UNDERGROUND MINE STABILITY

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Subjects

1. Rock mass structure and characterisation
2. In situ and induced stress
3. Rock mass properties
4. Rock mass classification
5. Underground excavation failure mechanism
6. Instrumentation

Rock Mass Classification

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Rock Mass Classification

1. Engineering Rock Mass Classification
2. Geomechanics Classification (Rock Mass Rating, RMR)
3. Modifications to RMR for Mining (MRMR)
4. Rock Tunnelling Quality Index (Q)
5. Using Rock Mass Classification Systems

Complement

1. A generic method for rock mass classification (Khatik and Nandi, 2018)
2. Evaluation of rock mass deformability using empirical methods – A review (Zhang, 2017)
3. Rock Mass Quality Rating (RMQR) System: Its Application to Estimation of Geomechanical Characteristics of Rock Masses and to Rock Support Selection for Underground Caverns and Tunnels (Aydan and Ulusay, 2014)

Complement

4. Engineering Rock Mass Classification – Tunneling, Foundation, and Landslides (Singh and Goel, 2011)
5. Engineering Rock Mass Classifications (Bieniawski, 1989)

Philosophy of Engineering Classifications

Rock mass classifications form the backbone of the empirical design approach and are widely employed in rock engineering. Engineering rock mass classifications have recently been quite popular and are used in feasibility designs. *When used correctly*, a **rock mass classification** can be a powerful tool in these designs.

Philosophy of Engineering Classifications

On many projects the classification approach is <u>the only practical basis</u> for the design of complex underground structures.

Philosophy of Engineering Classifications

Engineering rock mass classification systems have been widely used for the following reasons:

1. They provide better communication between planners, geologists, designers, contractors, and engineers.
2. An engineer's observations, experience, and judgement are correlated and consolidated more effectively by an engineering (quantitative) classification system.

Philosophy of Engineering Classifications

3. Engineers prefer numbers in place of descriptions; hence, an engineering classification system has considerable application in an overall assessment of the rock quality.
4. The classification approach helps in the organization of knowledge and is amazingly successful.

Philosophy of Engineering Classifications

5. An <u>ideal application</u> of engineering rock mass classification occurs in the planning of hydroelectric projects, tunnels, cavern, bridges, silos, building complexes, hill roads, rail tunnels, and so forth.

Philosophy of Engineering Classifications

The classification system, in the last 60 years of its development, has been cognizant of the new advances in rock support technology starting from steel rib supports to the latest supporting techniques such as rock bolts and steel fiber reinforced shotcrete (SFRS).

Philosophy of Classification System

No single classification is valid for assessment of all rock parameters. Selection of a classification for estimating a rock parameter is, therefore, based on experience. It is necessary to account for fuzzy variation of rock parameters after following for uncertainty; thus, it is *better* to assign a range of ratings for each parameter. There can be a wide variation in the engineering classifications at a location.

Need for Engineering Geological Map

First, a geological map on **macro-scale (1:50,000)** should be prepared before tunneling or laying foundations. Then an engineering geological map on **micro-scale (1:1,000)** should be prepared soon after excavation.

Need for Engineering Geological Map

This map should **highlight geological details** for an excavation and support system. These include Q, RMR, all the shear zones, faults, dip and dip directions of all joint sets (discontinuities), highest ground water table (GWT), and so forth along tunnel alignment.

Need for Engineering Geological Map

If an engineering geological map is not prepared then the use of a tunnel boring machine (TBM) is not advisable, because the TBM may get stuck in the weak zones.

Management of Uncertainties

- ☐ Empirical approaches
- ☐ Numerical or analytical approaches
- ☐ Observational approaches

Empirical approaches

The empirical approach, based on rock mass classifications, is the most popular because of its simplicity and ability to manage uncertainties. Geological and geotechnical uncertainties can be tackled effectively using proper classifications. Moreover, this approach allows designers to make on-the-spot decisions regarding supporting measures if there is a sudden change in the geology.

Analytical approaches

The analytical approach, on the other hand, is based on assumptions and obtaining correct values of input parameters. This approach is both time-consuming and expensive.

Observational approaches

The observational approach, as the name indicates, is based on monitoring the efficiency of the support system.

Management of Uncertainties

Classifications are likely to be invalid in areas where there is damage due to blasting and weathering such as in cold regions, during cloudbursts, and under oceans. If the rock has *extraordinary geological occurrence (EGO) problems*, then these should be solved under the guidance of national and international experts.

Present-day Practice

Present-day practice is a combination of all of the previously described approaches. This is basically a *design as you go* approach. Experience led to the following strategy of refinement in the design of support systems.

In feasibility studies

Empirical correlations may be used for estimating rock parameters.

At the design stage

In situ tests should be conducted for major projects to determine the actual rock parameters. It is suggested that in situ triaxial tests should be conducted extensively, because it is found to affect both the strength and deformation modulus of rock masses in tunnels.

At the initial construction stage

Instrumentation should be carried out in drifts, caverns, intersections, and other important locations with the objective of acquiring field data on displacements both on the support excavated surfaces and within the rock mass. Instrumentation is also essential for monitoring construction quality.

At the initial construction stage *(cont.)*

Experience confirms that instrumentation in a complex geological environment is the key to success for a safe and steady tunneling rate. These data should be utilized in computer modeling for back analysis of both the model and its parameters (Sakurai, 1993).

At the construction stage

Forward analysis of rock structures should be carried out using the back analyzed model and the parameters of rock masses. Repeated cycles of back analysis and forward analysis (BAFA) may eliminate many inherent uncertainties in geological mapping and knowledge of engineering behavior of rock masses.

At the construction stage *(cont.)*

Where broken/plastic zones are predicted, the borehole extensometers should reveal a higher rate of displacement in the broken zone than in the elastic zone. The predicted displacements are *very sensitive* to the assumed model, parameters of rock masses and discontinuities, in situ stresses, and so forth.

Introduction

During the **feasibility and preliminary design stages** of a project, when very little detailed information is available on the rock mass and its stress and hydrologic characteristics, the use of a rock mass classification scheme can be of considerable benefit.

Different classification systems place different emphases on the various parameters, and it is recommended that *at least* two methods be used at any site during the **early stages** of a project.

Introduction

One or more rock mass classification schemes can be used to build up a picture of **the composition and characteristics of a rock mass** to provide **initial estimates of support requirements**, and to provide **estimates of the strength and deformation properties of the rock mass.**

Introduction

However, the use of these design procedures requires access to relatively **detailed information** on in situ stresses, rock mass properties and planned excavation sequence, none of which may be available at an early stage in the project.

As this information becomes available, the use of the rock mass classification schemes should be **updated** and used in conjunction with **site specific analysis**.

Engineering Rock Mass Classification

1. Rock Load Classification Method (by Terzaghi)
2. Stand-Up Time Classification (by Lauffer-Pacher)
3. Rock Quality Designation, RQD index (by Deere)
4. Rock Structure Rating, RSR Concept (by Wickham, Tiedemann, and Skinner)

Rock Load Classification Method (by Terzaghi)

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Rock Load Classification Method (by Terzaghi)

The *earliest* reference to the use of rock mass classification for the design of tunnel support is in a paper by **Terzaghi (1946)** in which the rock loads, carried by steel sets, are estimated on the basis of a descriptive classification.

Rock Load Classification Method (by Terzaghi)

It is interesting to examine the rock mass descriptions included in his original paper because he draws attention to those **characteristics that dominate rock mass behavior**, *particularly* in situations where gravity constitutes the dominate driving force.

Rock Load Classification Method (by Terzaghi)

The clear and concise definitions and the practical comments included in these descriptions are good examples of the type of engineering geology information, which is *most useful* for engineering design.

Terzaghi's descriptions

- **Intact** rock contains neither joints nor hair cracks. On account of the injury to the rock *due to blasting*, spalls may drop off the roof several hours or days after blasting. This is known as a spalling condition (breaking into smaller pieces; breaking off in fragments). Hard, intact rock may also be encountered in the popping condition involving the spontaneous and violent detachment of rock slabs from the sides or roof.

Terzaghi's descriptions

- **Stratified** rock consists of individual strata with little or no resistance against separation along the boundaries between the strata. The strata may or may not be weakened by transverse joints. In such rock the spalling conditions is quite common.

Stratified rock

Terzaghi's descriptions

- **Moderately jointed** rock contains joints and hair cracks, *but* the blocks between joints are locally grown together or *so intimately interlocked* that vertical walls do not require lateral support. In rocks of this type, *both* spalling and popping conditions may be encountered.

Moderately jointed rock

Terzaghi's descriptions

- **Blocky and seamy** rock consists of chemically intact or almost intact rock fragments which are entirely separated from each other and imperfectly interlocked. In such rock, vertical walls may require lateral support.

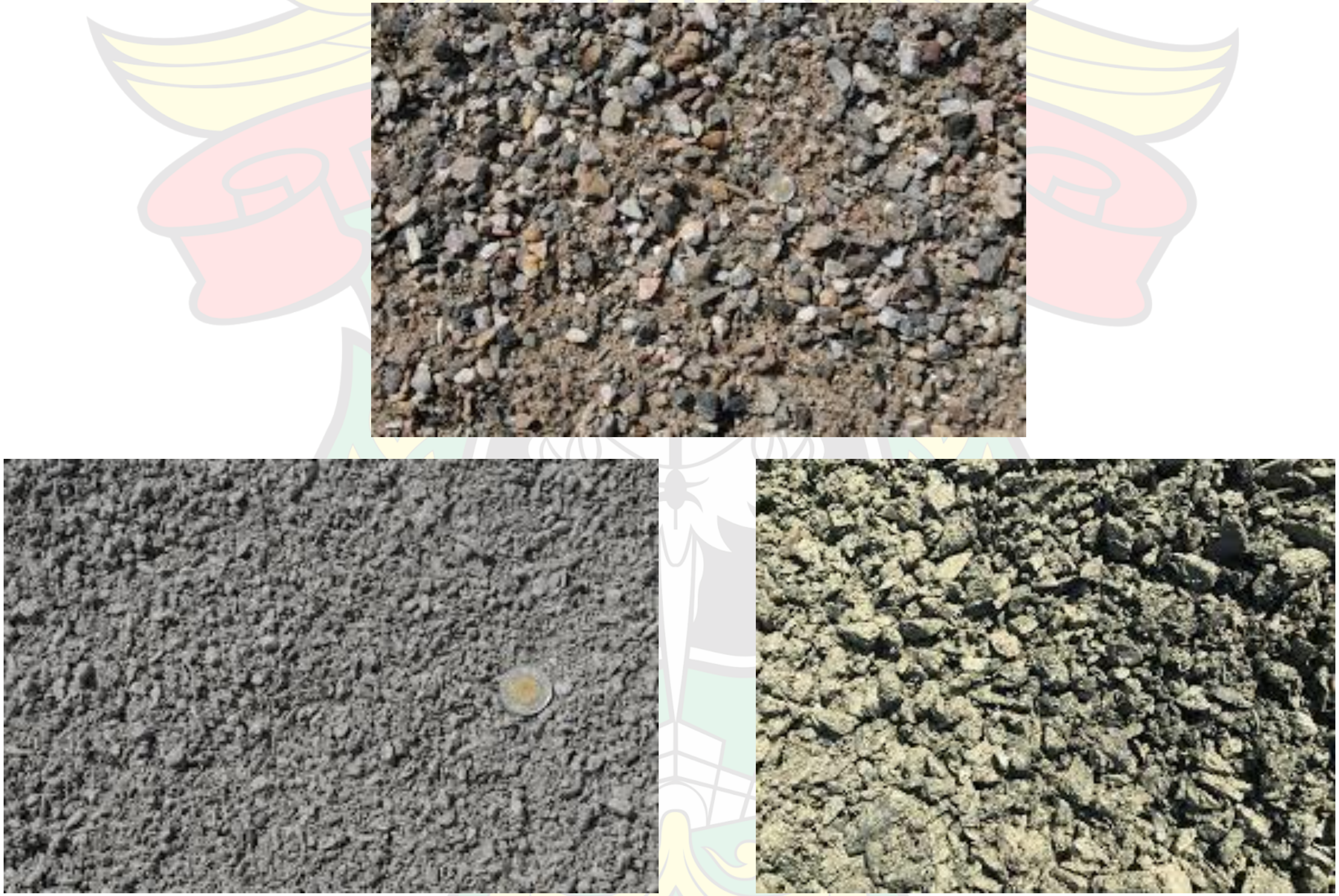
Blocky and seamy rock

Blocky and seamy rock

Terzaghi’s descriptions

- **Crushed** but chemically intact rock has the character of crusher run. If most or all of the fragments are as small as fine sand grains and no recementation has taken place, crushed rock below the water table exhibits the properties of a water-bearing sand.

Crushed rock



Terzaghi’s descriptions

- **Squeezing** rock slowly advances into the tunnel without perceptible volume increase. A prerequisite for squeeze is high percentage of microscopic and sub-microscopic particles of micaceous minerals or clay minerals with a low swelling capacity.

