

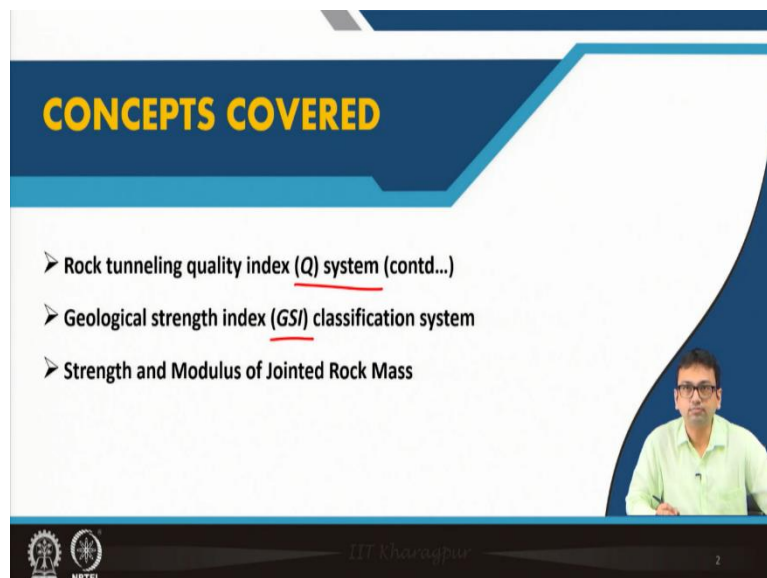
Rock Mechanics and Tunneling
Professor Dr. Debarghya Chakraborty
Department of Civil Engineering
Indian Institute of Technology, Kharagpur
Lecture 26
Rock mass classification (continued)

(Refer Slide Time: 00:34)



Hello everyone. I welcome all of you to the fifth lecture of module 5. So, in module 5, we are discussing about the rock mass classification and this will be the last lecture of this module.

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In this lecture a problem will be solved on Q-system which was discussed in detail in the previous lecture.

Then we will learn another classification system that is called the geological strength index, GSI classification system. We will see its importance later when we will learn about the weak round hill criteria. And after learning these two things, at the end, we will little bit discuss about the strength and modulus of jointed rock mass.

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Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Table 1: RQD values in Q-system

Class	Quality of Rock	RQD value (%)
A	Very poor	0 - 25
B	Poor	25 - 50
C	Fair	50 - 75
D	Good	75 - 90
E	Excellent	90 - 100

Notes: (i) Where RQD is reported or measured as ≤ 10 (including 0), a nominal value of 10 is used to evaluate Q. (ii) RQD intervals of 5, i.e., 100, 95, 90, etc., are sufficiently accurate.

Source: Barton (2002)*

*Barton, N. 2002. Some new Q-value correlations to assist in site characterization and tunnel design. *International Journal of Rock Mechanics and Mining Sciences*, 39(2), 185-216.



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To solve the table Barton 2002 tables (modified) have been kept.

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Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Table 2: Joint set number J_n for Q-system

Class	Description	J_n
A	Massive, no or few joints	0.5 - 1.0
B	One joint set	2
C	One joint set plus random joints	3
D	Two joint sets	4
E	Two joint sets plus random joints	6
F	Three joint sets	9
G	Three joint sets plus random joints	12
H	Four or more joint sets, random, heavily jointed, 'sugar cube', etc.	15
J	Crushed rock, earthlike	20

Notes: (i) For tunnel intersections, use $(3.0 \times J_n)$. (ii) For portals use $(2.0 \times J_n)$

Source: Barton (2002)



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Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Table 3: Joint Roughness number J_r

Class	Joint Roughness number	J_r
(a) Rock wall contact, and (b) Rock wall contact before 10 cm shear		
A	Discontinuous joints	4
B	Rough or 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	Zone containing clay minerals thick enough to prevent rock wall contact	1.0
I	Sandy, gravelly or crushed zone thick enough to prevent rock wall contact	1.0

Notes: (i) Descriptions refer to small and intermediate scale features, in that order, (ii) Add 1.0 if the mean spacing of the relevant joint set > 3 m. (iii) $J_r = 0.5$ can be used for planar, slickensided joints having lineations, provided the lineations are orientated for minimum strength. (iv) J_r and J_a classification is applied to the joint set or discontinuity that is least favourable for stability both from the point of view of orientation and shear resistance, τ (where $\tau \approx \sigma_n \tan^2(1/2 J_r)$).

Source: Barton (2002)



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Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Table 4: Joint Alteration Number J_a

Class	Joint Alteration Number	ϕ , (approx.)	J_a
(i) Rock wall contact (no mineral fillings, only coatings)			
A	Tight healed, hard, non-softening, impermeable filling, i.e., quartz or epidote	-	0.75
B	Unaltered joint walls, surface staining only	25 - 35°	1.0
C	Slightly altered joint walls. Non-softening mineral coatings, sandy particles, clay-free disintegrated rock, etc.	25 - 30°	2.0
D	Silty- or sandy-clay coatings, small clay fraction (non-softening)	20 - 25°	3.0
E	Softening or low friction clay mineral coatings, i.e., kaolinite or mica. Also chlorite, talc, gypsum, graphite, etc., and small quantities of swelling clays.	8 - 16°	4.0

Source: Barton (2002)



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Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Table 4: Joint Alteration Number J_a (contd...)

