

Assignment 3 - Solution

(Due: 27 February, 2018 by 17:00)

- Q1.** A tunnel is to be driven through slightly weathered granite with a dominant joint set dipping at 60° against the direction of the drive. Index testing and logging of diamond drilled core give typical point load strength index values of 8 MPa and average RQD values of 70%. The slightly rough and slightly weathered joints are spaced at 300 mm, have a persistence of 2 m with no infilling material and a separation of < 1 mm. The tunnel is to be excavated at 300 m below ground level and the groundwater table is 5 m below the ground surface. The unit weight of the rock is approximately 27 kN/m^3 . The major principal stress acts horizontally and is **twice** the vertical stress. Estimate the **RMR** value, determine the **stand-up time** and propose appropriate tunneling support measures if the tunnel span is 12 m.

Solution:

Parameter	Value	Rating
Strength, $I_{s(50)}$	8 MPa	12
RQD (%)	70%	13
Joint Spacing*	300 mm = 0.3 m	10
Condition of joints	Use detailed classification table	22
Groundwater	$u/\sigma_1 = 0.18$	7
Rating adjustment	Tunnel driven against dip, dip = 60° , fair	-5
	RMR =	59

Detailed classification for the condition of joints:

Parameter	Value	Rating
Persistence (m)	2 m	4
Aperture (mm)	< 1 mm	4
Roughness	slightly rough	3
Infilling (gouge)	none	6
Weathering	slightly weathered	5
	Rating =	23

The minor principal stress is the vertical stress and is calculated as:

$$\sigma_v = \sigma_3 = \gamma \times z = 27 \times 300 = 8100 \text{ kN/m}^2 = 8.10 \text{ MPa}$$

The joint water pressure can be calculated as the pressure corresponding to 295 m of water:

$$u = \gamma_w \times z_w = 9.81 \times 295 = 2893.95 \text{ kN/m}^2 = 2.89 \text{ MPa}$$

The major principal stress is the horizontal stress and it is twice the vertical stress:

$$\sigma_h = \sigma_1 = 2\sigma_3 = 2 \times 8.10 = 16.2 \text{ MPa}$$

$$\frac{u}{\sigma_1} = \frac{2.89}{16.2} = 0.18$$

The **RMR = 59**, and rock mass is classified as Class III, Fair rock. The stand-up time of a tunnel with a 12 m-roof span is about 200 hours (between 100 and 1000 hours). Appropriate support measures will include a combination of rock bolts (length 6 m) and shotcrete (thickness 50 – 100 mm).

Q2. A 10 m-span underground tunnel is to be excavated in a norite rock mass at a depth of 900 m below surface. The rock mass contains two sets of joints controlling stability. The joints, with average spacing of 180 mm, are undulating, rough and unweathered with very minor surface staining and separation < 1mm. RQD values range from 85% to 95% and laboratory tests on core samples of intact rock give an average uniaxial compressive strength of 171 MPa. The principal stress directions are approximately vertical and horizontal and the magnitude of the horizontal principal stress is approximately 1.5 times that of the vertical principal stress. The rock mass is locally damp but there is no evidence of flowing water. Estimate **RMR, Q and GSI**. Using the **Q-index**, propose appropriate **tunneling support measures** (take ESR=1.0). Assume a unit weight of 27 kN/m³ for the rock mass and the tunnel driven parallel to the strike of the main joint set dipping at 47°.

