Bulletin of Department of Geology, Tribhuvan University, Kathmandu, Nepal, vol. 24, 2023, pp. 37-46
DOI:https://doi.org/10.3126/bdg.v24i.68376

A Comparison of Statistical Validity of In-Situ Hydraulic Conductivity Prediction Models of Rock Mass Inferred from Borehole Logs and Lugeon Test Data

Ujjwal Kharel* and Suman Panthee
Central Department of Geology, Tribhuvan University, Kirtipur, Nepal

ABSTRACT

In-situ hydraulic conductivity is a vital property in rock engineering for jointed rock mass. Understanding its correlation with rock mass parameters is crucial for water circulation. Therefore, a study was carried out to develop statistically significant empirical relationships between hydraulic conductivity and various rock mass parameters to estimate in-situ hydraulic conductivity from Lugeon test and various rock mass parameters obtained from borehole logs.

The study initially aimed to establish a correlation between hydraulic conductivity and Rock Quality Designation (RQD). However, the outcomes were unsatisfactory, prompting further research. Later, two more robust models were developed, namely the HC-model and modified HC-model. The HC-model incorporated four rock mass parameters, including Rock Quality Designation Index, Depth Index, Gouge Content Designation Index, and Lithology Permeability Index, achieving a maximum coefficient of determination (R^2) of 0.46. The modified HC-model included six parameters, encompassing fracture frequency and theoretical aperture, resulting in an improved R^2 of 0.69. Both models significantly outperformed RQD-alone predictions ($R^2 < 0.10$), highlighting the need for incorporating multiple rock mass parameters in predicting hydraulic conductivity due to a complex interplay of various factors. However, the effects of joint persistence and roughness are limiting in the present analysis.

Key words: Hydraulic conductivity, Rock mass parameters, Lugeon Test, HC-model, Modified HC-model.

Received : 14 May 2023 **Accepted:** 25 October 2023

INTRODUCTION

Hydraulic conductivity is a physical property which measures the ability of a material to transmit fluid through pore spaces and fractures in the presence of an applied hydraulic gradient (Darcy, 1856). Measurement and quantification of hydraulic conductivity and understanding of water flow inside jointed rock mass has a wide range of applications in mining and civil engineering. Many civil engineering tasks such as tunnel construction, dam construction, mine development, petroleum extraction work and slope stabilization require the estimation of hydraulic conductivity for fractured rock mass. Hydraulic conductivity data are crucial to estimate the grouting volume and grouting type to seal the subsurface joints, fracture and cavities to prevent underground water seepage and for foundation purpose.

It is commonly known that the fluid flow in rock masses mainly occurs in fractured and cavities associated with stratification, joints, tectonic activities, karst dissolution etc. Therefore, knowledge of exact distribution and rock mass parameters, such as dip, dip direction, aperture, spacing, frequency, roughness, infill, alteration, persistence, is essential for identifying as the key measures to describe the fluid flow.

There are several methods of quantifying the hydraulic conductivity of fine- and coarse-grained soil from constant head and falling head test method in field and laboratory. But the hydraulic conductivity of subsurface fractured rock mass can only be quantified more accurately from in-situ field tests known as water pressure test or Lugeon test or packer test or rock mass permeability test. This test was initially proposed by Maurice Lugeon, a Swiss geologist in 1933 which is later modified by Houlsby (1976). Lugeon's test (Lugeon 1933) is a constant head type test which is conducted in an isolated section of boreholes by injecting water at constant pressure into the rock mass through a perforated pipe bounded by the pneumatic packers and this discharge is measured using flow meter.

The calculation and interpretation of water pressure test data can also be done by the equations developed by Hvorslev (1951), United States Department of the Interior Bureau of Reclamation, USBR (1960)

*Corresponding Author
Email: ujjwal.kharel1234@gmail.com (Ujjwal Kharel)

and Moye (1967). Besides from field and laboratory method, several researchers have proposed the empirical equations for the estimation of hydraulic conductivity which were based on the concept that rock mass permeability decreases with depth (Snow 1970; Louis 1969 and Wei et al. 1995).

Determining of permeability values for rock formations is difficult than for soil formations due to factors like rock quality, joint density and fracture values. In-situ testing of permeability is often expensive and time-consuming. Therefore, it is necessary to estimate statistically significant relationship between apparent in-situ permeability with various rock mass parameters from boreholes. This approach will assist in the planning detailed field investigations during design and construction, contributing to time and cost efficiency. Ultimately, it will improve the overall effectiveness of detailed investigations for a specific site.

GEOLOGICAL SETTING OF THE STUDY AREA

Geologically, the study area lies on the Lesser Himalaya of Mid-Western Nepal. The major rock types observed in the exposures and drilled rock cores in the vicinity of the study area are grayish black slate to graphitic slate and light gray to dark gray dolomitic limestone and gray limestone (Fig.1). The rock in and around the vicinity of the investigation area can be divided into two lithological units viz. Dolomite unit and Slate unit (Lamsal et.al.,2021). The dolomite unit in the study area is dark gray to medium dark gray color, medium to thickly bedded Dolomitic limestone rock with the presence of few domed shaped stromatolites structures. The slate unit in the study area comprises dark black, thin to medium bedded slate to graphitic slate rock with slaty cleavage appearances. An alluvial fan was developed by Andheri Khola, which is morphologically flat and marshy.

