Evaluation of Weathered Rock Mass Strength and Deformation Using Weathering Indices

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Abstract. Rock weathering and the resulting effects on geotechnical properties of weathered rock mass has long been a concern for geotechnical engineering practicing since the strength and deformational properties of weathered rock masses is needed for analysis and design of underground openings, open pits and excavations for foundations of dams, bridges and high-rise buildings in and on weathered rock mass. It is a very challenging task to obtain required core samples to determine the strength and deformation behavior for the assessment of weathered rock mass performance. This is because of weathering which causes change in fabric of rock by creating voids and micro cracks after dissolving grain boundaries particularly, at higher stage of weathering. This paper attempt to present a method of sampling and testing of weathered rocks and proposed a weathered rock mass indices chart for estimating rock mass strength and deformation properties. To investigate the applicability of the proposed weathered rock mass indices chart for other regions, available data from literature for same rock has been used along with the extensive testing data generated in the present investigation Deccan plateau basaltic rocks.

1. Introduction
Geotechnical investigations are needed starting at initial design stages of dams, slopes, foundation, bridge and underground structures. Over the years, there have been some successful attempts made to study strength deformational behavior of intact and jointed rocks in the laboratory [15]. Further, standard laboratory tests, for measuring strength and deformational behavior of intact rocks strength and deformation by International Society for Rock Mechanics (ISRM) and several researchers have established correlation with physico-mechanical index properties including porosity, density, point load strength and rebound hammer strength) of intact rocks. Generally, the intact rock properties are studied extensively and more or less well established. However, intact rocks strength and deformation behavior are influenced by many factors, among that weathering of the rocks is one of the crucial factors that drastically reduces the engineering properties of the rocks.

2. Review of weathered rock mass classification systems
In practice there has been agreement to classify rock material and mass into six weathering grades, ranging from fresh rock to residual soil based on visual impression. Since Moye (1955) several classifications for weathered rock material and mass were suggested. The use of weathering classification system and subsequent weathering state designation is very subjective and highly dependent on
professional judgment and experience. The first step in proposing a weathered rock classification is to determine the critical parameters of rocks relating to classification purpose. The most common classification system was for the weathered rock mass is the International Society for Rock Mechanics (ISRM, 1981) [12], where the weathering states vary between W1 to W5 (fresh to completely weathered).

The transition between the different weathering states is gradual. Judgment, consistency and experience in weathering classification are very important. Even though, classifying the different degree of weathered rock samples qualitatively is more subjective and it depends on the person classifying the samples. It is easier to distinguish highly weathered and fresh rocks over the slightly and moderately weathered one. However, experience showed that weathering classification is more consistent for slightly weathered rock than highly weathered rock. Therefore, the use of objective and consistent criterion to designate weathering states throughout a project is very important and recommended, since having one consistent error in weathering classification is easier to deal with than having many errors that can get complicated at a further state of a project.

In addition to ISRM, 1981[12] weathered rock classification; several researchers suggested weathering indices representing weathered rock mass including Dearman and Irfan, (1978) [9], Gupta and Rao, (2001) [11] and Ayalew et al., (2002) [1], Chala and Rao (2017) [6] and Chala, E. T. (2018) [5]. Most important rock mass weathering indices including: (i) degree of discolorations along joint plane, (ii) presence of original structure, (iii) rock to soil ratio, (iv) degree of weathering along joint plane, (v) angularity of copestone, (vi) opening of joint/aperture, (vii) NX core recovery, (viii) and rock quality designation (RQD). Gupta and Rao (2001) [11] selected five indices of rock mass commonly influenced by weathering namely: (i) Predominant weathering grade of rock material (Rs), (ii) State of joint weathering (Jwt) (iii) Number of joints per meter of the scan line (Jn), (iv) Joint width (Jwd) and (v) Water presence (W). All parameters are combined in a graded scale, to express the condition of weathering zones of rock mass (Rw). However, this knowledge limited to the academic area not fully developed, in practice the widely used rock mass classification system including different degree of weathering and alteration of the rock mass is the Geological strength Index (GSI) chart.

