Chapter 8. Strength of rock and rock masses

1. Definitions

(1) Intact rock: - The unfractured blocks which occur between structural discontinuities in a typical rock mass

- Ranging from a few millimeters to several meters in size

- Generally elastic and isotropic

(2) Joints - A particular type of geological discontinuity

(3) Strength - The maximum stress level which can be carried by a specimen

2. Strength of intact rock

(1) Hoek and Brown's attempt:

- The failure criterion of good agreement with rock strength values (50 mmϕ, core orientation $\perp$ discontinuity surface)

- Mathematically simple expression

- Possibly of extension to deal with the failure of jointed rock mass

Hoek and Brown's attempt:

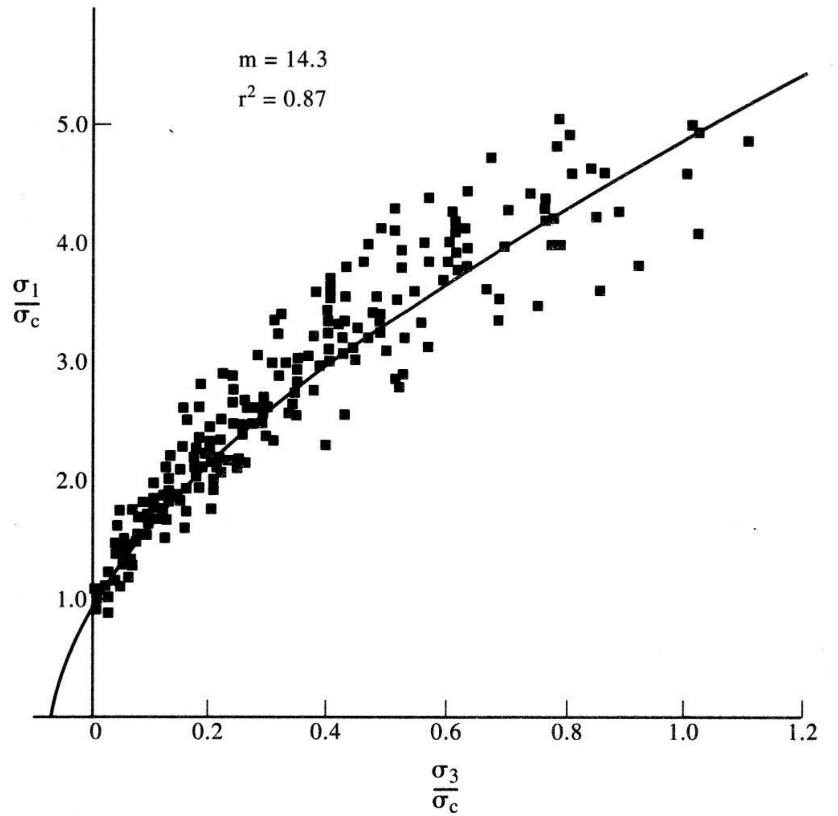

Figure 6.20 The Hoek–Brown empirical failure criterion.

Compare with Mohr-Coulomb failure criterion?

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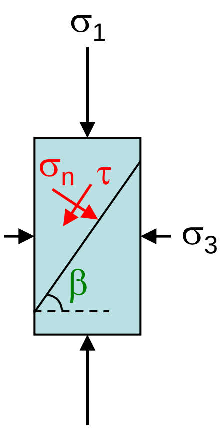


Shear strength

$$\boxed{\tau = c + \sigma_n \tan\phi}$$

c = cohesion
ϕ = friction angle

Stresses acting on the shear surface

$$\sigma_n = \frac{1}{2}(\sigma_1 + \sigma_3) + \frac{1}{2}(\sigma_1 - \sigma_3)\cos 2\beta$$

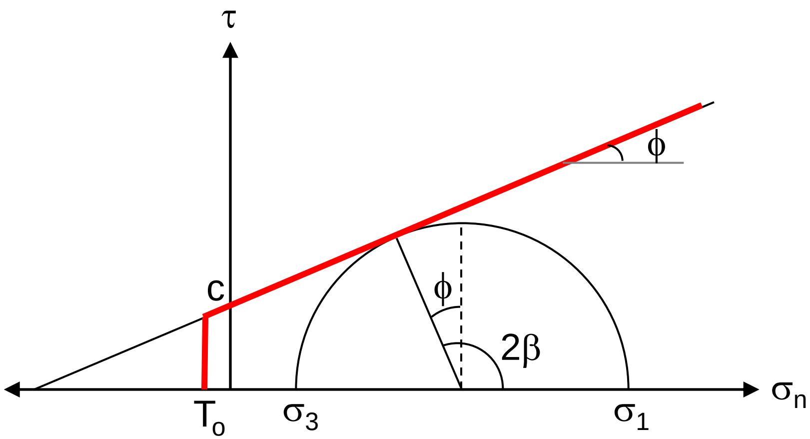
$$\tau = \frac{1}{2}(\sigma_1 - \sigma_3)\sin 2\beta$$

Therefore,

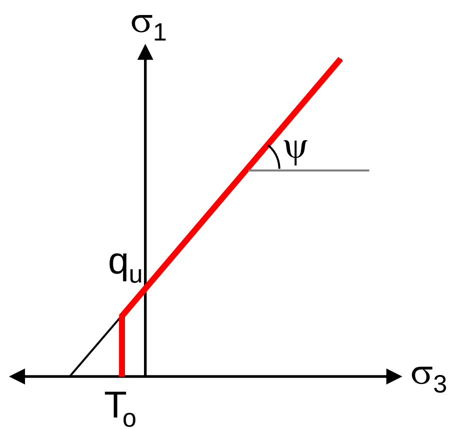
$$\frac{1}{2}(\sigma_1 - \sigma_3)\sin 2\beta = c + \left\{\frac{1}{2}(\sigma_1 + \sigma_3) + \frac{1}{2}(\sigma_1 - \sigma_3)\cos 2\beta\right\}\tan\phi$$

Solving for σ_1,

$$\sigma_1 = \frac{2c + \sigma_3\{\sin 2\beta + \tan\phi(1 - \cos 2\phi)\}}{\sin 2\beta - \tan\phi(1 + \cos 2\beta)}$$



$$\tau = c + \sigma_n \tan\phi$$



$$\sigma_1 = q_u + \sigma_3 \tan\psi$$

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

$$= \frac{2c \cdot \cos\phi}{1 - \sin\phi} + \sigma_3 \frac{1 + \sin\phi}{1 - \sin\phi}$$

2. Strength of intact rock

(2) Hoek and Brown failure criterion

$$\sigma_1' = \sigma_3' + \sigma_c \left(m_i \frac{\sigma_3'}{\sigma_c} + 1 \right)^{\frac{1}{2}}$$

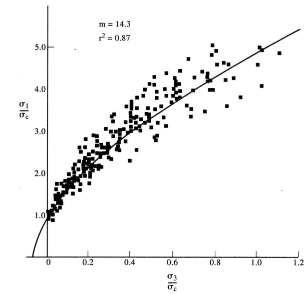


Figure 6.20 The Hoek–Brown empirical failure criterion.

