Quantitative Classification of Rock Mass

- Description of Joints:

  Orientation, Persistence, Roughness, Wall Strength, Aperture, Filling, Seepage, Number of sets, Block size, spacing.

  ISRM commission’s report

  Classification of Rock Material

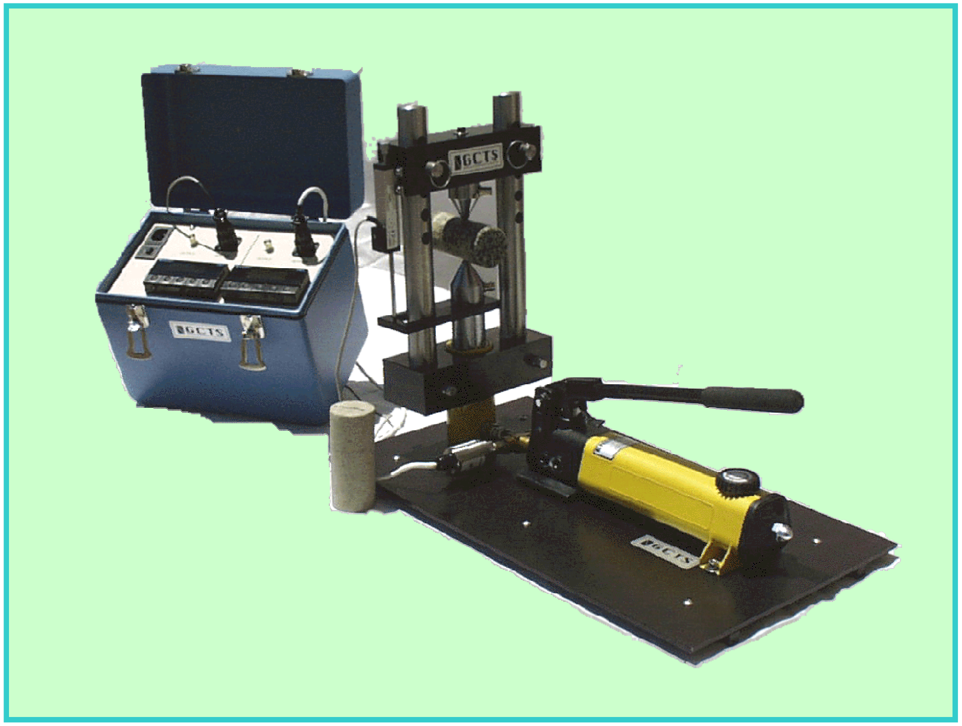
  Based on Uniaxial Compressive Strength

Point Load Index

- Quick evaluation for uniaxial strength (field or lab setup)
- ASTM D 5731 procedures
- Little sample preparation (cores, pieces)
- Measure force (P) to crunch intact rock specimen
- Point Load Index: $I_s = P/d_e^2$ where d_e = equivalent core diameter

Fig.8-1

Point Load Index



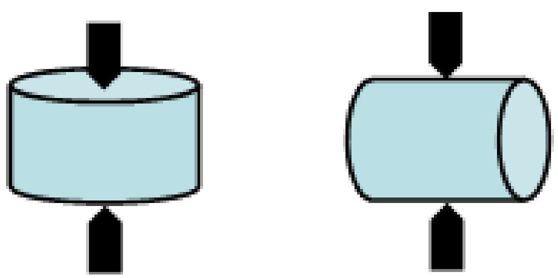
GCTS Device

Roctest Equipment

Strength and Deformation

Point Load Index

Point load test is a simple index test for rock material. It gives the standard point load index, $I_{s(50)}$.



Granite	5 – 15
Gabbro	6 – 15
Andesite	10 – 15
Basalt	9 – 15
Sandstone	1 – 8
Mudstone	0.1 – 6
Limestone	3 – 7
Gneiss	5 – 15
Schist	5 – 10
Slate	1 – 9
Marble	4 – 12
Quartzite	5 – 15

Strength and Deformation

Correlation between Point Load Index and Strengths

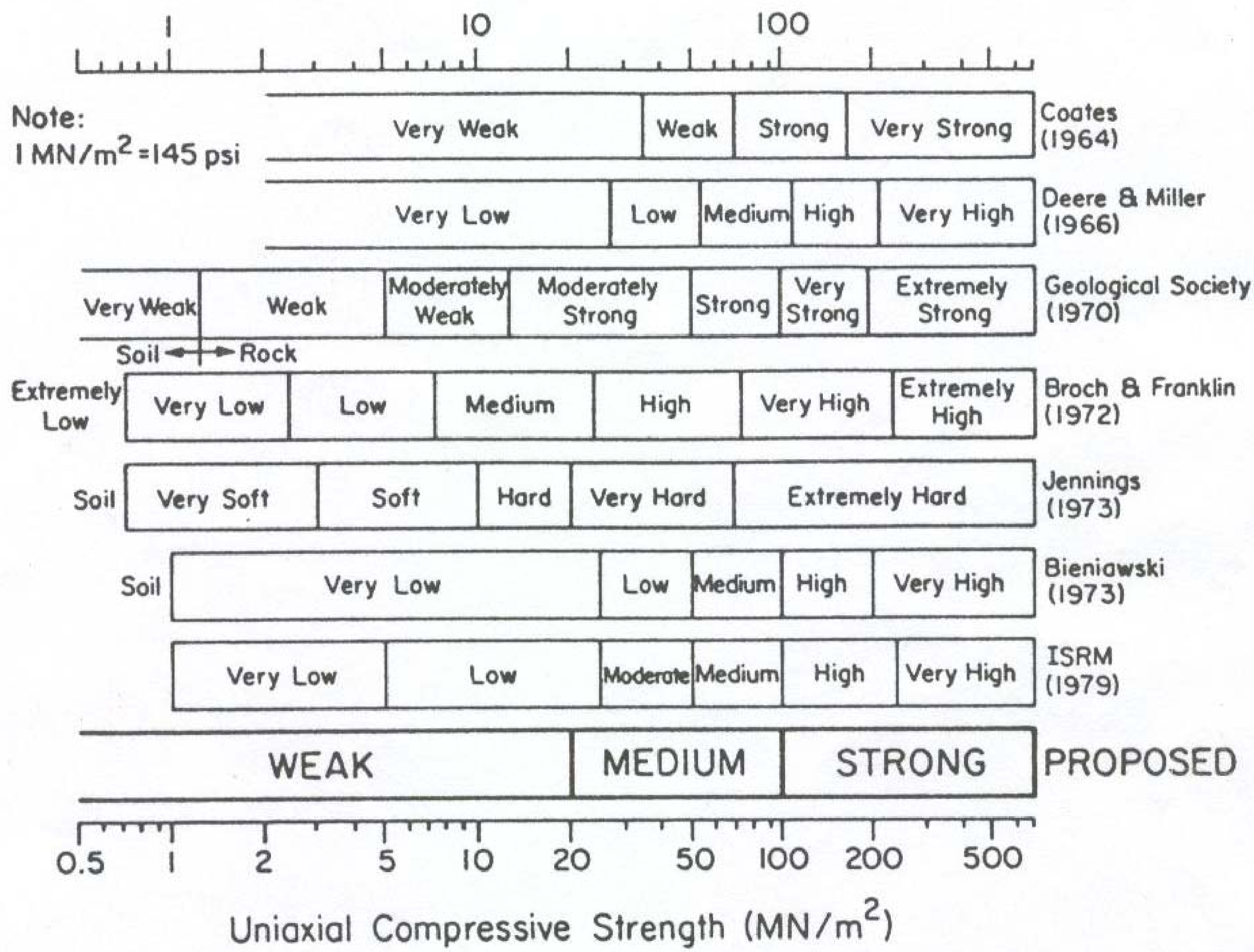
$\sigma_c \approx 22\ I_{s(50)}$
Correction factor can vary between 10 and 30.

$\sigma_t \approx 1.25\ I_{s(50)}$

$I_{s(50)}$ **should be used as an independent strength index.**

Uniaxial Compressive Strength		Ranges for some Common Rock Material
Term	Kg/cm^2	Schist, Silt stone VW-W, Sand Stone, Lime stone –VW-M,Granite, Basalt, Gneiss, Quartzite, Marble –MS-VS
Very Weak- VW	< 70	
Weak- W	70-200	
Medium Strong-MS	200-700	
Strong- S	700-1400	
Very Strong- VS	> 1400	

Classification for Rock Material Strength

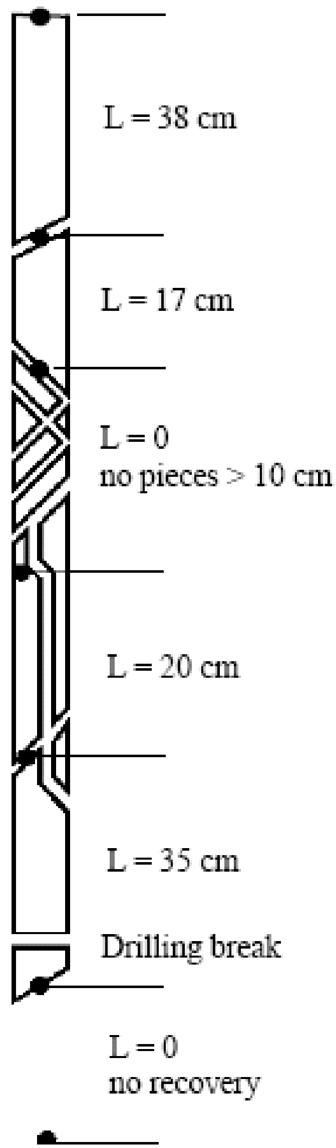


Rock Quality Designation (RQD) or Modified Core Recovery

$$RQD = \frac{\Sigma x_i}{L}$$

x_i = lengths of individual pieces of core $\geq$ 10 cm

L is the total length of the drill run



Total length of core run = 200 cms

$$RQD = \frac{\sum \text{Length of core pieces} > 10 \text{ cm length}}{\text{Total length of core run}} \times 100$$

$$RQD = \frac{38 + 17 + 20 + 35}{200} \times 100 = 55\ \%$$

Figure 4.1: Procedure for measurement and calculation of *RQD* (After Deere, 1989).

Indirect Methods of determination of RQF

Seismic Method -

$RQD = (V_f / V_l)^2 * 100$

Ratio of velocity in the field to that in the lab

Volumetric Count -

$RQD = 115 - 3.3 * J_v$

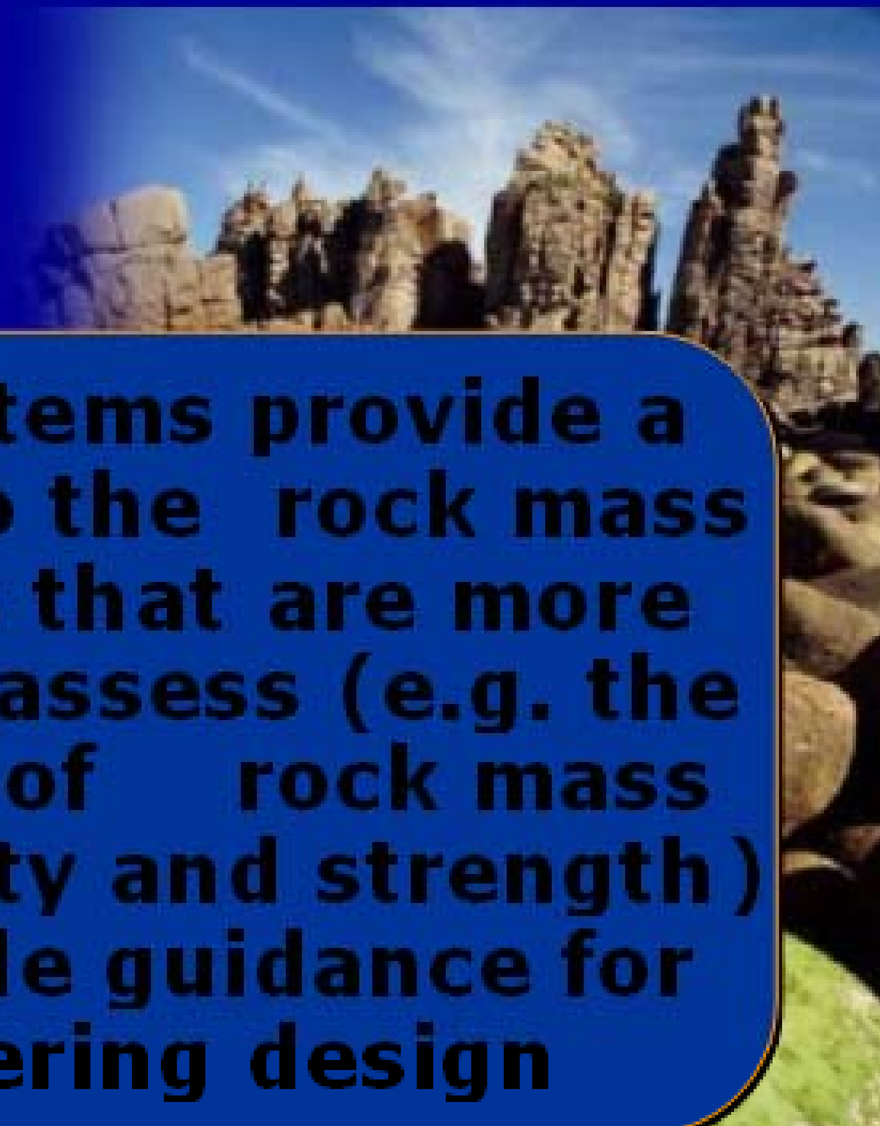
where J_v is a measure of number of joints within a unit volume of rock mass

RQD

	RQD
A. Very poor	0 – 25
B. Poor	25 – 50
C. Fair	50 – 75
D. Good	75 – 90
E. Excellent	90 - 100

Rock Mass Classification Systems

All the rock mass classification systems consider a few of the key rock mass parameters, and assign numerical values to the classes within which these parameters lie for a given rock type

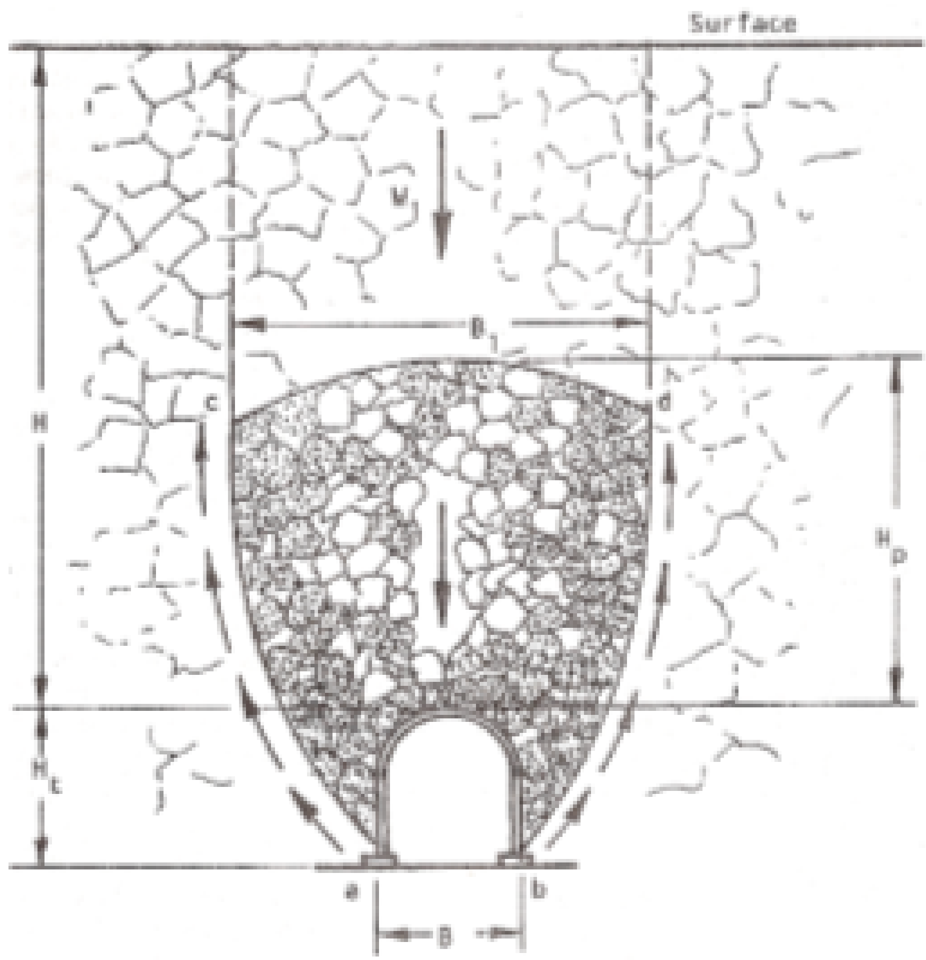


These systems provide a short-cut to the rock mass properties that are more difficult to assess (e.g. the prediction of rock mass deformability and strength) and provide guidance for engineering design

Rock Mass Clasification

Rock Load Factor

It classifies rock mass into 9 classes. The concept used in this classification system is to estimate the rock load to be carried by the steel arches installed to support a tunnel.



