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Assessing Rock Mass Permeability Using Discontinuity Properties

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Abstract

Field measurement of rock mass permeability is essential that numerous factors influence its directional magnitude. Lugeon test is a popularly conducted field instrument in order to measure hydraulic conductivity of a rock mass. Discontinuity orientation, spacing and discontinuity surface quality, infill presence and type play essential role in permeability of the rock mass in addition to rock material itself. Geological Strength Index (*GSI*) is a parameter used in Gen. Hoek-Brown failure criterion and supporting empirical equations in order to estimate rock mass strength and deformability parameters. Frequently used Rock Quality Designation (*RQD*) and *GSI* and Lugeon values were combined in order to generate a relation among them. The proposed relationships are produced by interpretation of geotechnical core logging and Lugeon test results.

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Keywords: hydraulic conductivity; rock mass; in situ tests; Lugeon test; rock mass permeability

1. Introduction

Groundwater has great influence on rock engineering structures. Difficulties may include construction operations, rock mass deformation and stability. Hydraulic conductivity, pore water pressure, water pressure acting along the joints are all important as well as water sensitivity of the rock material. Understanding of groundwater condition is crucial for surface structures on rock masses, foundations, slopes [1, 2, 3]. For underground rock structures, information about ground water pressure and water inflow rate is essential [4, 5] since it strongly influences operational issues as well as stability of the structure and supports. Operational issues may include pump selection and infrastructure design for water discharge, foreseeing a need for grouting, water sealing. Permeability character of ground plays important role for also surface structures such as dams and foundations [6, 7].

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2. Hydraulic conductivity

For water flow through a saturated granular material, Darcy's law [8] is widely accepted:

$$Q=A\times K\times i \tag{1}$$

Total flow (Q in m^3/s) is directly proportional to the cross-sectional area of flow (A in m^2), hydraulic conductivity (or called as coefficient of permeability in m/s) and hydraulic gradient i. i is a ratio of pressure difference (Δh) along a particular flow length (l in m) can be represented as:

$$i=\Delta h/l \tag{2}$$

In addition to the intrinsic permeability of the geological material represented by k_i, hydraulic conductivity, K is dependent on the fluid properties which are unit weight γ and viscosity μ:

$$K=k_i\,(\gamma / \mu) \tag{3}$$

Hydraulic conductivity (coefficient of permeability) can be measured in both laboratory scale and field scale and then can be utilized for calculation of total inflow of groundwater in a particular area. For soil material, all pores or voids are accepted to be interconnected [9] and in general, gradation, density, porosity, void ratio, saturation degree, and stratification influence permeability [10]. There are rock formations which may represent soil like permeability behaviour with interconnected voids representing high porosity. Generally intact rock is very well cemented with mineral grains which contain tiny pores. The pores or voids are not interconnected however may represent at least very low permeability if rock is not fractured (Fig. 1).

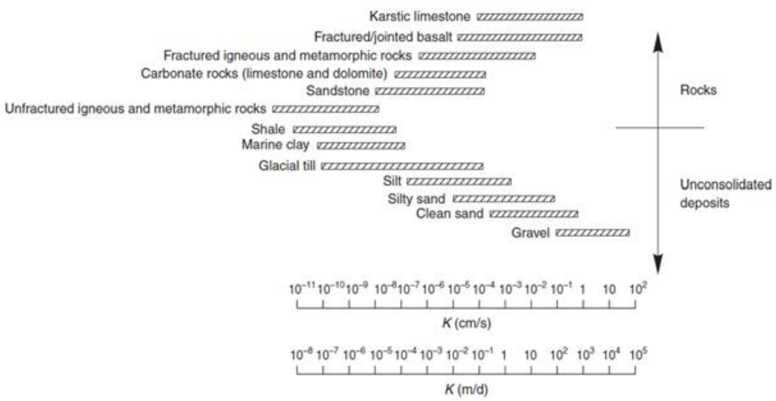

Fig. 1. Hydraulic conductivity of various geological units (after Atkinson [11]).

Permeability of the intact rock and the rock mass alters due to the presence and frequency of discontinuities. Discontinuity condition, namely: persistence, tightness, aperture, roughness, infill type, filling thickness of the discontinuities also govern the water flow rate through a rock mass as well as affecting rock mass strength. In-situ stress also influences water flow. Field scale estimation and measurement of permeability becomes more important when the interest area is a rock mass.

