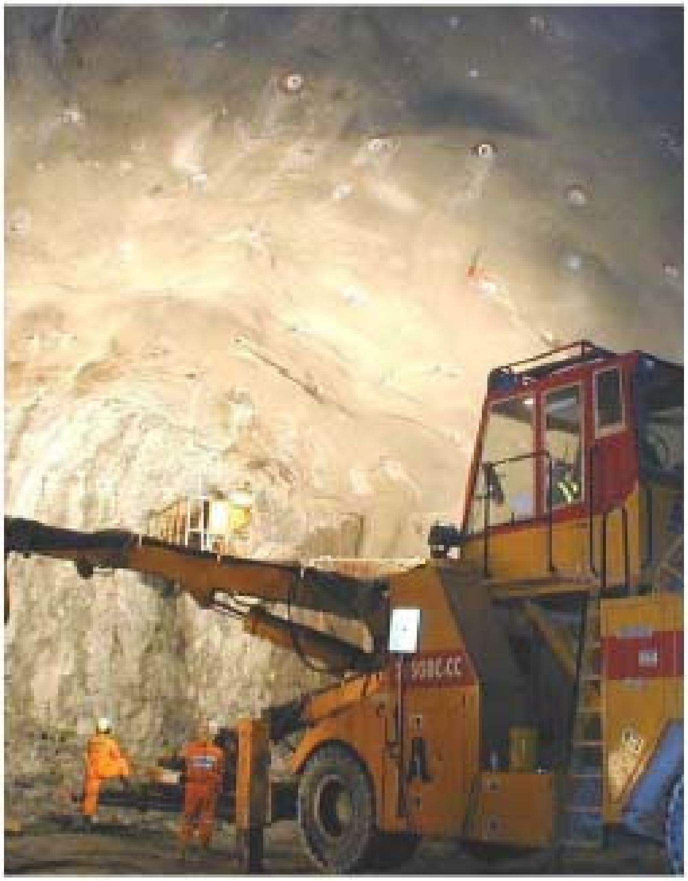
Rock Support

Rock tunnel support are divided into two categories:

Temporally support: This is a short-term measure only to provide a safe working environment for continuous excavation. Common techniques are bolts and shotcrete.

Permanent support: This is long-term support for a life-span of the tunnel. The methods available are steel set, cast-in concrete, concrete segment, bolt, shotcrete (with or without steel fibre reinforcement).

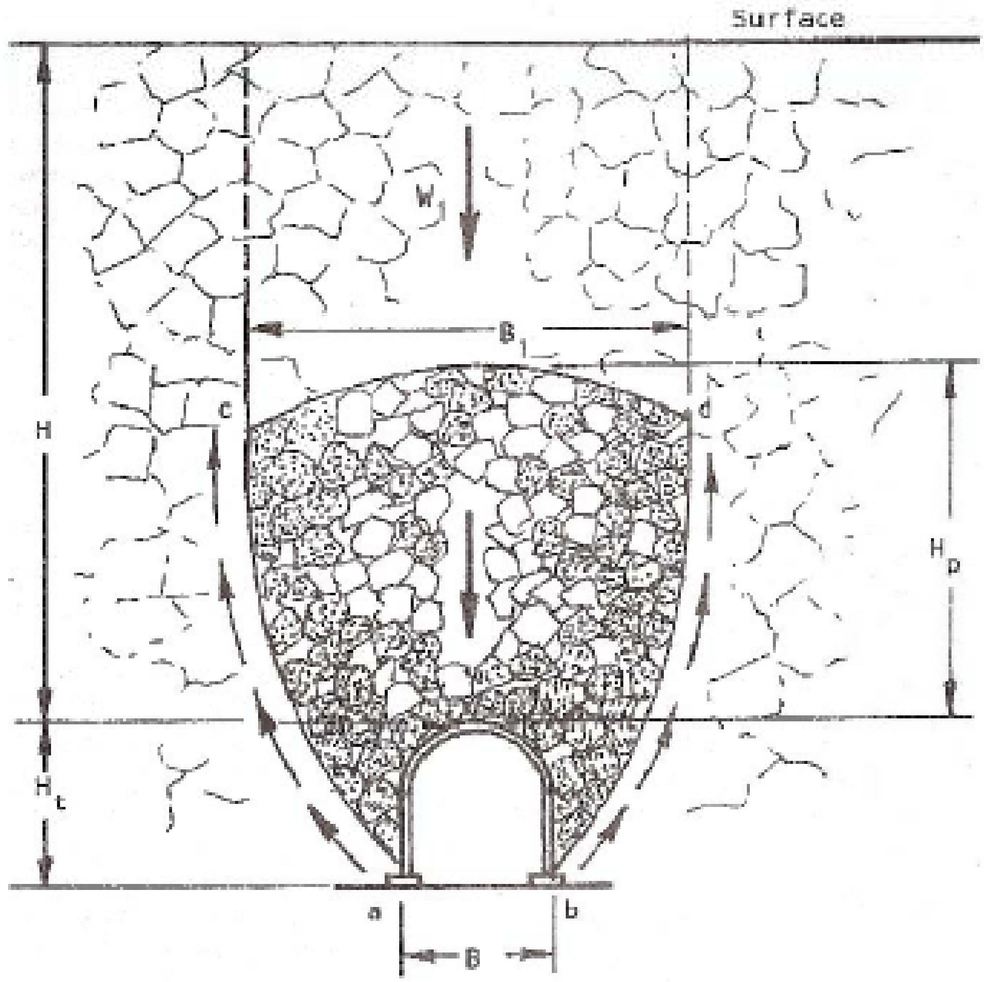
Rock Support



Two main rock support systems: bolt and shotcrete (left, for D&B and TBM tunnels) and concrete segment (right, for TBM tunnels).

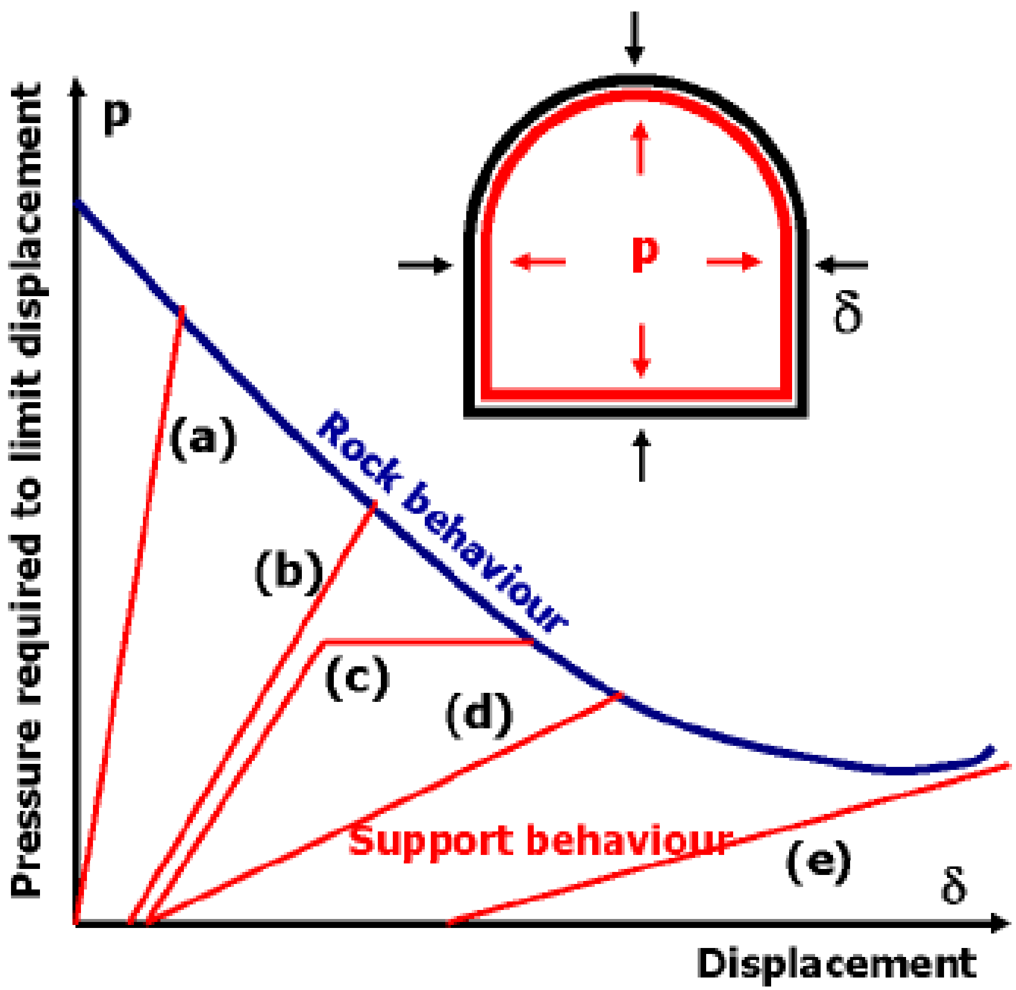
Rock Support: Mechanics and Design

1942, based on rail tunnel experiences in the Alps, Terzaghi introduced Rock Load Factor, first time classified rock into 9 behaviour classes, ranging from solid massive to squeezing and swelling. It allows to estimate the total load that the steel arch need to design for.



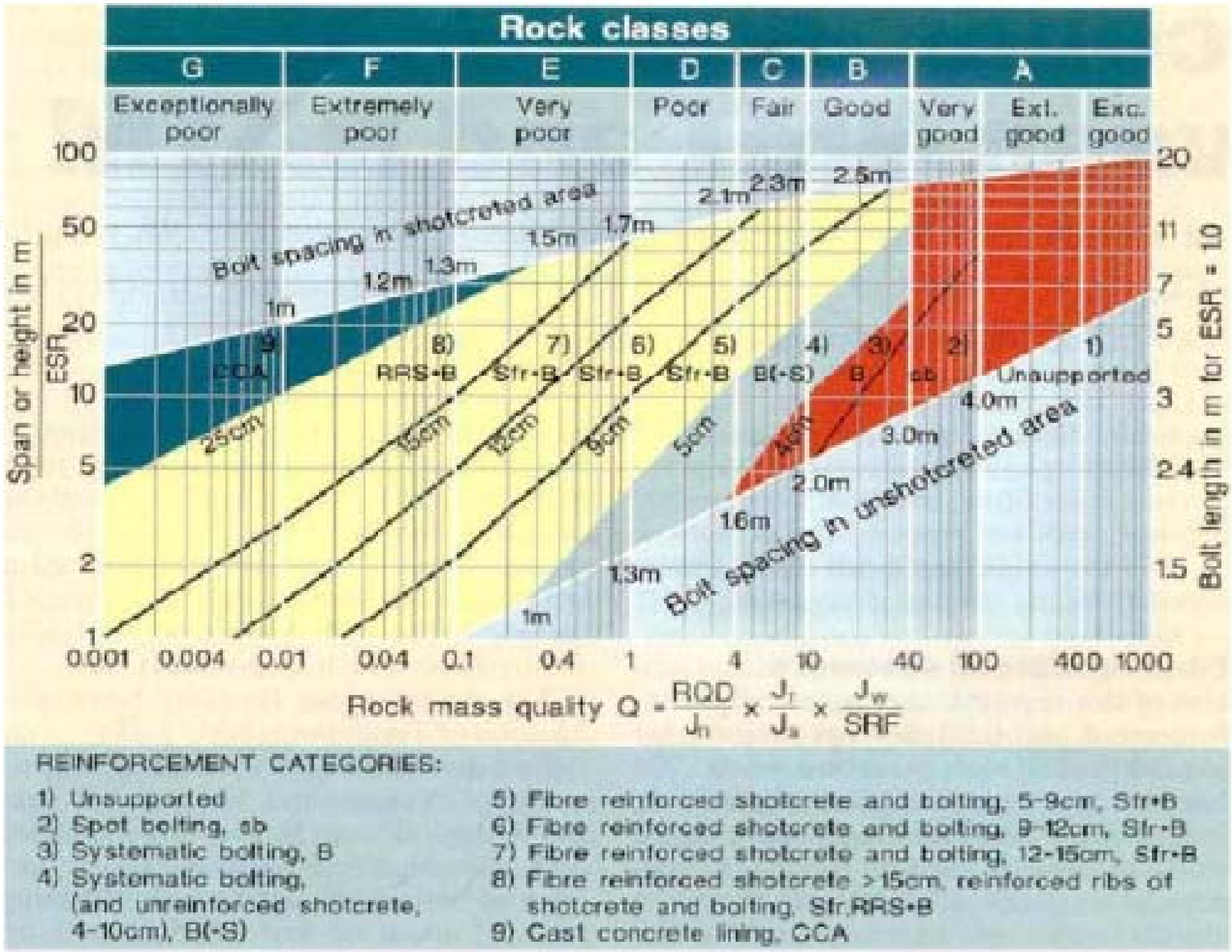
Rock Support: Mechanics and Design

1960-70s, Ground-support interaction and observation based support design concept introduced. It allows ground deformation and stress redistribution, to optimise the support applied to the rock, by taking the rock-support interaction into account.



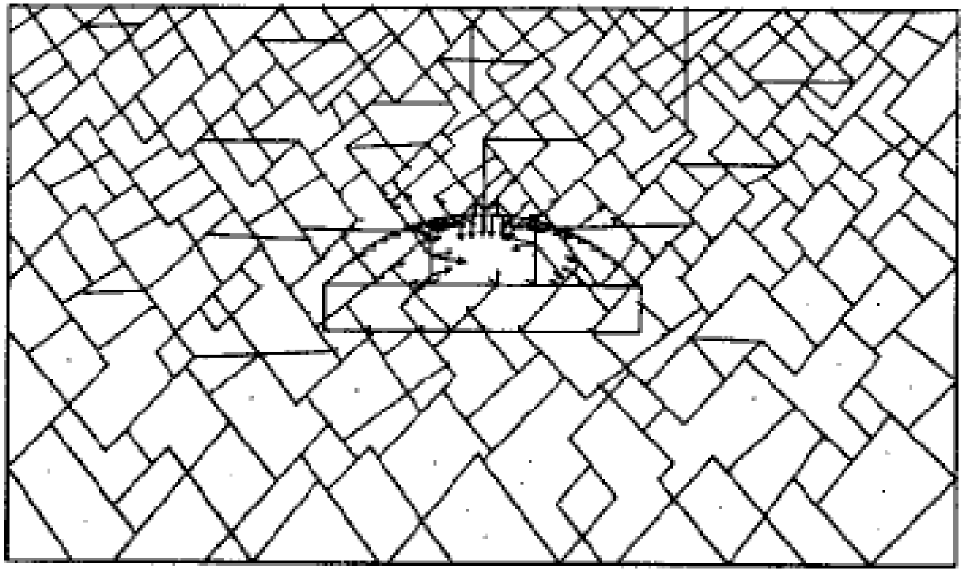
Rock Support: Mechanics and Design

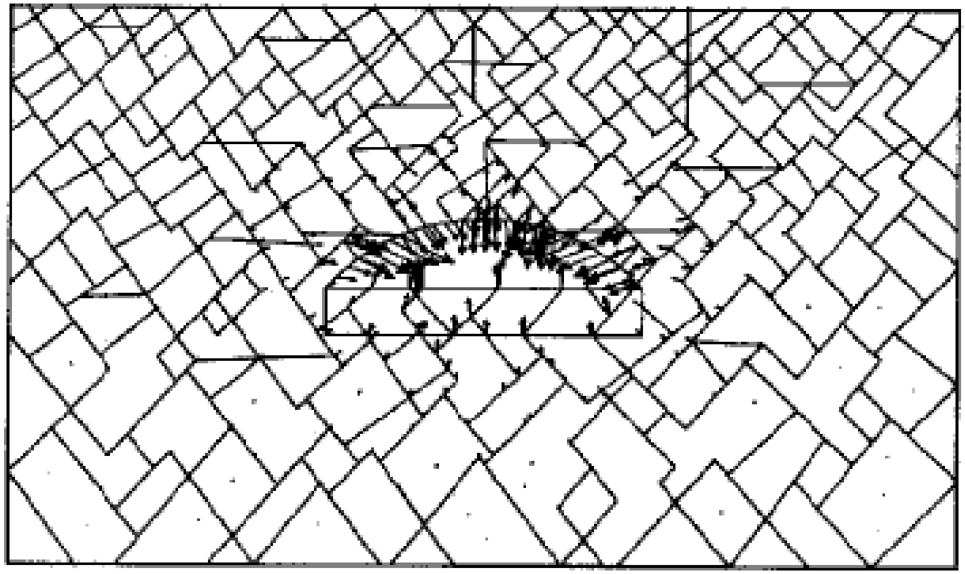
1970s, Rock mass quality classifications (RMR and Q) introduced as tools for rock mass quality assessment and basis for rock support design.



