Journal of Rock Mechanics and Tunnelling Technology (JRMTT)
27 (1) 2021 pp 49-62

Available online at www.isrmtt.com

Weathering and its Influence on Rock Slope Stability in Hilly Areas

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ABSTRACT

Weathering takes place in all environments but is most intense in hot, wet climates where it may be expected to extend to great depths. The weathering of soft rocks is one of the primary causes of slope failure and shallow landslide in hilly areas. Weathering also affects the civil engineering works located on or within the rock mass. The degree of weathering has been correlated with engineering properties and behavior of rocks by some researchers, which is presented here. A limiting value of laboratory uniaxial compressive strength (UCS) of soft rocks is suggested which are likely to be influenced by weathering. It has also been highlighted that the rocks showing no reaction during 1st wetting-drying-cycle and cracking and/or beginning of decay up to 50% of the original mass up to 3rd cycle in slake durability test shall require special attention to take care of weathering effects during the designed life of engineering structure on or within the rock mass at shallow depths. The paper also discusses the condition of discontinuities (including the roughness and alteration) and its influence on ultimate values of slope mass rating (SMR), rock mass rating (RMR) and rock mass quality (Q).

Keywords:Weathering; uniaxial compressive strength; slake durability test; rock engineering; soft rocks

1. INTRODUCTION

Most civil engineering works are located close to the surface where the ground mass is affected by the weathering. Weathering implies decay and change in state from an original condition to a new condition as a result of external processes. Weathering takes place in all environments but is most intense in hot, wet climates where weathering may be expected to extend to great depths.

Weathering affects the mechanical properties of rock material and mass on the surface and at depths through physical and chemical weathering processes. Physical weathering leads to the opening of discontinuities by rock fractures, progressively breaking down the original rock to a soil-like material representing advanced stages of weathering. Chemical weathering results in chemical changes in minerals. Both physical and chemical weathering changes hard mineral into softer ones and loosens up the structure of a rock. Thus, reducing its strength (complete weathering creates soil). This means that even a hard rock like granite may behave differently when exposed to weathering conditions. Thus, weathering affects the engineering structures built at or near the earth's surface.

The weathering of soft rocks is one of the primary causes of slope failure and shallow landslides in hilly areas. Therefore, understanding the nature of weathering is an important step in predicting the occurrence of slope failure and land-slides, including their timing, type and extent. In general, a slope becomes unstable gradually as the weathering of rocks proceeds inward from its surface and it typically fails during heavy rainfall or soon after. This type of failure is widely known from many places, especially from monsoon regions. Frequent failures along steep slopes composed of soft, degradable rocks are believed to be mainly attributed to the weathering of rocks, because individual failures are very shallow and they tend to repeat over time.

The thickness of weathered zone keeps on increasing with time. It is understood that a slope failure occurs when the thickness of weathered zone attains a threshold value. Immediately after a failure occurs, the thickness of the weathered zone is considerably reduced, then it gradually increases again as the newly exposed surface begin to weather. Weathering and slope failures repeat in this manner.

The Geological Strength Index (GSI) system has been developed to deal with rock masses comprised of interlocking angular blocks in which the failure process is dominated by block sliding and rotation without a great deal of intact rock failure (Hoek and Brown, 2019). With weathering on rock slopes the interlocking of rock blocks is adversely affected. If the weathering has penetrated the rock to the extent that the discontinuities and the structure have been lost, then the rock mass must be assessed as a soil and the GSI system no longer applies (Marinos et al., 2005). All rock mass classifications are not applicable to the water-soluble rocks with the solution cavities.

Mehrotra et al. (1991) advocated the necessity of long-term evaluation of rock engineering parameters in theHimalaya which is not only seismo-tectonically active but also a weather sensitive zone. They observed that some rocks in the lesser Himalayas may be significantly affected for their strength and deformation characteristics once the rock mass is saturated during reservoir filling/operation. Also the rock mass in general in Himalayan region are soft and weathered having mineralogical composition highly prone to chemical attacks. These rocks appear to have some soluble contents/erodible joints filling and thus need to be investigated thoroughly on long-term basis. Saturation reduces modulus of deformation and cohesion of the soft rocks significantly.

Mitra (1991) analyzed the meteorological data (approx 10 years period) for a project located in soft rocks in lower Himalayan region and highlighted the effect of weathering parameters on long-term behavior on different components of underground power house in weak rocks.

