

A Comparison of Rock Mass Deformation Modulus from Empirical Correlations Versus Plate Load Test at Pare Hydro-electric Power Project, Papum Pare, Arunachal Pradesh



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1 Introduction

In rock mechanics and rock engineering, determination of deformability of rock masses becomes most important for the design and analysis of different structures constructed on rock as it describes the relationship between the applied load and the resulting strain. Since natural rock masses inherently come with weaknesses in the form of discontinuities such as joints, bedding planes, faults, it becomes important to characterize the rock mass in a precise manner. The International Society for Rock Mechanics [1] has defined the modulus of deformation of a rock mass (E_m) as the ratio of stress to the corresponding strain including both elastic and inelastic behaviour during the loading of a rock mass [1]. The static modulus of deformation is among the parameters that best represents the mechanical behaviour of a rock and a rock mass, in particular when it comes to underground excavations. The deformation modulus is, therefore, a cornerstone of many geomechanical analyses [2]. Deformation modulus of a rock mass can be estimated using various established empirical correlations and in-situ tests like plate loading test (PLT), plate jacking test (PJT) and Goodman Jack test, etc. However, most of the in-situ tests are difficult to operate, time consuming and expensive, due to which conducting large number of in-situ tests is not feasible, so in-situ tests are conducted only at a few locations of the whole project site. Lesser number of in-situ tests cannot properly characterize the rock mass as a whole. This factor drives an engineer to rely on the empirical correlations to estimate the deformation modulus in a simple and effortless manner. Several researchers have worked and still been working on the development of empirical correlations from which deformation modulus value can be obtained. In this paper, some of the correlations suggested by the researchers such as Hoek and Brown [3], Isik et al. [4], Sonmez et al. [5], etc., have been used.

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2 Description of the Site

The present study has been carried out at the dam site of river Pare situated in the state of Arunachal Pradesh, India. The detailed geological mapping encompasses 250 m upstream and 300 m downstream of the dam axis, which trend along $N74^{\circ}E-S74^{\circ}W$ covering an area of $77,500\text{ m}^2$. The Pare river flows towards SSE direction between the left and right abutment which are bounded by rocky slopes or high-level terraces trending in NNW–SSE direction. The study area lies in the Upper Siwalik formation (Tertiary Group) consisting of brownish and grey coloured, fine to medium-grained concretionary, soft, friable, pebble impregnated, salt-pepper textured sandstone, sand rock and pebble beds which are moderately jointed. The rock mass prevailing at the dam site has been found to be weak and was identified with bedding planes and four joint sets (Bedding Plane, J1, J2, J3, J4) having different orientations. The ground water table was at greater depth, but seepage was observed all throughout the drift.

3 Rock Mass Characterization at the Dam Site

The rock mass classification improves the quality of site investigation by quantifying the input data and enables better engineering judgement and due to this, the effectiveness of the project improves. For the design of slopes, foundation and underground excavation, almost any form of analysis is required for reliable estimates of strength and deformation characteristics of rock mass. The rock mass present at the site is characterized by using geological strength index (GSI).

3.1 Geological Strength Index (GSI)

The geological strength index (GSI) was first developed by Hoek [6] to characterize the jointed rock mass based on the geological description of the rock without direct access. Out of all the rock mass classification systems, the GSI system considers both Hoek–Brown and Mohr–Coulomb strength parameters for design purpose. GSI incorporates the mass blockiness and the discontinuity conditions, which are the main parameters essential for the assessment of a rock mass.

The values of GSI were calculated for the location where in-situ tests were carried out. To estimate the value of GSI, the chart given by Marinos and Hoek [7] and equation given by Cai et al. [8] in terms of its quantification by block volume and joint condition factor are considered. The GSI values obtained in the studied area were in the range of 38–56 as observed from Table 1. The disturbance factor (D) for the rock mass present at the dam site is taken to be 0.7 for small scale blasting at the site.

Table 1 Computation of GSI values at the dam site

Joint	Planarity	J_w	J_s	J_a	J_c	V_b	GSI
Bedding plane	Smooth planner	1	1	1	1	10,000	45.3
J1	Smooth planner	1	1	1	1	500	38
J2	Smooth planner	1	1	1	1	500	38
J3	Rough undulating	1.5	1.5	1	2.25	10,000	54
J4	Rough undulating	1.5	1.5	1	2.25	20,000	56

J_w discontinuity weaviness in m, J_s small scale smoothness in cm
 J_a joint alteration factor, J_c joint condition factor; V_b block volume in cm^3

4 Estimation of Deformation Modulus (E_d) of Rock Mass

In spite of being sophisticated, the in-situ deformation modulus is considered to be one of the most important parameters required for geo-engineering investigation. Based on the statistical analysis, several empirical equations are developed for indirect estimation of deformation modulus. Accurate values can seldom be found because in-situ tests may be subjected to measurement errors due to the blasting process or from equipments or test site preparation. It is never recommended to directly go for an empirical correlation for obtaining the values of E_m for a site, rather in-situ methods must be preferred as the results obtained from empirical correlations might sometimes deviate substantially from the actual values of the deformation modulus of the rock mass. There are two ways by which the deformation modulus of rock masses can be determined, viz. In-situ measurements and empirical correlations.

