108.01

工程地質

Engineering Geology

第十五週

工程地質之計量化

授課教師：邱雅筑

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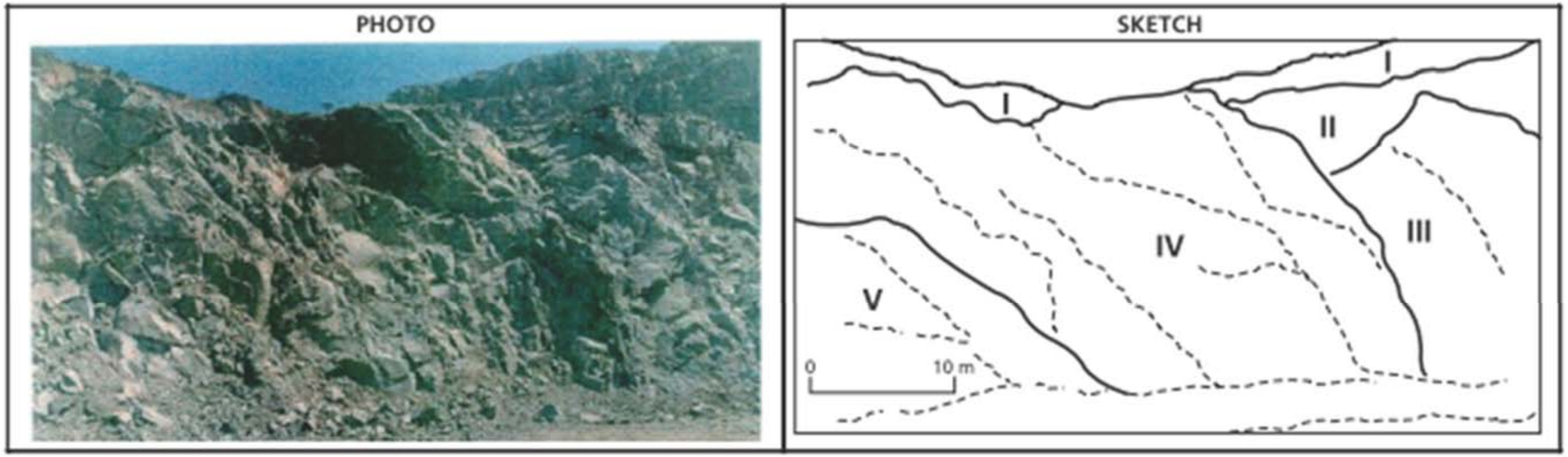
岩體分類法

- **Rock mass classifications**岩體分類法：Obtaining geomechanical parameters to use when designing engineering projects.
- The most frequently used geomechanical classifications nowadays are the RMR and the Q classifications.



岩體評分法 Rock Mass Rating (RMR)

- Developed by Z. T. Bieniawski in 1973 at the South African Council of Scientific and Industrial Research (**CSIR**), and updated in 1979 and 1989. Also called the **Geomechanics Classification** (地質力學評分法).
- 評分項目包含：
  1. Uniaxial compressive strength (UCS) of intact rock material
  2. Rock quality designation (RQD)
  3. Joint or discontinuity spacing
  4. Joint condition
  5. Groundwater condition
  6. Joint orientation

1.**Uniaxial compressive strength (UCS)** of intact rock

- 岩石材料的單軸壓縮強度
- 分7級，1, 5, 25, 50, 100, 250 MPa

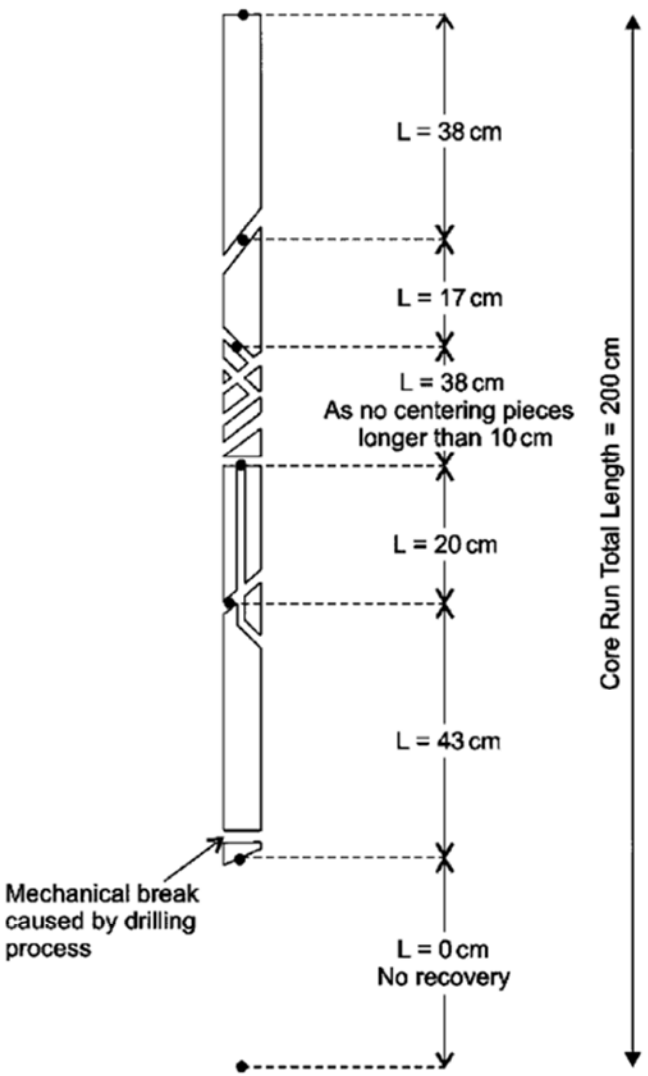
TABLE 6.1 Strength of Intact Rock Material (強度越強，分數越高)

Qualitative description	Compressive strength (MPa)	Point load strength (MPa)	Rating
Extremely strong*	>250	8	15
Very strong	100–250	4–8	12
Strong	50–100	2–4	7
Medium strong*	25–50	1–2	4
Weak	5–25	Use of UCS is preferred	2
Very weak	1–5	-do-	1
Extremely weak	<1	-do-	0

At compressive strength of rock material less than 1.0 MPa, many rock materials would be regarded as soil.
**Terms redefined according to ISO 14689.*

Sources: Bieniawski, 1979, 1984; ISO14689-1, 2003.