Squeezing rock

a)

No-squeezing

Squeezing

b)

c)

No squeezing

Low squeezing; bolts take load

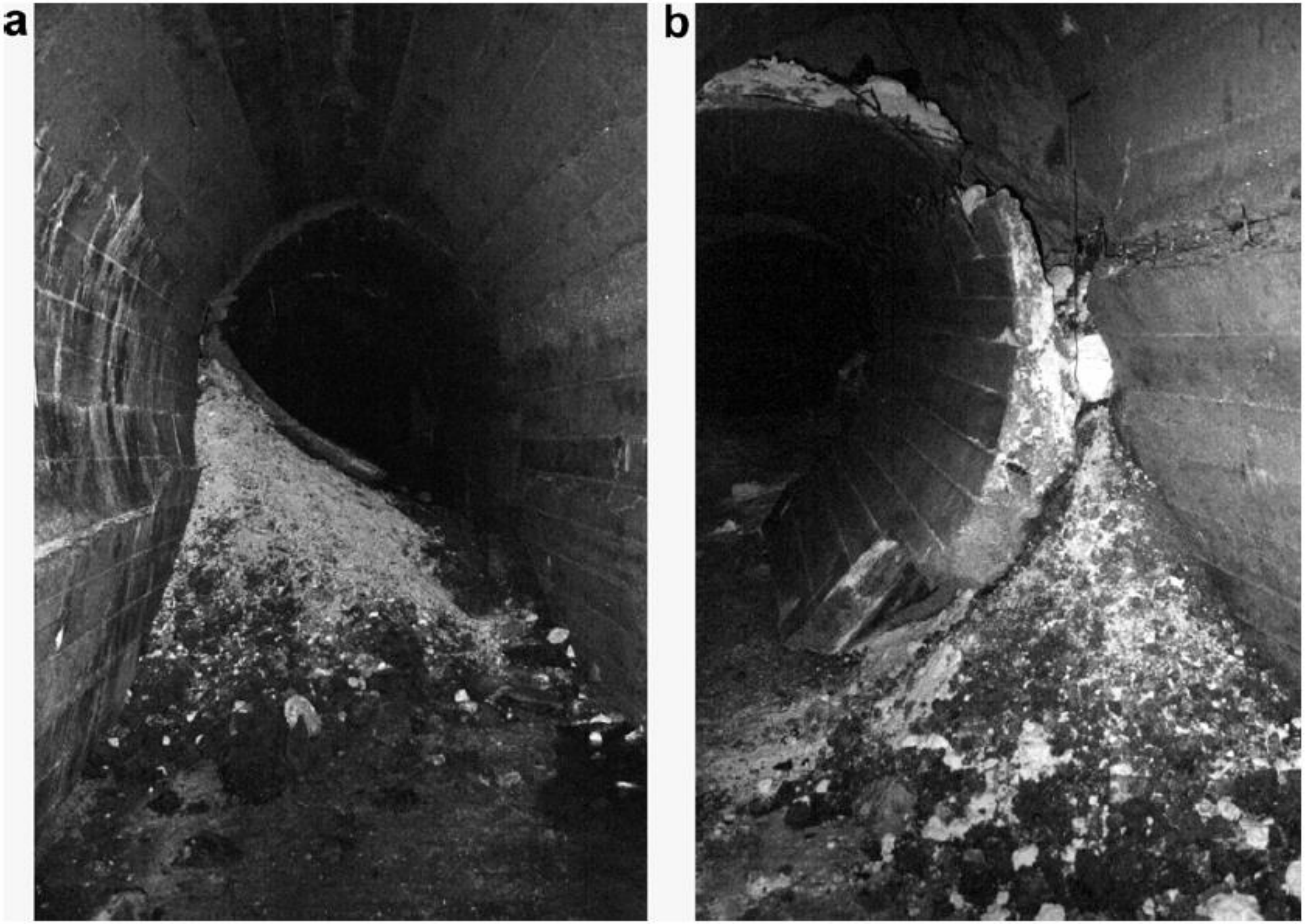
Moderate squeezing; convergence

Extreme squeezing

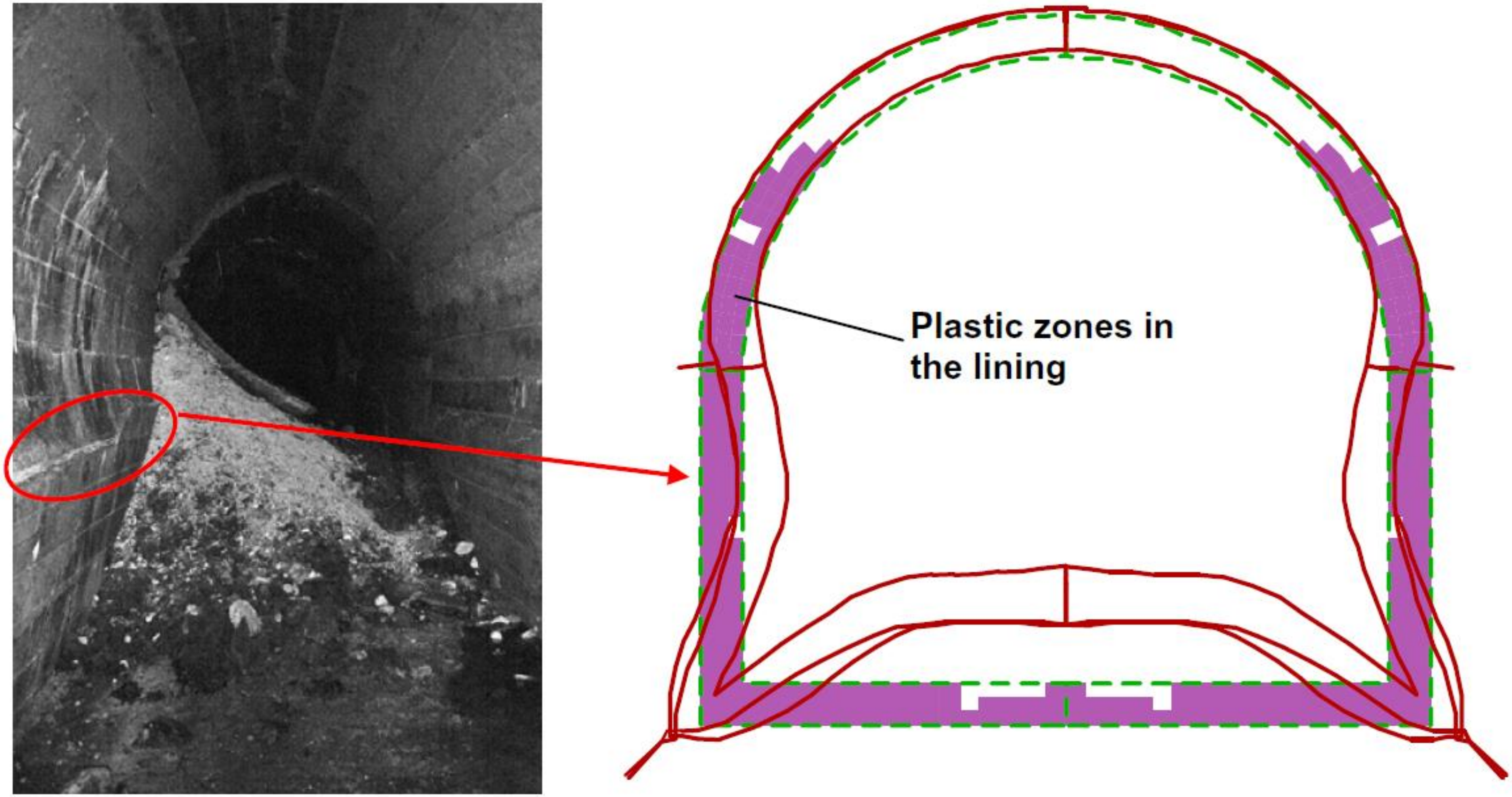
Terzaghi’s descriptions

- **Swelling** rock advances into the tunnel chiefly on account of expansion. The capacity to swell seems to be limited to those rock that contain clay minerals such as montmorillonite, with a high swelling capacity.

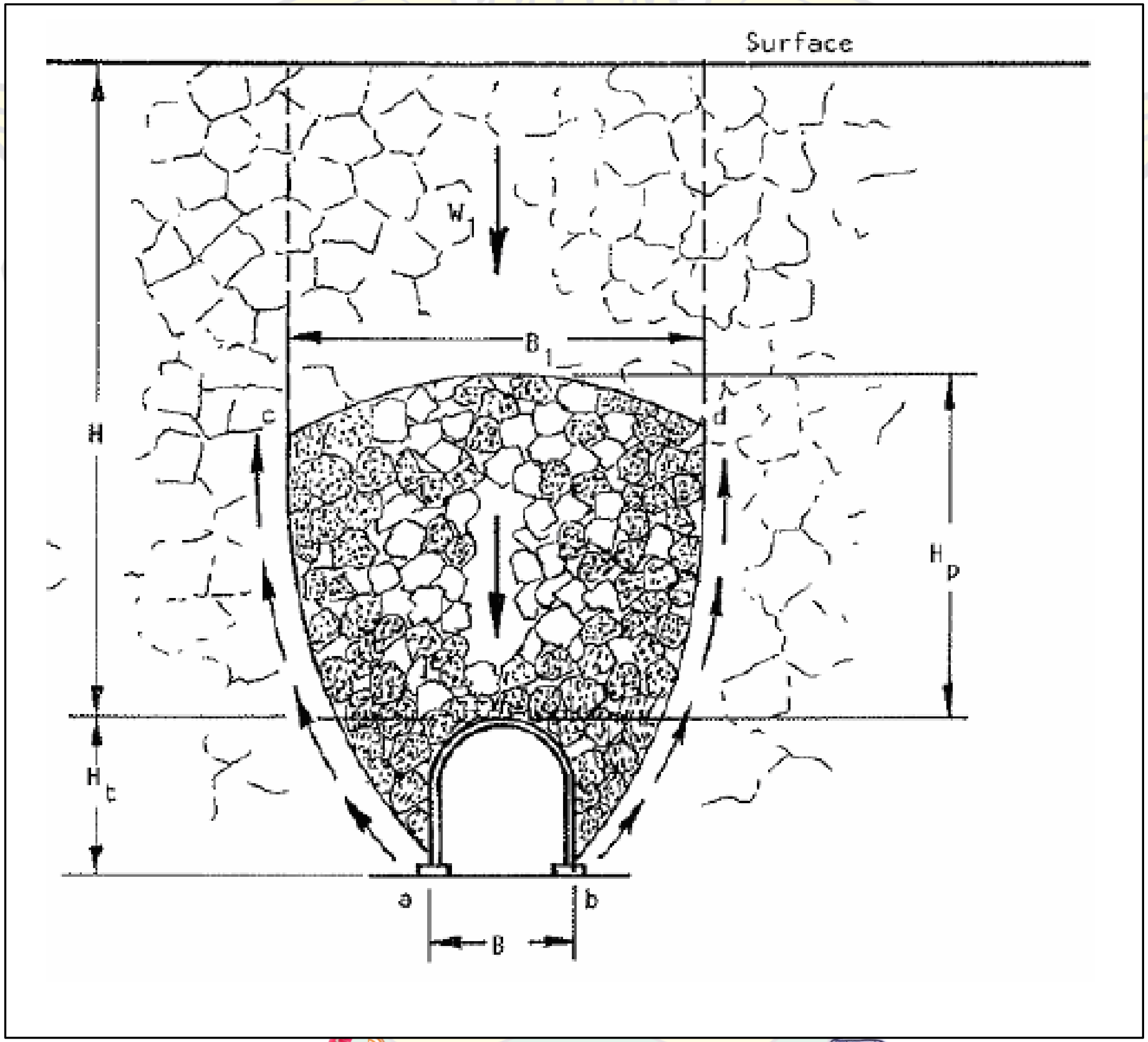
Swelling rock



Swelling rock (Barla, 2007)



Rock Load Classification Method (by Terzaghi)



Generalized Rock Load Classification Method (by Terzaghi)

Rock conditions	Rock load, H_p (ft)
1. Hard and intact	Zero
2. Hard stratified or schistose	0 – 0.5B
3. Massive, moderately jointed	0 – 0.25B
4. Moderately blocky and seamy	0.25B – 0.20 $(B+H_t)$
5. Very blocky and seamy	(0.20 – 0.60) $(B+H_t)$
6. Completely crushed but chemically intact	(0.60 – 1.10) $(B+H_t)$
6a. Sand and gravel	(1.10 – 1.40) $(B+H_t)$
7. Squeezing rock, moderate depth	(1.10 – 2.10) $(B+H_t)$
8. Squeezing rock, great depth	(2.10 – 4.50) $(B+H_t)$
9. Swelling rock	Up to 250 ft
B = Tunnel width (ft), H_t = Tunnel height (ft)	

Stand-Up Time Classification (by Lauffer-Pacher)

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Stand-Up Time Classification (by Lauffer-Pacher)

Lauffer (1958) proposed that the stand-up time for an unsupported span is *related to* the quality of the rock mass in which the span is excavated.

