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Rock Mechanics Investigations by Direct and Indirect Methods

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ABSTRACT

The paper includes the evaluation of parameters of rock and rock mass through rock mechanics investigation in laboratory and field for a powerhouse complex. The modulus of deformation evaluated by different methods have been compared using plate jacking test, plate loading test for rock mass and laboratory tests on intact rock. These results have further been compared using indirect methods of rock mass classifications such as Q-system and rock mass rating (RMR). The modulus of deformation by conducting large size plate jacking tests with deformation measurements by using multi point borehole extensometers has been compared with the respective values obtained from different methods. The properties of rock and rock mass have been compared for shear strength parameters and modulus of deformation. The classification approach appears to be reliable.

Keywords: Rock mechanics, Deformability; In-situ shear tests; Plate jacking test; Plate load test

1. INTRODUCTION

Strength, deformability and shear strength parameters are the basic requirement of analysis of dam and underground structures by numerical modelling. It is, therefore, necessary to evaluate input parameters accurately for numerical modelling to get the results matching with instrumentation after the construction of structure on or inside rock. Hence, rock mechanics investigations, both laboratory and in-situ, are essential preliminary step for analysis and design of dam and underground structures. The objects for conducting such rock mechanics investigations are to assess general suitability of site based on testing and to enable an adequate and economic design.

The ground is naturally variable and often the nature of these variations is not known in advance. In order to evaluate properly the nature of the ground and to achieve the objectives of the site investigations, it is essential that the testing work be planned properly, suitable methods be adopted, undertaken and supervised by experienced personnel. In order to collect data and achieve the project objectives, laboratory and in-situ investigations are performed.

M/s Indian Geotechnical Services (IGS) carried out in–situ soil and rock mechanics tests/investigations and laboratory testing. Field and laboratory tests were conducted on selected rock samples to determine the design parameters, confirming to relevant codes and specifications. In-situ rock mechanics tests at the project site and laboratory tests were conducted for the investigations at Bursar Hydroelectric Project, Jammu & Kashmir.

The geology of powerhouse complex mainly comprises of granite/gneissose granite, schistose quartzite and quartz mica schist.

The paper deals with rock mechanics investigations to determine shear strength parameters and modulus of deformation for a powerhouse complex by conducting in-situ tests on rock mass and laboratory tests on intact rock. These results have further been compared using indirect methods of rock mass classifications such as Q-system and rock mass rating (RMR).

2. BURSAR HYDROELECTRIC PROJECT

The proposed Bursar hydroelectric project envisages the construction of 284 m high concrete gravity dam with top length of 722 m near Pakal village across Marusudar river with a 120 MW dam toe powerhouse, a 6.8 km long HRT and 680 MW powerhouse (PH) near Lopara village on right bank of river. The project can be approached by 47 km long road from Kishtwar to Drangdhuran after which only foot/mule track exists with rough and difficult terrain for 19 km to Lopara (surface powerhouse) and 26 km up to dam site at Pakal village. The nearest rail head is at Jammu which is situated at a distance of 240 km from Kishtwar. The site is approachable by Air from Jammu Airport as well as from Srinagar Airport.

Bursar project is located in Kishtwar district of J&K, on river Marusudar, the main right bank tributary of river Chenab. Marusudar originates from Nun-kun glacier in Warwan village from higher Himalaya and joins Chenab at Bhandarkot. The project area lies in Lesser Himalaya and remained largely unexplored due to inaccessibility and remoteness. Major part of the valley is unapproachable. However, fair weather road is available from Kishtwar to Drangdhuran going through Patimahal and Ikhala beyond which mule path exists for 26 km.

The river flows in sinus loops at places apart from minor kinks and bends during its course from origin to the confluence with river Chenab at Bhandarkot. Major loop in the river course is seen between villages Lopara in North to Drangdhuran in South. Thereafter, it takes a sharp bend near Daddhar and flow almost a Southern course up to its confluence with Chenab. Near village Sondar, where another loop is formed, the Marusudar is joined by Kiar, Kibar and Nanthan nalas.

