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# Assessment of Deformability Characteristics of Sandstone by Direct and Indirect Methods –A Case Study

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**Abstract.** Knowledge of the stress-strain properties of rock and rock mass is important for any rock engineering project involving rock. Deformability behaviour of rock or rock mass is denoted by modulus of deformation ($E_d$). Deformation modulus of intact rock can be evaluated in laboratory, whereas, field testing is required for in-situ modulus of discontinuous rock mass. Uniaxial jacking test is one of the direct methods used for assessment of in-situ deformation modulus. Indirect methods based on correlations between rock mass classifications and deformation modulus developed by many researchers, are also available. Results of 28 in-situ tests conducted on fresh, hard, compact, medium grained sandstone have been compared with values derived from empirical equations developed by Bieniawski (1978), Barton et. al (1980), Serafim and Pereira (1983), Barton (1995), Barton (1996) and Singh &Bhasin (1996). Q values of rock mass ranges from 3.4 to 10. The study reveals that the modulus from indirect estimates gives very high modulus of rock mass. Indirect estimate suggested by Barton (1996) for excavation disturbed zone, provides value near to direct estimate i.e., in-situ data set. Study further reveals, the empirical equations based on Q system of rock classifications are valid for Q>1.

**Keywords:** Deformability Characteristics; Sandstone; In-situ tests; Empirical corrections; Q-system

## 1 Introduction

Rock masses are discontinuous and often have heterogeneous and anisotropicproperties. Since, the rock mass cannot be fabricated according to the project requirements; the properties has to be established. Moreover, there is no single parameter or index, which can fully describe the properties of jointed rock mass. Various parameters have different significance and only if combined, they can describe a rock mass satisfactorily (Bieniawski, 1984). According to Lama and Vutukuri (1978), the engineering properties of a rock mass depend far more on the system of geological discontinuities within the rock mass than on the strength of the rock itself. Further, the strength of a rock mass is often governed by the interlocking bonds of the unit "elements" forming the rock mass.

Knowledge of the rock mass deformation modulus isimportant in any rock-engineering project involving tunnellining design, or dam foundations. The deformability of rock mass is dependent mainly uponthe compressive strength of the intact rock materials, joints, bedding planes, ground water condition, applied stressand its condition and softer beds in the system. Different methods have been proposed for measuring or estimating the deformationmodulus. These vary from in-situ tests (Heuze& Salem,1977) to modulus estimation using rock mass classification systems (Hoek &Diederichs, 2006). The accuracy and reliability of in-situ tests depend on thequality of test execution and consistency of the theoreticalassumptions with the real rock mass conditions. Plate loadtests, dilatometer tests, and flat jack tests are often usedin rock engineering projects.

Engineering properties of rock mass can be determined by different methods; which arebroadly classified into two general categories viz., direct and indirect methods. The directmethods include laboratory and in-situ tests, are somewhat time-consuming and expensive. The indirect methods include empirical or theoretical correlations, combination of intact rock& discontinuity properties using analytical and numerical methods and back analysis usingfiled observations.

The direct methods include laboratory and in-situ tests. The direct methods have different limitations. To obtain realistic results of rock mass properties, rock of different volumes having a number of different known discontinuity configurations should be tested at relevant stress levels. Such an experimental program however, would be much time-consuming and expensive. ISRM, ASTM and BIS standards provide guidance related to the specific procedures for performing the actual laboratory and in-situ tests. The indirect methods include empirical or theoretical correlations, combination of intact rock and discontinuity properties using analytical or numerical methods and back analysis using field observations of the prototype. The indirect methods such as the empirical or theoretical correlations can be used to analyse the data from tests and investigate the reasons for the variation.

Rock mass classification plays an important role in estimating the strength and deformability of rock masses and in assessing the stability of rock slopes. They also serve as an index to rock rippability, dredgeability, excavibility, cuttability and cavibility. During the past 50 years, around the world there have been numerous efforts to create a suitable engineering rock mass classification system so that the preliminary evaluation of feasibility, development and stability/service of engineering structures/projects is fairly reliable.

Hari Dev (2020) highlighted the factors affecting deformability characteristics of rock mass viz; stress level, weathering, repetitive loading and anisotropic behaviour. In the present paper, an effort is made to compare the results of in-situ tests with the results estimated from empirical relations derived from different rock mass classification systems.