2. Rock quality designation (RQD)



$$RQD = \frac{118}{200} \times 100 = 59\%$$

$$\text{Core Recovery} = \frac{156}{200} \times 100 = 78\%$$

FIGURE 4.1 Procedure for measurement and calculation of rock quality designation (RQD). *(From Deere, 1989)*

$$\mathrm{RQD} = \frac{\text{sum of core pieces} \geq 10\ \text{cm}}{\text{total drill run}} . 100,\ \%$$

- 大於10 cm的部分之長度總和占岩心全長比例。
- 分5級，25, 50, 75, 90

(RQD越大，分數越高)

TABLE 6.2 Rock Quality Designation

Qualitative description	RQD (%)	Rating
Excellent	90–100	20
Good	75–90	17
Fair	50–75	13
Poor	25–50	8
Very poor	<25	3

Source: Bieniawski, 1979.

RQD之應用

- 波速

$$RQD = (V_F/V_L)^2 \cdot 100$$

(關聯完整岩石與岩體力學特性)

V_F is in situ compressional wave velocity
V_L is compressional wave velocity in intact rock core

- Deformation modulus of the rock mass
  - Zhang and Einstein (2004)

$$\frac{E_d}{E_r} = 10^{0.0186\, RQD - 1.91}$$

E_d and E_r are the deformation moduli of the rock mass and the intact rock

RQD之應用

- Volumetric Joint Count (J_v): the number of joints within a unit volume of rock mass 數字越大，代表岩體越破碎

$$J_v = \sum_{i=1}^{J} \left(\frac{1}{S_i} \right)$$

S_i is the average joint spacing in meters for the i^{th} joint set

J is the total number of joint sets except the random joint set.

  - clay-free rock masses, long or flat blocks (Palmstrom, 1982)

$$RQD = 115 - 3.3\, J_v$$

  - for blocks of a cubical (bar) shape (Palmstrom, 2005).

$$RQD = 110 - 2.5\, J_v$$

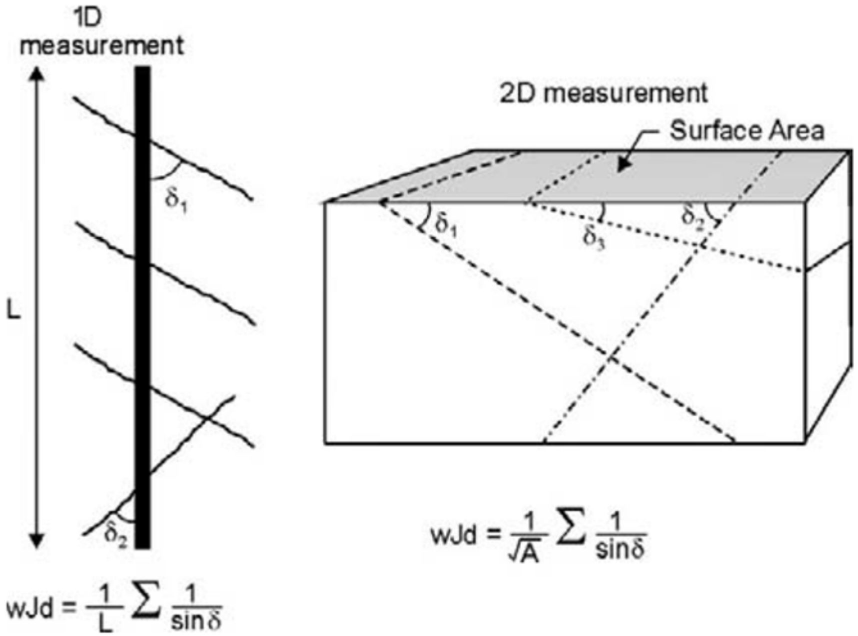
加權節理密度

Weighted joint density (Palmstrom, 1996)

- Based on the measurement of the angle between each joint and the surface or the drill hole.
- Weighted joint density (wJd) (只有J大寫)

$$\text{for measurements in rock surface:}\quad wJd = \frac{1}{\sqrt{A}}\sum f_i$$

$$\text{for measurements along a drill core or scan line:}\quad wJd = \frac{1}{L}\sum f_i$$



δ is the intersection angle

A is the size of the observed area in m^2

L is the length of the measured section along the core or scan line

f_i is a rating factor

To solve the problem of small intersection angles and to simplify the observations, the angles have been divided into intervals

FIGURE 4.2 The intersection between joints and a drill core hole (left) and between joints and a surface (right). *(From Palmstrom, 1996)*

- Intervals for which a rating of f i has been selected

for measurements in rock surface: $wJd = \frac{1}{\sqrt{A}} \sum f_i$

for measurements along a drill core or scan line: $wJd = \frac{1}{L} \sum f_i$

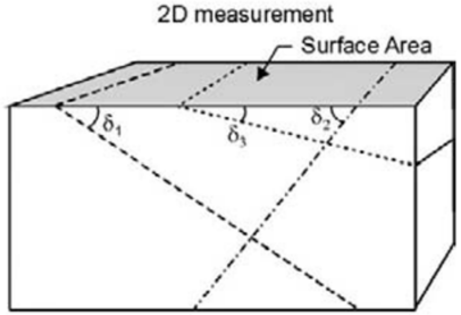


TABLE 4.3 Angle Intervals and Rating of the Factor f_i (交角越小，加權越重)

Angle interval (between joint and borehole or surface)	1/sinδ	Chosen rating of the factor f_i
$\delta > 60°$	<1.16	1
$\delta = 31–60°$	1.16–1.99	1.5
$\delta = 16–30°$	2–3.86	3.5
$\delta < 16°$	>3.86	6

Source: Palmstrom, 2005.