σ_1': major principal effective stress at failure
σ_3': minor principal effective stress at failure
σ_c: uniaxial compressive strength of the intact rock (50 mmϕ $\times$ 100 mmH lab test result)
m_i: material constant for the intact rock

For smaller diameter (d in mm) cores,

$$\sigma_c = \frac{\sigma_{cd}}{\left(\frac{50}{d}\right)^{0.18}}$$

Ex) For 35 mmϕ, σ_{cd} = 90 MPa was obtained.

$$\sigma_c = \frac{90\,\mathrm{MPa}}{\left(\frac{50}{35}\right)^{0.18}} = 90\,\mathrm{MPa} \times 0.938 = 84\,\mathrm{MPa}$$

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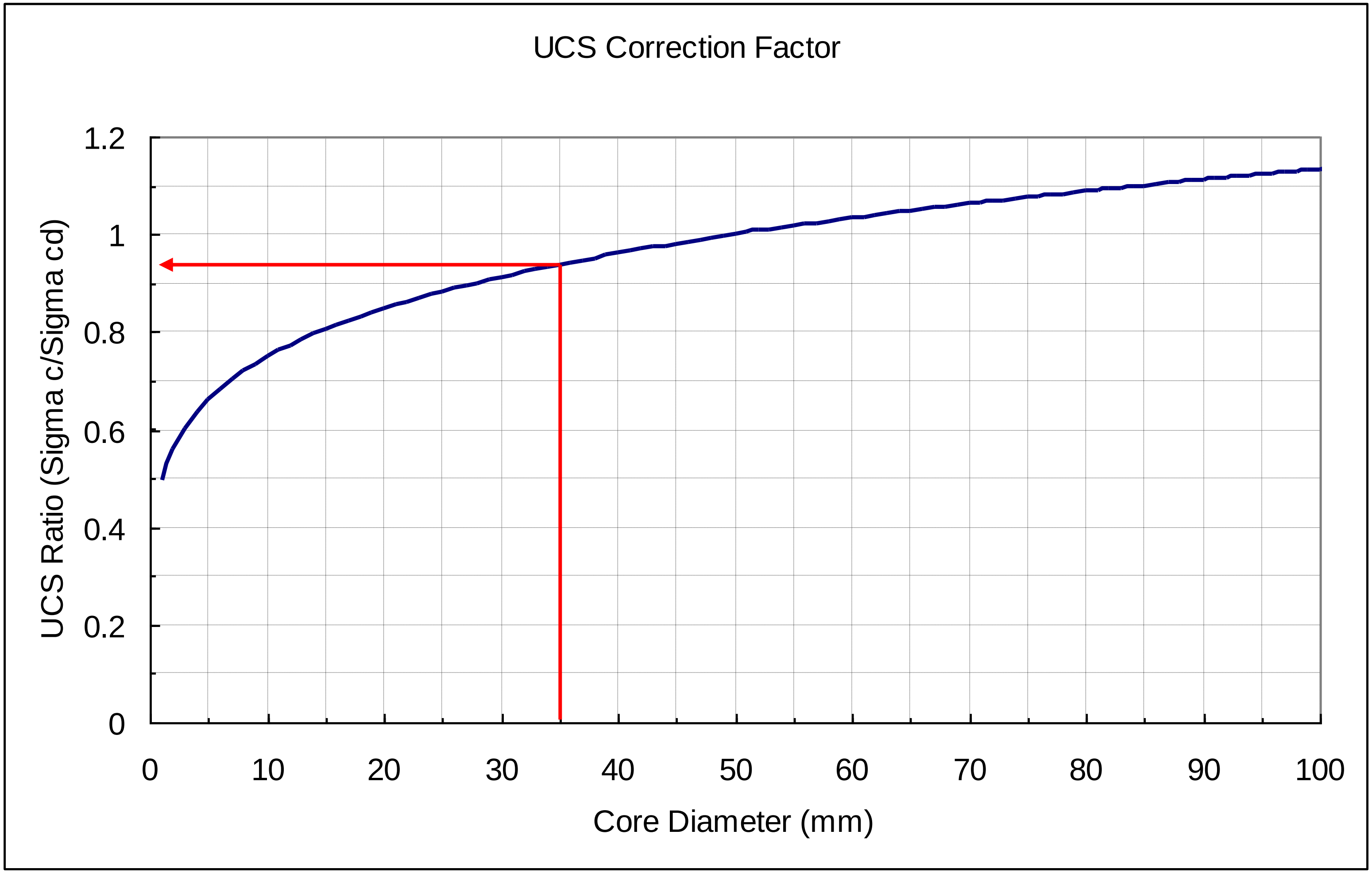
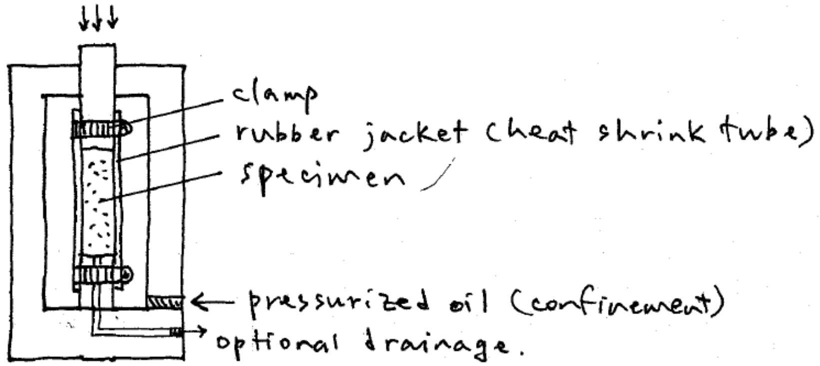


$$\sigma_c = \frac{\sigma_{cd}}{(50/d)^{0.18}} \qquad \frac{\sigma_c}{\sigma_{cd}} = \frac{1}{(50/d)^{0.18}}$$

