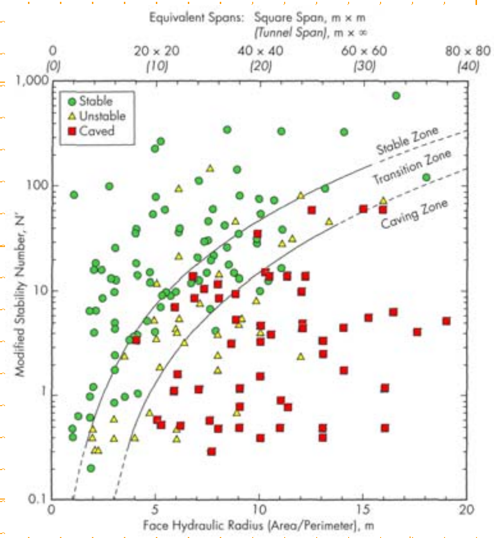
EOSC433/536:

Geological Engineering Practice I – Rock Engineering

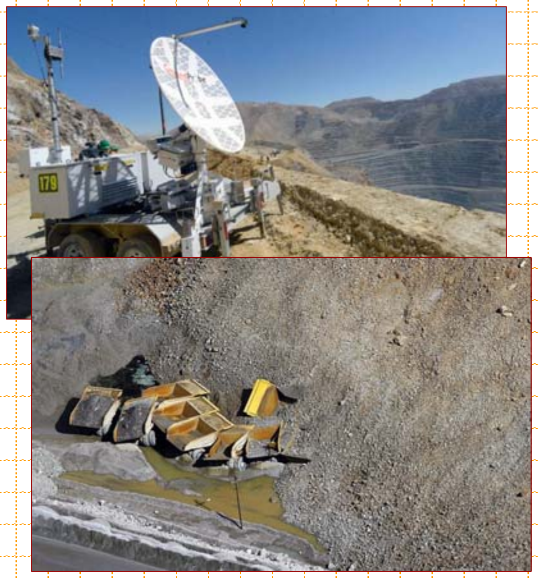
Lecture 5: Empirical Design & Rock Mass Characterization



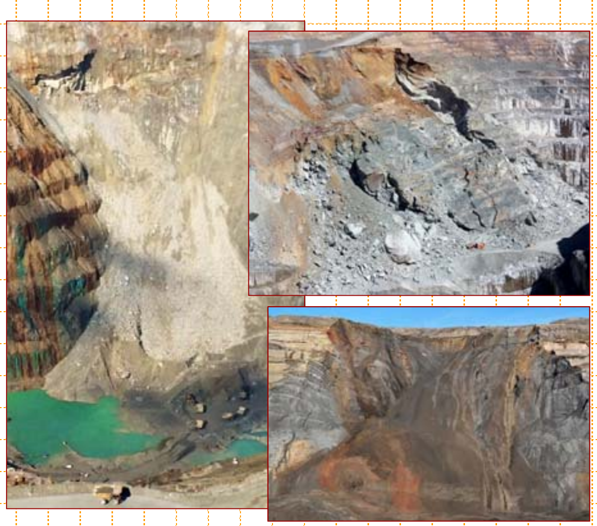
Open Pit Rockslide Runout

Deseret News (2013)

Open Pit Rockslide Runout



Rockslide Runout Database



Label	Mine	Date	Source
1	Bingham Canyon	2013	Pankow et al., 2014
2	Goldstrike	2001	Rose, 2011
3	Goldstrike	2005	Rose, 2011
4	Goldstrike	2007	Rose, 2011
5	Goldstrike	2009	Rose, 2011
6	Anonymous	2003	Anonymous
7	Afton	1986	Reid and Stewart, 1986
8	Nchanga	2004	Naismith and Wessels, 2005
9	Case 2	-	Rose and Hungr, 2007
10	Grasberg	2003	Moffett and Adkerson, 2003
11	Brilliant Cut	1941	Hamel, 1971
12	Twin Buttes	1971	Seegmiller, 1972
13	Steep Rock	1975	Brawner and Stacey, 1979
14	Tripp	1970	Miller, 1983
15	Cuajone	1999	Hormazabal et al., 2013
16	Letlhakane/DK1	2005	Kayesa, 2006
17	Berkeley	1978	Goldberg and Frizzell, 1989
18	Geita	2007	Dyke, 2009
19	Monroe County Quarry	2000	Kelly et al., 2002
20	Gold Quarry	2005	Bates et al., 2005
21	Gold Quarry	2009	Yang et al., 2011
22	Gold Quarry	2009	Yang et al., 2011
23	Brenda	2001	Weichert, 1994
24	Chuquicamata	1969	Voight and Kennedy, 1979
25	Shirley Basin	1971	Atkins and Pasha, 1973
26	Aguas Claras	1992	Martin and Stacey, 2013
27	Collolar	2011	Unosat, 2011
28	Liberty	1966	Broadbent and Zavodni, 1981
29	Angooran	2008	Behbahani et al., 2013
30	Telfer	1992	Szwedzicki, 2001
31	Luscar	1979	Cruden and Masoumzadeh, 1987
32	KBI Morgul	1989	Nasuf et al., 1993
33	Sunrise Dam	2000	Speight, 2002
35	Homestake Pitch	1983	Cremeens, 2003
36	Mt Isa	1965	Rosengren, 1972
37	Cyprus Bagdad	-	Google Earth, 2014
38	Santa Barbara	2005	D'Elia et al., 1996
39	Savage River	2010	Hutchinson, 2013
40	Kirka Borax	1974	Türk and Koca, 1994
41	Anonymous	2014	Anonymous
42	Cowal	-	Google Earth, 2014
43	Cowal	-	Google Earth, 2014
44	Goldstrike	1997	Rose and Sharon, 2000
45	Goldstrike	1997	Rose and Sharon, 2000

Whittall *et al.* (2016)