3. GEOLOGY OF PROJECT

Kishtwar region is located South-East of Kashmir valley and lies between Pir Panjal and Great Himalayan range. The different mountain ranges dissected by the drainage system of Chenab and Marusudar rivers form the topographic features of area. The area represents a typical lesser Himalayan type of rugged topography comprising high ranges and deeply dissected valleys, escarpments and cliff faces. The Marusudar river is flowing North to South and controls the drainage of the area. The Marusudar valley is widened beyond village Hanzal. It loops at places and as a result big river terraces are observed near village Hanzal, Lopara, Sirshi, Sondar and Drangdhuran.

The layout of Bursar project is housed in Kibar formation under Kishtwar group of rocks. The crystalline rocks of Kishtwar area have been regarded as Precambrian because of their metamorphic characters and by absence of fossil remains. These rocks form the NW continuation of the Himalayan crystallines in general, which consists mainly of the metamorphic and granitic rocks.

The granitic intrusive bodies of the area have been grouped in this formation. Many granite bodies of lesser dimension occur in Mughal Maidan, Dachhan area (Ikhala, Drangdhuran, Lopara and Hanzal) of Marusudar valley. The intrusive granites have imbibed country rock resulting in the development of biotite gneiss near the contact. The most abundant granite gneiss has porphyroblast of feldspar placed in a finer matrix of quartz, muscovite and biotite. Other lithounits included in this formation are grey/white quartzites, quartz-mica schist, and micaceous quartzite etc. In Marusudar valley, massive granitic gneisses show a conformable junction with foliated/ biotite gneiss around upstream of Sinjarar nala.

The geology of powerhouse complex at Lopara mainly comprises of granite/gneissose granite, schistose quartzite and quartz mica schist. The project area falls in seismic Zone IV.

4. LABORATORY INVESTIGATIONS OF ROCK

This paper covers the following investigations of rock determined as per IS Codes and ISRM Suggested Methods (ISRM,1981):

- Uniaxial compressive strength, UCS, (IS: 9143 – 1979),
- Deformability characteristics: modulus of elasticity and Poisson's ratio, (IS: 9221 – 1979),
- Shear strength parameters: cohesion and friction angle, (IS: 13047 – 1991),
- Compression and shear wave velocities, and
- Index properties.

Eleven drill holes were drilled at powerhouse complex. The results of laboratory tests for index properties and engineering properties on rock cores from different depths are given in Table 1.

Table 1: Summary of intact rock properties based on laboratory tests at powerhouse site

Rock Parameter	Type of rock		
	Granite / gneissose granite	Schistose quartzite	Quartz mica schist
Index properties			
Dry density, γ_{dry} (g/cc)	2.60	2.61	2.63
Bulk density, γ_{sat} (g/cc)	2.61	2.61	2.63
Water content (%)	0.06	0.13	0.13
Water absorption (%)	0.63	0.65	0.70
Slake durability index (%)	97.52	97.01	--
Strength and deformability characteristics in uniaxial compression			
Uniaxial compressive strength, σ_{ci}, dry (MPa)	70	124	--
Uniaxial compressive strength, σ_{ci}, saturated (MPa)	68	117	--
Modulus of elasticity, E, dry (GPa)	32	65	--
Modulus of elasticity, E, saturated (GPa)	28	64	--
Poisson's ratio, υ, dry	0.14	0.11	--
Poisson's ratio, υ, saturated	0.11	0.10	--

Compression and shear wave velocities			
Compressive (P) wave velocity, dry (km/sec)	3.82	4.96	4.60
Compressive (P) wave velocity, saturated (km/sec)	5.02	6.10	5.79
Shear wave velocity, dry (km/sec)	2.34	3.03	2.74
Shear wave velocity, saturated (km/sec)	2.96	3.48	3.48
Shear strength parameters			
Apparent cohesion, c (MPa)	11.02	--	--
Friction angle, φ (Degree)	58.10	--	--

The 54 mm diameter cores extracted from Nx size (76 mm) drill holes were selected to determine the rock properties in laboratory. All the tests for assessment of strength under various stress states, i.e. uniaxial compressive, indirect tensile and triaxial shear test (for shear strength parameters) have been performed for dry and saturated samples.