METHODOLOGY

Data from two drill hole sites up to the depth of 80m were chosen to compare the statistical significance between in-situ hydraulic conductivity and various rock mass parameters in the form of HC-model and modified HC-model. The in-situ permeability of rock mass was performed and interpreted using modified Lugeon water Pressure tests as per the requirements and methods suggested by Houlsby (1976). Other relevant rock mass parameters like recovery, RQD index, at each depth of investigations were obtained from the core logs.

In present research, the in-situ permeability of rock mass was delineated by conducting water pressure test of rock using modified lugeon water pressure test methods as proposed by Houlsby (Eqn.1).

$$\text{Lugeon value} = \text{water intake (Litres/meter/min)} \times \frac{10\ (\text{bars})}{\text{Test presure (bars)}} \quad \text{......................... (Eqn.1)}$$

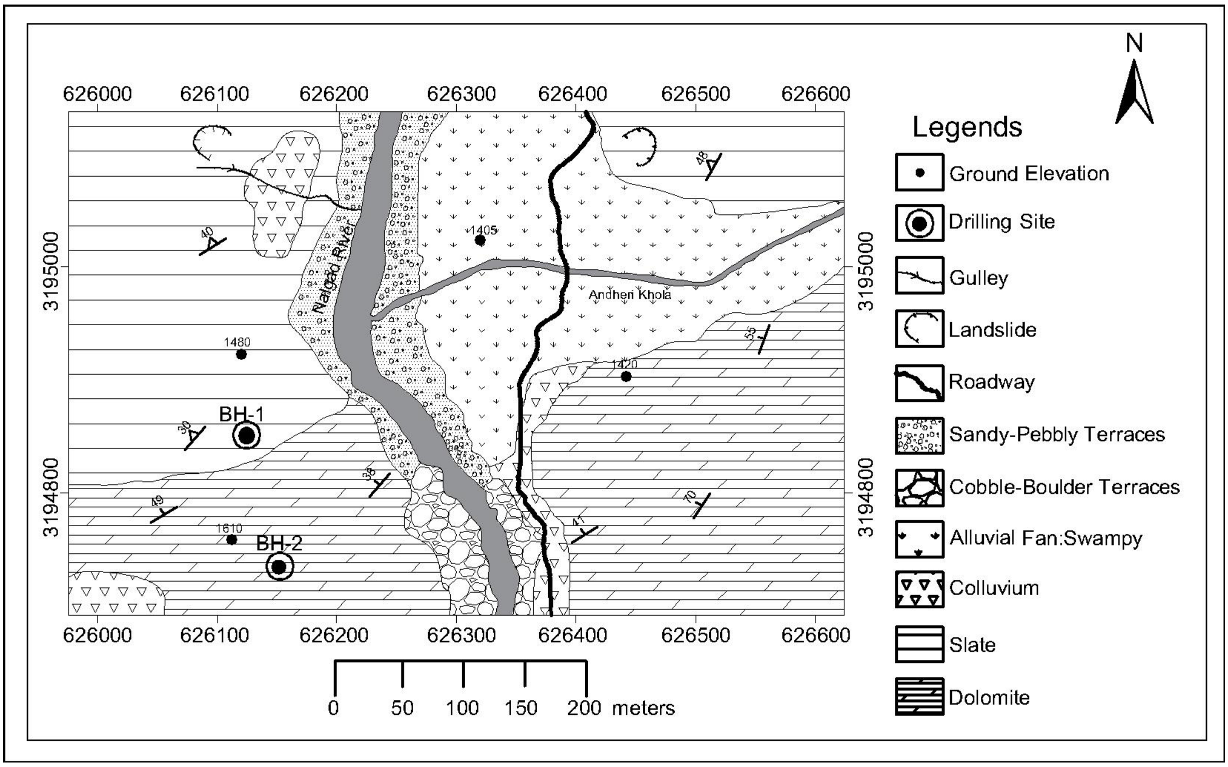

Fig. 1: Engineering geological map of the study area.

According to Fell et.al. (2005) the value of one Lugeon is equivalent to 1.3×10^{-5} cm/sec. Zoorabadi (2023) had reported that the long ago established lugeon value of 1.3×10^{-5} cm/sec only consists of one boundary conditions and does not cover all the potential boundary conditions encountered in the field.

a) The empirical HC-Model

The HC model is based on new rock mass classification system known as HC- System first proposed by Hsu et al. (2011) and consists of four component rock mass parameters: Rock Quality Designation (RQD), Depth Index (DI), Gouge Content Designation (GCD) and Lithology permeability index (LPI) which is calculated as the product of four parameters and can be given by the following equation 2.

$$HC=\left(1-\frac{RQD}{100}\right)(DI)(1-GCD)(LPI) \ldots \text{(Eqn.2)}$$

Hence using Eqn.2, the HC- value was calculated.

b) Modified HC-Model

The concept of modified HC-model for the prediction of rock mass hydraulic conductivity is a new approach in this research but was inspired from the HC-model of Hsu et al. (2011). Initially proposed HC-model consists of only four component rock mass parameters but this modified HC-model incorporates other two influential rock mass parameters like Fracture Frequency (FF) and theoretical aperture (e) which can be easily obtained from the borehole log data. Hence the modified HC model presented in this study consists of following six components parameters as: Rock Quality Designation (RQD), Depth Index (DI), Lithology permeability Index (LPI), Fracture Frequency (FF) and theoretical aperture (e) where the first four parameters are from HC-model of Hsu et al. (2011).The data set for parameter like Fracture Frequency was measured in the field from the core sample by simply counting the number of natural fractures and breaks identified per meter through the visual observation of the obtained core samples by neglecting mechanically induced fracture as far as possible. On the other hand, theoretical aperture (e) was obtained from the back calculation of aperture from cubic law of parallel plate analogy as shown in equation 3.