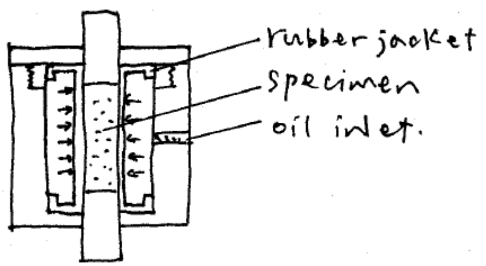
2. Strength of intact rock

(3) σ_c and m_i obtained from the results of triaxial tests

- Conventional triaxial cell

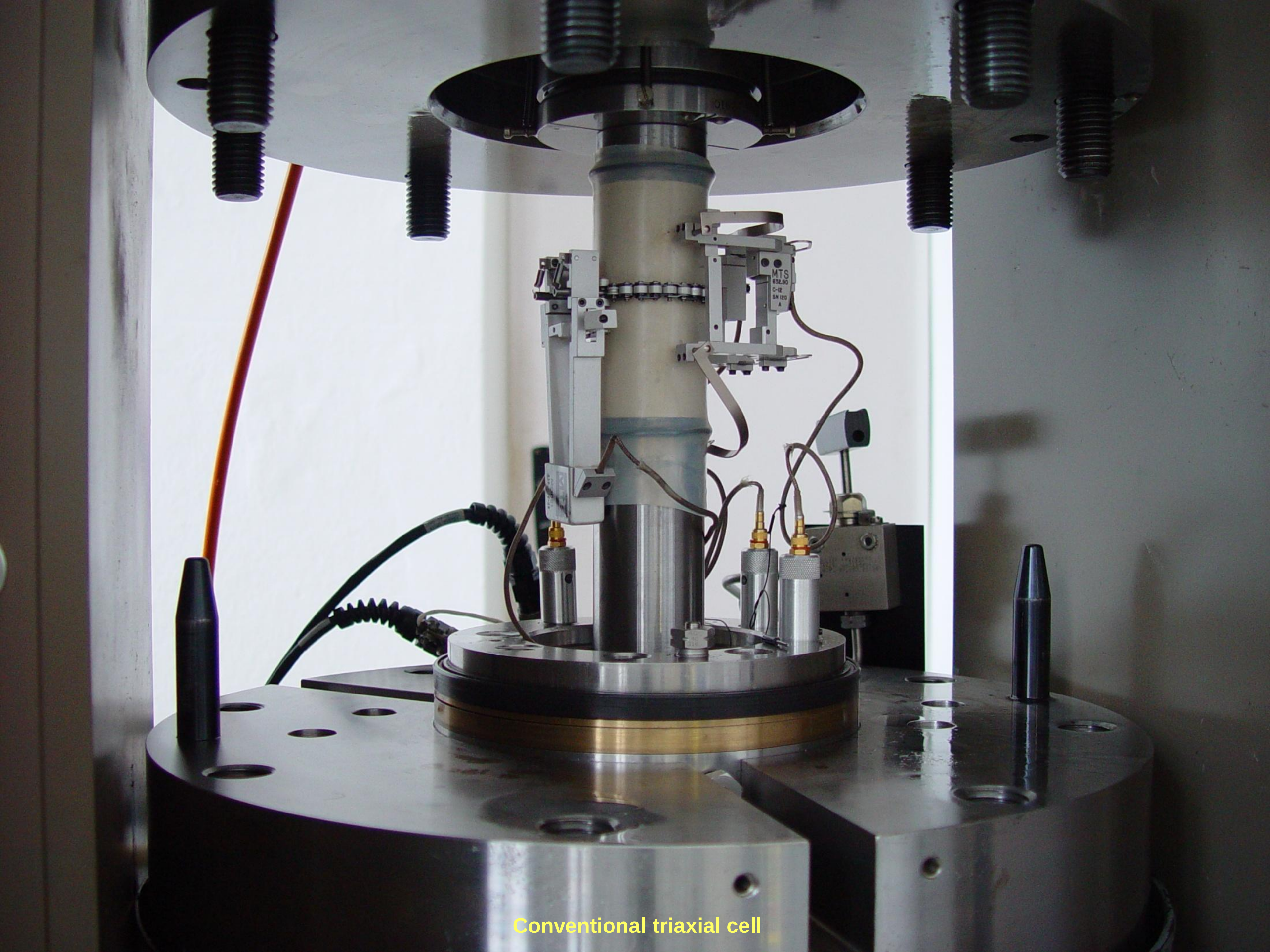


- Hoek cell

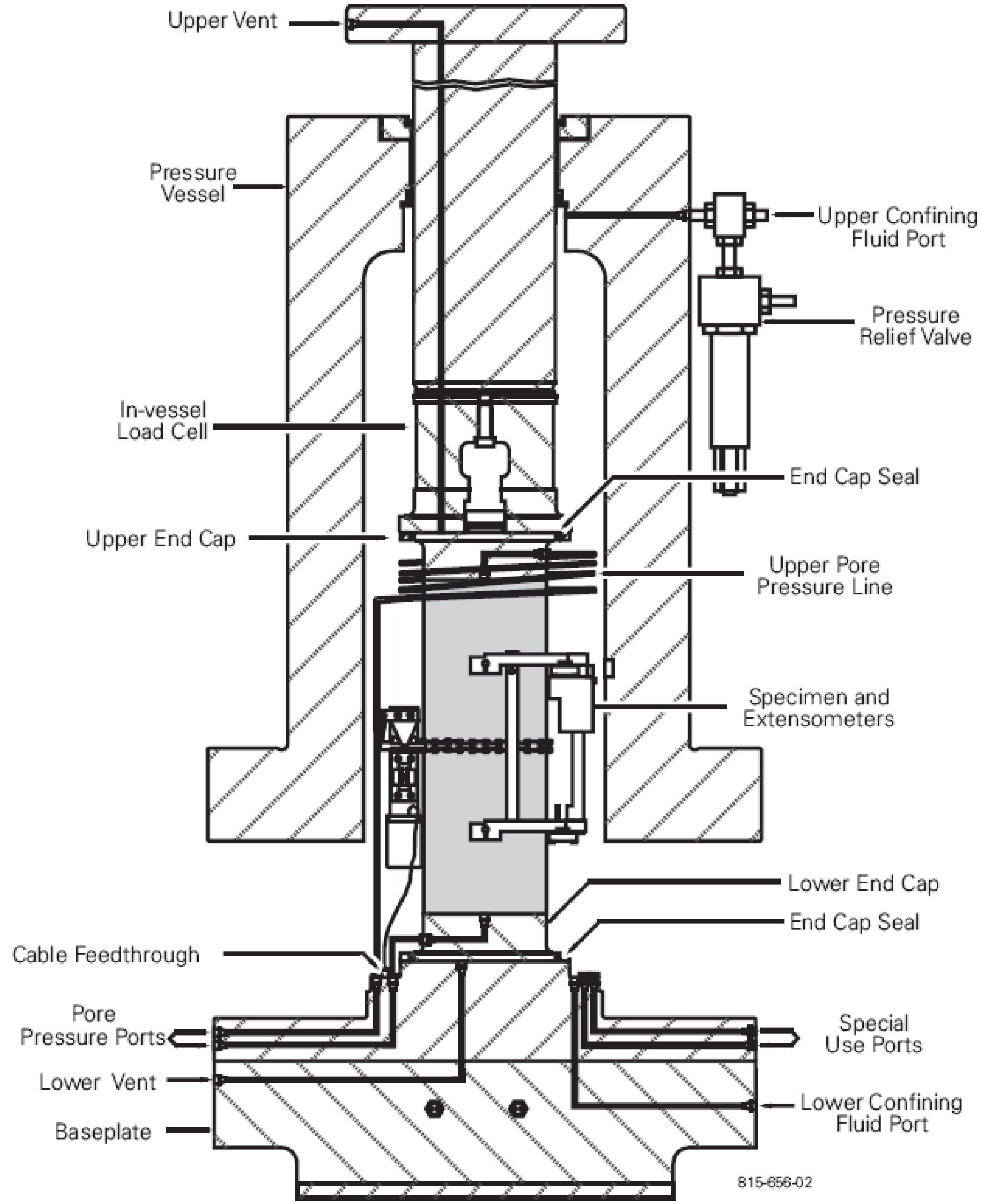


Conventional triaxial cell

Conventional triaxial cell

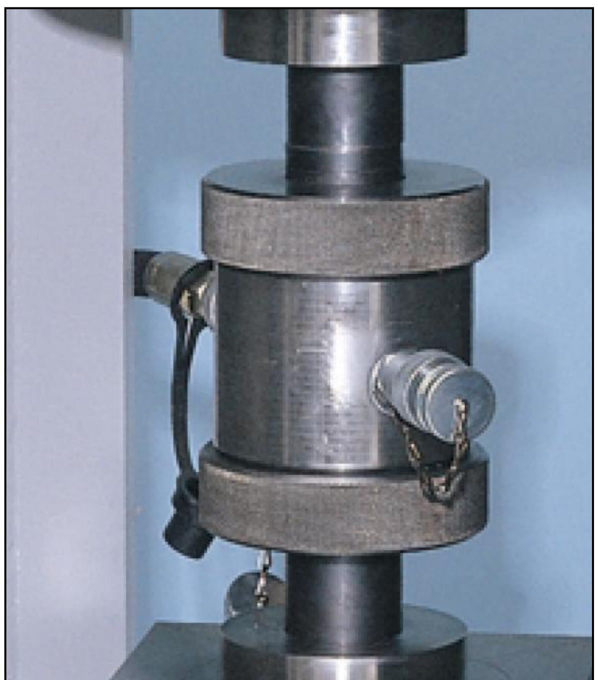


Conventional triaxial cell



Typical Triaxial Cell Assembly


ROCTEST



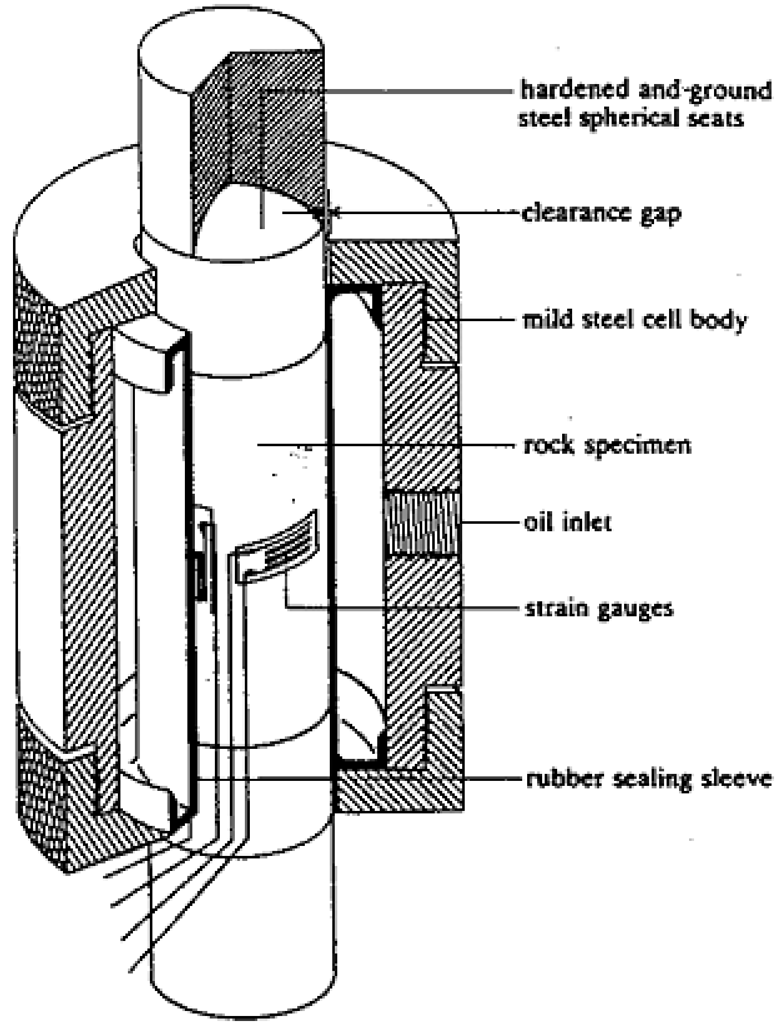
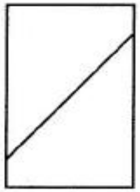
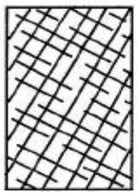
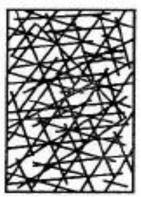

hardened and ground steel spherical seats
clearance gap
mild steel cell body
rock specimen
oil inlet
strain gauges
rubber sealing sleeve

Table 8.1: Summary of rock mass characteristics, testing methods and theoretical considerations.

	Description	Strength characteristics	Strength testing considerations	Theoretical
	Intact rock	Brittle, elastic and generally isotropic behaviour	Triaxial testing of core specimens relatively simple and inexpensive and results are usually reliable	Behaviour of elastic isotropic rock is adequately understood for most pracical applications
	Intact rock with a single inclined discontinuity	Highly anisotropic, depending on shear strength and inclination of discontinuity	Triaxial tests difficult and expensive. Direct shear tests preferred. Careful interpretation of results required	Behaviour of discontinuities adequately understood for most practical applications
	Massive rock with a few sets of discontinuities	Anisotropic, depend-ing on number, orientation and shear strength of discontinuities	Laboratory testing very difficult because of sample disturbance and equipment size limitations	Behaviour of complex block interaction in sparsely jointed rock masses poorly understood
	Heavily jointed rock masses	Reasonably isotropic, highly dilatant at low stress levels with particle breakage at high stress levels	Triaxial testing of representative samples extremely difficult because of sample disturbance	Behaviour of interlocking angular pieces poorly understood
	Compacted rockfill or weakly cemented conglomerates	Reasonably isotropic, less dilatant and lower strength than in situ rock due to destruction of fabric	Triaxial testing simple but expensive due to large equipment required to accommodate samples	Behaviour reasonably well understood from soil mechanics studies on granular materials
	Loose waste rock or gravel	Poor compaction and grading allow particle movement resulting in mobility and low strength	Triaxial or direct shear testing simple but expensive due to large size of equipment	Behaviour of loosely compacted waste rock and gravel adequately understood for most applications