The laboratory tests were performed on three types of rock such as granite/gneissose granite, schistose quartzite and quartz mica schist. Some parameters could not be determined due to non-availability of sufficient rock specimen. There is insignificant or slight deterioration of properties when tested under saturated condition as given in Table 1.

5. SHEAR STRENGTH PARAMETERS IN POWERHOUSE DRIFT

The shear strength parameters were required for the design of surface powerhouse at Lopara. The in-situ block shear tests were conducted to evaluate shear strength parameters. Summary of results based on in-situ shear test are given in Table 2.

The shear strength parameters of rock to rock interface for Granite/gneissose granite rock mass, cohesion and friction angle are 0.41 MPa (c) and 55.88° (φ), and 0.18 MPa (c_r) and 49.52° (Φ_r) for peak and residual shear strength, respectively.

The shear strength parameters of intact rock are higher than in-situ magnitudes of rock mass. There is not much difference in friction angle between in-situ (55.88°) and laboratory (58°). However, there is significant difference in cohesion determined from laboratory (11.02 MPa) and in-situ tests (0.41 MPa) due to joints. Cohesion in the laboratory is about 5 to 30 times higher than determined in-situ. Similar results were discussed by Singh (2009a) for different projects.

Table 2: Summary of shear strength parameters in powerhouse drift

Rock to Rock Interface				Intact Rock	
Peak shear strength parameters		Residual shear strength parameters		Intact rock shear strength parameters	
Cohesion, c MPa	Friction angle, Φ°	Cohesion, c_r MPa	Friction angle, Φ_r°	Cohesion, c MPa	Friction angle, Φ°
0.41	55.88	0.18	49.52	11.02	58.10

The cohesion mobilized in underground openings is likely to be much more than that obtained by the in-situ block shear tests. Because rock mass is restrained to dilate on all the sides except towards opening, whereas the in-situ block is not restrained from dilatation. So the strength parameters should be back-calculated from the monitored displacements around the underground openings, using the software. Thus the strength parameters in Table 2 are applicable to the surface powerhouse only and not for the underground structures.

6. PLATE LOAD TEST IN POWERHOUSE DRIFT

6.1 Test Procedure

Five plate load tests (PLT) were conducted in powerhouse drift to evaluate the deformability of rock mass. Rock surface, at the invert and crown of the drift were smoothened by chiselling to obtain parallel horizontal face, about 5 cm more than the size of test plate (60 cm diameter). At the selected test site, the top reaction pad was prepared with cement mortar and using 25 mm thick MS plates. Both the pads were cast and kept parallel to each other.

The testing equipment was assembled with 25 mm thick and 60 cm diameter MS plates at the bottom and top followed by 45 cm and 30 cm diameter plates. Thereafter, a hydraulic jack of 300 tonnes capacity was placed. The gap between top plates and jack was filled by steel pipes. To remove the small gap and complete the assembly packing, plunger of the jack was moved upward. The load was applied by means of jack and pump. The photograph of plate load test is shown in Fig. 1.

Figure 1: View of plate load test in powerhouse drift

The test was completed in 6 cycles of loading and unloading up to a maximum stress of 6 MPa by keeping first cycle of 1 MPa. The deformation/displacement was recorded using 4 dial gauges with an accuracy of 0.01 mm installed diagonally on the bottom and top plates as is visible in Fig. 1. These tests were conducted in accordance with provisions of IS 7317 (1993) and ISRM (1981).

The modulus of deformation for the loading cycle has been calculated by considering total deformation of a particular cycle during loading whereas modulus of elasticity was calculated by considering only elastic deformation or rebound during unloading for the same cycle using the following equation:

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

where

E = Modulus of deformation/elasticity,
P = Applied load,
m = Constant for the shape of plate (m = 0.95 for square plate and 0.96 for circular plate),
ν = Poisson's ratio,
δ = Deformation corresponding to load, and
A = Area of plate.