Since, we know the equation 3 from cubic law of parallel plate analogy (Snow 1969) as:

$$k=\frac{ge^2}{12V} \ldots\ldots\ldots\ldots \text{(Eqn.3)}$$

Where, the parenthesis k=isotropic coefficient of hydraulic conductivity, g=gravity, e=joint theoretical aperture, v=coefficient of kinematic viscosity of fluids.

$$\text{or, } e=\sqrt{\frac{12kv}{g}} \qquad \text{[Rearranging Eqn.3]}$$

$$\text{or,} e=\sqrt{\frac{12\times1.307\times10^{-6}(m^2/s)\times k(m/s)}{9.8\ (m/s^2)}}$$; kinematic viscosity of water(v)=1.307×10^{-6} m^2/s

or, $e = 1.265\times10^{-3}\ \sqrt{k}$; units in m……..(Eqn.4).

Hence, on the basis of aforementioned six parameters the new rock mass classification system was developed called as "modified HC-system" and can be calculated as;

Modified HC- value=

$$\left(1-\frac{RQD}{100}\right)(DI)(1-GCD)(LPI)(FF)(e) \ldots \text{(Eqn.5)}$$

RESULTS

The borehole logs and packer (Lugeon) test data obtained from field were carefully processed and analyzed to obtain various results which were discussed in brief in this section. Altogether 80 Lugeon test data performed in 40 test section of 2 drill holes site, in the discontinuous dolomite and slate rock unit were reviewed. The obtained value of hydraulic conductivity from water pressure test on field ranges on average from a minimum of 4LU (5.20×10^{-5}cm/sec) to a maximum of 91LU (1.18×10^{-3}cm/sec) for both first cycle test and second cycle test carried out at same section of boreholes. The majority of flow patterns obtained were turbulent flow. The permeability results were classified using Quinones-Rozo (2010) classification and found that 34% of the flow is highly conductive (i.e. Many open discontinuities), 33% medium conductive (i.e. Some Open discontinuity), 19.5% moderately conductive (i.e. Few Partly Open discontinuities) and 13.5% low conductive (i.e. Tight discontinuities).

Estimating hydraulic conductivity from HC-Model

The HC- model of predicting hydraulic conductivity was initially proposed by Hsu et al. (2011) and is based on new rock mass classification system which incorporates the following four component parameters as: Rock Quality Designation Index (RQD), Depth Index (DI), Gouge Content

Designation Index (GCD) and Lithology Permeability Index (LPI). On the basis of these four aforementioned parameters, HC-values can be calculated using equation 4. After calculating HC values related to the respective depth interval from rock core log data, regression analysis was performed between HC- index values and in-situ hydraulic conductivity obtained from packer test to estimate the dependence of HC on hydraulic conductivity. The regression results indicated that a power law relationship exists with a greater coefficient of determination between HC values and hydraulic conductivity for both the borehole BH-1 and BH-2. The calculated results of HC-values from HC-System is shown in Table 2 for BH-1 and in Table 3 for BH-2. Similarly, the graphical representation figure of obtained HC-model of BH-1 and BH-2 are shown in Fig.2 and Fig. 3 respectively. From the HC model of two boreholes, the following set of equations (6 and 7) were obtained by conducting power law regression analysis between HC-value and hydraulic conductivity.

For borehole BH-1;

$$K=0.0006\,(HC)^{0.7251}\ ,\ R^2=0.46 \ldots\ldots\ldots \text{(Eqn. 6)}$$

For Borehole BH-2;

$$K=0.00001\,(HC)^{-0.626}\ ,\ R^2=0.25 \ldots\ldots\ldots \text{(Eqn. 7)}$$

The HC-value always lies between 0 and 1. The HC-value close to 1 indicates zone of highly conductive rock mass.

Lithology Permeability Index (LPI) was accounted on new rock mass classification system of Hsu et al. (2011) as shown in Table 1. It should be noted that the value of (1-GCD) in Table 2 and 3 is equal to 1 as because in this research the core sample is assumed to be gouge free (i.e. GCD=0).

Table 1: Rating for lithology permeability index (Modified after B.B.S Singhal and R.P. Gupta 1999; Bear 1972; Hsu et al. 2011)

Lithology	Average hydraulic conductivity Range	Range of LPI rating	Suggested LPI Rating
Sandstone	$10^{-7.5}$	0.8-1.0	1
Silty Sandstone	-	0.9-1.0	0.95
Shale interbedded with some Sandstone	-	0.5-0.7	0.6
Dolomite	10^{-8}	0.6-0.8	0.7
Limestone	10^{-9}	0.6-0.9	0.7
Shale	$10^{10.5}$	0.4-0.6	0.5
Sandy Shale/Slate	-	0.5-0.6	0.6
Siltstone / Claystone	10^{-11}	0.2-0.4	0.3
Granite /Basalt	$10^{11.5}$	0.1-0.2	0.15

Table 2: Calculated results for HC-system for borehole BH-1, data set of first cycle test only