Class	Joint Alteration Number	ϕ , (approx.)	J_a
(ii) Rock wall contact before 10 cm shear (thin mineral fillings)			
F	Sandy particles, clay-free disintegrated rock, etc.	25 - 30°	4
G	Strongly over-consolidated, non-softening clay mineral fillings (continuous, but < 5 mm in thickness)	16 - 24°	6
H	Medium or low over-consolidation, softening, clay mineral fillings (continuous, but < 5 mm in thickness)	12 - 16°	8
J	Swelling clay fillings, i.e., montmorillonite (continuous, but < 5 mm in thickness). Value of J_a depends on the percent of swelling clay size particles, and access to water, etc.	6 - 12°	8 - 12
(iii) No rock wall contact when sheared (thick mineral fillings)			
K, L, M	Zones or bands of disintegrated or crushed rock and clay (refer G, H and J for description of clay conditions)	6 - 24°	6, 8, or 8 - 12
N	Zones or bands of Silty- or sandy-clay, small clay fraction (non-softening)	-	5
O, P, R	Thick, continuous zones or bands of clay (refer G, H and J for description of clay conditions)	6 - 24°	10, 13 or 13 - 20

Source: Barton (2002)



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Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Table 5: Joint water reduction factor J_w

Class	Joint water reduction factor	Approx. water pressure (kg/cm ²)	J_w
A	Dry excavation or minor inflow, i.e., < 5 liter/min locally	< 1.0	1.0
B	Medium inflow or pressure, occasional outwash of joint fillings	1 – 2.5	0.66
C	Large inflow or high pressure in competent rock with unfilled joints	2.5 – 10	0.5
D	Large inflow or high pressure, considerable outwash of joint fillings	2.5 – 10	0.33
E	Exceptionally high inflow or water pressure at blasting, decaying with time	> 10	0.2 – 0.1
F	Exceptionally high inflow or water pressure continuing without noticeable decay	> 10	0.1 – 0.05

Source: Barton (2002)

Notes: (i) Factors C to F are crude estimates. Increase J_w if drainage measures are installed. (ii) Special problems caused by ice formation are not considered. (iii) For general characterization of rock masses distant from excavation influences, the use of $J_w = 1.0, 0.66, 0.5, 0.33$, etc. as depth increases from say 0–5, 5–25, 25–250 to >250 m is recommended, assuming that RQD/J_w is low enough (e.g. 0.5–25) for good hydraulic connectivity. This will help to adjust Q for some of the effective stress and water softening effects, in combination with appropriate characterization values of SRF. Correlations with depth-dependent static deformation modulus and seismic velocity will then follow the practice used when these were developed.





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Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Table 6(i): Stress Reduction Factor SRF

Class	Weakness zones intersecting excavation, which may cause loosening of rock mass when tunnel is excavated	SRF
A	Multiple occurrences of weakness zones containing clay or chemically disintegrated rock, very loose surrounding rock (any depth)	10
B	Single weakness zones containing clay or chemically disintegrated rock (depth of excavation ≤ 50 m)	5
C	Single weakness zones containing clay or chemically disintegrated rock (depth of excavation > 50 m)	2.5
D	Multiple shear zones in competent rock (clay-free), loose surrounding rock (any depth)	7.5
E	Single shear zones in competent rock (clay-free) (depth of excavation ≤ 50 m)	5
F	Single shear zones in competent rock (clay-free) (depth of excavation > 50 m)	2.5
G	Loose, open joints, heavily jointed or 'sugar cube', etc. (any depth)	5

Source: Barton (2002)

Notes: (i) Reduce these values SRF by 25-50% if the relevant shear zones only influence but do not intersect the excavation. This will also be relevant for characterization.





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Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Table 6(ii): Stress Reduction Factor SRF (contd...)

Class	Competent rock, rock stress problems	σ_1 / σ_3	σ_θ / σ_3	SRF
H	Low stress, near surface, open joints	> 200	< 0.01	2.5
J	Medium stress, favorable stress condition	200 – 10	0.01 – 0.03	1
K	High stress, very tight structure. Usually favorable to stability, may be unfavorable to wall stability	10 – 5	0.3 – 0.4	0.5 – 2
L	Moderate slabbing after > 1 hour in massive rock	5 – 3	0.5 – 0.65	5 – 50
M	Slabbing and rock burst after a few minutes in massive rock	3 – 2	0.65 – 1	50 – 200
N	Heavy rock burst (strain-burst) and immediate dynamic deformation in massive rock	< 2	> 1	200 – 400

Notes: (ii) For strongly anisotropic virgin stress field (if measured): When $5 \leq \sigma_1 / \sigma_3 \leq 10$, reduce σ_1 to $0.75\sigma_1$; When $\sigma_1 / \sigma_3 > 10$, reduce σ_1 to $0.5\sigma_1$; where σ_3 is unconfined compressive strength, σ_1 and σ_3 are major and minor principal stresses, and σ_θ is the maximum tangential stress (estimated from elastic theory). (iii) Few case records are available where the depth of crown below surface is less than span width. Suggest increase in SRF from 2.5 to 5 for such cases (refer H). (iv) Cases L, M, and N are usually most relevant for support design of deep tunnel excavations in hard massive rock masses, with RQD/J_r ratios from about 50–200. (v) For general characterization of rock masses distant from excavation influences, the use of SRF = 5, 2.5, 1.0, and 0.5 is recommended as depth increases from say 0–5, 5–25, 25–250 to >250 m. This will help to adjust Q for some of the effective stress effects, in combination with appropriate characterization values of J_r . Correlations with depth-dependent static deformation modulus and seismic velocity will then follow the practice used when these were developed.

Source: Barton (2002)



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Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Table 6(iii): Stress Reduction Factor SRF (contd...)

Class	Squeezing rock: plastic flow of incompetent rock under the influence of high rock pressure	σ_θ / σ_c	SRF
O	Mild squeezing rock pressure	1 – 5	5 – 10
P	Heavy squeezing rock pressure	> 5	10 – 20

Notes: (vi) Cases of squeezing rock may occur for depth, $H > 350 Q^{1/3}$ according to Singh (1993)*. Rock mass compression strength can be estimated from $\sigma_{cm} \approx 5\gamma Q_c^{1/3}$ (MPa), where γ is the rock density in t/m^3 , and $Q_c = Q \times \sigma_c / 100$, (Barton, 2000)**.