## 2 Direct Estimate

Deformation modulus of rock mass can be estimated by conducting Plate Jacking Tests or Plate Loading Test or Goodman Jack tests. Among the three tests conducting plate load tests are simpler and deformations are measured at the surface. These methods are explained in detail by Palmström and Singh (2001); IS: 7317 (2015); ISRM (2007). These tests provide design parameters which representative of rock mass at the site. In-situ tests are more reliable than laboratory tests or from empirical methods. However, conducting in-situ tests are expensive and time taking. Exploratory drift or open foundation is to be excavated in controlled manner in order to reduce blast disturbed zone. Further muck or loose rocks are to be removed and fresh rock surface is to be exposed for making site preparation.

Plate load tests conducted at two different dam sites viz. Thana Plaun HEP and Ujh Multipurpose Project are considered for the study. A total of 28 plate load tests were conducted to study deformability characteristic of rock mass. Number of test, deformation modulus, uniaxial compressive strength (UCS) and geological description are given in table 1.

**Table 1.** Details of Plate Load Tests

| Sl. No. | Project Name & Location | Nos. of Plate Load Tests | Stress Level (MPa) | Average Deformation Modulus ($E_d$) GPa | Intact Rock UCS, MPa | Geological Description |
|---|---|---|---|---|---|---|
| 1 | Thana Plaun HEP, Himachal Pradesh | 18 | 3.5 | 1.11 | 30 | Medium grained Sandstone Q: 3.4 to 10.0 |
| 2 | Ujh Multipurpose Project, J & K | 10 | 5.0 | 1.88 | 13 | Hard, Compact Sandstone Q: 5.0 to 9.0 |

All the tests values have been considered for averaging the $E_d$ values. It is to be remembered that deformation modulus values vary with stress level at which test is being conducted.

Q values at the test locations considered in this paper have Q in the range of 3 to 10. The in-situ results have been compared with indirect estimates by using empirical equations. As suggested by Palmström and Singh (2001), plate load tests results were also multiplied by a factor of 2.5 in order to account for blast disturbed zone effects and compared with indirect estimates.

## 3 Indirect Estimates

Indirect estimates are derived from correlations developed between in-situ data set and rock mass classification. Numerous equations were developed using rock mass classification system such as RMR, Q and GSI. Initially, Bieniawski (1978) given linear equation for prediction of the deformation modulus of rock masses for RMR>50 and for RMR<50, Serafim and Pereira (1983) developed power equation. The field data used in this study is available in the form of Q-System, thereby RMR based equations have been converted into Q-based by applying the relation RMR = 15LogQ + 50 given by Barton (1995); Barton (2002).

Barton et. al (1980) proposed logarithmic relation based on Q system for hard rocks i.e., Q>1. This equation is similar to Bieniawski (1978) as RMR and Q are correlated logarithmically. Later, Barton (1995) modified into a power equation incorporating uniaxial compressive strength and Barton (1996) proposed equation for estimating modulus in excavation damage zone. Singh &Bhasin (1996) proposed equation for rock mass with Q>1 based on the field data collected in India. Geological Strength Index (GSI) based equations also proposed by Hoek & Brown (1997) similar to Serafim and Pereira (1983).

Equations given in Table 2 were considered for the study in evaluating the equations based on CSMRS in-situ test data.

**Table 2.** Empirical Equation for Indirect estimation of $E_d$ values

| | Author | Equation ($E_d$ in MPa) | Remarks |
|---|---|---|---|
| 1 | Bieniawski (1978) | $E_d$ = 2RMR-100 or | RMR>50 |
| | | $E_d = 30 \log_{10} Q$ | Converted into Q using Barton (1995) |
| 2 | Barton et. al. (1980) | $E_d = 25 \log_{10} Q$ | Range from |
| | | | 10LogQ to 40LogQ |
| 3 | Serafim& Pereira (1983) | $E_d = 10^{(RMR-10)/40}$ or | RMR<50 |
| | | $E_d = 10^{(15 \log_{10} Q+40)/40}$ | Converted into Q using Barton (1995) |
| 4 | Barton (1995) | $E_d = 10 Q_c^{1/3}$ | where $Q_c = Q \times UCS/100$ |
| 5 | Singh &Bhasin (1996) | $E_d = 12.5 \log_{10} Q$ | Applicable for Q>1 |
| 6 | Barton (1996) | $E_d = 3 Q_c^{1/2}$ | where $Q_c = Q \times UCS/100$ |
| | | | (Excavation disturbed zone) |