4.1 In-Situ Methods

The deformation modulus values at the dam site were estimated using plate loading test (PLT). Plate load test was conducted as per IS 1888–1982 in which vertical load was applied to the test plate (plate dimension 0.45 m × 0.45 m, thickness 25 mm) by means of hydraulic jack against rolled steel joist capable of providing reaction and the settlement was recorded by two dial gauges of 0.01 mm sensitivity each positioned on either side of the plate and held by datum bars resting on immovable support on either side of the plate. The reaction for the jack was obtained from a kentledge placed on platform supported at a minimum distance of 3.5 times the size of test plate from its centre. The observations of the plate load test were obtained in the form of load-settlement data and subsequently, E_m values are calculated using Eq. (1) as shown in Table 2.

As per IS Code 7317 1993 [9], E_m values are calculated using the formula given below:

Table 2 Deformation modulus of rock mass of Pare H.E Project, Pare, A.P.

Applied pressure (MPa)	Deformation, δ (mm)		Elastic rebound, e (mm)	Deformability modulus (GPa)	
	Loading	Unloading		E_m	E_i
1.125	2.31	0.75	1.56	0.17	0.25
2.25	3.63	1.69	1.94	0.22	0.41
3.375	4.36	2.65	1.71	0.27	0.71
4.5	4.82	2.82	2	0.33	0.79
5.625	5.21	3.05	2.16	0.38	0.92

E_i deformation modulus of intact rock

$$E_m = \frac{mP(1 - \nu^2)}{\delta\sqrt{A}} \tag{1}$$

where

- E_m = Deformation Modulus of the subgrade (Rock Mass)
- m = Displacement coefficient
- P = Total normal surface load
- ν = Poisson’s ratio
- δ = average surface displacement of rock mass
- A = area of the loading plate.

4.2 Empirical Correlations

In this research paper, the empirical correlations which contain the parameter GSI are only considered. Deformation modulus of rock mass can be estimated in a much easier way with the help of empirical formulae suggested by various researchers depending on the quality of the rock mass. Though there are different empirical equations available for estimating the E_m values of rock masses as mentioned earlier, not all the empirical equations are considered in this study.

Deformation modulus (E_m) with GSI. Nevertheless, there are different methods which define GSI but a general international standard has not been specified yet. Based on this index the value of E_m can be determined indirectly as different correlations are suggested by various researchers (such as Beiki et al. [10], Hoek and Brown [3], Hoek and Diederichs [11], Isik et al. [4], Sonmez et al. [5]), which not only takes GSI into account but also E_i and unconfined compressive strength of intact rock (σ_c). Table 3 shows the various correlations used in this study. Using these correlations, the values of E_m were calculated corresponding to the GSI values obtained. After that, statistical analysis was performed for the development of the correlation between E_m and GSI, respectively, as presented in Table 4.

Table 3 Selected equations for estimating E_m (GPa) based on GSI

Empirical relation	Proposed by
$E_m = (s_c/100)^{0.5} 10^{(GSI - 10)/40}$	Hoek and Brown [3]
$\frac{E_m}{E_T} = (s^a)^{0.4}; s = e^{\frac{GSI-100}{9}}; a = \frac{1}{2} + e^{\frac{-GSI}{15} - \frac{-20}{6}}$	Sonmez et al. [5]
$E_m = 100 \left(\frac{1 - \frac{D}{2}}{1 + e^{\frac{75 + 25D - GSI}{11}}} \right)$	Hoek and Diederichs [11]
$E_m = 0.0054GSI$	Isik et al. [4]
$E_m = \tan\{1.56 + \ln(GSI)^2\}^{1/2} s^{1/3}$	Beiki et al. [10]

D disturbance factor; s, a rock mass constants

Table 4 Statistical results of calculated theoretical values of E_m based on GSI

GSI value	Deformation modulus of rock mass (E_m , GPa)			
	Mean (Geometric)	Maximum	Minimum	Standard deviation
45.3	0.12264	0.6984	0.0464	0.27
38	0.1309	0.4587	0.0633	0.16
38	0.1631	0.4587	0.0633	0.15
54	0.2637	1.1524	0.0688	0.43
56	0.2967	1.293	0.0694	0.48

5 New Correlations Developed

To indirectly estimate the deformation modulus for the rock masses present at the dam site, certain empirical relationships, applicable to the site conditions has been preferred from the literature available, using which the E_m values were calculated corresponding to the GSI values obtained from the geomechanical classification, the quantitative chart and the equation suggested by Cai and Kaiser [8], respectively. A simple regression analysis has been performed to obtain the relationship between deformation modulus and GSI.