Surface Measurement of wJd

- the weighted joint density measurement produces values that are somewhat higher than the known value for the volumetric joint count (Palmstrom, 1996)

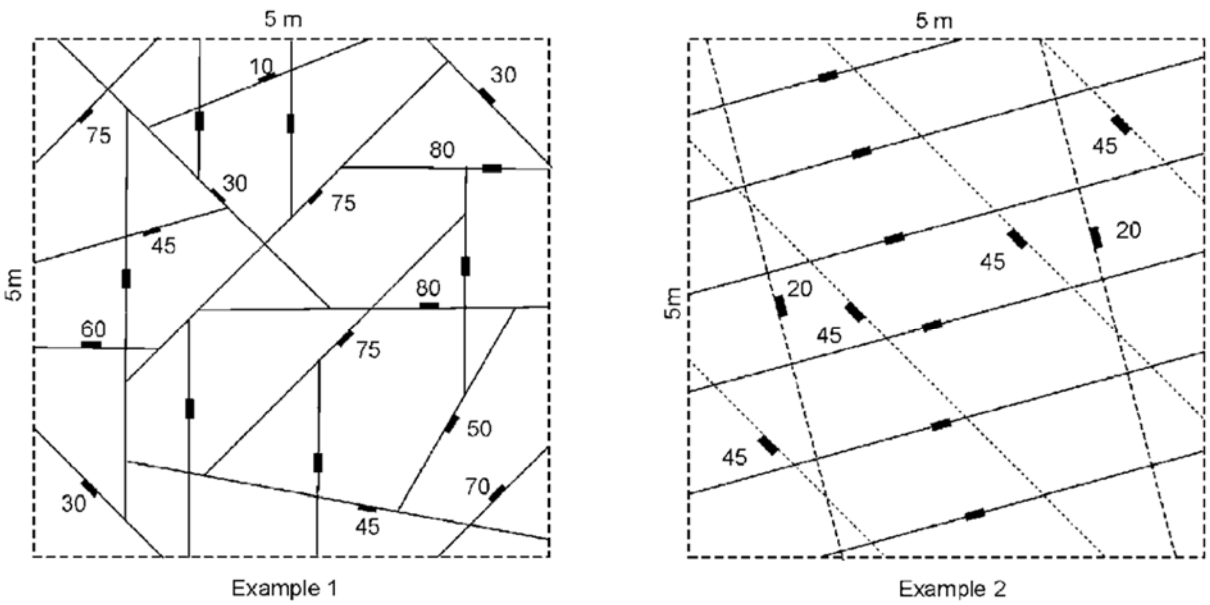


FIGURE 4.3 Two examples of jointing on a surface. *(From Palmstrom, 1996)*

TABLE 4.3 Angle Intervals and Rating of the Factor f_i

Angle interval (between joint and borehole or surface)	1/sinδ	Chosen rating of the factor f_i
$\delta > 60°$	<1.16	1
$\delta = 31–60°$	1.16–1.99	1.5
$\delta = 16–30°$	2–3.86	3.5
$\delta < 16°$	>3.86	6

Source: Palmstrom, 2005.

TABLE 4.4 Calculation of Weighted Joint Density from Analysis of Jointing Shown for the Surfaces in Figure 4.3

Location	Area (A) m^2	Number of joints (n) within each interval >60°	31–60°	16–30°	<16°	Total number of joints	Number of weighted joints $N_w = \sum n \times f_i$	wJd = (1/√A) N_w	Jv
Example 1	25	12	4	3	1	20	34.5	6.9	
Example 2	25	6	4	2	0	12	19	3.8	3.05
Rating of f_i =		1	1.5	3.5	6				

Source: Palmstrom, 1996.

Drill Hole Measurements of wJd

- By Palmstrom(1996)
- The 5 m long part of the core has been divided into the following three sections with similar density of joints.

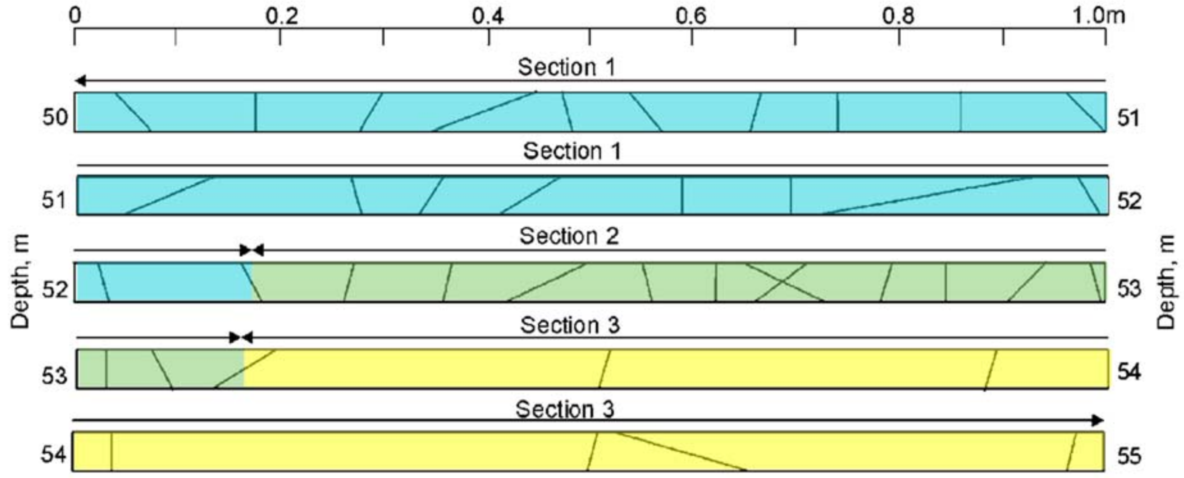


FIGURE 4.4 Example of jointing along part of a borehole. *(From Palmstrom, 1996)*