Rockslide Runout Database

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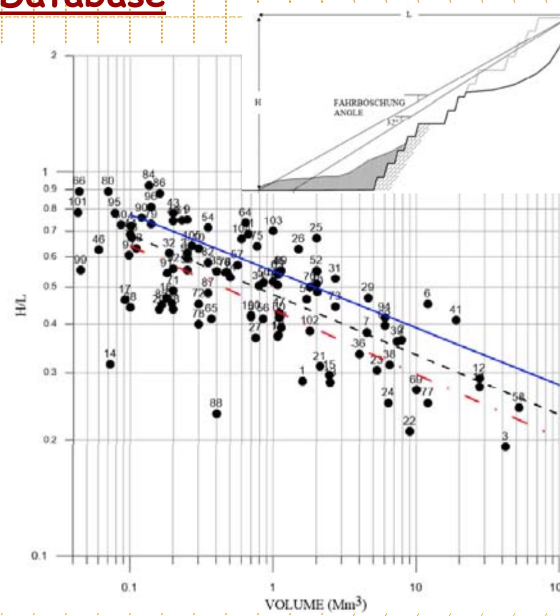
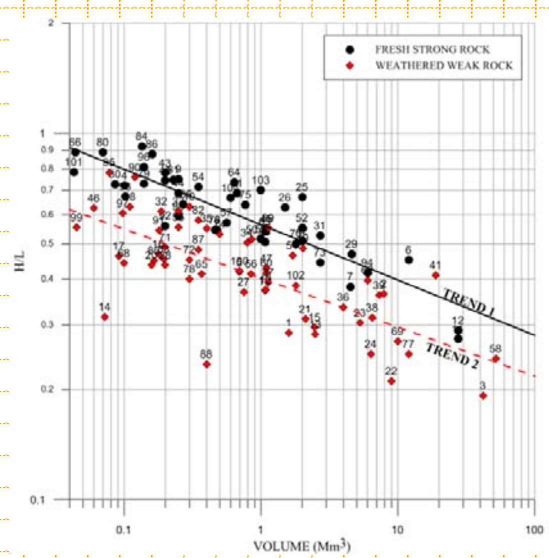
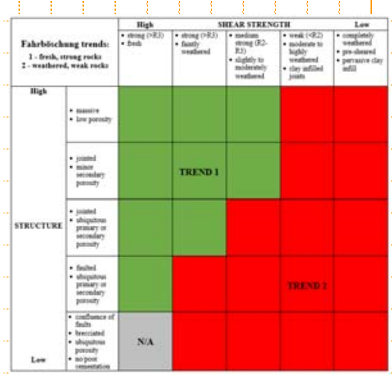


Whittall *et al.* (2016)

Open Pit Rockslide Runout Exceedance

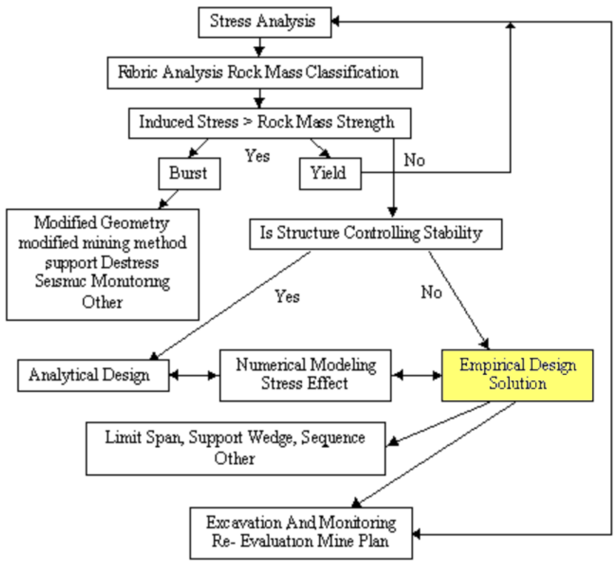




Whittall *et al.* (2016)

Empirical Design in Geotechnical Engineering

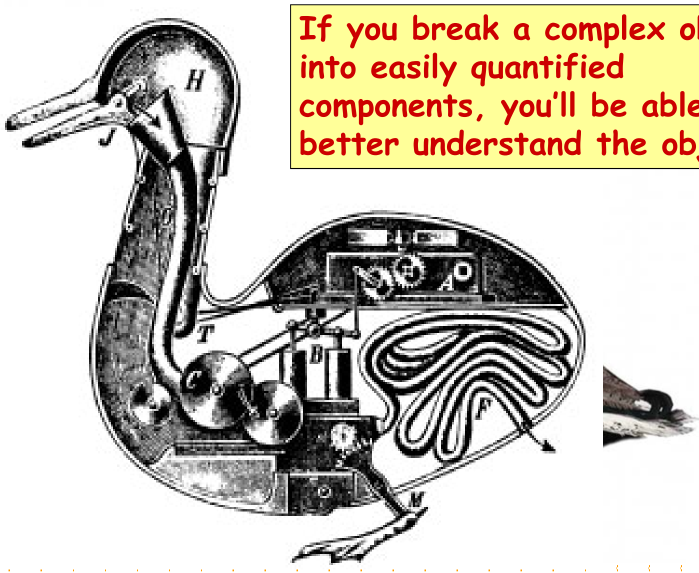
"Empirical design" is based upon experience or observation alone, without using scientific method or theory. Its application to engineering design relies on comparing the experiences of past practices to predict future behaviour based upon the factors most critical towards the design.



Pakalnis (1996)

Empirical Design & Classification Systems

If you break a complex object into easily quantified components, you'll be able to better understand the object



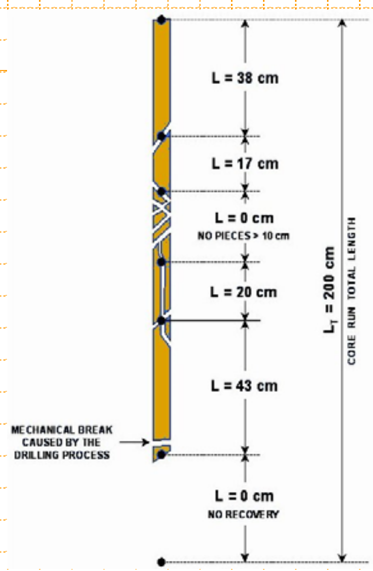
Empirical Design & Classification Systems

The objectives of rock mass classifications are to:

- Identify the most important parameters influencing the rock mass.
- Divide a rock mass formation into groups of similar behaviour.
- Provide a basis for understanding the characteristics of each rock mass class.
- Relate experiences of rock conditions at one site to those at another.
- Derive quantitative data and guidelines for engineering design.
- Provide a common basis for communication between geologists and engineers.

The boundaries of the structural regions usually coincide with a major structural feature such as a fault or with a change in rock type. In some cases, significant changes in discontinuity spacing or characteristics, within the same rock type, may necessitate the division of the rock mass into a number of small structural regions.

Rock Quality Designation (RQD)



$$RQD = \frac{\sum Rock\ Pieces \geq 10\,cm}{Core\ Run\ Total\ Length} \times 100\,(\%)$$

$$RQD = \frac{38 + 17 + 0 + 20 + 43 + 0}{200} \times 100\,(\%)$$

$$RQD = 59\,\%\ \ (FAIR)$$

RQD (%)	Geotechnical Quality
< 25	VERY POOR
25 to 50	POOR
50 to 75	FAIR
75 to 90	GOOD
90 to 100	EXCELLENT

Rock Mass Classification: RMR

The Rock Mass Rating (RMR) system was developed in 1973 in South Africa by Prof. Z.T. Bieniawski. The advantage of his system was that only a few basic parameters relating to the geometry and mechanical conditions of the rock mass were required.

In applying this system, the rock mass is divided into a number of structural domains and each is classified separately. Because parameters are not equally important, weighted ratings are allocated.