Solution:

a) RMR

Parameter	Value	Rating
Strength, UCS	171 MPa	12
RQD (%)	85% to 95%, take a more conservative rating	17
Joint Spacing	0.18 m	8
Condition of joints	Rough and unweathered, aperture <1 mm	25
Groundwater	Damp, but no flowing water	10
Rating adjustment	Strike parallel to tunnel axis, Dip=47°, very unf.	-12
RMR =		60

The **RMR = 60**, and rock mass is classified as Class III, Fair rock.

b) Q-index

Parameter	Value	F-Ia	Value
RQD	85% to 95%, use a more conservative value	RQD	85
Joint Set Number	Two joint sets, "D"	J _n	4
Joint Roughness Number	Undulating, rough, "B"	J _r	3
Joint Alteration Number	Unweathered with very minor surface staining, "B"	J _a	1
J. water reduction factor	Damp, but no flowing water, "A"	J _w	1
Stress Reduction factor	Competent rock, $\sigma_c / \sigma_1 = 4.7$	SRF	11.75
Q =			5.43

The minor principal stress is the vertical stress and is calculated as:

$$\sigma_v = \sigma_3 = \gamma \times z = 27 \times 900 = 24300 \text{ kN} / \text{m}^2 = 24.3 \text{ MPa}$$

The major principal stress is the horizontal stress and it is 1.5 times the vertical stress:

$$\sigma_h = \sigma_1 = 1.5\sigma_3 = 1.5 \times 24.3 = 36.45 \text{ MPa}$$

$$\frac{\sigma_c}{\sigma_1} = \frac{171}{36.45} = 4.7$$

$$Q = \left(\frac{RQD}{J_n} \right) \left(\frac{J_r}{J_a} \right) \left(\frac{J_w}{SRF} \right) = \left(\frac{85}{4} \right) \left(\frac{3}{1} \right) \left(\frac{1}{11.75} \right) = 5.43$$

The **Q = 5.43**, and rock mass is classified as Class **C**, Fair rock. Appropriate support measures (reinforcement category 4) will include a combination of rock bolts (length 3 m and spacing 2.3 m) and unreinforced shotcrete (thickness 4-10 cm).

c) GSI

Parameter	Value
Rock Mass Structure	Two joint sets, intermediate between "massive" and "blocky"
J. surface conditions	rough and unweathered with very minor surface staining, "very good" to "good"
GSI =	77±5

Q3. The following triaxial compression data was recorded at failure on the basis of tests on intact rock core specimens. Pore-water pressures were not measured during the tests (assume zero).

Specimen	1	2	3	4	5	6
σ_{1f} (MPa)	330.00	363.00	412.50	450.00	530.00	630.00
σ_{3f} (MPa)	12.50	24.00	37.50	50.00	75.00	110.00

- Plot the Mohr-Coulomb failure envelope in σ_1 - σ_3 space and estimate the intact rock strength parameters (unconfined compressive strength, cohesion and internal angle of friction);
- Determine the intact rock strength parameters m_i and σ_{ci} from a plot of $(\sigma_1 - \sigma_3)^2$ vs σ_3 and plot the theoretical Hoek-Brown failure envelope in σ_1 - σ_3 space.
- You are requested to test two additional core samples of similar rock under confining stress levels of 45 and 65 MPa, respectively. At what levels of applied axial stress would you ideally expect these intact core specimens to fail?
- At several sites in an underground mine where these core specimens were

recovered, in-situ stress conditions, in terms of (σ_1, σ_3) were measured. For three sites, the major and minor principal stress components were determined to approximate:

Site	σ_1	σ_3
	(MPa)	(MPa)
A	330	10
B	350	40
C	370	80

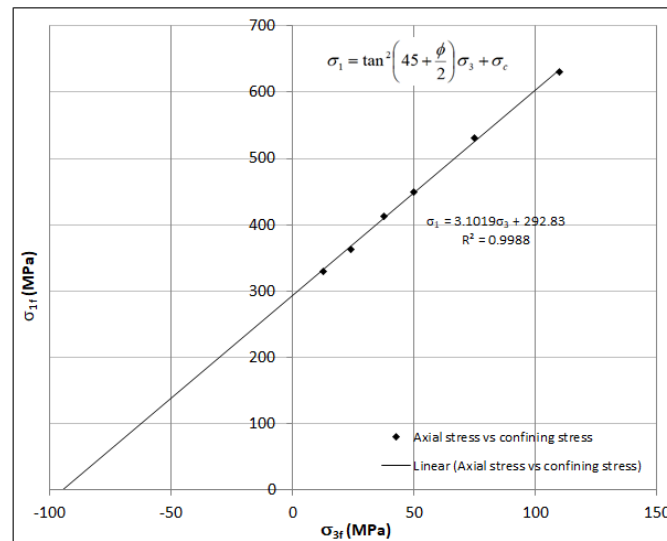
Discuss the conditions of stability that exist for these three triaxially-confined rock sites and the relative change in stability conditions which occurs as the level of rock confinement increases.