Rock Class	Definition	Rock Load Factor Hp (feet) (B and H_t in feet)	Remark
I. Hard and intact	Hard and intact rock contains no joints and fractures. After excavation the rock may have popping and spalling at excavated face.	0	Light lining required only if spalling or popping occurs.
II. Hard stratified and schistose	Hard rock consists of thick strata and layers. Interface between strata is cemented. Popping and spalling at excavated face is common.	0 to 0.5 B	Light support for protection against spalling. Load may change between layers.
III. Massive, moderately jointed	Massive rock contains widely spaced joints and fractures. Block size is large. Joints are interlocked. Vertical walls do not require support. Spalling may occur.	0 to 0.25 B	Light support for protection against spalling.
IV. Moderately blocky and seamy	Rock contains moderately spaced joints. Rock is not chemically weathered and altered. Joints are not well interlocked and have small apertures. Vertical walls do not require support. Spalling may occur.	0.25 B to 0.35 (B + H_t)	No side pressure.
V. Very blocky and seamy	Rock is not chemically weathered, and contains closely spaced joints. Joints have large apertures and appear separated. Vertical walls need support.	(0.35 to 1.1) (B + H_t)	Little or no side pressure.
VI. Completely crushed but chemically intact	Rock is not chemically weathered, and highly fractured with small fragments. The fragments are loose and not interlocked. Excavation face in this material needs considerable support.	1.1 (B + H_t)	Considerable side pressure. Softening effects by water at tunnel base. Use circular ribs or support rib lower end.
VII. Squeezing rock at moderate depth	Rock slowly advances into the tunnel without perceptible increase in volume. Moderate depth is considered as 150 ~ 1000 m.	(1.1 to 2.1) (B + H_t)	Heavy side pressure. Invert struts required. Circular ribs recommended.
VIII. Squeezing rock at great depth	Rock slowly advances into the tunnel without perceptible increase in volume. Great depth is considered as more than 1000 m.	(2.1 to 4.5) (B + H_t)	
IX. Swelling rock	Rock volume expands (and advances into the tunnel) due to swelling of clay minerals in the rock at the presence of moisture.	up to 250 feet, irrespective of B and H_t	Circular ribs required. In extreme cases use yielding support.

Comments on the Rock Load Factor Classification

(a) It provides reasonable support pressure estimates for small tunnels with diameter up to 6 metres.

(b) It gives over-estimates for large tunnels with diameter above 6 metres.

(c) The estimated support pressure has a wide range for squeezing and swelling rock conditions for a meaningful application.

ROCK STRUCTURE RATING (RSR)

- Wickham et. al. (1972) suggested this based on observation of small tunnels supported by steel ribs.
- RSR = A + B + C

  Parameter A, Geology: General appraisal of geological structure on the basis of:
- a. Rock type origin (igneous, metamorphic, sedimentary).
- b. Rock hardness (hard, medium, soft, decomposed).
- c. Geologic structure (massive, slightly faulted/folded, moderately faulted/folded,
- intensely faulted/folded).

- *Parameter B, Geometry*: Effect of discontinuity pattern with respect to the direction of the tunnel drive on the basis of:

  a. Joint spacing.

  b. Joint orientation (strike and dip).

  c. Direction of tunnel drive
- *Parameter C*: Effect of groundwater inflow and joint condition on the basis of:

  a. Overall rock mass quality on the basis of A and B combined.

  b. Joint condition (good, fair, poor).

  c. Amount of water inflow (in gallons per minute per 1000 feet of tunnel)..

Table 1: Rock Structure Rating: Parameter A: General area geology

	Basic Rock Type				Geological Structure			
	Hard	Medium	Soft	Decomposed				
Igneous	1	2	3	4		Slightly	Moderately	Intensively
Metamorphic	1	2	3	4		Folded or	Folded or	Folded or
Sedimentary	2	3	4	4	Massive	Faulted	Faulted	Faulted
Type 1					30	22	15	9
Type 2					27	20	13	8
Type 3					24	18	12	7
Type 4					19	15	10	6

Table 2: Rock Structure Rating: Parameter *B*: Joint pattern, direction of drive

	Strike ⊥ to Axis					Strike || to Axis		
	Direction of Drive					Direction of Drive		
	Both	With Dip		Against Dip		Either direction		
	Dip of Prominent Joints [a]					Dip of Prominent Joints		
Average joint spacing	Flat	Dipping	Vertical	Dipping	Vertical	Flat	Dipping	Vertical
1. Very closely jointed, < 2 in	9	11	13	10	12	9	9	7
2. Closely jointed, 2-6 in	13	16	19	15	17	14	14	11
3. Moderately jointed, 6-12 in	23	24	28	19	22	23	23	19
4. Moderate to blocky, 1-2 ft	30	32	36	25	28	30	28	24
5. Blocky to massive, 2-4 ft	36	38	40	33	35	36	24	28
6. Massive, > 4 ft	40	43	45	37	40	40	38	34

Table 3: Rock Structure Rating: Parameter *C*: Groundwater, joint condition

Anticipated water inflow gpm/1000 ft of tunnel	Sum of Parameters *A* + *B* 13 - 44 Joint Condition [b]			45 - 75		
	Good	Fair	Poor	Good	Fair	Poor
None	22	18	12	25	22	18
Slight, < 200 gpm	19	15	9	23	19	14
Moderate, 200-1000 gpm	15	22	7	21	16	12
Heavy, > 1000 gp	10	8	6	18	14	10

[a] Dip: flat: 0-20°; dipping: 20-50°; and vertical: 50-90°

[b] Joint condition: good = tight or cemented; fair = slightly weathered or altered; poor = severely weathered, altered or open

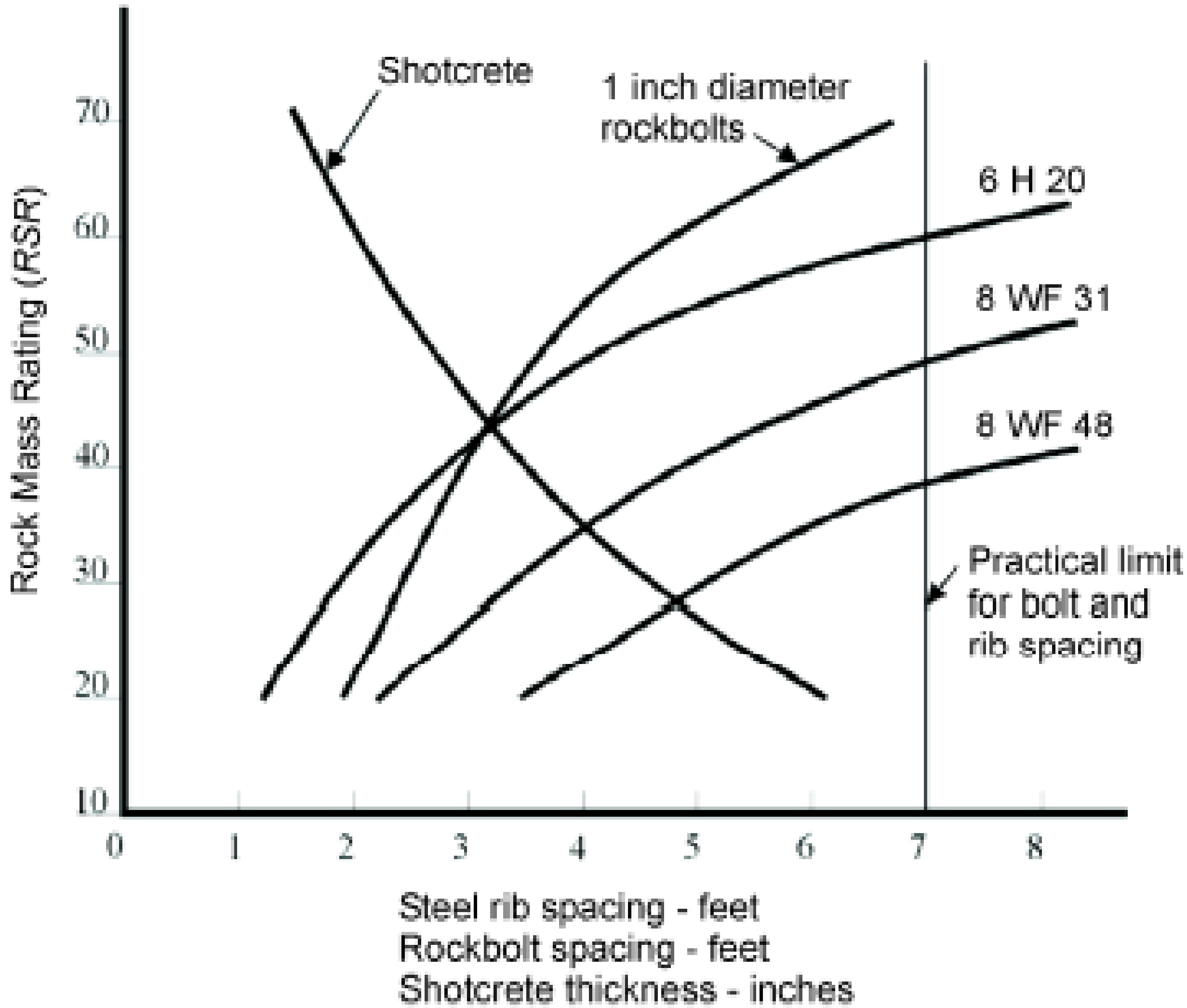


Figure 2: *RSR* support estimates for a 24 ft. (7.3 m) diameter circular tunnel. Note that rockbolts and shotcrete are generally used together. (After Wickham et al 1972).


RMR system
Bieniawski, 1989

Rock Mass Rating RMR

RMR system incorporates 5 basic parameters.

(a) Strength of intact rock material: uniaxial compressive strength or point load index;

(b) RQD;

(c) Spacing of joints: average spacing of all rock discontinuities;

(d) Condition of joints: joint aperture, roughness, joint surface weathering and alteration, infilling;

(e) Groundwater conditions: inflow or water pressure.

The RMR index is evaluated by using the following parameters

1

The uniaxial compressive strength of the intact rock. This can also be evaluated , at least for compressive strength values > 25 MPa, by the Point-Load strength index

The RMR index is evaluated by using the following parameters

2

The RQD (Rock Quality Designation index) as determined on the basis of the length of intact borehole core

The RMR index is evaluated by using the following parameters

3

The Discontinuity Spacing

The RMR index is evaluated by using the following parameters

4

The Condition of Discontinuity Surfaces

4

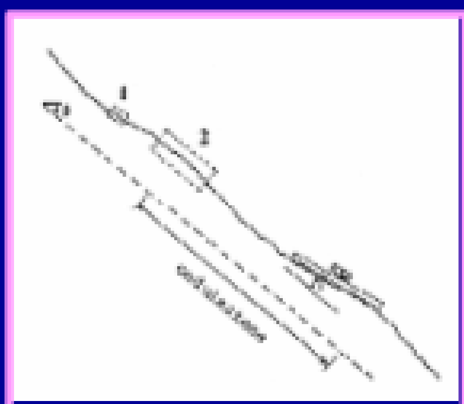
Condition of Discontinuity Surfaces

Weathering

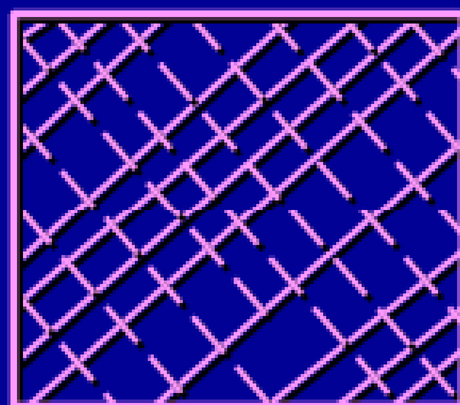
Aperture

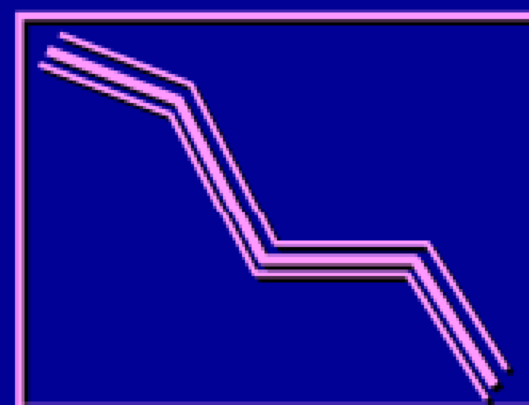
Infilling

roughness



persistence





The RMR index is evaluated by using the following parameters

5

The Groundwater

RMR System

To each classification parameter (1 to 5 as mentioned above) a Rating can be assigned. The sum of the resulting numerical Ratings gives the RMR Rock Mass Class

Note: the RMR is determined on the basis of 5 parameters only (i.e. without considering the adjustment due to the effect of the orientation of discontinuities relative to the engineered structure)

RMR or ‘Geomechanics Classification’

Parameter	Assessment of values and rating				
Intact rock UCS, MPa	>250	100–250	50–100	25–50	1–25
Rating	15	12	7	4	1
RQD %	>90	75–90	50–75	25–50	< 25
Rating	20	17	13	8	3
Mean fracture spacing	> 2 m	0·6–2 m	200–600 mm	60–200 mm	< 60 mm
Rating	20	15	10	8	5
Fracture conditions	rough tight	open < 1 mm	weathered	gouge < 5 mm	gouge > 5 mm
Rating	30	25	20	10	0
Groundwater state	dry	damp	wet	dripping	flowing
Rating	15	10	7	4	0
Fracture orientation	v. favourable	favourable	fair	unfavourable	v. unfavourable
Rating	0	−2	−7	−15	−25

Rock mass rating (RMR) is sum of the six ratings

Note that orientation ratings are negative

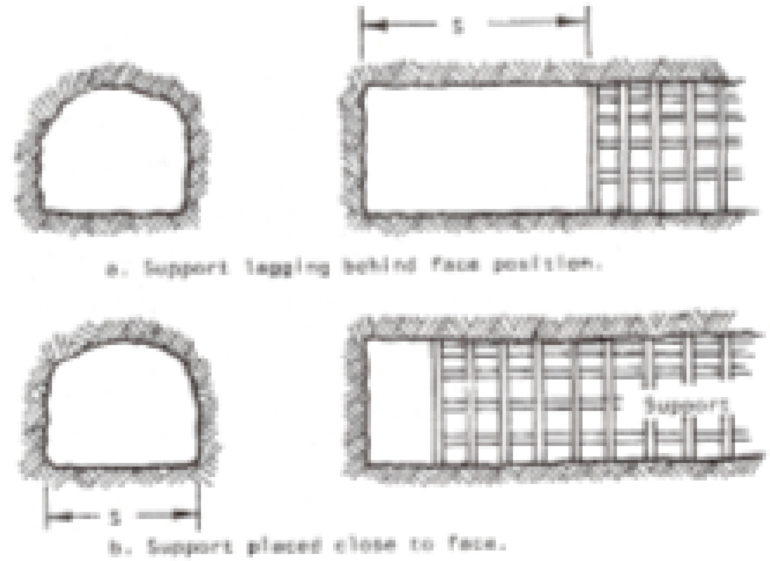
Guideline properties of Rock Mass Classes

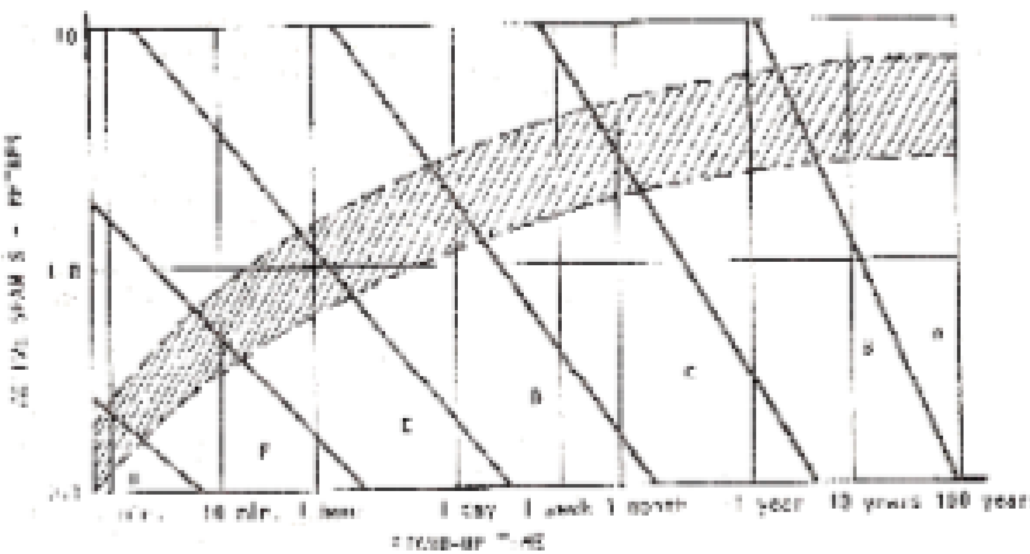
Guideline Properties of Rock Mass Classes

Class	I	II	III	IV	V
Description	very good rock	good rock	fair rock	poor rock	very poor rock
RMR	80–100	60–80	40–60	20–40	< 20
Q Value	> 40	10–40	4–10	1–4	<1
Friction angle φ (°)	> 45	35–45	25–35	15–25	<15
Cohesion (kPa)	> 400	300–400	200–300	100–200	< 100
SBP (MPa)	10	4–6	1–2	0·5	< 0·2
Safe cut slope (°)	> 70	65	55	45	< 40
Tunnel support	none	spot bolts	pattern bolts	bolts + shotcrete	steel ribs
Stand up time for span	20 yr for 15 m	1 yr for 10 m	1 wk for 5 m	12 h for 2 m	30 min for 1 m