Although weathering of rock mass occurs in geological periods, the importance to understanding the changes in the physical behavior and mass engineering must be given much attention. This is because demands of infrastructural developments for a country's growth often expose the varying weathered zones due to cuttings in to the rock mass. Heavy blasting should not be used for road cuttings in Himalaya to reduce rock slides.

In addition to the climatic conditions, the rate of weathering of a rock mass depends upon, the type of rock mass (mineral composition), its cementing material, strength of rock, presence of joints, faults, shear zones and other discontinuities. The engineering structures located on or within the rock mass has a designed life of generally 100 years. Some rocks are not much affected by the weathering in the designed life of 100 years, whereas there are some rocks which are affected considerably by weathering in the designed life of 100 years. Hence, such rocks need special attention and are in the focus of this paper.

The paper is an attempt to discuss the degree of weathering and its effect on rock properties and rock behavior. In addition a limiting value of UCS is suggested for the attention of designers. It has also been highlighted that the rocks showing no reaction during 1st wetting-drying-cycle and cracking and/or beginning of decay up to 50% of the original mass up to 3rd cycle in slake durability test shall require special attention to take care of the effects of weathering during the designed life of engineering structure on or within the rock mass at shallow depths.

The paper also discusses the condition of discontinuities (including the roughness and alteration) and its influence on the ultimate values of RMR, SMR and Q. The content of the paper is mainly taken from Goel and Mitra (2015).

2. DEGREE OR GRADE OF ROCK MASS WEATHERING

On the basis of the visual assessment of the rock mass degraded due to weathering, the rock mass is classified as 'fresh' to 'residual soil' (British Standards - BS5930, 1981) as shown in Table 1 to represent the *state of weathering* of a rock mass. Almost same weathering classification or degree of weathering of rock mass is suggested by International Society for Rock Mechanics (ISRM).

Table 1 - Degrees of rock mass weathering (BS5930, 1981)

Term	Degree/Grade of Weathering	Description
Fresh	I	No visible sign of rock material weathering; perhaps slight discoloration on major discontinuity surface
Slightly weathered	II	Discoloration indicates weathering of rock material and discontinuity surfaces. All rock material may be discolored by weathering
Moderately weathered	III	Less than half of the rock material is decomposed or disintegrated to a soil. Fresh or discolored rock is present either as a continuous framework or as core stones
Highly weathered	IV	More than half of the rock material is decomposed or disintegrated to a soil. Fresh or discolored rock is present either as a discontinuous framework or as core stone
Completely weathered	V	All rock material is decomposed and/or disintegrated to soil. The original mass structure is still largely intact
Residual soil	VI	All rock material is converted to soil. The mass structure and material fabric is destroyed. There is a large change in volume, but the soil has not been significantly transported

Santi (2006) has proposed Table 2 showing the relation between various engineering properties and weathering grades. Quantitative values shown in Table 2 were originally determined for weathered granite byDearman et al. (1978), Krank and Watters (1983), Lee and de Freitas (1989) and also include correlationsfor shale and siltstone using data from Santi (1995). Table 2 can be judiciously used as a guide to get an idea of behavior of various weathering grade rocks.

Table 2 - Engineering properties of rocks related to weathering grades (Santi, 2006)

Engineering Property	Fresh, I	Slightly weathered, II	Moderately weathered, III
Foundation condition	Suitable for concrete and earthfill dams	Suitable for concrete and earthfill dams	Suitable for small concrete structures, earthfill dams
Excavability	In general blasting necessary	In general blasting necessary	Generally blasting needed, but ripping may be possible depending upon the jointing intensity
Building material	Very durable, difficult to shape, excellent aesthetic properties, good aggregate	Very durable, but less aesthetically pleasing due to discoloration, good aggregate	Poor subject to deterioration, not suitable as an aggregate
Slope stability	Excellent; can stand vertically unsupported (1/4:1 H:V)	Excellent; can stand vertically unsupported (1/2:1 H:V)	Very good; can stand vertically unsupported, but subject to deterioration for long term stability (1:1 H:V)
Benches and surface protection structures are advisable, particularly for more highly weathered material. The presence of through-going adversely oriented structures is not taken into account.			
Tunnel support	Not required unless joints are closely spaced or adversely oriented	Not required unless joints are closely spaced or adversely oriented	Light steel sets on 0.6 to 1.2m centers
Point load strength (MPa)	9-18	5-12.5	2-6
Schimdt hammer value (MPa)	59-62	51-56	37-48
Moisture content (%)	0.06-0.30	0.15-0.29	0.25-0.49
Unconfined compressive strength (MPa)	125-260	100-175	60-120
RQD (%)	75, usually 90	75, usually 90	50-75
Core recovery (%) NX	90	90	90
Drilling rates (m/hr) (Diamond NX)	2-4	2-4	8-10
Permeability	Low to medium	Medium to high	Medium to high
Seismic velocity (m/sec)	3050-5500	2500-4000	1500-3000