The Geological strength index chart has been introduced initially by Hoek et al. (1997) [8] and subsequently. Cai et al. (2004) [4], Sonmez and Ulusay (1999) [23], Russo (2007) [19], 2009) [20] and Hoek et al. (2013) have published quantified GSI charts which currently in use in rock engineering practice. Hoek et al., 2013 incorporate two main parameters (i) Joint condition (Jcond89) rating defined by Bieniawski (1989)[2], (ii) Block size derived from the rock quality designation (RQD) defined by Deere (1963)[7] and Palmstrom (2005)[15]. The use of RQD for various weathered rock grade is not possible since RQD does not consider core size less than 10 cm in length. Practically, in higher stages of weathered rock mass, it is hardly to find core size greater than 10cm. Therefore, GSI 2013 currently in practice is not applicable for various weathered and altered rock mass strength assessments since it considers RQD as key classification of the rock mass. Having this gap in mind extensive field and laboratory work carried out on different degree of weathered rock profile to find out a weathering indices that able to quantify or estimate different degree of weathered and decomposed rock mass strength and deformational behaviour.

3. Field investigation and description of weathered rock

In the present study, various degrees of weathered rocks of have been studied at both material and mass scale. Block and core samples were collected from each stage of weathering for experimental study in laboratory. The specimens were first grouped based on colour, surface texture, staining and physical appearance. The weathering state was assigned as fresh (W1), slightly weathered (W2), moderately weathered (W3), highly weathered (W4), completely weathered (W5) and Residual soil (W6). Large numbers of fresh, slightly and moderately weathered block samples that can yield large number of core specimen as per ISRM standard have been obtained. Completely weathered basaltic rocks which were highly prone to collapse were immediately covered (with plaster and carton) and safely transported to Rock Engineering Laboratory. Fresh basalt from quarry, road cut slope, and hydropower project sites where collected to examine their physico-mechanical properties.
3.1 Sample preparations and testing

The selected block rock samples from each variety have been cut to portable size to fit into the core drilling and cutting machines. A heavy-duty diamond drill assembly, equipped with 54mm (NX size) internal diameter diamond core bit, a water-feeding system and cutting speed option, have been used for core drilling. It is often difficult to obtain core segments that are of the correct size as per International Society of Rock Mechanics (ISRM, 1979) [13] protocols in weathered rock formations. Therefore, a machine having cutter of diamond saw was used for a higher stage weathered rocks and 5 cm cubical samples have been prepared.

| Typical Photography | Weathering state and description | Texture | Appearance |
|---------------------|----------------------------------|---------|------------|
| Weathering State W1 | Very competent, get full core length | Light to medium gray | Fine texture |
|                     | Intact, no sign of fractures on the surface. |         | Very minor pitting |
|                     | Concrete-like appearance |         |            |
| Weathering State W2 | Appear competent | Creamy color | Coarser texture |
|                     | Beginning of discolor, staining surface | Minor pitting |            |
|                     | Get full core length for strength tests |         |            |
| Weathering State W3 | Appear somewhat competent/somewhat fragile | Dark creamy color | Even coarser texture |
|                     | It is possible to get core sample but not required length for strength tests | Whitis color also seen | Pitting is very evident |
|                     | Never full core diameter |         |            |
|                     | Earthy-type fracture appearance |         |            |
| Weathering State W4 | Appear very fragile | Very dark creamy color to yellowish color | Very coarse texture |
|                     | It is very difficult to get core some, while drilling | Whitish color also seen | Major pitting |
|                     | It is become soil/earthy material |         | Smearing of the saw blade on specimens is often noted |
| Weathering State W5 | Very fragile, easily disintegrated by hand | Very dark creamy color to yellowish color | Unable to obtain specimen for testing |
|                     | The samples completely broken by hand or simple geological hammer completely broken | Whitish color also seen |            |

...................... Weathering State W Residual soil
Each cylindrical sample has been prepared according to ISRM suggested methods (ISRM, 1979) [13] with diameter of 54 mm and length to diameter (L/D) ratio of 2, 1 and 0.5 for UCS, Point load and Brazilian tensile strength respectively.

The ends of each sample have been made to be flat to ± 0.01 mm and parallel to each other. The tolerance limits suggested by (ISRM, 1979) [13] had been adhered while preparing individual specimens for different strength tests. Cubical specimens have been prepared for highly and completely weathered categories of samples due to difficulties in coring.