3. Lugeon Test

Lugeon test is a commonly employed in-situ test in order to measure rock mass permeability and sometimes called as packer test. Test got its name from Maurice Lugeon in 1933. Lugeon test is a constant head type permeability test. The test is carried out at an interval of a borehole and different locations along the borehole. Testing section is insulated by upper and lower inflatable packers which fit to the borehole. A maximum test pressure should be decided before the test. The value should not cause hydraulic fracturing of the borehole walls. The test is generally conducted at five stages or more. At each stage a particular percentage of maximum pressure is kept constant and applied for 10 minutes. Water loss at each stage must be logged. After application of maximum pressure stage, pressure stages are lowered gradually in the same way [12, 13].

The permeability value obtained in this test gives information on the number, persistence and opening of the rock discontinuities which intersect the wall of the borehole in the test section. Results are expressed in Lugeon (represented by *uL* or *L*) units. A Lugeon (*uL*) is defined as the water loss of 1 litre/minute per metre length of test section at an effective pressure of 1 MPa [14].

$$Lugeon=uL=(q/L)\times(P_0/P) \tag{4}$$

Here Lugeon value is calculated by using water loss q (lt/min), testing length L (m), Reference pressure P_0 (1 MPa) and pressure applied at a test stage P (MPa). In Table 1, Lugeon values and corresponding classification values are given.

Table 1. Condition of rock mass discontinuities associated with different Lugeon values (after Quiñones-Rozo [12]).

Lugeon Range	Classification	Hydraulic conductivity Range (cm/sec)	Condition of Rock Mass Discontinuities	Reporting Precision (Lugeons)
< 1	Very Low	$< 1x10^{-5}$	Very Tight	< 1
1–5	Low	$1x10^{-5}$–$6x10^{-5}$	Tight	± 0
5–15	Moderate	$6x10^{-5}$–$2x10^{-4}$	Few Partly Open	± 1
15–50	Medium	$2x10^{-4}$– $6x10^{-4}$	Some Open	± 5
50–100	High	$6x10^{-4}$–$1x10^{-3}$	Many Open	± 10
> 100	Very High	$> 1x10^{-3}$	Open Closely spaced or voids	> 100

4. Geological Strength Index and its quantification

The Rock Quality Designation index (*RQD*) was developed by Deere et al. [15] to provide a quantitative estimate of rock mass quality from drill core logs. *RQD* is defined as the percentage of intact pieces longer than 100 mm in total length. Still, value is being used as an input parameter for many rock mass classification systems as well as being direct parameter for several correlations.

Aydan et al. [4] proposed a new rock mass classification system with a broad review of commonly used classification systems. Researchers also gave relations between rock mass strength/deformability parameters and rock mass classification systems.

The original Hoek-Brown failure criterion was developed in order to provide input strength and deformability parameters for the design of underground excavations. The importance of Hoek-Brown failure criterion was to link the mathematical relation to geological facts. The geological facts are represented by Geological Strength Index chart. The index is still being developed as the major tool for geological data provider for the Hoek-Brown criterion [16]. Hoek and Marinos [17] revised Hoek-Brown criterion. The mathematical expressions are regenerated between the parameters: "*m, s, a* and *GSI*". *D*, blast damage parameter is added to the new equations. This version is currently being used and details are explained in [16]. Marinos [18] presented an updated *GSI* chart for heterogeneous rock masses and possible failure types corresponding to several geological formations.

The nature of rock mass classification systems and also *GSI* rating have some deficiencies. *GSI* charts are based on visual impression and the index value is identified by experience of the engineer. Thus, different rock mass classification estimates can be found by different engineers on the same rock mass. Sonmez and Ulusay [19, 20] modified the *GSI* chart to decrease engineers' bias. This modified and quantitative *GSI* chart considers two terms namely, "structure rating, *SR*" based on volumetric joint count (*Jv*) and "joint surface condition rating, *SCR*", estimated from input parameters (e.g., roughness, weathering and infilling).

Cai et al. [21] suggested an approach for the *GSI* system building on the concept of block size and conditions. Their resulting approach adds quantitative measures to the system. This *GSI* chart considers quantitative block volume (*Vb*) and the descriptive joint condition factor. Block volume is suggested for three or more joint sets and with an assumption of prismatic blocks. This situation causes a limitation in the estimation of *Vb* for blocks with different geometries which was also emphasized by Palmstrom [22] and Sonmez et al. [23].

Russo [24, 25] combined Rock Mass Index (*RMi*) and *GSI* with additional relations to excavation behaviour and stability.

Hoek et al. [26] presented another quantification method for *GSI* and modified *GSI* chart by omitting upper (intact or massive) and lower rows (laminated sheared) from the chart given in [17].