In a tunnel, the active unsupported span is defined as the span of the tunnel or the distance between the face and the nearest support, if this is greater than the tunnel span.

Stand-Up Time Classification (by Lauffer-Pacher)

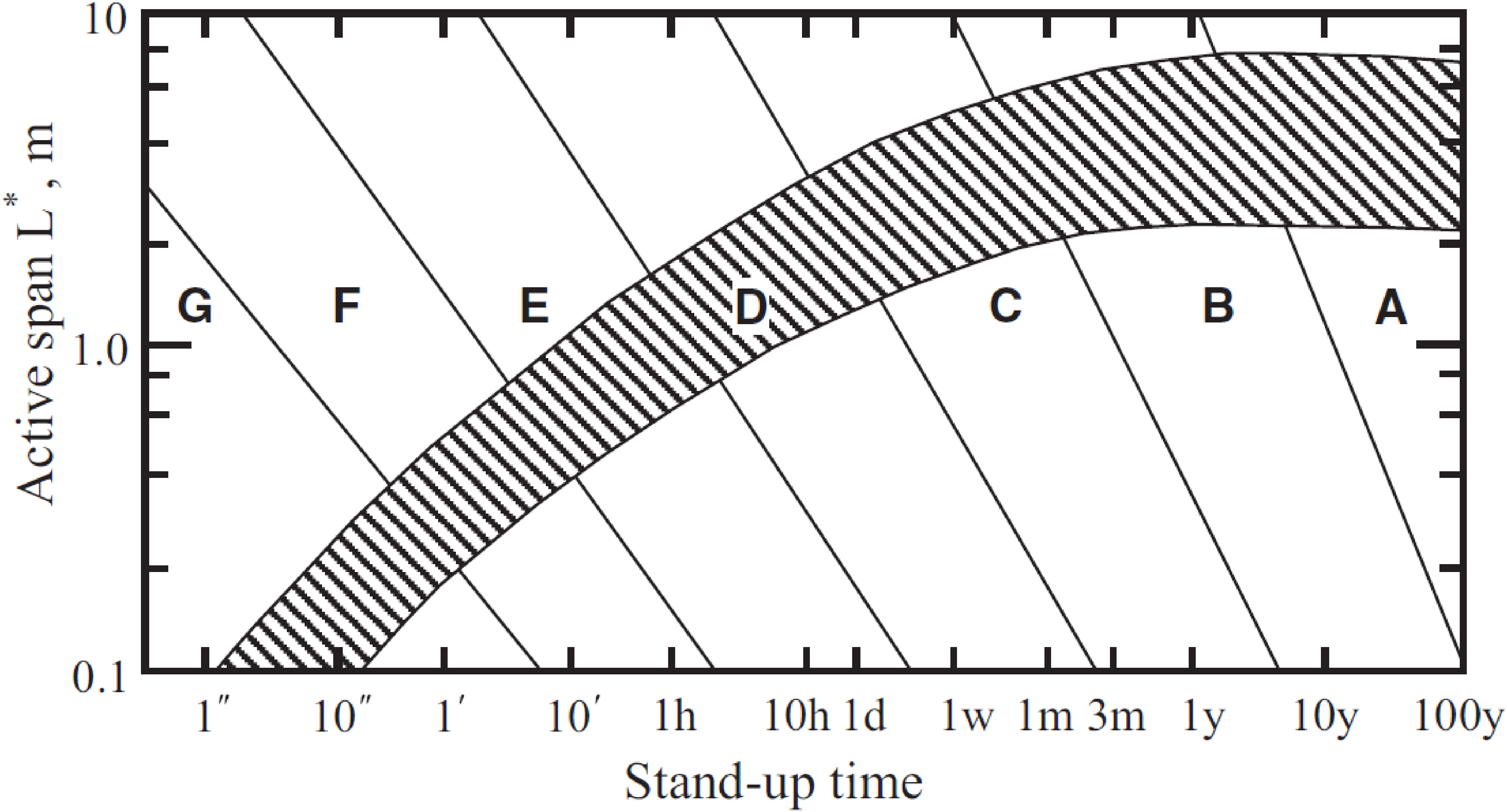
The stand-up time is the period of time that a tunnel will stand unsupported after excavation. Lauffer's original classification has since been modified by a number of authors, notably Pacher et al (1974), and now forms part of the general tunneling approach known as **the New Austrian Tunnelling Method (NATM)**.

(Please find more about NATM in the book of Engineering Rock Mass Classification Ch. 8 by Goel, R.K. and Singh, B.)

Stand-Up Time Classification (by Lauffer-Pacher)

The significance of the stand-up time concept is that an increase in the span of the tunnel *leads to* a significant reduction in the time available for the installation of support. This classification introduced the stand-up time and the span as relevant parameters in determining the type and amount of tunnel support, and it has influenced the development of more recent rock mass classification systems.

Active Span Versus Stand-Up Time for Different Classes of Rock Mass (Lauffer, 1958). A – Best Rock Mass; G – Worst Rock Mass. Shaded area indicates the practical range.

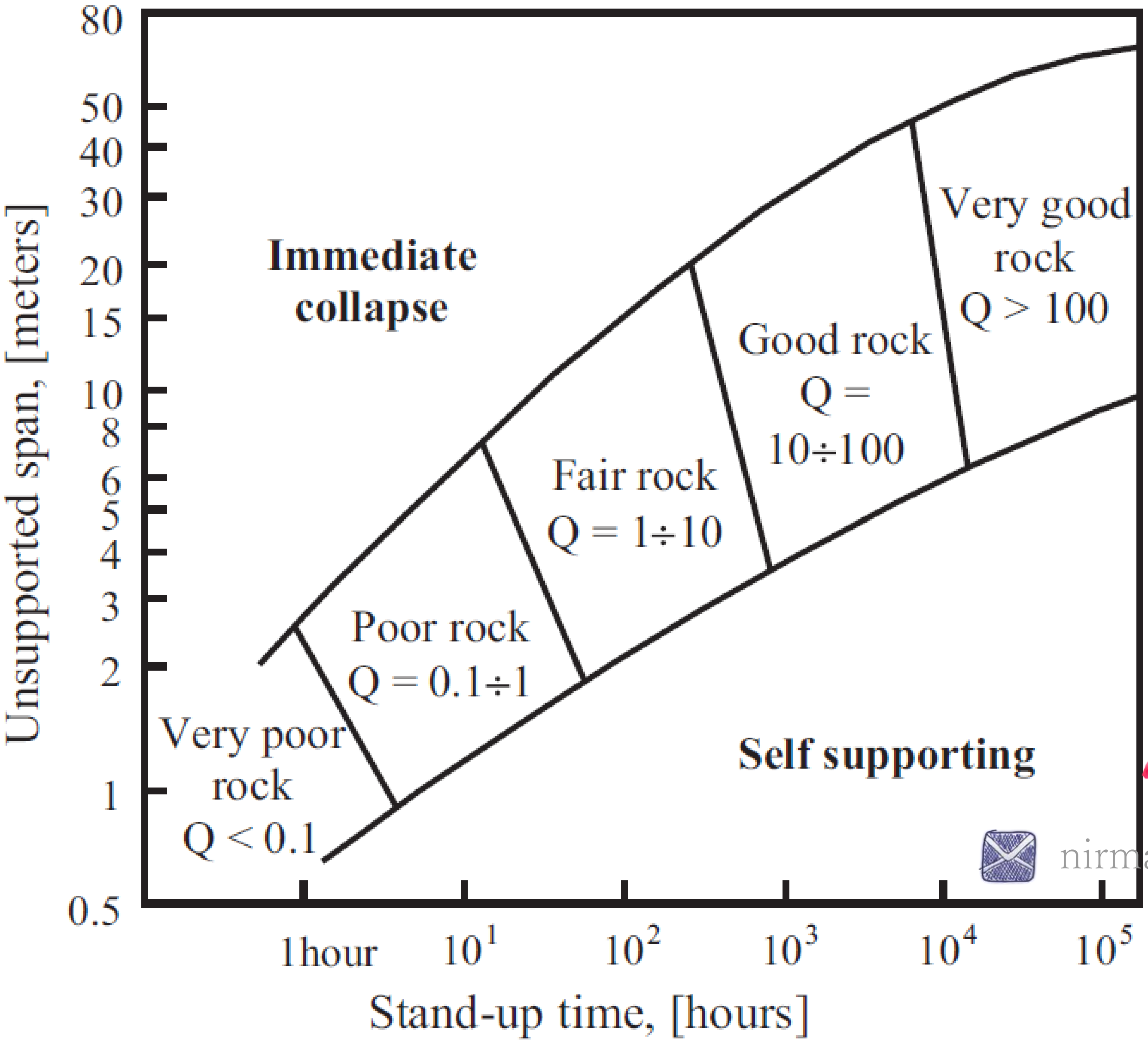


Active Span Versus Stand-Up Time for Different Classes of Rock Mass (Lauffer, 1958). A – Best Rock Mass; G – Worst Rock Mass. Shaded area indicates the practical range.

In previous figure, the letters refer to the rock class corresponding to *Terzaghi's classification*.

A : Intact rock
B : Stratified rock
C : Moderately jointed rock
D : Blocky and seamy rock
E : Crushed rock
F : Squeezing rock
G : Swelling rock

Stand-Up Time and Rock Mass Classification (Q-System) with Unsupported Span (Barton et al., 1975)



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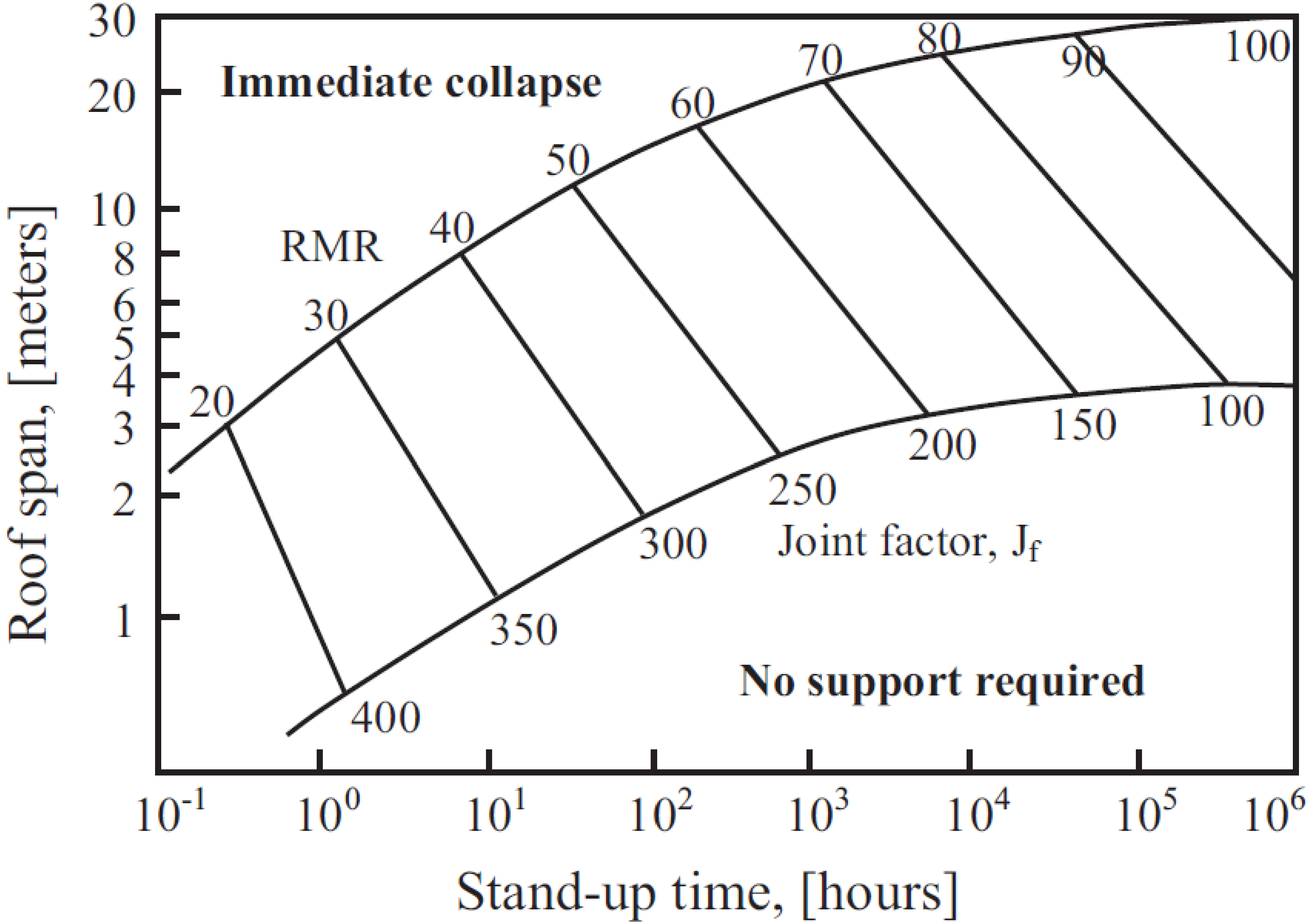
Stand-Up Time and Rock Mass Classification (RMR-System) with Roof Span (Bieniawski, 1993)