Bore hole	Test Interval	RQD	1-RQD/100	$DI=1-\frac{Lc}{Lt}$	1-GCD	LPI	HC-Value	$K_{in-situ}$ cm/sec
BH-1	6-9	53	0.47	0.90	1	0.6	0.2538	1.38E-04
	9-12	0.01	0.99	0.86	1	0.6	0.5159	3.56E-04
	12-15	26	0.74	0.82	1	0.6	0.3640	4.27E-04
	15-18	21	0.79	0.78	1	0.6	0.3697	1.45E-04
	21-24	9.6	0.90	0.70	1	0.77	0.4872	1.78E-04
	24-27	13	0.87	0.66	1	0.77	0.4421	1.22E-03
	27-30	49.7	0.50	0.62	1	0.75	0.2338	1.08E-04
	30-33	66	0.34	0.58	1	0.6	0.1183	4.05E-04
	37-40	38	0.62	0.49	1	0.6	0.1810	6.46E-04
	40-43	18.4	0.87	0.45	1	0.77	0.2806	4.00E-04
	43-46	23.9	0.76	0.41	1	0.77	0.2382	2.96E-04
	46-49	34	0.66	0.37	1	0.75	0.1815	1.76E-04
	49-52	4.08	0.96	0.33	1	0.65	0.2036	2.48E-04
	52-55	15.2	0.85	0.29	1	0.65	0.1580	4.56E-05
	58-61	16.6	0.83	0.21	1	0.65	0.1120	1.18E-04
	64-67	17	0.83	0.13	1	0.6	0.06308	3.29E-05
	72-75	28.7	0.71	0.02	1	0.6	0.00855	2.51E-05

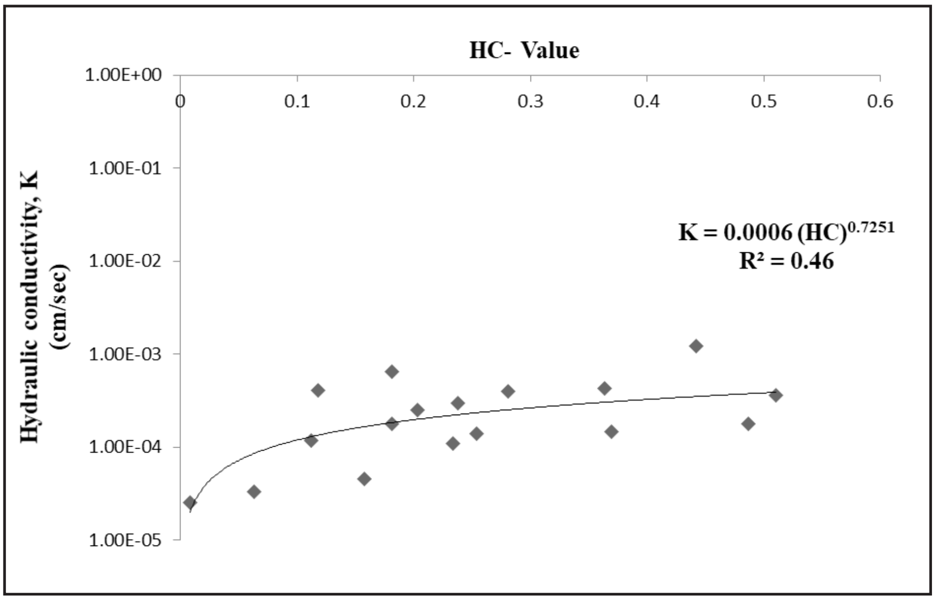

Fig. 2: Relationship between hydraulic conductivity and HC- values estimated from HC-model for BH-1

Table 3: Calculated results for HC-system for borehole BH-2, data set of first cycle test only.

Bore hole	Test Interval	RQD	1-RQD/100	$DI=1-\frac{Lc}{Lt}$	1-GCD	LPI	HC-Value	$K_{in-situ}$, cm/sec
BH-2	21-24	0.01	1.000	0.71	1	0.7	0.4980	1.23E-04
	24-27	10.44	0.896	0.67	1	0.7	0.4220	2.34E-04
	27-30	6.66	0.933	0.63	1	0.7	0.4146	8.94E-05
	30-33	13.83	0.862	0.60	1	0.7	0.3596	5.32E-05
	36-39	0.01	1.000	0.52	1	0.7	0.3634	7.45E-04
	39-42	0.01	1.000	0.48	1	0.7	0.3365	8.08E-04
	42-45	1.6	0.984	0.44	1	0.7	0.3047	9.07E-04
	45-48	5.61	0.944	0.40	1	0.7	0.2668	5.26E-04
	48-51	31.32	0.687	0.37	1	0.7	0.1757	2.83E-04
	51-54	26.4	0.736	0.33	1	0.7	0.1684	5.06E-04
	54-57	19.33	0.807	0.29	1	0.7	0.1629	7.09E-04
	57-60	19.33	0.807	0.25	1	0.7	0.1412	7.90E-04
	60-63	37	0.630	0.21	1	0.7	0.0933	1.31E-04
	63-66	12.2	0.878	0.17	1	0.7	0.1064	7.48E-04
	66-69	9.33	0.907	0.13	1	0.7	0.0854	1.10E-03
	69-72	20.66	0.793	0.10	1	0.7	0.0534	8.09E-04
	72-75	4.76	0.952	0.06	1	0.7	0.0385	1.11E-03