Discontinuity condition rating guidelines of *RMR* (Table 2) [27] and *RQD* values can be combined in order to obtain a quantified value of *GSI*. Alternatively, joint rougness number, J_r, Joint alteration number, J_a of Q-system [28, 29] can be used in the quantification of discontinuity surface condition. For degree of block structure, *RQD* is taken into account.

Table 2. Guidelines for classification of discontinuity conditions $JCond_{89}$, after Bieniawski [27].

Discontinuity length (persistence) Rating	< 1 m 6	1 to 3 m 4	3 to10 m 2	10 to 20 m 1	More than 20 m 0
Separation (aperture) Rating	None 6	< 0.1 mm 5	– 1.0 mm 4	1 – 5 mm 1	More than 5 mm 0
Roughess Rating	Very rough 6	Rough 5	Slightly rough 3	Smooth 1	Slickensided 0
Infilling (gouge) Rating	None 6	Hard infilling < 5mm 4	Hard filling > 5 mm 2	Soft infilling < 5mm 2	Soft infilling > 5mm 0
Weathering Rating	Unweathered 6	Slightly weathered 5	Moderate weathering 3	Highly weathered 1	Decomposed 0

Quantified *GSI* ratings can be calculated by both *RMR* and *Q-system* input parameters, as below [26]:

$$GSI = 1.5\times JCond_{89} + RQD/2 \tag{5}$$

$$GSI = 52\times (J_r/J_a) / (1+J_r/J_a) + RQD/2 \tag{6}$$

GSI quantification by Hoek et al. [26] can be considered to be practical since the parameters used are well known paramaters among rock engineers. The author of this study also utilized several *GSI* quantification methods to borehole investigations and underground openings concluding that approaches of Cai et al. [21] and Hoek et al. [26] are working consistently.

GSI covers important properties related to the permeability of the rock mass. Vertical axis is on structural quality of the rock mass and a good indicator of discontinuity density. This parameter can be represented by *RQD*, volumetric joint count, block volume, discontinuity spacing parameters. Considering *GSI* chart, downward direction will naturally lead to higher permeability.

Horizontal axis of *GSI* is related to discontinuity condition. Sonmez et al. [23], reduced Table 2 parameters to roughness, weathering and infilling ratings for GSI. Hoek et al. [26] added aperture and persistence of discontinuities and used RMR_{89} description of discontinuity conditions, (Table 2). Considering the items in Table 2, straightforward predictions can be made: with increasing persistence and aperture, permeability will be naturally higher. The smoother the discontinuity, higher the permeability. Infilling and weathering parameters are tricky since weathering is not necessarily related to clay occurrence but it can be true frequently. Soft infilling can be accepted as clay minerals and practically less pervious or even impervious. However, a hard fill which is tightly interlocked and intact will presumably less pervious, too. Without any infilling, a discontinuity can be pervious but very tight interlocking will drastically affect the permeability. It is possible to observe thick calcite fillings along fault zones or other kind of discontinuities which improves fractured rock mass by means of water tightness. Absence of infilling is the only option for relatively high permeability. It means, discontinuity condition axis cannot be used as an indicator of permeability.

5. Geology of the study area

Lugeon tests were conducted in Soma lignite coal basin. The area is located at Soma province in Manisa/Turkey. An open cast mine is under operation in the northern region of the basin where the coal seam lies at shallow depth. In neighbourhood, underground coal mines are in operation at a depth range of 150–400 m. New underground coal mines are being projected having greater mining depth from 700 m to 1200 m which are owned by the state and private companies at an approximate distance of 5 km far from the mines under operation.

4 boreholes were subjected to Lugeon testing in the area. All of them were drilled in order to conduct geotechnical and hydrogeological investigations of proposed mine access openings: shafts and decline. Borehole depths were adjusted considering the investigated part of the decline and shafts. In Soma Coal basin, Miocene aged coal seam (named as KM2) is being mined. Overburden consists of Miocene aged marl and limestone at the roof of the KM2 coal. Pliocene aged sedimentary units cover Miocene formations. Volcanic units are also present especially in Pliocene formations in the form of Andesite, Basalt or Agglomerate. Borehole descriptions and lithology are present, (Fig. 2):