- (e). For similar intact rock material, unconfined, it is anticipated that a momentary axial stress of 350 MPa will be applied. What confinement stress must be applied to this specimen, prior to axial loading, to just prevent failure from occurring at this level of applied axial stress?

Hint: Use the Mohr-Coulomb failure criterion to answer parts (c) and (d), and the Hoek-Brown failure criterion to answer part (e).

Solution:

- a). See plot below.

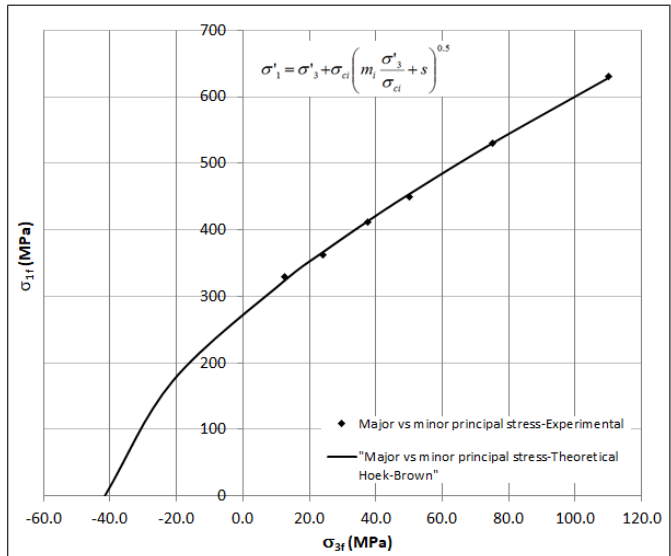
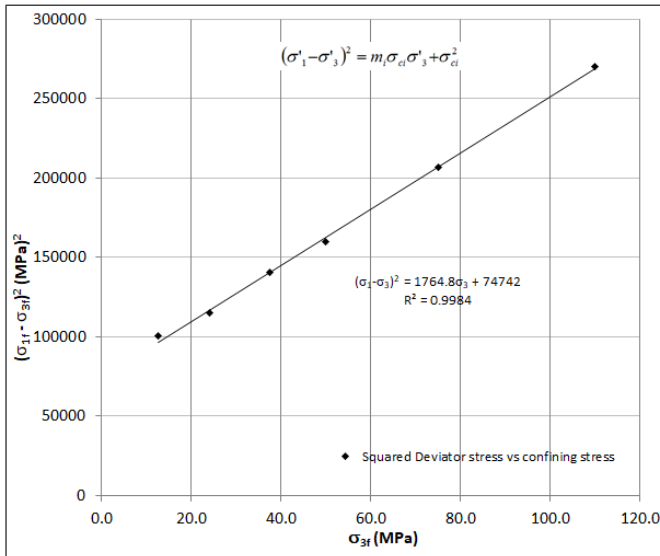


$$\sigma_{ci} = 292.83 \text{ MPa}$$

$$\tan^2\left(45 + \frac{\phi}{2}\right) = 3.1019 \rightarrow \phi = 30.8^\circ$$

$$\sigma_{ci} = 2c \tan\left(45 + \frac{\phi}{2}\right) = 2c \tan\left(45 + \frac{30.8}{2}\right) = 292.83 \rightarrow c = 83.13 \text{ MPa}$$

b). See plots below.