2. Strength of intact rock

(4) Tables can be used for σ_c and m_i instead of triaxial tests

Table 8.2: Field estimates of uniaxial compressive strength.

Grade*	Term	Uniaxial comp. strength (MPa)	Point load index (MPa)	Field estimate of strength	Examples**
R6	Extremely strong	> 250	>10	Rock material only chipped under repeated hammer blows, rings when struck	Fresh basalt, chert, diabase, gneiss, granite, quartzite
R5	Very strong	100-250	4-10	Requires many blows of a geological hammer to break intact rock specimens	Amphibolite, sandstone, basalt, gabbro, gneiss, granodiorite, limestone, marble, rhyolite, tuff
R4	Strong	50-100	2-4	Hand held specimens broken by a single blow of geological hammer	Limestone, marble, phyllite, sandstone, schist, shale
R3	Medium strong	25-50	1-2	Firm blow with geological pick indents rock to 5 mm, knife just scrapes surface	Claystone, coal, concrete, schist, shale, siltstone
R2	Weak	5-25	***	Knife cuts material but too hard to shape into triaxial specimens	Chalk, rocksalt, potash
R1	Very weak	1-5	***	Material crumbles under firm blows of geological pick, can be shaped with knife	Highly weathered or altered rock
R0	Extremely weak	0.25-1	***	Indented by thumbnail	Clay gouge

* Grade according to ISRM (1981).

**All rock types exhibit a broad range of uniaxial compressive strengths which reflect the heterogeneity in composition and anisotropy in structure. Strong rocks are characterised by well interlocked crystal fabric and few voids.

***Rocks with a uniaxial compressive strength below 25 MPa are likely to yield highly ambiguous results under point load testing.

Table 8.3: Values of the constant m_i for intact rock, by rock group. Note that values in parenthesis are estimates.

Rock type	Class	Group	Texture: Course	Texture: Medium	Texture: Fine	Texture: Very fine
SEDIMENTARY	Clastic		Conglomerate (22)	Sandstone 19	Siltstone 9	Claystone 4
				← Greywacke (18) →		
	Non-Clastic	Organic		← Chalk 7 →		
				← Coal (8-21) →		
		Carbonate	Breccia (20)	Sparitic Limestone (10)	Micritic Limestone 8	
		Chemical		Gypstone 16	Anhydrire 13	
METAMORPHIC	Non Foliated		Marble 9	Hornfels (19)	Quartzite 24	
	Slightly foliated		Migmatite (30)	Amphibolite 31	Mylonites (6)	
	Foliated*		Gneiss 33	Schists (10)	Phyllites (10)	Slate 9
IGNEOUS	Light		Granite 33		Rhyolite (16)	Obsidian (19)
			Granodiorite (30)		Dacite (17)	
	Dark		Diorite (28)		Andesite 19	
			Gabbro 27	Dolerite (19)	Basalt (17)	
			Norite 22			
	Extrusive pyroclastic type		Agglomerate (20)	Breccia (18)	Tuff (15)	

*These values are for intact rock specimens tested normal to foliation. The value of m_i will be significantly different if failure occurs along a foliation plane (Hoek, 1983).