Rock Support: Mechanics and Design

Since 1980s numerical modelling methods were used for analysis and design. Notably, discrete element method (DEM) was applied to model discontinuous rock masses.





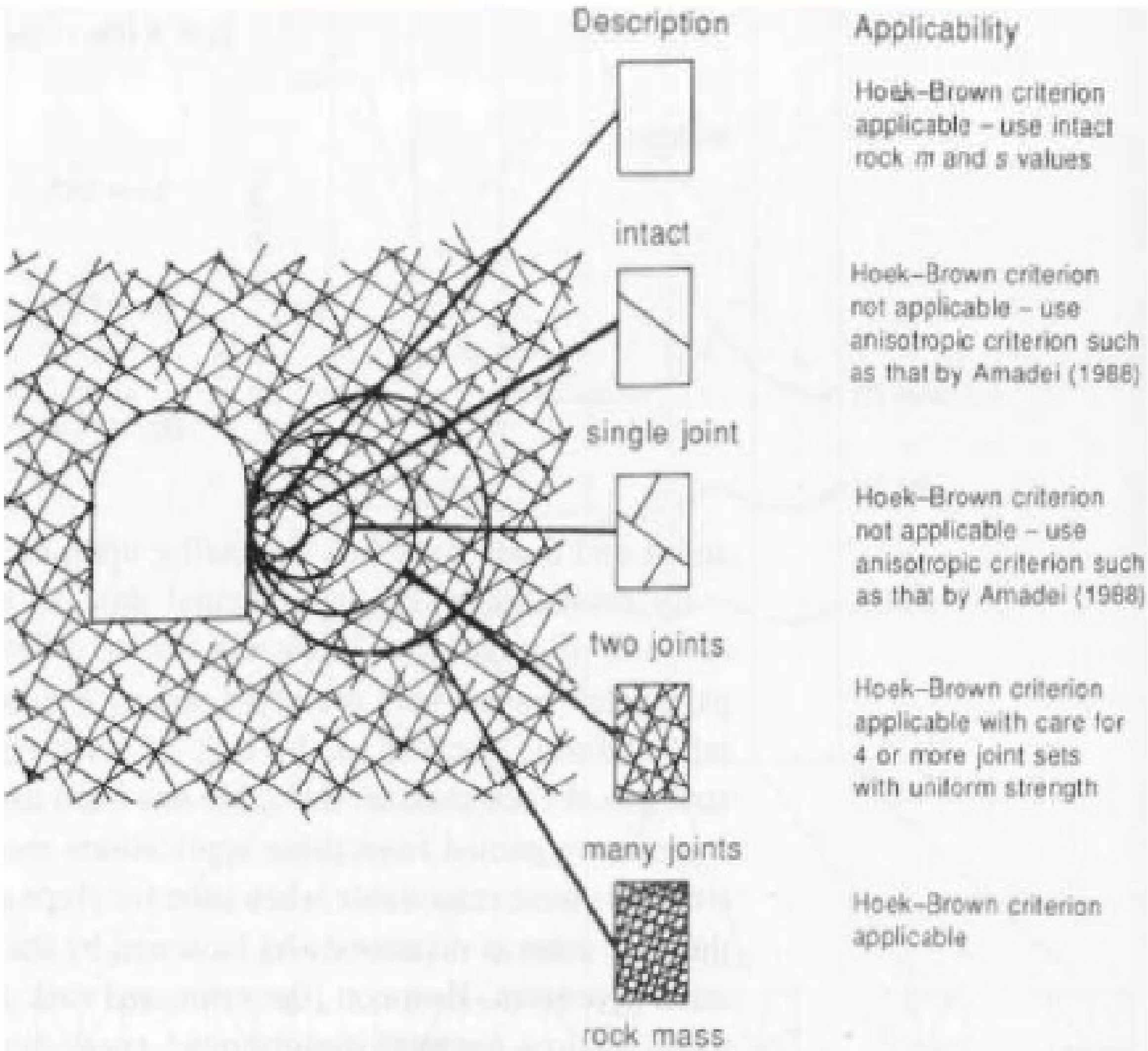
DEM modelling on support design and stability analysis for the 61 m span cavern in Gjovik, Norway.

EPFL Laboratoire d

Rock Support: Mechanics and Design

1980s, Hoek-Brown strength criterion was developed, and was improved with the introduction of Geological Strength Index (GSI) in 1990s.

It is the most widely used criterion to estimate rock mass strength, and to provide rock mass parameters for design.

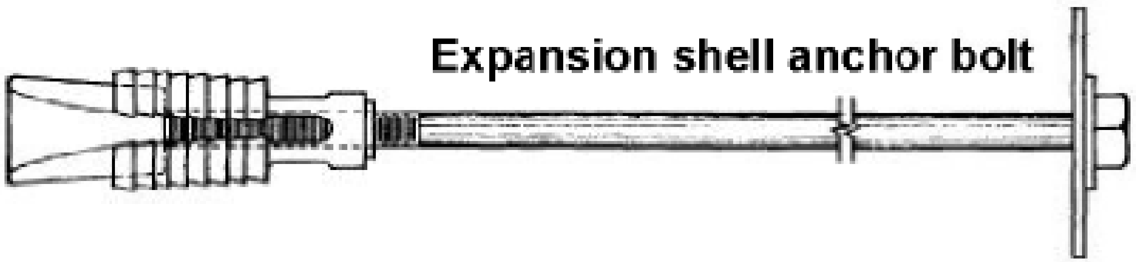


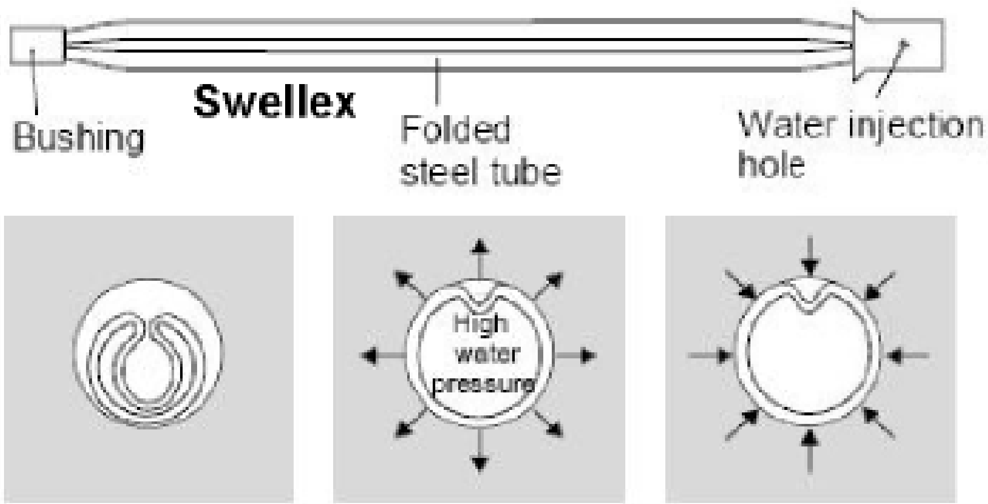
Rock Support: Methods and Materials

Before 1950s, steel arch is the main support method.

In 1920s, rock bolts were tried and became widely used since 1950s, seeing the development of expansion shell anchor.

1970s, split set, and 1980s, Swellex was introduced.

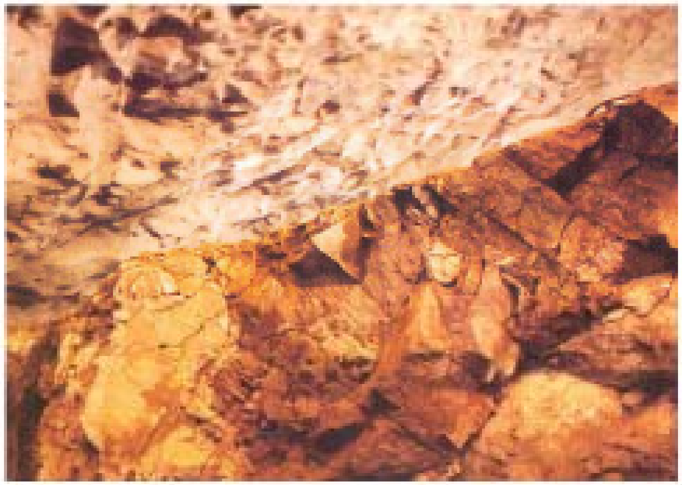




Rock Support: Methods and Materials

1950s, dry-mix and 1960s wet-mix sprayed concrete introduced, and since 1980s, wet-mix became widely applied.

1970s, steel fibre reinforced sprayed concrete (SFRS) was experimented and in 1980s it gained wide applications.

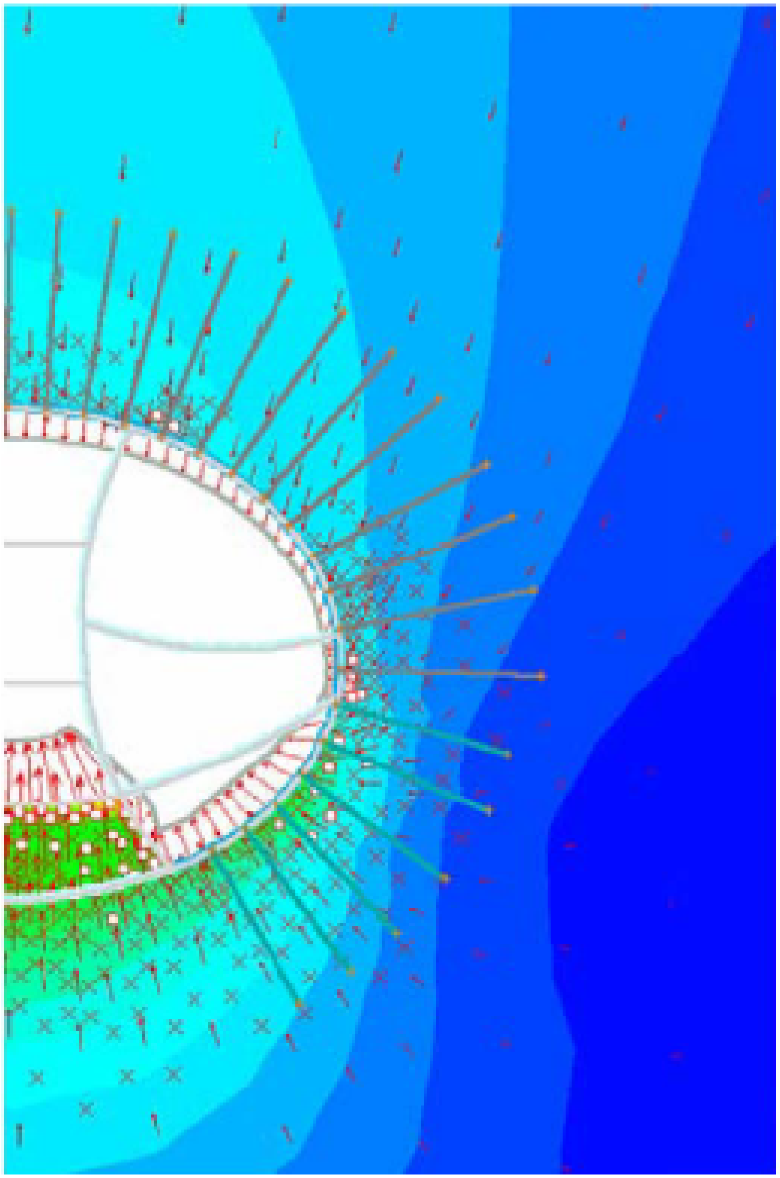


Rock Support: Support Design Today

Support design based on rock mass quality classifications, mainly, RMR and Q, mostly for competent rock masses.

Support design and implementation based on sequential excavation and observation, particularly for poor ground.

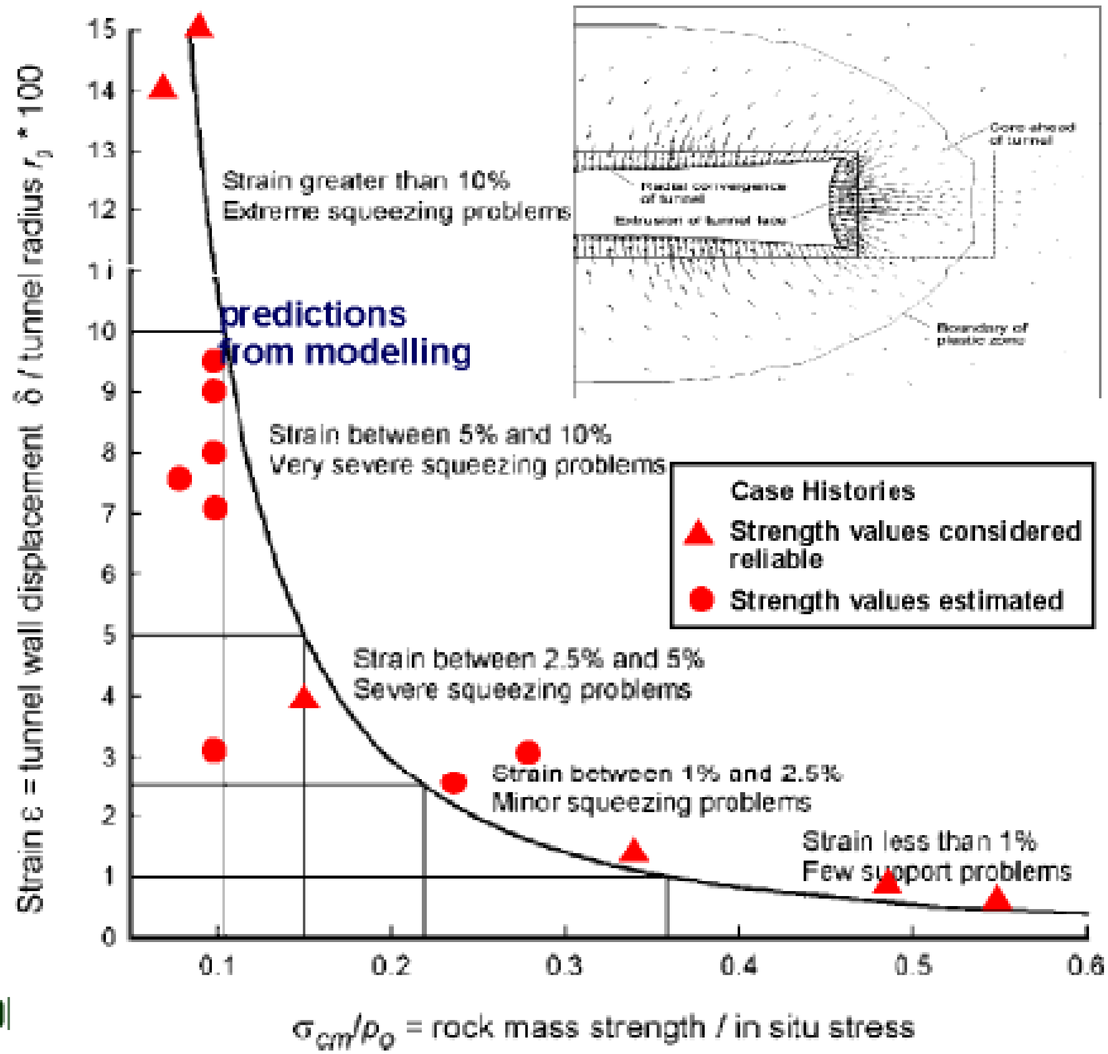
Physical and numerical modelling for non-precedent or special cases.