Considering the Poisson's ratio of the granite/ gneissose granite rock equal to 0.14 based on laboratory tests and as the 60 cm diameter circular plate used in testing, Eq. 1 reduces to:

$$E = \frac{0.0017705P}{\delta} \tag{2}$$

where,

E = Modulus of deformation/elasticity, GPa,
P = Applied load, Tonnes, and
δ = Deformation corresponding to load, cm.

The Eq. 2 was used to calculate the moduli of deformation and elasticity using total deformation of the loading cycle and elastic deformation of unloading cycle, respectively.

6.2 Test Locations

The powerhouse drift was excavated with drill and blast method. One set comprising of five plate load tests were performed in powerhouse drift from RD 7 m to RD 52 m. Description of surface at each test location is given in Table 3.

The rock mass type is granite/gneissose granite throughout the length of the drift. The RMR value varies from 42 to 71 with a mean value of 58 as given in Table 3. The RQD value varies from 55.6 to 82 %.

Table 3: Details of five plate load test in powerhouse drift

Test No.	RD (m)	Rock type	RMR	RQD %	Description of surface to be sheared					Ground water condition
					Rough-ness	Filling material	Dip direction/dip amount (S-1)	Persis-tence m	Spacing of set (cm)	
PLT-1	7	Granite/ gneissose granite	66	68.8	Rough planar	No filling material (Tight aperture)	35°/40°	1-3	2 to 20	Dry
PLT-2	14		60	55.6			36°/30°	1-3	6 to 40	Dry
PLT-3	38		53	75.4			35°-45°/45°	1-3	5 to 30	Dry to damp
PLT-4	45		42	72.1			30°- 40°/ 28°-45°	1-3	10 to 25	Dry to damp
PLT-5	52		71	82.0			35°/45°	1-3	5 to 25	Dry

6.3 Test Results and Discussions

Five in-situ plate load tests in vertical direction were conducted in powerhouse drift at five different RDs. The deformations were measured at crown and invert for each test and the loads were applied in six cycles (in the increment of 1 MPa each) of loading and unloading by applying a maximum stress of 6 MPa.

The applied stress versus deformation curves for crown and invert of PLT-5 are shown in Figs. 2 and 3, respectively. The analysis of test results for 5 PLTs are given in Tables 4 to 6.

Based on the results of PLTs and curves in Figs. 2 and 3, the total deformation (W_d) and elastic rebound (W_e) are calculated and given in Table 4 as measured at the crown and invert of drift. All deformations are increasing with the increase in applied stress level.

The modulus of deformation and modulus of elasticity are calculated using Eqs. 1 and 2 and total deformation (W_d) and elastic rebound (W_e) from Table 4. The magnitudes of moduli of deformation and elasticity are given in Table 5 at the crown and invert of drift for all 5 plate load tests. The modulus values are increasing with the increase in stress level.

