Rock Mechanics & Experiment
암석역학 및 실험

Lecture 10. Method of Analysis & Rock Mass Classification
Lecture 10. 암석역학 해석법 및 암반분류

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Outline

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- Method of analysis
  - Analytical Method
  - Empirical Method
  - Numerical Method
- Empirical Method
  - Rock Mass Rating (RMR)
  - Q-system

Methods of Rock Engineering analysis
Method of analysis

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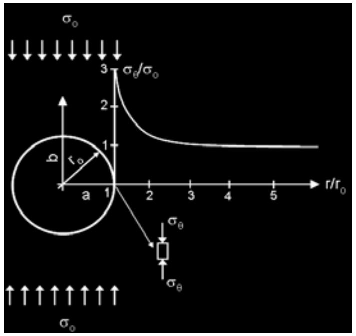
- 해석적 방법 (Analytical method)
  - 알려져 있는 수학적 해를 이용하여 응력과 변위를 계산
  - 커쉬해 (Kirsch solution): 원형공동주위의 응력상태를 알려주는 대표적인 수학적 해임.
- 경험적 방법 (Empirical method)
  - 축적된 경험을 이용하여 여러 범주에 점수를 부여하여 해석
  - 암반분류법이 대표적인 예 (RMR (Rock Mass Rating), Q-system)
- 수치해석적 방법 (Numerical Method)
  - 주어진 경계조건과 형상에서 컴퓨터 시뮬레이션을 이용하여 응력과 변위를 계산 (편미분방정식을 푸는 것임)
  - 복잡한 형상에서 효과적임
  - 유한요소법 (Finite Element Method, FEM), 유한차분법 (Finite Difference Method, FDM), 개별요소법 (Discrete Element Method, DEM)



Stress distribution around a circular opening

Methods of Rock Engineering analysis
Method of analysis – Analytical method

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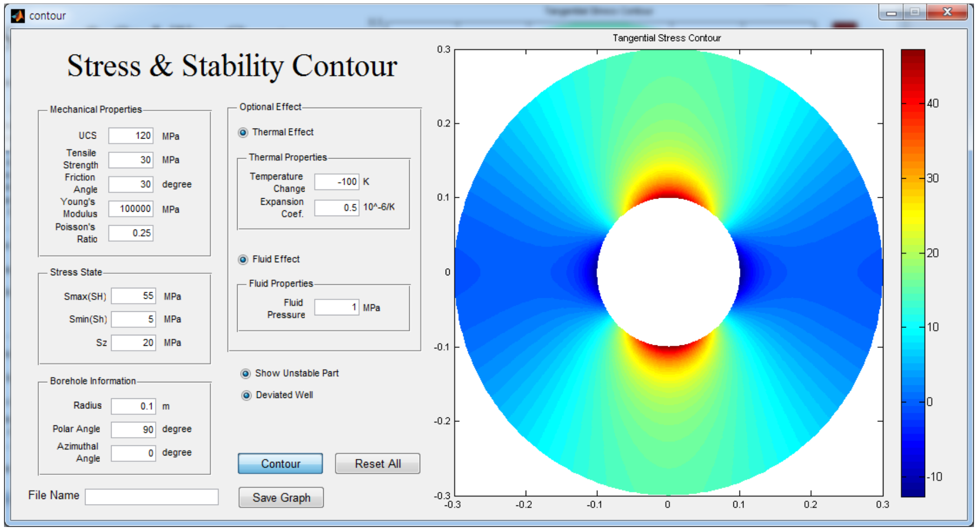
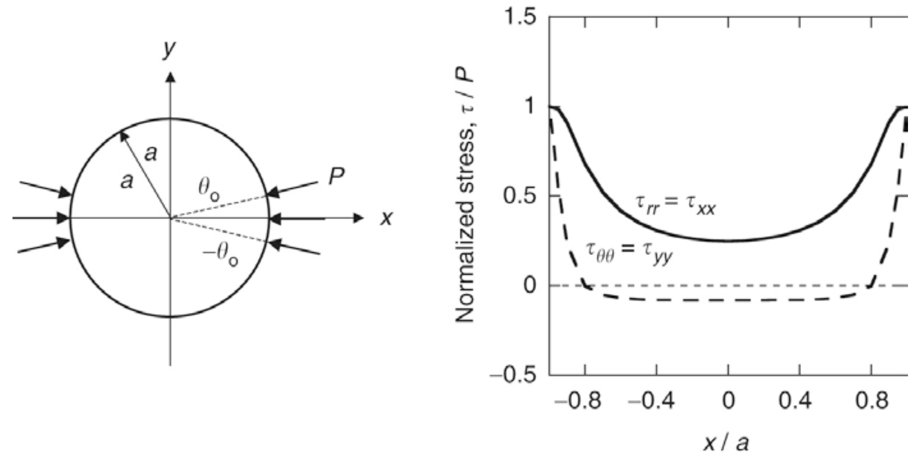
Kirsch solution



Diametral compression

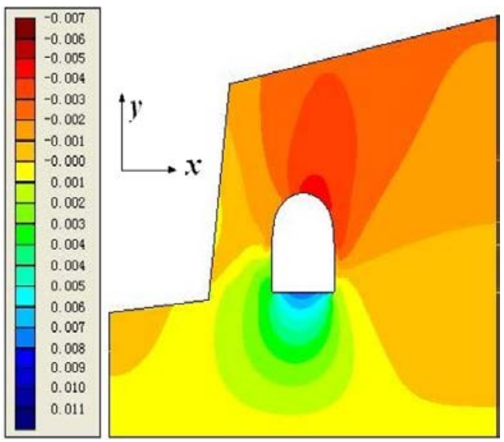


- Numerous analytical solutions exist – fast evaluation & still powerful
- However, 1) complex geometry, 2) multiple formation, 3) complex boundary condition, 4) complex process cannot be handled accurately, 5) obtaining input parameters are often very difficult.

Courtesy of Kwon S

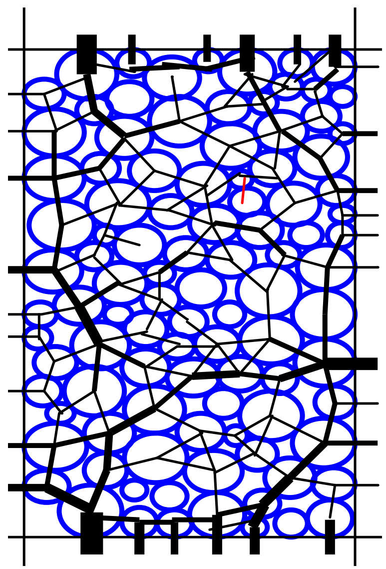
- 수치해석적 방법
  - 유한요소법 (Finite Element Method), 유한차분법 (Finite Difference Method), 경계요소법 (Boundary Element Method) 등의 방법 사용
  - 암반의 변위, 응력 등을 수학식(편미분 방정식)으로 표현하여 이의 근사해를 푸는 방법
- 연속체 해석
  - 암반 절리의 영향을 고려하지 않음
- 불연속체 해석
  - 암반 절리의 영향이 클 때 이용 (개별요소법, Discrete Element Method)