Source: Barton (2002)

* Singh, B. 1993. Norwegian method of tunneling workshop. New Delhi: CSMR.

** Barton, N. 2000. TBM tunneling in jointed and faulted rock. Rotterdam: Balkema, 173p.



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Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Table 6(iv): Stress Reduction Factor SRF (contd...)

Class	Swelling rock: chemical swelling activity depending on presence of water	SRF
R	Mild swelling rock pressure	5 – 10
S	Heavy swell rock pressure	10 – 15

Source: Barton (2002)



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Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Table 7: Rock mass classification based on Q – system (Barton et al., 1974)

Q - value	Class	Remarks
400 – 1000	A	Exceptionally good
100 – 400	A	Extremely good
40 – 100	A	Very good
10 – 40	B	Good
4 – 10	C	Fair
1 – 4	D	Poor
0.1 – 1.0	E	Very poor
0.01 – 0.1	F	Extremely poor
0.001 – 0.01	G	Exceptionally poor

Source: Deb and Verma (2016)



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Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Problem on Q – system

- It is proposed to construct an underground tunnel 800 m below the ground. The drilled cores have an RQD of 90% and the number of joint set is found to be 1. The joints are discontinuous and tight healed, hard with impermeable filling. The average uniaxial compressive strength of the cores is 450 MPa. The major principal stress acts horizontally and is 1.5 times the vertical stress. The unit weight of the rock is approximately 30 kN/m³. The excavation is relatively dry, with some dampness and negligible inflow. Estimate the Q-value.

Source: Sivakugan et al. (2013)



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Example problem: It is proposed to construct an underground tunnel 800 m below the ground. The drilled cores have an RQD of 90 % and the number of joint set is found to be 1. The joints are discontinuous and tight healed, hard with impermeable filling. The average uniaxial compressive strength of the core is 450 MPa. The major principal stress acts horizontally and is 1.5 times the vertical stress. The unit weight of the rock is approximately 30 kN/m³. The excavation is relatively dry with some dampness and negligible inflow, so dry with some dampness and negligible inflow. Estimate Q-value.

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Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Solution:

- RQD = 90%; $\gamma_{\text{rock}} = 30 \text{ kN/m}^3$
- Number of joint sets = 1
 - Joint set number, $J_n =$ (As per Table 2)
- Joints are discontinuous
 - Joint roughness number, $J_r =$ (As per Table 3)
- Joint walls are tightly healed, hard with impermeable filling
 - Joint alteration number, $J_a =$ (As per Table 4)
- Excavation is relatively dry with some dampness and negligible flow
 - Joint water reduction factor, $J_w =$ (As per Table 5)



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Solution:

- RQD = 90%; $\gamma_{\text{rock}} = 30 \text{ kN/m}^3$
- Number of joint sets = 1
 - Joint set number, $J_n = 2$ (As per table 2)
- Joints are discontinuous
 - Joint roughness number, $J_r = 4$ (As per table 3)
- Joint walls are tight healed, hard with impermeable filling
 - Joint alteration number, $J_a = 0.75$ (As per table 4)
- Excavation is relatively dry with some dampness and negligible inflow
 - Joint water reduction factor, $J_w = 1$ (As per table 5)
- Vertical stress at the depth (z) of 800 m (minor principal stress, σ_3)

$$= \gamma_{\text{rock}} * (z) = 30 * 800 = 24000 \text{ kPa} = \mathbf{24 \text{ MPa}}$$
- The major principal stress (σ_1) = $1.5 \sigma_3 = 1.5 * 24 = \mathbf{36 \text{ MPa}}$
- Uniaxial compressive strength of rock (σ_c) = **450 MPa**
- So, $\sigma_c / \sigma_1 = 450 / 36 = \mathbf{12.5}$
- Rock component class -J; strength reduction factor, SRF = **1** (As per table 6(ii))
- Q value = $(\text{RQD} / J_n) \times (J_r / J_a) \times (J_w / \text{SRF}) = (90 / 2) (4 / 0.75) (1 / 1) = \mathbf{240}$
- As per table 7, the rock mass quality is **extremely good (class A)**

- (Refer Slide Time: 05:51)

Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Solution (contd...):

- Vertical stress at the depth (z) of 800 m (minor principal stress, σ_3) = ($\gamma_{\text{rock}} \times z$) =
- The major principal stress (σ_1) = $1.5 \sigma_3$ =
- Uniaxial compressive strength of the rock (σ_c) = 450 MPa
- So, σ_c / σ_1 =
- Rock component class – J; The strength reduction factor, SRF = (As per Table 6(ii))
- Q value = $(RQD / J_n) \times (J_r / J_d) \times (J_w / SRF)$
- =
- As per Table 7, the rock mass quality is



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Classification based on Rock Tunneling Quality Index (Q) system (contd...)

✓ Table 2: Joint set number J_n for Q-system

Class	Description	J_n
A	Massive, no or few joints	0.5 – 1.0
B	✓ One joint set	2
C	One joint set plus random joints	3
D	Two joint sets	4
E	Two joint sets plus random joints	6
F	Three joint sets	9
G	Three joint sets plus random joints	12
H	Four or more joint sets, random, heavily jointed, 'sugar cube', etc.	15
J	Crushed rock, earthlike	20

Source: Barton (2002)

Notes: (i) For tunnel intersections, use $(3.0 \times J_n)$. (ii) For portals use $(2.0 \times J_n)$



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Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Problem on Q – system

- It is proposed to construct an underground tunnel 800 m below the ground. The drilled cores have an RQD of 90% and the number of joint set is found to be 1. The joints are discontinuous and tight healed, hard with impermeable filling. The average uniaxial compressive strength of the cores is 450 MPa. The major principal stress acts horizontally and is 1.5 times the vertical stress. The unit weight of the rock is approximately 30 kN/m³. The excavation is relatively dry, with some dampness and negligible inflow. Estimate the Q-value.