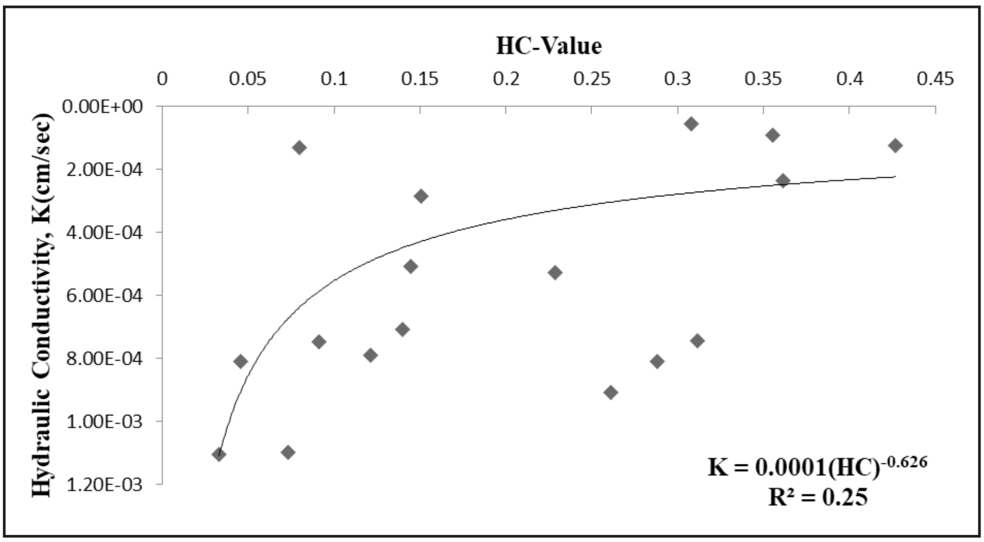

Fig.3: Relationship between hydraulic conductivity and HC- values estimated from HC-model for BH-2

Estimating hydraulic conductivity from modified HC-model

The concept of modified HC-model for the prediction of rock mass hydraulic conductivity was inspired from the HC-model of Hsu et al. (2011). Since, the HC-model developed in the previous section consists of only four component parameters but this new and updated HC model attempts to integrate two more influential rock mass parameters, namely fracture frequency and fracture aperture. Hence the modified HC model presented consists of following components parameters as: Rock Quality Designation (RQD), Depth Index (DI), Lithology permeability Index (LPI), Fracture Frequency (FF) and theoretical aperture (e). The parameters like RQD, DI and LPI are obtained in a similar way as that of the HC-model mentioned in the methodology section whereas the data for additional parameters used in the modified HC-model like fracture frequency was extracted from the borehole logs and the theoretical aperture (e) was obtained from the reverse calculation from the cubic law of parallel plate analogy using equation 3 and 4, as mentioned in the methodology section. Using the above six aforementioned parameters, the modified HC index value was calculated using equation 5.

Modified HC- value=

$$\left(1-\frac{RQD}{100}\right)(DI)(1-GCD)(LPI)(FF)(e) \quad \text{... [From Eqn. 5]}$$

After calculating the modified HC values related to the respective depth interval, regression analysis was performed between HC- index values and in-situ hydraulic conductivity obtained from the packer test to estimate the dependence of modified HC values on hydraulic conductivity. The calculated modified HC-index values and the regression analysis result performed between modified HC-values and in-situ hydraulic conductivity of borehole BH-1 are shown in Table 4 and Fig.4 respectively. The regression analysis is by a power-law relationship with coefficient of determination of 0.69. The empirical equation for modified HC-model obtained from the analysis is presented below.

$K=0.0032(H.C)^{0.6128}$, $R^2 = 0.69$ …………………… (Eqn. 8)

Discussions

El Naqa (2000) and Qureshi (2014) had successfully developed the statistically significant logarithmic and exponential empirical relationship between hydraulic conductivity and RQD with maximum coefficients of determination (R^2) of 0.61 and 0.74 respectively. Similar methodology was employed as a part of this research to see the statistical dependence of rock mass hydraulic conductivity with RQD but in present research the coefficient of determination obtained from regression analysis between hydraulic conductivity and RQD of all the observed set of equation is very low for both