A. CLASSIFICATION PARAMETERS AND THEIR RATINGS

	Parameter		Ranges of values						
1	Strength of intact rock material	Point-load strength index (MPa)	>10	4 - 10	2 - 4	1 - 2	For this low range, uniaxial compressive test is preferred		
		Uniaxial compressive strength (MPa)	>250	100 - 250	50 - 100	25 - 50	5 - 25	1 - 5	<1
		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		>2m	0.6 - 2m	200 - 600mm	60 - 200mm	<60mm		
		Rating	20	15	10	8	5		
4	Condition of discontinuities		Very rough surfaces Not continuous No separation Unweathered wall rock	Slightly rough surfaces Separation <1mm Slightly weathered wall rock	Slightly rough surfaces Separation <1mm Highly weathered wall rock	Slickensided surfaces or Gouge <5mm thick or Separation 1 - 5mm Continuous	Soft gouge >5mm thick or Separation >5mm Continuous		
		Rating	30	25	20	10	0		
5	Groundwater	Inflow per 10m tunnel length (l/min)	None	<10	10 - 25	25 - 125	>125		
		ratio (joint water pressure)/(major principal stress)	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		

B. RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS

Strike and dip orientations		Very favourable	Favourable	Fair	Unfavourable	Very Unfavourable
Ratings	Tunnels & mines	0	-2	-5	-10	-12
	Foundations	0	-2	-7	-15	-25
	Slopes	0	-5	-25	-50	

Bieniawski (1989)

Rock Mass Classification - RMR

The adjusted value gives the final RMR value for the rock mass, for which several rock mass classes are described.

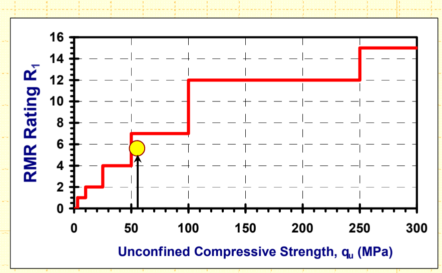
C. ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS

Rating	100 ← 81	80 ← 61	60 ← 41	40 ← 21	< 21
Class number	I	II	III	IV	V
Description	Very good rock	Good rock	Fair rock	Poor rock	Very poor rock

For example:

A mudstone outcrop contains three fracture sets. Set '1' comprises bedding planes; these are highly weathered, slightly rough and continuous. The other two sets are jointing; both are slightly weathered and slightly rough. The strength of the intact rock is estimated to be 55 MPa with an RQD of 60% and a mean fracture spacing of 0.4 m. The fractures are observed to be damp.

$$RMR = 6 + R_2 + R_3 + R_4 + R_5$$



Harrison & Hudson (2000)

Rock Mass Classification - RMR

Example:

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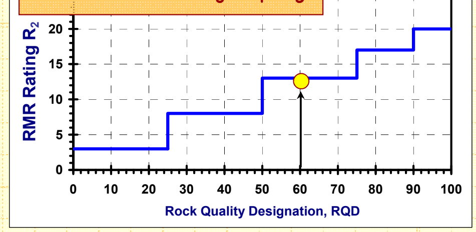
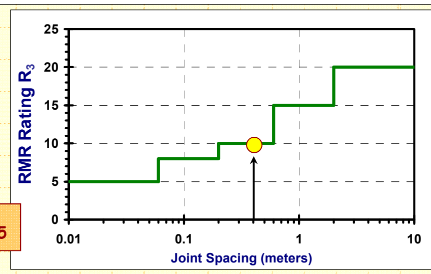
$RMR = 6+12+R_3+R_4+R_5$





$RMR = 6+12+10+R_4+R_5$

Harrison & Hudson (2000)

Rock Mass Classification - RMR

Example:

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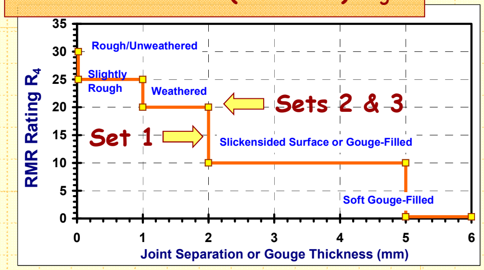
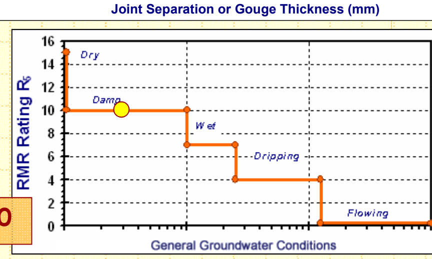
$RMR = 6+12+10+(15 \text{ to } 20)+R_5$





$RMR^* = 53 \text{ to } 58$

$RMR = 6+12+10+(15 \text{ to } 20)+10$

Harrison & Hudson (2000)

Rock Mass Classification: Q-System

The Q-system of rock mass classification was developed in 1974 in Norway by Prof. N. Barton. The system was proposed on the basis of an analysis of 212 tunnel case histories from Scandinavia.

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

where

- RQD = rock quality designation,
- J_n = joint set number (related to the number of discontinuity sets),
- J_r = joint roughness number (related to the roughness of the discontinuity surfaces),
- J_a = joint alteration number (related to the degree of alteration or weathering of the discontinuity surfaces),
- J_w = joint water reduction number (relates to pressures and inflow rates of water within the discontinuities), and
- SRF = stress reduction factor (related to the presence of shear zones, stress concentrations and squeezing and swelling rocks).

… the motivation of presenting the Q-value in this form is to provide some method of interpretation for the 3 constituent quotients.

Rock Mass Classification: Q-System

The first quotient is related to the rock mass geometry. Since RQD generally increases with decreasing number of discontinuity sets, the numerator and denominator of the quotient mutually reinforce one another.

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

The second quotient relates to "inter-block shear strength" with high values representing better 'mechanical quality' of the rock mass.

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

The third quotient is an 'environment factor' incorporating water pressures and flows, the presence of shear zones, squeezing and swelling rock and the *in situ* stress state. The quotient increases with decreasing water pressure and favourable *in situ* stress ratios.