$$\sigma_{ci}^2 = 74742 \rightarrow \sigma_{ci} = 273.39 \text{ MPa}$$

$$m_i \sigma_{ci} = 1764.8 \rightarrow m_i = 6.46$$

The theoretical Hoek-Brown envelope is given by:

$$\sigma_1 = \sigma_3 + \sigma_{ci} \left(m_i \frac{\sigma_3}{\sigma_{ci}} + s \right)^{0.5}$$

Where $s = 1.0$ for intact rock. Substituting the values of σ_{ci} and m_i into the H-B equation:

$$\sigma_1 = \sigma_3 + 273.39 \left(6.46 \times \frac{\sigma_3}{273.39} + 1.0 \right)^{0.5}$$

c). For confining stresses (σ_3) of 45 and 65 MPa, the axial stress at failure can be determined by applying the Mohr-Coulomb failure criterion:

$$\sigma_3 = 45 \text{ MPa}$$

$$\sigma_1 = \sigma_{ci} + \sigma_3 \tan^2 \left(45 + \frac{\phi}{2} \right) = 292.83 + 45 \tan^2 \left(45 + \frac{30.8}{2} \right) = 432.27 \text{ MPa}$$

$$\sigma_3 = 65 \text{ MPa}$$

$$\sigma_1 = \sigma_{ci} + \sigma_3 \tan^2 \left(45 + \frac{\phi}{2} \right) = 292.83 + 65 \tan^2 \left(45 + \frac{30.8}{2} \right) = 494.25 \text{ MPa}$$

d). For each site, the axial stress that would cause failure at the existing confining stress can be determined by applying the Mohr-Coulomb failure criterion. Next, the existing axial stress is compared with the one determined from the Mohr-Coulomb failure envelope to evaluate the stability condition at the site.

For Site A:

$$\sigma_3 = 10 \text{ MPa}$$

$$\sigma_1 = \sigma_{ci} + \sigma_3 \tan^2 \left(45 + \frac{\phi}{2} \right) = 292.83 + 10 \tan^2 \left(45 + \frac{30.8}{2} \right) = 323.82 \text{ MPa} < \sigma_{1(\text{existing})} = 330 \text{ MPa}$$

The rock mass at the site will be **unstable** as the existing axial stress is higher than the axial stress that would produce failure.

For Site B:

$$\sigma_3 = 40 \text{ MPa}$$

$$\sigma_1 = \sigma_{ci} + \sigma_3 \tan^2 \left(45 + \frac{\phi}{2} \right) = 292.83 + 40 \tan^2 \left(45 + \frac{30.8}{2} \right) = 416.78 \text{ MPa} > \sigma_{1(\text{existing})} = 350 \text{ MPa}$$

The rock mass at the site will be **stable** as the existing axial stress is lower than the axial stress that would produce failure.

For Site C:

$$\sigma_3 = 80 \text{ MPa}$$

$$\sigma_1 = \sigma_{ci} + \sigma_3 \tan^2 \left(45 + \frac{\phi}{2} \right) = 292.83 + 80 \tan^2 \left(45 + \frac{30.8}{2} \right) = 540.72 \text{ MPa} > \sigma_{1(\text{existing})} = 370 \text{ MPa}$$

The rock mass at the site will be stable as the existing axial stress is **lower** than the axial stress that would produce failure.

As the level of rock confinement (i.e., the confining stress) increases with depth, the stability is improved.

e). The confining stress required to just prevent failure is calculated from the H-B failure envelope:

$$\sigma_1 = 350 \text{ MPa}$$

$$\sigma_1 = \sigma_3 + 273.39 \left(6.46 \times \frac{\sigma_3}{273.39} + 1.0 \right)^{0.5}$$

$$350 = \sigma_3 + 273.39 \left(6.46 \times \frac{\sigma_3}{273.39} + 1.0 \right)^{0.5} \rightarrow \sigma_3 = 19.53 \text{ MPa}$$

- Q4.** A long tunnel of circular cross section is located 900 m below ground surface. In the plane perpendicular to the tunnel axis, the in-situ principal stresses are vertical and horizontal. The vertical stress, σ_v is equal to the overburden stress, and the horizontal stress is defined by $0.2\sigma_v$. The unit weight of the rock mass is 28 kN/m^3 , the compressive strength is defined by the Mohr Coulomb failure criterion with $c = 3.3 \text{ MPa}$ and $\phi = 28^\circ$.
- (a). Will the rock fail ('burst') into the excavated tunnel?
- (b). What level of prestressing (i.e., σ_3) in the form of struts, rock bolting and so on is required to ensure that the tunnel can just resist the failure?