Rock Support: Support Design Today

Support design criteria coupling analysis, modelling and in situ measurement, i.e., integrated design.

Prediction of squeezing combining strength criterion and numerical modelling, for different rock mass strength to in situ stress ratios (Hoek 2000)



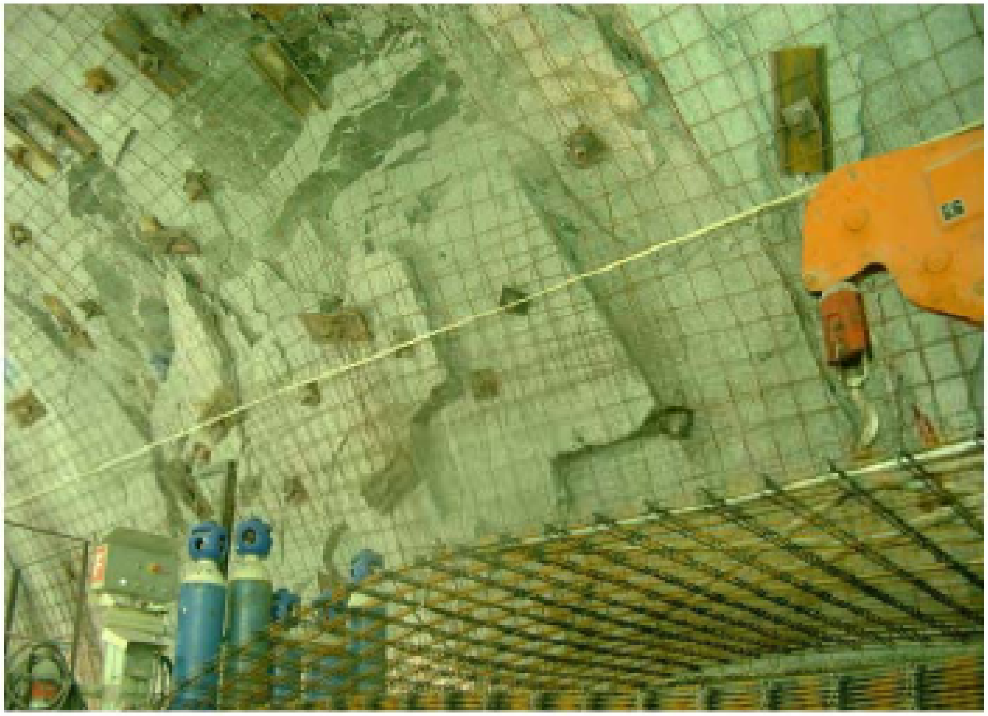
Labo

Rock Support: Support Methods Today

A wide selection of end-anchored, frictional, and fully grouted rock bolts are available.

For quick initial support, both in D&B and gripper TBM tunnelling, anchored and frictional bolts are used.

To combine initial and permanent support, anchored bolts are used and followed by full grouting.



Initial support by bolts, wire mesh and shotcrete at Lötschberg base tunnel.

Rock Support: Support Methods Today

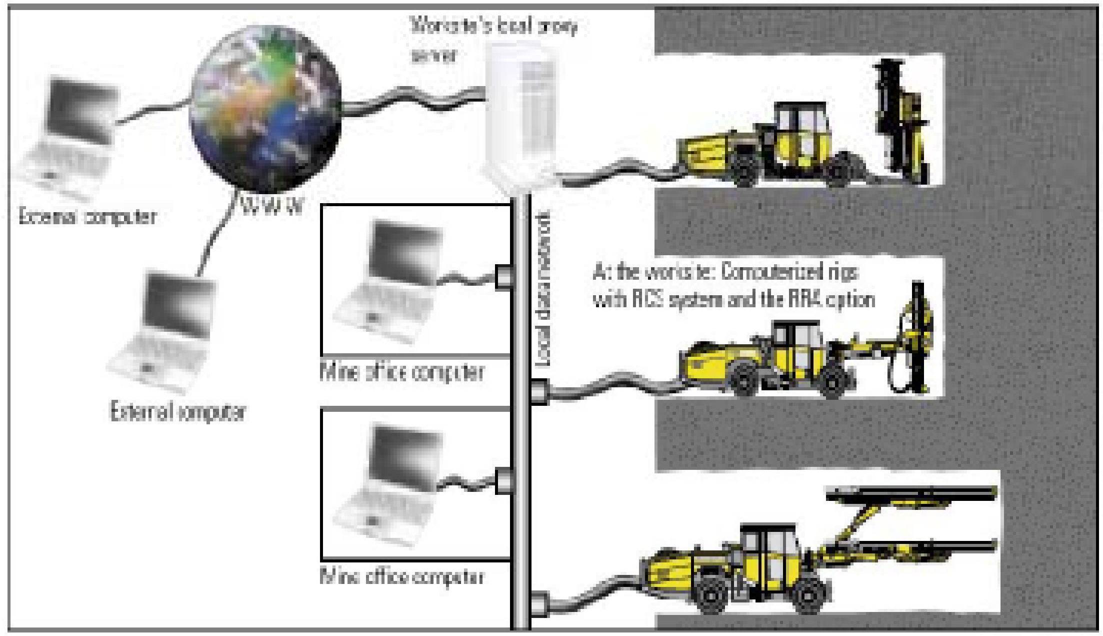
Wet-mix sprayed concrete is the main method, and often with steel fibre reinforcement (SFR).

Additives can be added to improve concrete performance, mainly to gain strength faster.

This 30 m span cavern was supported typically by fully grouted spot anchor bolts, and SFRS concrete. UAF caverns in granite, Singapore (1999-2002).

Future R&D: Excavation Machine

- Full automation of drilling jumbo and remote control.
- Laser and other new rock cutting technologies.



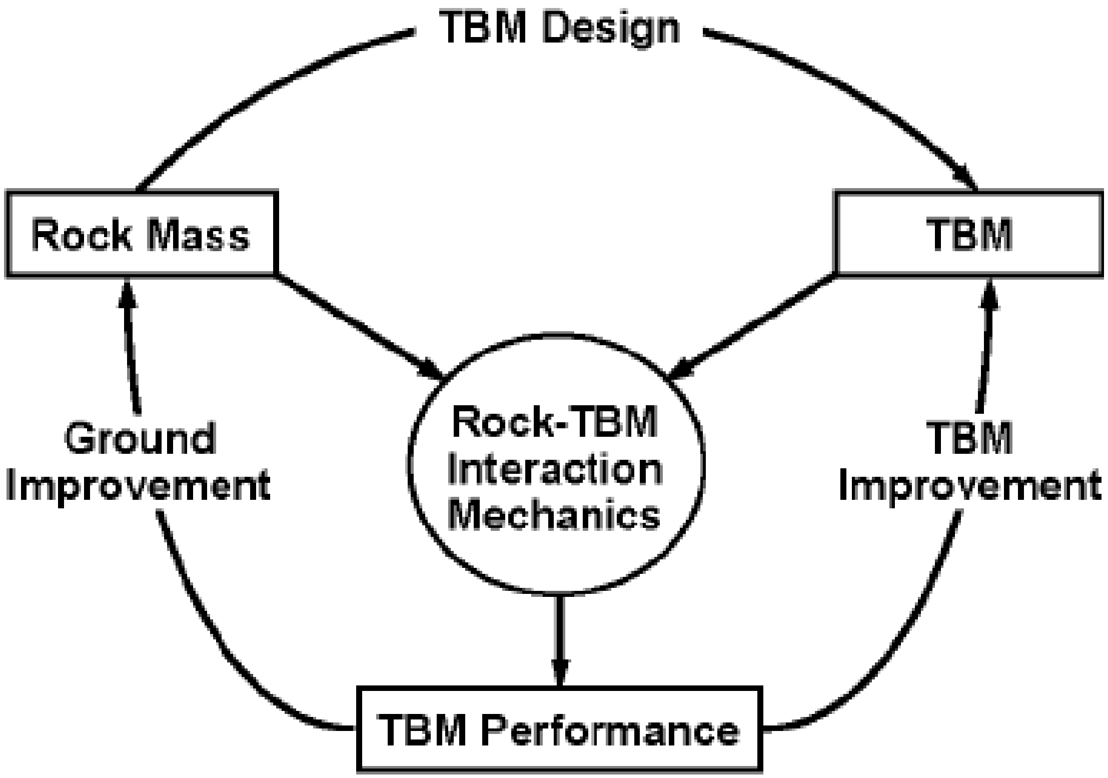
- Invention of pollution-free explosives.
- TBM to increase net penetration rate and cutter life in very hard and abrasive rocks.
- TBM able to excavate through complex and variable geology, i.e., universal TBM.

Future R&D: Rock-Machine Interaction

A rock mass classification scheme, incorporating appropriate rock mass properties for TBM excavation;

A TBM performance prediction model for various rock and complex geology;

A guide for TBM operation in complex ground.



Future R&D: Rock Support Mechanics

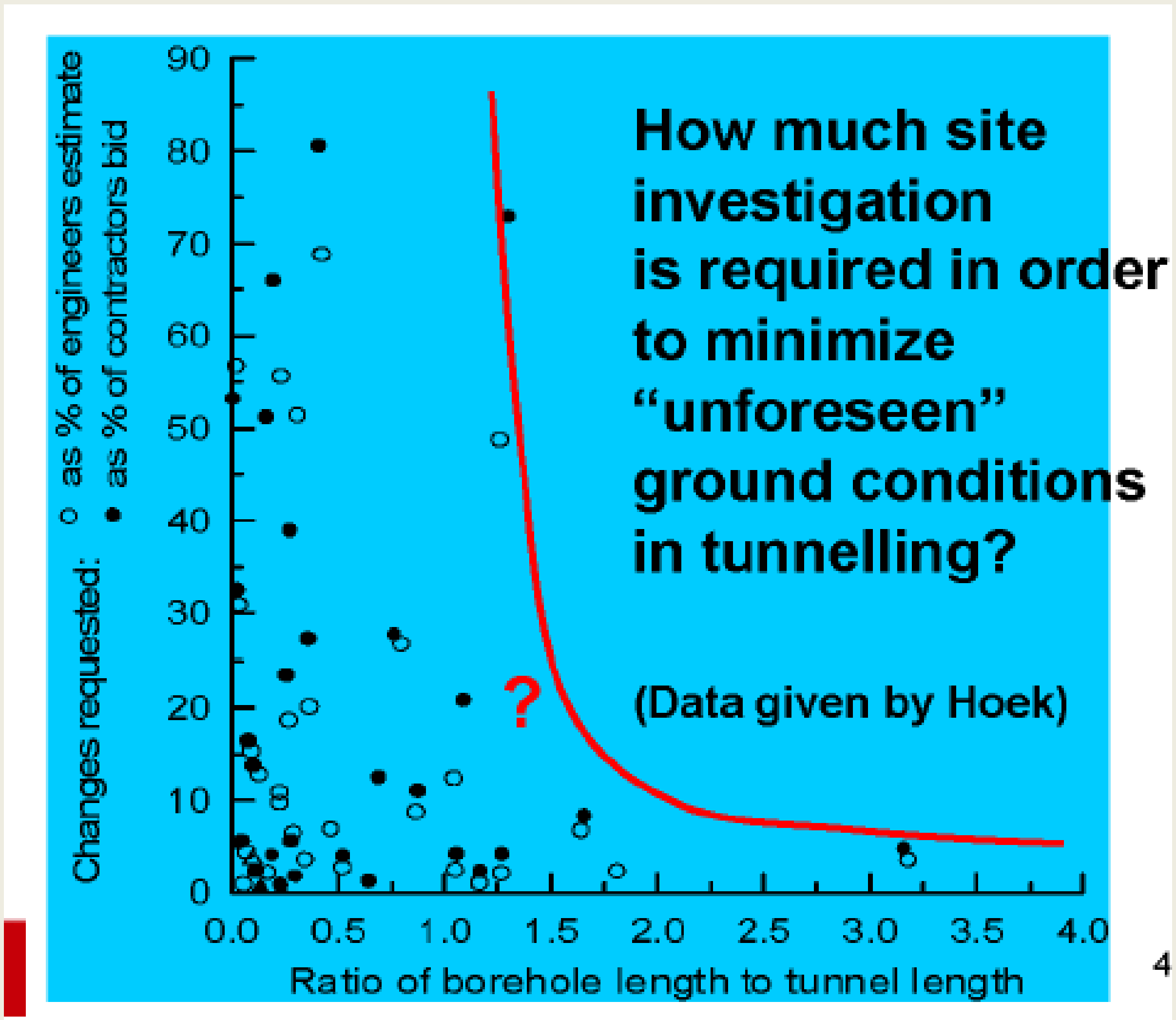
Short and long term behaviour of complex grounds, e.g., squeezing and spalling.

Effects of changing ground condition and environment on the durability and long term stability of tunnels.

Support mechanism of large opening, the effectiveness of bolts.

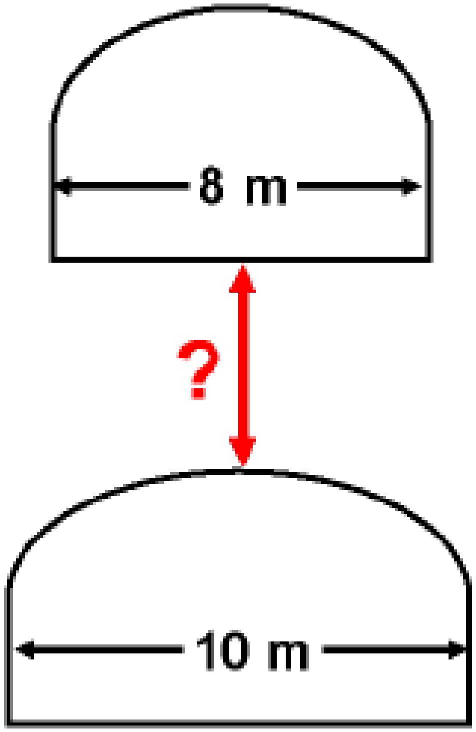
Rock support mechanism and method for tunnel under dynamic loads.

Example of Challenges- Unforeseen Ground conditions



Examples of Challenges:

Empirical or Numerical Design?



Case example, minimum rock separation between two near parallel tunnels, UAF Project, Singapore

Original empirical design: 15 m

Optimised by numerical modelling: 8 m

Considering rock mass properties, stress conditions, effects of rock reinforcement, and construction method/sequence.

Construction implication: saved 200 m tunnelling in granite.

Examples of Challenges:

TBM in Blocky and Faulted Rocks

TBMs have difficult to progress through highly fractured rock mass, faulted zones, mixed ground, squeezing and spalling rocks. A re-examine of TBM fragmentation mechanism is needed.