## 4 Results and Discussions

Deformation modulus of rock mass estimated from direct and indirect estimates are given in Table 3 & 4 for Thana Plaun HEP, Himachal Pradesh and Ujh Multipurpose Project, J & K respectively. Ratio between direct estimate and indirect estimate has also been worked. It could be seen that indirect estimates provides modulus values ranging from 2 to 25 times the direct estimate values from plate load tests. It could be seen from Table 3, that all the empirical equations except Barton (1966) predict very high modulus of rock mass in comparison with in-situ modulus. The ratio of average values of $E_{d\ (in\text{-}situ)}$ to $E_{d\ (empirical)}$ is ranging from3.9 to 22.4; when plate load test results are multiplied by a factor of 2.5, Barton (1996) gives closely matching results.

**Table 3.** Modulus values from direct and indirect estimates – Thana PlaunHEP, Himachal Pradesh

| Test ID. | Q | Ed (GPa) | Barton et. al. (1980) | Bieniawski (1978) | Serafim and Pereira (1983) | Barton (1995) | Barton (1996) | Singh &Bhasin (1996) | Sandstone x 2.5 |
|---|---|---|---|---|---|---|---|---|---|
| PLT-1 | 6.0 | 0.49 | 19.45 | 23.34 | 19.58 | 12.14 | 4.02 | 9.73 | 1.22 |
| PLT-2 | 6.0 | 0.39 | 19.45 | 23.34 | 19.58 | 12.14 | 4.02 | 9.73 | 0.98 |
| PLT-3 | 6.0 | 0.27 | 19.45 | 23.34 | 19.58 | 12.14 | 4.02 | 9.73 | 0.68 |
| PLT-4 | 7.0 | 0.41 | 21.13 | 25.35 | 20.74 | 12.77 | 4.35 | 10.56 | 1.02 |
| PLT-5 | 8.0 | 1.72 | 22.58 | 27.09 | 21.81 | 13.35 | 4.65 | 11.29 | 4.30 |
| PLT-6 | 10.0 | 0.58 | 25.00 | 30.00 | 23.71 | 14.37 | 5.20 | 12.50 | 1.46 |
| PLT-7 | 10.0 | 1.73 | 25.00 | 30.00 | 23.71 | 14.37 | 5.20 | 12.50 | 4.33 |
| PLT-8 | 8.0 | 0.82 | 22.58 | 27.09 | 21.81 | 13.35 | 4.65 | 11.29 | 2.04 |
| PLT-9 | 7.3 | 1.38 | 21.58 | 25.90 | 21.07 | 12.95 | 4.44 | 10.79 | 3.46 |
| PLT-10 | 6.0 | 0.31 | 19.45 | 23.34 | 19.58 | 12.14 | 4.02 | 9.73 | 0.77 |
| PLT-11 | 6.0 | 0.65 | 19.45 | 23.34 | 19.58 | 12.14 | 4.02 | 9.73 | 1.62 |
| PLT-12 | 7.0 | 1.10 | 21.13 | 25.35 | 20.74 | 12.77 | 4.35 | 10.56 | 2.76 |
| PLT-13 | 4.0 | 0.76 | 15.05 | 18.06 | 16.82 | 10.62 | 3.29 | 7.53 | 1.89 |
| PLT-14 | 7.1 | 1.61 | 21.28 | 25.54 | 20.86 | 12.83 | 4.38 | 10.64 | 4.03 |
| PLT-15 | 7.1 | 1.59 | 21.28 | 25.54 | 20.86 | 12.83 | 4.38 | 10.64 | 3.98 |
| PLT-16 | 7.5 | 2.01 | 21.88 | 26.25 | 21.29 | 13.07 | 4.50 | 10.94 | 5.03 |
| PLT-17 | 8.0 | 2.18 | 22.58 | 27.09 | 21.81 | 13.35 | 4.65 | 11.29 | 5.45 |
| PLT-18 | 3.4 | 1.95 | 13.29 | 15.94 | 15.82 | 10.07 | 3.03 | 6.64 | 4.88 |
| Average in-situ tests ($E_d$) | | 1.11 | 20.65 | 24.77 | 20.50 | 12.63 | 4.29 | 10.32 | 2.77 |
| Ratio $E_{d\ (In\text{-}situ)}$/ $E_{d(empirical)}$ | | | 18.64 | 22.37 | 18.51 | 11.41 | 3.87 | 9.32 | |
| Ratio $E_{d\ (PJT\ arrived)}$/ $E_{d(empirical)}$ | | 2.77 | 7.46 | 8.95 | 7.40 | 4.56 | 1.55 | 3.73 | 1.00 |