Table 2. Physical properties of rocks at various grades of weathering stage.

| Rock type                | Description       | n (%) | $\gamma_{dry}$ (kN/m$^3$) | $\gamma_{sat}$ (kN/m$^3$) | Vp (m/s) |
|-------------------------|-------------------|-------|---------------------------|---------------------------|----------|
| CBW0 (Fresh)            |                   |       |                           |                           |          |
|                         |                   | Min   | Mean                      | Max                        | Mean     |
|                         |                   | 0.1   | 0.4                       | 0.9                        | 29       |
|                         |                   |       |                           |                           |          |
| CBW1 (Slightly weathered)|                   | 1.0   | 1.4                       | 2.0                        | 28       |
|                         |                   |       |                           |                           |          |
| CBW2 (Moderately weathered)|                | 0.7   | 1.8                       | 2.2                        | 27       |
|                         |                   |       |                           |                           |          |
| CBW3 (Highly weathered) |                   | 5.0   | 7                         | 10                         | 26       |
|                         |                   |       |                           |                           |          |
| CBW4 (Completely weathered)|              | 15    | 21                        | 25                         | 22       |

n = porosity in %, $\gamma_{dry/sat}$ (kN/m$^3$) = unit weight under dry and saturated condition respectively, Vp (m/s) = Sonic wave velocity.

4. Applicability of Rock mass Indices in Representing Weathered Rock mass

Rock mass indices are simplistic representations of a rock mass. In the 1970s, engineering rock mass classification systems were developed that sought to characterize a rock mass with a single index based on selected rock mass qualities such as intact rock strength, joint characteristics, and groundwater conditions. Subsequently the common rock mass classification system including the rock mass rating (RMR) system of Bieniawski (1973)[1989], the Q-system (Q) of Barton et al. (1974)[3] and GSI (Hoek et al.,1997)[13] were developed incorporating several rock mass indices (five to six parameters) to represent the rock mass conditions. Most of these rock mass classification indices devised from physical weathering (joint behaviour) and place less weightage on chemical weathering indices. The use of geomechanical classification system must be done carefully by giving attention to lithological characteristics those have potential to weathering to incorporate all significant and reliable indices in the classifications.

The existing weathered material and mass classifications are semi-quantitative and have also not given much attention to lithological characteristics. The use of RQD for various weathered rock grades is not possible since RQD does not consider core size less than10 cm. practically, in higher stage of weathered rock mass core size greater than specified core size is hardly found. The study on applicability of index/physical property and characteristics indicate that the total core recovery (TCR)/and fracture frequency along with Schmidt Rebound hammer (R$_s$) value of respective weathering grade to be reliable strength indices for weathered rock mass strength characterization. Because in the TCR calculations a very piece of core size obtained in the total core run is considered along with a very sensitive simple mechanical index test called rebound hammer value which can be used for the characterization of various degree of weathered rock strengths.
4.1 Characterization of weathered rocks based on drilling parameters and rebound hammer value

The proposed weathered rock mass strength chart has been constructed based on total core recovery (TCR) and Rebound hammers strength (R_N) tests the present investigation. To investigate the applicability of the proposed chart for other regions, available data from literature has been used along with the directly data generated in the present investigation. However, as direct use these two parameters (TCR and RN) are difficult since overlapping of results are common in higher stage of weathered rock mass. To measure the extent of respective grade of weathered rock mass strength the TCR and R_N values compared with the values of fresh one and boundary limit values are fixed.