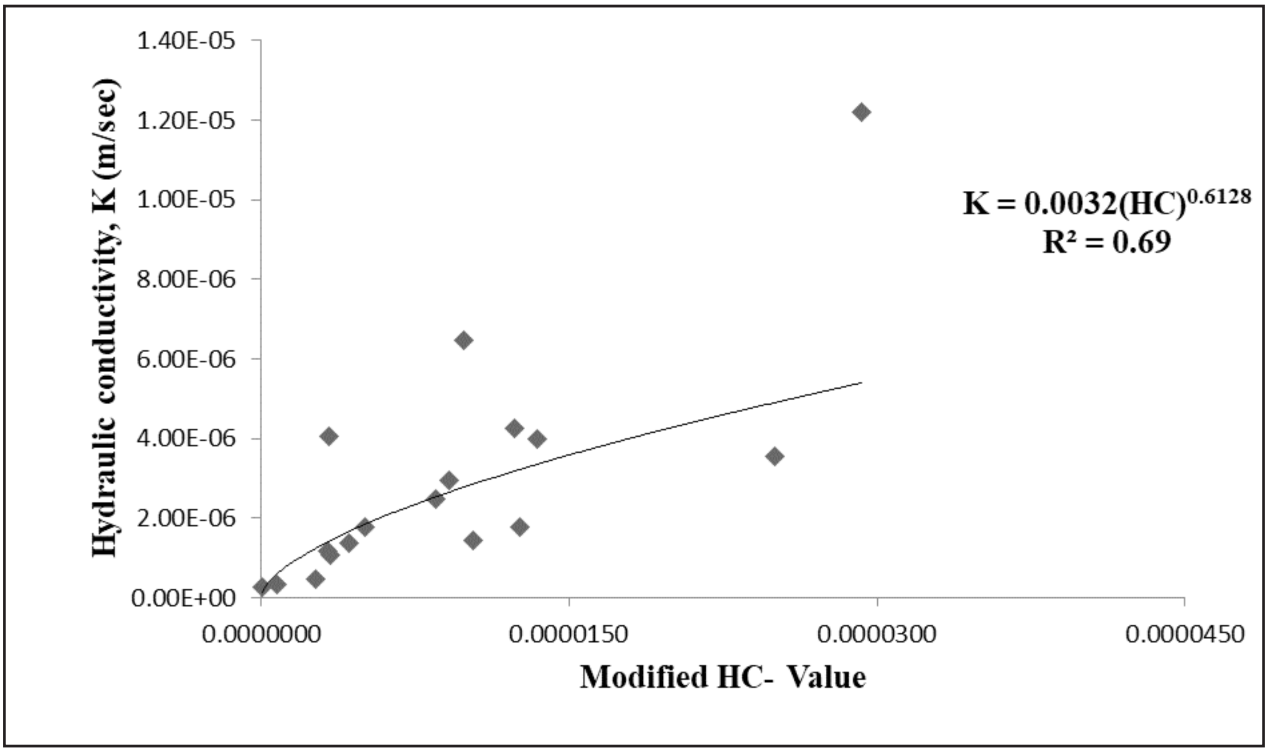

Fig. 4: Empirical relationship between hydraulic conductivity and modified HC-value estimated from modified HC-model for BH-1

Table 4: Calculated result for modified HC-value from borehole BH-1.

Bore hole	Test Depth (m)	RQD	1-RQD/ 100	DI	1-GCD	LPI	No. of fracture per 3m	Fracture Frequency per meter (FF)	Fracture aperture (e), m	Modified HC-value	$K_{in\text{-}situ}$, (m/sec)
BH-1	6-9	53.0	0.47	0.90	1	0.60	34	11.3	1.49E-06	4.27E-06	1.38E-06
	9-12	0.01	0.9999	0.86	1	0.60	61	20.3	2.39E-06	2.51E-05	3.56E-06
	12-15	26.0	0.74	0.82	1	0.60	39	13.0	2.61E-06	1.24E-05	4.27E-06
	15-18	21.0	0.79	0.78	1	0.60	55	18.3	1.52E-06	1.03E-05	1.45E-06
	21-24	9.6	0.904	0.70	1	0.77	46	15.3	1.69E-06	1.26E-05	1.78E-06
	24-27	13.0	0.87	0.66	1	0.77	45	15.0	4.42E-06	2.93E-05	1.22E-05
	27-30	49.7	0.503	0.62	1	0.75	33	11.0	1.31E-06	3.38E-06	1.08E-06
	30-33	66.0	0.34	0.58	1	0.60	33	11.0	2.54E-06	3.31E-06	4.05E-06
	37-40	38.0	0.62	0.49	1	0.60	51	17.0	3.22E-06	9.90E-06	6.46E-06
	40-43	18.4	0.816	0.45	1	0.77	57	19.0	2.53E-06	1.35E-05	4.00E-06
	43-46	23.9	0.761	0.41	1	0.77	53	17.7	2.18E-06	9.17E-06	2.96E-06
	46-49	34.0	0.66	0.37	1	0.75	50	16.7	1.68E-06	5.07E-06	1.76E-06
	49-52	4.08	0.9592	0.33	1	0.65	63	21.0	1.99E-06	8.52E-06	2.48E-06
	52-55	15.2	0.848	0.29	1	0.65	59	19.7	8.55E-07	2.66E-06	4.56E-07
	58-61	16.6	0.834	0.21	1	0.65	64	21.3	1.37E-06	3.28E-06	1.18E-06
	64-67	17.0	0.83	0.13	1	0.60	50	16.7	7.25E-07	7.63E-07	3.29E-07
	72-75	28.7	0.713	0.02	1	0.60	42	14.0	6.34E-07	7.59E-08	2.51E-07

exponential and logarithmic fit, which is clearly evident in figure 5, making the statistical validity of all the observed set of equations between hydraulic conductivity and RQD almost insignificant and questionable.

The possible geological explanation behind the limited correlation observed between hydraulic conductivity and RQD could be attributed to factors such as the presence of a dolomitic terrain, potentially containing caverns and cavities in the study area that complicate permeability estimation, leading to inaccuracies in permeability calculation and unsuccessful correlation with RQD. The study carried out by Lamsal (2020) also suggested the presence of cavities through the analysis of Electrical Resistivity Tomography (ERT) results in