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

Rock Mass Classification – Examples

- ✓ blocky rock
- ✓ low stress regime
- ✓ minimal but systematic ground support
- ✓ RMR = 70 (good rock)
- ✓ Q = 15 (good rock)

Courtesy - Golder Associates

Rock Mass Classification – Examples

- ✓ Weak, foliated rock
- ✓ low stress regime
- ✓ RMR = 40 (poor to fair rock)
- ✓ Q = 0.9 (v.poor to poor rock)

Courtesy - Golder Associates

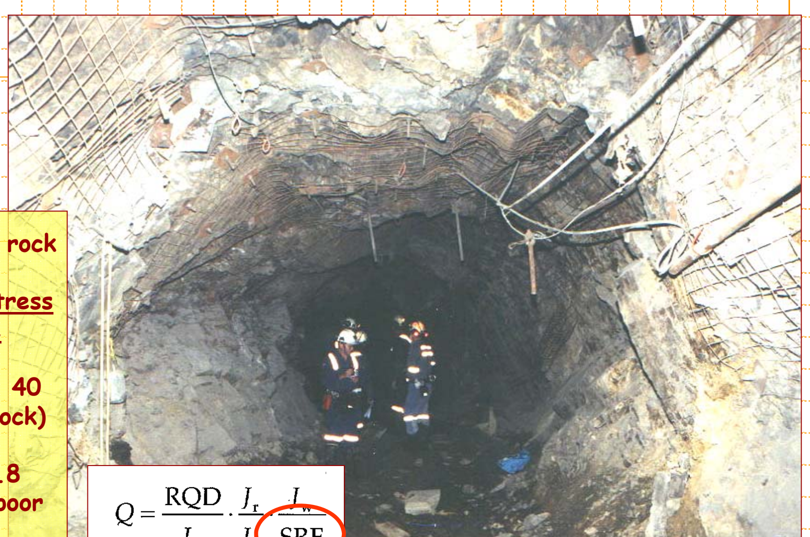
Rock Mass Classification – Examples

- massive, strong rock
- extremely high stress regime
- rockburst failure, complete closure of drift, extremely heavy support, screen retains failed rock
- RMR = 80 (good to v.good rock)
- Q = 0.5 (very poor rock)

Courtesy - Golder Associates

Rock Mass Classification – Examples

- blocky rock
- high stress regime
- RMR = 40 (fair rock)
- Q = 0.8 (very poor rock)

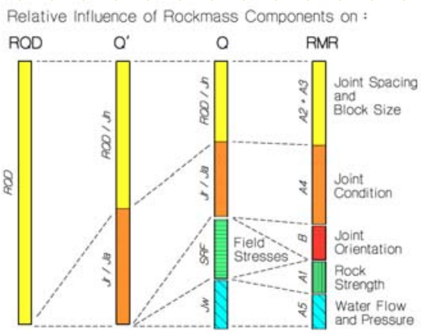


$$Q = \frac{RQD}{J_n} \cdot \frac{J_r}{J_a} \cdot \frac{J_w}{SRF}$$

Courtesy - Golder Associates

Rock Mass Classification – RMR versus Q

Hutchinson & Diederichs (1996)

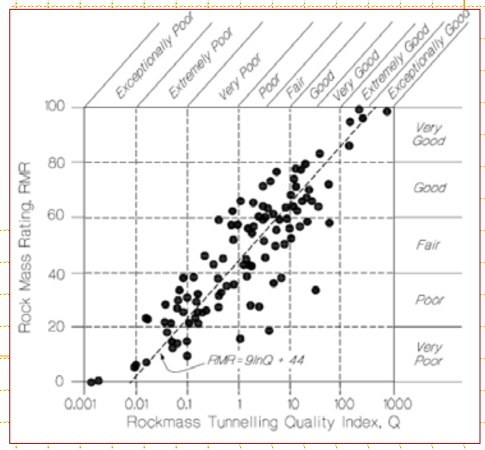


$$RMR = 9\ ln_e Q + 44$$

$$RMR = 21\ log_{10} Q + 44$$

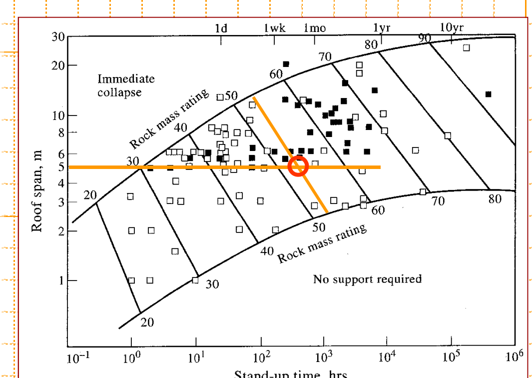
$$Q = 10^{(RMR - 44)/21}$$

Bieniawski (1993)



Classification Systems & Empirical Design

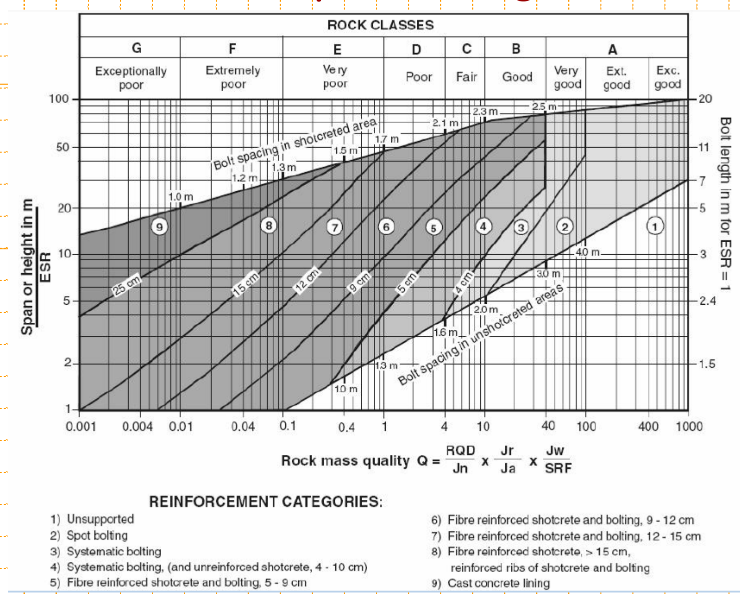
Rock masses can be extremely complex, making the derivation of predictive equations difficult. As an alternative, rock mass classification methods have been calibrated against large databases of case histories to provide guidelines for support design.



Bieniawski (1989)

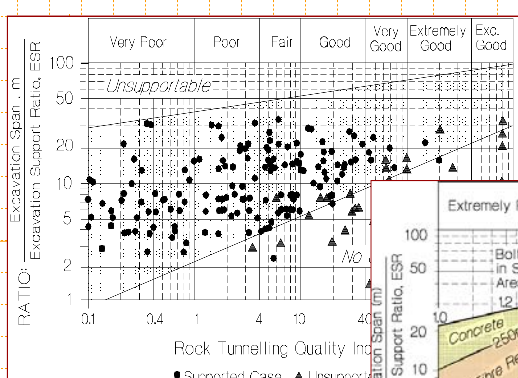
Empirical design of stand-up time, the duration within which an unsupported excavation will remain serviceable, after which significant caving and failure may occur. The database used in its development examined 351 civil tunnel and underground mine case histories.