| DWZ | Representation | Description | TCR (%) | BLV | RQD (%) |
|-----|----------------|-------------|---------|-----|---------|
| I   | Fresh          | No visible sign of rock material weathering; perhaps slight discoloration on major discontinuity surface. | > 90    | 50-100 |
| II  | Slightly weathered | Discoloration indicates weathering of rock material and discontinuity surfaces. External surface may be somewhat weaker than in its fresh condition. | 89-70   | 90 | 50-100 |
| III | Moderately weathered | Less than half of the rock material is decomposed and/or disintegrated to soil. Fresh or discolored rock is present in either continuous framework / core stones. | 69-50   | 70 | 0-50 |
| IV  | Highly weathered | All rock material is decomposed and/or disintegrated to soil. The original mass structure is still largely intact. | 49-10   | 50 | 0-50 |
| V   | Completely weathered | All rock material is converted to soil. The mass structure and material fabric are destroyed. There is a large change in volume, but the soil has not been significantly transported. | 9-0     | 10 | NA     |
| VI  | Residual soil  | All rock material is converted to soil. The mass structure and material fabric are destroyed. There is a large change in volume, but the soil has not been significantly transported. | Zero    | 0  | NA     |

DWZ: Degree of weathered Zone

| Table 4. Boundary limit value of R_N for respective weathered core samples. |
|-----------------------------|-----------------|---------|---------|---------|
| Literature value            | Present study   |        |         |
| DWZ | Range of Rebound hammer value | Range values | Mean | BLV |
|-----|--------------------------------|---------------|------|-----|
| I   | 33.8 to 69.6 (48.4)            | > 60          | 60   | 100 |
| II  | 28.53 to 56.5 (43.82)          | 60 to 40 (52.75) | 53   | 88  |
| III | 13.2 to 37.5 (24.89)           | 40 to 20 (16.28) | 17   | 28  |
| IV  | 11.18 to 35 (20.602)           | 20 to 10 (13.2) | 13   | 21  |
| V   | 6.4 to 18 (13.78)              | < 10          | 10   | 16  |

The boundary limit value (BLV) for Rebound number values 88, 28, 21 and 16 have been selected to distinguish slightly, moderately, highly, and completely weathered rock mass zones, respectively (table 4) and for TCR, the BLV are 90.70, 50, 10 and 0 to define slightly, moderately, highly, completely weathered and residual soil zones respectively (table 3). The combined results can be represent different degree of weathered rock mass units and named as “Weathering Indices chart (WI-CHART)”.

The WI-CHART constructed based on boundary limit value of Total core recover and rebound hammer values of as shown in figure 1. To illustrate the effectiveness of proposed weathering indices chart in numerical modeling of weathered rock mass; the core samples available from already drilled boreholes have been studied.
From the borehole data, the total core recovery (TCR) and rebound hammer (RN) value of respective cores samples are determined. The average of strength value obtained from Geological strength index and weathering indices chart by RN values and TCR proposed in the study have been considered in the analysis but the result of numerical modeling using Weathering Indices chart; WI-CHART beyond the scope of the present paper.

**Figure 1.** Proposed weathering indices chart (WI Chart) by rebound hammer values (RN) and total core recover (TCR).

The trend/ regression between rebound hammer and total core recover (TCR) of different degree of weathered rock mass units are carried out using table 4 and table 3 data respectively and the data’s are best fit to linear (figure 2a) and logarithmic (figure 2b) $R^2 = 0.8$ and 0.9 respectively and presented as figure 2.

**Figure 2.** The trend/ regression between average rebound hammer and total core recover (TCR) values for different degree of weathered rock mass units.
5. Conclusion and Recommendation

- The use of geomechanical classification system must be done carefully by giving attention to lithological characteristics which have potential to include all significant and reliable quantitative input data in the classifications rock masses.
- The study on applicability of index property and characteristics indicate that the total core recovery (TCR) along with Rebound hammer (RN) value of respective weathering grade are reliable and simple weathering indices for weathered rock mass strength characterization in preliminary design of foundation on weathered rock mass. However, as direct use of these two parameters also is difficult since overlapping of the results are common in higher stages of weathered rock mass as observed in the study.
- To measure the extent of respective grade of weathered rock mass strength, the TCR and RN values are compared with the values of fresh one and boundary limit value fixed. The combined result is used for defining “different degree of weathered rock mass zone which can be represented as Weathering Indices Chart (WI-Chart).
- WI-Chart has been constructed based on the Boundary limit value of TCR and rebound hammer values and presented in the chart.
- The weathering indices chart proposed can be used in Numerical modeling in similar way of geological strength index (GSI) used by linking to rock strength criteria to evaluate or and determine the strength and deformational behavior of different degree of weathered rock masses as in put in numerical modeling.

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