Table 2 continued

Engineering Property	Highly weathered, IV	Completely weathered,V	Residual Soil, VI
Foundation condition	Suitable for earthfill dams	Suitable for low earthfill dams	Generally unsuitable
Excavability	Generally ripping and/or scraping necessary	Scraping	Scraping
Building material	Unsuitable, not useable as an aggregate	Too angular and poorly graded to serve as an aggregate by itself	Too poorly graded to be used as an aggregate by itself, but may serve as a sand filler if screened
Slope stability	Good; can stand vertically unsupported upto 7.5m high, greater heights should be 1:1 H:V with benches, deteriorates with time (1:1 to 1.5:1 H:V)	Moderate; can stand unsupported at 1:1 H:V with benches to catch detritus (1.5:1 to 2:1 H:V)	Very poor; unstable because of low cohesion, greatly influenced by ground water, best removed (1.5:1 to 2:1 H:V)

Benches and surface protection structures are advisable, particularly for more highly weathered material. The presence of through-going adversely oriented structures is not taken into account.			
Tunnel support	Steel sets, partial lagging, 0.6 to 0.9 m centers	Heavy steel sets, complete lagging on 0.6 to 0.9 m centers. If tunnelling below water table, possibility of soil flow into tunnel	Heavy steel sets, complete lagging on 0.6 to 0.9 m centers. If tunnelling below water table, possibility of soil flow into tunnel
Point load strength (MPa)	0.3-0.9	0.1-0.5	--
Schimdt hammer value (MPa)	12-21	5-20	--
Moisture content (%)	0.37-3.8	7.84-21.0	12.24-22.1
Unconfined compressive strength (MPa)	35-55	1-10	<1
RQD (%)	0-50	0 or does not apply	0 or does not apply
Core recovery (%) NX	15 to 70 depending on percentage of core stones	15 as sand	15 as sand
Drilling rates (m/hr) (Diamond NX)	8-12	10-13	10-13
Permeability	High	Medium	Low
Seismic velocity (m/sec)	1000-2000	500-1000	500-1000

Borrelli et al. (2007) have compared the weathering grade with slope stability (or landslide) for plutonic and metamorphic rocks of medium to high grade. They highlighted that the percentage of landslide area included in classes III and II is small (about 1%), and that the percentage of landslide areas in class VI (38%) and class V (37%) is always higher than that in class IV (24%). It is confirmed at a detailed scale (1:10,000) that the rock mass weathering grade is an indicator of slope instability predisposition (Borrelli et al., 2004 and Gullà et al., 2004).

3. WEATHERABILITY

Weatherability or weathering resistance is different from the degree of weathering or weathering grade. As mentioned earlier, the weathering grade represents the state of weathering of a rock mass, whereas weatherability is the resistance to weathering of a rock mass. *For example*, a fresh claystone rock mass (Grade I) is less resistant to weathering and therefore its engineering properties may considerably change in the designed life. On the other hand, a moderately weathered granite (Grade III) is resistant to weathering and therefore its engineering properties may not change considerably in the designed life. Hence, weatherability is an important property to know.

With passage of time a fresh rock weathers to residual soil. The weathering rate varies from rock to rock and from region to region. Generally, the soft sedimentary rocks like siltstone, claystone, shales, mudstones, poorly cemented sandstone and other rocks having presence of fast weathering minerals and uniaxial compressive strength (UCS) less than 40MPa (Bell, 1983) are likely to be affected most by weathering during the engineering life span of a structure. Hence, engineering structures and slopes on such rocks are vulnerable to weathering.

Bell (1983) reported a case of slope failure in Lias clay in Northampton shire, which was primarily due to swelling in the clay. It took 43 years to reduce the strength of the clay below the critical level at which the sliding occur. *Can weatherability of soft rocks (or potential to suffer further short-term damage) be related with time?* If this is done, the effect of weathering on the stability of engineering structure can also be related and accordingly the structures can be designed taking care of the effects of rock mass weathering.

Sake durability index gives an idea about the weatherability (resistance to weathering) of rocks as discussed below.