3. Strength of jointed rock masses

For intact rock,

$$\sigma_1' = \sigma_3' + \sigma_c \left(m_i \frac{\sigma_3'}{\sigma_c} + 1 \right)^{\frac{1}{2}}$$

(1) General form of the Hoek-Brown criterion

$$\sigma_1' = \sigma_3' + \sigma_c \left(m_b \frac{\sigma_3'}{\sigma_c} + s \right)^a \qquad \frac{\sigma_1'}{\sigma_c} = \frac{\sigma_3'}{\sigma_c} + \left(m_b \frac{\sigma_3'}{\sigma_c} + s \right)^a$$

s, a = constants (characteristics of the rock mass)

σ_1', σ_3': axial and confining effective principal stresses

σ_c: uniaxial compressive strength of intact rock piece

m_b: value of the constant m for the rock mass

(2) For most rocks of good to reasonable quality (tightly interlocking angular rock pieces): a = 0.5

$$\sigma_1' = \sigma_3' + \sigma_c \sqrt{m_b \frac{\sigma_3'}{\sigma_c} + s}$$

(3) For poor quality rock mass (no tensile strength or cohesion): s = 0

$$\sigma_1' = \sigma_3' + \sigma_c \left(m_b \frac{\sigma_3'}{\sigma_c} \right)^a$$

(4) Above equations are of no practical value unless m_b, s and a can be estimated in some way.

- **Hoek & Brown (1988) suggested a method to estimate them from RMR (≥ 25)**
- **Not satisfactory for all rock qualities**

Table 5.8. Approximate relationship between rock mass quality and constants (after Hoek and Brown, 1980)

Empirical failure criterion $\sigma_1 = \sigma_3 + \sqrt{m\sigma_c\sigma_3 + s\sigma_c^2}$ σ_1 = major principal stress; σ_3 = minor principal stress; σ_c = uniaxial compressive strength of intact rock, and m, s = empirical constants	Carbonate rocks with well developed crystal cleavage Dolomite, limestone and marble	Lithified argillaceous rocks Mudstone, siltstone, shale and slate (normal to cleavage)	Arenaceous rocks with strong crystals and poorly developed crystal cleavage Sandstone and quartzite	Fine grained polymineralic igneous crystalline rocks Andesite, dolerite, diabase and rhyolite	Coarse grained polymineralic igneous and metamorphic crystalline rocks
Intact rock samples					
Laboratory size specimens free from joints RMR = 100 Q rating 500	$m = 7.0$ $s = 1.0$	$m = 10.0$ $s = 1.0$	$m = 15.0$ $s = 1.0$	$m = 17.0$ $s = 1.0$	$m = 2$ $s = 1$
Very good quality rock mass					
Tightly interlocking undisturbed rock with unweathered joints at 1 to 3 m RMR = 85 Q rating 100	$m = 3.5$ $s = 0.1$	$m = 5.0$ $s = 0.1$	$m = 7.5$ $s = 0.1$	$m = 8.5$ $s = 0.1$	$m = 1$ $s = 0$
Good quality rock mass					
Fresh to slightly weathered rock, slightly disturbed with joints at 1 to 3 m RMR = 65 Q rating 10	$m = 0.7$ $s = 0.004$	$m = 1.0$ $s = 0.004$	$m = 1.5$ $s = 0.004$	$m = 1.7$ $s = 0.004$	$m = 2$ $s = 0$
Fair quality rock mass					
Several sets of moderately weathered joints spaced at 0.3 to 1 m RMR = 44 Q rating 1	$m = 0.14$ $s = 0.0001$	$m = 0.20$ $s = 0.0001$	$m = 0.30$ $s = 0.0001$	$m = 0.34$ $s = 0.0001$	$m = 0$ $s = 0$
Poor quality rock mass					
Numerous weathered joints at 30 to 500 mm with some gouge. Clean compacted waste rock RMR = 23 Q rating 0.1	$m = 0.04$ $s = 0.00001$	$m = 0.05$ $s = 0.00001$	$m = 0.08$ $s = 0.00001$	$m = 0.09$ $s = 0.00001$	$m = 0$ $s = 0$
Very poor quality rock mass					
Numerous heavily weathered joints spaced < 50 mm with gouge. Waste rock with fines RMR = 3 Q rating 0.01	$m = 0.007$ $s = 0$	$m = 0.010$ $s = 0$	$m = 0.015$ $s = 0$	$m = 0.017$ $s = 0$	$m = 0$ $s = 0$

Notation: RMR – rock mass rating from the Geomechanics Classification;
Q – quality of rock mass from the Q-System.

Table 8.4: Estimation of constants m_b/m_i, s, a, deformation modulus E and the Poisson's ratio ν for the Generalised Hoek-Brown failure criterion based upon rock mass structure and discontinuity surface conditions. Note that the values given in this table are for an *undisturbed* rock mass.

GENERALISED HOEK-BROWN CRITERION

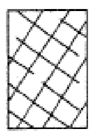
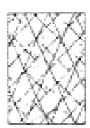
$$\sigma_1' = \sigma_3' + \sigma_c \left(m_b \frac{\sigma_3'}{\sigma_c} + s \right)^a$$

σ_1' = major principal effective stress at failure

σ_3' = minor principal effective stress at failure

σ_c = uniaxial compressive strength of *intact* pieces of rock

m_b, s and a are constants which depend on the composition, structure and surface conditions of the rock mass

STRUCTURE	SURFACE CONDITION	VERY GOOD Very rough, unweathered surfaces'	GOOD Rough, slightly weathered, iron stained surfaces	FAIR Smooth, moderately weathered or altered surfaces	POOR Slickensided, highly weathered surfaces with compact coatings or fillings containing angular rock fragments	VERY POOR Slickensided, highly weathered surfaces with soft clay coatings or fillings
 BLOCKY -very well interlocked undisturbed rock mass consisting of cubical blocks formed by three orthogonal discontinuity sets	m_b/m_i s a E_m ν GSI	0.60 0.190 0.5 75,000 0.2 85	0.40 0.062 0.5 40,000 0.2 75	0.26 0.015 0.5 20,000 0.25 62	0.16 0.003 0.5 9,000 0.25 48	0.08 0.0004 0.5 3,000 0.25 34
 VERY BLOCKY-interlocked, partially disturbed rock mass with multifaceted angular blocks formed by four or more discontinuity sets	m_b/m_i s a E_m ν GSI	0.40 0.062 0.5 40,000 0.2 75	0.29 0.021 0.5 24,000 0.25 65	0.16 0.003 0.5 9,000 0.25 48	0.11 0.001 0.5 5,000 0.25 38	0.07 0 0.53 2,500 0.3 25
 BLOCKY/SEAMY-folded and faulted with many intersecting discontinuities forming angular blocks	m_b/m_i s a E_m ν GSI	0.24 0.012 0.5 18,000 0.25 60	0.17 0.004 0.5 10,000 0.25 50	0.12 0.001 0.5 6,000 0.25 40	0.08 0 0.5 3,000 0.3 30	0.06 0 0.55 2,000 0.3 20
 CRUSHED-poorly interlocked, heavily broken rock mass with a mixture of angular and rounded blocks	m_b/m_i s a E_m ν GSI	0.17 0.004 0.5 10,000 0.25 50	0.12 0.001 0.5 6,000 0.25 40	0.08 0 0.5 3,000 0.3 30	0.06 0 0.55 2,000 0.3 20	0.04 0 0.60 1,000 0.3 10

Note 1: The in situ deformation modulus E_m is calculated from Equation 4.7 (page 47, Chapter 4). Units of E_m are MPa.