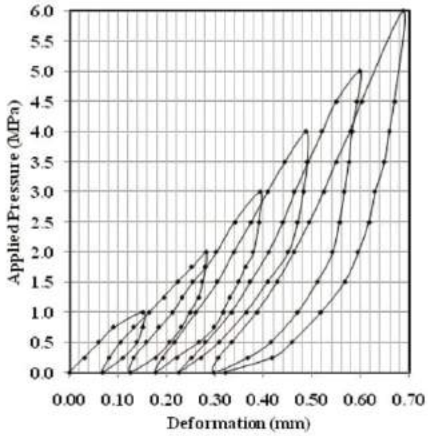

Figure 2: Stress versus deformation curve for PLT-5 at RD 52 m at crown

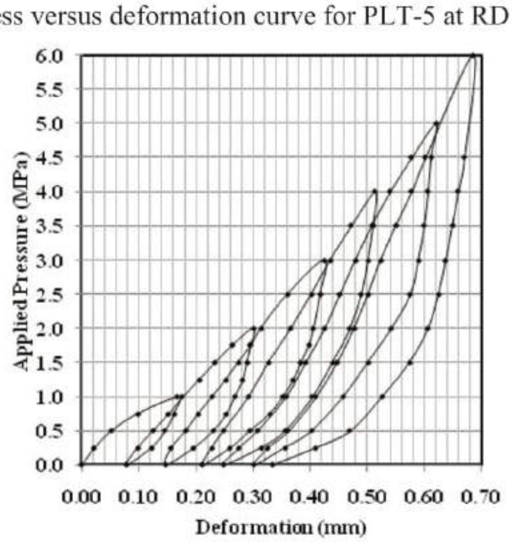

Figure 3: Stress versus deformation curve for PLT-5 at RD 52 m at invert

The minimum, maximum and average values of modulus of deformation (E_d) and modulus of elasticity (E_e) are given in Table 6 at the drift crown and invert along with modulus ratio of E_e/E_d. The average value of modulus of deformation increases from 2.70 to 6.83 GPa at the crown and 2.25 to 5.71 GPa at the invert of drift with the increase of applied stress level from 1 to 6 MPa. Hence, the average magnitude of modulus of deformation at the drift crown is higher than at the invert as given in Table 6 for applied stress level from 1 to 6 MPa.

The average value of modulus of elasticity increases from 5.70 to 7.81 GPa at the crown and 4.66 to 6.56 GPa at the invert of drift with the increase in applied stress level from 1 to 6 MPa. However, modulus ratio (E_e/E_d) decreases from 2.11 to 1.14 at the crown and from 2.07 to 1.15 at the invert of drift with increase in stress level from 1 to 6 MPa. The modulus of deformation increases with the increase in stress level.

Table 4: Total and elastic deformation at crown and invert for 5 cycles at different stress level

Cycle no.	Stress level MPa	Total deformation, W_d and Elastic deformation, W_e (mm)									
		PLT-1		PLT-2		PLT-3		PLT-4		PLT-5	
		W_d	W_e	W_d	W_e	W_d	W_e	W_d	W_e	W_d	W_e
Deformation at drift crown											
1	1	0.189	0.101	0.195	0.098	0.211	0.098	0.192	0.085	0.151	0.067
2	2	0.197	0.167	0.214	0.174	0.290	0.200	0.252	0.174	0.214	0.157
3	3	0.286	0.229	0.320	0.254	0.323	0.253	0.325	0.268	0.269	0.216
4	4	0.348	0.285	0.383	0.310	0.370	0.318	0.350	0.273	0.311	0.264
5	5	0.344	0.297	0.374	0.340	0.478	0.397	0.377	0.337	0.374	0.300
6	6	0.413	0.330	0.467	0.380	0.520	0.490	0.430	0.388	0.390	0.367
Deformation at drift invert											
1	1	0.201	0.114	0.232	0.108	0.232	0.101	0.348	0.174	0.168	0.078
2	2	0.192	0.150	0.244	0.184	0.296	0.210	0.414	0.301	0.223	0.154
3	3	0.292	0.214	0.344	0.271	0.357	0.283	0.644	0.434	0.278	0.214
4	4	0.324	0.279	0.421	0.338	0.424	0.360	0.775	0.618	0.303	0.266
5	5	0.405	0.306	0.464	0.400	0.486	0.418	0.891	0.757	0.373	0.320
6	6	0.440	0.361	0.539	0.469	0.554	0.483	1.026	0.899	0.385	0.352

Table 5: Modulus of deformation and modulus of elasticity at different stress level