4. SLAKE DURABILITY CLASSIFICATION AND WEATHERABILITY

Based upon tests on representative shales and clay stones for two numbers of 10 minute cycle after drying, Gamble (1971) found the slake durability index to vary over the whole range from 0 to 100%. There are no visible connections between durability and geological age, but durability increases linearly with density and inversely with natural water/moisture content. Based on his results, therefore, Gamble proposed a classification on slake durability with a group name ranging from a very high durability to very low durability. The slake durability classification is useful in the selection of rock aggregates for road, rail line, concrete and shotcrete.

Hard rocks are characterized by a high to very high uniaxial compressive strength combinedwith small pore volumes. In these rocks water seepage happens very slowly and onlyon a small scale. Rock materials of a medium compressive strength but coarser grain sizeand larger pore volume, e.g. sandstones, can be durable as well. Since water seepage is muchfaster in those rocks, a pore water pressure is unlikely to develop, and doesn't exceed the grainbinding/bond strength.

Weak rocks however are characterized by a reduced compressive strength and/or a biggerpore volume. In these rocks a better hydraulic conductivity causes the faster percolation ofwater to weaken the rock material during wetting-drying-cycles.

The main purpose of slake-durability test is to evaluate the weathering resistance of rocks,specially the soft rocks like shales, mudstones, siltstones and other clay-bearing rocks. Based on the slake durability test and crystallization test as per DIN (1990),Nickmann et al. (2006) have proposed a classification system consisting of 6 categories of durability from VK0 to VK5 (Table 3).

Table 3 - Classification of weak rocks based on the behavior in 3-cycle wetting-drying-test and the crystallization test (Nickmann et al., 2006)

VK	Class	Description
VK 0	Hard rock	No change up to the 3rd wetting-drying-cycle, may be small losses because of loosened aggregates during sample preparation (< 5%), no reaction in the crystallization test (loss < 10%)
VK 1	Low slake durability	No change up to the 3rd wetting-drying-cycle, may be small losses because of loosened aggregates during sample preparation (< 5%), losses in the crystallization test > 10%
VK 2	slow slake durability	No reaction during 1st wetting, up to 3rd cycle cracking and/ or beginning of decay up to 50% of the original mass
VK 3	Medium slake durability	During 1st wetting cracking or loss of smaller aggregates (max. 10% of mass), but the sample remains preserved. Up to the 3rd cycle decay up to 95% of the original mass
VK 4	Rapid and high slake durability	During 1st wetting disintegration up to 75%; up to the 3rd cycle decay up to 100% of the original mass
VK 5	Immediate and very high slake durability	Spontaneous decay into aggregates <25% during 1st wetting, up to 3rd cycle almost complete decay

Nickmann et al. (2006) have also co-related category of durability (VK) with the uniaxial compressive strength (UCS) of rock as shown in Fig. 1.