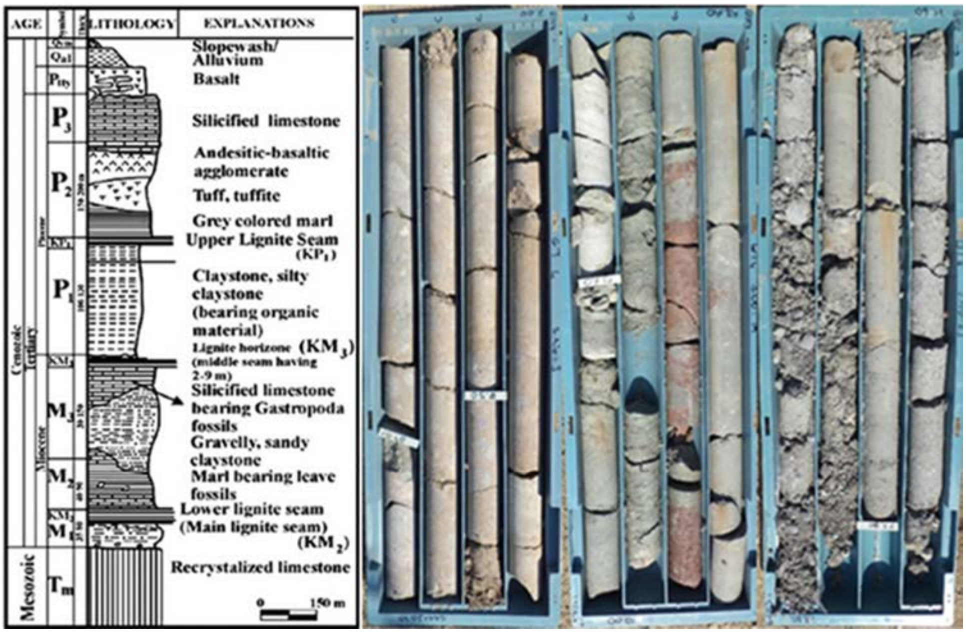

Fig. 2. Generalized stratigraphy of Soma coal basin (left),(Aksoy et al. [30]), volcanic and sedimentary rock samples (right).

BH1: 3 Lugeon tests were conducted along this borehole from the depth of 27 to 76 m. Rock type at test locations are agglomeratic, basaltic, andesitic tuff variations.

BH2: 10 Lugeon test results from the depths 8 to 80 m were obtained. Siltstone and conglomerate layers are present with clay and sand.

BH3: 22 Lugeon tests were applied at depths from 40 to 340 m interval. From 40 to 140 m fractured andesite, from 140 to 236 m tuffitic agglomerate and from 236 to 306 m andesite, from 306 to 340 m basalt, andesite and 10 m thick silicified limestone fractured with slickensides were observed.

BH4: 31 Lugeon tests were applied at depths from 15 to 386 m and from 684 to 772 m. First 125 m, borehole passed through fractured tuff, andesite, and agglomerate. From 125 to 228 m, geological units are siltsone, claystone, marl. From 228 to 276 m, dacite, andesitic agglomerate and tuff reappears. At geological unit contacts, sheared and slickensided discontinuity surfaces were observed. From 276 to 383 m, Pliocene aged claysone, conglomerate, siltstone, sandstone and marl layers are present, named as P2C. From 684 to 772 m depth, P1 pliocene claystone, siltstone layers, Miocene limestones (M3) and Miocene Marl (M2) units are present.

Failed tests were identified and finally discarded. The common reason of unsuccessful testing is improper insulation of the test interval or totally impervious condition or the rock mass. A by-pass flow can be detected due to discontinuity network in the rock mass and treating the rock mass for the problem may cause alternating the properties of the mass. However, the important point is detecting the leakage and disregarding the test. Some of the proper tests resulted in indicating practically impervious test intervals. Practically, no flow occurred in those tests due to massive and impervious rock mass or blockage of joints. There can be several reasons for that but the data cannot be used at this time and the tests which exhibit refusal were disregarded.

6. New relationships between Lugeon and GSI

It is a fact that for any parameter representing rock mass quality from rock engineering point of view, any hydraulic conductivity value is possible due to the complex nature of the mass. This finding is validated in previous section by plotting *RQD*, discontinuity condition rating and *GSI* against Lugeon which are used for rock engineering purposes. Although *GSI* combines degree of jointing of the rock mass and discontinuity surface condition which are essentially governing factors on hydraulic conductivity. Additionally, interlocking and tightness of discontinuities due to field stress, anisotropy due to discontinuity orientation are accepted to influence permeability which are not considered in the study.

Kayabasi et al. [31] used non-linear tools to propose relations by utilizing package programs. In this study, the problem is handled in a way considering the physical meaning of the parameters and seeking the factors influencing permeability. Then, the relationships are developed manually considering the influence of several parameters. Proposed equations are evaluated comparing the actual values to estimated values.