3. Strength of jointed rock masses

$$\sigma_1' = \sigma_3' + \sigma_c \left(m_b \frac{\sigma_3'}{\sigma_c} + s \right)^a$$

$$\sigma_1' = \sigma_3' + \sigma_c \left(m_i \frac{\sigma_3'}{\sigma_c} + 1 \right)^{\frac{1}{2}}$$

(5) Geological Strength Index (GSI): ~10 → 100

For GSI > 25 (undisturbed rock mass),

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

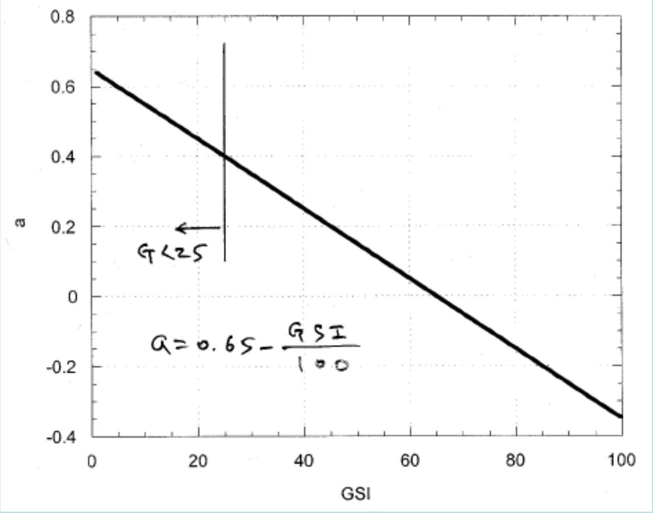
$$s = \exp\left(\frac{GSI - 100}{9} \right)$$

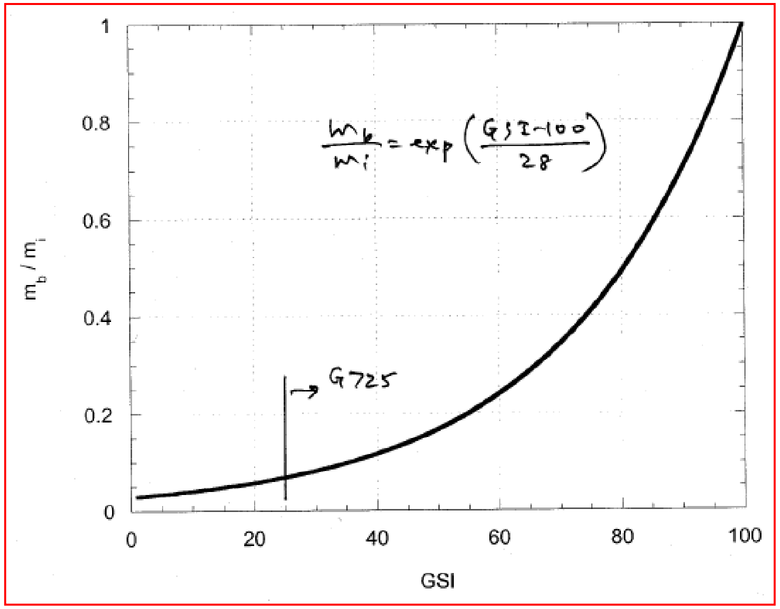
$$a = 0.5$$

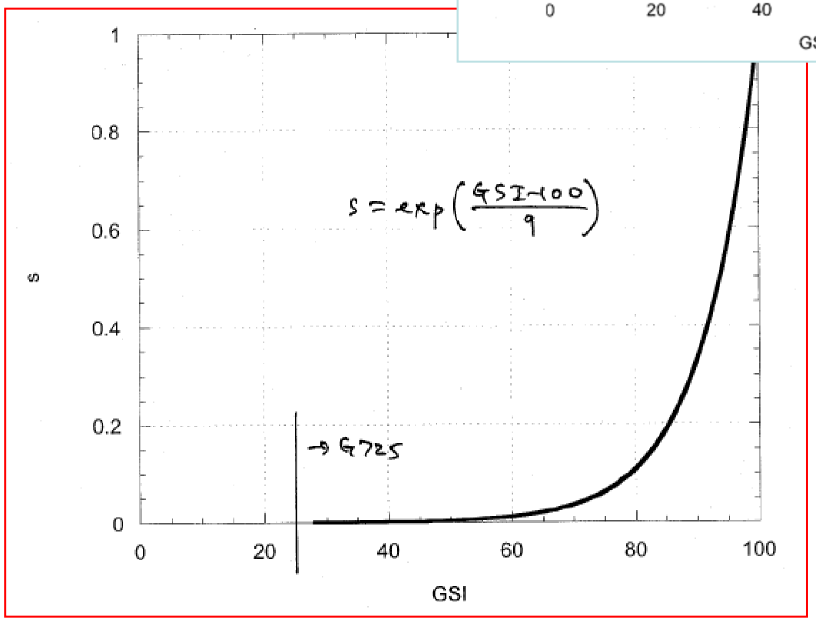
For GSI < 25 (disturbed rock mass),

$$s = 0$$

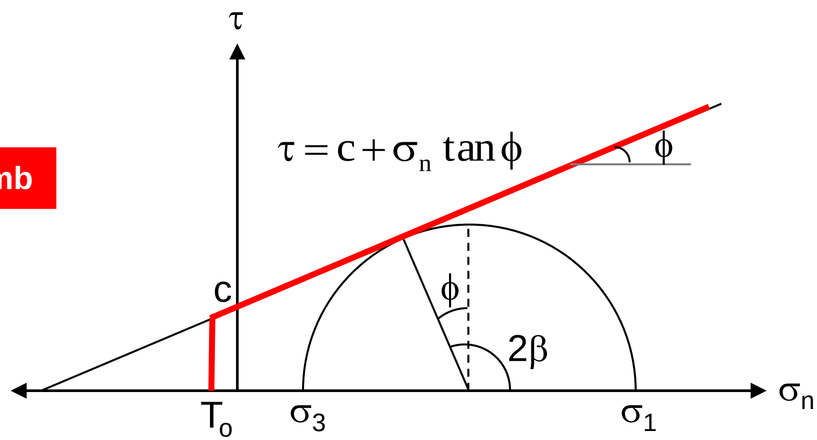
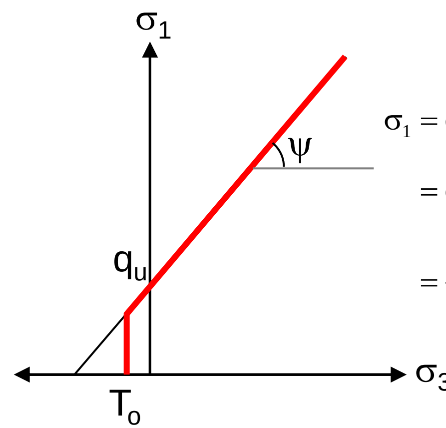
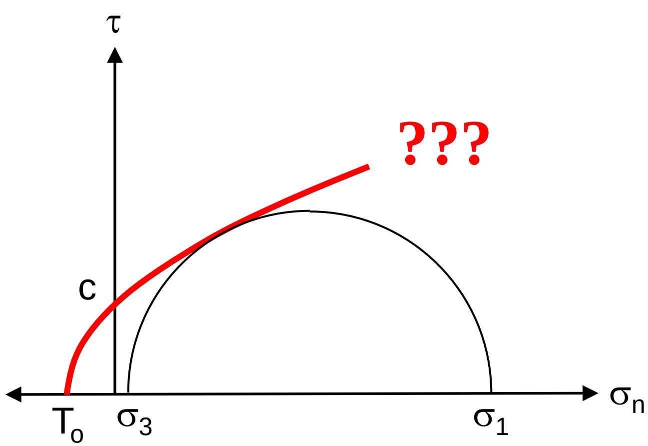
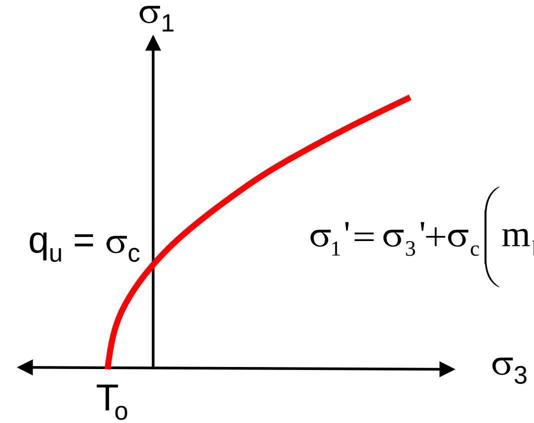
$$a = 0.65 - \frac{GSI}{100}$$







Mohr-Coulomb vs. Hoek-Brown Failure Criterion?