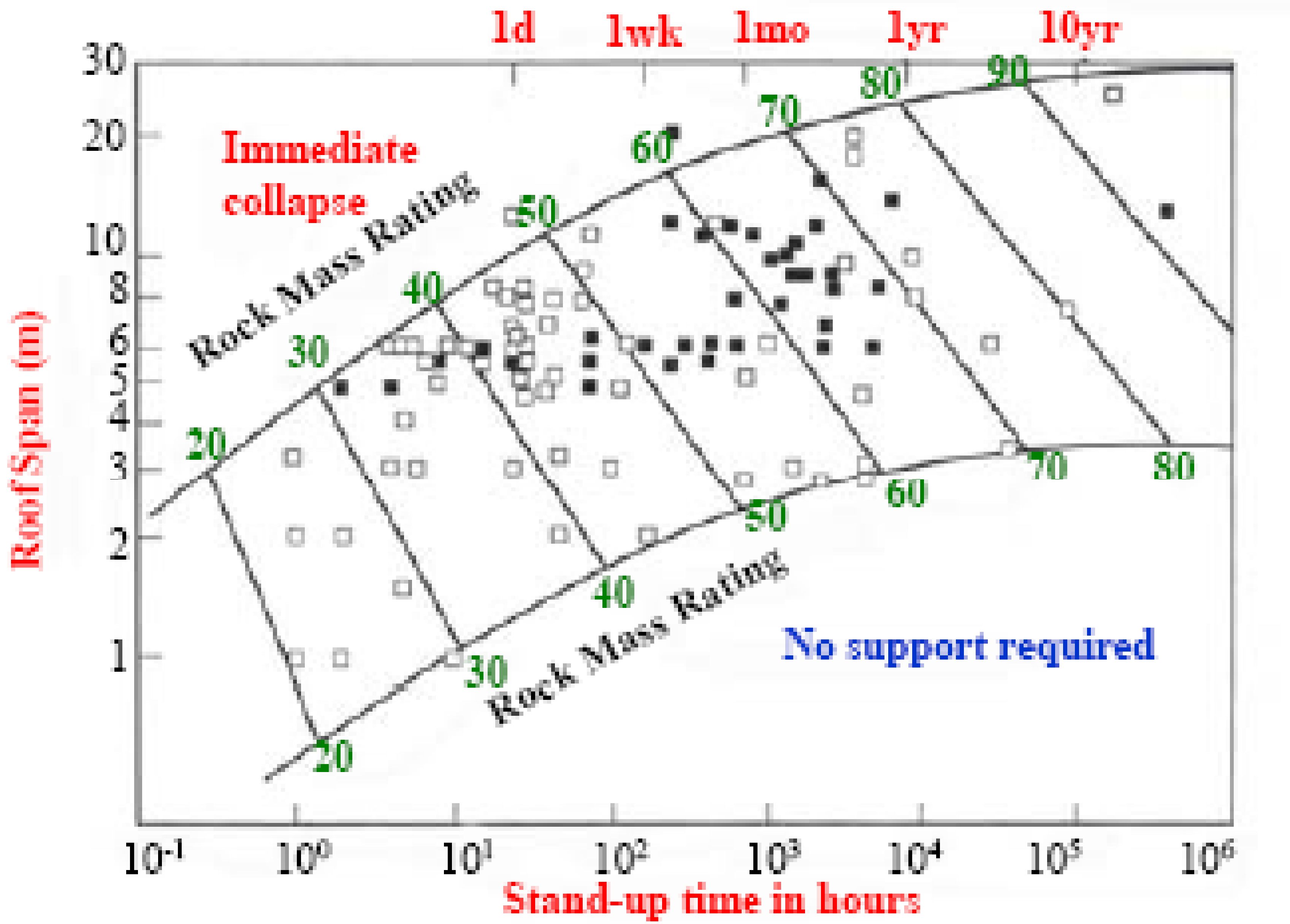
Active Span and Stand-Up Time

Stand-up time is the length of time which an excavated opening can stand without any mean of support . Rock classes are assigned according to the stand-up time.





RMR and STAND-UP TIME



Evaluation of Tunn... based on RMR

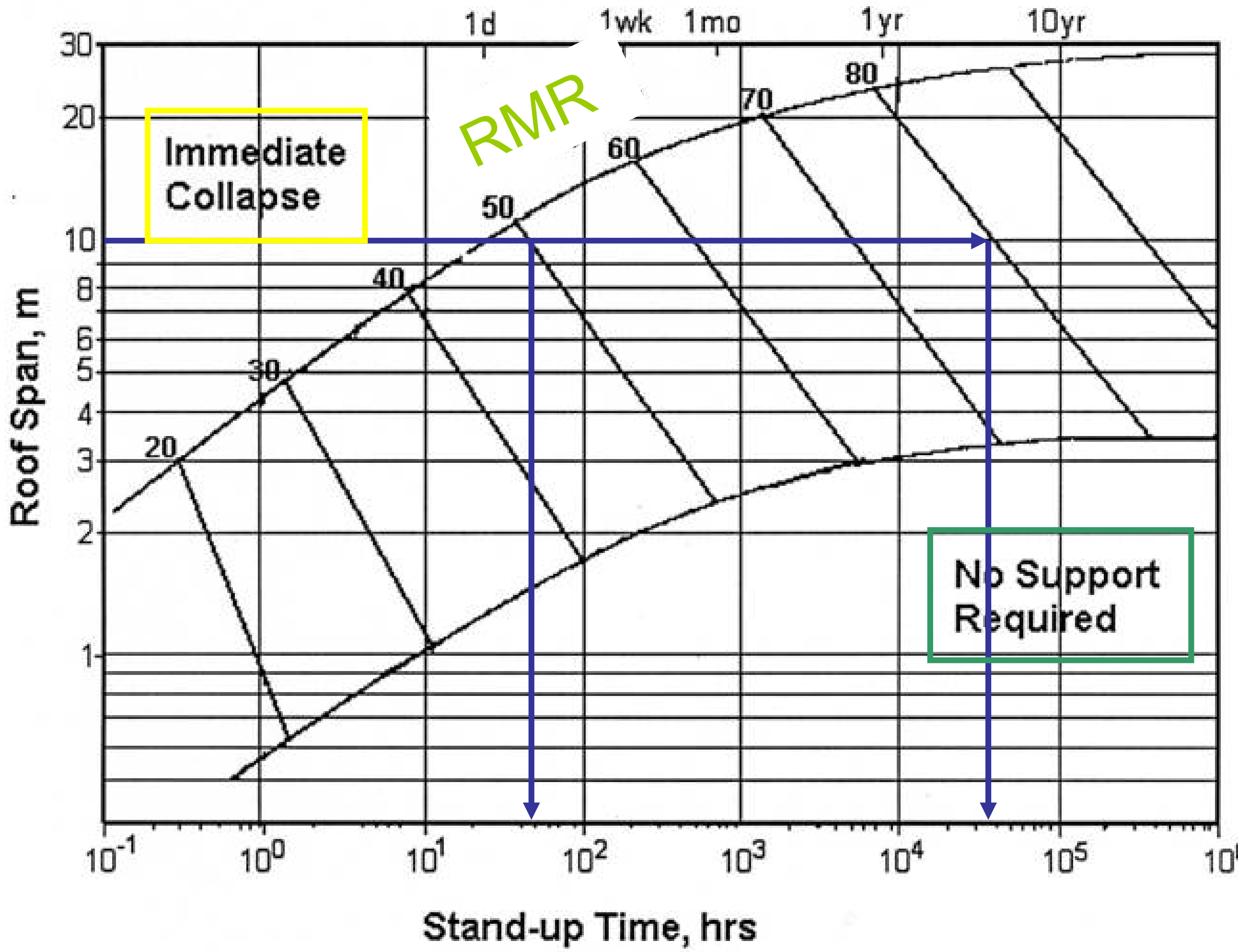
<u>Example:</u> 10 m span

RMR = 80

Stand up time > 4 years

RMR = 50

Stand up time ≈ 2 days



Parameters for RMR – Table 6.2.1a

RMR and rock mass quality

RMR Ratings	81 - 100	61 - 80	41 - 60	21 - 40	< 20
Rock mass class	A	B	C	D	E
Description	very good rock	good rock	fair rock	poor rock	very poor rock
Average stand-up time	10 year for 15 m span	6 months for 8 m span	1 week for 5 m span	10 hours for 2.5 m span	30 minutes for 0.5 m span
Rock mass cohesion (KPa)	> 400	300 - 400	200 - 300	100 - 200	< 100
Rock mass friction angle	> 45°	35° - 45°	25° - 35°	15° - 25°	< 15°

RMR modified for slopes or tunnels

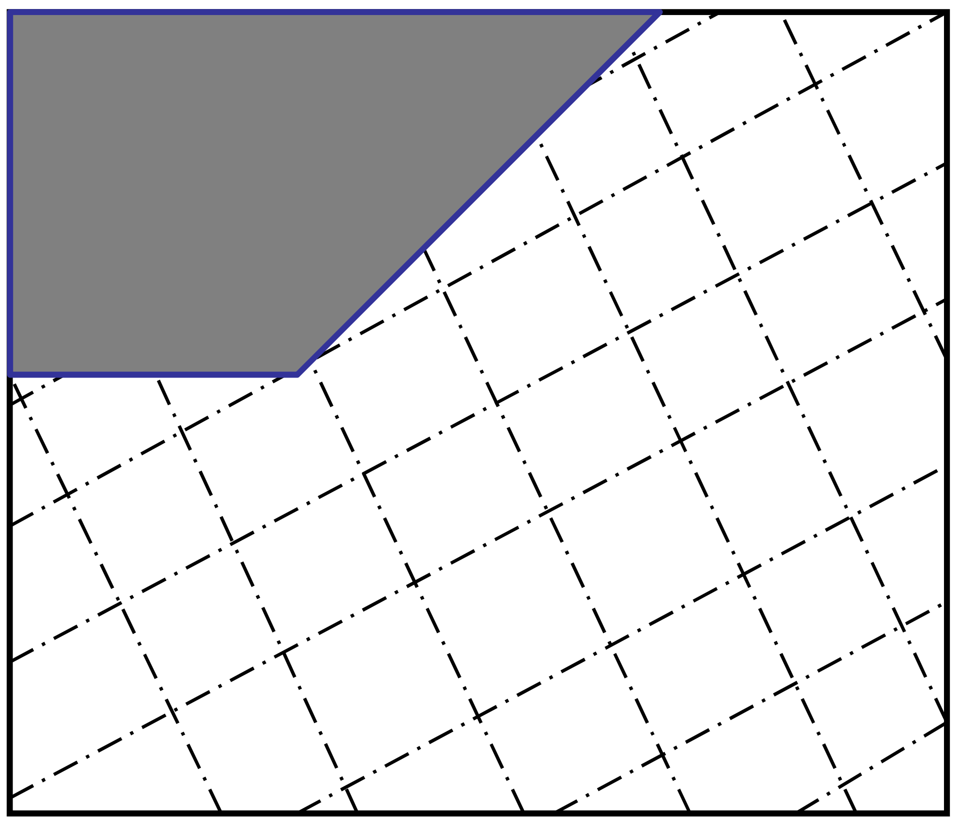
Additional factors applied to RMR_{basic}

- Accounts for excavation method

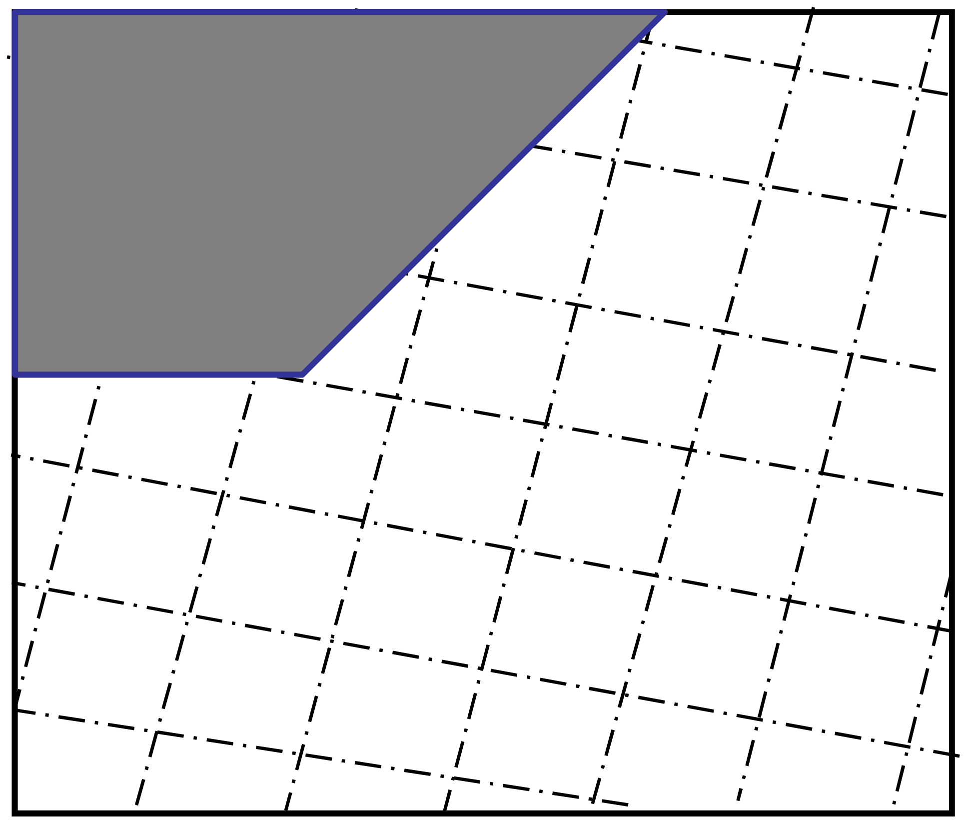
BUT moreover,

- Accounts for joint orientation wrt the excavation
  - Unfavourable conditions, **deduct points from RMR_{basic}**
  - *refer section F of Table*

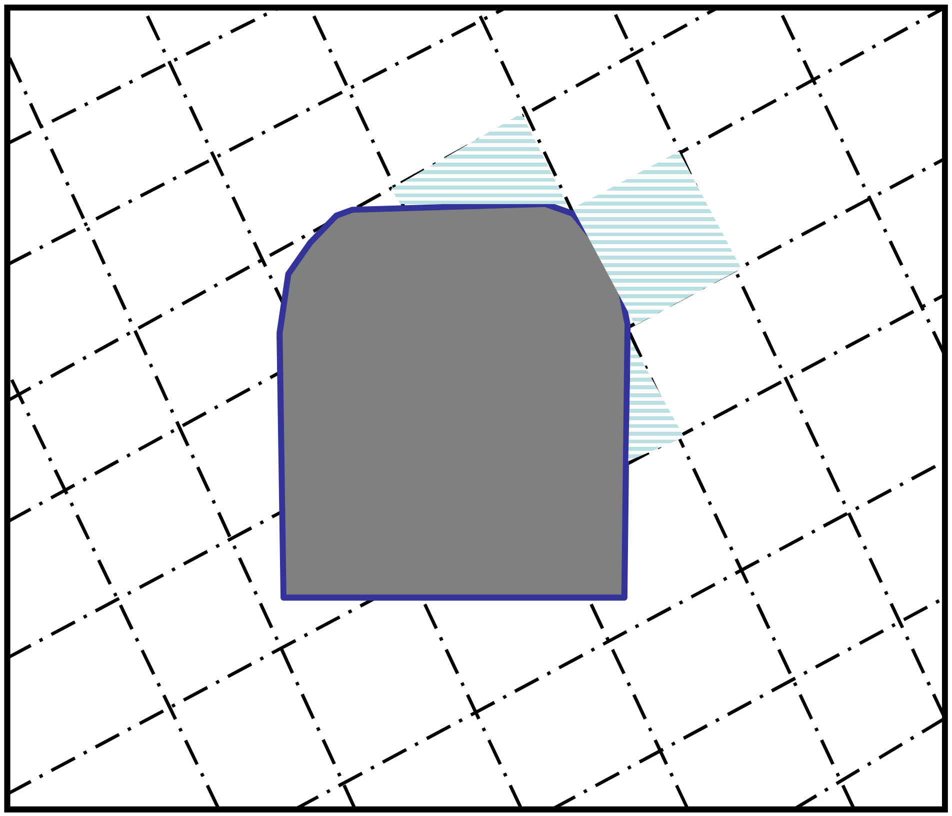
Slopes - un*favourable*



Slopes - *favourable*



Tunnels - un*favourable*



Tunnels - *favourable*

- Widely spaced joints?