Numerical Analysis
Introduction

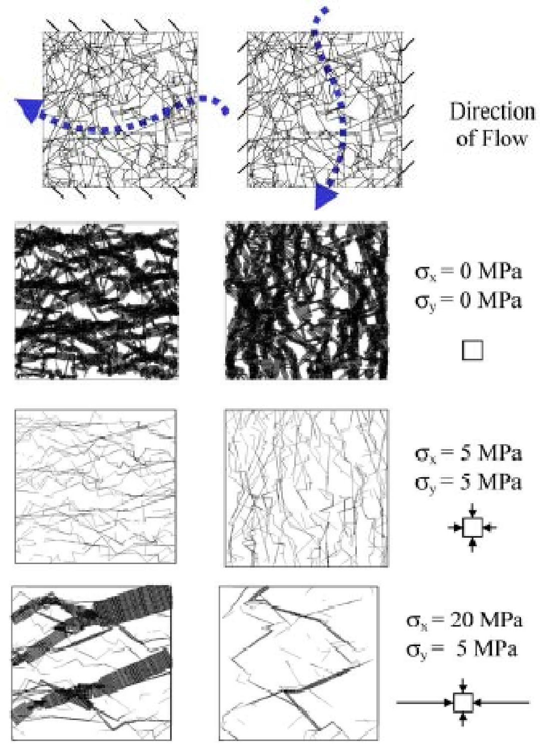


Vertical displacement by FEM (Sun & Wang, 2006)

FDM produce similar results



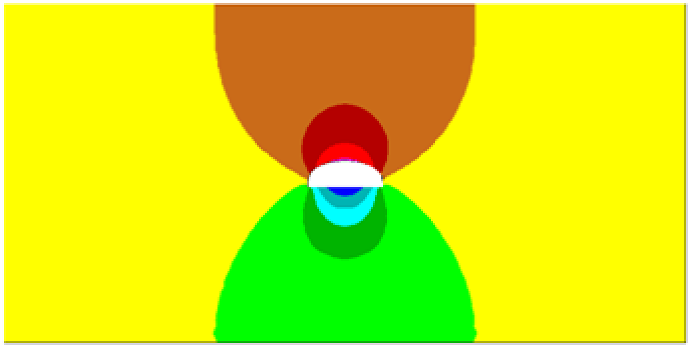
Force distribution in rock grains, DEM (Min et al., 2008)



Effect of stress on fluid flow, DEM (Min et al., 2004)

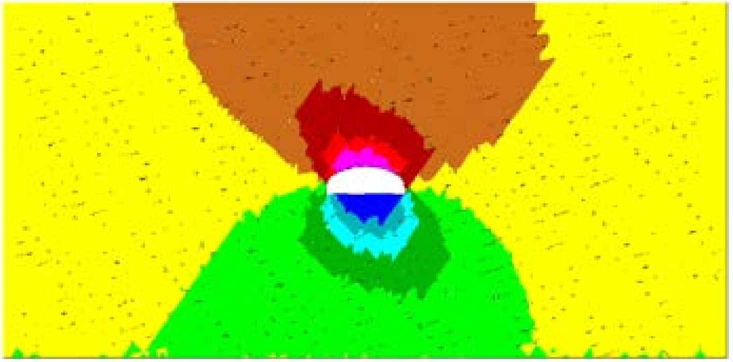
Introduction

- When geometry is not simply circular



vertical displacement

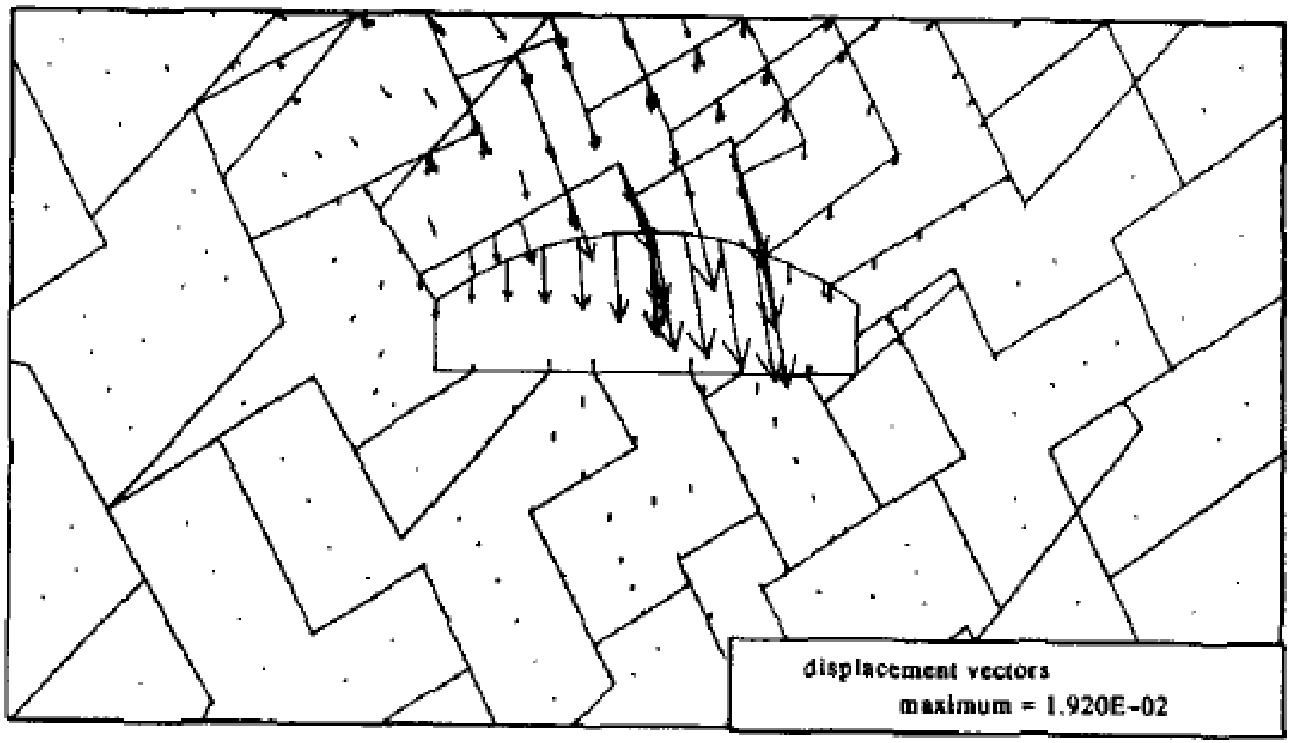
- When fractures around rock is considered



vertical displacement

Introduction – example (1)

- Underground ice hockey stadium in Norway – discontinuum method was used for design



노르웨이 여빅 지하아이스하키 경기장 (Barton et al., 1994)

Numerical Analysis
Introduction – example (2)