Similarly, in Table 4, all the empirical equations except Barton (1966) predict very high modulus of rock mass in comparison with in-situ modulus. The ratio of average values of $E_{d\ (in\text{-}situ)}$ to $E_{d\ (empirical)}$ is ranging from 1.5 to 13.7; when plate load test results are multiplied by a factor of 2.5, Barton (1996) gives closely matching results.

**Table 4.** Modulus values from direct and indirect estimates – Ujh Multipurpose Project, J & K

| Test ID. | Q | Ed (GPa) | Barton et. al. (1980) | Bieniawski (1978) | Serafim and Pereira (1983) | Barton (1995) | Barton (1996) | Singh &Bhasin (1996) | Sandstone x 2.5 |
|---|---|---|---|---|---|---|---|---|---|
| PLT-1 | 5.0 | 0.814 | 17.47 | 20.97 | 18.29 | 8.67 | 2.42 | 8.74 | 2.04 |
| PLT-2 | 6.0 | 0.966 | 19.45 | 23.34 | 19.58 | 9.21 | 2.65 | 9.73 | 2.42 |
| PLT-3 | 7.0 | 1.637 | 21.13 | 25.35 | 20.74 | 9.69 | 2.86 | 10.56 | 4.09 |
| PLT-4 | 8.0 | 2.208 | 22.58 | 27.09 | 21.81 | 10.13 | 3.06 | 11.29 | 5.52 |
| PLT-5 | 7.0 | 0.868 | 21.13 | 25.35 | 20.74 | 9.69 | 2.86 | 10.56 | 2.17 |
| PLT-6 | 8.0 | 2.451 | 22.58 | 27.09 | 21.81 | 10.13 | 3.06 | 11.29 | 6.13 |
| PLT-7 | 7.0 | 1.390 | 21.13 | 25.35 | 20.74 | 9.69 | 2.86 | 10.56 | 3.48 |
| PLT-8 | 8.0 | 2.042 | 22.58 | 27.09 | 21.81 | 10.13 | 3.06 | 11.29 | 5.11 |
| PLT-9 | 9.0 | 3.871 | 23.86 | 28.63 | 22.80 | 10.53 | 3.24 | 11.93 | 9.68 |
| PLT-10 | 8.0 | 2.527 | 22.58 | 27.09 | 21.81 | 10.13 | 3.06 | 11.29 | 6.32 |
| Average in-situ tests ($E_d$) | | 1.88 | 21.45 | 25.74 | 21.01 | 9.80 | 2.91 | 10.72 | 4.69 |
| Ratio $E_{d\,(In\text{-}situ)}/E_{d(empirical)}$ | | | 11.42 | 13.71 | 11.19 | 5.22 | 1.55 | 5.71 | |
| Ratio $E_{d\,(PJT\ arrived)}/E_{d(empirical)}$ | | 4.69 | 4.57 | 5.48 | 4.48 | 2.09 | 0.62 | 2.28 | 1.00 |

From laboratory test, modulus of intact rock reported in the DPR of the Project varies from 7.2 to 25 MPa, whereas equations by Barton et. al (1980), Bieniawski (1978), Serafim and Perira (1983) predicts modulus of rock mass ($E_d$) as higher than the intact rock modulus.

CSMRS in-situ plate load test data and adjusted data by multiplication with factor of 2.5 are plotted in Fig. 1 along with envelope of empirical equations as given in Table 1. It is revealed that Barton (1996) equation which is proposed for excavation damage zone provides nearly matching results to in-situ test results. On applying multiplication factor of 2.5 to plate load test results, the adjusted data set matches closely with Barton (1996) equation. Equation proposed by Singh and Bhasin (1966) act as upper bound to adjusted in-situ test data.