Solution:

a). Note that:

The major principal stress is the vertical stress and is calculated as:

$$\sigma_v = \sigma_1 = \gamma \times z = 28 \times 900 = 25200 \text{ kN/m}^2 = 25.2 \text{ MPa}$$

The minor principal stress is the horizontal stress and it is 0.2 times the vertical stress:

$$\sigma_h = \sigma_3 = 0.2\sigma_1 = 0.2 \times 25.2 = 5.04 \text{ MPa}$$

The maximum vertical stress the rock can withstand at this level of confinement is given by:

$$\sigma_3 = 5.04 \text{ MPa}$$

$$\sigma_{ci} = 2c \tan\left(45 + \frac{\phi}{2}\right) = 2(3.3) \tan\left(45 + \frac{28}{2}\right) = 10.98 \text{ MPa}$$

$$\sigma_1 = \sigma_{ci} + \sigma_3 \tan^2\left(45 + \frac{\phi}{2}\right) = 10.98 + 5.04 \tan^2\left(45 + \frac{28}{2}\right) = 24.94 \text{ MPa} < \sigma_{1(\text{existing})} = 25.2 \text{ MPa}$$

The rock will burst into the tunnel as the existing vertical stress is greater than the vertical stress at failure.

b). To prevent failure, lateral support should be provided in the form of bolting, struts, etc. Set:

$$\sigma_1 = \sigma_{1(\text{existing})} = 25.2 \text{ MPa}$$

$$\sigma_1 = \sigma_{ci} + \sigma_3 \tan^2\left(45 + \frac{\phi}{2}\right)$$

$$25.2 = 10.98 + \sigma_3 \tan^2\left(45 + \frac{28}{2}\right) \rightarrow \sigma_{3(\text{required})} = 5.13 \text{ MPa}$$

The additional lateral support is given by:

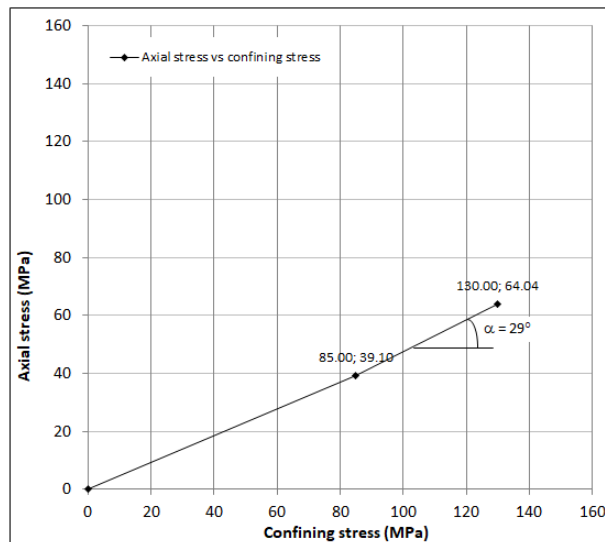
$$\sigma_{3(\text{support})} = \sigma_{3(\text{required})} - \sigma_{3(\text{existing})} = 5.13 - 5.04 = 0.09 \text{ MPa}$$

Q5. A strain-controlled compression test has been conducted on a weak soapstone such that the specimen length remained unchanged throughout: as the axial stress, σ_a , was increased, so the confining pressure, p , was increased so that **no net axial strain resulted**. A plot of axial stress (vertical axis) against confining pressure (horizontal axis) gave an initial straight line passing through the origin. At a critical confining pressure of $p = 85$ MPa (when $\sigma_a = 39.1$ MPa), the slope of the σ_a vs p plot suddenly changed to 29° and remained constant for the rest of the test. This change in slope may be taken to represent the **yield point**.