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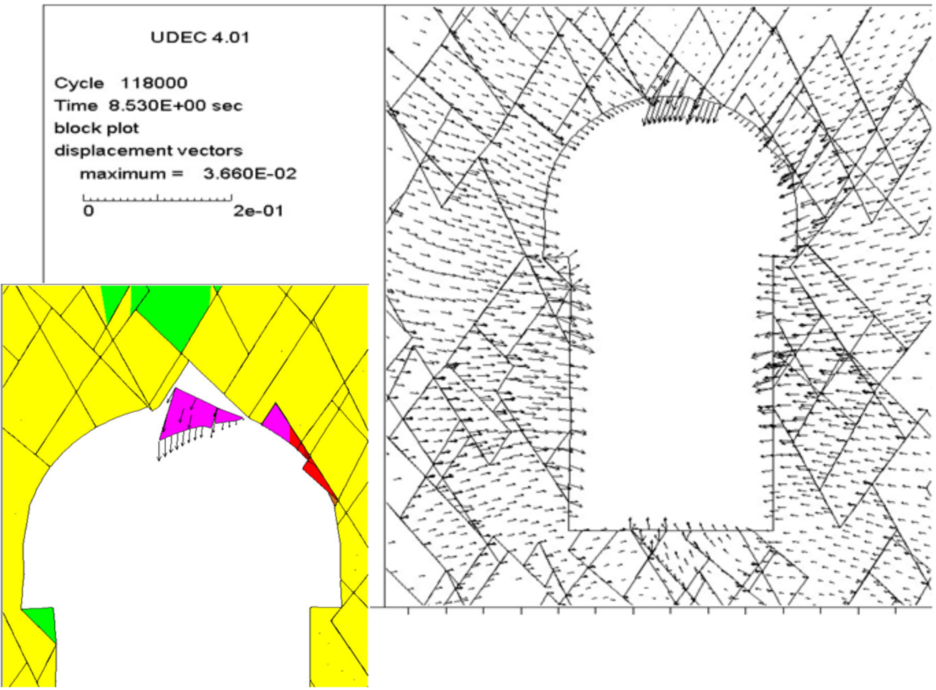
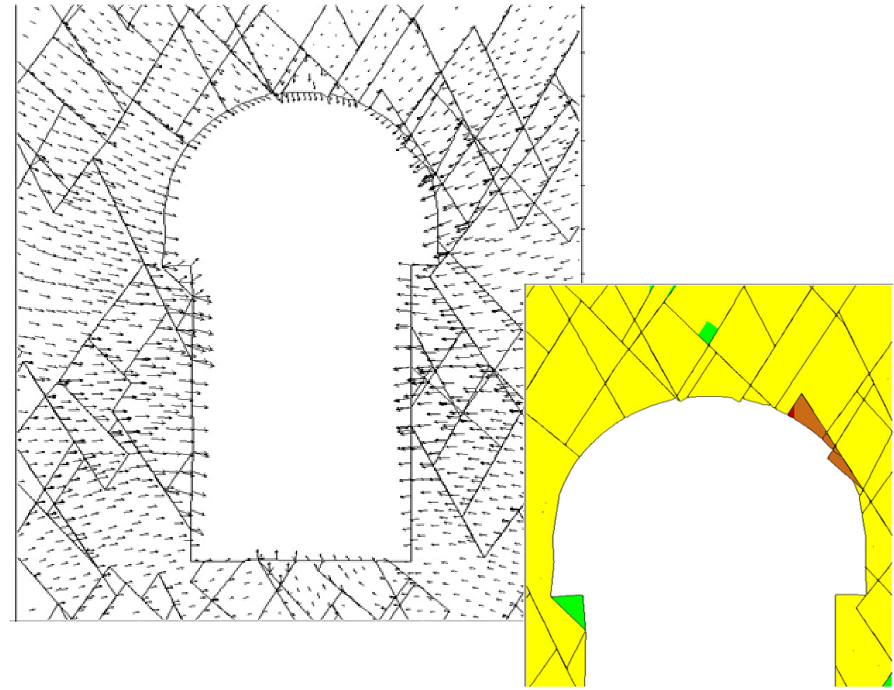


절리면 마찰각 25도



절리면 마찰각 35도

Numerical Analysis
Introduction – example (2)

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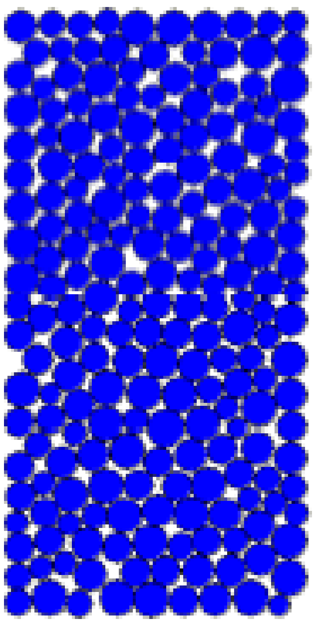
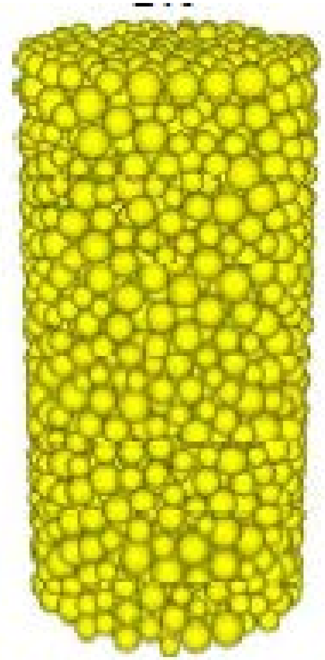
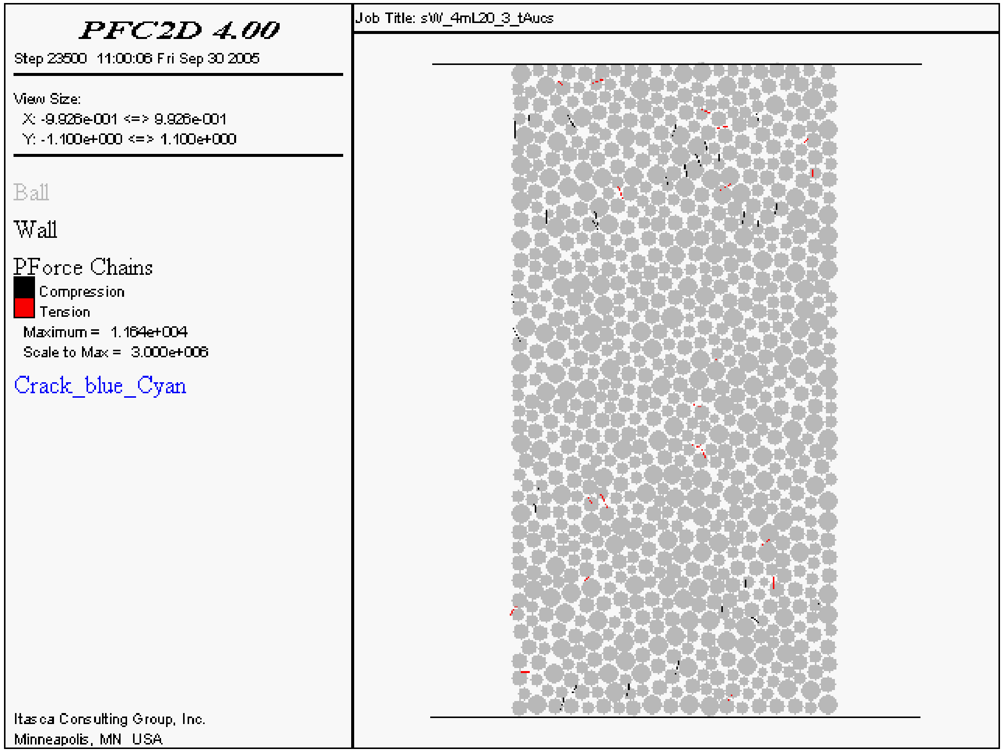
– Computer simulation of rock failure using discrete element method (개별요소법에 의한 파괴 모사 (컴퓨터로 만든 돌?))



2D



3D



Empirical Analysis
Introduction

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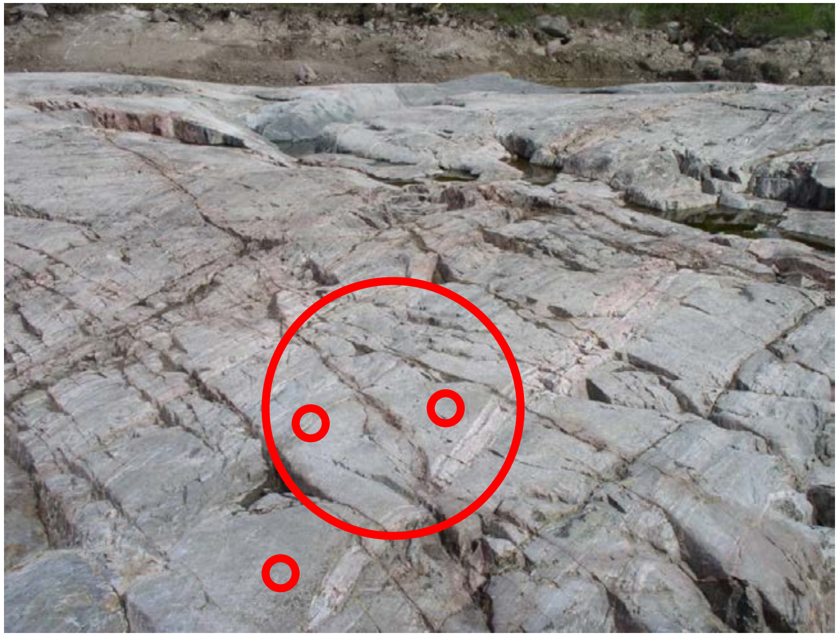