Examples of Challenges:

Rock Self-Support Mechanism

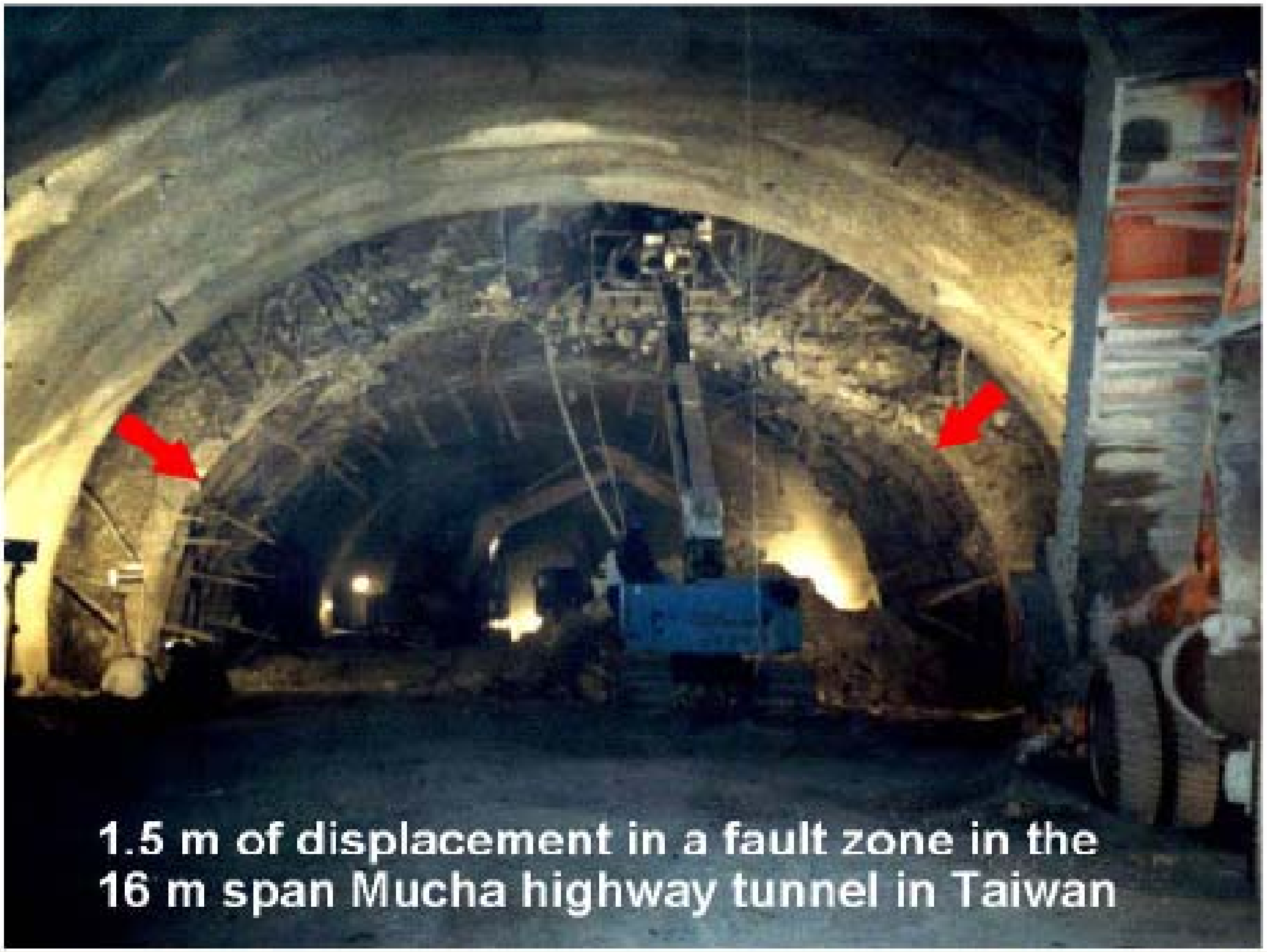
Rock Conditions & Bolt Parameters	Gjovik Cavern, Norway (Based on Broch at el. 1996)	UAF Cavern, Singapore
Typical Rock Mass Quality	1~30	4~36
Vertical Stress, MPa	1	2~3
Maximum Horizontal Stress	3.5	8.2
Minimum Horizontal Stress	2	4.6
Ratio of Horizontal to Vertical Stress	2~3.5	2~3
Tunnel/cavern span, meters	61	30
Type of Rock Bolts	Fully grouted rebars	Fully grouted bolts
Bolt lengths	6 (with alternating 12 m long cables	5
Spacing, meters	2.5 x 2.5	1.5~2.4
Bolt Capacity, KN	220	250
Minimum Measured Loads, KN	1~1.5	3~12
Typical Measured Loads, KN	30~60	20~60
Typical Load Percentage	13~27%	8~24%
Maximum Measured Load, KN	87	70
Max Load Percentage	40%	28%

Low load on bolts suggests rock is self-supporting.

How effective are bolt and shotcrete in rock support?

Examples of Challenges:
Squeezing and Weak/Poor Rocks

Although known as a stress induced problem, it is still difficult to predict and to quantify deformation and load inserted on lining, for tunnels in squeezing and weak/poor rock masses.



Examples of Challenges:

Durability and Long-Term Stability

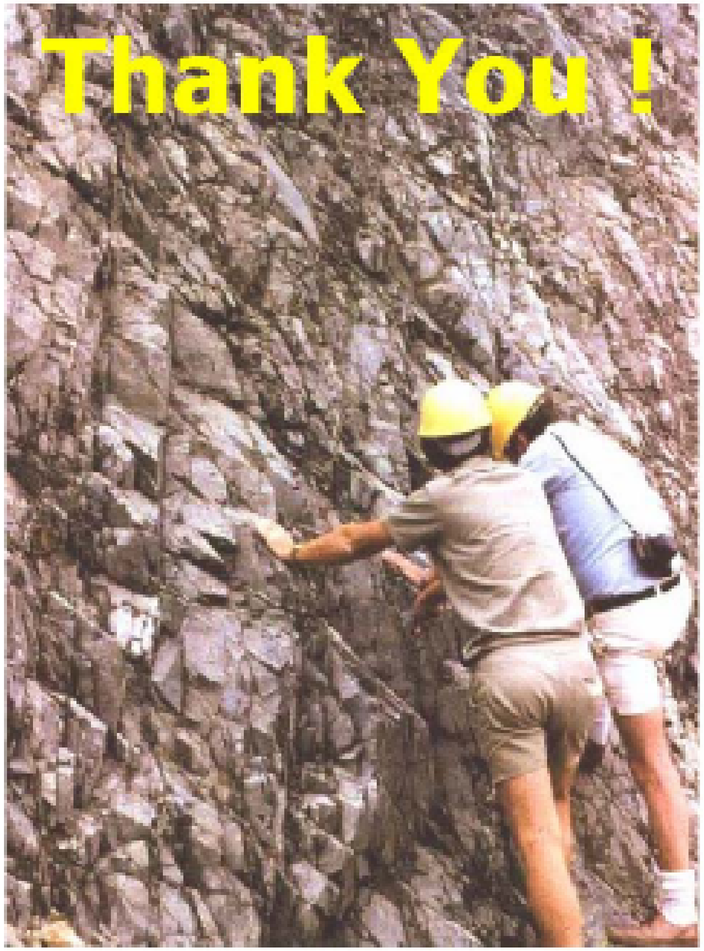
To understand the effects of time and environment change on rock and support, and to be able to quantify structural degradation and damage.

Tunnelling in Rock: Continuing Battles

Tunnelling is fighting through the ground.

We certainly need good weapons (machines and materials). More importantly we need to know enemy (ground): what are they, and how do they respond when under attack (construction)?

To win the complete battle, we must know the ground before, during and after tunnelling, i.e., in situ properties of rock, and the mechanics of rock-construction-environment interaction.



Rock Mass Rating Systems

ROCK MASS RATING SYSTEM
or **RMR**

Bieniawski (1972)

- *numerous amendments since*

For assessing the stability of rock slopes

RMR Basic System = RMR_{basic}

- Strength of the intact rock
- RQD
- Groundwater

Discontinuities:

- Spacing, length, roughness
- Aperture width, infill, weathering

9 ratings to add ⇒ RMR_{basic} = 100 maximum

Elements of RMR

1. **Strength** based on σ_c (UCS) or I_{s50} — 15 pts
   – 25:1 ratio
   – σ_c = 250 MPa or more; **15** points
2. **RQD** Rock Quality Designation — 20 pts
   – < 25%; 3/**20** points only

Elements of RMR

3. Groundwater

- Inflow rate
- $u_{joint}:\sigma_1$
  - If > 0.5; zero points?
- Dry, damp, wet, dripping, flowing?

15 pts

Elements of RMR - discontinuities

4. Spacing — 20 pts
   - 2 m or more; 20 points
   - < 60 mm; 5 points
5. General condition (refer section E) — 30 pts
   - Roughness
   - Continuity
   - Opening
   - Weathering

RMR modified for slopes or tunnels

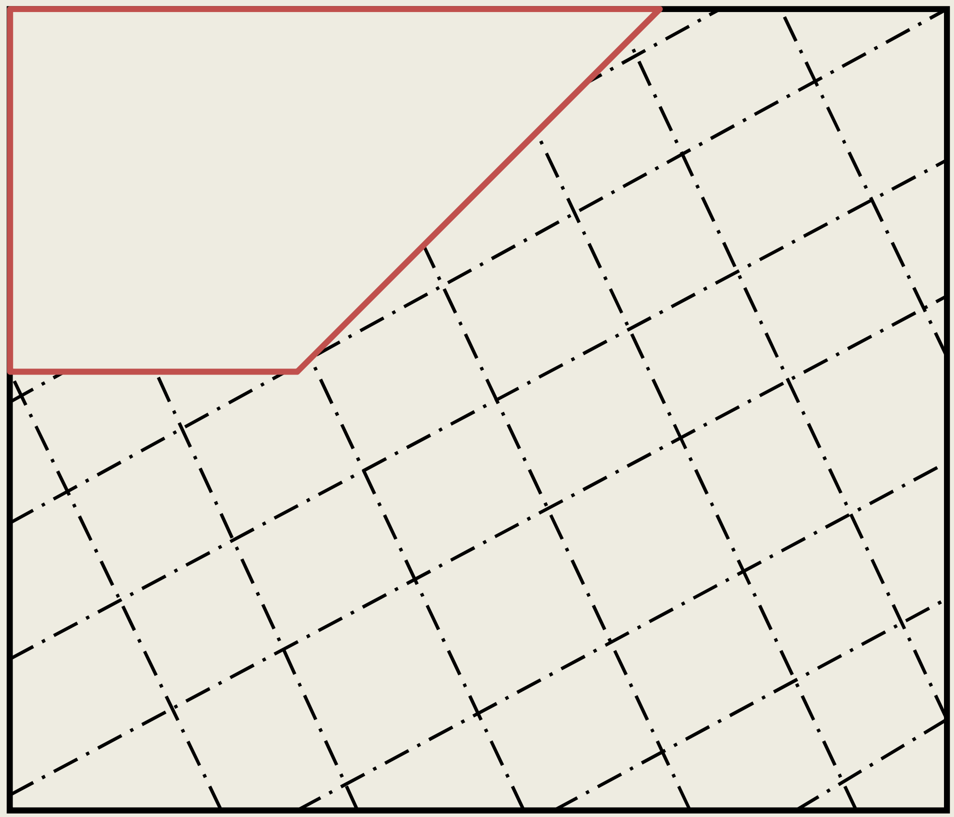
Additional factors applied to RMR_{basic}