RMR & Tunnels

- “Stand up time” for various tunnel spans based on RMR
- Unreinforced tunnels
  - no advice re support e.g. shotcrete or rockbolts/anchors

Shotcrete = sprayed concrete, lightly reinforced


Q system
Barton et al., 1974

In a similar way to the RMR system, the Q rating is developed by assigning values to six parameters

1. RQD

2. Number of discontinuity sets (J_n)

3

Roughness of the "most unfavourable" discontinuity (J_r)

4

Degree of alteration or filling along the weakest discontinuity (J_a)

5

Water inflow (J_w)

6

Stress Condition (SRF)

NGI Q-System Rating for Rock Masses

(Barton, Lien, & Lunde, 1974)

$$Q = \left(\frac{RQD}{J_n}\right)\left(\frac{J_r}{J_a}\right)\left(\frac{J_w}{SRF}\right)$$

Norwegian Classification for Rock Masses

Q - Value	Quality of Rock Mass
< 0.01	Exceptionally Poor
0.01 to 0.1	Extremely Poor
0.1 to 1	Very Poor
1 to 4	Poor
4 to 10	Fair
10 to 40	Good
40 to 100	Very Good
100 to 400	Extremely Good
< 400	Exceptionally Good

PARAMETERS FOR THE Q-Rating of Rock Masses

1. RQD = Rock Quality Designation = sum of cored pieces > 100 mm long, divided by total core run length

2. Number of Sets of Discontinuities (joint sets)	= J_n
Massive	0.5
One set	2
Two sets	4
Three sets	9
Four or more sets	15
Crushed rock	20

3. Roughness of Discontinuities*	= J_r
Noncontinuous joints	4
Rough, wavy	3
Smooth, wavy	2
Rough, planar	1.5
Smooth, planar	1
Slick and planar	0.5
Filled discontinuities	1

*Note: add +1 if mean joint spacing > 3 m

4. Discontinuity Condition & Infilling	= J_a
4.1 Unfilled Cases	
Healed	0.75
Stained, no alteration	1
Silty or Sandy Coating	3
Clay coating	4
4.2 Filled Discontinuities	
Sand or crushed rock infill	4
Stiff clay infilling < 5 mm	6
Soft clay infill < 5 mm thick	8
Swelling clay < 5 mm	12
Stiff clay infill > 5 mm thick	10
Soft clay infill > 5 mm thick	15
Swelling clay > 5 mm	20

5. Water Conditions	
Dry	1
Medium Water Inflow	0.66
Large inflow in unfilled joints	0.5
Large inflow with filled joints that wash out	0.33
High transient flow	0.2 to 0.1
High continuous flow	0.1 to 0.05

6. Stress Reduction Factor**	= SRF
Loose rock with clay infill	10
Loose rock with open joints	5
Shallow rock with clay infill	2.5
Rock with unfilled joints	1

**Note: Additional SRF values given for rocks prone to bursting, squeezing and swelling by Barton et al. (1974)

Rock Tunnelling Quality Index, Q
(or Norwegian Q system), Barton et al., 1974

$$Q = \left(\frac{RQD}{Jn}\right) \times \left(\frac{Jr}{Ja}\right) \times \left(\frac{Jw}{SRF}\right)$$

RQD = Rock Quality Designation	100 - 10
Jn = Joint set number	1 – 20
Jr = Joint roughness factor	4 -1
Ja = Joint alteration and clay fillings	1 – 20
Jw = Joint water inflow or pressure	1 – 0.1
SRF = stress reduction factor	1 – 20

Typically: $0.01 < Q < 100$

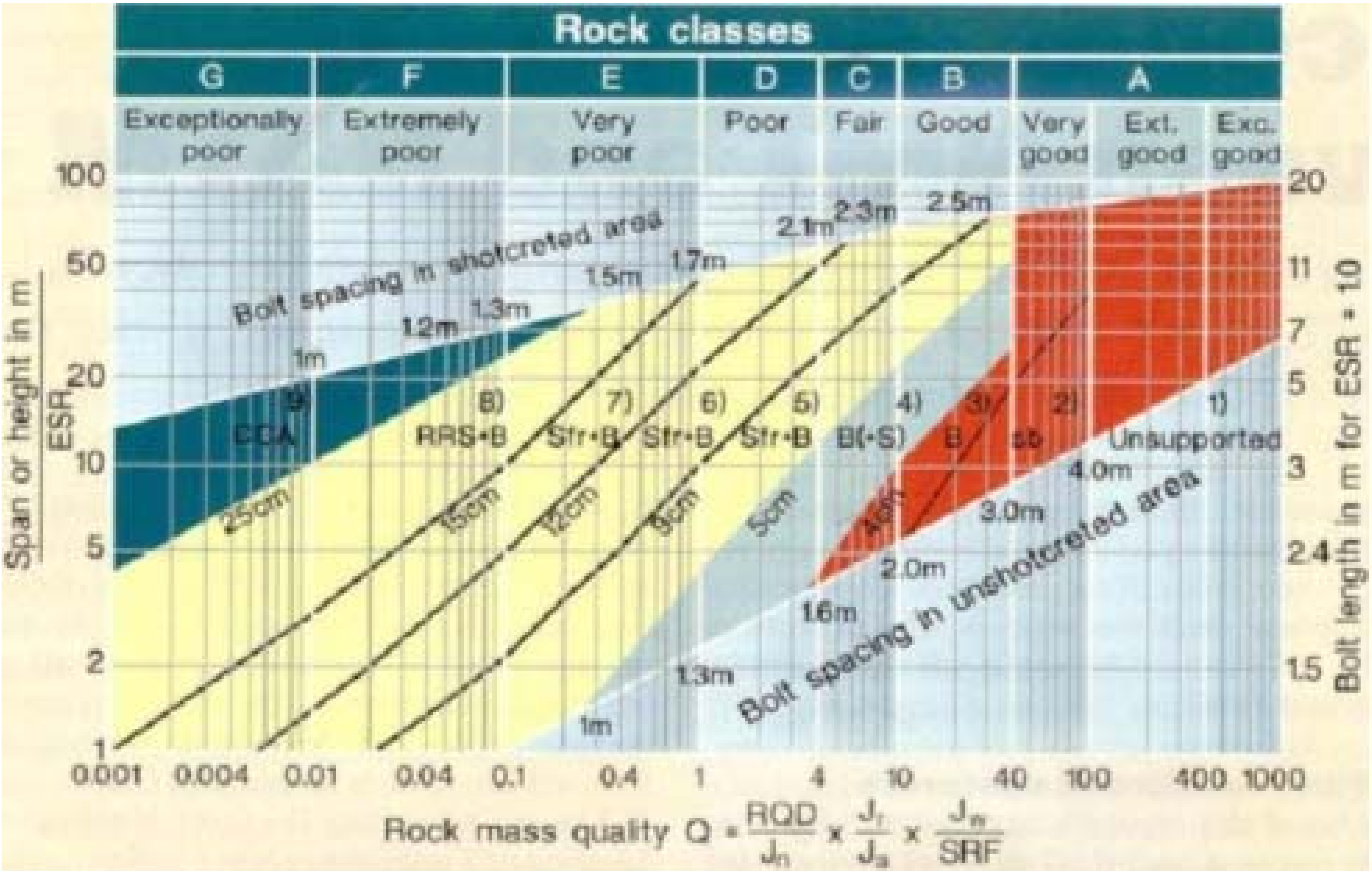
Q system

$$Q = \left(\frac{RQD}{Jn}\right) \times \left(\frac{Jr}{Ja}\right) \times \left(\frac{Jw}{SRF}\right)$$

- (RQD/Jn) = crude measure of block size
- (Jr/Ja) = roughness/friction of surfaces
- (Jw/SRF) = ratio of two stress parameters (active stress)

Q-value and rock mass quality

Q-value	Class	Rock mass quality
400 ~ 1000	A	Exceptionally Good
100 ~ 400	A	Extremely Good
40 ~ 100	A	Very Good
10 ~ 40	B	Good
4 ~ 10	C	Fair
1 ~ 4	D	Poor
0.1 ~ 1	E	Very Poor
0.01 ~ 0.1	F	Extremely Poor
0.001 ~ 0.01	G	Exceptionally Poor

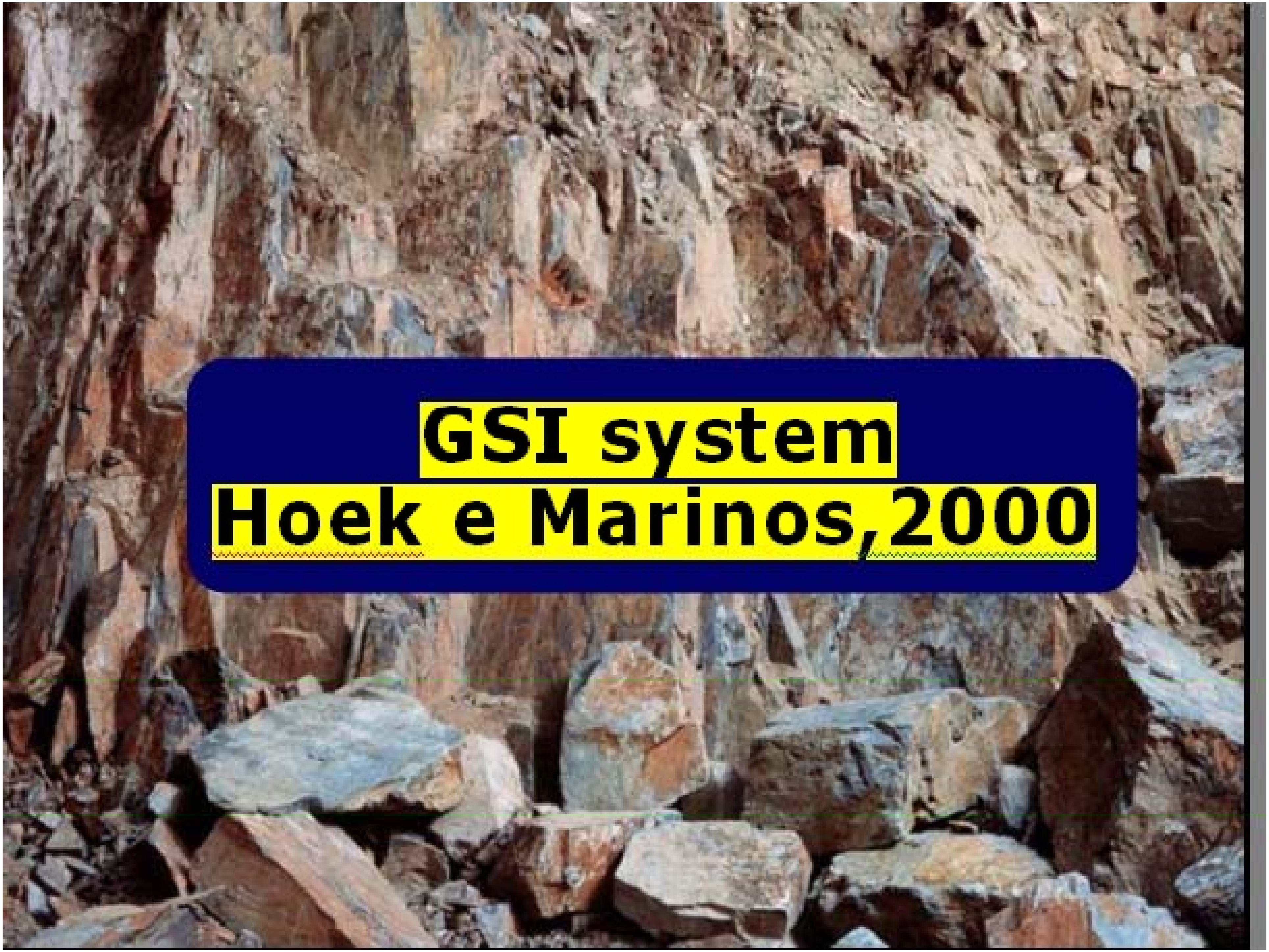


REINFORCEMENT CATEGORIES:

1) Unsupported
2) Spot bolting, sb
3) Systematic bolting, B
4) Systematic bolting, (and unreinforced shotcrete, 4-10cm), B(+S)
5) Fibre reinforced shotcrete and bolting, 5-9cm, Sfr+B
6) Fibre reinforced shotcrete and bolting, 9-12cm, Sfr+B
7) Fibre reinforced shotcrete and bolting, 12-15cm, Sfr+B
8) Fibre reinforced shotcrete >15cm, reinforced ribs of shotcrete and bolting, Sfr,RRS+B
9) Cast concrete lining, CCA

Excavation Support Ratio (ESR)

Excavation Category		ESR
A	Temporary mine openings.	3 – 5
B	Permanent mine openings, water tunnels for hydro-electric projects, pilot tunnels, drifts and headings for large excavations.	1.6
C	Storage rooms, water treatment plants, minor road and railway tunnels, surge chambers and access tunnels in hydro-electric project.	1.3
D	Underground power station caverns, major road and railway tunnels, civil defense chamber, tunnel portals and intersections.	1.0
L	Underground nuclear power stations, railway stations, sports and public facilities, underground factories.	0.8


GSI system
Hoek e Marinos,2000

The GSI index is developed by considering the following

1

Condition of discontinuity surfaces

(A) Very rough, fresh and unweathered surfaces

The GSI index is developed by considering the following

1

Condition of discontinuity surfaces

(B) Rough, slightly weathered, iron stained surfaces

The GSI index is developed by considering the following

1

Condition of discontinuity surfaces

(C) Smooth, moderatly weathered, and altered surfaces

The GSI index is developed by considering the following

1

Condition of discontinuity surfaces

(D) Slickensided, or highly weathered surfaces with compact coatings or fillings of angular fragments

The GSI index is developed by considering the following

1

Condition of discontinuity surfaces

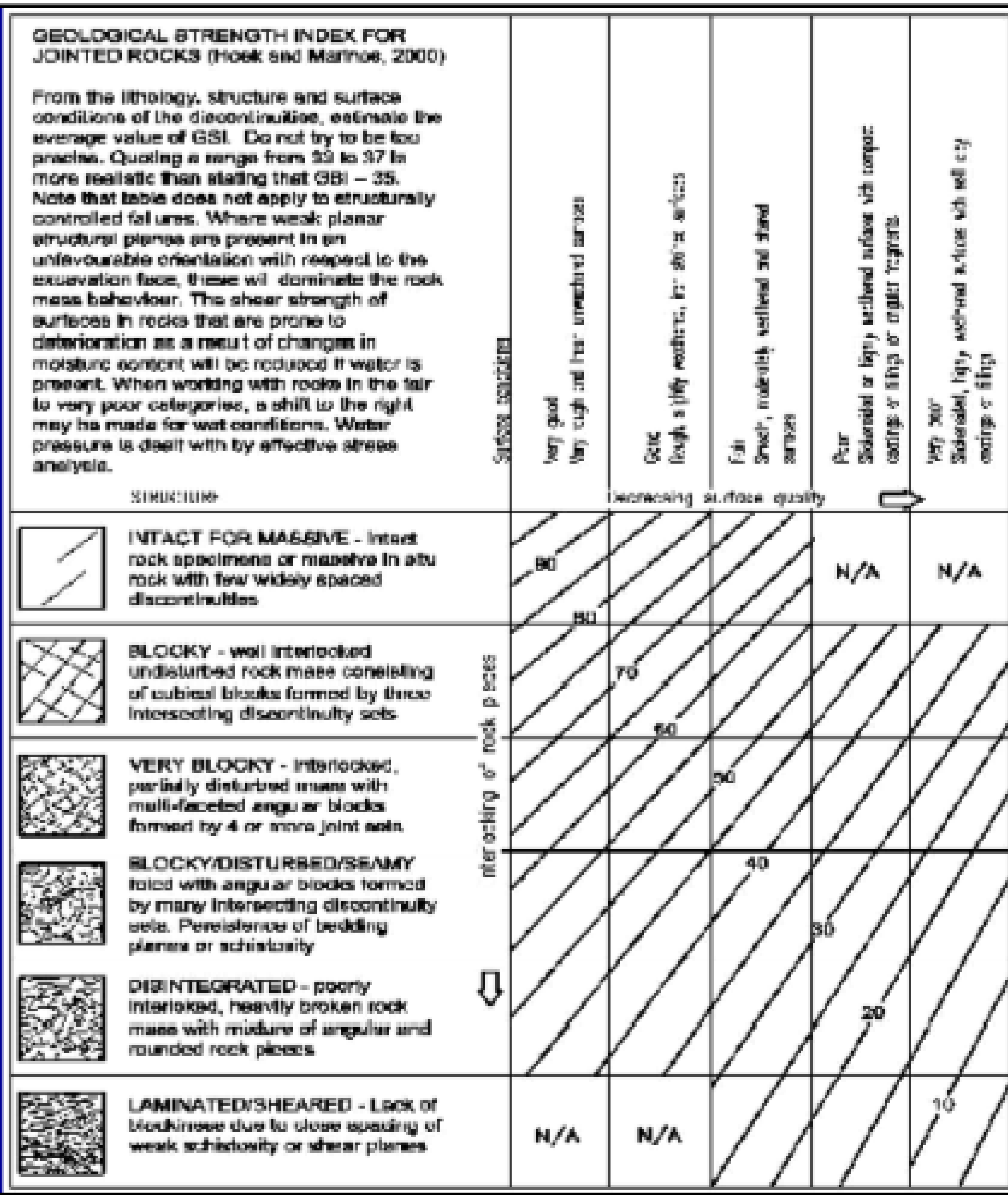
(E) Slickensided, highly weathered surfaces with soft clay coatings or fillings

2 Rock Mass Structure

3 Interlocking of rock blocks

Geological Strength Index, GSI

- Developed by Hoek, Kaiser, & Bawden (1995), Hoek & Brown (1997).
- GSI from Q-system: $$GSI = 9\log\left[\left(\frac{RQD}{J_n}\right)\left(\frac{J_r}{J_a}\right)\right] + 44$$
- GSI from Geomechanics system where RMR > 25: $$GSI = 10 + \sum_{i=1}^{4}\left(R_i\right)$$
- Chart approach based on structure & surface quality


GEOLOGICAL STRENGTH INDEX FOR JOINTED ROCKS (Hoek and Marinos, 2000)
From the lithology, structure and surface conditions of the discontinuities, estimate the average value of GSI. Do not try to be too precise. Quoting a range from 33 to 37 is more realistic than stating that GSI = 35. Note that table does not apply to structurally controlled failures. Where weak planar structural planes are present in an unfavourable orientation with respect to the excavation face, these will dominate the rock mass behaviour. The shear strength of surfaces in rocks that are prone to deterioration as a result of changes in moisture content will be reduced if water is present. When working with rocks in the fair to very poor categories, a shift to the right may be made for wet conditions. Water pressure is dealt with by effective stress analysis.
Surface conditions
Very good
Good
Fair
Poor
Very poor
STRUCTURE
Decreasing surface quality
INTACT OR MASSIVE - intact rock specimens or massive in situ rock with few widely spaced discontinuities
BLOCKY - well interlocked undisturbed rock mass consisting of cubical blocks formed by three intersecting discontinuity sets
VERY BLOCKY - interlocked, partially disturbed mass with multi-faceted angular blocks formed by 4 or more joint sets
BLOCKY/DISTURBED/SEAMY - folded with angular blocks formed by many intersecting discontinuity sets. Persistence of bedding planes or schistosity
DISINTEGRATED - poorly interlocked, heavily broken rock mass with mixture of angular and rounded rock pieces
LAMINATED/SHEARED - Lack of blockiness due to close spacing of weak schistosity or shear planes
Decreasing interlocking of rock pieces
90
80
70
60
50
40
30
20
10
N/A
N/A
N/A
N/A

Geological Strength Index GSI

GSI was aimed to estimate the reduction in rock mass strength for different geological conditions. The system gives a GSI value estimated from rock mass structure and rock discontinuity surface condition. The direct application of GSI value is to estimate the parameters in the Hoek-Brown strength criterion for rock masses.