Forsmark, Sweden, 2004

Forsmark, Sweden, www.skb.se

Introduction

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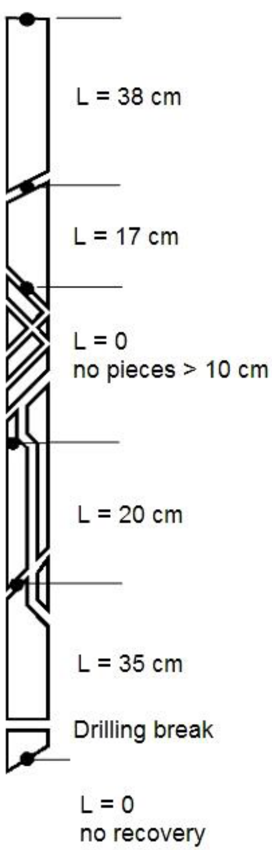
- RQD (Rock Quality Designation) – Deere (1964)
- RMR (Rock Mass Rating) – Bieniawski (1973)
- Q-system (Barton 등, 1974)

Empirical Analysis
RQD

- RQD (Rock Quality Designation): 전체 코어길이 중 길이가 10cm 이상 되는 코어길이의 합을 백분율로 나타낸 값.



Total length of core run = 200 cms

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

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

RQD	암질
25>	매우 불량
25-50	불량
50-75	보통
75-90	양호
90-100	매우 양호

Empirical Analysis
Rock Mass Rating (RMR, Bieniawski, 1989)

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RMR(100) = 무결암강도(15) + RQD(20) + 절리간격(20) + 절리상태(30) + 지하수(15)

변 수			평 점 범 위						
1	무결암의 강도	점하중강도지수	〉10MPa	4~10MPa	2~4MPa	1~2MPa	이 범위에서는 단축압축강도 시험이 필요함		
		단축압축강도	〉250MPa	100~250MPa	50~100MPa	20~50MPa	5-25 MPa	1-5 MPa	〈1 MPa
	평 점		15	12	7	4	2	1	0
2	R Q D		90 ~ 100%	75 ~ 90 %	50 ~ 75%	25 ~ 50%	〈 25%		
	평 점		20	17	13	8	3		
3	절리간격		〉2m	0.6 ~ 2m	200~600mm	60~200mm	〈 60mm		
	평 점		20	15	10	8	5		
4	절리상태		매우 거침. 연속성이 없음. 벌어짐이 없음. 절리면이 풍화되지 않음.	약간 거침. 분리틈새〈1mm 절리면이 약간 풍화.	약간 거침. 분리틈새〈1mm 절리면이 심하게 풍화.	매끄러운면 또는 충전물〈5mm 두께 또는 분리틈새 1~5mm 연속적인 절리면	연약한 충전물〉5mm 두께 또는 분리틈새〉5mm 연속적인 절리면		
	평 점		30	25	20	10	0		
5	지하수	터널길이 10m당 출수량	없음	〈10 리터/분	10-25 리터/분	25-125 리터/분	〉125		
		비 $\frac{절리수압}{최대주응력}$	또는 0	또는 0.0 ~ 0.1	또는 0.1 ~ 0.2	또는 0.2 ~ 0.5	또는 〉0.5		
		일반상태	또는 완전 건조	또는 습 기	또는 젖은 상태	또는 물방울 떨어짐	또는 흘러내림		
	평 점		15	10	7	4	0		

A. RMR 변수 및 평점

변수			평점 범위						
1	무결암의 강도	점하중강도지수	〉10MPa	4~10MPa	2~4MPa	1~2MPa	이 범위에서는 단축압축강도 시험이 필요함		
		단축압축강도	〉250MPa	100~250MPa	50~100MPa	20~50MPa	5~25 MPa	1~5 MPa	〈1 MPa
	평점		15	12	7	4	2	1	0
2	RQD		90 ~ 100%	75 ~ 90 %	50 ~ 75%	25 ~ 50%	〈 25%		
	평점		20	17	13	8	3		
3	절리간격		〉2m	0.6 ~ 2m	200~600mm	60~200mm	〈 60mm		
	평점		20	15	10	8	5		
4	절리상태		매우 거침. 연속성이 없음. 벌어짐이 없음. 절리면이 풍화되지 않음.	약간 거침. 분리틈새〈1mm 절리면이 약간 풍화.	약간 거침. 분리틈새〈1mm 절리면이 심하게 풍화.	매끄러운면 또는 충전물〈5mm 두께 또는 분리틈새 1~5mm 연속적인 절리면	연약한 충전물〉5mm 두께 또는 분리틈새〉5mm 연속적인 절리면		
	평점		30	25	20	10	0		
5	지하수	터널길이 10m당 출수량	없음	〈10 리터/분	10-25 리터/분	25-125 리터분	〉125		
			또는	또는	또는	또는	또는		
		비 $\frac{\text{절리수압}}{\text{최대주응력}}$	0	0.0 ~ 0.1	0.1 ~ 0.2	0.2 ~ 0.5	〉0.5		
			또는	또는	또는	또는	또는		
		일반상태	완전 건조	습 기	젖은 상태	물방울 떨어짐	흘러내림		
	평점		15	10	7	4	0		

Empirical Analysis
Rock Mass Rating (RMR, Bieniawski, 1989)

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B. 불연속면의 방향에 따른 평점보정

절리의 주향과 경사		매우 유리	유 리	보 통	불 리	매우 불리
평 점	터 널	0	-2	- 5	-10	-12
	기 초	0	-2	- 7	-15	-25
	사 면	0	-5	-25	-50	-60

← 보정

C. 분류평점 합계에 의한 암반등급

평점 합계	100 ~ 80	80 ~ 61	60 ~ 41	40 ~ 21	〈 20
암반 등급	I	II	III	IV	V
암반 상태	매우 양호	양호	보통	불량	매우 불량

← 등급

D. 암반등급의 의미

암반 등급	I	II	III	IV	V
평균 자립시간	15m 폭으로 20년	10m 폭으로 1년	5m 폭으로 1주일	2.5m 폭으로 10시간	1m 폭으로 30분
암반의 점착력	〉400 kPa	300 ~ 400 kPa	200 ~ 300 kPa	100 ~ 200 kPa	〈 100 kPa
암반의 마찰각	〈 45°	35° ~45°	25° ~35°	15° ~25°	〈 15°

← 의미

Empirical Analysis

Rock Mass Rating (RMR, Bieniawski, 1989)

