coatings i.e., kaolinite or mica. Also chlorite, talc, gypsum, graphite, etc. and small quantities of swelling clays	8 - 16°	4.0
b) Rock wall contact before 10 cm shear (thin mineral fillings)			
F	Sandy particles, clay free disintegrated rock, etc.	25 - 30°	4.0
G	Strongly over consolidated non-softening clay mineral fillings (continuous, but < 5 mm thickness)	16 - 24°	6.0
H	Medium or low over consolidation, softening, clay mineral fillings (continuous, but < 5 mm thickness)	12 - 16°	8.0
J	Swelling clay fillings, i.e. montmorillonite (continuous, but < 5 mm thickness). Value of Ja depends on percent of swelling clay-size particles, and access to water, etc.	6 - 12°	8 - 12
c) No rock wall contact when sheared (thick mineral fillings)			
K,L,M	Zones or bands of disintegrated or crushed rock and clay (see G, H, J for description of clay condition)	6 - 24°	6, 8, or 8 - 12
N	Zones or bands of silty- or sandy-clay, small clay fraction (non-softening)	---	5.0
O,P,R	Thick, continuous zones or bands of clay (see G, H, J for description of clay condition)	6 - 24°	10, 13, or 13 - 20

5. Joint Water Reduction Factor		**Water pres. (kg/cm^2)**	**Jw**
A	Dry excavations or minor inflow, i.e. < 5 l/min locally	<1	1.0
B	Medium inflow or pressure, occasional outwash of joint fillings	1 - 2.5	0.66
C	Large inflow or high pressure in competent rock with unfilled joints	2.5 - 10	0.5
D	Large inflow or high pressure, considerable outwash of joint fillings	2.5 - 10	0.33
E	Exceptionally high inflow or water pressure at blasting, decaying with time	> 10	0.2 - 0.1
F	Exceptionally high inflow or water pressure continuing without	> 10	0.1 -

	noticeable decay		0.05
Notes: i) Factors C to F are crude estimates; increase Jw if drainage measures are installed. ii) Special problems caused by ice formation are not considered.			

6. Stress Reduction Factor		**SRF**
a) Weakness zones intersecting excavation, which may cause loosening of rock mass when tunnel is excavated		
A	Multiple occurrences of weakness zones containing clay or chemically disintegrated rock, very loose surrounding rock (any depth)	10
B	Single weakness zones containing clay or chemically disintegrated rock (depth of excavation ≤ 50 m)	5
C	Single weakness zones containing clay or chemically disintegrated rock (depth of excavation > 50 m)	2.5
D	Multiple shear zones in competent rock (clay free), loose surrounding rock (any depth)	7.5
E	Single shear zones in competent rock (clay free) (depth of excavation ≤ 50 m)	5.0
F	Single shear zones in competent rock (clay free) (depth of excavation > 50 m)	2.5
G	Loose, open joints, heavily jointed or ‘sugar cube’, etc. (any depth)	5.0
Note: i) Reduce these values of SRF by 25 - 50 % if the relevant shear zones only influence but do not intersect the excavation.		

b) Competent rock, rock stress problems		**σ_c/σ_1**	**σ_θ/σ_c**	**SRF**
H	Low stress, near surface, open joints	> 200	< 0.01	2.5
J	Medium stress, favourable stress condition	200 - 10	0.01 - 0.3	1
K	High stress, very tight structure. Usually favourable to stability, may be unfavourable for wall stability	10 - 5	0.3 - 0.4	0.5 - 2
L	Moderate slabbing after > 1 hour in massive rock	5 - 3	0.5 - 0.65	5 - 50
M	Slabbing and strain-burst after a few minutes in massive rock	3 - 2	0.65 - 1	50 - 200
N	Heavy strain-burst and immediate dynamic deformations in massive rock	< 2	> 1	200 - 400
Note: ii) For strongly anisotropic virgin stress field (if measured): when 5 $\leq\sigma_1/\sigma_3\leq$ 10, reduce σ_c to 0.75 σ_c. When $\sigma_1/\sigma_3>$ 10, reduce σ_c to 0.5 σ_c. Here, σ_c = unconfined compression strength, σ_1 and σ_3 are the major and minor principal stresses, and σ_θ = maximum tangential stress (estimated from elastic theory). iii) Few case records available where depth of crown below surface is less than span width. Suggest SRF increase from 2.5 to 5 for such cases (see H)				

c) Squeezing rock: plastic flow of incompetent rock under the influence of	σ_θ/σ_c	SRF

high rock pressure.			
O	Mild squeezing rock pressure	1.5	5 - 10
P	Heavy squeezing rock pressure	> 5	10 - 20
Note: iv) Cases of squeezing rock may occur for depth H > 350 $Q^{1/3}$ (Singh et al 1992). Rock mass compression strength can be estimated from q = 7 γ $Q^{1/3}$ (MPa) where γ = rock density in gm/cc (Singh 1993).			
d) Swelling rock: chemical swelling activity depending on pressure of water			
R	Mild swelling rock pressure		5 - 0
S	Heavy swelling rock pressure		10 - 15

Note: Jr and Ja classification is applied to the joint set or discontinuity that is least favourable for stability both from the point of view of orientation and shear resistance (where $\tau = \sigma_n \tan (Jr/Ja)$
$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF}$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$Q = wV$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$R < 5$

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

$R \geq 5$

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

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

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

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

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

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

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

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

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

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

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

$$h_e = eh$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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