Source: Sivakugan et al. (2013)



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Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Table 3: Joint Roughness number J_r

Class	Joint Roughness number	J_r
(a) Rock wall contact, and (b) Rock wall contact before 10 cm shear		
A	Discontinuous joints	4
B	Rough or 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	Zone containing clay minerals thick enough to prevent rock wall contact	1.0
I	Sandy, gravelly or crushed zone thick enough to prevent rock wall contact	1.0

Notes: (i) Descriptions refer to small and intermediate scale features, in that order, (ii) Add 1.0 if the mean spacing of the relevant joint set > 3 m. (iii) $J_r = 0.5$ can be used for planar, slickensided joints having lineations, provided the lineations are orientated for minimum strength. (iv) J_r and J_a classification is applied to the joint set or discontinuity that is least favourable for stability both from the point of view of orientation and shear resistance, τ (where $\tau \approx \sigma_n \tan^2(\psi/J_r)$).

Source: Barton (2002)



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Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Table 4: Joint Alteration Number J_a

Class	Joint Alteration Number	ϕ , (approx.)	J_a
(i) Rock wall contact (no mineral fillings, only coatings)			
A	Tight healed, hard, non-softening, impermeable filling, i.e., quartz or epidote	-	0.75
B	Unaltered joint walls, surface staining only	25 - 35°	1.0
C	Slightly altered joint walls. Non-softening mineral coatings, sandy particles, clay-free disintegrated rock, etc.	25 - 30°	2.0
D	Silty- or sandy-clay coatings, small clay fraction (non-softening)	20 - 25°	3.0
E	Softening or low friction clay mineral coatings, i.e., kaolinite or mica. Also chlorite, talc, gypsum, graphite, etc., and small quantities of swelling clays.	8 - 16°	4.0

Source: Barton (2002)



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Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Table 5: Joint water reduction factor J_w

Class	Joint water reduction factor	Approx. water pressure (kg/cm ²)	J_w
A	Dry excavation or minor inflow, i.e., < 5 liter/min locally	< 1.0	1.0
B	Medium inflow or pressure, occasional outwash of joint fillings	1 - 2.5	0.66
C	Large inflow or high pressure in competent rock with unfilled joints	2.5 - 10	0.5
D	Large inflow or high pressure, considerable outwash of joint fillings	2.5 - 10	0.33
E	Exceptionally high inflow or water pressure at blasting, decaying with time	> 10	0.2 - 0.1
F	Exceptionally high inflow or water pressure continuing without noticeable decay	> 10	0.1 - 0.05

Notes: (i) Factors C to F are crude estimates. Increase J_w if drainage measures are installed. (ii) Special problems caused by ice formation are not considered. (iii) For general characterization of rock masses distant from excavation influences, the use of $J_w = 1.0, 0.66, 0.5, 0.33$, etc. as depth increases from say 0-5, 5-25, 25-250 to >250 m is recommended, assuming that RQD/J_r is low enough (e.g. 0.5-25) for good hydraulic connectivity. This will help to adjust Q for some of the effective stress and water softening effects, in combination with appropriate characterization values of SRP. Correlations with depth-dependent static deformation modulus and seismic velocity will then follow the practice used when these were developed.

Source: Barton (2002)



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Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Problem on Q – system

Solution:

- $RQD = 90\%$; $\gamma_{rock} = 30 \text{ kN/m}^3$
- Number of joint sets = 1
 - Joint set number, $J_n = 2$ (As per Table 2)
- Joints are discontinuous
 - Joint roughness number, $J_r = 4$ (As per Table 3)
- Joint walls are tightly healed, hard with impermeable filling
 - Joint alteration number, $J_a = 0.75$ (As per Table 4)
- Excavation is relatively dry with some dampness and negligible flow
 - Joint water reduction factor, $J_w = 1$ (As per Table 5)



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Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Table 6(i): Stress Reduction Factor SRF

Class	Weakness zones intersecting excavation, which may cause loosening of rock mass when tunnel is excavated	SRF
A	Multiple occurrences of weakness zones containing clay or chemically disintegrated rock, very loose surrounding rock (any depth)	10
B	Single weakness zones containing clay or chemically disintegrated rock (depth of excavation ≤ 50 m)	5
C	Single weakness zones containing clay or chemically disintegrated rock (depth of excavation > 50 m)	2.5
D	Multiple shear zones in competent rock (clay-free), loose surrounding rock (any depth)	7.5
E	Single shear zones in competent rock (clay-free) (depth of excavation ≤ 50 m)	5
F	Single shear zones in competent rock (clay-free) (depth of excavation > 50 m)	2.5
G	Loose, open joints, heavily jointed or 'sugar cube', etc. (any depth)	5

Notes: (i) Reduce these values SRF by 25-50% if the relevant shear zones only influence but do not intersect the excavation. This will also be relevant for characterization.

Source: Barton (2002)



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Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Table 6(ii): Stress Reduction Factor SRF (contd...)