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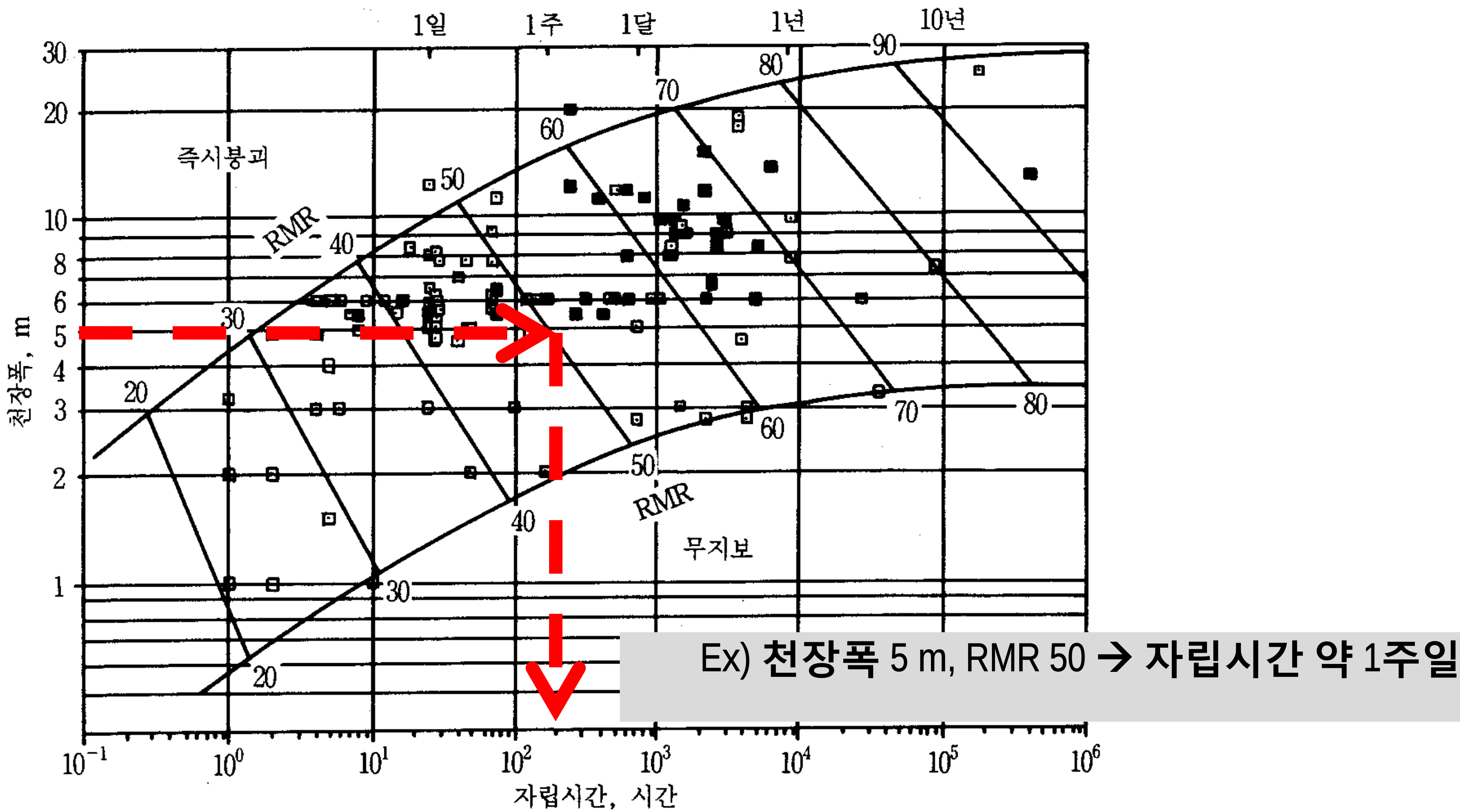

RMR 암반분류 등급에 대한 자립시간과 폭 사이의 상관관계: 검은사각형은 채광, 빈 사각형은 터널굴착시 천장붕괴 사례를 나타낸다. 실선의 곡선은 적용한계이다.

Empirical Analysis
Rock Mass Rating (RMR, Bieniawski, 1989)

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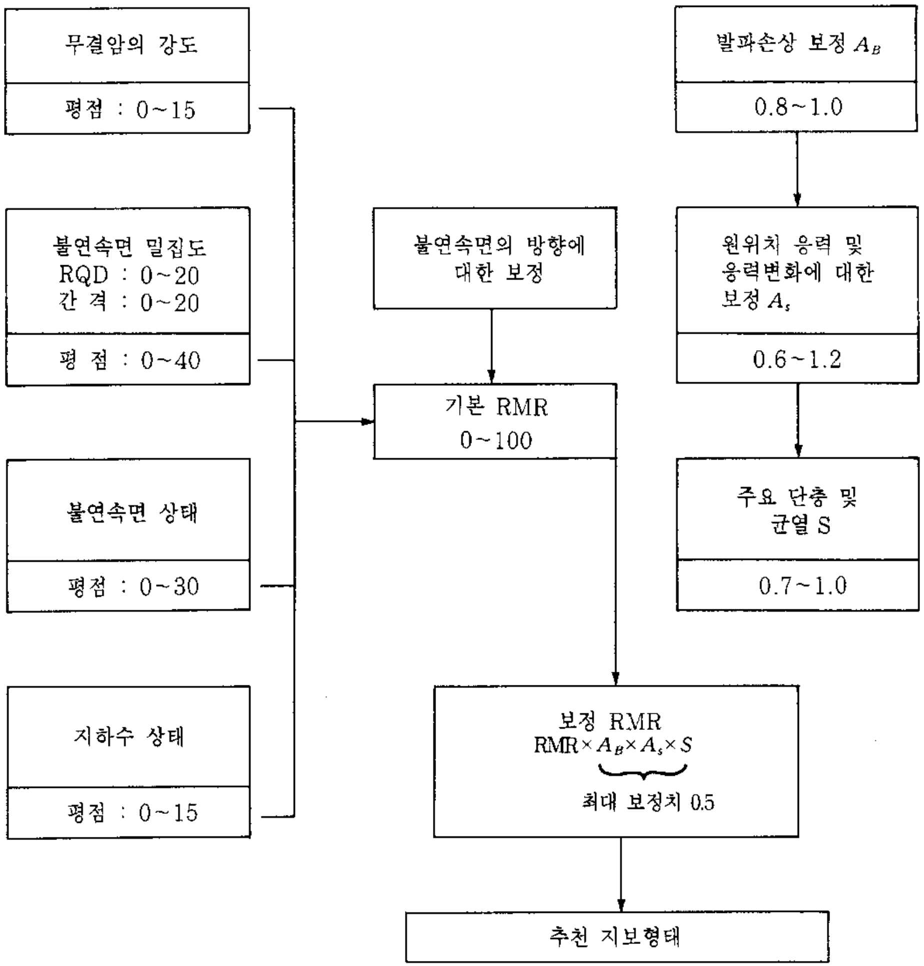

Empirical Analysis
Rock Mass Rating (RMR, Bieniawski, 1989)

터널 형상: 말발굽형; 터널 폭:10 m; 수직응력: 25 MPa 이하; 굴착방법: 천공발파

암반 등급	굴착 형태	지보 록볼트(20mm지름의 전면 접착형)	숏크리트	철재지보
1. 매우 양호한 암반 RMR : 81 100	전단면 : 3m 굴진	경우에 따라 국부적으로 록볼트 설치 이외의 지보설치는 일반적으로 불필요		
2. 양호한 암반 RMR : 61 80	전단면 : 1.0~1.5m 굴진 ; 막장 20m 후방까지 완전한 지보	천장부에 길이 3m, 간격 2.5m 록볼트를 설치, 경우에 따라 와이어메쉬도 함께 설치	천장부의 필요한 곳에 50mm 두께로 타설	불필요
3. 보통의 암반 RMR : 41-60	계단식(top heading & bench) : 상단면이 1.5~3m씩 굴진 ; 발파직후 지보 설치 시작 ; 막장에서 10m 후방까지 완전한 지보	길이 4m, 간격 1.5~2m의 록볼트를 천장부 및 측벽에 체계적으로 설치, 천장부는 와이어메쉬 설치	천장부에 50~100mm 두께, 측벽부에 30mm 두께로 타설	
4. 불량한 암반 RMR : 21-40	계단식 : 상단면이 1.0~1.5m씩 굴진 ; 굴착과 동시에 지보설치-막장 10m 후방	길이 4~5m, 간격1~1.5m의 록볼트를 와이어메쉬와 함께 천장부 및 측벽부에 체계적으로 설치	천장부에 100~150mm 두께, 측벽부에 100mm 두께로 타설	필요한 곳에 1.5m 간격의 소형 철재지보 설치
5. 매우 불량한 암반 RMR : < 20	복수터널을 이용한 굴착 : 상단면이 0.5~1.0m씩 굴진 ; 굴착과 동시에 지보설치 ; 발파후 가능한 빨리 숏크리트 타설	길이 5~6m, 간격 1~1.5m의 록볼트를 와이어메쉬와 함께 천장부 및 측벽부에 체계적으로 설치. 인버트에도 볼트 설치	천장부에 100~200mm 두께, 측벽부에 150mm 두께, 막장면에 50mm 두께로 타설	0.76m 간격의 중형 또는 대형 철재지보를 철재 살창(lagging)과 함께 설치. 필요하다면 포어폴(forepole) 설치. 인버트 폐합.