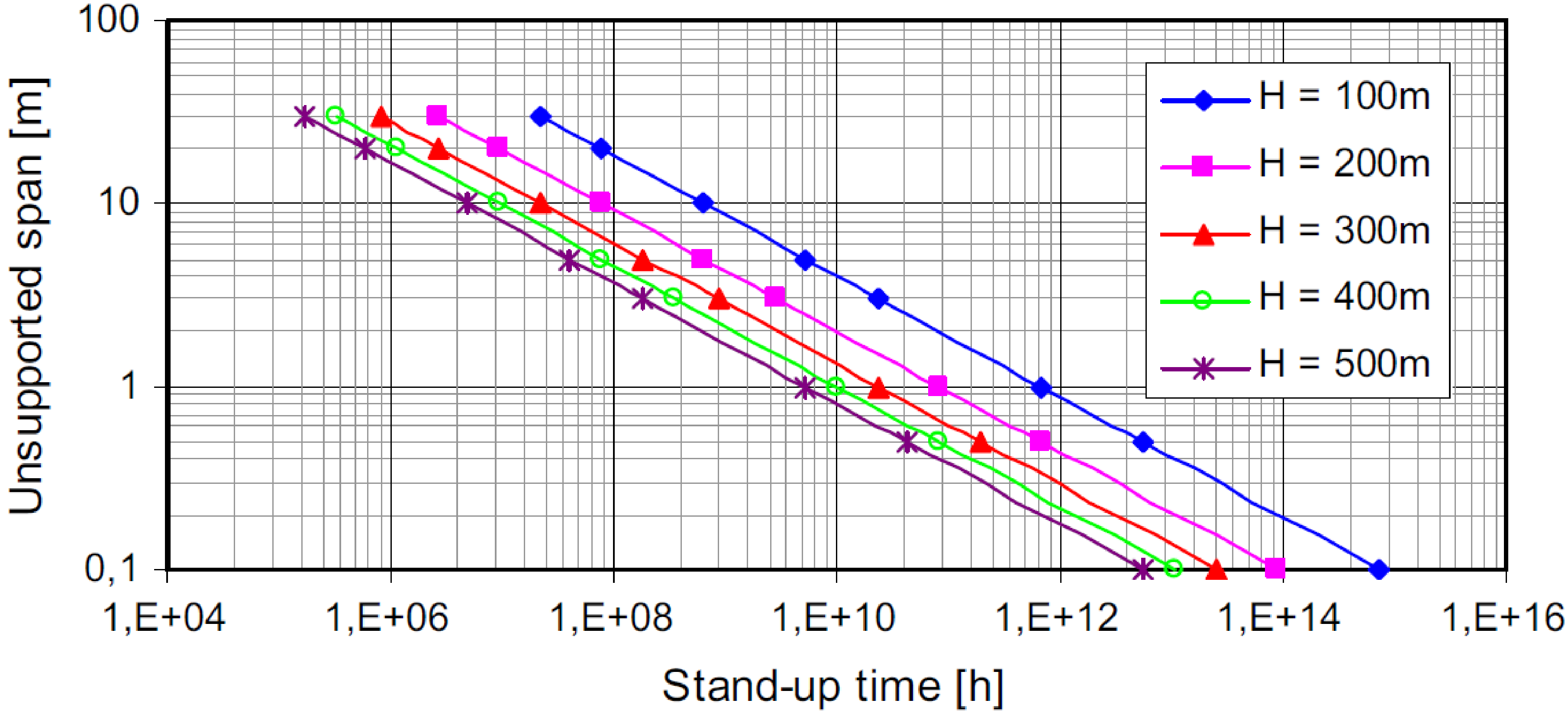


Stand-Up Time Classification (by Lauffer-Pacher)

Analytical solution for estimating the stand-up time of the rock mass surrounding tunnel (Nguyen, 2015)

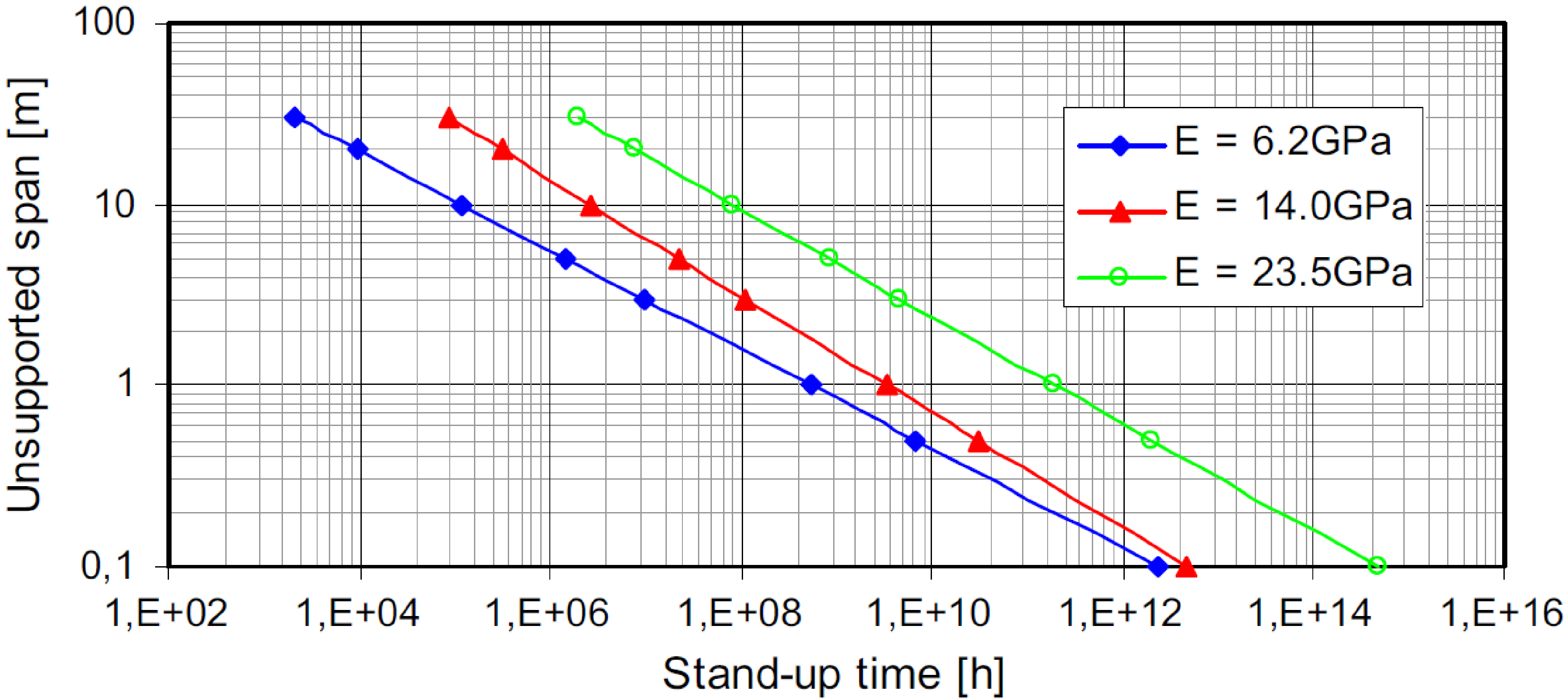
The Stand-Up Time for Different Tunnel Depths

(Nguyen, 2015)



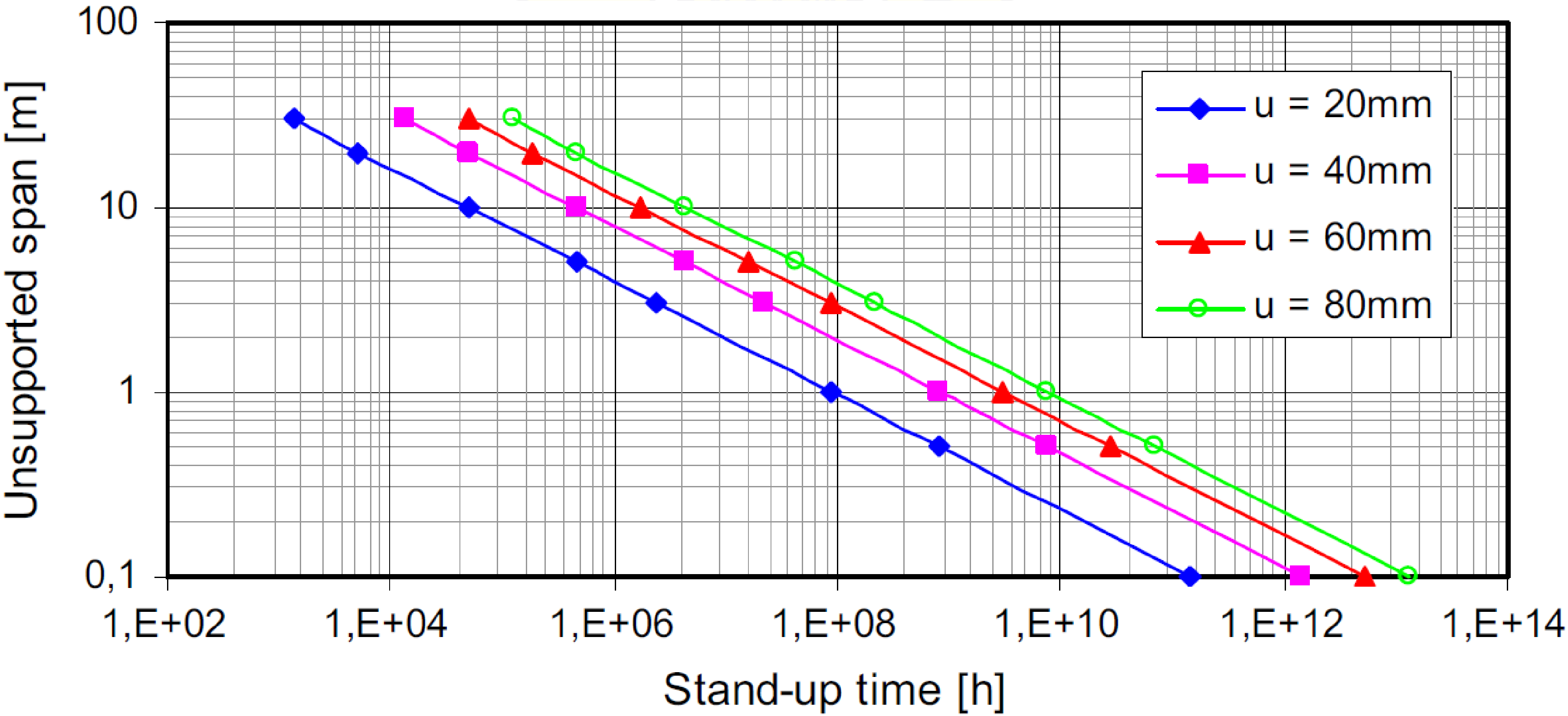
The Stand-Up Time for Different Rock Mass Qualities (Young's Modulus)

(Nguyen, 2015)



The Stand-Up Time for Different Critical Displacements

(Nguyen, 2015)



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Rock Quality Designation, RQD Index (by Deere)

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RQD Index (by Deere)

The Rock Quality Designation index (RQD) was developed by Deere (Deere et al 1967) to provide a quantitative estimate of rock mass quality from drill core logs. **RQD** is defined as the percentage of intact core pieces longer than 100 mm (4 inches) in the total length of core.