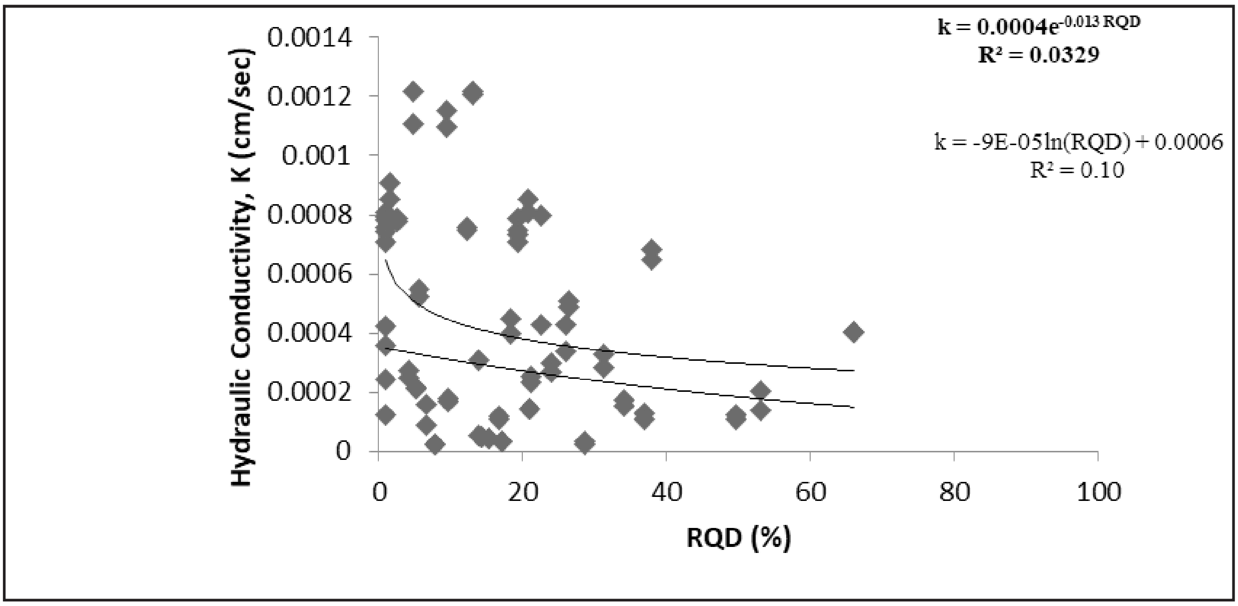

Fig. 5: Exponential and logarithmic regression analysis between representative hydraulic conductivity and RQD obtained using combined data of both boreholes.

the same area whose ERT alignment subsequently passes through BH-2. Additionally, the overall geotechnical properties of the core samples obtained are very poor, with core recovery and RQD both falling below 25%, possibly exerting a significant influence. It is noteworthy that the hydraulic conductivity of a rock mass is intricately linked to a combination of various parameters, including RQD, fracture frequency, aperture, persistence, joint infill etc. and is also highly dependent upon the geological and geotechnical criteria specific to the investigation area further influenced the complexity of the relationship. Consequently, this research suggests that developing a reliable predictive model solely based on the correlation between hydraulic conductivity and RQD alone may not always be feasible without considering the interplay of other influential rock mass parameters.

In the process of establishing a predictive model for hydraulic conductivity based solely on the Rock Quality Designation (RQD), regression analysis from the available data source did not yield the desired accuracy. This limitation prompted a broader exploration into a more comprehensive statistical model, referred to as the HC model, in the current research. Originally proposed by Hsu et al. (2011), the HC model considers hydraulic conductivity as a combined function of various rock mass parameters. This model incorporates four key parameters: Rock Quality Designation Index (RQD), Depth Index (DI), Gouge Content Designation Index (GCD), and Lithology Permeability Index (LPI), all readily obtainable from borehole data.

Hsu et al. (2011) successfully established a power-law empirical relationship between hydraulic conductivity and HC-value based on their innovative rock mass classification scheme, achieving a maximum coefficient of determination of 0.86. Building upon this foundation, similar research was undertaken in the present study to develop an empirical relationship between hydraulic conductivity and the HC-value. The resulting HC model exhibits a power-law relationship with a maximum coefficient of determination of 0.46 and 0.25 for boreholes BH-1 and BH-2, respectively (Fig. 2 and Fig. 3).While the coefficient of determination for the empirical equation derived from the HC model in the current research is not very high as that of Hsu et al. (2011) but, the outcome is very promising for the research conducted on limited time frame and limited data source in the sense that the accuracy of hydraulic conductivity prediction model goes on increasing on adding some more influential rock mass parameters on the model. This underscores the significance of incorporating these factors in refining the predictive capability of the model.

The HC-model, as formulated by Hsu et al. (2011), incorporate four key parameters in predicting permeability. However, it falls short of encompassing all potential influential parameters within the rock mass hydraulic conductivity system. Recognizing this limitation, the concept of a modified HC-model emerged in our research. This adapted hydraulic conductivity model integrates two additional influential parameters, namely Fracture Frequency (FF) and theoretical aperture (e), alongside the four parameters (RQD, GCD, DI, and LPI) used in the original HC-model.

Consequently, the modified HC-model, based on the incorporation of these six parameters, has been successfully developed in present research for BH-1. This modified model exhibits a superior fit with a power-law relationship and a significantly higher coefficient of determination of 0.69 (Fig. 4). Notably, our findings reveal that the accuracy and validity of hydraulic conductivity prediction using the modified HC-model (R^2=0.69 for BH-1) surpass those of the initially developed HC-model (R^2=0.46 for BH-1).