求這些做什麼？

更好地量化岩體破碎程度

TABLE 4.6 Calculation of the Weighted Joint Density from Registration of Jointing in the Borehole in Figure 4.4

Depth	(分段)全長 Length (L)	Number of joints (n) within each interval				Total number of joints	Number of weighted joints	wJd =
m	*m*	*>60°*	*31–60°*	*16–30°*	*<16°*		$N_w = \sum n \times f_i$	(1/L) N_w
50–52.17	2.17	11	6	2	1	20	33	15
52.17–53.15	0.98	9	3	2	0	14	20.5	20.9
53.15–55.0	1.85	5	0	1	0	6	8.5	4.6
Rating of f_i =		1	1.5	3.5	6			

Source: Palmstrom, 1996.

3. Joint or discontinuity spacing

- The linear distance between two adjacent discontinuities should be measured for all sets of discontinuities. 每組間距都要量。
- 分5級，0.06, 0.2, 0.6, 2 m

(間距越大，分數越高)

TABLE 6.3 Spacing of Discontinuities

Description	Spacing (m)	Rating
Very wide	>2	20
Wide	0.6–2	15
Moderate	0.2–0.6	10
Close	0.06–0.2	8
Very close	<0.06	5

If more than one discontinuity set is present and the spacing of discontinuities of each set varies, consider the unfavorably oriented set with lowest rating. ISO 14689 uses the term "extremely close" for joint spacing less than 0.02 m.

Sources: Bieniawski, 1979; ISO 14689-1, 2003.

4. Joint condition

- Includes roughness of discontinuity surfaces, their separation, length of continuity, weathering of the wall rock or the planes of weakness, and infilling (gouge) material

TABLE 6.4 Condition of Discontinuities

Description	Joint separation (mm)	Rating
Very rough and unweathered, wall rock tight and discontinuous, no separation	0	30
Rough and slightly weathered, wall rock surface separation <1 mm	<1	25
Slightly rough and moderately to highly weathered, wall rock surface separation <1 mm	<1	20
Slickensided wall rock surface, or 1–5 mm thick gouge, or 1–5 mm wide continuous discontinuity	1–5	10
5 mm thick soft gouge, 5 mm wide continuous discontinuity	>5	0

Source: Bieniawski, 1979.

4. Joint condition

- roughness of discontinuity surfaces, separation, length of continuity, weathering of the wall rock or the planes of weakness, and infilling (gouge) material各項的評分標準。

TABLE 6.5 The RMR System: Guidelines for Classification of Discontinuity Conditions (節理越粗糙、新鮮、緊密 分數越高)

Parameter*	Ratings				
Discontinuity length (persistence/ continuity)	<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 of discontinuity surface	Very rough	Rough	Slightly rough	Smooth	Slickensided
	6	5	3	1	0
Infillings (gouge)		Hard filling		Soft filling	
	None	<5 mm	>5 mm	<5 mm	>5 mm
	6	4	2	2	0
Weathering discontinuity surface	Unweathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed
	6	5	3	1	0

**Some conditions are mutually exclusive. For example, if infilling is present, it is irrelevant what the roughness may be, since its effect will be overshadowed by the influence of the gouge. In such cases use Table 6.4 directly.*

Source: Bieniawski, 1993.

5. Groundwater condition

- **Completely dry**, **damp**, **wet**, **dripping**, or **flowing**
- If actual water pressure data are available, these should be stated and expressed in terms of the ratio of the seepage water pressure to the major principal stress.

TABLE 6.6 Groundwater Condition （節理內水的影響越小，分數越高）

Inflow per 10 m tunnel length (L/min)	None	<10	10–25	25–125	>125
Ratio of joint water pressure to major principal stress	0	0–0.1	0.1–0.2	0.2–0.5	>0.5
General description	Completely dry	Damp	Wet	Dripping	Flowing
Rating	15	10	7	4	0

Source: Bieniawski, 1979.

6. Joint orientation (節理位態對預定工程的影響)

- The influence of the strike and dip of discontinuities is considered with respect to the direction of tunnel drivage, slope face orientation, or foundation alignment.
- 分5級。

TABLE 6.10 Adjustment for Joint Orientation

Joint orientation assessment for	Very favorable	Favorable	Fair	Unfavorable	Very unfavorable
Tunnels	0	−2	−5	−10	−12
Raft foundation	0	−2	−7	−15	−25
Slopes*	0	−5	−25	−50	−60

**It is recommended to use slope mass rating (SMR; Chapter 18).*

Source: Bieniawski, 1979.