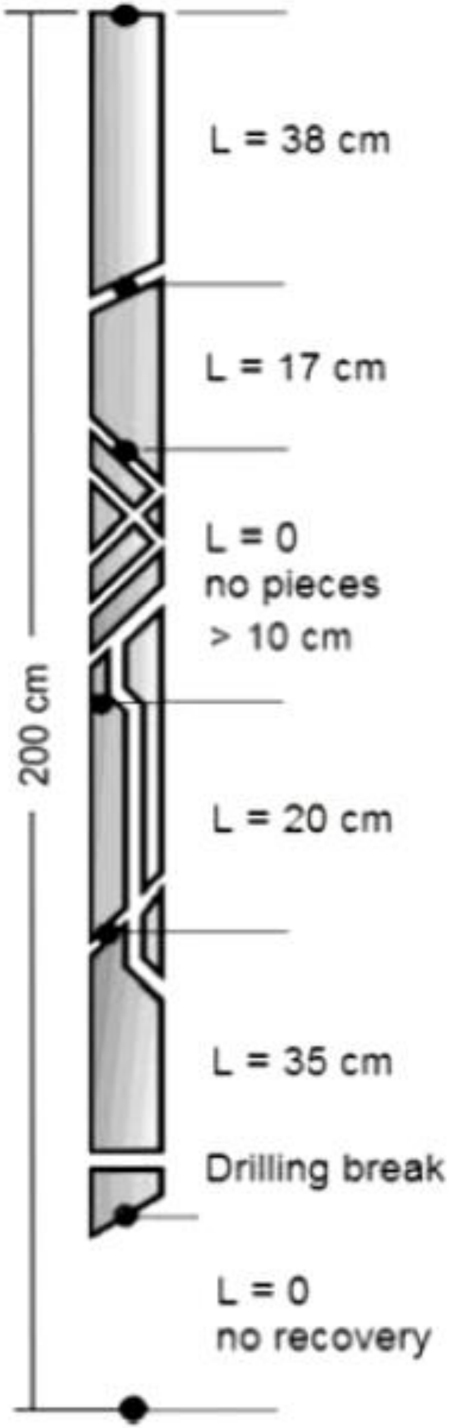
RQD Index (by Deere)

This quantitative index has been widely used as a red flag to identify low-quality rock zones which deserve greater scrutiny and which may require additional borings or other exploratory work.

RQD Index (by Deere)

For RQD determination, the International Society for Rock Mechanics (ISRM) recommends a core size. The core *should be at least* **NX size (54.7 mm or 2.15 inches in diameter)** and should be drilled with a double-tube core barrel.

Procedure for Measurement and Calculation of RQD (After Deere, 1989)



$$\text{RDQ} = \frac{\Sigma\text{Core pieces} > 10\text{ cm}}{\text{Total length of core run}} \times 100$$

$$\text{RDQ} = \frac{38 + 17 + 20 + 35}{200} = 55\ \%$$

RQD Index (by Deere)

The following relationship between the RQD index and the engineering quality of the rock was proposed by Deere (1968).

RQD (%)	Rock Quality
<25	Very poor
25-50	Poor
50-75	Fair
75-90	Good
90-100	Excellent

RQD Index (by Deere)

Palmstrom (1982) suggested that, *when no core is available* but discontinuity traces are visible in surface exposures or exploration adits, the RQD may be estimated from the number of discontinuities per unit volume.

RQD Index (by Deere)

The suggested relationship for clay-free rock masses is:

$$RQD = 115 - 3.3J_v$$

where J_v is the sum of the number of joints per unit length for all joint (discontinuity) sets known as the volumetric joint count.

RQD Index (by Deere)

RQD is a *directionally dependent* parameter and its value may change significantly, <u>depending upon the borehole orientation</u>. The use of the volumetric joint count can be quite useful in reducing this directional dependence.

RQD Index (by Deere)

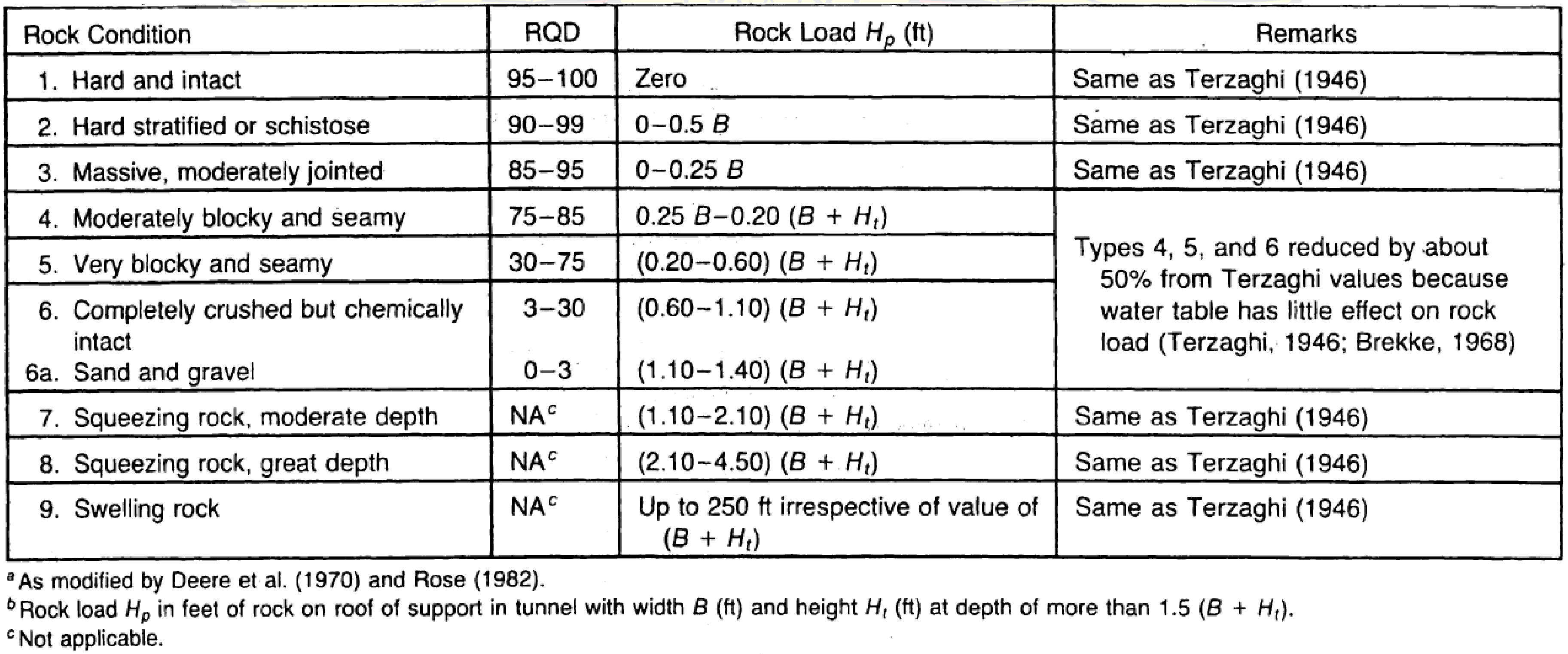
RQD is intended to represent the rock mass quality in situ. When using diamond drill core, care must be taken to ensure that fractures, which have been caused by handling or the drilling process, are identified and ignored when determining the value of RQD.

When using **Palmstrom's relationship** for exposure mapping, blast induced fractures should not be included when estimating J_v.

RQD Index (by Deere)

Cording and Deere (1972) attempted to relate the RQD index to Terzaghi’s rock load factors and presented tables relating tunnel support and RQD. They found that Terzaghi’s rock load concept should be limited to tunnels supported by steel sets, as it does not apply well to openings supported by rock bolts.

Relationship Between RQD and Terzaghi's Rock Load Factors



Rock Condition	RQD	Rock Load H_p (ft)	Remarks
1. Hard and intact	95–100	Zero	Same as Terzaghi (1946)
2. Hard stratified or schistose	90–99	0–0.5 B	Same as Terzaghi (1946)
3. Massive, moderately jointed	85–95	0–0.25 B	Same as Terzaghi (1946)
4. Moderately blocky and seamy	75–85	0.25 B–0.20 $(B + H_t)$	Types 4, 5, and 6 reduced by about 50% from Terzaghi values because water table has little effect on rock load (Terzaghi, 1946; Brekke, 1968)
5. Very blocky and seamy	30–75	(0.20–0.60) $(B + H_t)$	
6. Completely crushed but chemically intact	3–30	(0.60–1.10) $(B + H_t)$	
6a. Sand and gravel	0–3	(1.10–1.40) $(B + H_t)$	
7. Squeezing rock, moderate depth	NA[c]	(1.10–2.10) $(B + H_t)$	Same as Terzaghi (1946)
8. Squeezing rock, great depth	NA[c]	(2.10–4.50) $(B + H_t)$	Same as Terzaghi (1946)
9. Swelling rock	NA[c]	Up to 250 ft irrespective of value of $(B + H_t)$	Same as Terzaghi (1946)

[a] As modified by Deere et al. (1970) and Rose (1982).

[b] Rock load H_p in feet of rock on roof of support in tunnel with width B (ft) and height H_t (ft) at depth of more than 1.5 $(B + H_t)$.

[c] Not applicable.

RQD Index (by Deere)

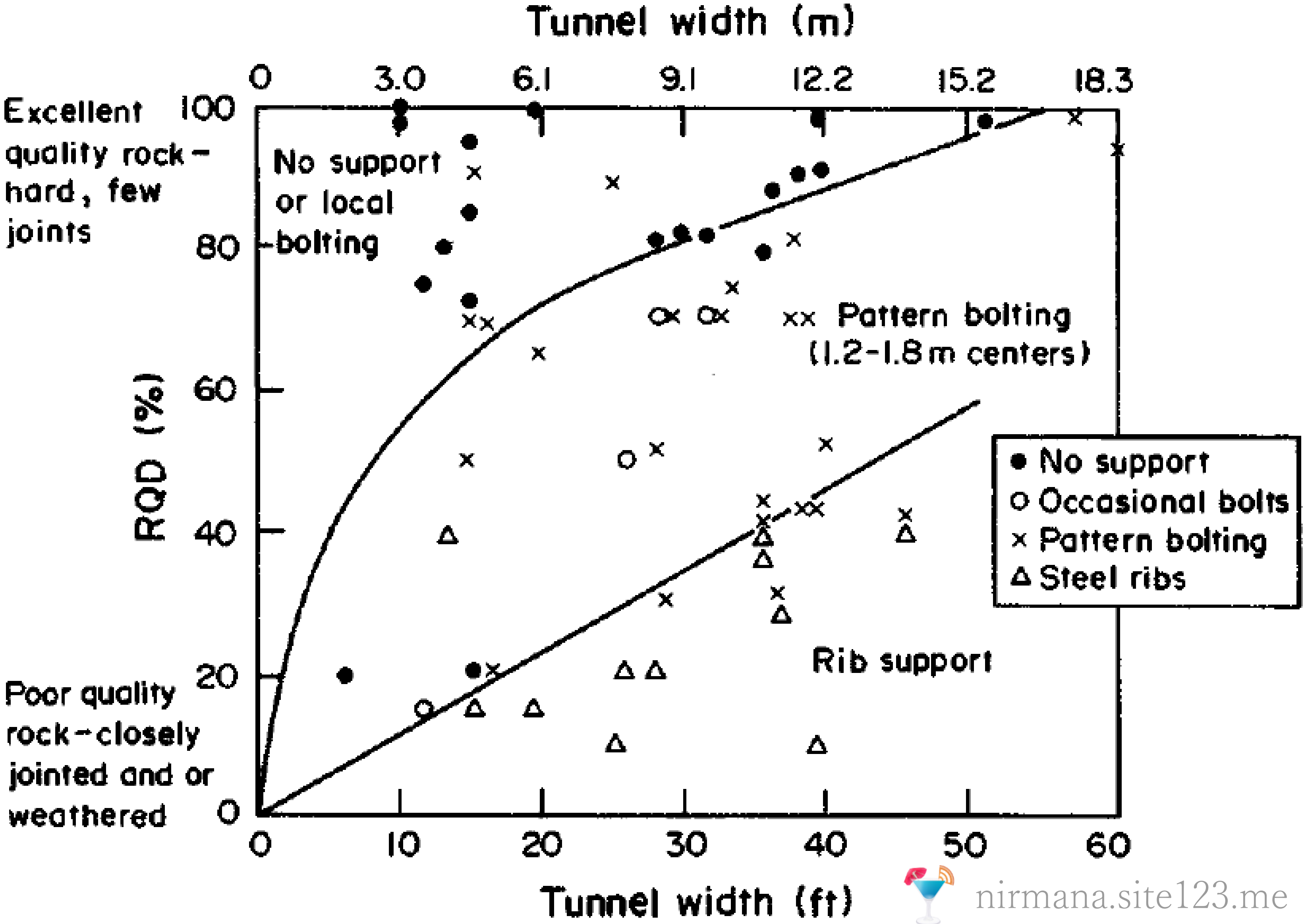
Merritt (1972) found that the **RQD** could be of <u>considerable value in estimating support requirements for rock tunnels</u>. He compared the support criteria based on his improved version, as a function of tunnel width and RQD, with those proposed by others.

Comparison of RQD and Support Requirements for a 6-m-Wide Tunnel[a]

	No Support or Local Bolts	Pattern Bolts	Steel Ribs
Deere et al. (1970)	RQD 75–100	RQD 50–75 (1.5–1.8-m spacing) RQD 25–50 (0.9–1.5-m spacing)	RQD 50–75 (light ribs on 1.5–1.8-m spacing as alternative to bolts) RQD 25–50 (light to medium ribs on 0.9–1.5-m spacing as alternative to bolts) RQD 0–25 (medium to heavy circular ribs on 0.6–0.9-m spacing)
Cecil (1970)	RQD 82–100	RQD 52–82 (alternatively, 40–60-mm shotcrete)	RQD 0–52 (ribs or reinforced shotcrete)
Merritt (1972)	RQD 72–100	RQD 23–72 (1.2–1.8-m spacing)	RQD 0–23

[a] Data interpolated from Merritt (1972) by Deere and Deere (1988).