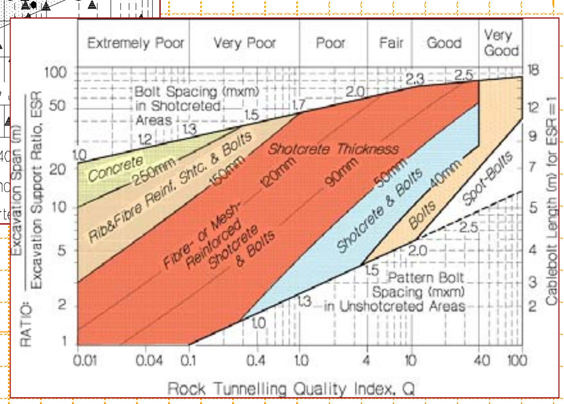
Experience-Base: Empirical Design



Grimstad & Barton (1993)

Empirical Design – Rock Support

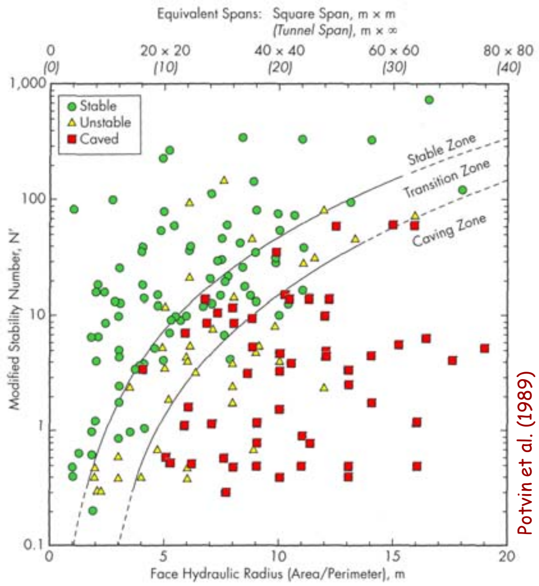




Kaiser *et al.* (2000)

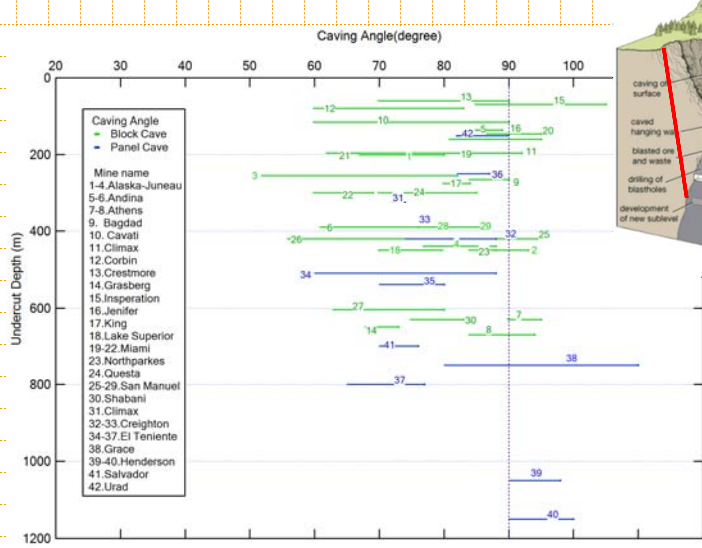
Empirical Design – Mine Stability

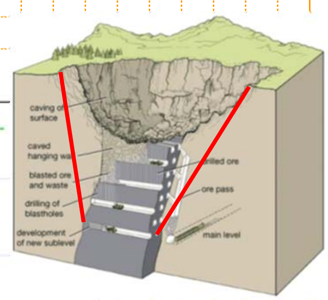
Mathew's Method, through various updates, compiles more than 189 case histories of unsupported open stopes plotted on the Stability Graph. Stable stopes were those that exhibited little or no deterioration during mining. Unstable stopes exhibited limited wall failure and/or block fallout involving less than 30% of the face area. Caved stopes suffered unacceptable failure.



Potvin et al. (1989)

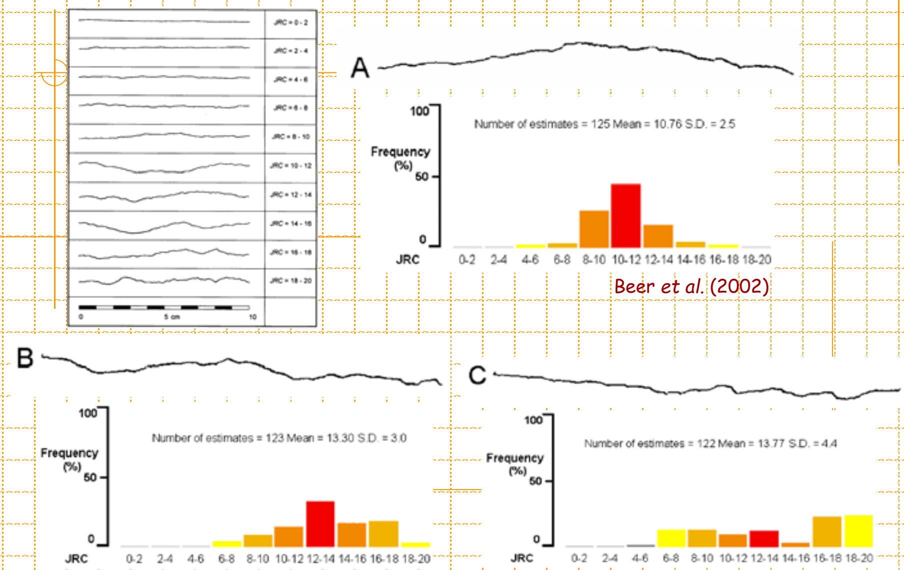
Empirical Design – Caving Subsidence Angles





Woo et al. (2013)

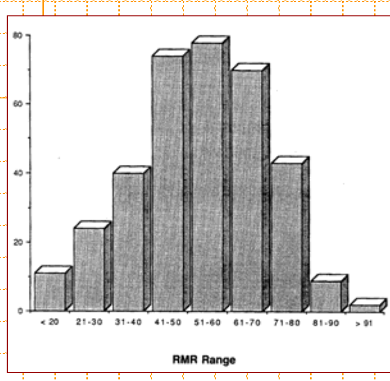
Subjectivity in Empirical Design - JRC

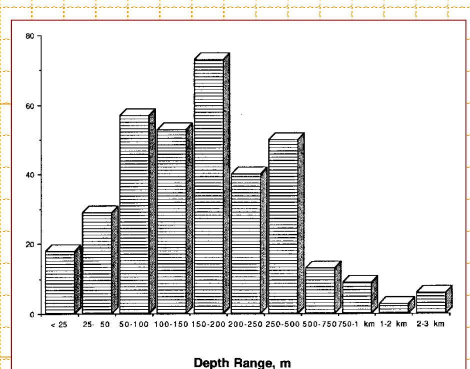


Beer *et al.* (2002)