GSI and rock mass quality

GSI Value	76 – 95	56 – 75	41 – 55	21 – 40	< 20
Rock Mass Quality	Very good	Good	Fair	Poor	Very poor

Example – Estimate RMR, Q and GSI

(a) Granite rock mass containing 3 joint sets, average RQD is 88%, average joint spacing is 0.24 m, joint surfaces are generally stepped and rough, tightly closed and unweathered with occasional stains observed, the excavation surface is wet but not dripping, average rock material uniaxial compressive strength is 160 MPa, the tunnel is excavated to 150 m below the ground where no abnormal high in situ stress is expected.

Rock material strength	160 MPa	Rating	12
RQD (%)	88%	Rating	17
Joint spacing (m)	0.24 m	Rating	10
Condition of joints	very rough, unweathered, no separation	Rating	30
Groundwater	wet	Rating	7
		RMR	76

RQD	88%	RQD	88
Joint set number	3 sets	J_n	9
Joint roughness number	rough stepped (⇒undulating)	J_r	3
Joint alteration number	unaltered, some stains	J_a	1
Joint water factor	wet only (dry excavation or minor inflow)	J_w	1
Stress reduction factor	$\sigma_c/\sigma_1 = 160/(150\times0.027) = 39.5$	SRF	1
Q	(88/9) (3/1) (1/1)		44

Rock Mass Structure: Blocky	Joint Surface Condition : Very good	GSI = 75±5

Example – Estimate RMR, Q and GSI

(b) A sandstone rock mass, fractured by 2 joint sets plus random fractures, average RQD is 70%, average joint spacing is 0.11 m, joint surfaces are slightly rough, highly weathered with stains and weathered surface but no clay found on surface, joints are generally in contact with apertures generally less than 1 mm, average rock material uniaxial compressive strength is 85 MPa, the tunnel is to be excavated at 80 m below ground level and the groundwater table is 10 m below the ground surface.

Rock material strength	85 MPa	Rating	7
RQD (%)	70%	Rating	13
Joint spacing (m)	0.11 m	Rating	8
Condition of joints	slightly rough, highly weathered, separation < 1mm	Rating	20
Groundwater	water pressure/stress = 0.32	Rating	4
		RMR	52

RQD	70%	RQD	70
Joint set number	2 sets plus random	J_n	6
Joint roughness number	slightly rough (⇒rough planar)	J_r	1.5
Joint alteration number	highly weathered only stain, (altered non-softening mineral coating)	J_a	2
Joint water factor	[illegible] = 7 bar 70 m water head = 7 kg/cm	J_w	0.5
Stress reduction factor	σ_c/σ_1 = 85/(80×0.027) = 39.3	SRF	1
Q	(70/6)(1.5/2)(0.5/1)		4.4

Rock Mass Structure: Blocky	Joint Surface Condition : Very good	GSI = 40±5

Example – Estimate RMR, Q and GSI

(c) A highly fractured siltstone rock mass, has 2 joint sets and many random fractures, average RQD is 41%, joints appears continuous observed in tunnel, joint surfaces are slickensided and undulating, and are highly weathered, joint are separated by about 3-5 mm, filled with clay, average rock material uniaxial compressive strength is 65 MPa, inflow per 10 m tunnel length is observed at approximately 50 litre/minute, with considerable outwash of joint fillings. The tunnel is at 220 m below ground.

Rock material strength	65 MPa	Rating	7
RQD (%)	41%	Rating	8
Joint spacing (m)	0.05 m	Rating	5
Condition of joints	continuous, slickensided, separation 1-5mm	Rating	10
Groundwater	inflow = 50 l/min	Rating	4
		RMR	34

RQD	41%	RQD	41
Joint set number	2 sets plus random	J_n	6
Joint roughness number	slickensided and undulating	J_r	1.5
Joint alteration number	highly weathered filled with 3-5 mm clay	J_a	4
Joint water factor	large inflow with considerable outwash	J_w	0.33
Stress reduction factor	σ_c/σ_1 = 65/(220×0.027) = 11	SRF	1
Q	(41/6) (1.5/4) (0.33/1)		0.85

Rock Mass Structure: Blocky	Joint Surface Condition : Very good	GSI = 20±5

Example – Estimate RMR, Q and GSI

	RMR	Quality	Q	Quality	GSI	Quality
(a) Granite	76	G	29	G	75	G
(b) Sandstone	52	F	4.4	F	40	F
(c) Siltstone	34	P	0.85	VP	20	VP

Other Rock Mass Classification Systems

Rock Mass Number, N

N is the rock mass quality Q value when SRF is set at 1, i.e.,

$N = (RQD / J_n)(J_r / J_a)(J_w)$

Rock Mass Index, RMi

$RMi = \sigma_c J_p$

σ_c is rock material strength.
J_p is jointing parameter for 4 joint characteristics: joint density, size, roughness, and alteration. J_p=1 for intact rock, J_p=0 for crushed rock masses.

TABLE V - SYMBOLS FOR BASIC GEOTECHNICAL DESCRIPTION

Interval for item (2) & (3) in cm	Layer thickness	Fracture Intercept	Uniaxial com. strength		Angle of Friction	
			kg/cm^2	Symbol	Degrees	Symbol
(1)	(2)	(3)	(4)	(5)	(6)	(7)
200	L_1	F_1	2000	S_1	> 45	A_1
60-200	L_2	F_2	600-2000	S_2	35-45	A_2
20-60	L_3	F_3	200-600	S_3	25-35	A_3
6-20	L_4	F_4	60-200	S_4	15-25	A_4
6	L_5	F_5	60	S_5	< 15	A_5

$q_a = q_c \cdot \frac{N_j}{4} \cdot \frac{N_a}{4}$

Quartz $L_2 f_4 S_3 A_2$

Slope Mass Rating (SMR)

- $SMR = RMR_{basic} – (F_1.F_2.F_3) + F_4$
- F_1, F_2 and F_3 are adjustment factors related to joint orientation with respect to slope orientation. F_4 is the correction factor for method of excavation.

TABLE 17.1

VALUES OF ADJUSTMENT FACTORS FOR DIFFERENT JOINT ORIENTATIONS (ROMANA, 1985)

Case of Slope Failure		Very Favourable	Favourable	Fair	Unfavourable	Very Unfavourable
P T W	$\|\alpha_j - \alpha_s\|$ $\|\alpha_j - \alpha_s - 180°\|$ $\|\alpha_i - \alpha_s\|$	>30°	30 - 20°	20 - 10°	10 - 5°	<5°
P/W/ T	F_1	0.15	0.40	0.70	0.85	1.00
P W	$\|\beta_j\|$ $\|\beta_i\|$	<20°	20 - 30°	30 - 35°	35 - 45°	>45°
P/W	F_2	0.15	0.40	0.70	0.85	1.00
T	F_2	1.0	1.0	1.0	1.0	1.0
P W	$\|\beta_j - \beta_s\|$ $\|\beta_i - \beta_s\|$	>10°	10 - 0°	0°	0 - (-10°)	< -10°
T	$\|\beta_j + \beta_s\|$	<110°	110 - 120°	>120°	--	--
P/W/T	F_3	0	-6	-25	-50	-60

NOTATIONS: *P - planar failure; T- toppling failure; W - wedge failure;* α_s *- slope strike;* α_j *- joi[nt] strike;* α_i *- plunge direction of line of intersection;* β_s *- slope dip and* β_j *- joint dip (s[ee] Figure 17.1);* β_i *- plunge of line of intersection*

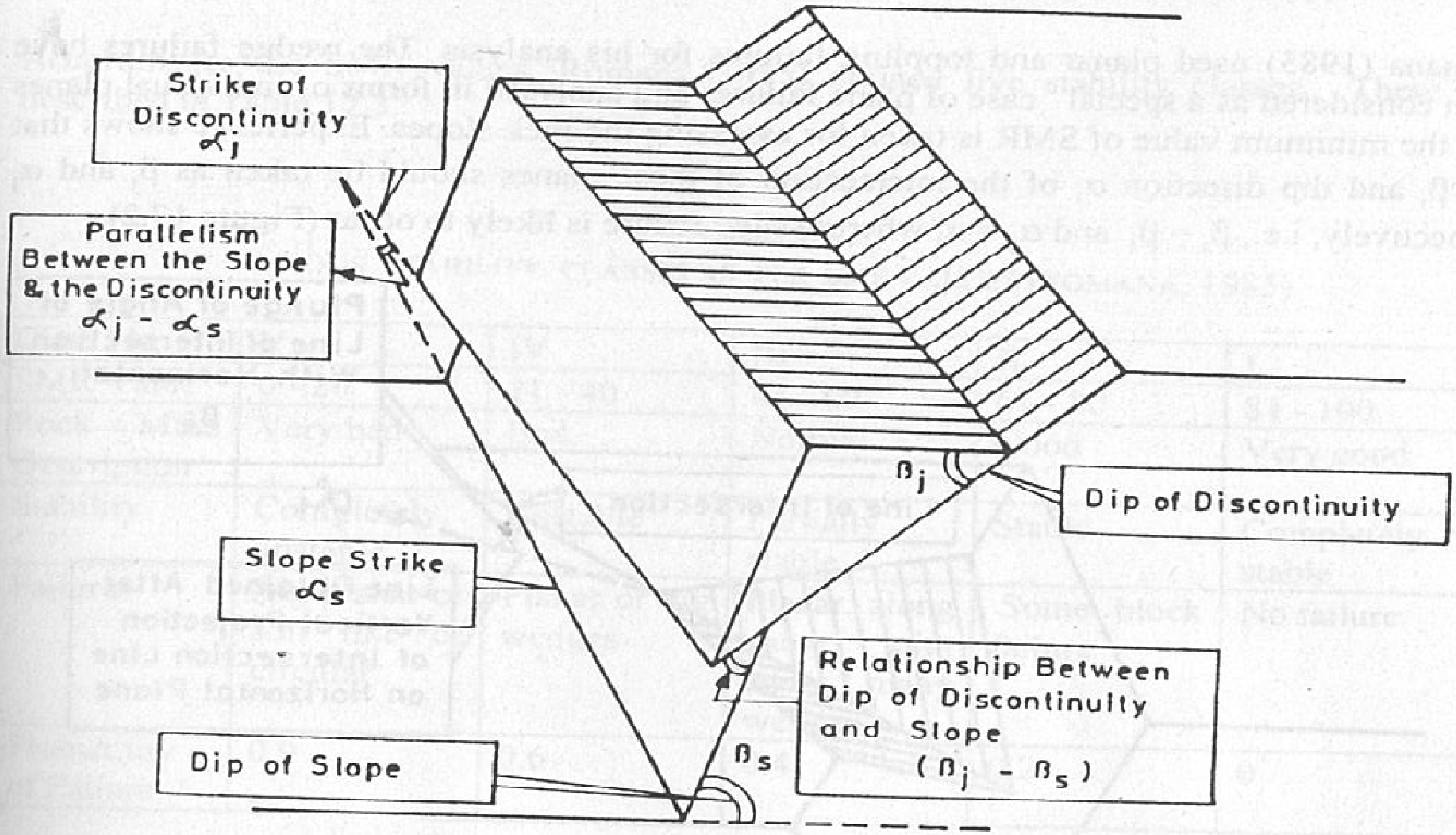


Figure 17.1: Planar failure

TABLE 17.2

VALUES OF ADJUSTMENT FACTOR F_4 FOR METHOD OF EXCAVATION (ROMANA, 1985)

Method of Excavation	F_4 Value
Natural slope	+15
Pre-splitting	+10
Smooth blasting	+8
Normal blasting or Mechanical excavation	0
Poor blasting	-8

TABLE 17.3

VARIOUS STABILITY CLASSES AS PER SMR VALUES (ROMANA, 1985)

Class No.	V	IV	III	II	I
SMR Value	0 - 20	21 - 40	41 - 60	61 - 80	81 - 100
Rock Mass Description	Very bad	Bad	Normal	Good	Very good
Stability	Completely unstable	Unstable	Partially stable	Stable	Completely stable
Failures	Big planar or soil like or circular	Planar or big wedges	Planar along some joint and many wedges	Some block failure	No failure
Probability of Failure	0.9	0.6	0.4	0.2	0

Suggested Supports for Various SMR classes

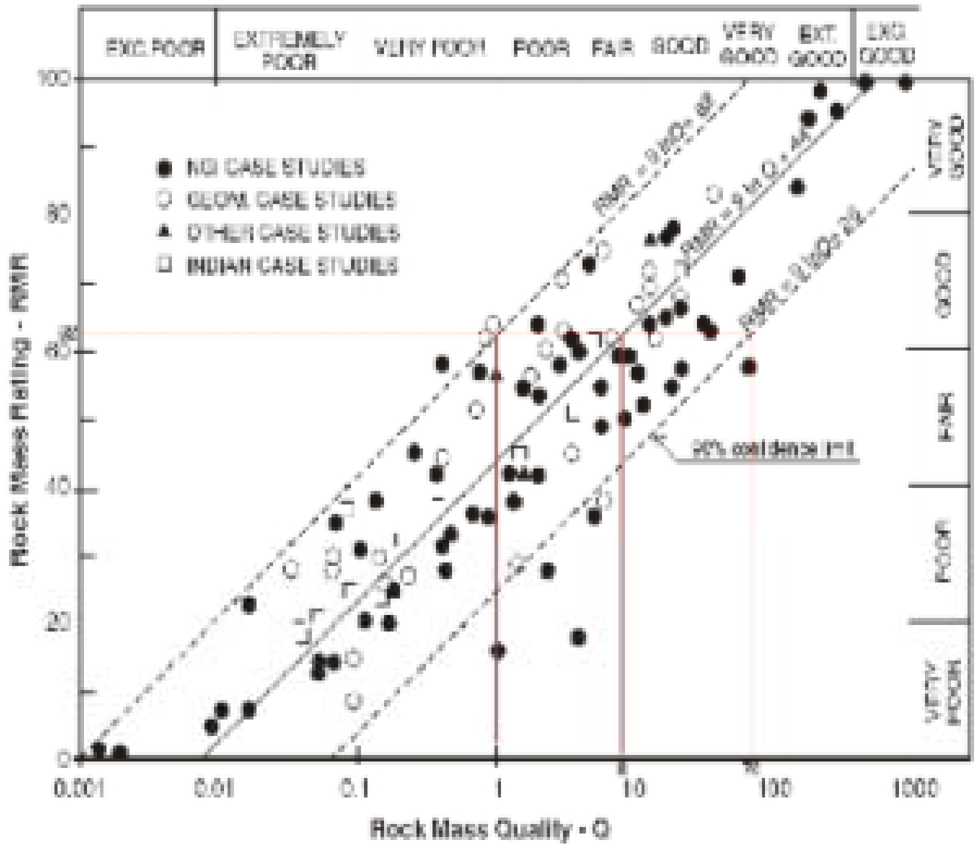
SMR Classes	SMR Values	Suggested Supports
I a	91-100	None
I b	81-90	None, scaling is required
II a	71-80	Spot Bolting
II b	61-70	Spot or systematic bolting
III a	51-60	Spot or systematic bolting, spot shotcrete
III b	41-50	Systematic bolting and shotcrete, toe wall
IV a	31-40	Anchors, systematic shotcrete, toe wall
IV b	21-30	Systematic reinforced shotcrete, toe wall, re-exacavation
V	11-20	Gravity or anchored wall, re-excavation

Correlation between Q, RMR and GSI

RMR = 9 lnQ + (44±18)

RMR = 13.5 logQ + 43

GSI = RMR – 5
(for GSI > 25)



Rock Mass Strength

Strength and deformation properties of a rock mass are governed by the existence of joints. Those rock mass properties are also related to the quality of the rock mass. In general, a rock mass of good quality (strong rock, few joints and good joint surface quality) have higher strength and higher deformation modulus than that of a poor rock mass.