Support Recommendations Based on RQD (After Merritt)



RQD Index (by Deere)

Although Merritt felt that the RQD could be of great value in estimating support requirements, he pointed out a serious **limitation** of his proposals:

“The RQD support criteria system has limitations in areas where the joints contain thin clay fillings or weathered material. Such a case might occur in near surface rock where weathering or seepage has produced clay which reduces the frictional resistance along joint boundaries. This would result in unstable rock although the joints may be widely spaced and the RQD high.”

RQD Index (by Deere)

Although the RQD is a simple and inexpensive index, alone it is not sufficient to provide an adequate description of a rock mass because it disregards joint orientation, tightness, and gouge (infilling) material. Essentially, it is a practical parameter based on **a measurement of the percentage of 'good' rock (core) interval of a borehole** (Deere and Deere, 1988).

RQD Index (by Deere)

Today, the **RQD** is used as a standard parameter in drill core logging and forms a basic element of the two major rock mass classification systems: **the RMR system and the Q-system**.

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Rock Structure Rating, RSR Concept (by Wickham, Tiedemann, and Skinner)

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RSR Concept

Wickham et al (1972) described a quantitative method for describing the quality of a rock mass and for selecting appropriate support on the basis of their **Rock Structure Rating (RSR) classification**. Historically this system was the first to make reference to shotcrete support. In spite of this limitation, it is worth examining the RSR system in some detail since it demonstrates the logic involved in developing a quasi-quantitative rock mass classification system.

RSR Concept

This concept was **the first complete rock mass classification system proposed** since that introduced by Terzaghi in 1946. The significance of the RSR system, in the context of this discussion, is that <u>it introduced the concept of rating each of the components</u> listed next to arrive at a numerical value of RSR = A + B + C *(maximum RSR = 100)*.

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 A, Geology

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

Parameter B, Geometry

Effect of discontinuity pattern with respect to the direction of the tunnel drive on the basis of:

a. Joint spacing;

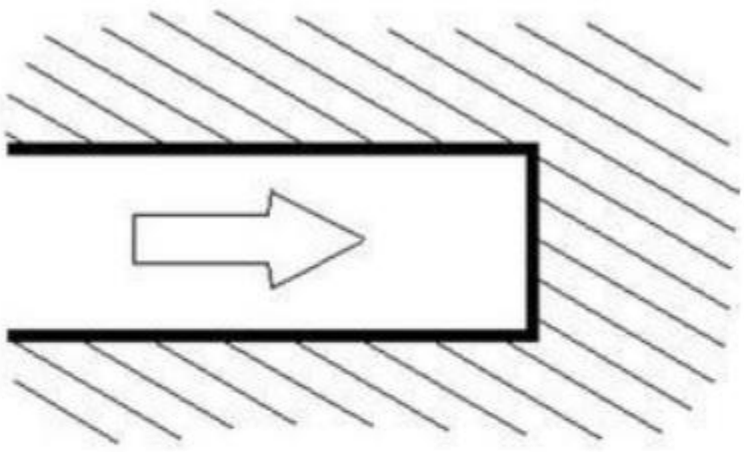
b. Joint orientation (strike and dip);

c. Direction of tunnel drive.

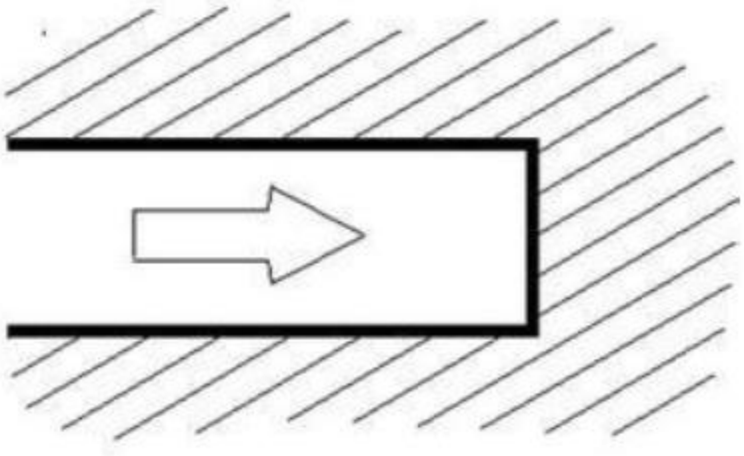
Parameter B, Geometry

	Strike ⊥ to Axis					Strike ǁ 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

Parameter B, Geometry



Drive with dip



Drive against dip

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).

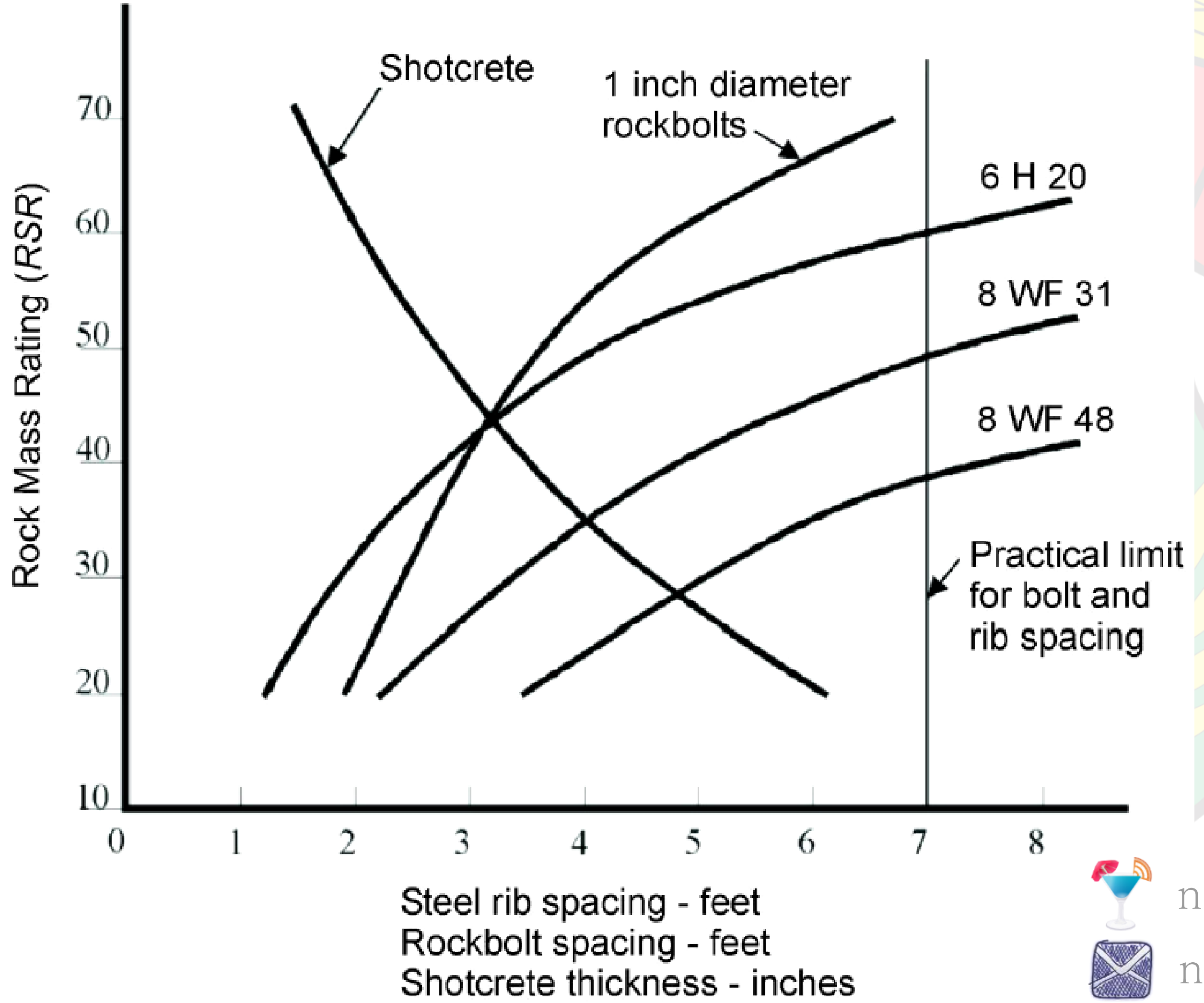
Parameter C

Anticipated water inflow gpm/1000 ft of tunnel	Sum of Parameters $A + B$					
	13 - 44			45 - 75		
	Joint Condition [b]					
	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

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)



RSR Concept

Although the RSR classification system *is not widely used today*, Wickham et al's work played a significant role in the development of the classification schemes.

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Geomechanics Classification (Rock Mass Rating, RMR)

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Geomechanics Classification

Bieniawski (1976) published the details of a rock mass classification called the Geomechanics Classification or the **Rock Mass Rating (RMR)** system. Over the years, this system has been successively refined as more case records have been examined. Bieniawski has made significant changes in the ratings assigned to different parameters. The discussion which follows will be based upon the 1989 version of the classification (**Bieniawski, 1989**).

Parameters of RMR System

- UCS of rock material
- Rock Quality Designation (RQD)
- Spacing of discontinuities
- Condition of discontinuities
- Groundwater conditions
- Orientation of discontinuities

Rock Mass Rating (RMR)

In applying this classification system, the rock mass is divided into a number of structural regions and each region is classified separately. The boundaries of the structural regions *usually coincide with a major structural feature* such as a fault or with a change in rock type.

Rock Mass Rating (RMR)

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.

RMR System: Classification Parameters and Their Ratings

Parameter			Range of Values						
1	Strength of intact rock material	PLI	> 10 MPa	4 – 10 MPa	2 – 4 MPa	1 – 2 MPa	For this low range - UCS test is preferred		
		UCS	> 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	Slightly rough surfaces Separation < 1 mm Slightly weathered walls	Slightly rough surfaces Separation < 1 mm Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge >5 mm thick or Separation > 5 mm Continuous		
	Rating		30	25	20	10	0		
5	Ground water	Inflow per 10 m tunnel length (l/m)	None	< 10	10 - 25	25 - 125	➢125		
		(Joint water press)/ (Major principal σ)	0	< 0.1	0.1 – 0.2	0.2 – 0.5	> 0.5		
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing		
	Rating		15	10	7	4	0		

RMR System:
6. Rating Adjustment for Discontinuity Orientation

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	-60

RMR System: Effect of Discontinuity Strike and Dip Orientation in Tunnelling

Strike perpendicular to tunnel axis		Strike parallel to tunnel axis	
Drive with dip – Dip 45-90°	Drive with dip – Dip 20-45°	Dip 45-90°	Dip 20-45°
Very favourable	*Favourable*	*Very unfavourable*	*Fair*
Drive against dip – Dip 45-90°	Drive against dip – Dip 20-45°	Dip 0-20°-Irrespective of strike	
Fair	*Unfavourable*	*Fair*	

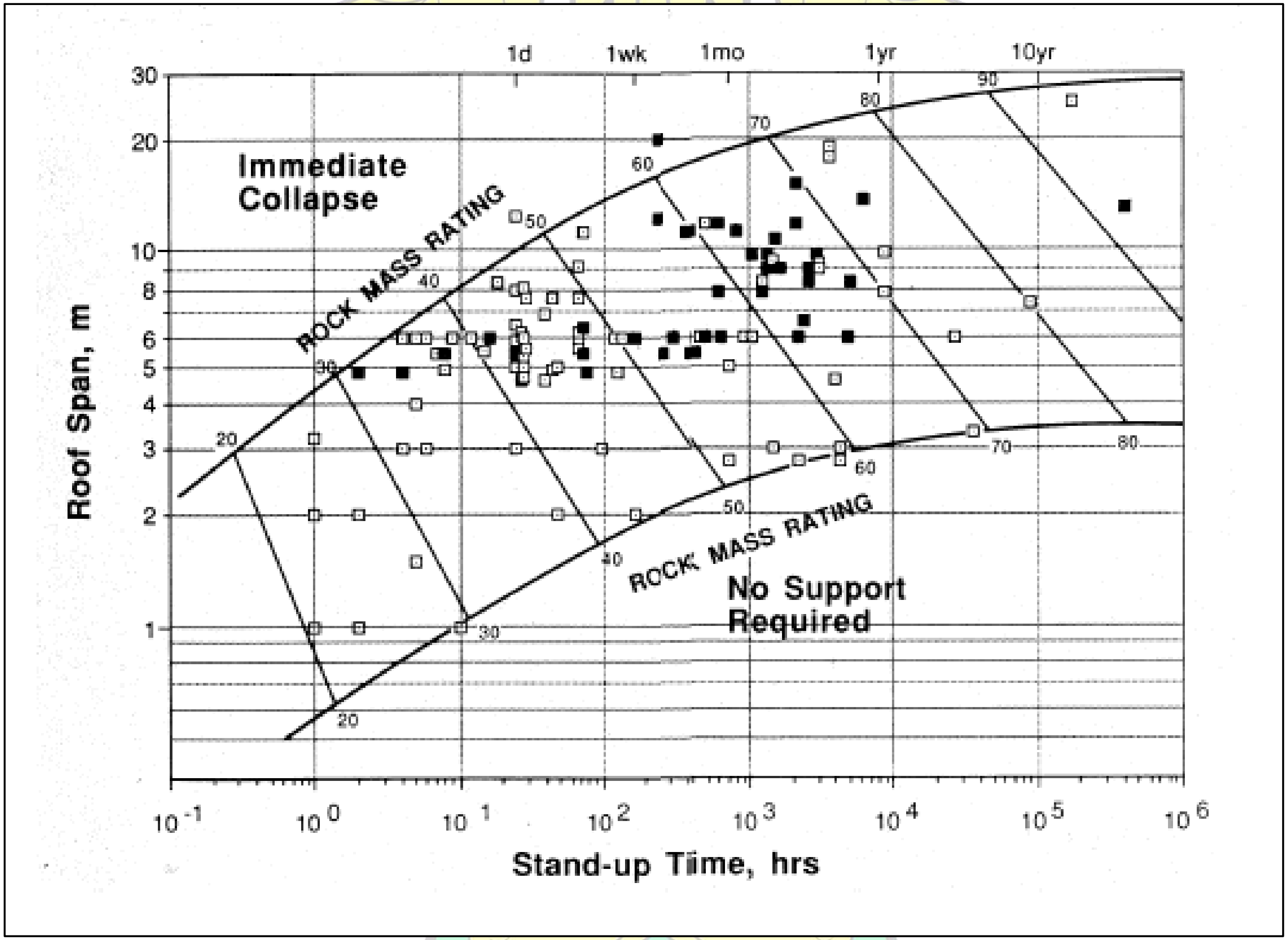
RMR System: Guidelines for Classification of Discontinuity Conditions