	σ - τ space	σ_1 - σ_3 space
Mohr-Coulomb		
Hoek-Brown		

$$\sigma_1 = q_u + \sigma_3 \tan\psi$$
$$= q_u + \sigma_3 \tan^2\left(45 + \frac{\phi}{2}\right)$$
$$= \frac{2c \cdot \cos\phi}{1 - \sin\phi} + \sigma_3 \frac{1 + \sin\phi}{1 - \sin\phi}$$

$$\sigma_1' = \sigma_3' + \sigma_c\left(m_b \frac{\sigma_3'}{\sigma_c} + s\right)^a$$

3. Strength of jointed rock masses

(6) Application to the Mohr-Coulomb failure criterion (Balmer, 1952)

$$\sigma_n = \sigma_3 + \frac{\sigma_1 - \sigma_3}{\partial\sigma_1 / \partial\sigma_3 + 1}$$

$$\tau = (\sigma_1 - \sigma_3)\sqrt{\partial\sigma_1 / \partial\sigma_3}$$

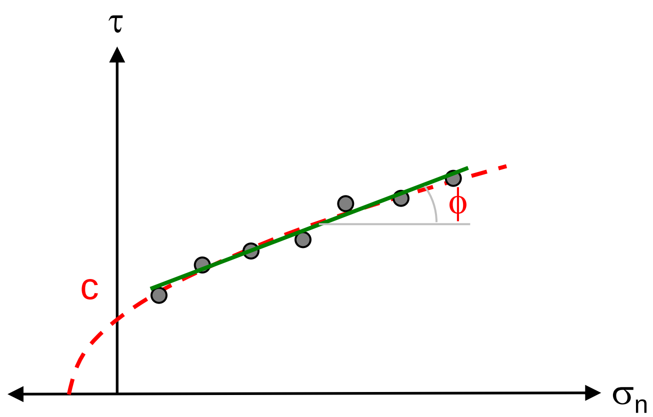
For GSI > 25, a = 0.5

$$\sigma_1' = \sigma_3' + \sigma_c\sqrt{m_b\frac{\sigma_3'}{\sigma_c} + s} \quad \rightarrow \quad \boxed{\frac{\partial\sigma_1}{\partial\sigma_3} = 1 + \frac{m_b\sigma_c}{2(\sigma_1 - \sigma_3)}}$$

For GSI < 25, s = 0

$$\sigma_1' = \sigma_3' + \sigma_c\left(m_b\frac{\sigma_3'}{\sigma_c}\right)^a \quad \rightarrow \quad \boxed{\frac{\partial\sigma_1}{\partial\sigma_3} = 1 + a \cdot m_b{}^a\left(\frac{\sigma_3}{\sigma_c}\right)^{a-1}}$$

A set of (σ_n, τ) values → σ_n - τ curve fitted (by linear regression analysis) → c and ϕ determined from the plot



Uniaxial compressive strength of rock mass

$$\sigma_{cm} = \frac{2c \cdot \cos\phi}{1 - \sin\phi}$$

A simple spreadsheet (i.e. Excel) calculation can be carried out.

ESTIMATE OF HOEK-BROWN AND MOHR-COULOMB PARAMETERS

Input : GSI = 62 sigci = 100 mi = 24

Output:		sig3	sig1	ds1ds3	sign	tau	signtau	signsq
mb/mi =	0.26	0.10	14.48	22.47	0.71	2.91	2.07	0.51
mb =	6.18	0.20	16.55	19.89	0.98	3.49	3.41	0.96
s =	0.015	0.39	20.09	16.68	1.50	4.55	6.85	2.26
a =	0.5	0.78	25.87	13.31	2.53	6.39	16.20	6.42
E =	19953	1.56	34.91	10.26	4.52	9.48	42.90	20.46
phi =	48	3.13	48.70	7.78	8.32	14.48	120.44	69.18
coh =	3.4	6.25	69.56	5.88	15.45	22.31	344.80	238.78
sigcm =	18.0	12.5	101.20	4.48	28.68	34.26	982.51	822.60
				Sums =	62.70	97.88	1519.17	1161.16

Cell formulae:

mb/mi = EXP((GSI-100)/28)
mb = mi*EXP((GSI-100)/28)
s = IF(GSI>25 THEN EXP((GSI-100)/9) ELSE 0)
a = IF(GSI>25 THEN 0.5 ELSE (0.65-GSI/200))
E = 1000*10^((GSI-10)/40)

$$E_m = 10^{\frac{RMR-10}{40}}$$

sig3 = sigci/2^n where n starts at 10 and decreases by 1 for each subsequent cell
sig1 = sig3+sigci*(((mb*sig3)/sigci) + s)^a
ds1ds3 = IF(GSI>25 THEN 1+(mb*sigci)/(2*(sig1-sig3)) ELSE 1+(a*mb^a)*(sig3/sigci)^(a-1))
sign = sig3+(sig1-sig3)/(1+ds1ds3)
tau = (sign-sig3)*SQRT(ds1ds3)
signtau = sign*tau signsq = sign^2

Linear regression analysis

phi = (ATAN((sum(signtau)-(sum(sign)*sum(tau))/8)/(sum(signsq)-((sum(sign))^2)/8)))*180/PI()
coh = (sum(tau)/8) - (sum(sign)/8)*TAN(phi*PI()/180)
sigcm = (2*coh*COS(phi*PI()/180))/(1-SIN(phi*PI()/180))

Figure 8.2: Spreadsheet for the calculation of Hoek-Brown and Mohr-Coulomb parameters.

*** See a spreadsheet calculation**

4. Use of rock mass classification for estimating GSI

(1) Bieniawski's 1976 RMR classification

Table 8.5: Part of Bieniawski's 1976 table defining the Geomechanics Classification or Rock Mass Rating (*RMR*) for jointed rock masses.

	PARAMETER		RANGE OF VALUES						
1	Strength of intact rock material	Point-load strength index	>8 MPa	4-8 MPa	2-4 MPa	1-2 MPa	For this low rangeuniaxial compressive test is preferred		
		Uniaxial compressive strength	>200 MPa	100-200 MPa	50-100 MPa	25-50 MPa	10-25 MPa	3-10 MPa	1-3 MPa
	Rating		15	12	7	4	2	1	0
2	Drill core quality *RQD*		90%- 100%	75%- 90%	50%-75%	25%-50%	< 25%		
	Rating		20	17	13	8	3		
3	Spacing of joints		> 3 m	1-3 m	0.3-1 m	50-300 mm	< 50 mm		
	Rating		30	25	20	10	5		
4	Condition of joints		Very rough surfaces Not continuous No separation Hard joint wall contact	Slightly rough surfaces Separation < 1 mm Hard joint wall contact	Slightly rough surfaces Separation < 1 mm Soft joint wall contact	Slickensided surfaces or Gouge < 5 mm thick or Joints open 1-5 mm Continuous joints	Soft gouge >5 mm thick or Joints open > 5 mm Continuous joints		
	Rating		25	20	12	6	0		

Σ_{max} = 90 + 10 (for groundwater condition)

Σ_{min} = 8 + 10 = 18

$RMR_{76'}$ < 18 (Inaccurate)

Bieniawski's 1989 RMR classification

Table 4.4: Rock Mass Rating System (After Bieniawski, 1989).