Rock Support

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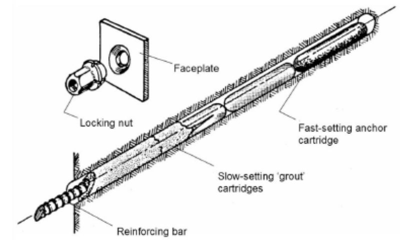
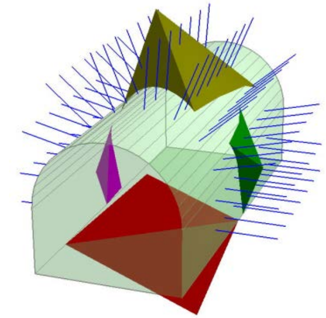
- 록볼트 (Rockbolts)
  - 암반을 붙잡아주는 강철봉 (철근)
  - 탈락가능성이 있는 암반을 붙잡아 줌





- 숏크리트 (Shotcrete)
  - 뿌리는 콘크리트,
    공기식(pneumatically)으로 뿜어주고
    고속으로 벽면에 뿌려지면서 다짐이 발생
  - 굴착에 따른 하중을 분담
- 콘크리트 라이닝 (Concrete Lining)
- 강지보 Steel bar/beam
- 와이어매쉬 (wire mesh)
- 뒷채움 (Backfill)

쇼크리트 코어채취, 1994

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Q-system (Barton, 2002)

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

Mark: 0.001 ~ 1000

블록의 크기 절리면 전단강도 활동성 응력

J_n = 절리군에 관련된 변수. 0.5(괴상) – 20(흙)

J_r = 절리면의 거칠기 변수. 0.5(매우 평탄)-4 (불연속적)

J_a = 절리면의 변질 변수. 0.75 (매우 견고)- 20(점토질)

J_w = 출수에 관련된 변수. 0.05 (과도한 출수)-1.0 (건조)

SRF = 응력저감계수. 0.5-20 (연약대, 응력/강도 비율 등)

Table 6: Classification of individual parameters used in the Tunnelling Quality Index Q

DESCRIPTION	VALUE	NOTES	
1. ROCK QUALITY DESIGNATION	*RQD*		
A. Very poor	0 - 25	1. Where *RQD* is reported or measured as ≤ 10 (including 0),	
B. Poor	25 - 50	a nominal value of 10 is used to evaluate *Q*.	
C. Fair	50 - 75		
D. Good	75 - 90	2. *RQD* intervals of 5, i.e. 100, 95, 90 etc. are sufficiently	
E. Excellent	90 - 100	accurate.	
2. JOINT SET NUMBER	J_n		
A. Massive, no or few joints	0.5 - 1.0		
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	1. For intersections use $(3.0 \times J_n)$	
G. Three joint sets plus random	12		
H. Four or more joint sets, random, heavily jointed, 'sugar cube', etc.	15	2. For portals use $(2.0 \times J_n)$	
J. Crushed rock, earthlike	20		
3. JOINT ROUGHNESS NUMBER	J_r		
a. Rock wall contact			
b. Rock wall contact before 10 cm shear			
A. Discontinuous joints	4		
B. Rough and irregular, undulating	3		
C. Smooth undulating	2		
D. Slickensided undulating	1.5	1. Add 1.0 if the mean spacing of the relevant joint set is	
E. Rough or irregular, planar	1.5	greater than 3 m.	
F. Smooth, planar	1.0		
G. Slickensided, planar	0.5	2. J_r = 0.5 can be used for planar, slickensided joints having	
c. No rock wall contact when sheared		lineations, provided that the lineations are oriented for	
H. Zones containing clay minerals thick enough to prevent rock wall contact	1.0 (nominal)	minimum strength.	
J. Sandy, gravely or crushed zone thick enough to prevent rock wall contact	1.0 (nominal)		
4. JOINT ALTERATION NUMBER	J_a	ϕr degrees (approx.)	
a. Rock wall contact			
A. Tightly healed, hard, non-softening, impermeable filling	0.75		1. Values of ϕr, the residual friction angle, are intended as an approximate guide
B. Unaltered joint walls, surface staining only	1.0	25 - 35	to the mineralogical properties of the
C. Slightly altered joint walls, non-softening mineral coatings, sandy particles, clay-free disintegrated rock, etc.	2.0	25 - 30	alteration products, if present.
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	

4. JOINT ALTERATION NUMBER	J_a	ϕ_r degrees (approx.)	
b. Rock wall contact before 10 cm shear			
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	
c. No rock wall contact when sheared			
K. Zones or bands of disintegrated or crushed	6.0		
L. rock and clay (see G, H and J for clay	8.0		
M. conditions)	8.0 - 12.0	6 - 24	
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)	6.0 - 24.0		
5. JOINT WATER REDUCTION	J_w	approx. water pressure (kgf/cm^2)	
A. Dry excavation or minor inflow i.e. < 5 l/m locally	1.0	< 1.0	
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	1. Factors C to F are crude estimates; increase J_w if drainage installed.
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	2. Special problems caused by ice formation are not considered.
F. Exceptionally high inflow or pressure	0.1 - 0.05	> 10	
6. STRESS REDUCTION FACTOR		*SRF*	
a. Weakness zones intersecting excavation, which may cause loosening of rock mass when tunnel is excavated			
A. Multiple occurrences of weakness zones containing clay or chemically disintegrated rock, very loose surrounding rock any depth)		10.0	1. Reduce these values of *SRF* by 25 - 50% but only if the relevant shear zones influence do not intersect the excavation
B. Single weakness zones containing clay, or chemically dis- tegrated rock (excavation depth < 50 m)		5.0	
C. Single weakness zones containing clay, or chemically dis- tegrated 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	

DESCRIPTION	VALUE			NOTES
6. STRESS REDUCTION FACTOR			*SRF*	
b. Competent rock, rock stress problems				
	σ_c/σ_1	σ_t/σ_1		2. 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 and σ_t to $0.6\sigma_c$ and $0.6\sigma_t$, where σ_c = unconfined compressive strength, and σ_t = tensile strength (point load) and σ_1 and σ_3 are the major and minor principal stresses.
H. Low stress, near surface	> 200	> 13	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	3. 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).
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	

ADDITIONAL NOTES ON THE USE OF THESE TABLES

When making estimates of the rock mass Quality (*Q*), the following guidelines should be followed in addition to the notes listed in the tables:

1. When borehole core is unavailable, *RQD* can be estimated from the number of joints per unit volume, in which the number of joints per metre for each joint set are added. A simple relationship can be used to convert this number to *RQD* for the case of clay free rock masses: $RQD = 115 - 3.3\,J_v$ (approx.), where J_v = total number of joints per m^3 ($0 < RQD < 100$ for $35 > J_v > 4.5$).
2. The parameter J_n representing the number of joint sets will often be affected by foliation, schistosity, slaty cleavage or bedding etc. If strongly developed, these parallel 'joints' should obviously be counted as a complete joint set. However, if there are few 'joints' visible, or if only occasional breaks in the core are due to these features, then it will be more appropriate to count them as 'random' joints when evaluating J_n.
3. The parameters J_r and J_a (representing shear strength) should be relevant to the weakest significant joint set or clay filled discontinuity in the given zone. However, if the joint set or discontinuity with the minimum value of J_r/J_a is favourably oriented for stability, then a second, less favourably oriented joint set or discontinuity may sometimes be more significant, and its higher value of J_r/J_a should be used when evaluating *Q*. The value of J_r/J_a should in fact relate to the surface most likely to allow failure to initiate.
4. When a rock mass contains clay, the factor *SRF* appropriate to loosening loads should be evaluated. In such cases the strength of the intact rock is of little interest. However, when jointing is minimal and clay is completely absent, the strength of the intact rock may become the weakest link, and the stability will then depend on the ratio rock-stress/rock-strength. A strongly anisotropic stress field is unfavourable for stability and is roughly accounted for as in note 2 in the table for stress reduction factor evaluation.
5. The compressive and tensile strengths (σ_c and σ_t) of the intact rock should be evaluated in the saturated condition if this is appropriate to the present and future in situ conditions. A very conservative estimate of the strength should be made for those rocks that deteriorate when exposed to moist or saturated conditions.