6. Joint orientation

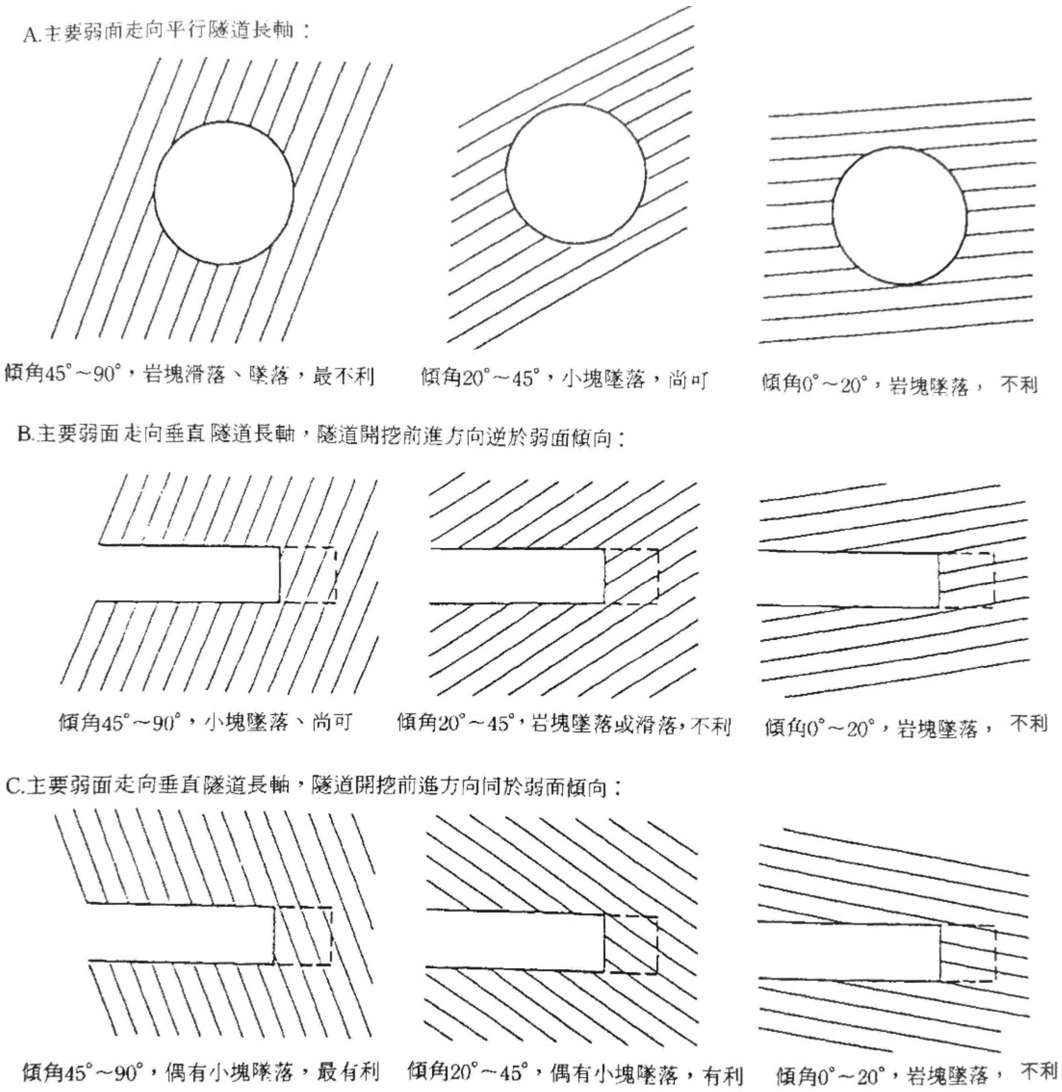


圖 12.9　主要弱面方位對隧道開挖穩定性之關係

TABLE 6.8 Assessment of Joint Orientation Effect on Tunnels

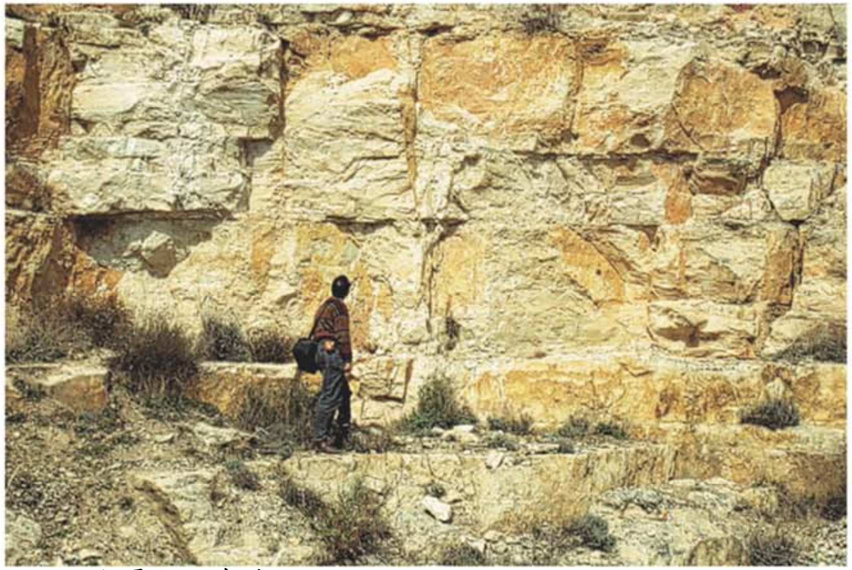
Strike perpendicular to tunnel axis				Strike parallel to tunnel axis		Irrespective of strike
Drive with dip		*Drive against dip*				
Dip 45°–90°	Dip 20°–45°	Dip 45°–90°	Dip 20°–45°	Dip 20°–45°	Dip 45°–90°	Dip 0°–20°
Very favorable	Favorable	Fair	Unfavorable	Fair	Very unfavorable	Fair

Source: Bieniawski, 1984.

RMR Class 1, 2

Table 3.27 **ROCK MASS QUALITY ACCORDING TO THE RMR INDEX**				
Class	**Quality**	**RMR rating**	**Cohesion (MPa)**	**Friction angle**
I	Very good	100–81	>0.4	>45°
II	Good	80–61	0.3–0.4	35°–45°
III	Fair	60–41	0.2–0.3	25°–35°
IV	Poor	40–21	0.1–0.2	15°–25°
V	Very poor	<20	<0.1	<15°

Class I (RMR = 81-100) and Class II (RMR= 61-80) rock masses



白堊紀石灰岩
Cretaceous dolomite. Very good quality. Two main sets of discontinuities.

Granite. Good quality. Several sets of weathered discontinuities.

RMR Class 3

Table 3.27 ROCK MASS QUALITY ACCORDING TO THE RMR INDEX				
Class	**Quality**	**RMR rating**	**Cohesion (MPa)**	**Friction angle**
I	Very good	100–81	>0.4	>45°
II	Good	80–61	0.3–0.4	35°–45°
III	Fair	60–41	0.2–0.3	25°–35°
IV	Poor	40–21	0.1–0.2	15°–25°
V	Very poor	<20	<0.1	<15°

Class III rock masses (RMR= 41-60)

奥陶紀石灰岩

Ordovician slate. Fair quality. High fracturing degree. Weathering degree: III.