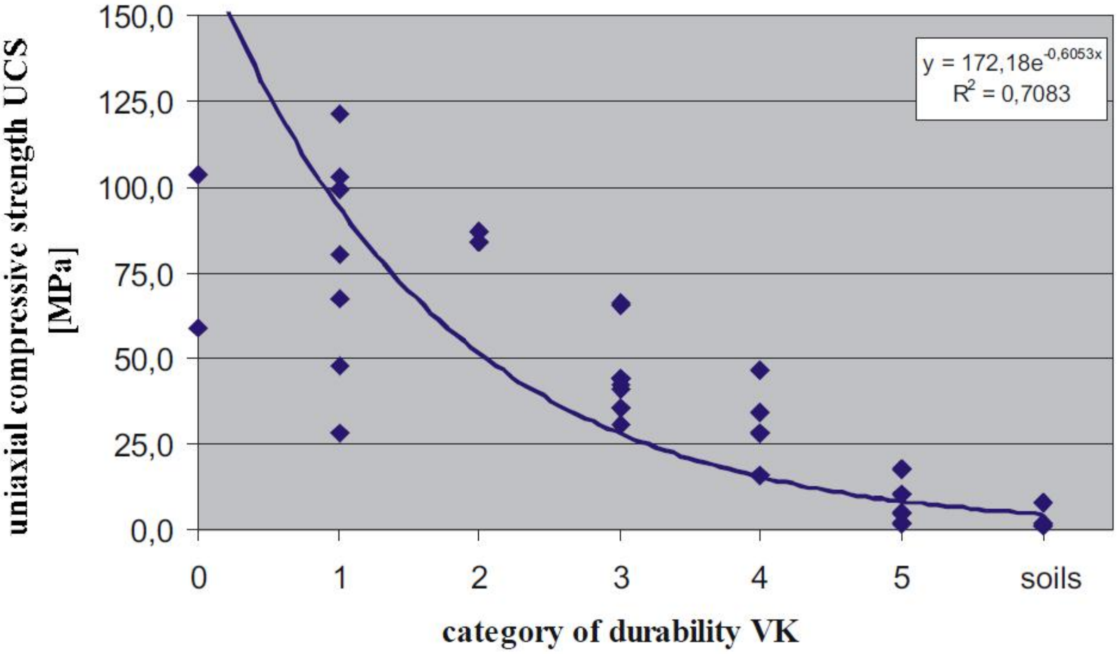

Figure 1- Relation between category of durability (VK) and uniaxial compressive strength (UCS) [after Nickmann et al., 2006]

It is expected that shales, mudstones, siltstones and other clay-bearing rockshaving UCS<50MPa are, in general, less resistant to weathering. Bell (1983) also observed that rocks having UCS less than 40MPa are likely to be affected most by weathering during the designed life of a structure. From Fig. 1, VK 2 has a UCS value of about 50 MPa. Table 3 shows that VK2 refers to, ‘No reaction during 1st wetting-drying-cycle, up to 3rd cycle cracking and/ or beginning of decay up to 50% of the original mass’. *Hence, engineering structure on rock having UCS<50MPa and showing this behavior in slake durability test shall require special attention to take care of weathering during its designed life. Also, rocks having VK category more than 2 as per Table 3 are more prone to weathering damage.*

5. INFLUENCE OF WEATHERING ON ROCK PROPERTIES

Table 4 presents a summary of the influence of weathering on some rock properties in terms of the fraction relative to fresh value. *For example*, a fresh rock having intact rock strength of 100MPa shall have UCS 88MPa on slight weathering.

It should be noted that the degree of weathering described as moderately, highly and completely weathered imply that a portion of the rock mass has decayed to geotechnical soil. The intact rock strength, thus, is of rock blocks which have undergone particular degree of weathering. As expected, the intact rock strength decreases with increasing degree of weathering. Weathering grades shown in Table 4 are taken from Table 1.

Table 4 - Variation in rock properties with degree of weathering (After Hack and Price, 1997)

Degree of weathering (BS 5930:1981), Table 1	Intact rock strength	Spacing of discontinuities	Condition of discontinuities	Number of Observations
Fresh, I	1.00	1.00	1.00	12
Slightly, II	0.88	0.93	0.99 (0.95)	168
Moderately, III	0.70	0.89	0.98 (0.8)	27
Highly, IV	0.35	0.63	0.89 (0.6)	6
Completely, V	0.02	0.55	0.77 (0.4)	2

Hack and Price (1997) highlighted the influence of weathering on intact rock strength, spacing of discontinuities and condition of discontinuities (Table 4). Table 4 shows that the condition of discontinuities in a rock mass is considerably less influenced by weathering than the intact rock strength and the spacing of discontinuities. Authors have observed that the condition of discontinuities is also considerably influenced in soft rock masses. In soft rock masses where deformations can occur independent of joints, the degree of jointing and joint friction factor is less significant than in hard rocks. The revised fraction values for soft rocks suggested by the authors for condition of discontinuities are shown in brackets in Table 4.

The influence of weathering on all rock mass parameters for ‘slightly’ and ‘moderately’ weathered rock mass is low, but strongly increases for ‘highly’ and ‘completely’ weathered rock mass (Table 4). This corresponds to the percentage of the rock material which is decomposed or disintegrated into soil, following the definition of the degree of weathering (Table 1). Other researchers have also shown similar reductions in strength parameter from weathering.

Intact rock strength in Table 4 has drastically reduced from 0.7 for moderately weathered rocks to 0.35 for highly weathered rocks. It shows that any highly weathered rock mass (Grade –IV, Table 2) having laboratory UCS of 35 to 55MPa shall require the same treatment for long-term behavior as any fresh soft rock mass.

Hack and Price (1997) have proposed the reduction factor for rock mass weathering (Table 4) in the context of a slope classification system. However, they suggest that these reduction factors may also be valid for other engineering projects in or on rock masses.

6. VARIATION IN RQD WITH DEGREE OF WEATHERING

Deere and Deere (1989) highlighted the variation in RQD with degree of weathering. According to them fresh and slightly weathered rock should be used in the RQD count; moderately weathered rock which resists hand breakage should be included but with a caution regarding its soundness; and highly weathered rock (that breaks under hand pressure), completely weathered, and residual soil should not be included.