Stress level, MPa	Modulus of deformation, E_d and Modulus of elasticity, E_e GPa									
	PLT-1		PLT-2		PLT-3		PLT-4		PLT-5	
	E_d	E_e	E_d	E_e	E_d	E_e	E_d	E_e	E_d	E_e
Vertical test at drift crown										
1	2.65	4.96	2.57	5.11	2.37	5.11	2.61	5.86	3.31	7.47
2	5.08	5.99	4.68	5.75	3.45	5.00	3.97	5.77	4.68	6.38
3	5.25	6.56	4.69	5.91	4.65	5.93	4.63	5.61	5.58	6.95
4	5.75	7.02	5.23	6.46	5.41	6.30	5.72	7.33	6.44	7.58
5	7.27	8.43	6.69	7.36	5.23	6.30	6.64	7.43	6.69	8.34
6	7.27	9.10	6.43	7.90	5.77	6.13	6.98	7.74	7.70	8.18
Vertical test at drift invert										
1	2.49	4.39	2.16	4.63	2.16	4.96	1.44	2.88	2.98	6.42
2	5.21	6.67	4.10	5.44	3.38	4.77	2.42	3.33	4.49	6.50
3	5.14	7.02	4.36	5.54	4.21	5.31	2.33	3.46	5.40	7.02
4	6.18	7.18	4.76	5.92	4.72	5.56	2.58	3.24	6.61	7.53
5	6.18	8.18	5.39	6.26	5.15	5.99	2.81	3.31	6.71	7.82
6	6.82	8.32	5.57	6.40	5.42	6.22	2.93	3.34	7.80	8.53

Overall, the modulus of deformation in powerhouse drift for both crown and invert varies from 2.93 to 7.80 GPa with an average value of 6.27 GPa at stress level of 6 MPa for all 5 plate load tests. Hence, a value of 6.27 GPa is recommended for modulus of deformation in powerhouse complex based on plate load test.

7. MODULUS OF DEFORMATION BY INDIRECT METHODS

The rock mass modulus of deformation in test drifts has been found to vary considerably between drift crown and invert. Such differences may largely be due to blast damage caused by the excavation process as described by Singh and Rajvansi (1996) and Singh and Bhasin (1996). The damage is mainly caused by development of cracks, displacement along existing joints, and disturbance of stresses. The effect of the blasts will vary with several features, such as rock properties, the amount of explosive used, the distance between the blast holes and the number of holes initiated at the same time, etc.

The zone around the tunnel influenced by blasting consists of two main types:

***The damaged* zone**, close to the tunnel surface, is dominated by changes in rock properties, which are mainly irreversible. It includes rocks in which new cracks have been created, existing cracks have been extended, and displacements along cracks have occurred.

Table 6: Average values of modulus of deformation and modulus of elasticity at different stress level along with modulus ratio

Stress level MPa	Modulus of deformation, E_d GPa			Modulus of elasticity, E_e GPa			Modulus ratio E_e/E_d
	Minimum	Maximum	Average	Minimum	Maximum	Average	
Vertical test at drift crown							
1	2.37	3.31	2.70	4.96	7.47	5.70	2.11
2	3.45	5.08	4.37	5.00	6.38	5.78	1.32
3	4.63	5.58	4.96	5.61	6.95	6.19	1.25
4	5.23	6.44	5.71	6.30	7.58	6.94	1.22
5	5.23	7.27	6.50	6.30	8.43	7.57	1.16
6	5.77	7.70	6.83	6.13	9.10	7.81	1.14
Vertical test at drift invert							
1	1.44	2.98	2.25	2.88	6.42	4.66	2.07
2	2.42	5.21	3.92	3.33	6.67	5.34	1.36
3	2.33	5.4	4.29	3.46	7.02	5.67	1.32
4	2.58	6.61	4.97	3.24	7.53	5.89	1.18
5	2.81	6.71	5.25	3.31	8.18	6.31	1.20
6	2.93	7.80	5.71	3.34	8.53	6.56	1.15

The *disturbed* zone occurs beyond the damaged zone, in which the changes are dominated by changes in stress state and hydraulic head. Here, the stress redistribution will cause block movements, aperture changes on natural joints, and/or elastic deformation of the rock. The changes from blasting in material properties, such as seismic velocity, Young's modulus, etc. are expected to be insignificant.