When *RQD* and *GSI* are known, Lugeon value can be correlated. Four mathematical expressions are generated which are true for $GSI \leq$ ~60 and all *RQD* (0–100) range. Discontinuity surface ratings ($JCond_{89}$) of the data set mostly lie in poor half of the *GSI* chart ($JCond_{89}$ < 13.5). Here, *RQD* is used as number between 0 and 100. Best fitting is conducted based on GSI, RQD and *uL* and Equation 5 is obtained.

$$GSI = [\ln(uL) + 1] \times (RQD/11) + 15 \tag{7}$$

Since Equation 5 is used for estimation of GSI, the equation is rearranged by inserting Equation 5 into 7;

$$uL = e^{[\,5.5 + (\,16.5Jcond - 165\,)\,/\,RQD]\,-1} \tag{8}$$

For equations, low Lugeon values can be observed in low *GSI* and low *RQD* zones due to presence of clay fillings. Increasing *GSI* will lead to higher Lugeon values. Additionally, in that expression, *RQD* and Lugeon related parts are multiplied.

In the following plot (Fig. 3a), directly observed *GSI* values by using directly core logs and equation 4. Here, if the slope of the trend line and R^2 are close to 1, it means the performance of the expressions are satisfactory. GSI values for Lugeon test intervals were initially calculated as minimum and maximum range. Then, average points are used in best fit. Totally 66 data points and Lugeon tests were used. Lugeon values on the GSI chart is also provided, (Fig. 3b).

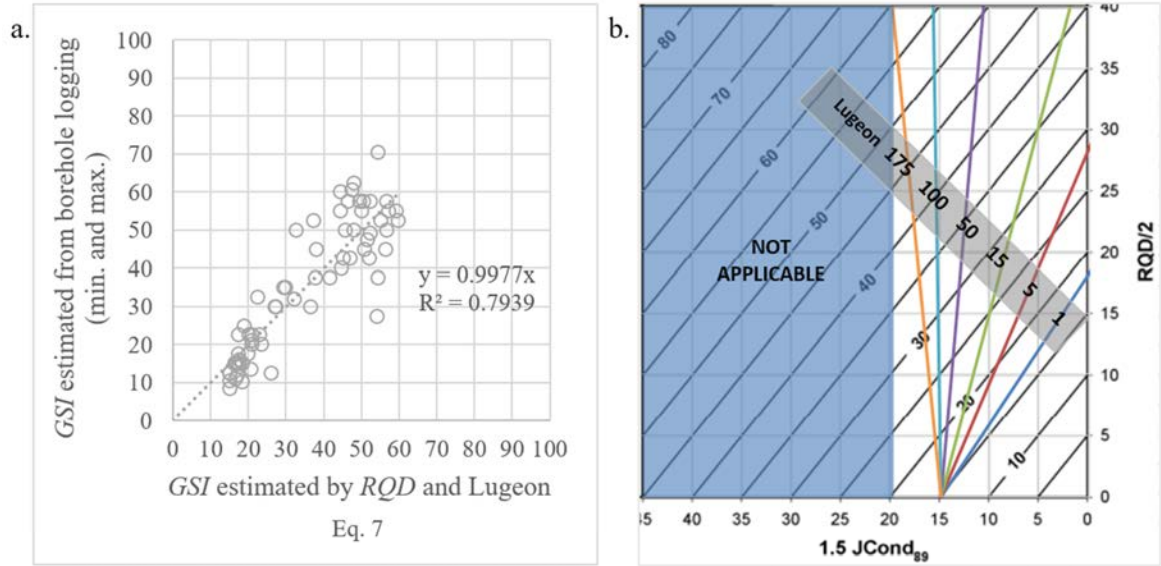

Fig. 3. (a) Comparison of observed *GSI* directly from borehole data and new relationships; (b) Lugeon values on GSI chart.

Majority of the samples consist of poor rock masses which causes the test sections exhibit permeable character. Additionally, when *GSI* chart is considered, samples mostly fall on the right-hand side of the chart with poor discontinuity surface conditions.

7. Conclusion

This research presents relationships among rock mass classification parameters (*GSI* and *RQD*) and permeability of the rock mass (Lugeon). A wide range of rock types and discontinuity conditions were subjected to testing and evaluation. Finally, successful equations are given in the paper. Implication of pre-existing and commonly used parameters for estimating rock mass permeability will provide higher applicability. Proposed equations can be used either for estimation of quantified *GSI* value or Lugeon value when *RQD* value is known for volcanic and sedimentary rock masses. Equations are currently accepted to be valid for *GSI*<60 and for all *RQD* values. Expanding the database used in the study will lead improvement of the quality of the relationships. One should keep this in mind that hydraulic conductivity through rock masses has strong complexity and in situ testing is crucial. However, in the absence of Lugeon tests, proposed equations can be used for poor rock masses or a quantified *GSI* value can be estimated where Lugeon testing is available.

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