Gurocak and Kilic (2005) have studied the variation in RQD value for different degrees of weathering in basalts. As per their study the RQD value decreases with the increase in degree of weathering. The work of Gurocak and Kilic (2005) and Table 4 have been used to derive the RQD factor in Table 5 for hard rocks.

Rock with an RQD value less than 50 percent should be assumed to be soil-like with regard to scour potential (www.fhwa.dot.gov downloaded on 12.2.2015).

Table 5 - Variation inRQD with degree of weathering for hard and soft rock masses

Degree of weathering (BS 5930:1981)	RQD Factor	
	Hard Rocks	Soft Rocks
Fresh	1.00	1.00
Slightly	0.80-0.90	0.70-0.80
Moderately	0.70	0.25 -0.50
Highly	0.30-0.50	0.0
Completely	0.05	0.0

In case of soft rocks (UCS< 50MPa), there are more chances of core breaks because of drilling process and sometimes it may be difficult to fit the broken pieces. It is suggested by Deere and Deere (1989) that when in doubt about a break, it should be considered as natural. Thus, the RQD obtained from drill-core in fresh un-jointed soft rock may not exceed 75%. Further, it has been observed that the reduction in RQD value with degree of weathering in soft rocks is at a faster rate compared to hard and strong rocks. As such, RQD factor for soft rocks with degree of weathering, as observed by authors, is given in Table 5.

Table 5implies that a fresh hard rock having RQD of 80% shall have RQD of approximately 4% when it is completely weathered.

7. MODIFICATIONS IN RMR DUE TO WEATHERING

Bieniawski's RMR (Bieniawski, 1989) has following six parameters.

(i) Uniaxial compressive strength of intact rock material,
(ii) Rock quality designation RQD,
(iii) Joint or discontinuity spacing,
(iv) Joint condition,
(v) Ground water condition, and
(vi) Joint orientation.

Out of the above six parameters, first five parameters (i.e. excluding 'joint orientation') give RMR_{Basic}. Tables 4 and 5 show the variation in the parameters of RMR_{Basic} with degree of weathering. The cumulative effect of weathering in RMR_{Basic} using Tables 4 and 5 is obtained as shown below in Table 6, as an example, for one case. The ground water condition and its rating have been assumed to be same.

Table 6 - Variation in RMR_{Basic} with weathering grade for Case-I data

Degree of weathering (BS 5930:1981)	Intact rock strength		Spacing of discontinuities		Condition of discontinuities		RQD		Water	RMR Basic
		Rating		Rating		Rating		Rating	Rating	
Fresh	1.00	10	1.00	9	1.00	20	1.00	14.5	10	63.5
Slightly	0.88	9	0.93	8.5	0.99(0.90)	18	0.85	10.5	10	56
Moderately	0.70	7	0.89	8	0.98 (0.7)	14	0.70	9	10	48
Highly	0.35	5	0.63	7.5	0.89 (0.55)	11	0.50	6	10	39.5
Completely	0.02	1	0.55	7	0.77 (0.4)	8	0.05	3	10	29

Case-I: Fresh rock has UCS=150MPa (Rating 10), RQD = 80% (Rating 14.5); Spacing of discontinutites = 25cm (Rating 9); Condition of discontinuities = Slightly rough and moderately to highly weathered, wall rock surface separation <1mm (Rating 20); Ground water = Damp (Rating 10).

Rating for different weathering grades in Table 6 has been obtained after multiplying the value of fresh rock with the fraction and selecting the rating (as per Bieniawski, 1989) for this value. *For example*, UCS is 150 MPa for rock, for slightly weathered rock the UCS would be 150*0.88 = 132MPa. Hence rating for 132MPa is obtained for slightly weathered rock from Bieniawski (1989).

It can be seen in Table 6 that a ‘fresh’ rock having RMR_{Basic} = 63.5 will have RMR_{Basic}=29 after it is ‘completely’ weathered.

The above example shows that the rock mass rating (RMR) of a freshly excavated rock mass, will change with time if left unprotected from weathering. Change in RMR values with degree of weathering in soft rock masses will be different. The soft rock masses having higher rate of weathering (clay rich rocks) will be badly affected with time. The granite and such other rocks, on the other hand, are weathering resistant and therefore the change in RMR_{Basic} may not be fast to observe in the designed life.