Nevertheless, when applied to BH-2, the modified HC-model doesn't fit well with greater accuracy and show the anomalous outcomes. This discrepancy can be attributed again to a notable factor—namely, very low core recovery resulting due to presence of cavities within the drill holes, as highlighted by Lamsal (2021). This circumstance poses challenges in accurately calculating the hydraulic conductivity value for the tested section and can be represented falsely. Additionally, the borehole data for BH-2 fails to truly represent the actual rock mass conditions, given the deficient core recovery, thereby resulting in a limited correlation. It is also essential to take note of the R^2 value for the HC-model applied to BH-2, which stands at a mere correlation of 0.25 most probably due to the similar challenges for this specific borehole.

Overall, present research highlights a positive trend in the coefficient of determination for different hydraulic conductivity prediction models with the inclusion of more influential rock mass parameters. This shows the importance of considering a broader spectrum of rock mass factors for more accurate predictions in the realm of rock mass hydraulic conductivity.

CONCLUSIONS

The research investigated the connection between hydraulic conductivity and Rock Quality Designation (RQD), concluding that RQD alone was not always sufficient to build a statistically significant model with higher accuracy. However, an empirical relationship between hydraulic conductivity and the HC- value known as the HC-model was successfully developed by incorporating four parameters with a coefficient of determination of 0.46 for BH-1 and 0.25 for BH-2. A more robust model, known as the modified HC-model was developed incorporating six parameters, demonstrated a maximum coefficient of determination of 0.69 for BH-1. These relationships offer practical alternatives to costly in-situ permeability testing, enhancing efficiency and cost-effectiveness in civil structure design. The findings emphasize the significance of multiple parameters hydraulic conductivity model, revealing that hydraulic conductivity in rock mass is a function of RQD, Gouge Content Designation Index, Lithology Permeability Index, Depth Index, Fracture Frequency, and fracture aperture. The research contributes valuable insights for planning field investigations which requires rock mass hydraulic conductivity, particularly in areas with similar geological and geotechnical characteristics.

ACKNOWLEDGEMENTS

The authors would like to express the sincere gratitude to Nalgad Hydropower Development Committee with special thanks for providing the necessary data sets to carry out this research. Furthermore, we would like to extend our special appreciation to the entire team involved in extensive geotechnical site investigations project carried out by Nalgad Hydropower Development Committee.

REFERENCES

Bear, J., 1972. Dynamics of Fluids in Porous Media. American Elsevier Publication Co., New York. 738 p.

Darcy, H., 1856. Les fontaines publiques de la ville de Dijon, exposition et application. Paris, Victor Dalmont.

Deere, D.U., 1964. Technical description of rock cores for engineering purpose. Rock Mechanics and Engineering Geology, v. 1, pp. 17-22.

El-Naqa, A., 2001. The hydraulic conductivity of the fractures intersecting Cambrian sandstone rock masses, central Jordan. Env. Geol., v. 40, pp. 973-982.

Fell, R., MacGregor, P., Stapledon, D., and Bell, G., 2005. Geotechnical engineering of dams. Tailor and Francis, London, UK. 1338 p.

Houlsby, A.C., 1976. Routine interpretation of the Lugeon water-test. Quart. Jour., Engg. Geol. Hydrogeol., v. 9, pp. 303-313.

Hvorslev, M. L., 1951. Time lag and soil permeability in groundwater observations. Waterways Experiment Station Corps of Engineers, U.S. Army, Vicksburg, Mississippi. v. 36, pp.50.

Hsu, S.M., Lo, H.C., Chi, S.Y., and Ku, C.Y., 2011. Rock mass hydraulic conductivity estimated by two empirical models. Developments in hydraulic conductivity research, pp. 1-27.

Lamsal, I., Ghimire, S., and Acharya, K.K., 2020. Geological and Geophysical Study in Udheri Khola Area, Nalgad Hydroelectric Project, Jajarkot District, Lesser Himalaya, Western Nepal. Bull. Dept. Geol., v. 22, 11-16. 10.3126/bdg.v22i0.33409.

Lugeon, M., 1933. Barrages et géologie. library de l'Université. Paris, Dunod. 430 p.

Louis, C., 1969. A study of groundwater flow in jointed rock and its influence on the stability of rock masses. Rock Mechanics Research Report, Imperial College, London, UK.

Moye, D. G., 1967. Diamond drilling for foundation exploration. Inst Engrs Civil Eng. Site Investigation Symposium.

Quiñones, C., 2010. Lugeon test interpretation, revisited. Collaborative management of integrated watersheds, US Society of Dams, 30th annual conference, pp. 405-414.

Qureshi, M.U., Khan, K. M., Bessaih, N., Al-Mawali, K., and Al-Sadrani, K., 2014. An empirical relationship between in-situ permeability and RQD of discontinuous sedimentary rocks. Elect. Jour. Geotech. Engg. v. 19, pp. 4781-4790.

Singhal, B.B.S., and Gupta, R.P., 1999. Applied hydrogeology of fractured rocks. Kluwer Academic Publishers, The Netherlands. 400 p.

Snow, D.T., 1969. Anisotropie permeability of fractured media. Water Resources Research, v. 5, pp. 1273-1289.

Wei, G., Kirby, J.T., Grilli, S.T., and Subramanya, R., 1995. A fully nonlinear Boussinesq model for surface waves. Part 1. Highly nonlinear unsteady waves. Journal of fluid mechanics, v. 294, pp. 71-92.

United States Bureau of Reclamation (USBR)., 1987. Design of small dams. US Department of the Interior, Bureau of Reclamation.

Zoorabadi, M. 2023. Lugeon Test: New insights Into the Calculated Hydraulic Conductivity. Quarterly Jour. Engg. Geol. Hydrogeol. qjegh 2023- 006.