- Determine the Poisson's ratio, ν of the rock from the slope of the initial portion of the σ_a vs p plot extending from the origin to the yield point. (Hint: Assume the Hooke's law is valid and use the elastic equations.)
- Assuming that the Mohr-Coulomb criterion is applicable beyond the yield point, determine σ_{ci} , c and ϕ for the rock. (Hint: Plot σ_1 vs σ_3 and extend the Mohr-Coulomb linear envelope to intersect the vertical axis).

Solution:

a). See plot below.



Assume validity of Hooke's law and apply the axial strain elastic equation:

$$\varepsilon_a = \frac{1}{E}(\sigma_a - 2\nu p) \text{ and note that the axial strain, } \varepsilon_a = 0$$

$$0 = \frac{1}{E}(\sigma_a - 2\nu p) \rightarrow \sigma_a = 2\nu p, \text{ which is the equation of a straight line with a slope} = 2\nu.$$

The slope of the initial portion of the plot is given by:

$$\text{slope} = \frac{39.10 - 0}{85.0 - 0} = 0.46$$

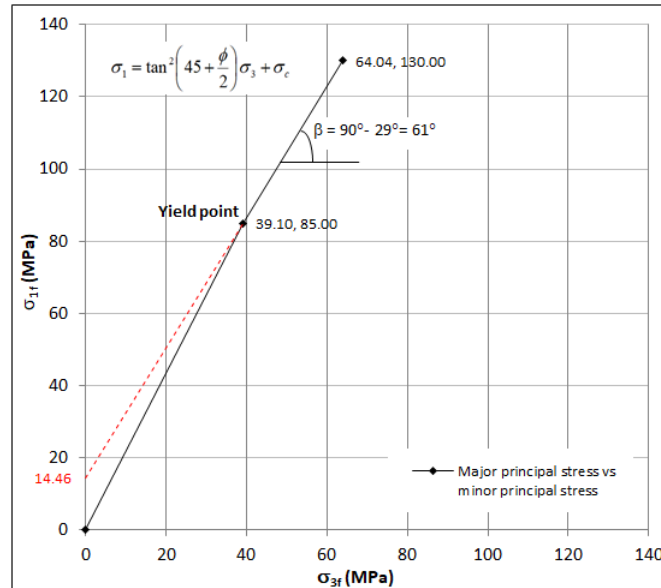
$$2\nu = 0.46 \rightarrow \nu = 0.23$$

Use the information about the angle of inclination of the line extending beyond the yield point to obtain the coordinates of another arbitrary point on that line.

For $x = 130 \text{ MPa} \rightarrow y = 39.10 + (130 - 85) \tan 29^\circ = 64.04 \text{ MPa}$

b). See plot below and note that the major principal stress is the confining stress and the minor principal stress is the axial stress, i.e.

$$\sigma_a = \sigma_3 \text{ and } p = \sigma_1$$



The Mohr-Coulomb linear envelope (second portion of the plot beyond the yield point) is then extended to intersect the vertical axis:

$$x = 0 \text{ Pa} \rightarrow \sigma_{ci} = y = 85 - (39.10 - 0) \tan 61^\circ = 14.46 \text{ MPa}$$

$$\sigma_{ci} = 14.46 \text{ MPa}$$

$$\tan^2\left(45 + \frac{\phi}{2}\right) = \tan 61^\circ = 1.804 \rightarrow \phi = 16.7^\circ$$

$$\sigma_{ci} = 2c \tan\left(45 + \frac{\phi}{2}\right) = 2c \tan\left(45 + \frac{16.7}{2}\right) = 14.46 \rightarrow c = 5.4 \text{ MPa}$$