Ordovician quartzite. Fair quality. High fracturing degree. Very hard intact rock.

RMR Class 4, 5

Table 3.27 ROCK MASS QUALITY ACCORDING TO THE RMR INDEX				
Class	**Quality**	**RMR rating**	**Cohesion (MPa)**	**Friction angle**
I	Very good	100–81	>0.4	>45°
II	Good	80–61	0.3–0.4	35°–45°
III	Fair	60–41	0.2–0.3	25°–35°
IV	Poor	40–21	0.1–0.2	15°–25°
V	Very poor	<20	<0.1	<15°

Class IV (RMR= 21-40) and Class V (RMR ≤20) rock masses

Ordovician quartzite. Poor quality. Weathered and heavily jointed rock mass.

Palaeozoic slate. Very poor quality. Heavily jointed. Degree of weathering: V.

岩體評分法 Rock Mass Rating (總表)

Table 3.26 ROCK MASS RATING SYSTEM

A. Classification parameters

1	Strength of intact rock material (MPa)	Point-load strength index	>10	10–4	4–2	2–1	Uniaxial compressive strength (MPa)
		Uniaxial compressive strength	>250	250–100	100–50	50–25	25–5 5–1 <1
	Rating		15	12	7	4	2 1 0
2	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	0.2–0.6 m	60–20 mm	<60 mm
	Rating		20	15	10	8	5
4	Conditions of discontinuities (see E)		Very rough surfaces. Not continuous. No separation. Unweathered wall rock.	Slightly rough surfaces. Separation <1 mm. Slightly weathered walls.	Slightly rough surfaces. Separation <1 mm. Highly weathered walls.	Slickensided surfaces. or Gouge <5 mm thick or Separation 1–5 mm. Continuous.	Soft gouge >5 mm thick. Separation >5 mm. Continuous.
	Rating		30	25	20	10	0
5	Ground water	Inflow per 10 m tunnel length	None	<10 litres/min	10–25 litres/min	25–125 litres/min	>125 litres/min
		(Joint water press)/(Mayor principal stress)	0	0.0–0.1	0.1–0.2	0.2–0.5	>0.5
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing
	Rating		15	10	7	4	0

B. Rating adjustment for discontinuity orientations *(see F)*

Strike and dip orientations		Very favourable	Favourable	Fair	Unfavourable	Very unfavourable
Rating	Tunnels and mines	0	–2	–5	–10	–12
	Foundations	0	–2	–7	–15	–25
	Slopes	0	–5	–25	–50	–60

C. Rock mass classes

Class	I	II	III	IV	V
Description	Very good	Good	Fair	Poor	Very poor
Rating	100–81	80 – 61	60 – 41	40 – 21	<20

Table 3.26 ROCK MASS RATING SYSTEM (CONT.)

D. Meaning of rock classes

Class number	I	II	III	IV	V
Average stand-up time	20 yrs for 15 m span	1 yr 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	>400 kPa	300–400 kPa	200–300 kPa	100–200 kPa	<100 kPa
Friction angle of rock mass	>45°	35°–45°	25°–35°	15°–25°	<15°

E. Guidelines for classification of discontinuity conditions

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

F. Effect of discontinuity strike and dip orientation in tunnelling

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

(Bieniawski, 1989).

Table 3.27 ROCK MASS QUALITY ACCORDING TO THE RMR INDEX

Class	Quality	RMR rating	Cohesion (MPa)	Friction angle
I	Very good	100–81	>0.4	>45°
II	Good	80–61	0.3–0.4	35°–45°
III	Fair	60–41	0.2–0.3	25°–35°
IV	Poor	40–21	0.1–0.2	15°–25°
V	Very poor	<20	<0.1	<15°

RMR法的應用 隧道的平均自立時間(不加支撐可以持續的時間)

- Average Stand-up Time for an Arched Roof
  - The stand-up time depends upon an effective (unsupported) span of the opening, which is defined as the width of the opening or the distance between the tunnel face and the last support (whichever is smaller)

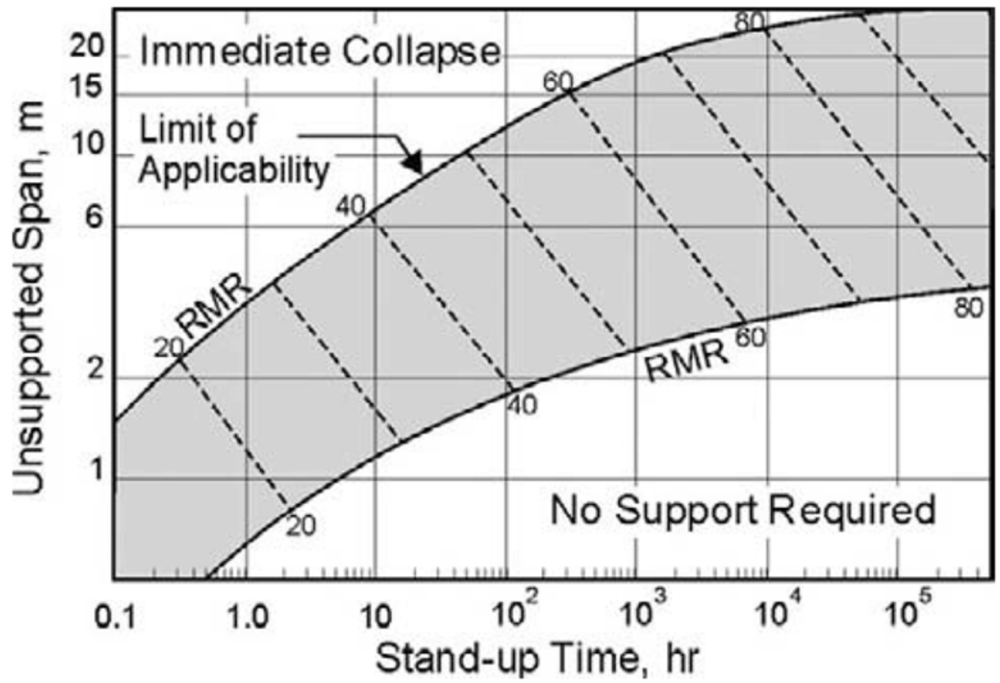


FIGURE 6.1 Stand-up time versus unsupported span for various rock mass classes according to RMR. *(From Bieniawski, 1984)*