- Accounts for excavation method

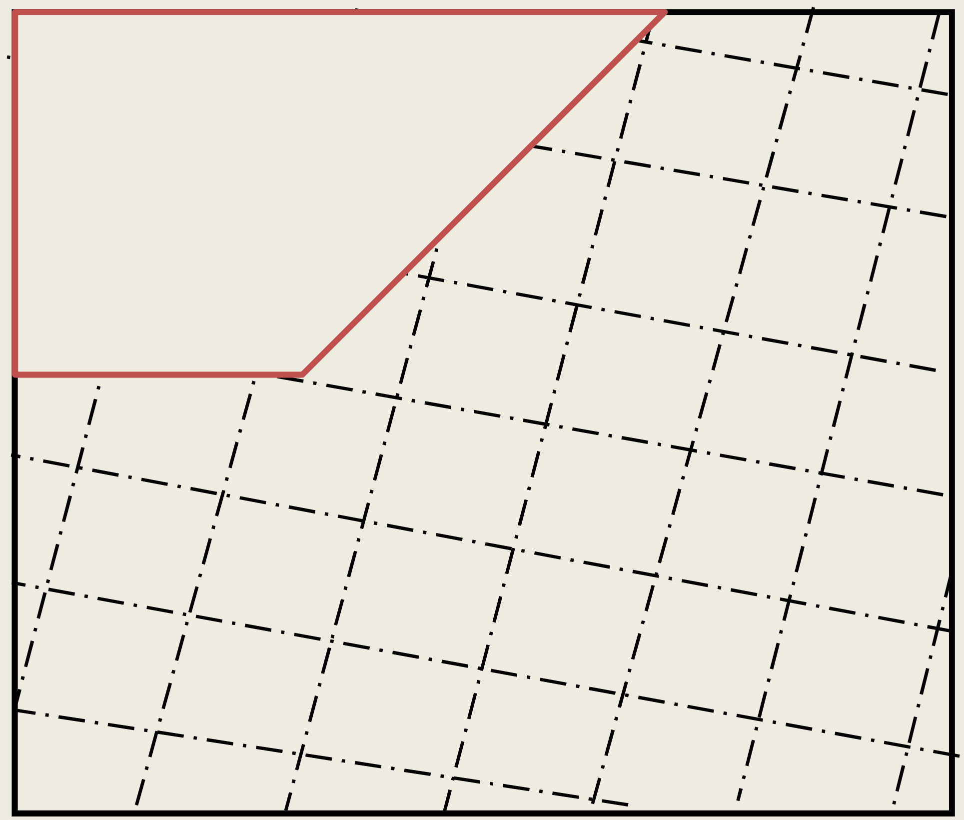
BUT moreover,

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

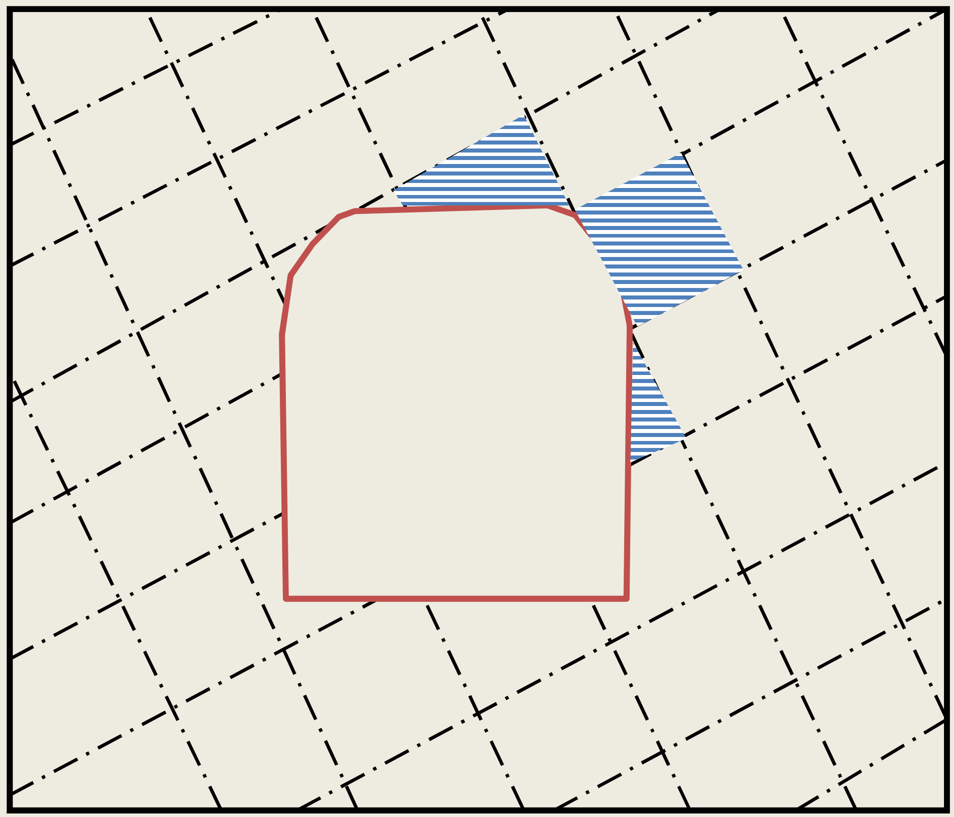
Slopes - un*favourable*



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

Evaluation of Tunnels based on RMR

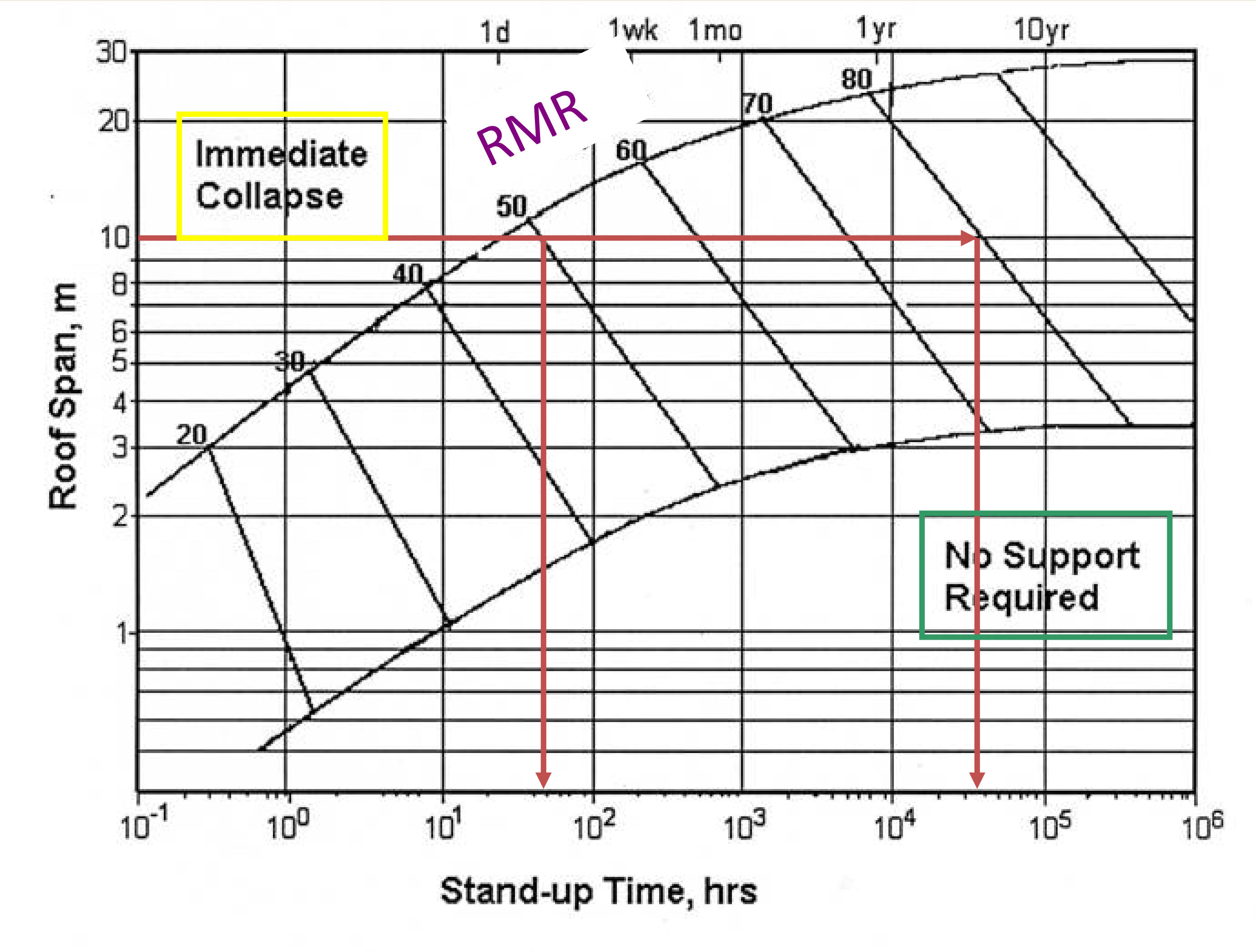
<u>Example:</u> 10 m span

RMR = 80

Stand up time > 4 years

RMR = 50

Stand up time ≈ 2 days



Class of Rock from RMR

RMR	Description	Class
100-81	Very good	I
80-61	Good	II
60-41	Fair	III
40-21	Poor	IV
<21	Very poor	V

An Alternative Rating System

NGI index or Q rating

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

- RQD as before
- J_n = joint set number
  - (0.5 – 20: massive rock to a crushed rock
- The ratio RQD:J_n ~ **“block size”**

Q System

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

- J_r = joint roughness number (0 - 6)
- J_a = the joint alteration number
  - 0.75 – 4?: hard to soft filling; $J_a = fn(\phi_r)$
- The ratio $J_r{:}J_a \sim$ joint roughness & friction

Q System

JRC	0	1-5	5-10[1]	5-10[1]	10-15[2]	15-20
$\mathbf{J_r}$	0.5	1	1.5	3	3	6

1. "slightly rough", planar v undulating
2. "rough/regular" and undulating

Q System

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

- J_w = joint water reduction factor
  (1 – 0.05: dry to water under pressure)
- SRF = the stress reduction factor
  (0.5 – 20: low stress & favourable orientation to high stress)

1. RQD

Very poor	0-25
Poor	25-50
Fair	50-75
Good	75-90
Excellent	90-100

2 . JOINT SET NUMBER, J_n

One joint set	2
Two joint sets	4
Two joint set + random	6
Three joint sets	12

- Notes refer to tunnelling & possibly greater J_n

3. JOINT ROUGHNESS NUMBER, J_r (*<u>not for open joints</u>*)

Description	**JRC**	**J_r**
Discontinuous joints	15 - 20	4
Smooth undulating	1 - 5	2
Smooth planar	1 - 5	1
Slickensided planar	0	0.5

4. JOINT ALTERATION NUMBER, J_a

Description	**ϕ_r (°)**	**J_a**
Unaltered joint walls, surface staining only	25 - 35	1
Slightly altered joint walls, **no clay**	25 - 30	2
Silty/sandy coatings, **some clay**	20 - 25	3
Kaolinite, mica, chlorite, talc, gypsum, graphite and/or some swelling clay	8 - 16	4

5. JOINT WATER REDUCTION, J_w

Description	**J_w**
Dry excavation or minor inflow	1
Large inflow, or high pressure in competent rock with unfilled joints	0.5
Exceptionally high inflow or pressure	0.1 - 0.05

6. STRESS REDUCTION FACTOR

Description	$\sigma_c : \sigma_1$	SRF
Low stress, near surface rock	200	2.5
Medium stress	200 - 10	1
Mild rockburst (massive rock)	5 – 2.5	5 - 10

Tunnels and the Q rating

- Require D_e and ESR
  - D_e = equivalent dimension

    = ratio of excavation span **or** height to ESR
  - ESR = excavation support ratio

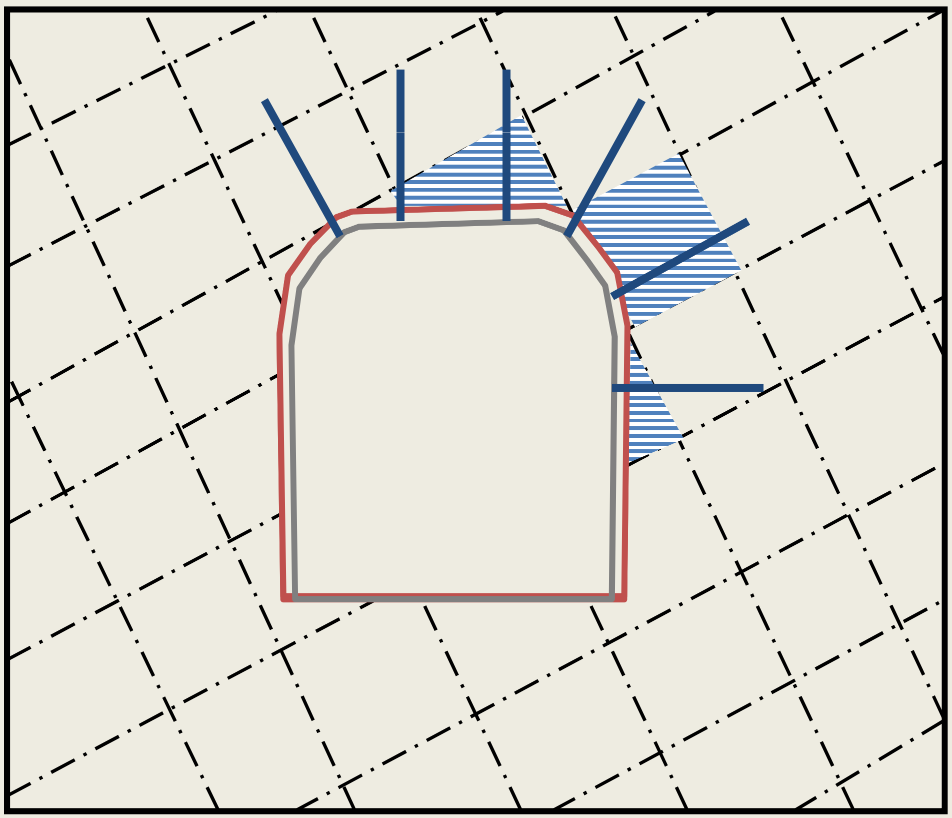
  ESR = *fn*(the tunnel use & **level of risk** chosen)

ESR Values (Barton et al 1974)

Temporary mine openings	3 - 5
Permanent mine openings, water tunnels for hydro power, etc.	1.6 - 2
Power stations, **major road & railway tunnels**, etc.	1
Underground nuclear power stations, railway stations, etc.	0.8

Tunnel Support

Lining, e.g. shotcrete



Rockbolts

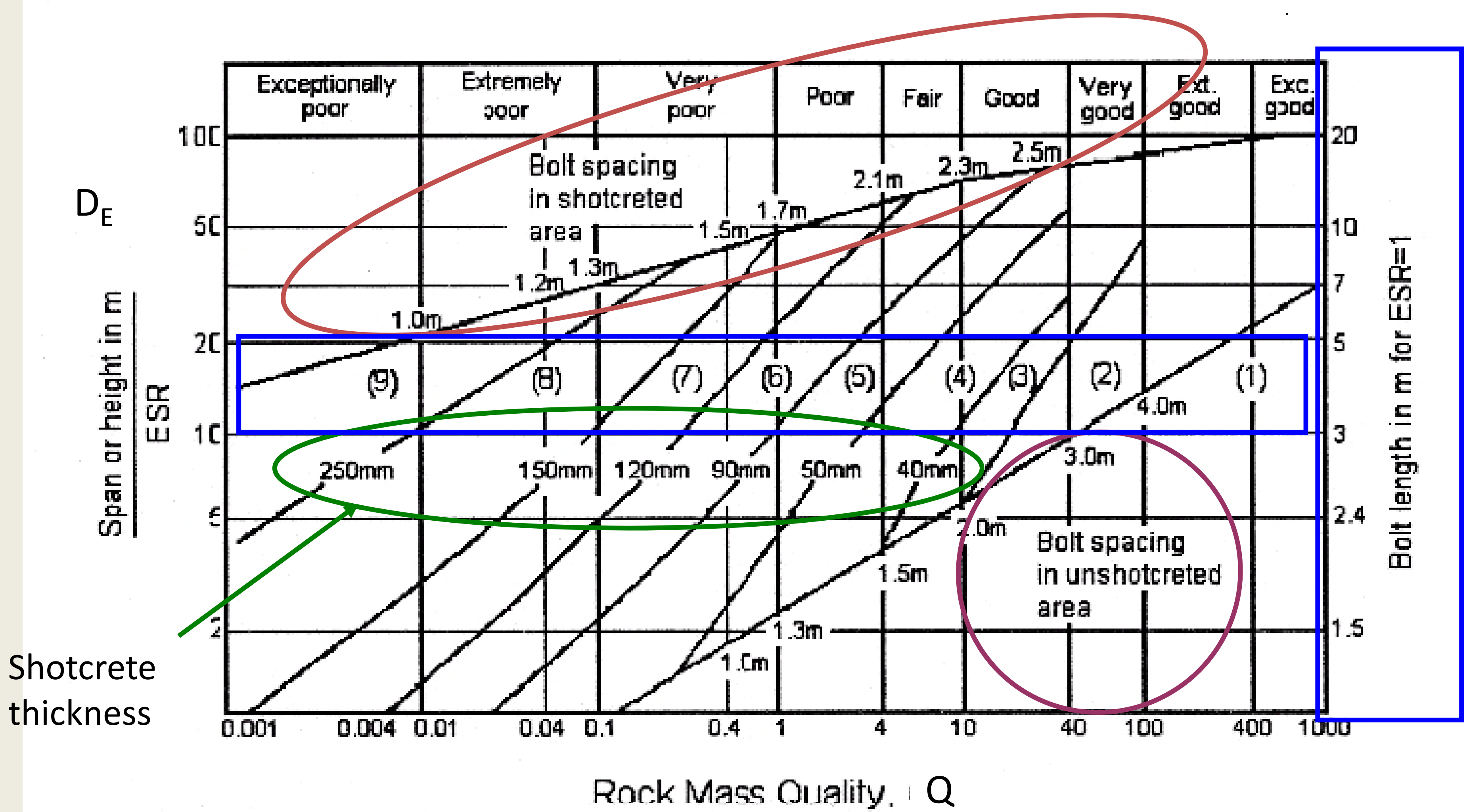


Figure 1. The Q system Tunnel Reinforcement Design Chart (Barton[7], 1996)

Areas within the chart

• area 1	• unsupported
• area 2	• spot bolting
• area 3	• systematic bolting (SB)
• area 4	• SB + 40-50 mm shotcrete
• area 5	• SB + 50-90 mm FRS
• area 6	• SB + 90-120 mm FRS
• area 7	• SB + 120-150 mm FRS
• area 8	• SB + 150-120 mm FRS, ribbed
• area 9	• Cast concrete lining

FRS = fibre reinforced shotcrete

Tunnels and the Q rating

Example:

10 m span ESR = 2

Q= 40

10 m span ESR = 1

Q= 40

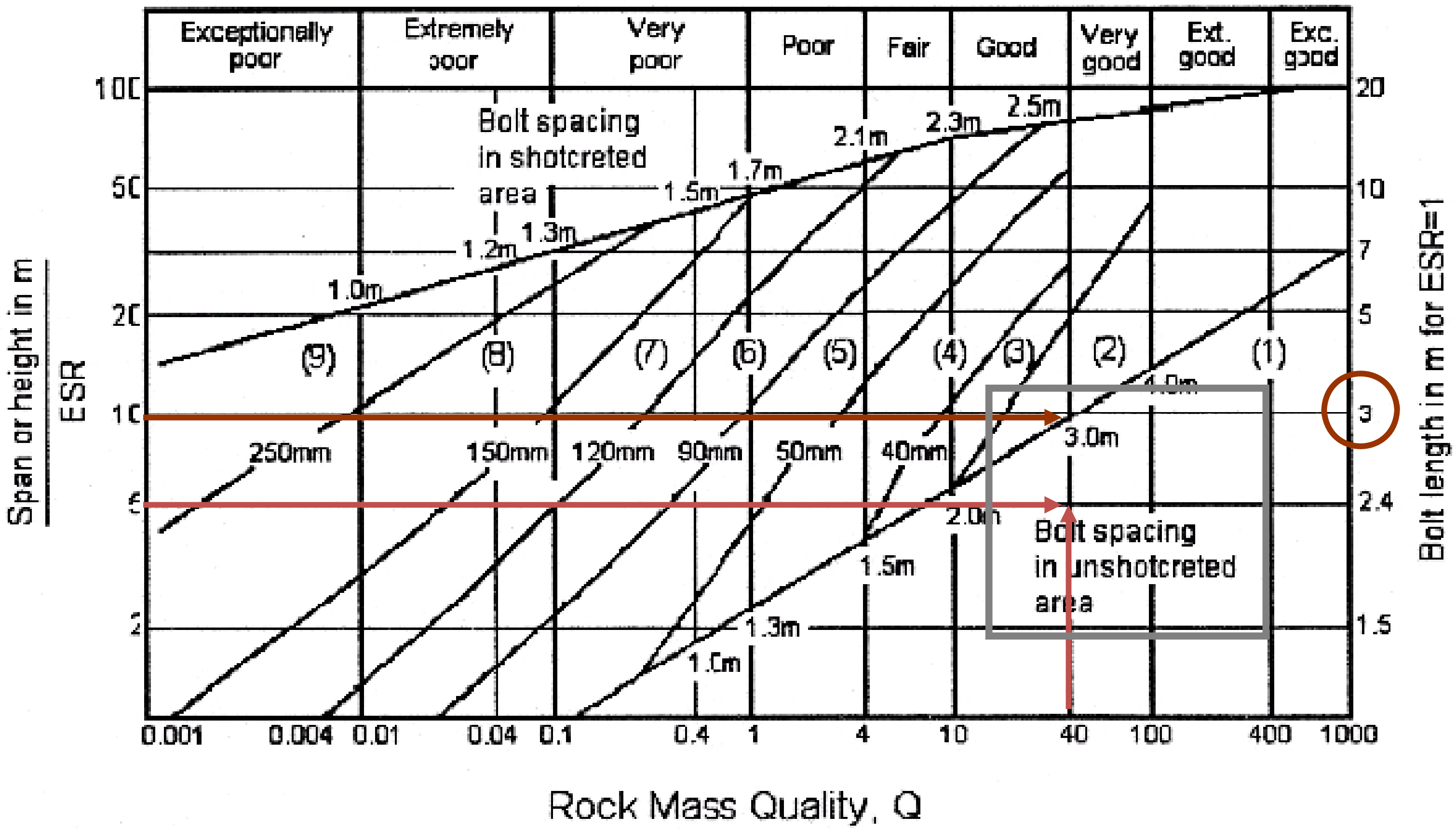


Figure 1. The Q system Tunnel Reinforcement Design Chart (Barton[7], 1996)

Tunnels and the Q rating

Example:

10 m span ESR = 1

Q = 1.0

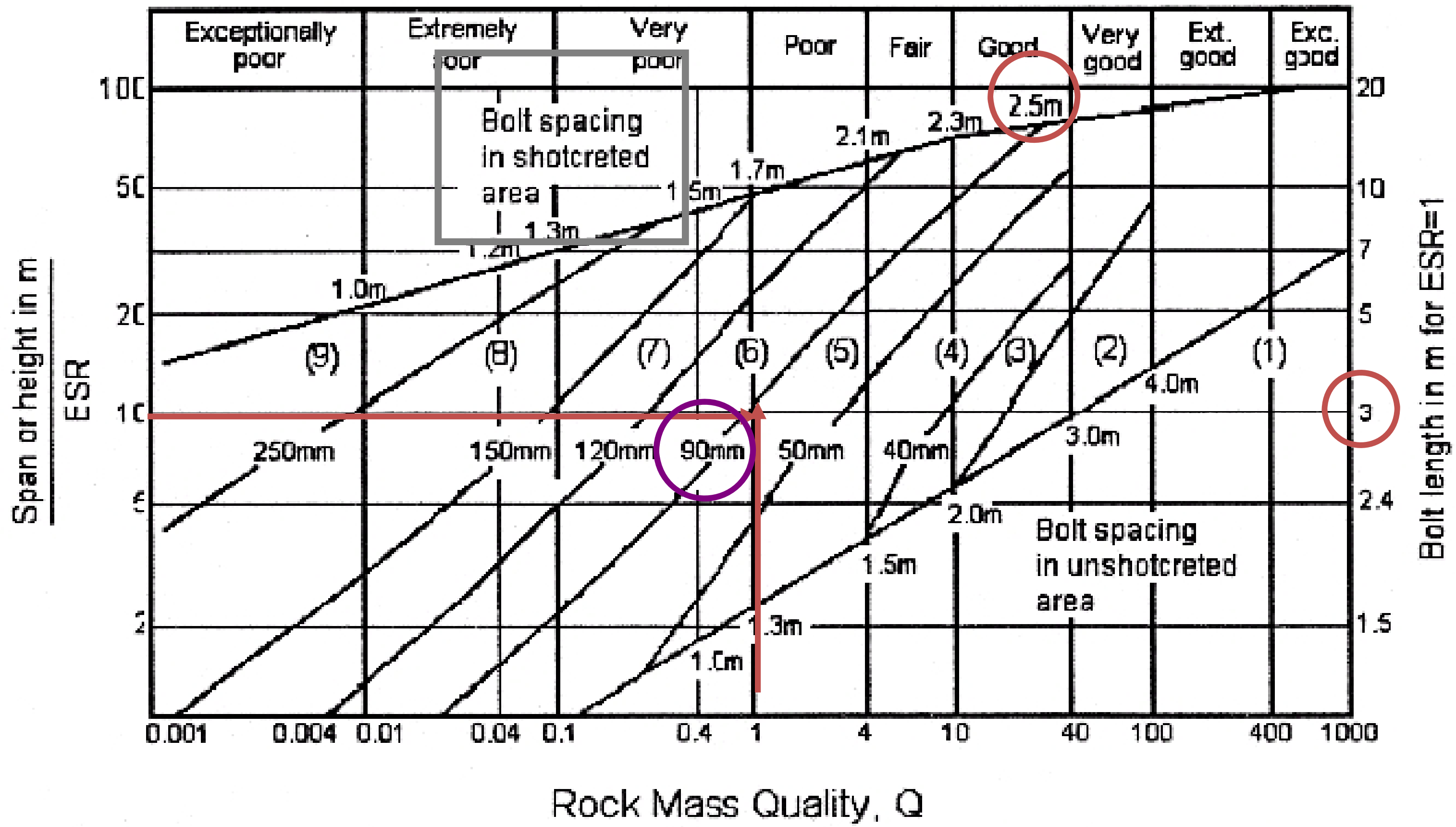


Figure 1. The Q system Tunnel Reinforcement Design Chart (Barton[7], 1996)

Evaluation of Tunnels based on Q rating

<u>Example:</u>

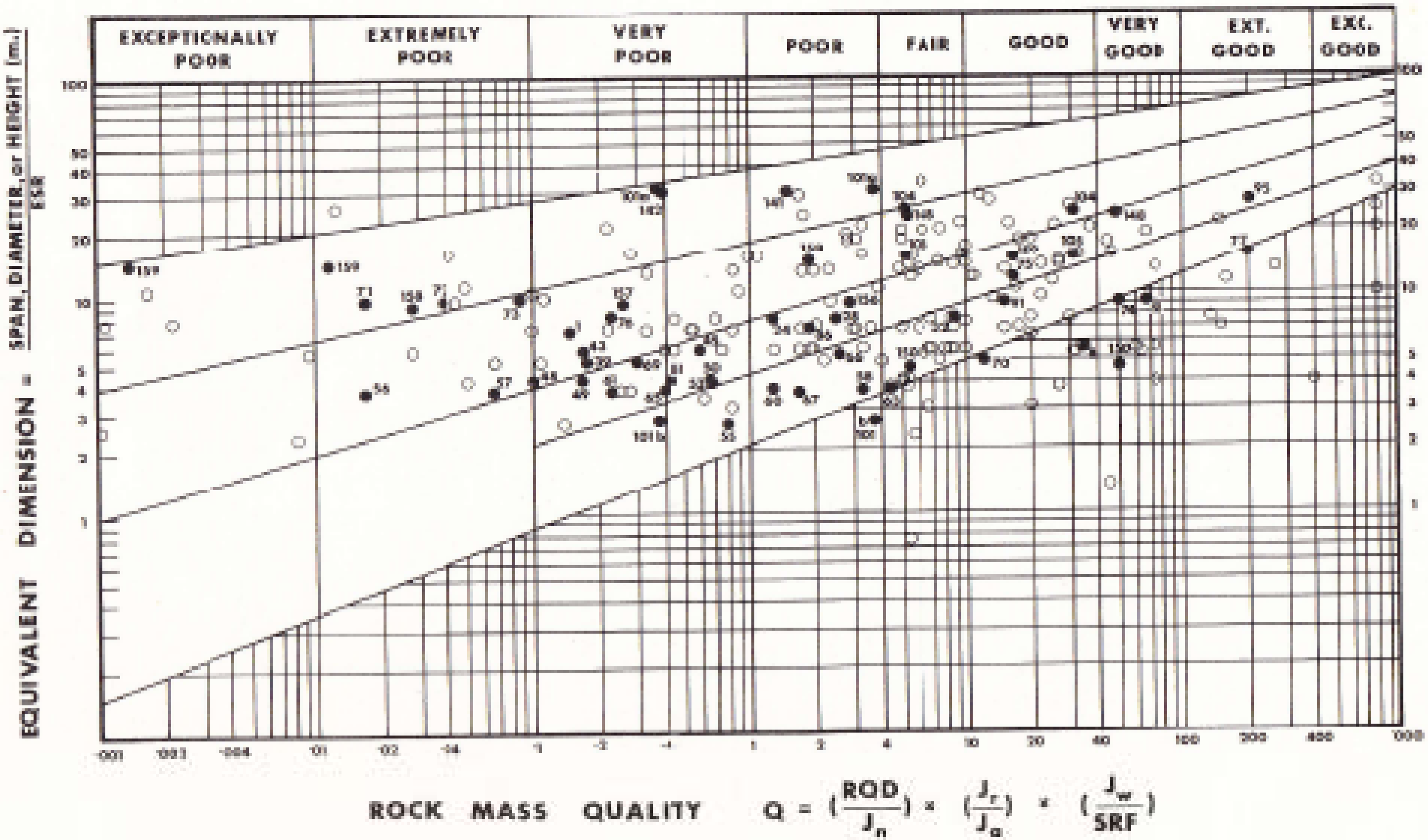
- 10 m span & ESR = 2
- Q = 40

Area 1: UNSUPPORTED

- 10 m span & ESR = 1
- Q = 40

Area (2): SPOT BOLTING

Requires rockbolts at 3 m spacing, 3 m long (max)



EXCEPTIONALLY POOR
EXTREMELY POOR
VERY POOR
POOR
FAIR
GOOD
VERY GOOD
EXT. GOOD
EXC. GOOD
EQUIVALENT DIMENSION = SPAN, DIAMETER, or HEIGHT (m.) / ESR
ROCK MASS QUALITY Q = (RQD/Jn) × (Jr/Ja) × (Jw/SRF)

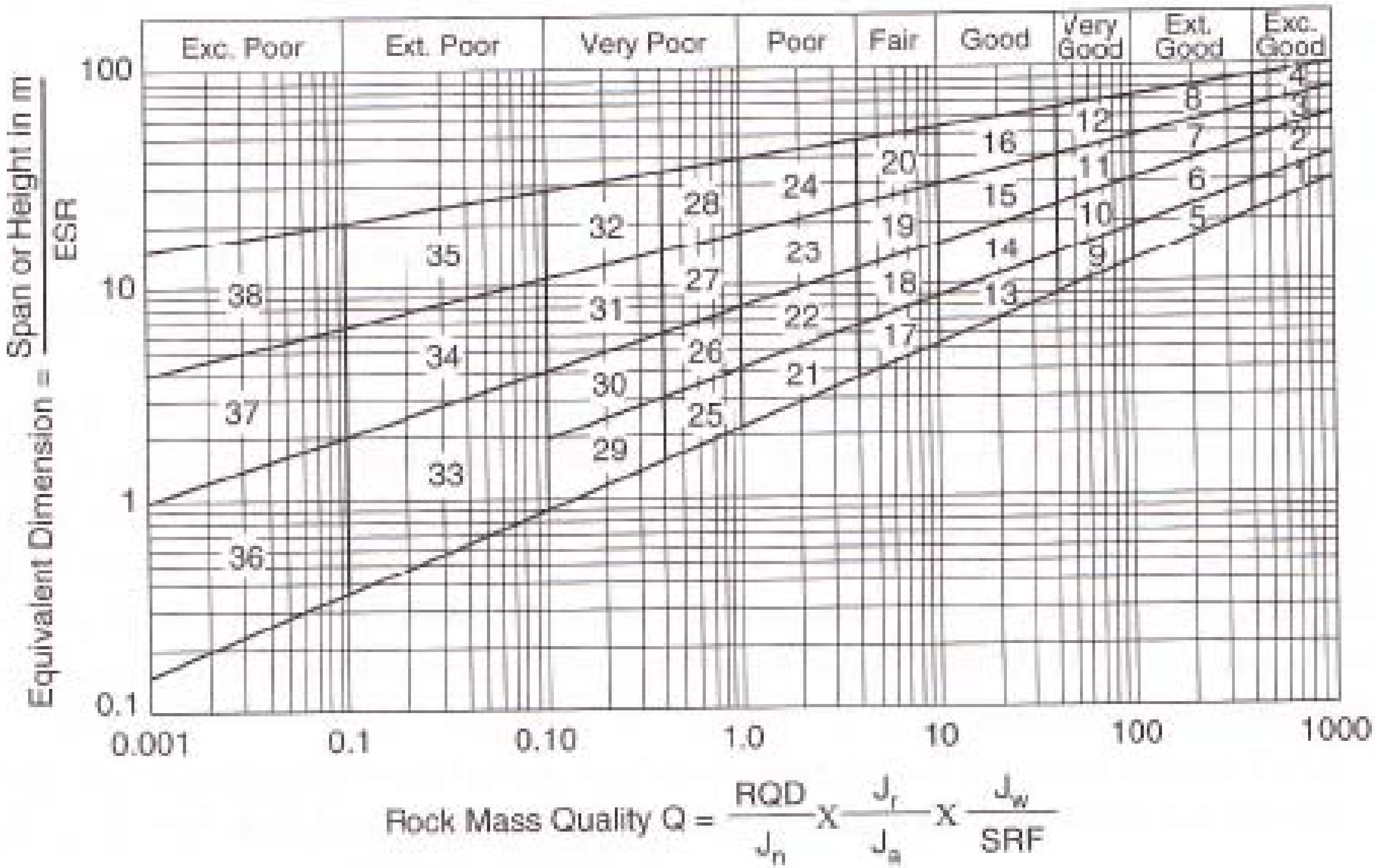
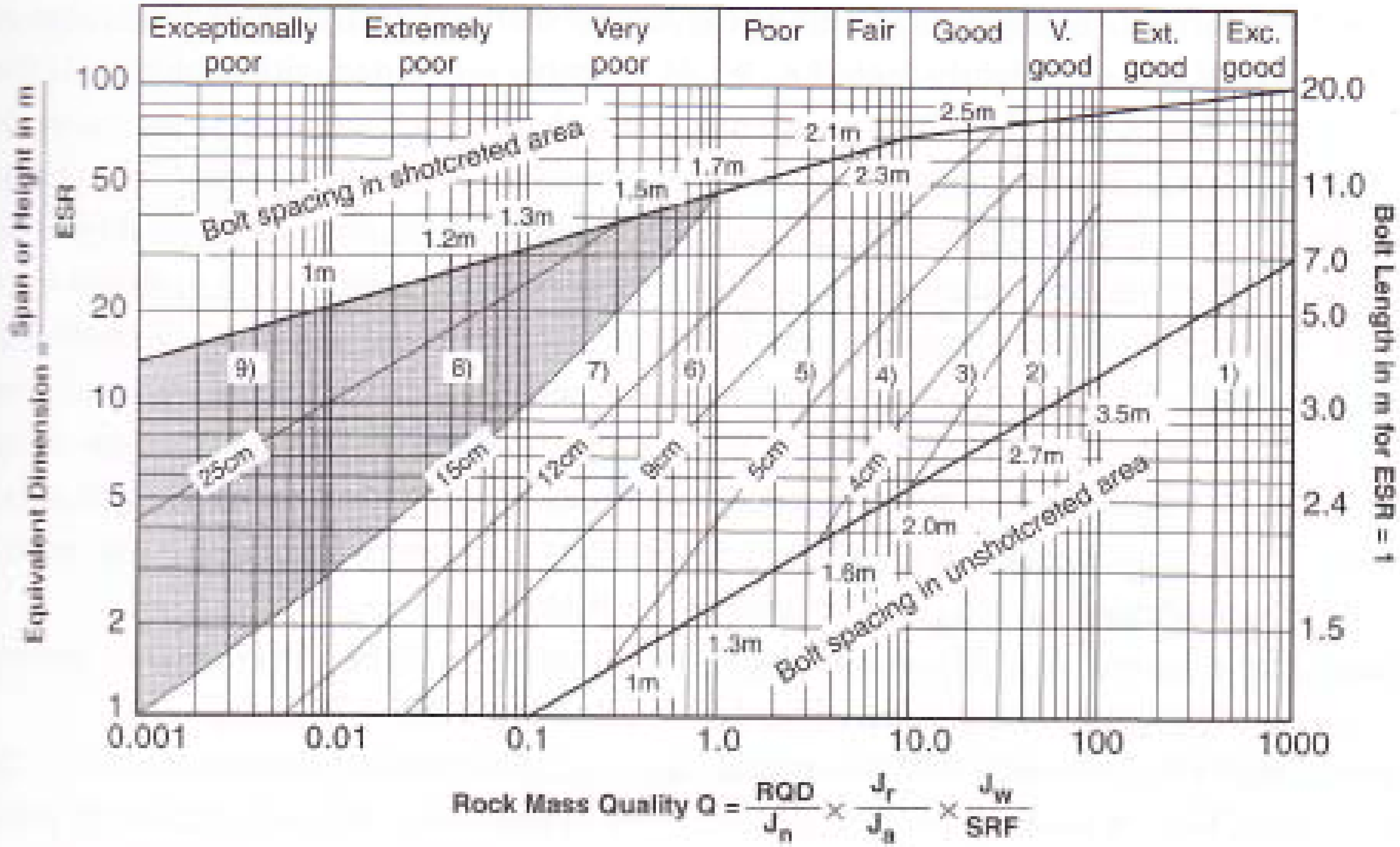


Fig. 10.1 Tunnel support chart showing 38 support categories (Barton et al., 1974).