Discontinuity length (persistence)	< 1 m	1 – 3 m	3 – 10 m	10 – 20 m	> 20 m
	6	4	2	1	0
Separation (aperture)	None	< 0.1 mm	0.1 – 1.0 mm	1 – 5 mm	> 5 mm
	6	5	4	1	0
Roughness	Very rough	Rough	Slightly rough	Smooth	Slickensided
	6	5	3	1	0
Infilling (gouge)	None	Hard filling < 5 mm	Hard filling > 5 mm	Soft filling < 5 mm	Soft filling > 5 mm
	6	4	2	2	0
Weathering	Unweathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed
	6	5	3	1	0

RMR System: Meaning of Rock Classes

	Ratings				
	81 – 100	61 – 80	41 – 60	21 – 40	< 21
Class number	I	II	III	IV	V
Description	Very good rock	Good rock	Moderate rock	Poor rock	Very poor rock
Average stand-up time	20 yrs for 15 m span	1 year for 10 m span	1 week for 5 m span	10 hrs for 2.5 m span	30 min for 1 m span
Cohesion of rock mass (kPa)	> 400	300 – 400	200 – 300	100 – 200	< 100
Friction angle of rock mass (deg)	> 45	35 – 45	25 – 35	15 – 25	< 15

RMR System: Roof Span Vs Stand-Up Time



Rock Mass Rating (RMR)

Bieniawski (1989) published a set of guidelines for the selection of support in tunnels in rock for which the value of RMR has been determined (see the next table). **Note that these guidelines** have been published for a 10 m span horseshoe shaped tunnel, constructed using drill and blast methods, in a rock mass subjected to a vertical stress <25 MPa (equivalent to a depth below surface of <900 m).

RMR System: Excavation and Support (10 m span rock tunnels)

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.			
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: < 21	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..

Rock Mass Rating (RMR)

Support load can be determined from the RMR system as proposed by Unal (1983):

$$P = \frac{100 - RMR}{100} \gamma B$$

where P = the support load, kN;

B = the tunnel width, m;

γ = the rock density, kg/m^3.

Rock Mass Rating (RMR)

- A great deal of engineering judgement is needed in the application of **rock mass classification** to support design.
- It should be noted that a set of guidelines for the selection of support in tunnels has not had a major revision since 1973. In many mining and civil engineering applications, **steel fibre reinforced shotcrete** may be considered in place of wire mesh and shotcrete.

Rock Mass Rating (RMR)

- ☐ Finally, note that the ranges on *slide 105* follow the recommendations of the International Society of Rock Mechanics (ISRM) Commissions on Standardization and on Classification. The interest reader is referred to a document entitled *Suggested Methods for Quantitative Description of Discontinuities in Rock Masses* (ISRM, 1982).

Suggested methods for the quantitative description (Barton-ISRM, 1978)

1. Orientation
2. Spacing
3. Persistence
4. Roughness
5. Wall strength
6. Aperture
7. Filling
8. Seepage
9. Number of sets
10. Block size
11. Drill core

READ MORE

Rock Mass Rating (RMR)

EXERCISE

A tunnel is to be driven through slightly weathered granite with a dominant joint set dipping at 60° against the direction of the drive. Index testing and logging of diamond drilled core give typical Point-load strength index values of 8 MPa and average RQD values of 70%. The slightly rough and slightly weathered joints with a separation of <1mm, are spaced at 300 mm. Tunneling conditions are anticipated to be wet.

Try to determine the RMR value.

Modifications to RMR for Mining

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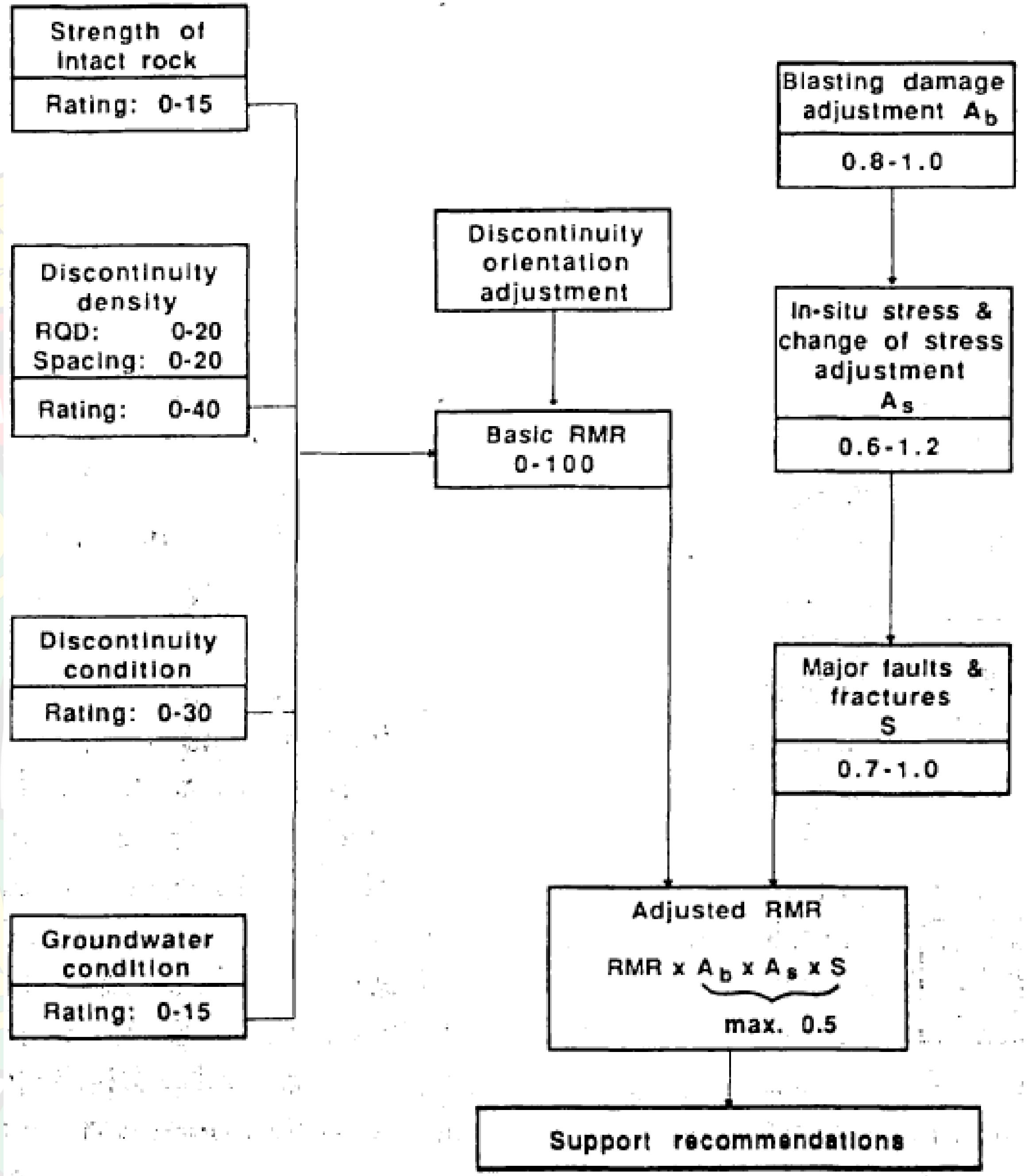
Modifications to RMR for Mining

Bieniawski's Rock Mass Rating (RMR) system was *originally* based upon case histories drawn from civil engineering. Consequently, the mining industry tended to regard the classification as somewhat conservative and several modifications have been proposed in order to make the classification more relevant to mining applications. A comprehensive summary of these modifications was compiled by Bieniawski (1989).

Modified Rock Mass Rating (MRMR)

Laubscher (1977, 1984), Laubscher and Taylor (1976), and Laubscher and Page (1990) have described a **Modified Rock Mass Rating** system for mining. This MRMR system takes the basic RMR value, as defined by Bieniawski, and *adjust it* to account for in situ and induced stresses, stress changes, and the effects of blasting and weathering. A set of support recommendations is associated with the resulting MRMR value.

Adjustments to The RMR System for Mining Applications



Modified Rock Mass Rating (MRMR)

In using Laubscher's MRMR system it should be borne in mind that many of the case histories upon which it is based are derived from caving operations. Originally, block caving in asbestos mines in Africa formed the basis for the modifications but, subsequently, other case histories from around the world have been added to the database.

Modified Basic Rock Mass Rating (MBR)

Cummings et al (1982) and Kendorski et al (1983) have also modified Bieniawski's RMR classification to produce the **Modified Basic RMR (MBR)** system for mining. This system was developed for block caving operations in the USA.

Modified Basic Rock Mass Rating (MBR)

It involves the use of different ratings for the original parameters used to determine the value of RMR and the subsequent adjustment of the resulting MBR value to allow for blast damage, induced stresses, structural features, distance from the cave front, and size of the caving block. Support recommendations are presented for isolated or development drifts as well as for the final support of intersections and drifts.

Rock Tunnelling Quality Index (Q)

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Q-System

On the basis of an evaluation of a large number of case histories of underground excavations, **Barton et al (1974)** of the Norwegian Geotechnical Institute proposed a Tunnelling Quality Index (Q) for the determination of rock mass characteristics and tunnel support requirements.