Class	Competent rock, rock stress problems	σ_1 / σ_3	σ_3 / σ_1	SRF
H	Low stress, near surface, open joints	> 200	< 0.01	2.5
J	Medium stress, favorable stress condition	<u>200 – 10</u>	0.01 – 0.03	<u>1</u>
K	High stress, very tight structure. Usually favorable to stability, may be unfavorable to wall stability	10 – 5	0.3 – 0.4	0.5 – 2
L	Moderate slabbing after > 1 hour in massive rock	5 – 3	0.5 – 0.65	5 – 50
M	Slabbing and rock burst after a few minutes in massive rock	3 – 2	0.65 – 1	50 – 200
N	Heavy rock burst (strain-burst) and immediate dynamic deformation in massive rock	< 2	> 1	200 – 400

Notes: (ii) For strongly anisotropic virgin stress field (if measured): When $5 \leq \sigma_1 / \sigma_3 \leq 10$, reduce σ_3 to $0.75\sigma_3$; When $\sigma_1 / \sigma_3 > 10$, reduce σ_3 to $0.5\sigma_3$; where σ_3 is unconfined compressive strength, σ_1 and σ_3 are major and minor principal stresses, and σ_3 is the maximum tangential stress (estimated from elastic theory). (iii) Few case records are available where the depth of crown below surface is less than span width. Suggest increase in SRF from 2.5 to 5 for such cases (refer H). (iv) Cases L, M, and N are usually most relevant for support design of deep tunnel excavations in hard massive rock masses, with RQD/J_n ratios from about 50–200. (v) For general characterization of rock masses distant from excavation influences, the use of SRF = 5, 2.5, 1.0, and 0.5 is recommended as depth increases from say 0–5, 5–25, 25–250 to > 250 m. This will help to adjust Q for some of the effective stress effects, in combination with appropriate characterization values of J_n . Correlations with depth-dependent static deformation modulus and seismic velocity will then follow the practice used when these were developed.

Source: Barton (2002)



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Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Table 6(iii): Stress Reduction Factor SRF (contd...)

Class	Squeezing rock: plastic flow of incompetent rock under the influence of high rock pressure	σ_θ / σ_c	SRF
O	Mild squeezing rock pressure	1 – 5	5 – 10
P	Heavy squeezing rock pressure	> 5	10 -20

Source: Barton (2002)

Notes: (vi) Cases of squeezing rock may occur for depth, $H > 350 Q^{1/3}$ according to Singh (1993)*. Rock mass compression strength can be estimated from $\sigma_{cm} \approx 5\gamma Q_c^{1/3}$ (MPa), where γ is the rock density in t/m^3 , and $Q_c = Q \times \sigma_c / 100$, (Barton, 2000)**.

* Singh, B. 1993. Norwegian method of tunneling workshop. New Delhi: CSMRS.

** Barton, N. 2000. TBM tunneling in jointed and faulted rock. Rotterdam: Balkema, 173p.



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Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Table 6(iv): Stress Reduction Factor SRF (contd...)

Class	Swelling rock: chemical swelling activity depending on presence of water	SRF
R	Mild swelling rock pressure	5 – 10
S	Heavy swell rock pressure	10 – 15

Source: Barton (2002)



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Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Table 7: Rock mass classification based on Q – system (Barton et al., 1974)

Q - value	Class	Remarks
400 – 1000	A	Exceptionally good
100 – 400	A	Extremely good
40 – 100	A	Very good
10 – 40	B	Good
4 – 10	C	Fair
1 – 4	D	Poor
0.1 – 1.0	E	Very poor
0.01 – 0.1	F	Extremely poor
0.001 – 0.01	G	Exceptionally poor

Source: Deb and Verma (2016)



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Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Problem on Q – system

Solution (contd...):

- Vertical stress at the depth (z) of 800 m (minor principal stress, σ_3) = $(\gamma_{\text{rock}} * z) = (30)(800) = 24000 \text{ kPa}$
 $= 24 \text{ MPa}$
- The major principal stress (σ_1) = $1.5 \sigma_3 = (1.5)(24) = 36 \text{ MPa}$
- Uniaxial compressive strength of the rock (σ_c) = 450 MPa
- So, $\sigma_c / \sigma_1 = \frac{450}{36} = 12.5$
- Rock component class – I; The stress reduction factor, $\text{SRF} = 1$ (As per Table 6(ii))
- ✓ Q value = $(RQD / J_r) \times (J_1 / J_2) \times (J_3 / \text{SRF})$
 $= \left(\frac{90}{2}\right) \left(\frac{4}{0.75}\right) \left(\frac{1}{1}\right) = 240$ ✓ Ans
- As per Table 7, the rock mass quality is Extremely good (class A)

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(Refer Slide Time: 16:54)

Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Equivalent Dimension of an excavation

- Barton et al. (1974) defined equivalent dimension (D_e) of an excavation in order to relate the Q index with the stability and support requirements of the excavation.
- Equivalent dimension (D_e) can be defined as:
 - $D_e = \text{Excavation span (s) or diameter (d) or height (h) (in m) / Excavation support ratio (ESR)}$
- Span or diameter is used for analyzing the roof support. Source: Deb and Verma (2016)
- Height of the wall is used to analyze the wall support.
- ESR values generally vary from 0.8 to 5.

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Additionally, Barton et al. 1974 defined equivalent dimension i.e. D_e of an excavation in order to relate the Q index with the stability and support requirement of the excavation.

Equivalent dimension can be defined as

$D_e = \text{Excavation span (s) or diameter (d) or height (h) (in m) / Excavation support ratio (ESR)}$

Span or diameter is used for analyzing the roof support, also it is stated that the height of the wall is used to analyze the wall support.

ESR values generally vary from 0.8 to 5. ESR is the excavation support ratio.

(Refer Slide Time: 19:02)

Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Excavation support ratio (ESR)

Values of Excavation Support Ratio, ESR (Barton et al., 1974)		ESR
Type of Excavation		
A. Temporary mine openings		3 – 5
B. Vertical shafts:	Circular section	2.5
	Rectangular or square section	2.0
C. Permanent mine openings, water tunnels for hydro power (excluding high-pressure penstocks), pilot tunnels, drifts and headings for large excavations, etc.		1.6
D. Storage rooms, water treatment plants, minor road and railway tunnels, surge chambers, access tunnels, etc. (cylindrical caverns)		1.3
E. Power stations, major road, and railway tunnels, civil defence chambers, portal inter-sections, etc.		1.0
F. Underground nuclear power stations, railway stations, sports and public facilities, factories, etc.		0.8

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For ESR a table is provided by Barton et al. 1974. It gives different classes like A, B, C, D, E, F and different corresponding type of excavations are also written alongwith corresponding ESR values. Like first one is temporary mine opening which has an ESR value between 3 to 5.