REINFORCEMENT CATEGORIES

1) Unsupported
2) Spot bolting, sb
3) Systematic bolting, B
4) Systematic bolting (and unreinforced 4 to10cm, B(+S)shotcrete,
5) Fiber reinforced shotcrete and bolting, 5 to 9cm, S(fr)+B
6) Fiber reinforced shotcrete and bolting, 9 to 12cm, S(fr)+B
7) Fiber reinforced shotcrete and bolting, 12 to 15cm, S(fr)+B
8) Fiber reinforced shotcrete > 15cm, reinforced ribs of shotcrete and bolting, S(fr), RRS+B
9) Cast concrete lining,CCA

Fig. 10.2 Chart for the design of SFRS support (Grimstad & Barton, 1993).

Table 5. Estimates of Roof Support Pressures for Tunnels of 5 m and 10 m Span after Terzaghi (1946)

Assume: span = height, rock density $\gamma = 2.6\ t/m^3$

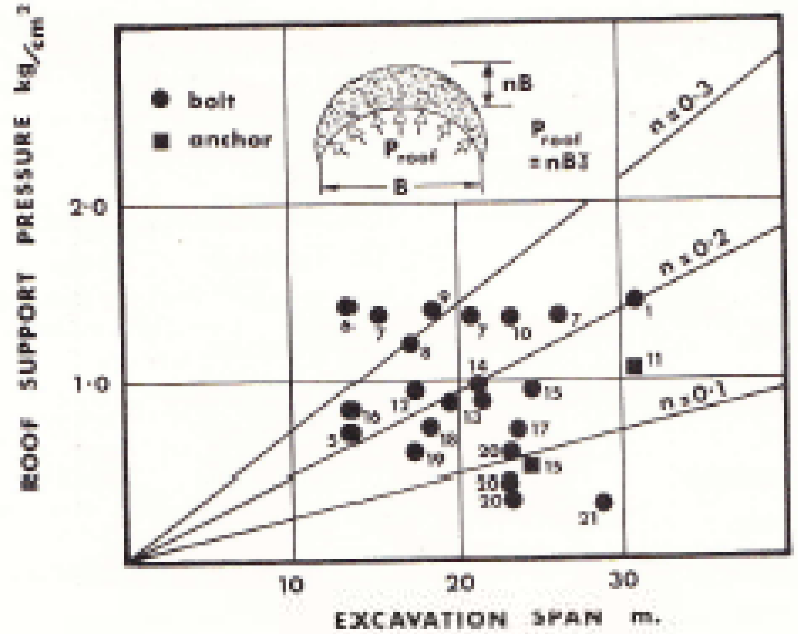
Description	Rock load estimates (m)	Support pressures kg/cm^2	
		B = H = 5 m	B = H = 10 m
1. Hard and intact	zero	0	0
2. Hard stratified or schistose	0 to 0.5 B	0 to 0.6	0 to 1.3
3. Massive, moderately jointed	0 to 0.25 B	0 to 0.3	0 to 0.6
4. Moderately blocky and seamy	0.25 B to 0.35 (B + H)	0.3 to 0.9	0.6 to 1.8
5. Very blocky and seamy	(0.35 to 1.10) (B + H)	0.9 to 2.9	1.8 to 2.9
6. Completely crushed but chemically intact	1.10 (B + H)	2.9	5.7
7. Squeezing rock, moderate depth	(1.10 to 2.10) (B + H)	2.9 to 5.5	5.7 to 10.9
8. Squeezing rock, great depth	(2.10 to 4.50) (B + H)	5.5 to 11.7	10.9 to 23.4
9. Swelling rock	up to 80 m any (B + H)	up to 20.8	up to 20.8

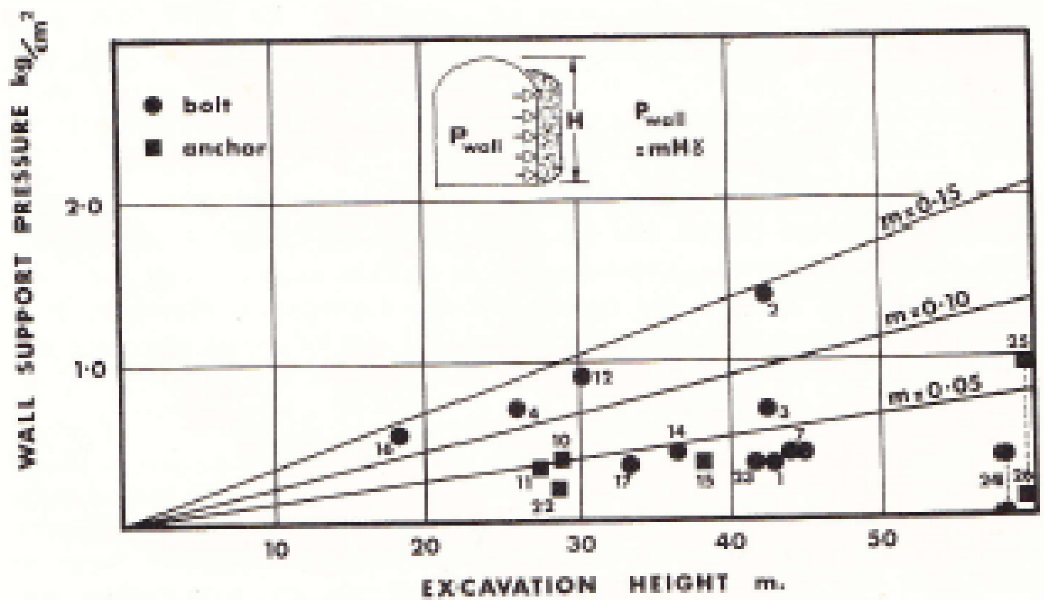
As a preliminary effort to relate rock mass quality Q to support pressure, the authors translated Terzaghi's nine rock mass descriptions into

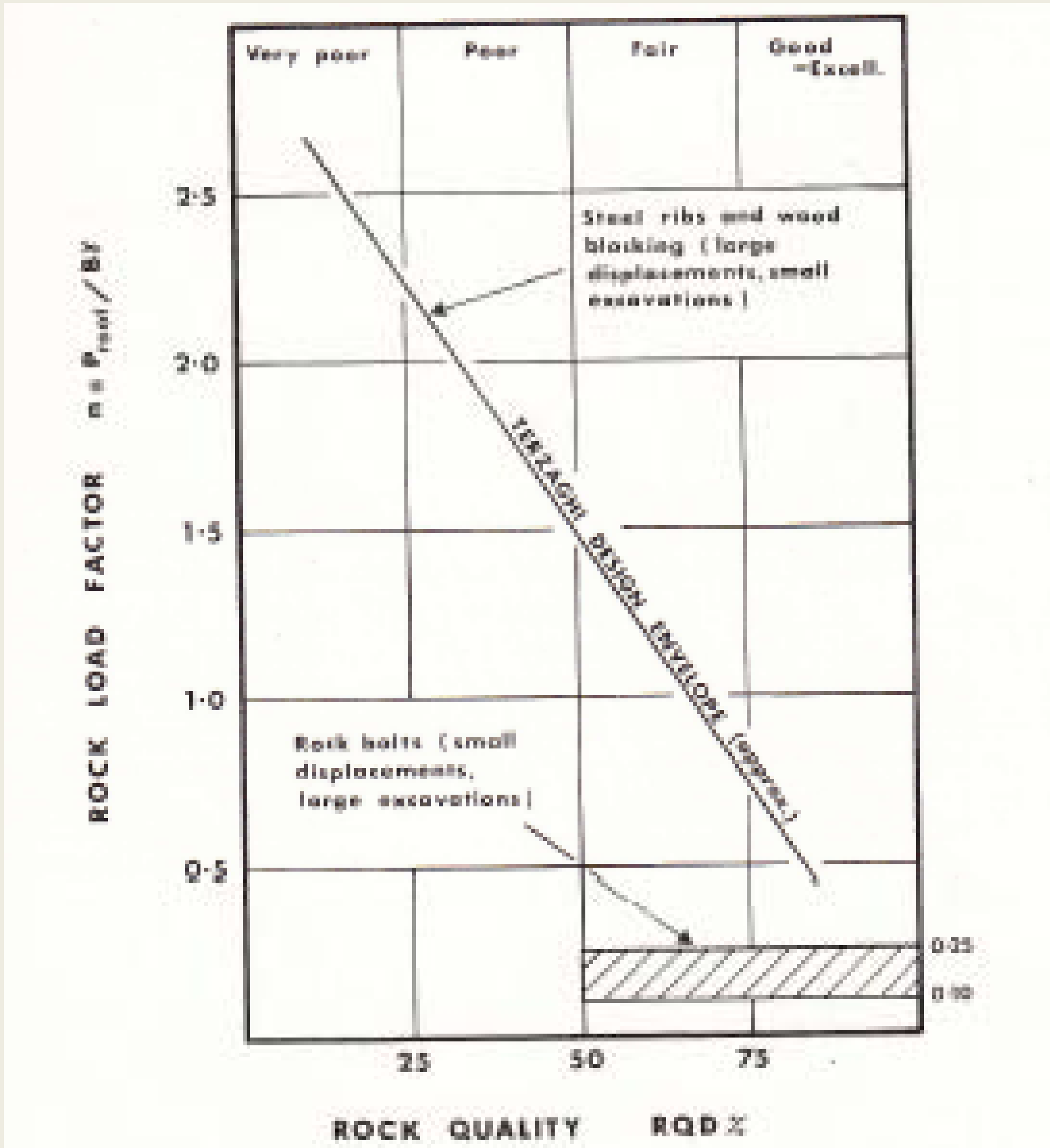
Table 6. Estimates of Rock Mass Quality Q for the Nine Classes of Rock Mass Listed in Table 5

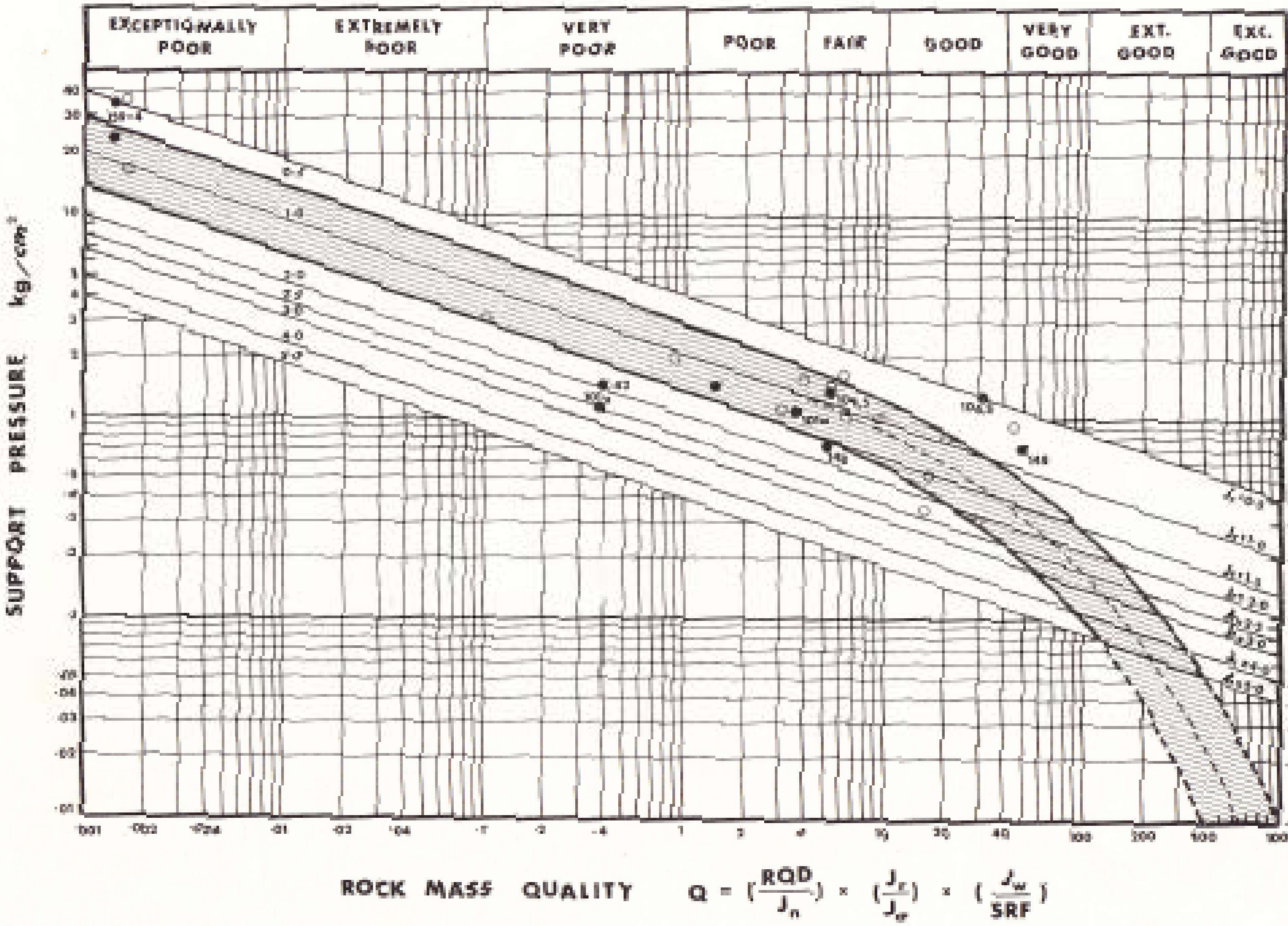
No.	*RQD*	J_n	J_r	J_a	J_w	*SRF*	Q (range)
1	100	≦2	4	1	1	1	≧200
2	≧30	3	1	1	1	1	20—10
3	100	6	≧1.5	1	1	1	50—25
4	80	9	1	≦3	0.66	1	6—2
5	50	12	1	≧3	0.66	1	1—0.4
6	20	15	1	2	≦0.66	5	0.08 —0.04
7	20	20	1	≧6	0.66	5—10	0.03 —0.01
8	0	20	1	≧6	0.33	10—20	0.004—0.001
9	0	20	1	12	≦0.66	10	0.003—0.001

values of the six classification parameters, as shown in Table 6. There is obviously room for alternative interpretation. However, the resulting ranges of Q were a useful starting point.