Q-System

The numerical value of the index Q varies on a logarithmic scale from 0.001 to a maximum of 1,000 and is defined by:

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

RQD	is the Rock Quality Designation
J_n	is the joint set number
J_r	is the joint roughness number
J_a	is the joint alteration number
J_w	is the joint water reduction factor
SRF	is the Stress Reduction Factor

Q-System

It appears that the rock tunneling quality *Q* can now be considered to be a function of only three parameters which are crude measures of:

1. block size (RQD/J_n)
2. inter-block shear strength (J_r/J_a)
3. active stress (J_w/SRF)

Rock Tunnelling Quality Index: Classification of RQD

Description		Value	Notes
A	Very poor	0 – 25	1. Where RQD is reported or measured as ≤ 10 (including 0), a nominal value of 10 is used to evaluate Q. 2. RQD intervals of 5, i.e. 100, 95, 90 etc. are sufficiently accurate.
B	Poor	25 – 50	
C	Fair	50 – 75	
D	Good	75 – 90	
E	Excellent	90 – 100	

Rock Tunnelling Quality Index: Classification of J_n

Description		Value	Notes
A	Massive, no or few joints	0.5 – 1.0	1. For intersections use ($3.0 \times J_n$) 2. For portals use ($2.0 \times J_n$)
B	One joint set	2	
C	One joint set plus random	3	
D	Two joint sets	4	
E	Two joint sets plus random	6	
F	Three joint sets	9	
G	Three joint sets plus random	12	
H	Four or more joint sets, random, heavily jointed, 'sugar cube', etc.	15	
J	Crushed rock, earthlike	20	

Rock Tunnelling Quality Index: Classification of J_r

Description		Value	Notes
a. Rock wall contact b. Rock wall contact before 10 cm shear			1. Add 1.0 if the mean spacing of the relevant joint set is greater than 3 m. 2. J_r = 0.5 can be used for planar, slickensided joints having lineations, provided the lineations are favourably oriented for minimum strength.
A	Discontinuous joints	4	
B	Rough and irregular, undulating	3	
C	Smooth undulating	2	
D	Slickensided undulating	1.5	
E	Rough or irregular, planar	1.5	
F	Smooth, planar	1.0	
G	Slickensided, planar	0.5	
c. No rock wall contact when sheared			
H	Zones containing clay minerals thick enough to prevent rock wall contact	1.0 (nominal)	
J	Sandy, gravely or crushed zone thick enough to prevent rock wall contact	1.0 (nominal)	

Rock Tunnelling Quality Index: Classification of J_a

	Description	Value	f_r (deg) (approx.)	Notes
a. Rock wall contact				Values of f_r, the residual friction angle, are intended as an approximate guide to the mineralogical properties of the alteration products, if present.
A	Tightly healed, hard, non-softening, impermeable filling	0.75		
B	Unaltered joint walls, surface staining only	1.0	25 – 35	
C	Slightly altered joint walls, non-softening mineral coatings, sandy particles, clay-free disintegrated rock, etc.	2.0	25 – 30	
D	Silty-, or sandy-clay coatings, small clay-fraction (non-softening)	3.0	20 – 25	
E	Softening or low-friction clay mineral coatings, i.e. kaolinite, mica. Also chlorite, talc, gypsum and graphite etc., and small quantities of swelling clays. (Discontinuous coatings, 1 - 2 mm or less)	4.0	8 – 16	

Rock Tunnelling Quality Index: Classification of J_a

Description		Value	f_r (deg) (approx.)	Notes
b. Rock wall contact before 10 cm shear				Values of f_r, the residual friction angle, are intended as an approximate guide to the mineralogical properties of the alteration products, if present.
F	Sandy particles, clay-free, disintegrating rock etc.	4.0	25 – 30	
G	Strongly over-consolidated, non-softening clay mineral fillings (continuous < 5 mm thick)	6.0	16 – 24	
H	Medium or low over-consolidation, softening clay mineral fillings (continuous < 5 mm thick)	8.0	12 – 16	
J	Swelling clay fillings, i.e. montmorillonite, (continuous < 5 mm thick). Values of J_a depend on percent of swelling clay-size particles, and access to water.	8.0 – 12.0	6 – 12	

Rock Tunnelling Quality Index: Classification of J_a

	Description	Value	f_r (deg) (approx.)	Notes
c. No rock wall contact when sheared				Values of f_r, the residual friction angle, are intended as an approximate guide to the mineralogical properties of the alteration products, if present.
K	Zones or bands of disintegrated or crushed.	6.0	6 – 24	
L	rock and clay (see G, H and J for clay conditions).	8.0		
M		8.0 – 12.0		
N	Zones or bands of silty- or sandy-clay, small clay fraction, non-softening.	5.0		
O	Thick continuous zones or bands of clay.	10.0 – 13.0		
P	& R. (see G.H and J for clay conditions).	13.0 – 20.0		

Rock Tunnelling Quality Index: Classification of J_w

	Description	Value	Approx. Water Press. (kgf/cm^2)	Notes
A	Dry excavation or minor inflow i.e. < 5 l/m locally	1.0	< 1.0	1. Factors C to F are crude estimates; increase Jw if drainage is installed. 2. Special problems caused by ice formation are not considered.
B	Medium inflow or pressure, occasional outwash of joint fillings	0.66	1.0 – 2.5	
C	Large inflow or high pressure in competent Rock with unfilled joints	0.5	2.5 – 10.0	
D	Large inflow or high pressure	0.33	2.5 – 10.0	
E	Exceptionally high inflow or pressure at blasting, decaying with time	0.2 – 0.1	> 10	
F	Exceptionally high inflow or pressure	0.1 – 0.05	> 10	

Rock Tunnelling Quality Index: Classification of SRF

Description		SRF	Notes
a. Weakness zones intersecting excavation, which may cause loosening of rock mass when tunnel is excavated			Reduce these values of SRF by 25 - 50% but only if the relevant shear zones influence do not intersect the excavation
A	Multiple occurrences of weakness zones containing clay or chemically disintegrated rock, very loose surrounding rock (any depth)	10.0	
B	Single weakness zones containing clay, or chemically disintegrated rock (excavation depth < 50 m)	5.0	
C	Single weakness zones containing clay, or chemically disintegrated rock (excavation depth > 50 m)	2.5	
D	Multiple shear zones in competent rock (clay free), loose surrounding rock (any depth)	7.5	
E	Single shear zone in competent rock (clay free) (depth of excavation < 50 m)	5.0	
F	Single shear zone in competent rock (clay free) (depth of excavation > 50 m)	2.5	
G	Loose open joints, heavily jointed or 'sugar cube' (any depth)	5.0	

Rock Tunnelling Quality Index: Classification of SRF

Description				SRF	Notes
b. Competent rock, rock stress problems		s_c/s_1	s_t/s_1		1. For strongly anisotropic virgin stress field (if measured): when $5 \le \sigma_1/\sigma_3 \le 10$, reduce σ_c to $0.8\sigma_c$ and σ_t to $0.8\sigma_t$. When $\sigma_1/\sigma_3 > 10$, reduce σ_c to $0.6\sigma_c$ and σ_t to $0.6\sigma_t$. 2. Few case records available where depth of crown below surface is less than span width. Suggest SRF increase from 2.5 to 5 for such cases (see H).
H	Low stress, near surface	> 10	> 10	2.5	
J	Medium stress	200 – 10	13 – 0.66	1.0	
K	High stress, very tight structure (usually favourable to stability, may be unfavourable to wall stability)	10 – 5	0.66 – 0.33	0.5 – 2	
L	Mild rockburst (massive rock)	5 – 2.5	0.33 – 0.16	5 – 10	
M	Heavy rockburst (massive rock)	< 2.5	< 0.16	10 – 20	
c. Squeezing rock, plastic flow of incompetent rock under influence of high rock pressure					
N	Mild squeezing rock pressure			5 – 10	
O	Heavy squeezing rock pressure			10 – 20	
d. Swelling rock, chemical swelling activity depending on presence of water					
P	Mild swelling rock pressure			5 – 10	
R	Heavy swelling rock pressure			10 – 15	

Rock Tunnelling Quality Index: Classification of SRF

Cases of **squeezing rock** may occur for depth H > $350Q^{1/3}$

Rock Tunnelling Quality Index: Classification of SRF (Grimstad & Barton, 1993)

(Barton et al, 1974)

Description			SRF
b. Competent rock, rock stress problems		s_c/s_1	
L	Mild rockburst (massive rock)	5 – 2.5	5 – 10
M	Heavy rockburst (massive rock)	< 2.5	10 – 20

(Grimstad & Barton, 1993)

Description			SRF
b. Competent rock, rock stress problems		s_c/s_1	
L	Moderate slabbing after >1 hour in massive rock	5 – 3	5 – 50
	Slabbing and rockburst after a few minutes in massive rock	3 – 2	50 – 200
M	Heavy rockburst (massive rock)	< 2	200 – 400

Rock Tunnelling Quality Index: ESR and De

- In relating the value of the index Q to the stability and support requirements of underground excavations, **Barton et al (1974)** defined an additional parameter which they called the **Equivalent Dimension (De)** of the excavation.
- This dimension is obtained by dividing the span, diameter or wall height of the excavation by a quantity called the **Excavation Support Ratio (ESR)**.

Rock Tunnelling Quality Index: ESR and De

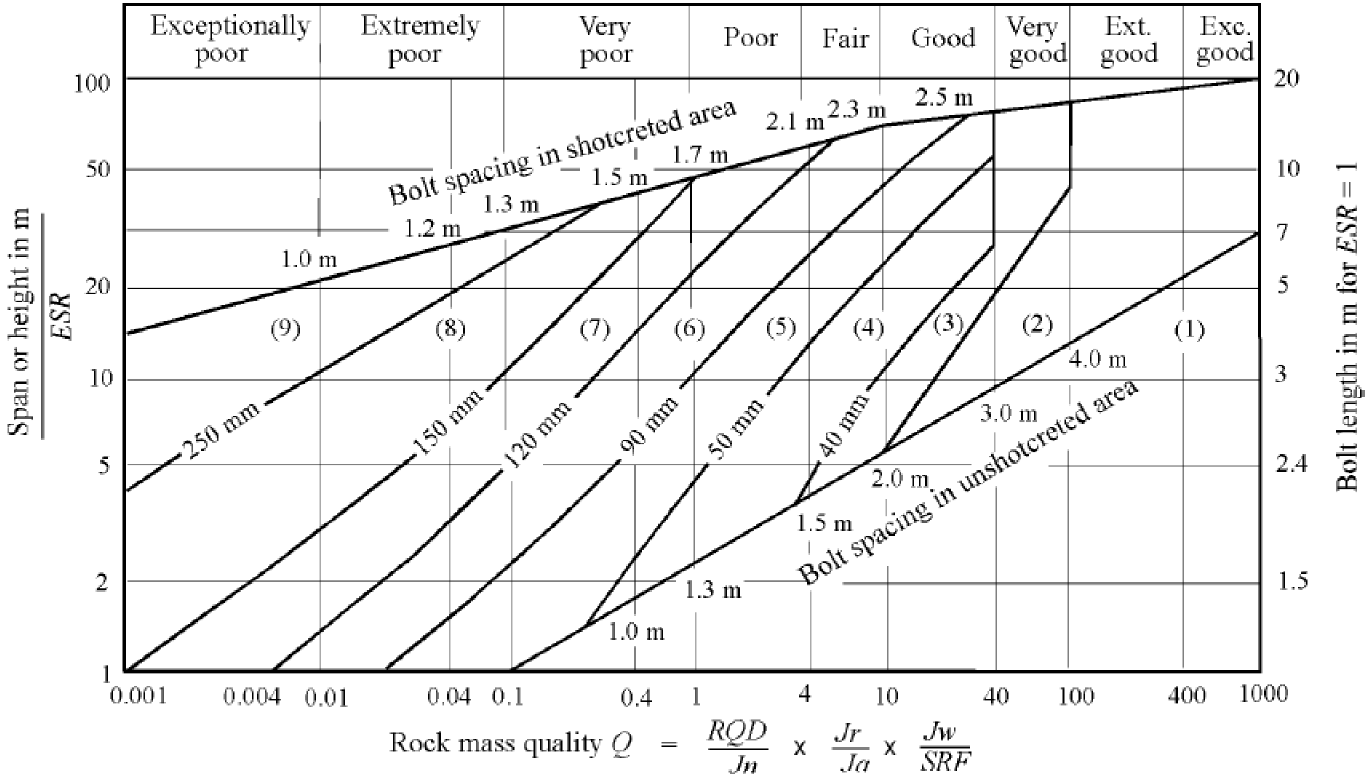
$$D_e = \frac{Span\ (m)}{ESR}$$

The value of ESR is related to the intended use of the excavation and to the degree of security which is demanded of the support system installed to maintain the stability of the excavation.

Rock Tunnelling Quality Index: ESR and De

Excavation category		ESR
A	Temporary mine openings.	3 – 5
B	Permanent mine openings, water tunnels for hydro power (excluding high pressure penstocks), pilot tunnels, drifts and headings for large excavations.	1.6
C	Storage rooms, water treatment plants, minor road and railway tunnels, surge chambers, access tunnels.	1.3
D	Power stations, major road and railway tunnels, civil defence chambers, portal intersections.	1.0
E	Underground nuclear power stations, railway stations, sports and public facilities, factories.	0.5

Rock Tunnelling Quality Index: Estimated Support Categories



REINFORCEMENT CATEGORIES

1) Unsupported
2) Spot bolting
3) Systematic bolting
4) Systematic bolting with 40-100 mm unreinforced shotcrete
5) Fibre reinforced shotcrete, 50 - 90 mm, and bolting
6) Fibre reinforced shotcrete, 90 - 120 mm, and bolting
7) Fibre reinforced shotcrete, 120 - 150 mm, and bolting
8) Fibre reinforced shotcrete, > 150 mm, with reinforced ribs of shotcrete and bolting
9) Cast concrete lining

Q-System

Please read more about Rock Mass Quality (Q-System) in the book of ***Engineering Rock Mass Classification*** *Ch. 8 by Goel, R.K. and Singh, B.*

Using Rock Mass Classification System

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RMR and Q-System

The two most widely used rock mass classifications are Bieniawski's **RMR** (1976, 1989) and Barton et al's ***Q*** (1974).

The differences between the systems lie in the different weightings given to similar parameters and in the use of distinct parameters in one or the other scheme.

The greatest difference between the two systems is the lack of **a stress parameter** in the RMR system.

Using Rock Mass Classification System

Throughout this course it has been suggested that the user of a rock mass classification scheme should check that the latest version is being used. It is also worth repeating that the use of two rock mass classification schemes side by side is advisable.

With Prof. Resat Ulusay, an author of ISRM Suggested Methods for Rock Characterization, Testing, and Monitoring. Bali, 2016.

THANK YOU

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