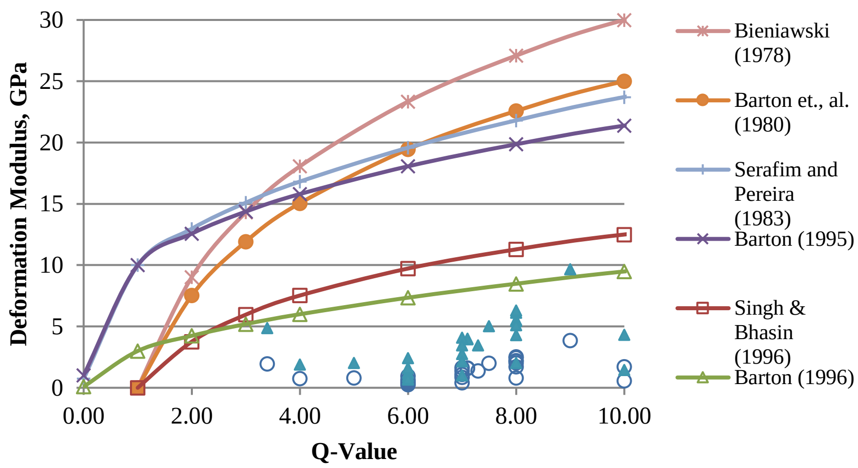


**Fig.1.** In-situ plate load test data along with envelope of empirical equations

Error prediction of empirical methods in comparison with in-situ test tests is shown in Fig. 2. In the figure, it can be seen clearly that the all empirical equations, predicts very high modulus values w.r.t. field test results. The –ve percentage of error indicates the over estimation of modulus values by empirical equations.

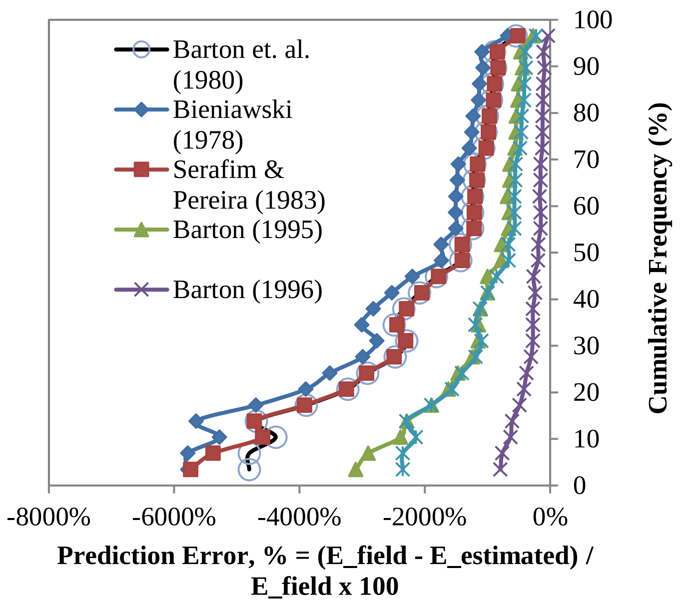


**Fig. 2.** Error Prediction of Empirical Methods

## 5 Summary

A total of 28 in-situ plate load results of sandstone rock mass from 2 projects were considered for the study. Results obtained from in-situ were compared with rock mass modulus values obtained using empirical correlations by various authors. Equations based on RMR and Q values were considered. The RMR based equations are converted in Q based using inter relations as given in Barton (1995). The following were summarized from this study;

1. All empirical equations are valid for fair to good rock mass with Q>1 or RMR>50. Even, the present paper studied based on CSMRS data has data for Q value in the range of 3 to 10. At present, no empirical equations available for estimating the deformation modulus for poor rock mass.
2. Equations developed by Bieniawaski (1978); Barton et. al. (1980); and Barton (1999) estimates very high modulus for rock mass as compared to in-situ test results.
3. Equations developed by Barton (1996) predict value nearer to in-situ test results. Plotting of in-situ plate load test results multiplied by a factor of 2.5 as suggested by Palmström and Singh (2001) gives is closely matching with equations given by Barton (1996). Singh &Bhasin (1996) equation acts as upper bound to the studied CSMRS data.
4. Barton (1996) equation can be applied for feasibility stage designs. However, for detailed stage design it is recommended to conduct in-situ tests by adopting stringent quality control in excavation and site preparation.
5. Error predication of empirical methods shows very high modulus values w.r.t. field test results.
6. As a way forward, more field data will be collected with different range of Q / RMR values for rock mass and correlations will validated. Moreover separate correlations may also be derived for different rock types.

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