Subjectivity in Empirical Design - Undersampling

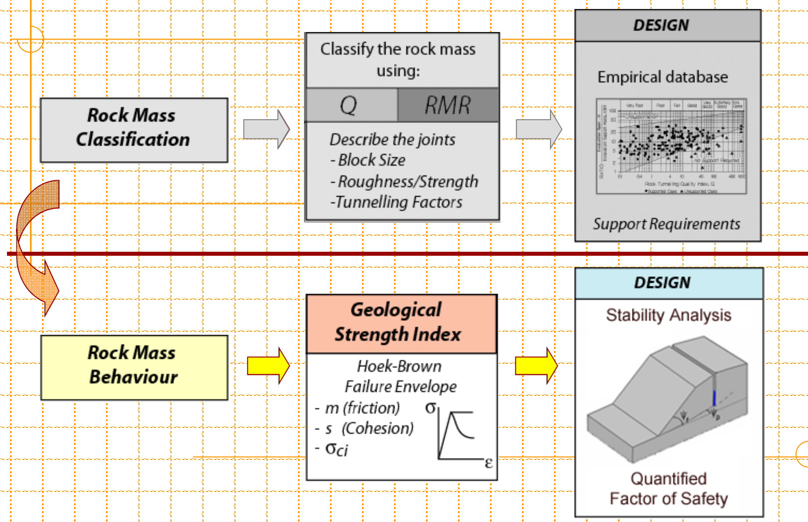
It must be remembered though, that such guidelines are drawn from previous experiences (i.e. case histories) and are therefore limited by the range of conditions under which these experiences were generated.



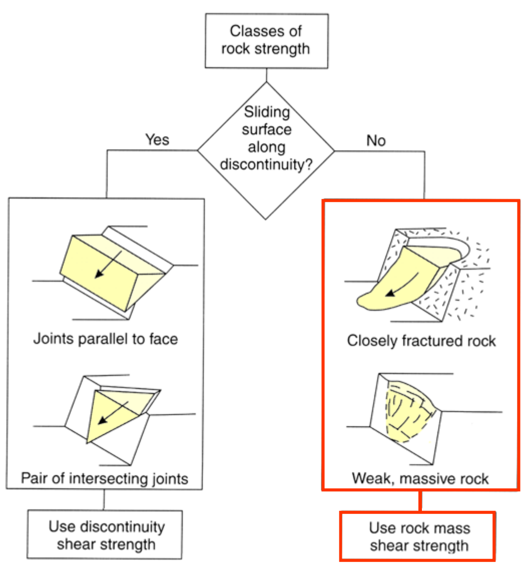


Bieniawski (1989)

Rock Mass Characterization vs. Classification



Rock Mass Properties - Strength

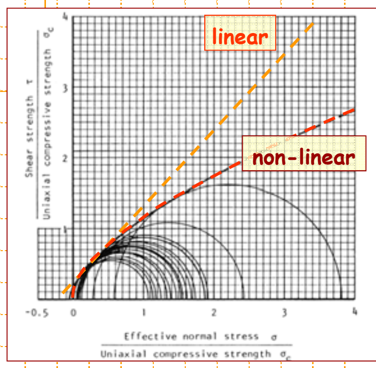


Wyllie & Mah (2004)

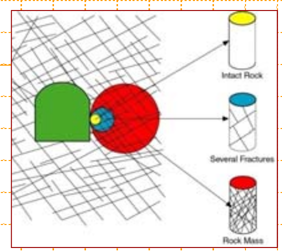
Remember!! – we're now talking about rock mass failure, not structurally controlled failures.

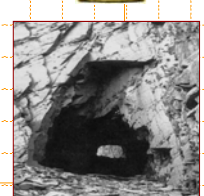
Problems with Mohr-Coulomb

Although the Mohr-Coulomb failure criterion remains one of the most commonly applied failure criterion, and is especially significant and valid for discontinuities and discontinuous rock masses, several key limitations apply to rock slope stability analyses.



Non-linear failure envelopes.

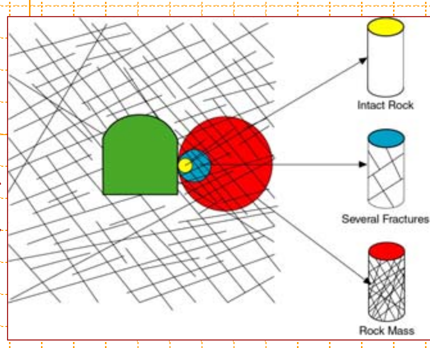




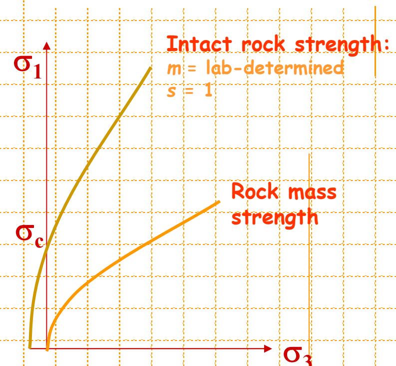
Scale effects.

Hoek-Brown Failure Criterion

Generalized Hoek-Brown failure criterion: $$\sigma_1' = \sigma_3' + \sigma_{ci}\left(m_b \frac{\sigma_3'}{\sigma_{ci}} + s\right)^a$$



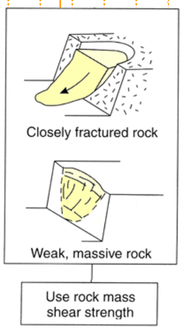
Hoek et al. (1995)

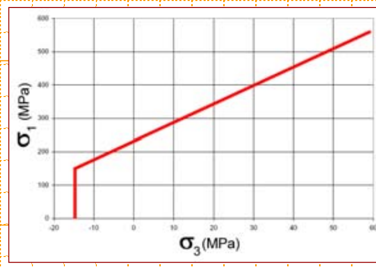


m & *s* are derived from empirical charts that are related to rock mass quality

→ *m* ~ Friction
s ~ Cohesion

Rock Mass Properties - Strength

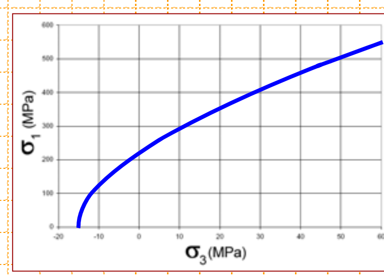




Mohr-Coulomb

$$\tau = c' + \sigma \tan\phi'$$

$$\sigma_1' = \frac{2c'\cos\phi'}{1-\sin\phi'} + \frac{1+\sin\phi'}{1-\sin\phi'}\sigma_3'$$