Palmstrom and Singh (2002) and Singh (2009b, 2011, 2014, 2116) proposed to multiply by factor 2.5 to the values of modulus of deformation determined by conducted plate load test or Goodman jack test to obtain realistic design value. The factor was obtained based on the results of large size plate jacking test and a comparison with plate load test, flat jack test and Goodman jack test. The ratio of plate jacking test (PJT) and plate loading test (PLT) i.e. PJT/PLT is suggested to be 2.5.in (Singh, 2009b).

On perusal of test results, it is seen that the values of deformation modulus, E_d varies from 4.96 to 7.75 GPa with an average value of 6.27 GPa at 6 MPa stress level. Accordingly, the deformation modulus for PJT, corresponding to the value of 6.27 GPa obtained in PLT, works out to be 15.68 GPa (6.27 x 2.5) as discussed by Singh (2009b).

The rock mass rating (RMR) system proposed by Bieniawski (1978) is also used for estimating the modulus of deformation (E_d) of rock mass by using the following equation:

$$E_d\ (GPa) = 2\,RMR - 100 \tag{3}$$

The Eq. 3 is valid for rock masses having a RMR value greater than 50. Serafim and Pereira (1983) extended the above equation to cover lower values of modulus where RMR is lesser than 50 as given below:

$$E_d\ (GPa) = 10^{\frac{RMR-10}{40}} \tag{4}$$

Barton (2002) developed the following equation and compared the results with Bieniawski (1978) and Serafim and Pereira (1983) with Q varying from 0.001 to 1000.

$$E_d\ (GPa) = 10 Q_c^{\frac{1}{3}} \tag{5}$$

Where Q_c is normalized Q value for UCS=100 MPa [$Q_c = Q.\ \sigma_{ci}/100$].

The Q value was determined from the following equation (Barton, 2002):

$$\mathrm{RMR} = 15 \log Q + 50 \tag{6}$$

Based on mean value of RMR as 58 from Table 7, the Q value was determined from Eq. 6 and found to be 3.5.

Table 7: Comparison of modulus of deformation between PLT and RMR

RMR	Test no.	RD, m	Modulus of deformation, E_d, GPa		
			Crown	Invert	Average
42	PLT-4	45	6.98	2.93	4.96
53	PLT-3	35	5.77	5.42	5.60
60	PLT-2	14	6.43	5.57	6.00
66	PLT-1	7	7.27	6.82	7.05
71	PLT-5	52	7.70	7.80	7.75

A comparison of modulus of deformation between PLT and RMR is given in Table 7. The average values of modulus of deformation for crown and invert along the length of the drift increases from 4.96 GPa to 7.75 GPa as the RMR value increases from 42 to 71. RMR value is 66 at RD 7 m and decreases to 42 at RD 45 m and again increases to maximum value of 71 at RD 51 m. The minimum value of RMR is 42 at RD 45 m and maximum is 71 at RD 52 m. Hence, it is necessary to conduct at least 5 tests in a drift to take an average value of modulus of deformation by considering rock mass variations inside a drift.

8. COMPARISON OF DEFORMABILITY BY DIFFERENT METHODS

Based on the results of Tables 6 and 7 and discussions above, the average values of modulus of deformation by in-situ plate load tests, plate jacking test, laboratory test, ratio of PJT/PLT by Singh and indirect method such as average value of 58 for RMR (58) and Q mean value of 3.5 in powerhouse complex are given in Table 8.