RMR法的應用 岩體凝聚力與摩擦角

- Cohesion and Angle of Internal Friction

TABLE 6.11 Design Parameters and Engineering Properties of Rock Mass

S. No.	Parameter/ properties of rock mass	RMR (rock class)				
		100–81 (I)	*80–61 (II)*	*60–41 (III)*	*40–21 (IV)*	*<20 (V)*
1	Classification of rock mass	Very good	Good	Fair	Poor	Very poor
2	Average stand-up time	20 years for 15 m span	1 year for 10 m span	1 week for 5 m span	10 hours for 2.5 m span	30 minutes for 1 m span
3	Cohesion of rock mass (MPa)*	>0.4	0.3–0.4	0.2–0.3	0.1–0.2	<0.1
4	Angle of internal friction of rock mass	>45°	35–45°	25–35°	15–25°	<15°
5	Allowable bearing pressure (T/m^2)	600–440	440–280	280–135	135–45	45–30
6	Safe cut slope (°) (Waltham, 2002)	>70	65	55	45	<40

During earthquake loading, the above values of allowable bearing pressure may be increased by 50% in view of rheological behavior of rock masses (see Chapter 20).
These values are applicable to slopes only in saturated and weathered rock mass.

Source: Bieniawski, 1993.

RMR法的應用 岩體變形模數

- Modulus of Deformation of rock mass.
- MRF, which is defined as a ratio of the modulus of deformation of a **rock mass** to the elastic modulus of the **rock material** obtained from the core.

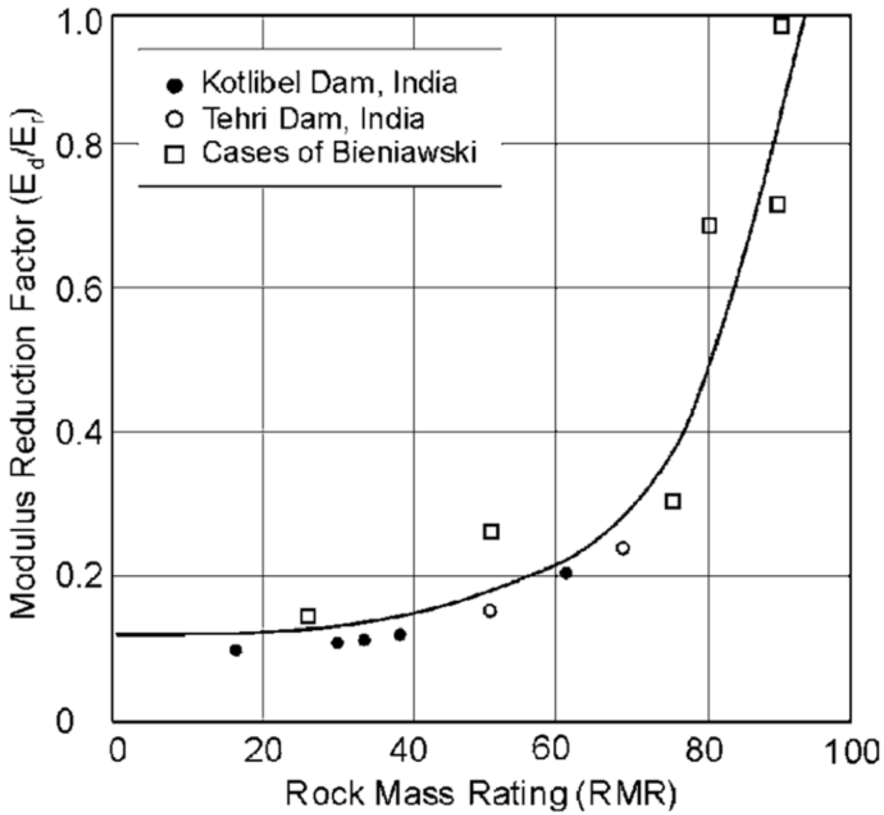


FIGURE 6.2 Relationship between rock mass rating (RMR) and modulus reduction factor. *(From Singh, 1979)*

- Singh (1979)

$$E_d = E_r \cdot \ MRF$$

- Bieniawski (1978) for hard rock masses (q_c > 100 MPa).

$$E_d = 2\ RMR - 100, GPa$$

(applicable for RMR > 50)

- Serafim and Pereira (1983)

$$E_d = 10^{(RMR-10)/40}, GPa$$

(applicable for RMR < 50 also)