Hoek-Brown Rock Mass Strength Criterion

Generalised Hoek-Brown Criterion

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

$$\sigma_1 = \sigma_3 + (m_b\, \sigma_3\, \sigma_{ci} + s\, \sigma_{ci}^2)^a$$

H-B criterion for rock material is a special form of the generalised equation when s =1, a = 0.5, m_b=m_i.

$$\sigma_1 = \sigma_3 + (m_i\, \sigma_3\, \sigma_{ci} + \sigma_{ci2})^{0.5}$$

Hoek-Brown Rock Mass Strength Criterion

σ_{ci} is consistently the uniaxial compressive strength of intact rock material, used in the Hoek-Brown criterion for rock material and for rock mass.

σ_1 is the rock mass strength at a confining pressure σ_3. σ_{ci} is the uniaxial strength of the intact rock in the rock mass. Parameter a is generally equal to 0.5.

Constants m_b and s are parameters that changes with rock type and rock mass quality. Table 6.5.2a shows m_b and s values.

Hoek-Brown Failure Criterion $\sigma_1/\sigma_c = \sigma_3/\sigma_c + (m_b \sigma_3/\sigma_c + s)^{0.5}$	Carbonate rocks - *dolomite, limestone, marble*	Argillaceous rocks - *mudstone, siltstone, shale, slate*	Arenaceous rocks - *sandstone, quartzite*	Fine grained igneous - *andesite, dolerite, basalt, rhyolite*	Coarse metamorphic & igneous - *gabbro, gneiss, granite*
Intact rock material RMR = 100 ,Q = 500	m_i = 7.0 s = 1.0	m_i = 10.0 s = 1.0	m_i = 15.0 s = 1.0	m_i = 17.0 s = 1.0	m_i = 25.0 s = 1.0
Very good quality rock mass RMR = 85, Q = 100	m_b = 3.5 s = 0.1	m_b = 5.0 s = 0.1	m_b = 7.5 s = 0.1	m_b = 8.5 s = 0.1	m_b = 12.5 s = 0.1
Good quality rock mass RMR = 65, Q = 10	m_b = 0.7 s = 0.004	m_b = 1.0 s = 0.004	m_b = 1.5 s = 0.004	m_b = 1.7 s = 0.004	m_b = 2.5 s = 0.004
Fair quality rock mass RMR = 44, Q = 1.0	m_b = 0.14 s = 0.0001	m_b = 0.20 s = 0.0001	m_b = 0.30 s = 0.0001	m_b = 0.34 s = 0.0001	m_b = 0.50 s = 0.0001
Poor quality rock mass *RMR = 23, Q = 0.1*	m_b = 0.04 s = 0.00001	m_b = 0.05 s = 0.00001	m_b = 0.08 s = 0.00001	m_b = 0.09 s = 0.00001	m_b = 0.13 s = 0.00001
Very poor quality rock mass *RMR = 3, Q = 0.01*	m_b = 0.007 s = 0	m_b = 0.01 s = 0	m_b = 0.015 s = 0	m_b = 0.017 s = 0	m_b = 0.025 s = 0

Hoek-Brown Rock Mass Strength Criterion

Development and application of the Hoek-Brown criterion lead to better definition of the parameters m_b and s.

Determination of m_i is improved, as in the next slide.

With GSI estimated, m_b can be calculated,

$m_b = m_i \exp[(GSI - 100)/28]$

Rock Type		Rock Name and m_i Values			
Igneous	Intrusive	Granite 32±3 Granodiorite 29±3	Diorite 25±5 Dolerite (16±5)	Gabbro 27±3 Norite 22±5	Peridotite (25±5)
	Extrusive	Rhyolite (16±5)	Andesite 25±5	Basalt (16±5) Diabase (16±5)	Porphyries (20±5)
	Volcanic		Agglomerate (19±3)	Tuff (13±5)	
Sedimentary	Clastic	Conglomerate (4±18) Breccia (4±16)	Sandstone 17±4	Siltstone 7±2 Marls (7±2)	Mudstone 4±2 Shale (6±2)
	Carbonate	Crystalline limestone (12±3)	Sparitic limestone (10±2)	Micritic limestone (9±2)	Dolomite (9±3)
	Chemical		Gypsum 8±2	Anhydrite 12±2	
	Organic			Coal (8±12)	Chalk 7±2
Metamorphic	Foliated	Gneiss 28±5	Schist 12±3	Phyllites (7±3)	Slate 7±4
	Slightly Foliated	Migmatite (29±3)	Amphibolite 26±6		
	Non Foliated	Quartzite 20±3	Meta-sandstone (19 ±3)	Hornfels (19±4)	Marble 9±3

Be careful with large uncertainty

Hoek-Brown Rock Mass Strength Criterion

For GSI > 25, i.e. rock masses of good to reasonable quality,

$s = \exp[(GSI - 100)/9]$

$a = 0.5$

This is the original Hoek-Brown criterion.

Example on Hoek-Brown Criterion and GSI

$$\sigma_1 = \sigma_3 + (m_b\, \sigma_3\, \sigma_{ci} + s\, \sigma_{ci}{}^2)^a$$

(a) Granite rock mass, σ_{ci}= 150 MPa, GSI=75, a = 0.5.

m_i for granite is 32,

$m_b = m_i \exp[(GSI - 100)/28] = 13.1$

$s = \exp[(GSI - 100)/9] = 0.062$

$\sigma_1 = \sigma_3 + (1956\, \sigma_3 + 1395)^{0.5}$

When $\sigma_3 = 0$, $\sigma_{cm} = 1395^{0.5} = 37.3$ MPa

Example on Hoek-Brown Criterion and GSI

σ1 = σ3 + (mb σ3 σci + s σci2)a

(c) Siltstone rock mass, σ_{ci}=65 MPa, GSI=20.

m_i for siltstone = 7

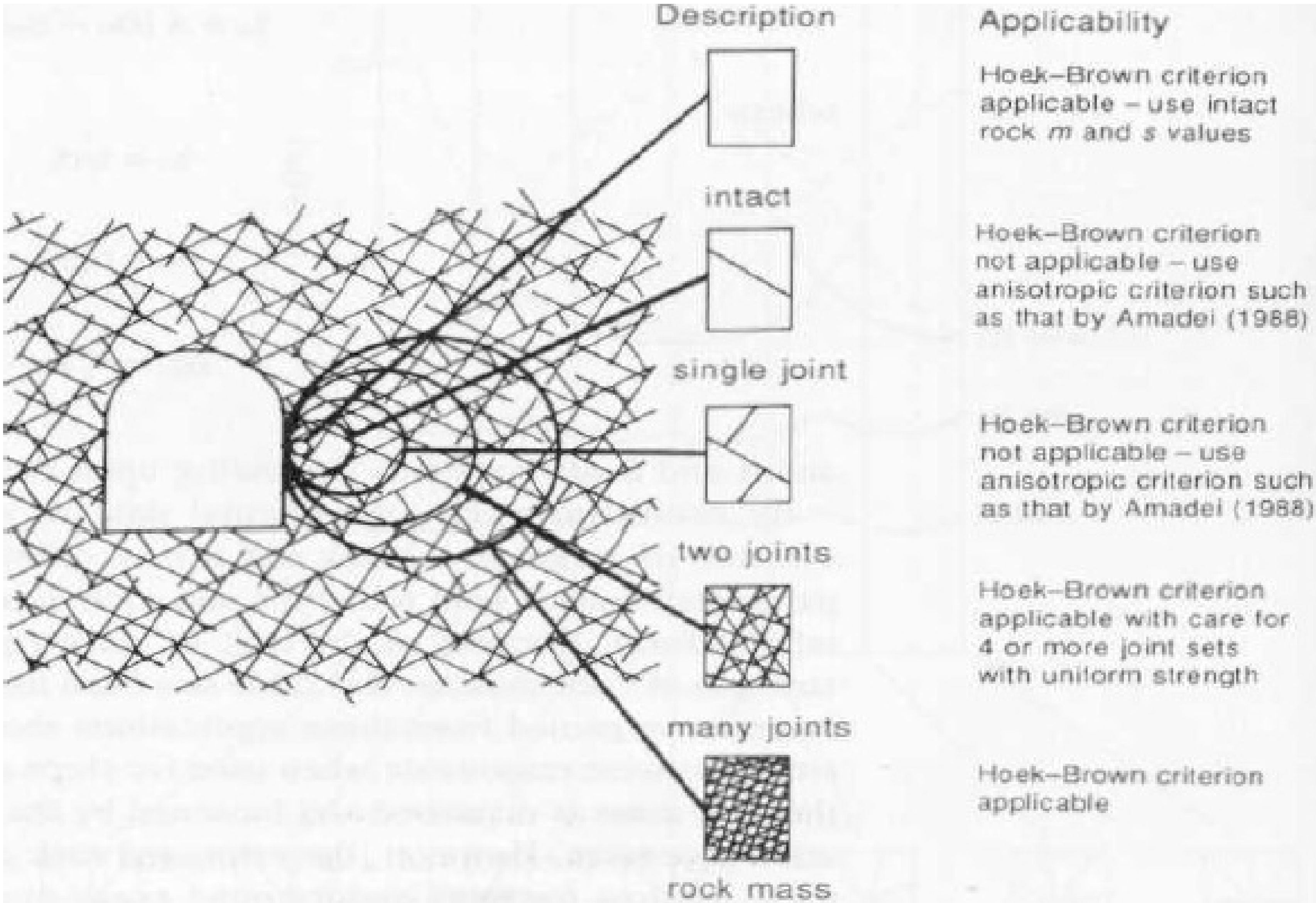
$m_b = m_i \exp[(GSI - 100)/28] = 0.40$

$s = \exp[(GSI - 100)/9] = 0.00014$

GSI < 25, $a = 0.65 - (GSI/200) = 0.55$

$\sigma_1 = \sigma_3 + (26\ \sigma_3 + 0.59)^{0.55}$

$\sigma_{cm} = 0.59^{0.55} = 0.75$ MPa


Description
Applicability
Hoek–Brown criterion
applicable – use intact
rock m and s values
intact
Hoek–Brown criterion
not applicable – use
anisotropic criterion such
as that by Amadei (1988)
single joint
Hoek–Brown criterion
not applicable – use
anisotropic criterion such
as that by Amadei (1988)
two joints
Hoek–Brown criterion
applicable with care for
4 or more joint sets
with uniform strength
many joints
Hoek–Brown criterion
applicable
rock mass

Hoek-Brown and Mohr-Coulomb Criteria

There is no direct correlation between linear M-C criterion and the non-linear H-B criterion.

When Mohr-Coulomb parameters c and ϕ are needed for design and modelling,

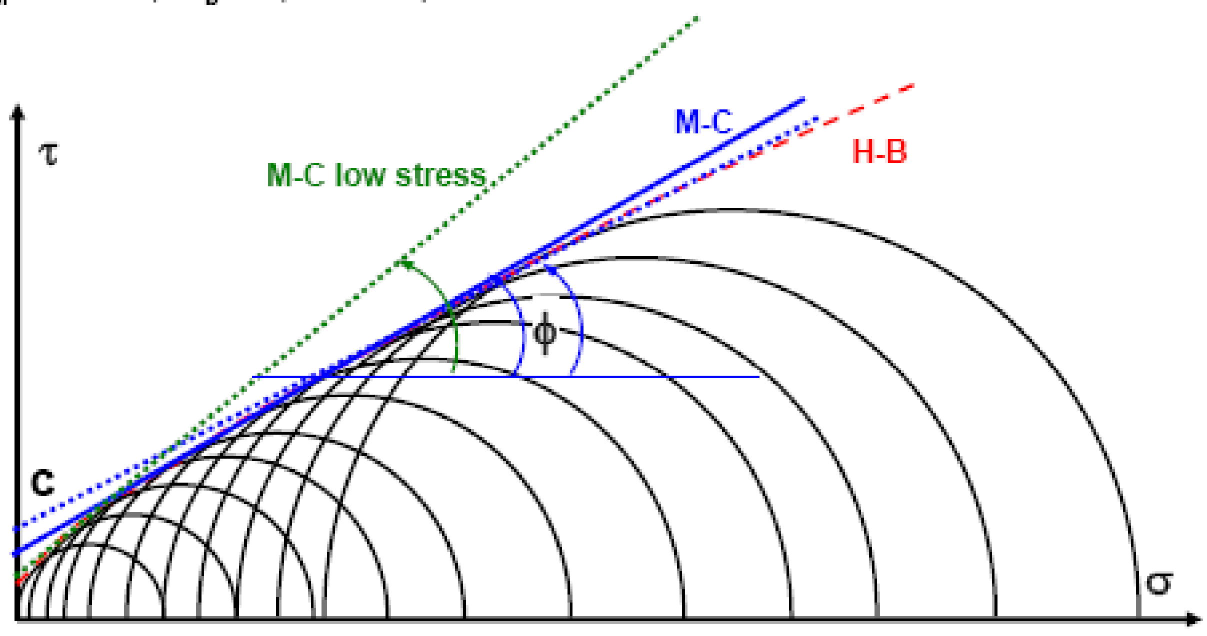
(i) Use direct test results on rock mass if available.

(ii) Use H-B to generate a series $\sigma_1 - \sigma_3$ data, plot them by Mohr circles, and fit them with the 'best' linear tangent envelope, to find c and ϕ.

Getting c and ϕ using Hoek-Brown Equation

σ_3	σ_1
0	6
2	12
4	17
6	21
8	25
10	28
12	32
15	37
20	45
30	61
40	75

σ_{ci}=100 MPa, m_b=0.3, s=0.004, a=0.5



Correlation of Rock Mass Quality and Properties

Correlations between rock mass strength and quality are by m_b and s in the Hoek-Brown criterion.

Better rock mass quality gives higher m_b and s, hence higher rock mass strength. When rock mass is solid and massive with few joints, rock mass strength is close to rock material strength. When rock mass is very poor (GSI < 25), rock mass has very low uniaxial compressive strength close to zero.

Correlation of Rock Mass Quality and Properties

Rock mass modulus (E_m, GPa) can be estimated from RMR and Q, for fair and better rock mass,

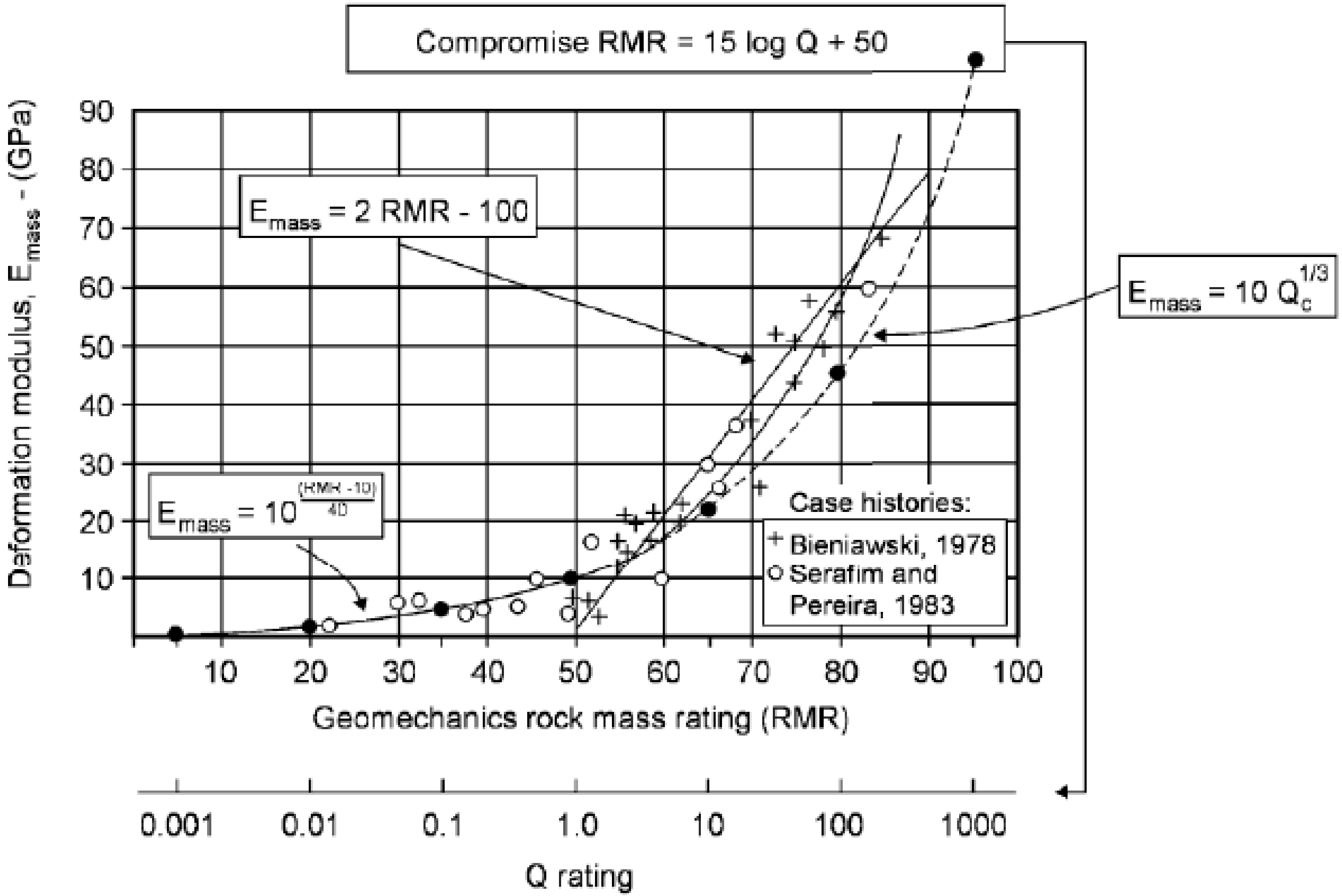
$E_m = 25 \log 10Q,$ for $Q > 1$

$E_m = 10\ (Q\ \sigma_{ci}/100)^{1/3}$

$E_m = 2\ RMR - 100,$ for $RMR > 50$

$E_m = 10^{(RMR-10)/40}$ for $20 < RMR < 85$

$E_m = 10^{(15 \log Q+40)/40}$



Compromise RMR = 15 log Q + 50
E_{mass} = 2 RMR - 100
$E_{mass} = 10\, Q_c^{1/3}$
$E_{mass} = 10^{\frac{(RMR-10)}{40}}$
Case histories:
+ Bieniawski, 1978
○ Serafim and Pereira, 1983
Deformation modulus, E_{mass} - (GPa)
90
80
70
60
50
40
30
20
10
10 20 30 40 50 60 70 80 90 100
Geomechanics rock mass rating (RMR)
0.001 0.01 0.1 1.0 10 100 1000
Q rating

Correlation of Rock Mass Quality and Properties

For poor rocks with σ_{ci}<100 MPa,

$$E_m = (\sigma_{ci}/100)^{0.5}\ 10^{(GSI-10)/40}$$

The equation is developed from the original E_m-RMR E_m-Q-σ_{ci} equation, to reflect the effect of rock strength change.