Slope mass rating (SMR) of Romana (1985) also uses RMR_{Basic}. Hence, it is suggested that SMR for the slope characterization or other such parameters collected for landslide study should also take care of the weathering effect for projecting the behavior of slope. SMR is not applicable to the cloud burst prone and steep valleys in the Himalaya when everything is washed out.

8. MODIFICATION IN Q-PARAMETERS DUE TO WEATHERING

Tunnel portal and shallow tunnels through soft and jointed rocks shall expect the maximum effect of weathering in terms of changes in the Q values with time, as mentioned above in RMR. With time, variation in Q value due to weathering is expected because of change in RQD, J_r and J_a. Moreover, in water charged shallow tunnels through competent rocks also, with the passage of time the altered material and fines along joint surface washed out resulting in the reduction of shear strength parameter values and loosening of rock blocks. This will influence the rating of SRF parameter.

The expected change in RQD is given in Table 5. Change in Jr and Ja are discussed as follows.

8.1 Joint Roughness Number and Joint Alteration Number (J_r and J_a)

The parameters J_r and J_a, given in Tables 7 and 8 respectively, represent roughness and degree of alteration of joint walls or filling materials. The parameters J_r and $J_a$is collected for the weakest critical joint set or clay-filled discontinuity in a given zone. In soft rock masses prone to weathering the J_r and J_a conditions are likely to change with time. In water charged soft rocks, the long-term behavior will be highly influenced by the weathering and thus vast changes in the rating of J_r and $J_a$are expected. This should also be taken care of in shallow tunnels having vertical to sub-vertical joints.

Table 7 - Joint roughness number J_r (Barton, 2002)

	Condition	$\mathbf{J_r}$
	(a) Rock wall contact and	
	(b) Rock wall contact before 10cm shear	
A.	Discontinuous joint	4.0
B.	Rough or irregular, undulating	3.0
C.	Smooth, undulating	2.0
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
J.	Sandy, gravelly or crushed zone thick enough to prevent rock wall contact	1.0

Notes:

(i) Descriptions refer to small-scale features and intermediate scale features, in that order

(ii) Add 1.0 if the mean spacing of the relevant joint set is greater than 3m

(iii) Jr = 0.5 can be used for planar, slickensided joints having lineation, provided the lineations are favourably oriented

(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

Table 7 shows that the rating for category (a) & (b) are same. But, with time due to weathering in water charged jointed soft rock, the roughness of joint will change and the joint has thicker filling changing J_r rating to category (c), i.e. 1. Similarly, rating of J_a will also be adversely influenced by weathering in soft and jointed rocks; Table 8 category (a) will shift to category (b). The effect of weathering can reach up to great depth in water charged rock masses and in the rocks having vertical to sub-vertical joints. This weathering effect shall always be there and considered for the evaluation of ultimate Q-value and design of tunnel supports below ground water table.

Table 8 - Joint alteration number J_a (Barton, 2002)

	Condition	J_a
(a) Rock wall contact (No mineral filling, only coating)		
A.	Tightly healed, hard, non-softening, impermeable filling, i.e. quartz or epidote	0.75
B.	Unaltered joint walls, surface staining only	1.0
C	Slightly altered joint walls. Non-softening mineral coatings, sandy particles, clay-free disintegrated rock, etc.	2.0
D	Silty or sandy clay coatings, small clay fraction (non-softening)	3.0
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, 1-2mm or less in thickness)	4.0
b) Rock wall contact before 10 cm shear (Thin mineral fillings)		
F	Sandy particles, clay-free disintegrated rock, etc.	4.0
G	Strongly over-consolidated, non-softening clay mineral fillings (continuous, <5mm in thickness)	6.0
H	Medium or low over-consolidation, softening, clay mineral fillings (continuous,	12-16

	<5mm in thickness)	
J	Swelling clay fillings, i.e. montmorillonite (continuous, <5 mm in thickness). Value of J_a depends on per cent of swelling clay-size particles, and access to water, etc.	8-12
(c) No rock wall contact when sheared (Thick mineral fillings)		
K,L,M	Zones or bands of disintegrated or crushed rock and clay (see G, H, J for description of clay condition)	6, 8 or 8-12
N	Zones or bands of silty or sandy clay, small clay fraction (non-softening)	5.0
O,P,R	Thick, continuous zones or bands of clay (see G, H, J for description of clay condition)	10, 13 or 13-20