RMR法的應用 岩體變形模數

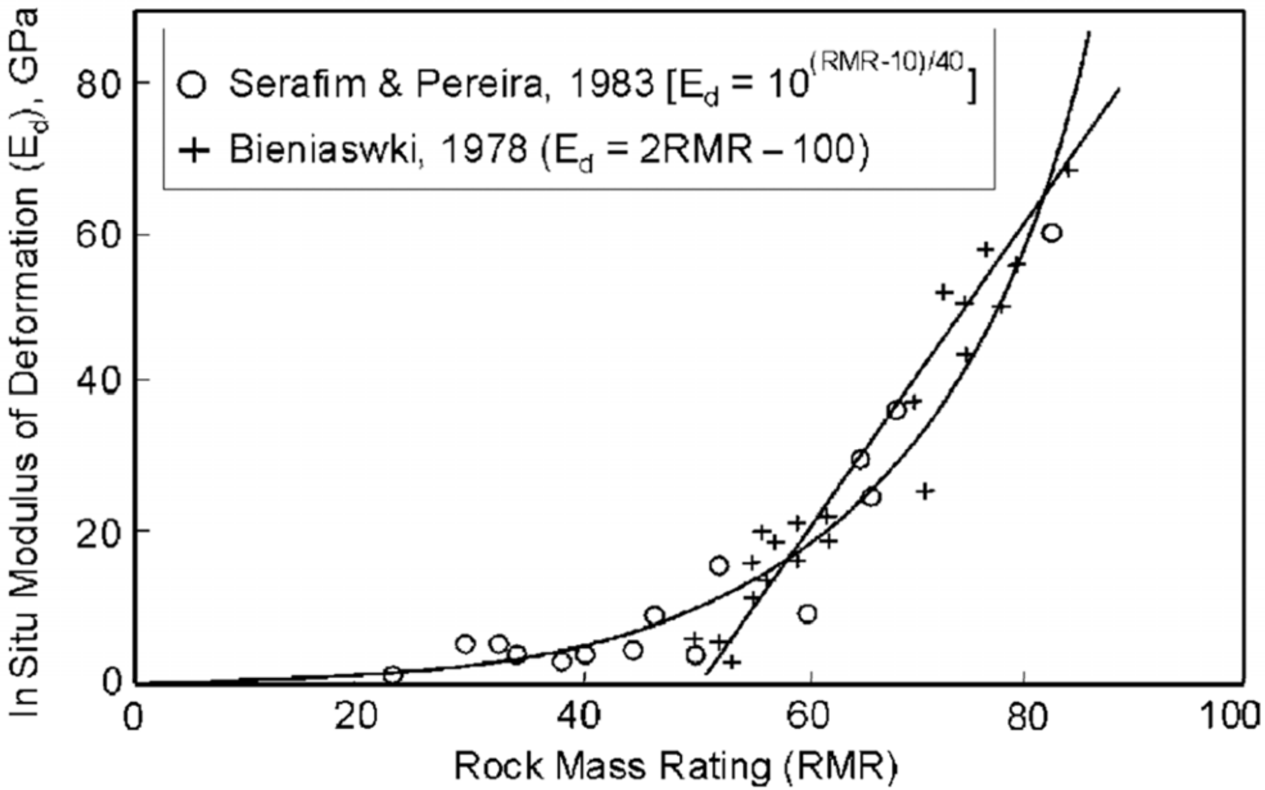


FIGURE 6.3 Correlation between modulus of deformation of rock masses and RMR. *(From Bieniawski, 1984)*

RMR法的應用 岩體變形模數

- The modulus of deformation of a dry and weak rock mass (q_c < 100 MPa) around underground openings located at depths exceeding 50 m is dependent upon confining pressure due to overburden and may be determined by the following correlation (Verman, 1993)

$$E_d = 0.3\,H^{\alpha} \cdot\ 10^{(RMR-20)/38}, \mathrm{GPa}$$

α = 0.16 to 0.30 (higher for poor rocks)

H = depth of location under consideration below ground surface in meters $\geq$ 50 m

- Read, Richards, and Perrin (1999)

$$E_d = 0.1(RMR/10)^{0.3}, \mathrm{GPa}$$

TABLE 8.14 Empirical Correlations for Overall Modulus of Deformation of Rock Mass in the Non-Squeezing Ground Condition (GSI & RMR << 100) 岩體變形模數

Authors	Expression for E_d (GPa)	Conditions	Recommended for
Bieniawski (1978)	$E_d = 2\ RMR - 100$	$q_c > 100$ MPa and $RMR > 50$	Dams
Serafim & Pereira (1983)	$E_d = 10^{(RMR-10)/40}$	$q_c \geq 100$MPa	Dams
Nicholson & Bieniawski (1990)	$E_d/E_r = 0.0028\ RMR^2 + 0.9\ e^{(RMR/22.82)}$	—	
Verman (1993)	$E_d = 0.3\ H\alpha.\ 10^{(RMR-20)/38}$	$\alpha = 0.16$ to 0.30 (higher for poor rocks) $q_c \leq 100$ MPa; $H \geq 50$ m; $J_w = 1$ Coeff. of correlation = 0.91	Tunnels
Mitri et al. (1994)	$E_d/E_r = 0.5[1\text{-}\cos(\pi\ RMR/100)]$	—	
Singh (1997)	$E_d = Q^{0.36}\ H^{0.2}$ $E_e = 1.5Q^{0.6}\ E_r^{0.14}$	$Q < 10$; $J_w = 1$ Coeff. of correlation for $E_e = 0.96$; $J_w \leq 1$	Dams and slopes Dams
Hoek et al. (2002)	$E_d = \left(1 - \frac{D}{2}\right)\sqrt{\frac{q_c}{100}} \cdot 10^{((GSI-10)/40)}$ $E_d = \left(1 - \frac{D}{2}\right) \cdot 10^{((GSI-10)/40)}$	$q_c \leq 100$ MPa D = disturbance factor (Table 26.4) $q_c \geq 100$ MPa	
Adachi & Yoshida (2002)	$E_d = 10^{(0.0431R-0.8853)}$	For weak rocks, R = In situ average Schmidt hammer rebound number	
Barton (2008)	$E_d = 10[Q \cdot q_c/100]^{1/3} < E_r$	$Q = 0.1 - 100$ $q_c = 10 - 200$ MPa	Tunnels
Zhang & Einstein (2004)	$\frac{E_d}{E_r} = 10^{0.0186\ RQD-1.91}$	For $0 \leq RQD \leq 100$	Preliminary analysis
Hoek & Diederichs (2006)	$E_d = \left[0.02 + \frac{1 - D/2}{1 + \exp((60 + 15\ D - GSI)/11)}\right]$		Tunnels, caverns, and dam foundations

The above correlations are expected to provide a mean value of modulus of deformation.