Empirical Analysis
Q-system (Barton, 2002)

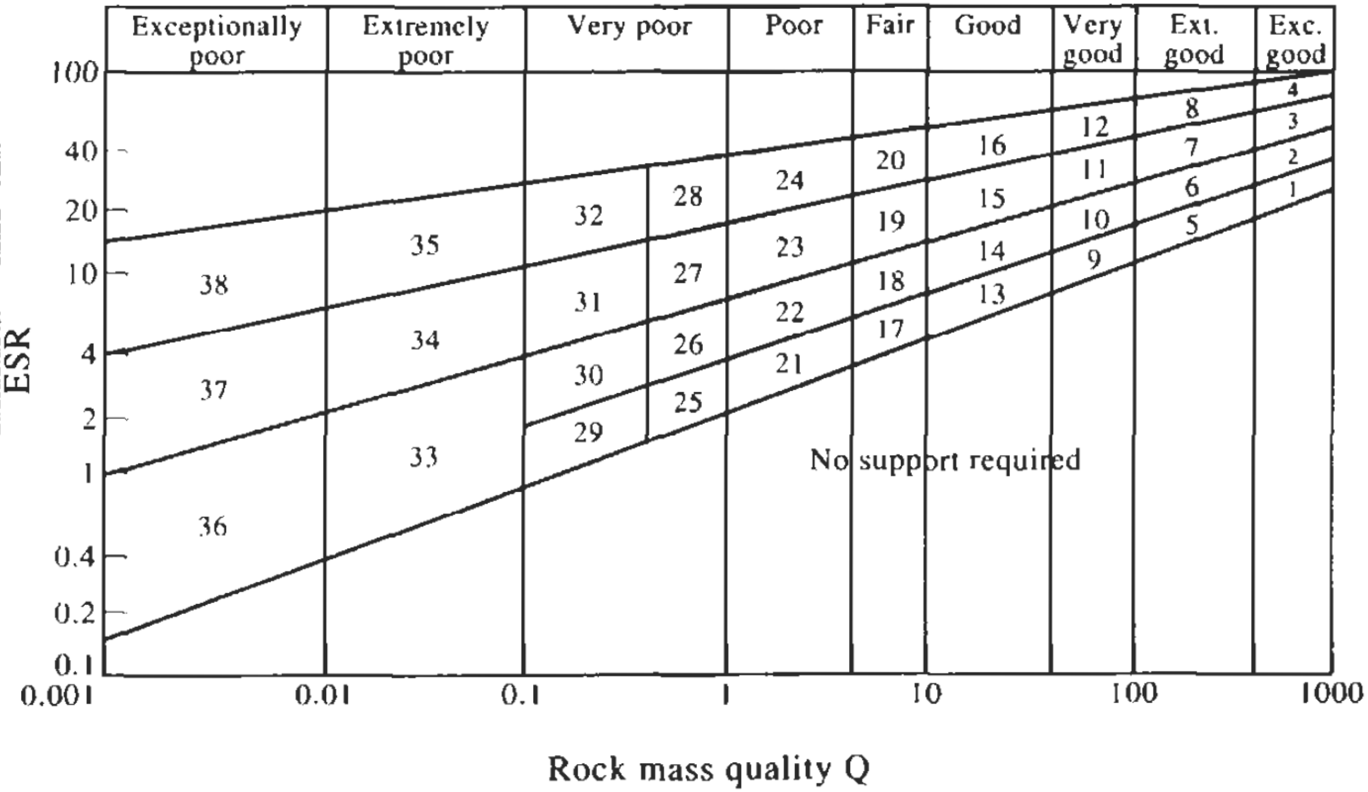
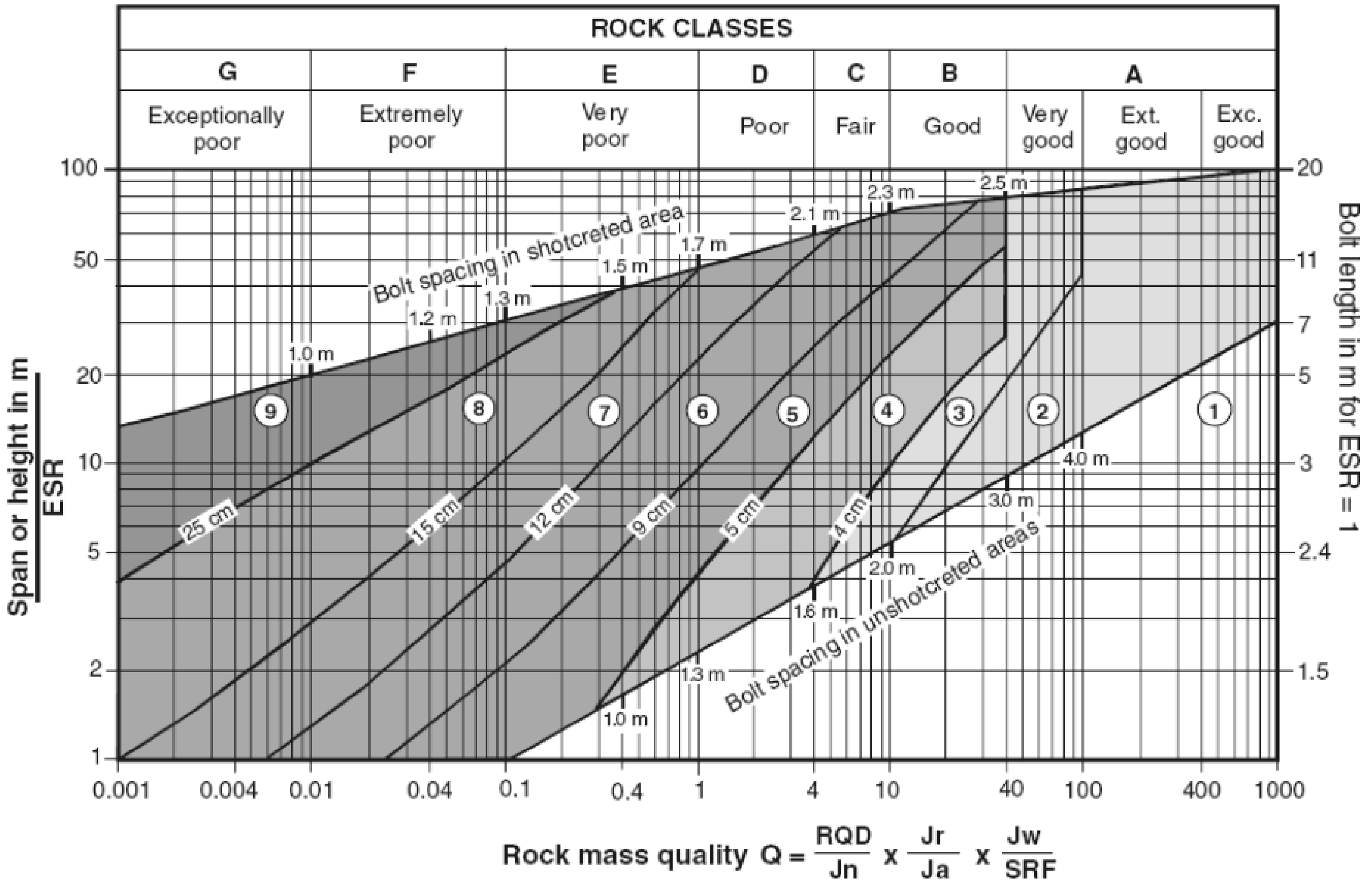


Figure 12.2 Support requirements for the Q-system (for fuller details see Bieniawski, 1989).