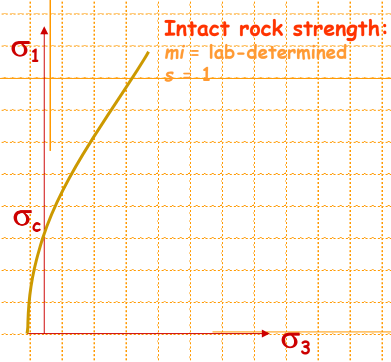


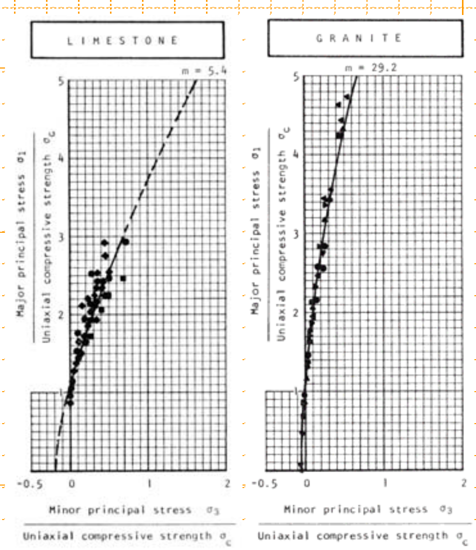
Generalized Hoek-Brown

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

Hoek-Brown Failure Criterion

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





Hoek & Brown (1997)

Hoek-Brown Failure Criterion

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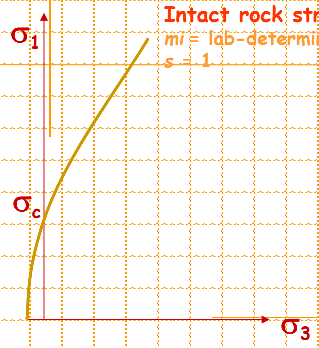
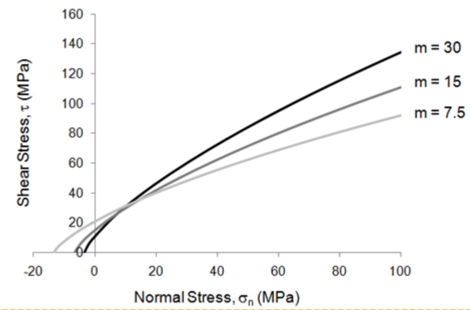
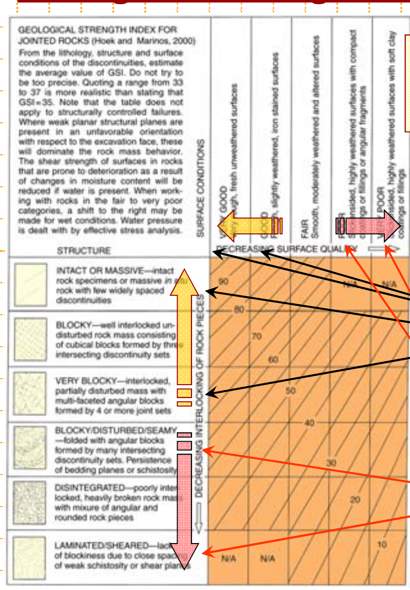




Eberhardt (2012)

Geological Strength Index (GSI)



The GSI provides a system for estimating the reduction in rock mass strength for different geological conditions.

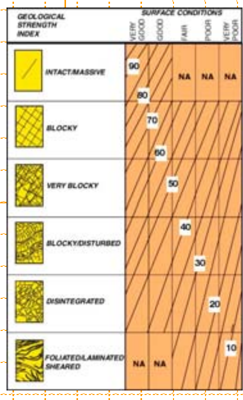
Values of GSI are related to both the degree of fracturing and the condition of the fracture surfaces.

mainly jointing

mainly faulting

GSI (for those familiar with rock mass classification)

Bieniawski (1989)



Hoek *et al.* (1995)

	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		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	Groundwater		None						
	Rating		15						

⇐ Not a rock mass characteristic!

For RMR 89* > 23: **GSI = RMR 89* -5**

For RMR 89* < 23: **GSI = 9 Log_eQ' + 44**

Where ⇒ $$Q' = \frac{RQD}{J_n} \times \frac{J_r}{J_a}$$

Note that the Q-system quotient terms "Jw/SRF" are dropped as these, likewise, are not rock mass characteristics!

Hoek-Brown Simplified Procedure

A simplified procedure to determine the Hoek-Brown rock mass strength parameters:

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

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

Rock type	Class	Group	Texture: Coarse	Medium	Fine	Very fine
IGNEOUS	Plutonic	Light	Granite 32 ± 3; Granodiorite (29 ± 3)	Diorite 25 ± 5		
		Dark	Gabbro 27 ± 3; Norite 20 ± 5	Dolerite (16 ± 5)		
	Hypabyssal		Porphyries (20 ± 5)		Diabase (15 ± 5)	Peridotite (25 ± 5)
	Volcanic	Lava		Rhyolite (25 ± 5); Andesite 25 ± 5	Dacite (25 ± 3); Basalt (25 ± 5)	
		Pyroclastic	Agglomerate (19 ± 3)	Breccia (19 ± 5)	Tuff (13 ± 5)	

Rock type	Class	Group	Texture: Coarse	Medium	Fine	Very fine
METAMORPHIC	Non Foliated		Marble 9 ± 3	Hornfels (19 ± 4); Metasandstone (19 ± 3)	Quartzites 20 ± 3	
	Slightly foliated		Migmatite (29 ± 3)	Amphibolites 26 ± 6	Gneiss 28 ± 5	
	Foliated**			Schists 12 ± 3	Phyllites (7 ± 3)	Slates 7 ± 4
SEDIMENTARY	Clastic		Conglomerates *; Breccias *	Sandstones 17 ± 4	Siltstones 7 ± 2; Greywackes (18 ± 3)	Claystones 4 ± 2; Shales (6 ± 2); Marls (7 ± 2)
	Non-Clastic	Carbonates	Crystalline Limestone (12 ± 3)	Sparitic Limestones (10 ± 2)	Micritic Limestones (9 ± 2)	Dolomites (9 ± 3)
		Evaporites		Gypsum 8 ± 2	Anhydrite 12 ± 2	
		Organic				Chalk 7 ± 2

Hoek-Brown Failure Criterion

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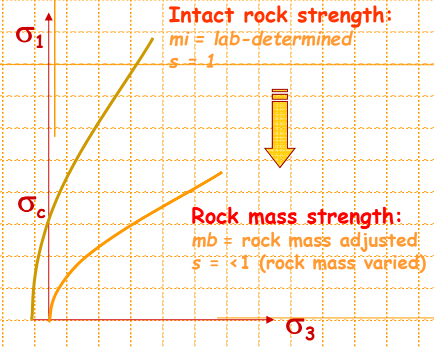


Hoek et al. (2002)

for GSI >25:

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

$$a = 0.5$$

for GSI <25:

$$s = 0$$

$$a = 0.65 - \frac{GSI}{200}$$

"s" is a rock mass constant based on how fractured the rock mass is (where s=1 for intact rock).