On the other hand, if we see the last one that is underground nuclear power station, railway stations, sports and public facilities, factories, etc. for that ESR is 0.8. Likewise for class E, if i.e. the power stations, major road and railway tunnels, civil defence chambers, portal inter-sections, etc. ESR is 1.

(Refer Slide Time: 20:19)

Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Rock bolt length (L) and Maximum unsupported span (S_{u_max})

- Rock bolt length (L): (Barton et al., 1974) ✓
 - $L \text{ (in m)} = 2 + (0.15 * B / ESR)$
 - ESR = Excavation support ratio ✓
 - B = Excavation width ✓
- Maximum unsupported span (S_{u_max}): (Barton et al., 1974)
 - $S_{u_max} \text{ (in m)} = 2 * ESR * Q^{0.4}$
 - Q = Rock tunneling quality index

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Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Excavation support ratio (ESR)

Values of Excavation Support Ratio, ESR (Barton et al., 1974)		ESR
Type of Excavation		
A. Temporary mine openings		3 - 5
B. Vertical shafts:	Circular section	2.5
	Rectangular or square section	2.0
C. Permanent mine openings, water tunnels for hydro power (excluding high-pressure penstocks), pilot tunnels, drifts and headings for large excavations, etc.		1.6
D. Storage rooms, water treatment plants, minor road and railway tunnels, surge chambers, access tunnels, etc. (cylindrical caverns)		1.3
E. Power stations, major road, and railway tunnels, civil defence chambers, portal inter-sections, etc.		1.0
F. Underground nuclear power stations, railway stations, sports and public facilities, factories, etc.		0.8

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Additional information:

- Rock bolt length (L): (Barton et al., 1974)
 - $L \text{ (in m)} = 2 + (0.15 * B / ESR)$
 - ESR = Excavation support ratio (using the table)
 - B = Excavation width
- Maximum unsupported span (S_{u_max}): (Barton et al., 1974)
 - $S_{u_max} \text{ (in m)} = 2 * ESR * Q^{0.4}$
 - Q = Rock tunneling quality index (already calculated)

(Refer Slide Time: 22:35)

Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Problem on Maximum unsupported span (S_{u_max})

Q. For a permanent mine opening having excavated span of 10 m, the equivalent dimension is found to be 8 m. What will be its maximum unsupported span if its Q value is 65?

Solution:

Excavated span (s) = 10 m

Equivalent dimension (D_e) = 8 m

Excavation support ratio (ESR) = $(s / D_e) = \frac{10}{8} = 1.25$

Q - index value = 65

Maximum unsupported span (S_{u_max}) = $2 * ESR * Q^{0.4} = 2 * (1.25) * (65)^{0.4} = 13.28 \text{ m}$

Ans

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Classification based on Rock Tunneling Quality Index (Q) system (contd...)

Equivalent Dimension of an excavation

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- Equivalent dimension (D_e) can be defined as:
 - $D_e = \text{Excavation span (s) or diameter (d) or height (h) (in m)} / \text{Excavation support ratio (ESR)}$
- Span or diameter is used for analyzing the roof support.
- Height of the wall is used to analyze the wall support.
- ESR values generally vary from 0.8 to 5.

Source: Deb and Verma (2016)



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Example problem: For a permanent mine opening having excavation span of 10 m, the equivalent dimension is found to be 8 m. What will be its maximum unsupported span if its Q-value is 65.

Solution:

Excavated span (s) = 10 m

Equivalent dimension (De) = 8 m

Excavation support ration (ESR) = (s / De) = 1.25

Q – index value = 65

Maximum unsupported span (S_{u_max}) = $2 * ESR * Q^{0.4} = 13.28 \text{ m (Ans)}$

Classification based on Geological Strength Index (GSI)

- The Geological Strength Index (GSI), introduced by Hoek (1994)*, helps in determination of properties of both hard and weak rock masses.
- It heavily relies on geological observations, and less on numerical values.
- Its value is ranging from about 10 for 'extremely poor rock masses' to 100 for 'extremely strong intact rock masses'.
- The relationship between rock mass structure and rock discontinuity surface conditions is used to estimate an average GSI value.

* Hoek, E. 1994, Strength of rock and rock masses, International Society of Rock Mechanics, 2, 4-16.



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(Refer Slide Time: 25:54)

Now, we will discuss about the classification based on geological strength index, GSI. It was introduced by Hoek in the year 1994, it helps in determination of properties of both hard and weak rock masses. It heavily relies on the geological observations and less on numerical values. Its value ranges from about 10 for extremely poor rock masses to 100 for extremely strong intact rock masses. The relationship between the rock mass structure and rock discontinuity surface conditions is used to estimate an average GSI value.

(Refer Slide Time: 27:01)

Classification based on Geological Strength Index (GSI) (contd...)

Estimation of Geological Strength Index (GSI) based on visual inspection of geological conditions (Hoek and Marinos, 2000)*

Structure	Surface conditions
✓ Intact or Massive	Very good ✓
✓ Blocky	Good ✓
✓ Very blocky	Fair ✓
✓ Blocky/Disturbed/Seamy	Poor ✓
✓ Disintegrated	Very poor ✓
✓ Laminated/Sheared	

*Hoek, E., and Marinos, P. G. 2000. Predicting tunnel squeezing problems in weak heterogeneous rock masses, *Tunnels and Tunneling International*, 132(11), 45-51.