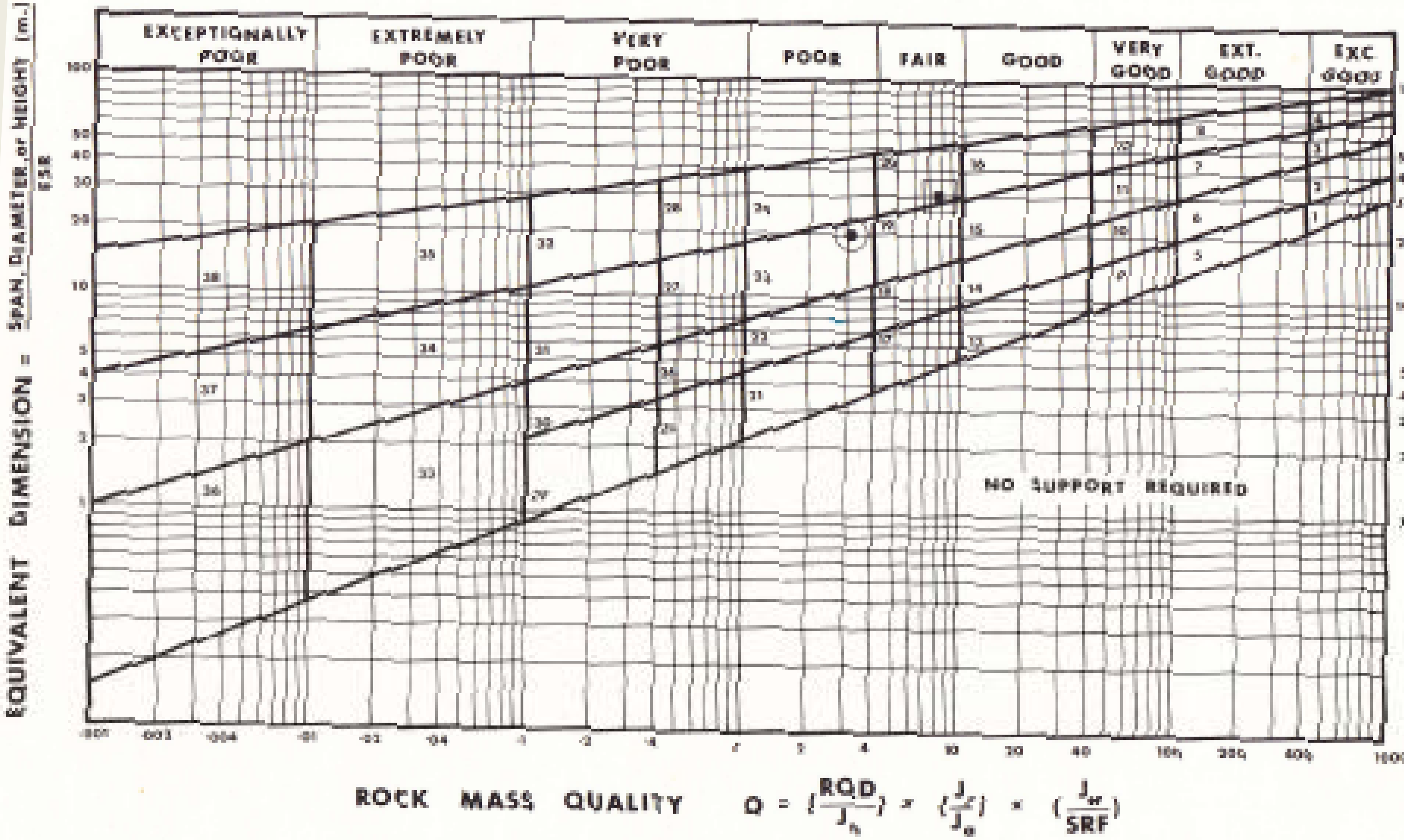

bolt
anchor
nB
P_{roof}
$P_{roof} = nB\delta$
B
n=0·3
n=0·2
n=0·1
2·0
1·0
10
20
30
ROOF SUPPORT PRESSURE kg/cm^2
EXCAVATION SPAN m.


bolt
anchor
P_{wall}
H
$P_{wall} = mH\delta$
m=0·15
m=0·10
m=0·05
2·0
1·0
10
20
30
40
50
WALL SUPPORT PRESSURE kg/cm^2
EXCAVATION HEIGHT m.


Very poor
Poor
Fair
Good
–Excell.
2·5
2·0
1·5
1·0
0·5
Steel ribs and wood blocking (large displacements, small excavations)
TERZAGHI DESIGN ENVELOPE (approx.)
Rock bolts (small displacements, large excavations)
0·25
0·10
25
50
75
ROCK QUALITY RQD %
ROCK LOAD FACTOR n = P roof / Bγ



EXCEPTIONALLY POOR
EXTREMELY POOR
VERY POOR
POOR
FAIR
GOOD
VERY GOOD
EXT. GOOD
EXC. GOOD
SUPPORT PRESSURE kg/cm²
ROCK MASS QUALITY $Q = \left(\frac{RQD}{J_n}\right) \times \left(\frac{J_r}{J_a}\right) \times \left(\frac{J_w}{SRF}\right)$


EXCEPTIONALLY POOR
EXTREMELY POOR
VERY POOR
POOR
FAIR
GOOD
VERY GOOD
EXT. GOOD
EXC GOOD
EQUIVALENT DIMENSION = SPAN, DIAMETER, or HEIGHT (m.) / ESR
NO SUPPORT REQUIRED
.001 .002 .004 .01 .02 .04 .1 .2 .4 1 2 4 10 20 40 100 200 400 1000
ROCK MASS QUALITY Q = (RQD / Jn) x (Jr / Ja) x (Jw / SRF)

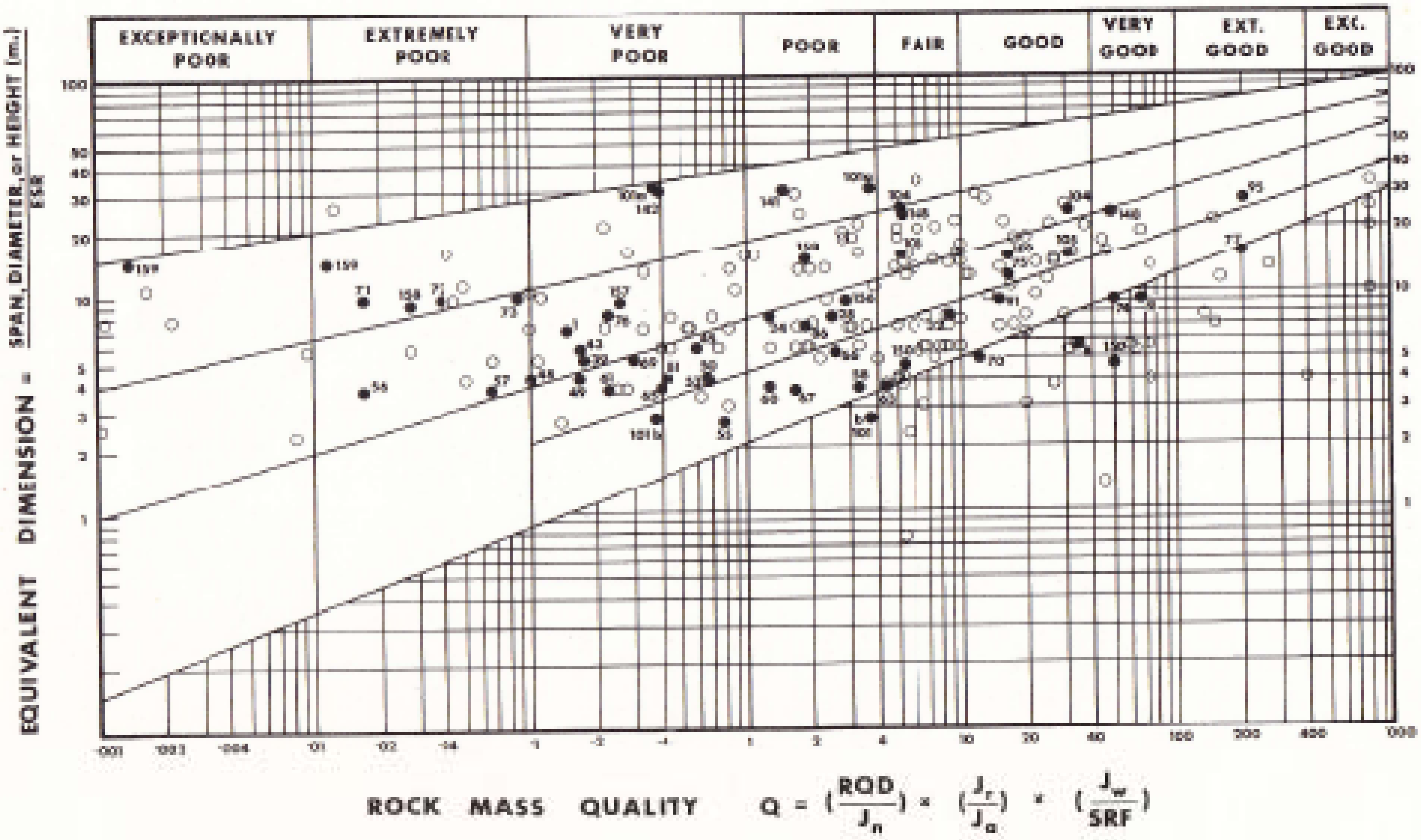

EXCEPTIONALLY POOR
EXTREMELY POOR
VERY POOR
POOR
FAIR
GOOD
VERY GOOD
EXT. GOOD
EXC. GOOD
EQUIVALENT DIMENSION = SPAN, DIAMETER, or HEIGHT (m.) / ESR
ROCK MASS QUALITY Q = (RQD/Jn) × (Jr/Ja) × (Jw/SRF)

Table 7. The Excavation Support Ratio (*ESR*) Appropriate to a Variety of Underground Excavations

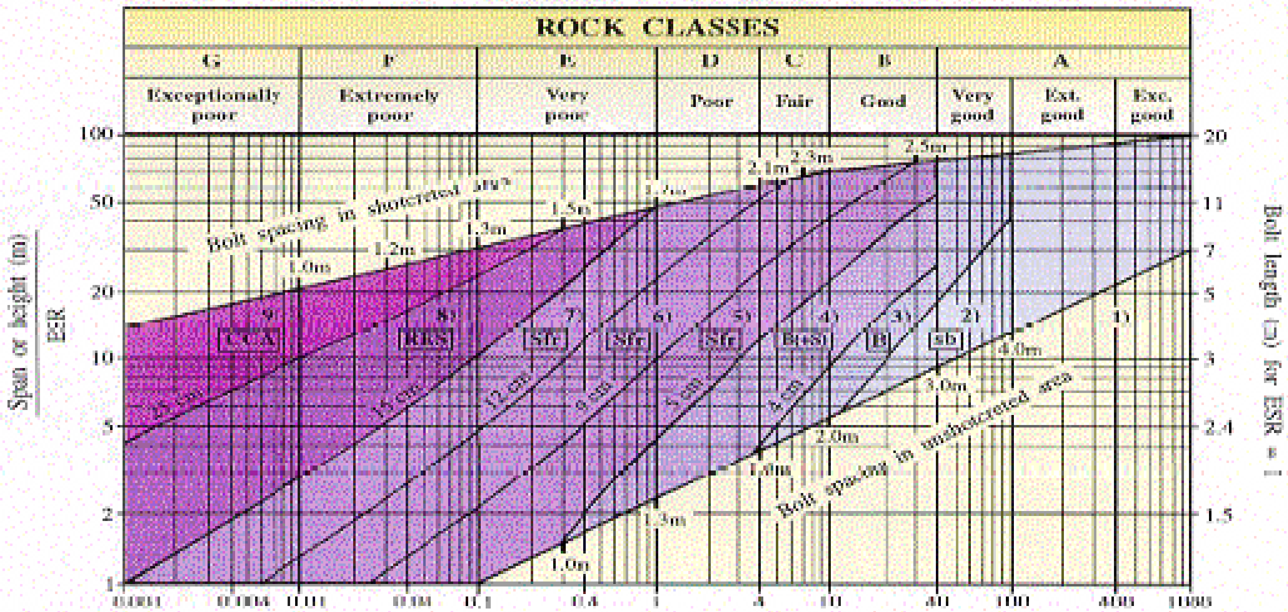
	Type of excavation	*ESR*	No. of cases
A.	Temporary mine openings etc.	ca. 3—5?	(2)
B.	Vertical shafts: (i) circular section	ca. 2.5?	(0)
	(ii) rectangular/square section	ca. 2.0?	(0)
C.	Permanent mine openings, water tunnels for hydro power (exclude high pressure penstocks), pilot tunnels, drifts and headings for large excavations etc.	1.6	(83)
D.	Storage rooms, water treatment plants, minor road and railway tunnels, surge chambers, access tunnels, etc. (cylindrical caverns?)	1.3	(25)
E.	Power stations, major road and railway tunnels, civil defence chambers, portals, intersections etc.	1.0	(79)
F.	Underground nuclear power stations, railway stations, sports and public facilities, factories etc.	ca. 0.8?	(2)

NMT

The Norwegian Method of Tunnelling

TUNNEL SUPPORT DESIGN

Using a new Q-system chart



Rock mass quality $Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF}$

REINFORCEMENT CATEGORIES:

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

Rock Bolt length

Roof: $L = 2 + 0.15B/ESR$

Walls: $L = 2 + 0.15H/ESR$

L = meters; B = Span; H = wall height;

ESR = Excavation Support Ratio

Quantifying shotcrete design

- Shotcrete not normally modelled as structural element in numerical analysis
- Nominal shear strength = 2 Mpa
- Nominal bonding strength = 0.5 Mpa
- Estimate rock wedge volume
- Compare block weight to shear strength and block weight to bonding strength
- ***Shotcrete increasingly accepted as final lining for tunnels***

Typical Rock Support

Class	Q	Type I	Type II	Type III
A	>40	Spot 40 mm	Spot 40 mm	Spot 40 mm
B	10-40	L3(2.4) 40 mm	L4(2.4) 40 mm	L5(2.4) 50 mm
C	4-10	L3(2.2) 40 mm	L4(2.2) 40 mm	L5(2.2) 50 mm
D	1-4	L3(1.9) 50 mm	L4(1.9) 50 mm	L5(1.9) 75 mm
E	< 1	L3(1.5) 75 mm	L4(1.5) 75 mm	L5(1.5) 100 mm

Note: L3(2.4) = rock bolt length of 3 m at 2.4m center-to-center spacing

Table 7. The Excavation Support Ratio (*ESR*) Appropriate to a Variety of Underground Excavations

	Type of excavation	*ESR*	No. of cases
A.	Temporary mine openings etc.	ca. 3—5?	(2)
B.	Vertical shafts: (i) circular section	ca. 2.5?	(0)
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C.	Permanent mine openings, water tunnels for hydro power (exclude high pressure penstocks), pilot tunnels, drifts and headings for large excavations etc.	1.6	(83)
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F.	Underground nuclear power stations, railway stations, sports and public facilities, factories etc.	ca. 0.8?	(2)

KEY POINTS?

- Rock mass rating systems are a useful way of forming **an** evaluation of rock masses
- The Q or NGI system was based on tunnelling
- The RMR (CSIR) system is more commonly used for slope stability
- The strength of rock masses can be judged from these systems