Squeezing Behaviour of Rock Mass

Squeezing of rock is the time dependent large deformation, which occurs around an openings, and is essentially associated with creep caused by exceeding shear strength.

Classification of squeezing degree,

(i) Mild squeezing: closure 1-3% of opening D;

(ii) Moderate squeezing: closure 3-5% of D;

(iii) High squeezing: closure > 5% of D.

Squeezing Behaviour of Rock Mass

Behaviour of rock squeezing is typically represented by rock mass deforms plastically into the opening. Rate of squeezing is time and stress dependent. Usually the rate is high at initial stage, say, several cm/day closure at beginning, reduces with time. Squeezing may continue for a long period. Squeezing may occur at shallow depths in weak and poor rock masses. Poor rock masses with moderate strength at great depth may also suffer from squeezing.

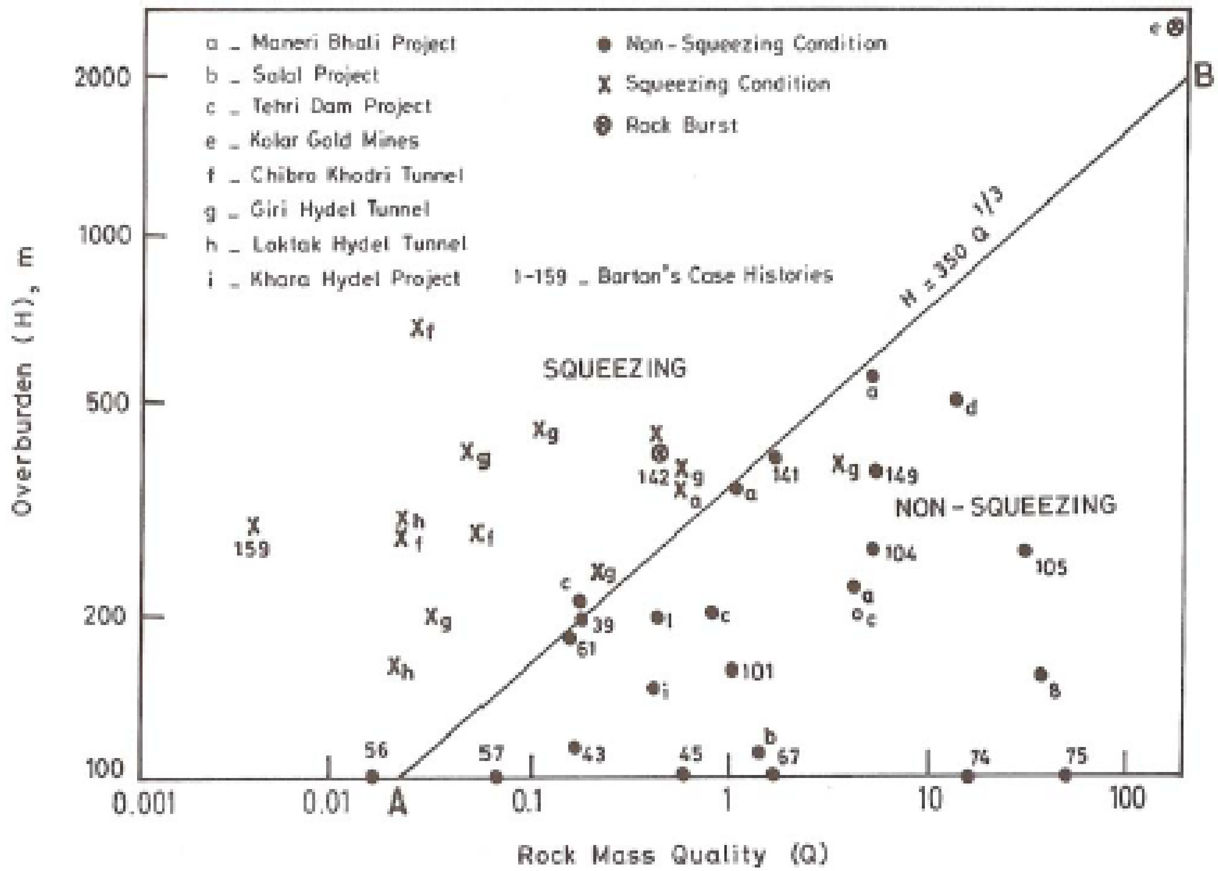
Squeezing Estimation by Rock Mass Classification Q

Squeezing:

Overburden
$H > 350\ Q^{1/3}$

Non-squeezing:

$H < 350\ Q^{1/3}$



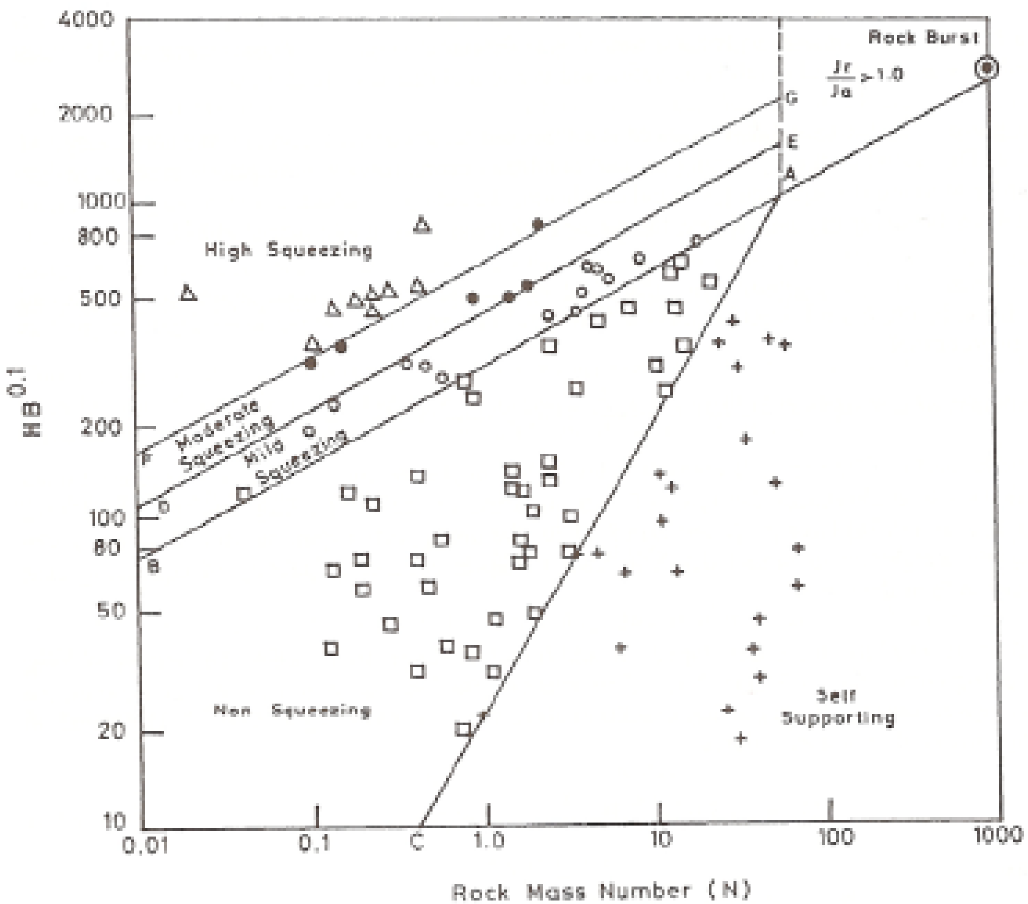
Squeezing Estimation by Rock Mass Classification N

Non-squeezing:
H $< 275\ N^{1/3})\ B^{-0.1}$

Mild squeezing:
H $> (275\ N^{1/3})\ B^{-0.1}$
$< (450\ N^{1/3})\ B^{-0.1}$

Moderate squeezing:
H $> (450\ N^{1/3})\ B^{-0.1}$
$< (630\ N^{1/3})\ B^{-0.1}$

High squeezing:
H $> (630\ N^{1/3})\ B^{-0.1}$



Squeezing Condition

Theoretically, squeezing conditions around a tunnel opening can occur when,

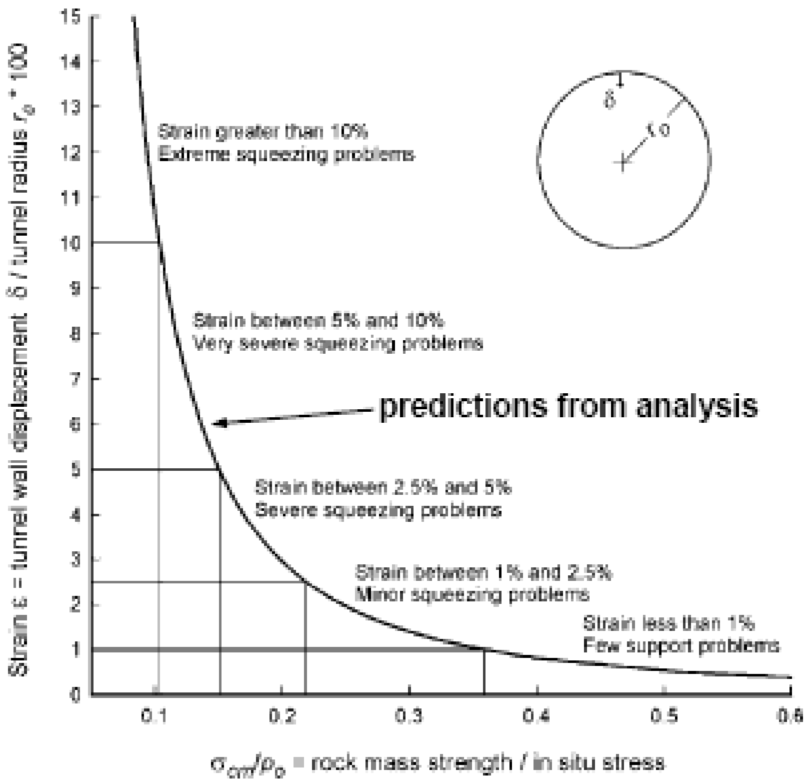
σ_θ > strength = $\sigma_{cm} + P_x A/2$

σ_θ is the tangential stress at the tunnel opening, σ_{cm} is the uniaxial compressive strength of the rock mass, P_x is the in situ stress in the tunnel axis direction, and A is a rock parameter proportion to friction.

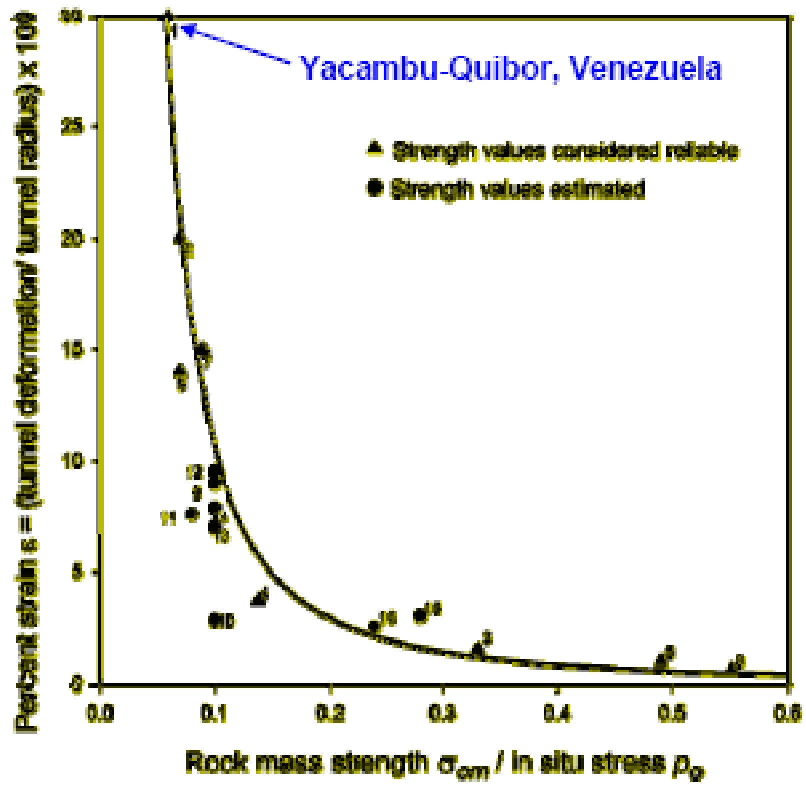
Squeezing Condition

Degree of Squeezing	σ_θ / σ_{cm} (ISRM)	σ_{cm} / σ_{situ} (Hoek)
Non squeezing	< 1.0	> 0.35
Mild squeezing	1.0 – 2.0	0.2 – 0.35
Moderate squeezing	2.0 – 4.0	0.15 – 0.2
High squeezing	> 4.0	< 0.15

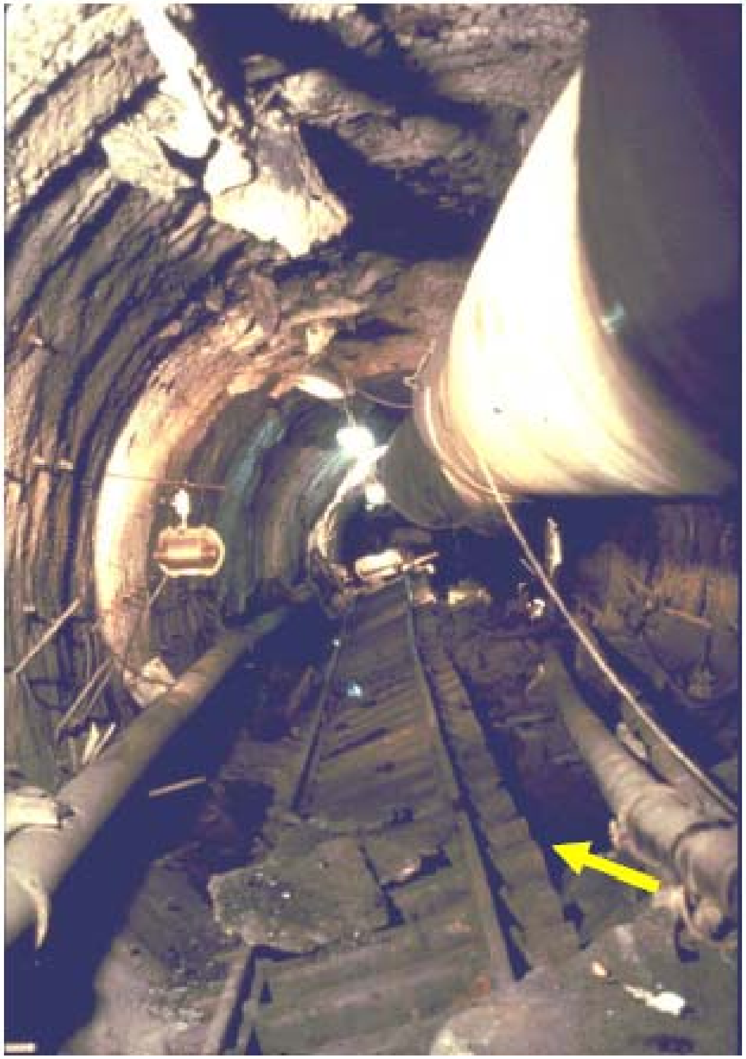
Squeezing can be correlated with the ratio of rock mass strength to in situ stress. Squeezing is possible when the ratio is less than 0.35 (Hoek 2000).