Classification based on Geological Strength Index (GSI)

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- The relationship between rock mass structure and rock discontinuity surface conditions is used to estimate an average GSI value.

* Hoek, E. 1994, Strength of rock and rock masses, *International Society of Rock Mechanics*, 2, 4-16.



Now, this estimation of geological strength index, GSI is based on visual inspection of geological conditions as per Hoek and Marinos, 2000. There we will notice that two things are there, one is structure, one is surface conditions.

Rock mass structure and surface conditions are two very important parameters for this index. In the table shown in the slide there are different kinds of structures shown with a clear picture and its description as intact or massive, blocky, very blocky, blocky/disturbed/seamy, disintegrated, and laminated/sheared and under surface conditions, they are like very good surface condition, good, fair, poor, very poor.

(Refer Slide Time: 28:13)

Classification based on Geological Strength Index (GSI) (contd...)

Geological Strength Index (GSI)
as per Hoek and Marinos (2000)

Source: Hoek and Brown (2019)*

GEOLOGICAL STRENGTH INDEX FOR JOINTED ROCKS (Hoek and Marinos, 2000)
From the history, structure and surface conditions of the discontinuities, estimate the average value of GSI. Do not try to be too precise. Giving a range from 10 to 20 is more realistic than giving one value. GSI = 10: Think that the rock mass is very weak and jointed. GSI = 20: Think that the rock mass is very strong and massive. GSI = 100: Think that the rock mass is very strong and massive. GSI = 100: Think that the rock mass is very strong and massive.

STRUCTURE	DISCONTINUITY SURFACE CONDITION	GSI
✓ INTACT OR MASSIVE - intact rock specimens or regions in situ rock with few widely spaced discontinuities	Very good	100
✓ BLOCKY - well interlocked and disintegrated rock mass consisting of cubical blocks formed by three intersecting discontinuity sets	Good	80
✓ VERY BLOCKY - interlocked, partially disintegrated rock mass consisting of cubical blocks formed by 4 or more joint sets	Fair	60
✓ BLOCKY/DISTURBED/SEAMY - blocky with angular blocks, formed by more than three discontinuity sets. Discontinuity sets are irregular and rough	Poor	40
✓ DISINTEGRATED - loosely held, broken, heavily jointed rock mass with traces of regular and irregular joint planes	Very poor	20
✓ LAMINATED/SHEARED - lack of interlocking due to close spacing of weak subparallel or shear planes	Very poor	10

* Hoek, E., and Brown, E. T. 2019. The Hoek-Brown failure criterion and GSI - 2018 edition, *Journal of Rock Mechanics and Geotechnical Engineering*, 11(3), 445-463.

Classification based on Geological Strength Index (GSI)

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- The relationship between rock mass structure and rock discontinuity surface conditions is used to estimate an average GSI value.

* Hoek, E. 1994, Strength of rock and rock masses, *International Society of Rock Mechanics*, 2, 4-16.

Classification based on Geological Strength Index (GSI) (contd...)

Estimation of Geological Strength Index (GSI) based on visual inspection of geological conditions (Hoek and Marinos, 2000)*

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✓ Disintegrated	Very poor ✓
✓ Laminated/Sheared	

*Hoek, E., and Marinos, P. G. 2000. Predicting tunnel squeezing problems in weak heterogeneous rock masses, *Tunnels and Tunnelling International*, 132(11), 45-51.



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So, now, let us focus on the just this table what is provided by Hoek and Marinos 2000 and let us see what are the things over there as I have stated the structure, structure and the surface conditions and under surface condition, you see very good, good, fair, poor, very poor and under structure as I have mentioned intact rock with the diagram it is shown what does it mean, intact or massive. So, it is also written intact rock specimens or massive in situ rock with few widely spaced discontinuities.

GSI values are given like you see the 10, 20, 30, 40 and so on till 90. As already mentioned GSI varies generally between 10 to 100. For example, suppose structure is blocky and surface condition is good then GSI will be 65.

Also, it is written that quoting a range from like 32 to 37 is more realistic than stating that GSI is exactly 35.

(Refer Slide Time: 32:26)

Classification based on Geological Strength Index (GSI) (contd...)

Rock mass classification based on Geological Strength Index (GSI) values:

GSI value	76-95	56-75	36-55	21-35	< 20
Rock mass quality	Very good	Good	Fair	Poor	Very poor

GSI can be approximated from RMR as:

$$GSI = RMR_{89} - 5$$

Here RMR_{89} is the value of RMR computed as per Bieniawski (1989)

Source: Deb and Verma (2016)



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Classification based on Geological Strength Index (GSI)

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- The relationship between rock mass structure and rock discontinuity surface conditions is used to estimate an average GSI value.

* Hoek, E. 1994, Strength of rock and rock masses, International Society of Rock Mechanics, 2, 4-16.



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Another table shows rock mass classification based on the GSI. So, it is stating that if the GSI value is like less than 20, it is very poor and 76 to 95 it is very good. So, a GSI value of 100 is for extremely strong intact rock masses.

Now, GSI can be approximately from RMR also.

$$GSI = RMR_{89} - 5$$

RMR_{89} is the value of RMR computed as per Bieniawski (1989). We have learned in detailed about the how to obtain the RMR value as per this tables given by Bieniawski.

(Refer Slide Time: 33:43)

Strength of Jointed Rock based on RMR

- Kalamaras and Bieniawski (1995)* suggested a relationship between the compressive strength of the jointed rock mass and that of intact rock through RMR based on the studies of Carter et al. (1991)** as
- ✓ ➤ $\sigma_{cj} = \sigma_{ci} \cdot \exp [(RMR - 100) / 24]$
- σ_{cj} = Uniaxial compressive strength of jointed rock mass
- σ_{ci} = Uniaxial compressive strength of intact rock
- According to Ramamurthy (2001)***, $\sigma_{cj} = \sigma_{ci} \cdot \exp [(RMR - 100) / 25]$

Source: Ramamurthy (2015)****

* Kalamaras, G. S. and Bieniawski, Z. T. 1995. A rock mass concept for coal seams incorporating the effect of time. *Proc. 8th Int. Congr. on Rock Mech.*, 1, 295 - 302.