A. CLASSIFICATION PARAMETERS AND THEIR RATINGS									
Parameter			Range of values						
1	Strength of intact rock material	Point-load strength index	>10 MPa	4-10 MPa	2-4 MPa	1-2 MPa	For this low range - uniaxial compressive test is preferred		
		Uniaxial comp. strength	>250 MPa	100-250 MPa	50-100 MPa	25-50 MPa	5-25 MPa	1-5 MPa	< 1 MPa
	Rating		15	12	7	4	2	1	0
2	Drill core Quality *RQD*		90%-100%	75%-90%	50%-75%	25%-50%	< 25%		
	Rating		20	17	13	8	3		
3	Spacing of discontinuities		> 2 m	0.6-2 . m	200-600 mm	60-200 mm	< 60 mm		
	Rating		20	15	10	8	5		
4	Condition of discontinuities (See E)		Very rough surfaces Not continuous No separation Unweathered wall rock	Slightly rough surfaces Separation < 1 mm Slightly weathered walls	Slightly rough surfaces Separation < 1 mm Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge >5 mm thick or Separation > 5 mm Continuous		
	Rating		30	25	20	10	0		
5	Ground water	Inflow per 10 m tunnel length (l/m)	None	< 10	10-25	25-125	> 125		
		(Joint water press)/ (Major principal σ)	0	< 0.1	0.1,-0.2	0.2-0.5	> 0.5		
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing		
	Rating		15	10	7	4	0		

Σ_{max} = 85 + 15 (for groundwater condition)

Σ_{min} = 8 + 15 = 23

$RMR_{89'}$ < 23 (Inaccurate)

4. Use of rock mass classification for estimating GSI

(1) Bieniawski's 1976 RMR classification

For $RMR_{76'} > 18$, $GSI = RMR_{76'}$

$RMR_{76'} < 18$, **Use Q' value. $RMR_{76'}$ cannot be used to estimate GSI)**

(2) Bieniawski's 1989 RMR classification

For $RMR_{89'} > 23$, $GSI = RMR_{89'} - 5$

$RMR_{89'} < 23$, **Use Q' value. $RMR_{89'}$ cannot be used to estimate GSI)**

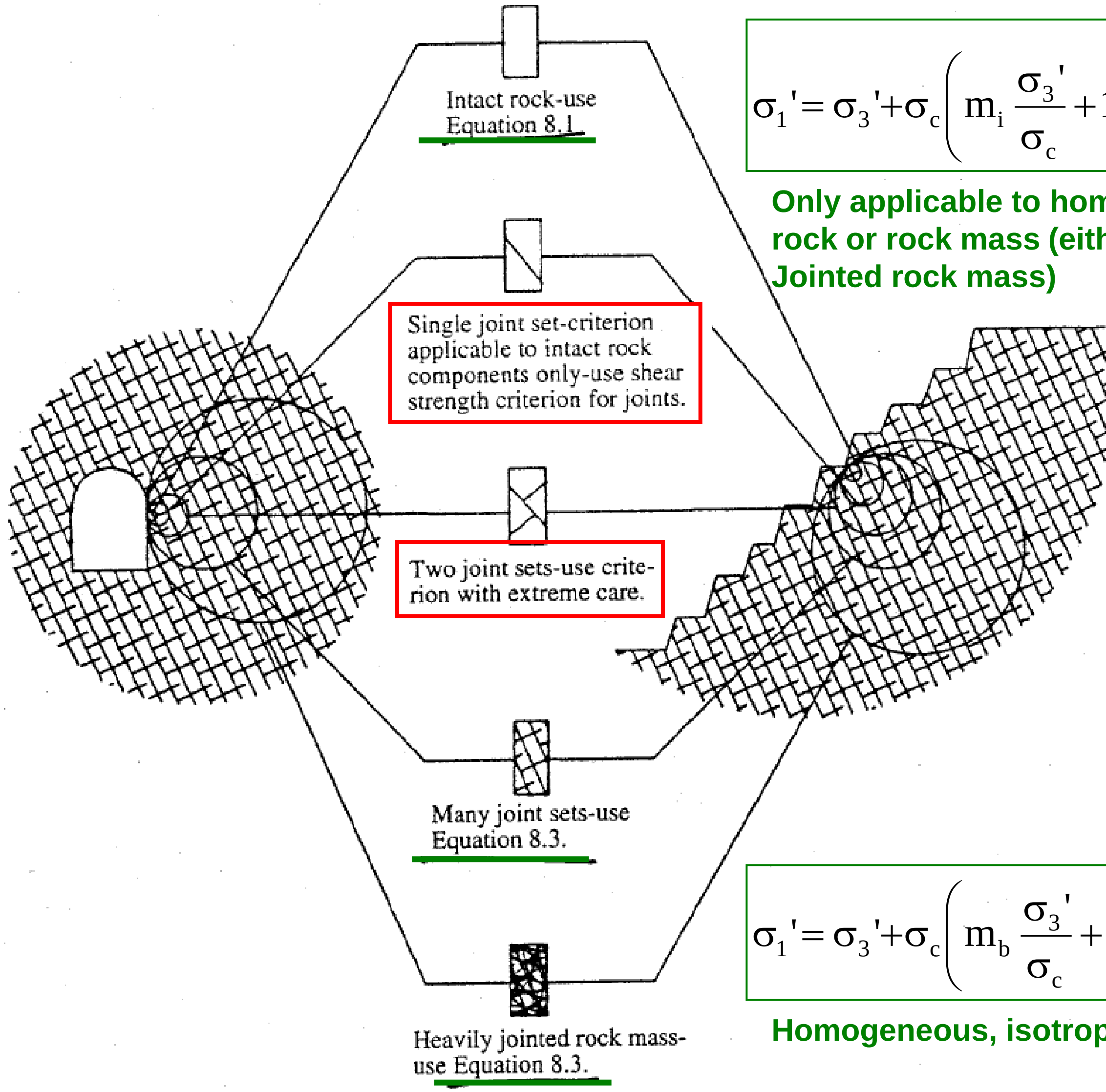
(3) Modified Barton, Lien and Lunde's Q' classification

$J_w = 1$, $SRF = 1$ **(Dry, medium stress condition)** ($Q_{min}' = 0.0208$, $GSI \approx 9$)

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

$$GSI = 9 \cdot \log_e Q' + 44$$

5. When to use the Hoek-brown failure criterion



$$\sigma_1' = \sigma_3' + \sigma_c \left(m_i \frac{\sigma_3'}{\sigma_c} + 1 \right)^{\frac{1}{2}}$$

Only applicable to homogeneous and isotropic rock or rock mass (either intact or heavily Jointed rock mass)

$$\sigma_1' = \sigma_3' + \sigma_c \left(m_b \frac{\sigma_3'}{\sigma_c} + s \right)^{a}$$

Homogeneous, isotropic

Figure 8.3: Rock mass conditions under which the Hoek-Brown failure criterion can be applied.