Prediction curve for squeezing for different rock mass strength to in situ stress ratios (Hoek 2000)



Tunnel squeezing case histories compared with prediction for squeezing (Hoek 2000)

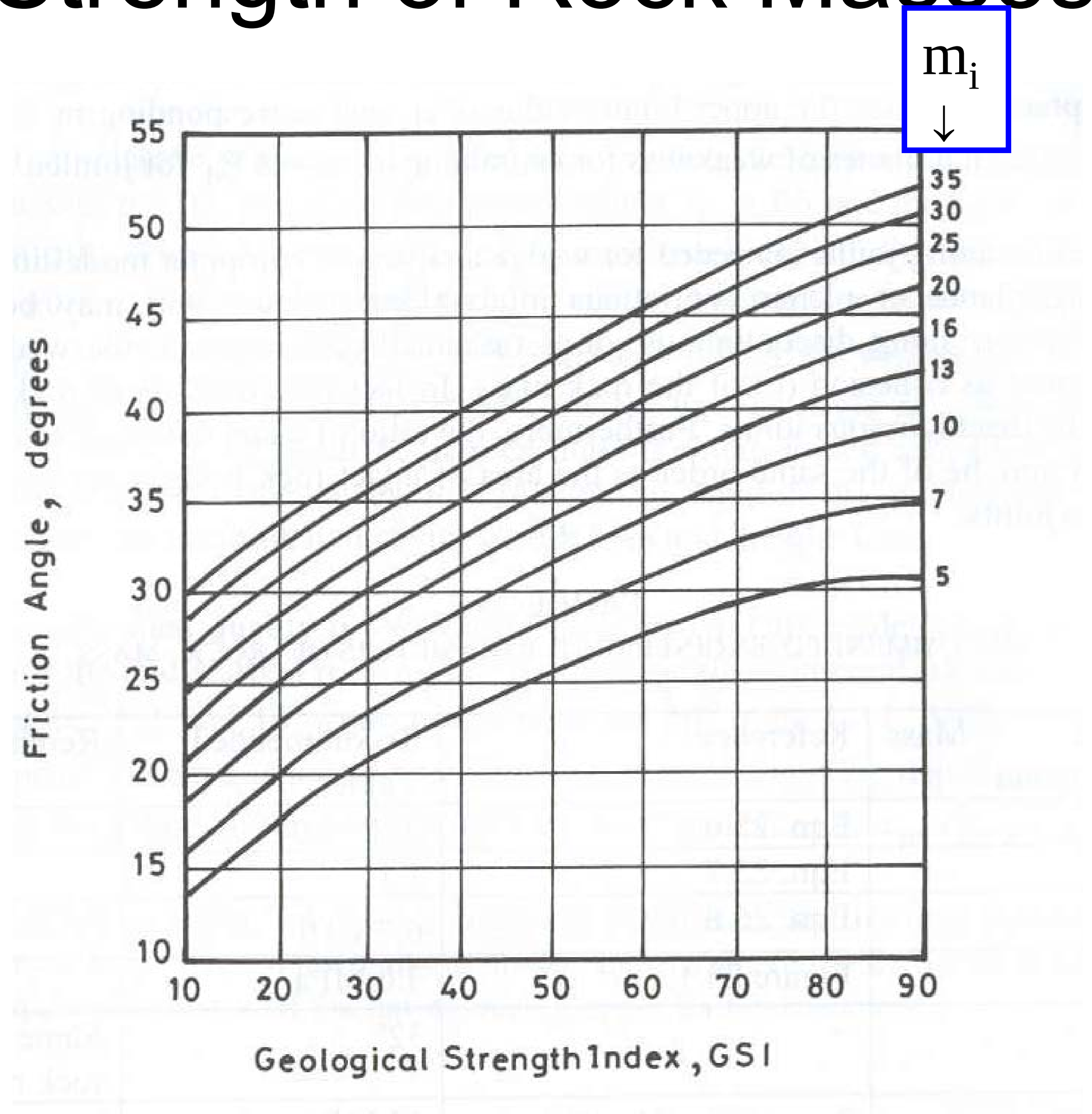



Squeezing in the Yacambu-
Quibor tunnel, Venezuela

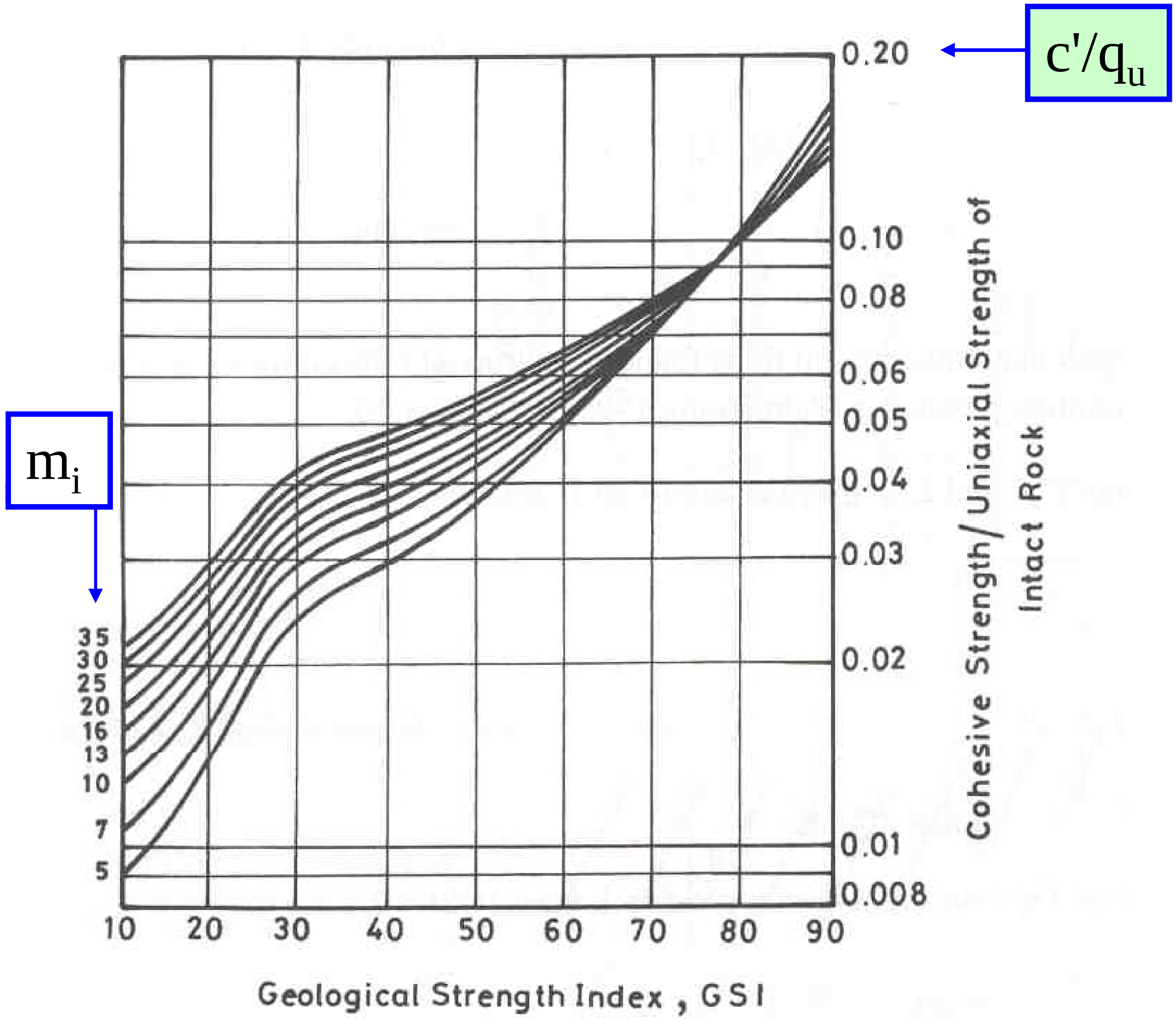
Rock Strength: m_i parameter

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

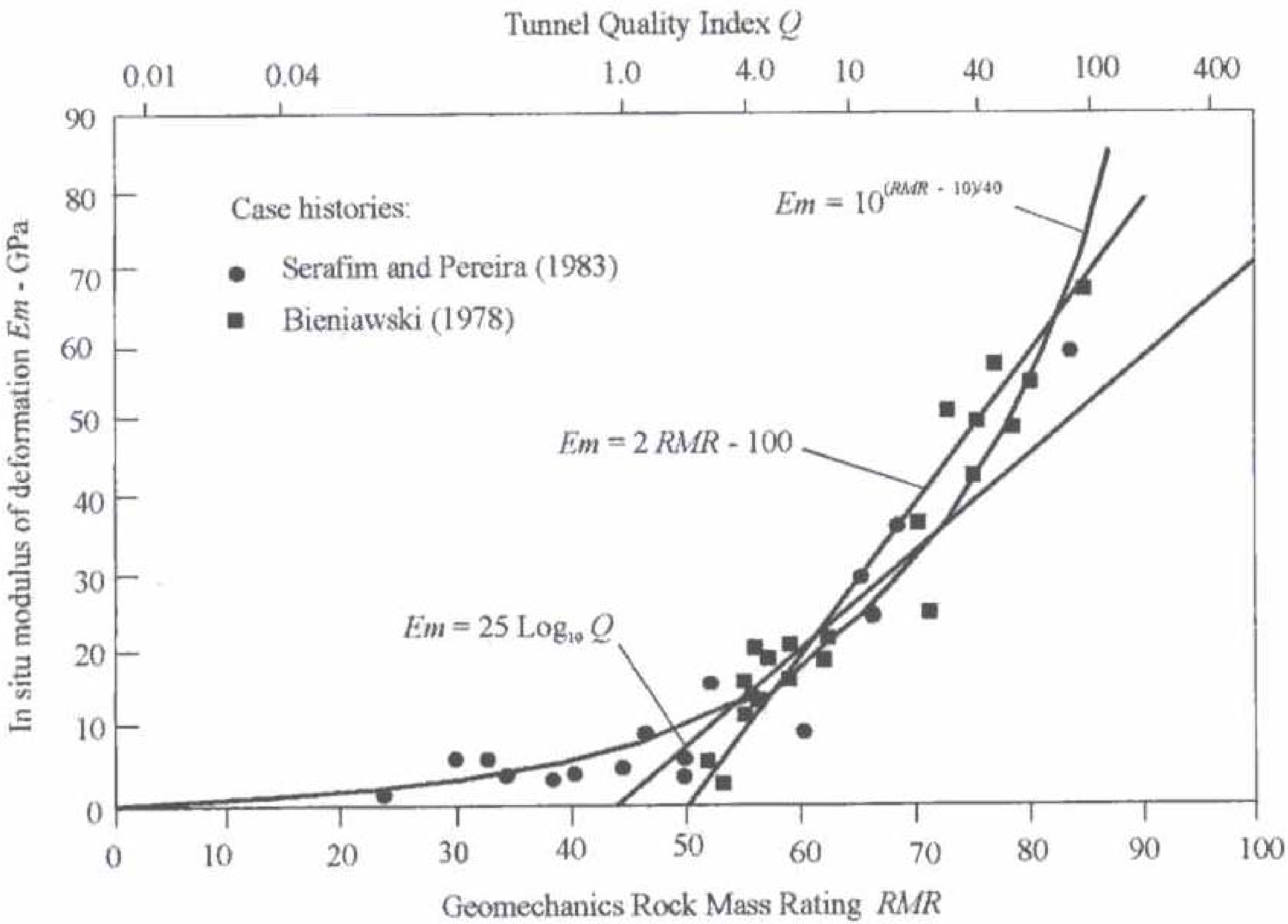
Strength of Rock Masses



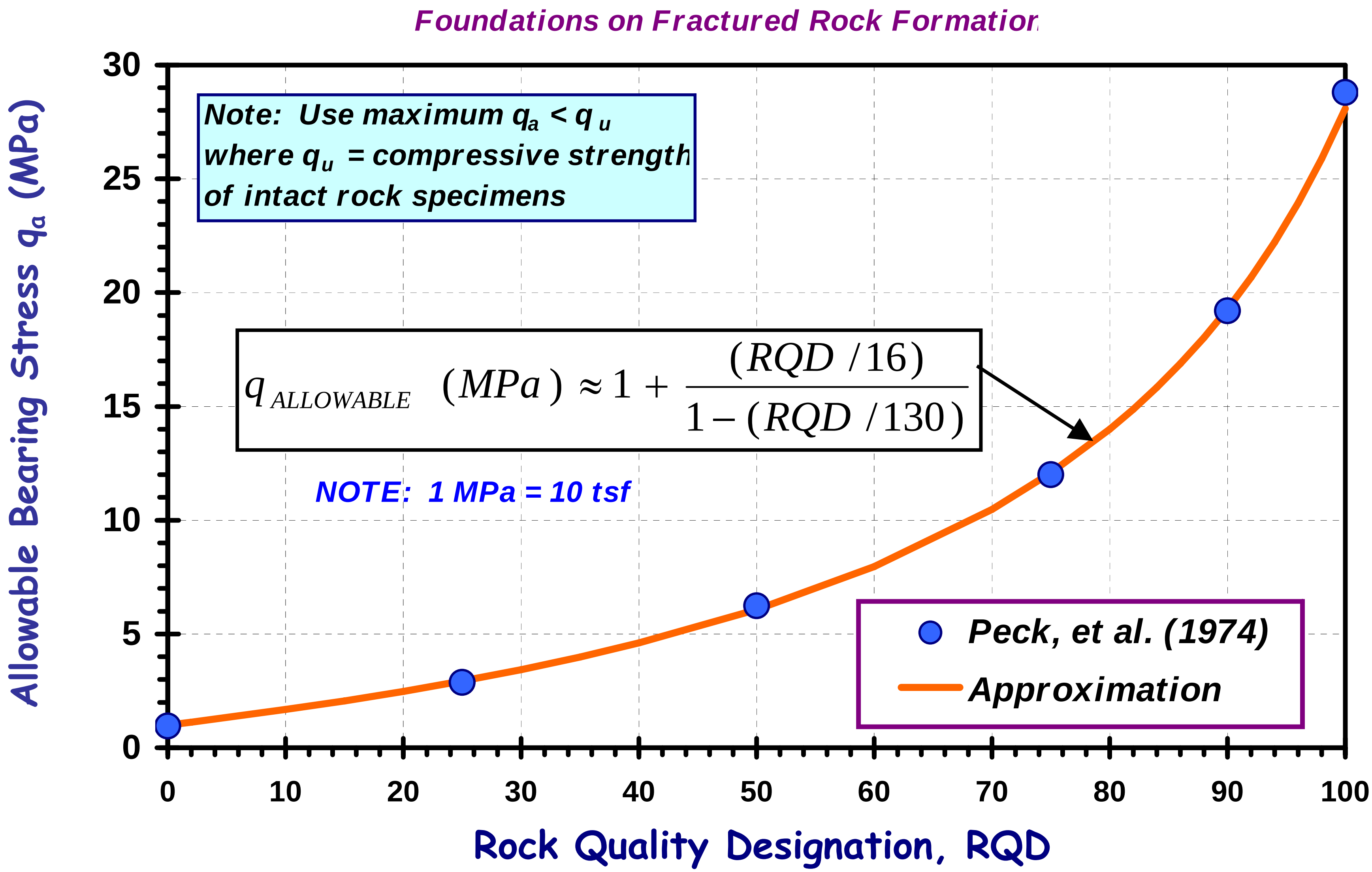
Strength of Rock Masses



Equivalent Modulus of Rock Masses (Table 10-7)



Allowable Bearing Stresses on Rock Masses



RMR SUPPORT GUIDELINES

Rock mass class	Excavation	Rock bolts (20 mm diameter, fully grouted)	Shotcrete	Steel sets
I - Very good rock RMR: 81-100	Full face, 3 m advance.	Generally no support required except spot bolting.		
II - Good rock RMR: 61-80	Full face, 1-1.5 m advance. Complete support 20 m from face.	Locally, bolts in crown 3 m long, spaced 2.5 m with occasional wire mesh.	50 mm in crown where required.	None.
III - Fair rock RMR: 41-60	Top heading and bench 1.5-3 m advance in top heading. Commence support after each blast. Complete support 10 m from face.	Systematic bolts 4 m long, spaced 1.5 - 2 m in crown and walls with wire mesh in crown.	50-100 mm in crown and 30 mm in sides.	None.
IV - Poor rock RMR: 21-40	Top heading and bench 1.0-1.5 m advance in top heading. Install support concurrently with excavation, 10 m from face.	Systematic bolts 4-5 m long, spaced 1-1.5 m in crown and walls with wire mesh.	100-150 mm in crown and 100 mm in sides.	Light to medium ribs spaced 1.5 m where required.
V - Very poor rock RMR: < 20	Multiple drifts 0.5-1.5 m advance in top heading. Install support concurrently with excavation. Shotcrete as soon as possible after blasting.	Systematic bolts 5-6 m long, spaced 1-1.5 m in crown and walls with wire mesh. Bolt invert.	150-200 mm in crown, 150 mm in sides, and 50 mm on face.	Medium to heavy ribs spaced 0.75 m with steel lagging and forepoling if required. Close invert.