GSI Disturbance Factor

Appearance of rock mass	*Description of rock mass*	*Suggested value of D*
	Small-scale blasting in civil engineering slopes results in modest rock mass damage, particularly if controlled blasting is used as shown on the left hand side of the photograph. However, stress relief results in some disturbance.	$D = 0.7$ Good blasting $D = 1.0$ Poor blasting
	Very large open pit mine slopes suffer significant disturbance due to heavy production blasting, and also due to stress relief from overburden removal.	$D = 1.0$ Production blasting
	In some softer rocks, excavation can be carried out by ripping and dozing, and the degree of damage to the slopes is less.	$D = 0.7$ Mechanical excavation

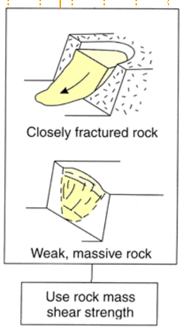
Wyllie & Mah (2004)

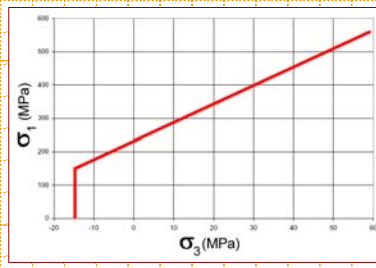
A disturbance factor, "D", may also be applied to the Hoek-Brown parameters to account for the degree to which a rock mass may have been subjected to blast damage and stress relaxation.

$$m_b = m_i \exp\left(\frac{GSI - 100}{28 - 14D}\right) \qquad s = \exp\left(\frac{GSI - 100}{9 - 3D}\right)$$

disturbance factor

Rock Mass Properties - Strength





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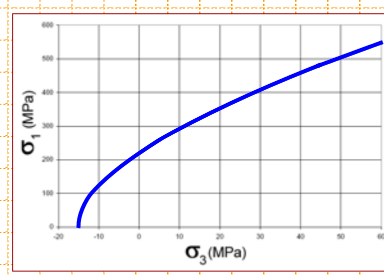

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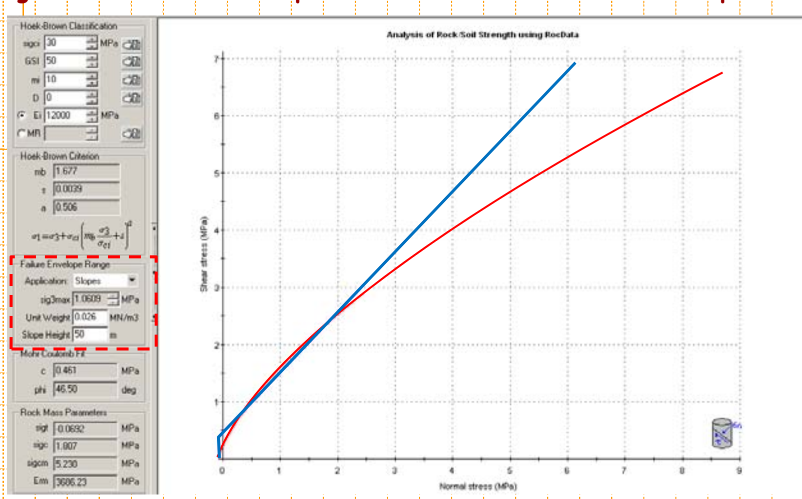
GSI, Hoek-Brown & Mohr-Coulomb

Where Mohr-Coulomb properties are required (or preferred because we have more experience and an intuitive feel for c and ϕ), these can be derived by fitting a linear failure envelope across the non-linear H-B envelope:



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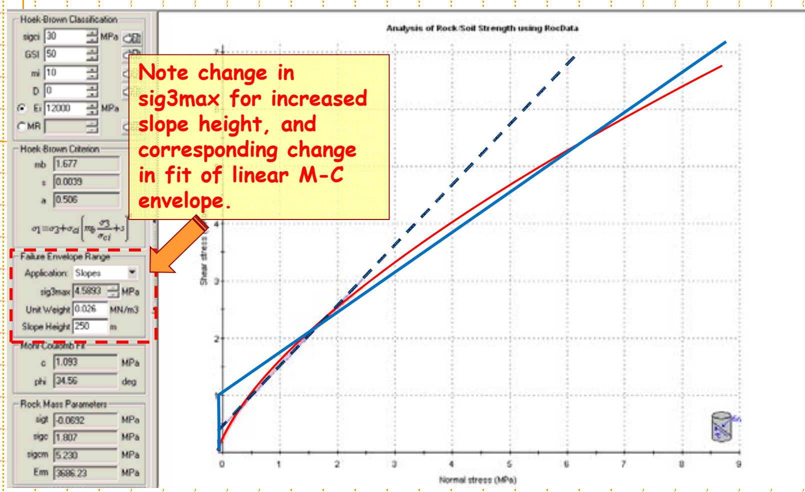
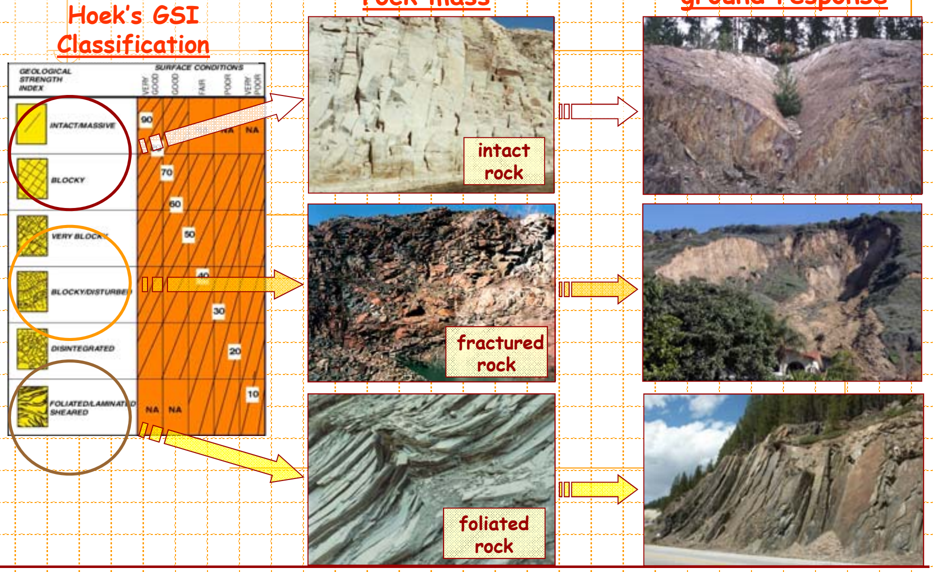


Applicability of the GSI?

Hoek's GSI Classification

rock mass

ground response



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