5.1 GSI Versus E_m

An attempt was made to develop a relationship between in-situ deformation modulus at the dam site and estimated GSI values by calculating the geometric mean as shown in Table 4. After that, a regression analysis was carried out in order to establish a relationship and found that the data fits best for the polynomial equation with a good coefficient of determination value of 0.731. The results obtained from the analysis have been enlisted in Table 5. The best fit curve, obtained from plotting the values

Table 5 Relationships between deformation modulus (E_m , GPa) and GSI values

Type of equation	Equation	Coefficient of Determination, R^2
Exponential	$E_m = 0.05e^{0.031GSI}$	0.427
Polynomial	$E_m = 0.001GSI^2 - 0.119GSI + 2.757$	0.731
Linear	$E_m = 0.007GSI - 0.116$	0.486
Logarithmic	$E_m = 0.338\ln(GSI) - 1.058$	0.456

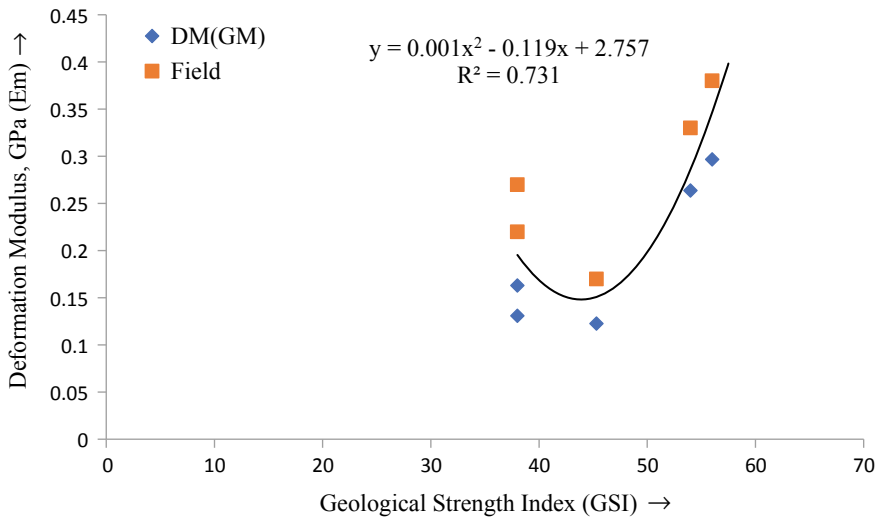


Fig. 1 Relationship between GSI and E_m

of deformation modulus (Geometric mean and Field value) against GSI, has been shown in Fig. 1.

6 Validation of Equation Developed

The equation developed as shown in Table 5, having the highest coefficient of determination (R^2) is checked for accuracy so that the values of estimated E_m go with good agreement with the values obtained at Pare Dam site.

The performance of the empirical equation obtained from regression analysis in the present study has been predicted using two parameters, viz. root means square errors (RMSE) and variance account for (VAF) as presented in Eqs. (2) and (3), respectively. If the values of RMSE and VAF were 0 and 100, respectively, then the

model is accepted to be excellent [12].

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=0}^N (y - y')^2} \quad (2)$$

$$\text{VAF} = \left[1 - \frac{\text{var}(y - y')}{\text{var}(y)} \right] \times 100 \quad (3)$$

where

y = The experimental E_m values, and

y' = The estimated E_m values.

The RMSE and VAF values were obtained using Eqs. (2) and (3) for the developed correlation were found to be 0.02 and 92.67, respectively. From these values, it can be said that the equation developed from the regression analysis yields a good prediction of the deformation modulus of the rock mass for the present site.

7 Limitations of the Correlations Developed

From this research work, we have obtained the following limitations:

1. As a few numbers of plate load tests were conducted at the dam site, the field E_m values obtained were very less. The equations developed would have been more precise if more field data would have been available.
2. As the joint spacing ranged widely, the V_b values obtained from the chart given by Cai and Kaiser [13] may not be precise due to which the field GSI values obtained may not be accurate and as a result the estimated E_m values based on the empirical equations of GSI may not tally exactly with the field values.
3. The GSI-based empirical correlations were developed for the GSI range of 32–56.
4. The developed correlation is valid only for weak rock masses.

8 Conclusions

In this study, new empirical correlations of deformation modulus of rock mass are developed based on GSI. From the plate loading test, the in-situ deformation modulus was calculated for the dam site and the values of in-situ GSI were calculated from the chart and the equation given by Cai and Kaiser [13]. Although it is considered that estimating the E_m values empirically is far easier, consumes less time and is less expensive than the in-situ measurements but due to limited availability of data for a site, the heterogeneity of the rock mass, its anisotropic nature sums together and results in different outcomes corresponding to different equations. A database

is created in order to calculate the E_m values from several empirical correlations using the GSI values obtained from quantitative measures of block volume and joint condition factor. A simple regression analysis has been performed to develop a relationship between the estimated E_m values with GSI and was found that the equation with the highest coefficient of determination is a polynomial function for GSI with a value of 0.731. Further, the RMSE and VAF values have been calculated and found out to be 92.673 and 0.02 for the developed correlation, which shows that the developed equation can be used with a good degree of accuracy for the given site.

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