** Carter, B. J., Scott Duncan, E. J., Lajtai, E. Z. 1991. Fitting strength criteria to intact rock. *Geotechnical and Geological Engineering*, 9, 73-81.

*** Ramamurthy, T. 2001. Shear strength response of some geological materials in triaxial compression. *International Journal of Rock Mechanics & Mining Sciences*, 38, 313-329.

**** Ramamurthy, T. 2015. *Engineering in Rocks for Slopes, Foundations and Tunnels*, Ed. 3, PHI Learning Pvt. Ltd.



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Now, we will discuss about the strength of jointed rock based on RMR. Kalamaras and Bieniawski (1995) suggested a relationship between the compressive strength of the jointed rock mass and that of intact rock through RMR based on the studies of Carter et al. 1991 and the expression is

$$\sigma_{cj} = \sigma_{ci} \times \exp[(RMR - 100) / 24]$$

where, σ_{cj} is the uniaxial compressive strength of jointed rock mass and σ_{ci} is the uniaxial compressive strength of intact rock.

According to Ramamurthy (2001)

$$\sigma_{cj} = \sigma_{ci} \times \exp[(RMR - 100) / 25]$$

(Refer Slide Time: 35:35)

Elastic Modulus of Jointed Rock based on RMR

- The relationship between the elastic modulus of jointed rock mass (E_j) and that of intact rock (E_i) considering RMR is given below (according to Ramamurthy, 2001).
 - $E_j = E_i \cdot \exp[(RMR - 100) / 17.4]$ ✓
- The above relationship is for the tangent modulus at 50% of the failure stress.
- Serafim and Pereira (1983) ** provided a relationship between E_j and RMR given as:
 - $E_j = 10^{[(RMR - 10) / 40]}$ in GPa

Source: Ramamurthy (2015)

* Serafim, J. L. and Pereira, J. P. 1983. Consideration of geomechanics classification of Bieniawski. *Proceedings, International Symposium on Engineering Geology and Underground Construction, Lisbon, I*, 33 – 44.





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Not only the uniaxial compressive strength, we can also estimate the elastic modulus of jointed rock based on RMR

$$E_{cj} = E_{ci} \times \exp[(RMR - 100)/17.4] \quad (\text{As per Ramamurthy (2001)})$$

This relationship is between the elastic modulus of jointed rock mass that is E_j and that of the intact rock E_i considering RMR is given. Above relationship is for the tangent modulus at 50% of the failure stress.

Another relationship is given by Serafim and Pereira (1983)

$$E_j = 10^{[(RMR - 10) / 40]} \quad \text{IN GPa}$$

It is obvious that RMR can be very useful to obtain not only the strength of jointed rock mass but also the elastic modulus.

(Refer Slide Time: 37:06)

Strength and Elastic Modulus of Jointed Rock based on GSI

- On the basis of GSI, the uniaxial compressive strength of jointed undisturbed rock mass for GSI > 25
 - $\sigma_{ci} = \sigma_{ci} * (s_j)^{0.5}$ ✓
 - $s_j = (GSI - 100) / 9$
- Hoek (1994)* proposed a relationship between E_j and σ_{ci} which is $E_j = M_{rj} * \sigma_{ci}$ ✓
 - M_{rj} = Modulus ratio of the jointed rock

Source: Ramamurthy (2015)

* Hoek, E. 1994. Strength of rock and rock masses, *International Society for Rock Mechanics News Journal*, 2, 4-16.

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Now similarly, on the basis of GSI the uniaxial compressive strength of jointed undisturbed rock mass for GSI > 25 can be obtain using the following expression.

$$\sigma_{cj} = \sigma_{ci} \times (s_j)^{0.5}$$

$$s_j = (GSI - 100) / 9$$

As per Hoek (1994)

$$E_j = M_{rj} \times \sigma_{cj}$$

where M_{rj} is modulus ratio of the jointed rock.

(Refer Slide Time: 38:28)

Strength and Elastic Modulus of Jointed Rock based on Q Value

- Barton (2002)* suggested a modified Q value (i.e., Q_c) to estimate E_j and σ_{cj} of rock mass by considering the influence of UCS of intact rock (σ_{ci}) in the following form
 - $Q_c = Q * (\sigma_{ci} / 100)$ ✓
- The Q_c is used for estimating E_j and σ_{cj} as
 - $\sigma_{cj} = 5 * \rho * (Q_c)^{1/3}$ in MPa ✓
 - $E_j = 10 * (Q_c)^{1/3}$ in GPa ✓
 - where ρ is the density of the rock mass in g/cm³

* Barton, N. 2002. Some new Q-value correlations to assist in site characterization and tunnel design, *International Journal of Rock Mechanics and Mining Sciences*, 39, 185-216.

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Barton (2002) suggested a modified Q-value i.e., Q_c to estimate this E_j and σ_{cj} of rock mass by considering the influence of UCS of intact rock that is σ_{ci} in the following form

$$Q_c = Q \times (\sigma_{ci} / 100)$$

Now, this Q_c is used to estimate σ_{cj} and E_j .

$$\sigma_{cj} = 5 \times \rho \times (Q_c)^{1/3} \text{ in MPa}$$

$$E_j = 10 \times (Q_c)^{1/3} \text{ in GPa}$$

(Refer Slide Time: 39:54)



So, thank you. With this, I am concluding our module 5. So, we will meet again with our module 6 in our next lecture. Thank you.