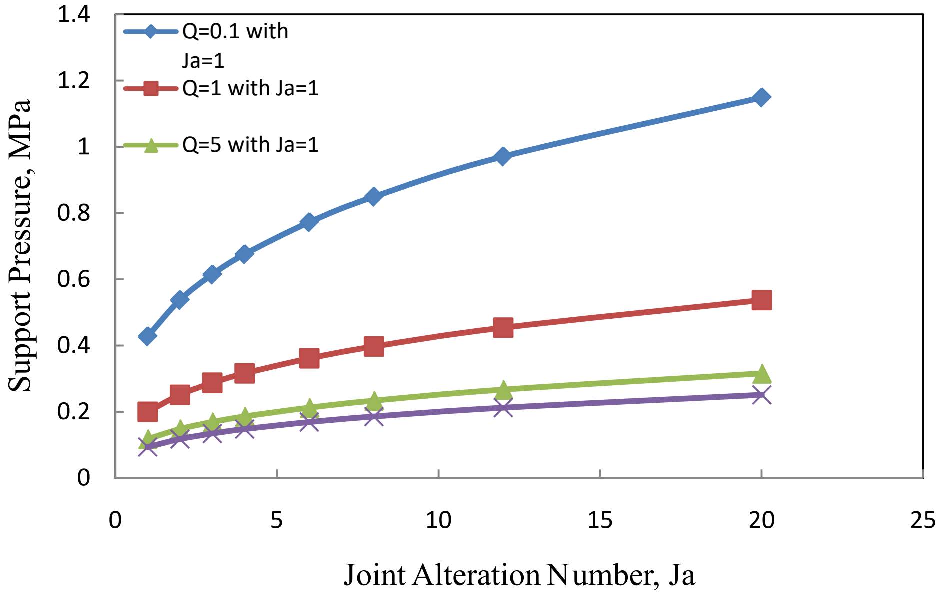

Figure 2 - Variation of support pressure with J_a

To study the effect of weathering in J_a and on support pressure a plot between J_a and support pressure is drawn and shown in Fig. 2. The support pressure is obtained by using the Barton's equation of estimating support pressure. Figure 2 shows four plots for different Q-values and assuming J_a=1. The variation in J_a (shown on Y-axis) will change the Q-value and thus the estimated support pressure.

It can be seen in Fig. 2 that weaker/poor rock mass (represented by plot of Q=0.1), which are likely to be affected most by the weathering, has considerable increase in support pressure with the increase in J_a rating. Hence, it is important to take care of weathering effect while computing **ultimate value** of Q and designing the long-term supports in soft rocks in adverse hydro-geological conditions specially in the hydropower tunnels. Bye-pass tunnel should be made to pass through highly landslide prone hills.

9. CONCLUSIONS

(i) Weatherability is different from the degree/grade of weathering. The weathering grade represents the state of weathering of a rock mass, whereas weatherability is the resistance to weathering of a rock mass.

(ii) The rock mass exposed to weathering agencies at shallow depth get weaker and weaker with time. The rate of weathering would be different from region to region and the rock mass types, which need to be investigated thoroughly. However, the rock mass at greater depth may be least affected due to absence of large variation of temperature, heavy blow of wind and other atmospheric changes.

(iii) Relation between various engineering properties and weathering grades are shown in Table 2, which can be used as a guide judiciously to get an idea of behavior of various grade rocks.

(iv) Intact rock strength, spacing of discontinuities and condition of discontinuities are adversely affected by weathering (Table 4). Condition of discontinuities in a rock mass is less influenced by weathering than the intact rock strength and the spacing of discontinuities.

(v) Engineering structure on rock mass having UCS of intact rock material less than 50MPa and VK category more than 2 (Table 3) shall require special attention to take care of weathering effect during its designed life.

(vi) Slake durability index is an important test to judge the weathering resistance of specially the soft rocks like shale, siltstone, mudstone and other clay-bearing rocks. Hence, it is suggested to carry out this test for all future designs of slopes, in particular.

(vii) Rock mass rating (RMR) and slope mass rating (SMR) shall also take care of the weathering effect on soft rocks (having VK category>2) as shown in Table 6. SMR is being vastly used for the study of slope or landslide.

(viii) Effect of weathering in Jr and Ja shall be considered for computing the ultimateQ-value for long-term support pressure for tunnels through soft and jointed rock masses charged with ground/rain water especially in areas where adverse hydro-geological conditions prevail. This should also be taken care of in shallow tunnels located in weathering prone rock masses/areas.

(ix) Saturation and weathering may significantly reduce the modulus of deformation and cohesion of soft rock mass.

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