ESR: excavation support ratio

Empirical Analysis
Q-system (Barton, 2002)



REINFORCEMENT CATEGORIES:

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

Empirical Analysis
Q-system (Barton, 2002)

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- 터널 종류에 따른 ESR (Excavation Support Ratio) 변화

굴 착 용 도	ESR
A. 임시적인 광산터널	2 ~ 5
B. 영구적 광산터널, 수력발전소 도수터널 (양수발전소의 고압 수압관터널 제외), 선진터널, 수평갱도, 대형 공동의 수평갱도와 상단터널(heading), 조압수조(surge chamber)	1.6 ~ 2.0
C. 저장공동, 수처리 공장, 소규모 도로 및 철도 터널, 진입터널(access tunnel)	1.2 ~ 1.3
D. 발전소, 대규모 고속도로 또는 철도 터널, 민방위용 공동, 출입구, 터널교차부	0.9 ~ 1.1
E. 지하 핵 발전소, 철도역, 스포츠나 공공시설, 공장, 대규모 개스파이프라인 터널	0.5 ~ 0.8

Empirical Analysis
RMR & Q-system

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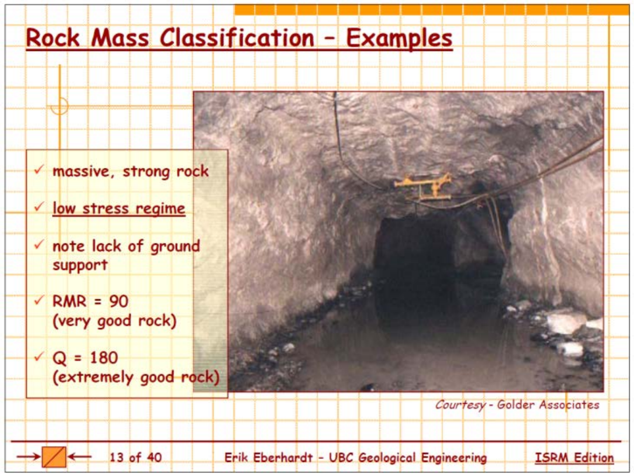

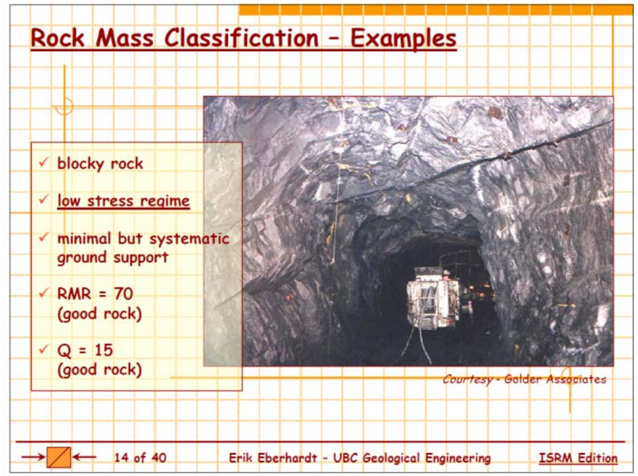

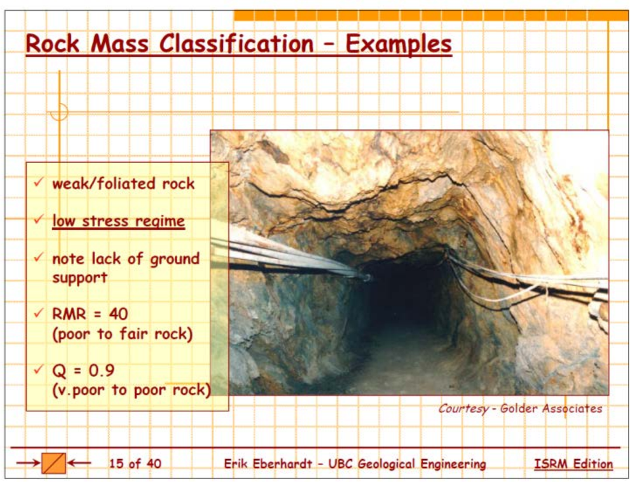

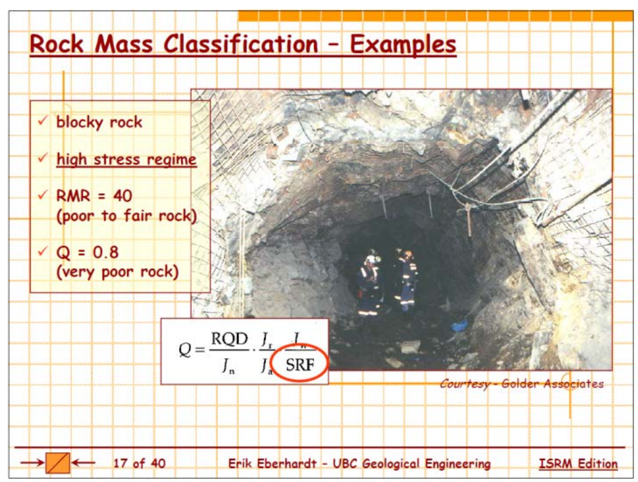

- From lecture note by Prof Eric Eberhardt (Univ British Columbia)

Stress-Strain Relationship (Hooke's Law)-보충

Relationship with V_p and V_s

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$$V_p^{\,2} = \left[\frac{E}{\rho} \frac{(1-\nu)}{(1+\nu)(1-2\nu)} \right]$$

$$V_s^{\,2} = \left[\frac{E}{\rho} \frac{1}{2(1+\nu)} \right]$$

$$E_{dyn} = \rho V_s^2 \frac{3V_p^2 - 4V_s^2}{V_p^2 - V_s^2}$$

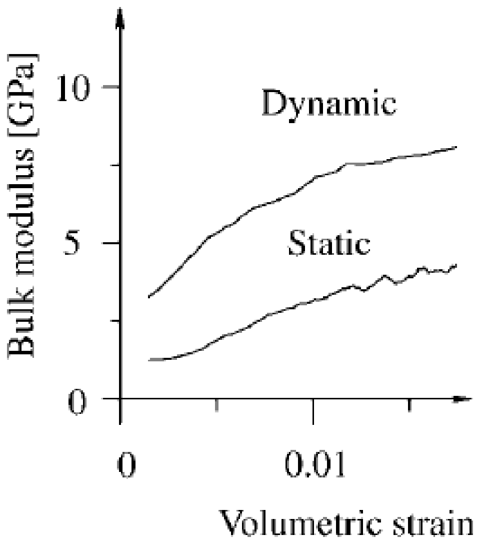
$$\nu_{dyn} = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)}$$

E_{dyn} : Dynamic Elastic Modulus

ν_{dyn} : Dynamic Poisson's Ratio

V_p : P wave velocity

V_s : S wave velocity



Dry red Wildmoor sandstone (Fjaer et al., 2008)

- In reality, Dynamic E ≠ Static E. Typically Dynamic E > Static E.
- Difference decrease with stronger, larger confinement