Table 8: Modulus of deformation by in-situ tests and indirect methods

S. No.	Test method	Modulus of deformation, GPa	PJT/Other methods	Test type
1	Plate jacking test (PJT)	15.06	1.0	In-situ
2	Plate loading test (PLT)	6.27	2.4	In-situ
3	Dilatometer test (DT)	4.31	3.5	In-situ
4	Laboratory test (LT)	65.04	0.23*	Laboratory
5	Singh (2009b)	15.68	0.96	In-situ
6	Barton (2002)	15.18	0.99	Indirect Q
7	Beiniawaski (1978)	16.00	0.94	Indirect RMR
8	Serafim and Pereira (1983)	15.85	0.95	Indirect RMR

** LT/PJT = 4.32*

Average value of RMR in powerhouse drift is 58 and the mean Q value is 3.5. The modulus of deformation of rock mass based on RMR is 16 GPa as calculated from Eq. 3 given by Bieniawski (1978). The modulus value based on RMR is 15.85 GPa from Eq. 4 as given by Serafim and Pereira (1983). The modulus value based on Q is 15.18 GPa as computed from Eq. 5 given by Barton (2002). The modulus of elasticity of intact rock is 4.32 times higher than modulus of deformation of rock mass.

The average value of deformation modulus obtained from 5 PLT increases from 4.96 to 7.75 GPa at stress level of 6 MPa in the drift with an overall average of 6.27 GPa. The value of 15.68 GPa (6.27 x 2.5 as recommended by Singh (2009b and 2016) is very close to 16 and 15.85 GPa evaluated from RMR, and 15.18 GPa evaluated from Q-system (Table 8). At this project site, the modulus of deformation determined by conducting in-situ PJT and evaluated from Singh (2009b), 2.5 times PLT, and indirect methods such as RMR and Q-system are very close.

It is, therefore, recommended to conduct plate jacking test to evaluate correct and appropriate value for modulus of deformation of rock mass.

As per Farmer and Kemeny (1992), the modulus of elasticity of intact rock sample is 5 to 20 times higher than the deformation modulus of the rock mass in-situ. Singh (2016) revised this variation from 3 to 20 times based on case studies from Himalaya.

The shear strength parameters of intact rock are higher than in-situ magnitudes of rock mass. Hence, it is mandatory to conduct in-situ tests for determination of modulus of deformation and shear strength parameters.

9. CONCLUSIONS AND RECOMMENDATIONS

Based on the above study, the following concluding remarks can be drawn:

- The shear strength parameters of intact rock are higher than in-situ magnitudes of rock mass. There is not much difference in friction angle between in-situ (56^0) and laboratory (58^0). However, there is significant difference in cohesion determined in laboratory on intact rock (11 MPa) and in-situ on rock mass (0.4 MPa) due to rock joints. Cohesion in the laboratory is about 5 to 30 times higher than determined by in-situ shear test.
- Modulus value of intact rock specimen tested in the laboratory is about 3 to 20 times more than the modulus of deformation of rock mass based on in-situ testing. The difference is dependent on jointing in the rock mass. Difference is very high for highly jointed rock mass.
- It is recommended to utilize large size plate jacking test with borehole deformation measurements to arrive at a final design value of modulus of deformation. However, the modulus of deformation of rock masses obtained by plate loading tests, Goodman jack tests and dilatometer tests may have to be multiplied by a factor of 2.5 to arrive at a reasonably good representative value. This factor may be derived exactly for a particular site by conducting in situ tests by different methods.
- Modulus value increases with the increase in applied stress during testing. The average magnitude of modulus of deformation at the drift crown is higher than at the invert. This is true due to more disturbances in rock mass at invert due to blasting during drift excavation.
- There are variations in the modulus values determined by different methods. Sometimes these variations are due to the change in the rock mass properties also. The results of deformability measurements must be analyzed by experience hands working in the field.
- Overall, the modulus of deformation in powerhouse drift for both crown and invert varies from 2.93 to 7.80 GPa with an average value of 6.27 GPa at stress level of 6 MPa for all 5 plate load tests. However, a value of 15 GPa is recommended for modulus of deformation in powerhouse complex based on plate jacking tests and indirect methods.
- The modulus of deformation by plate load test increases from 4.96 to 7.75 GPa with an average value of 6.27 GPa as RMR increases from 42 to 71 with a mean value of 58. Hence, it is necessary to conduct minimum of 5 tests in a drift for each rock type to cover the range of rock mass.
- Indirect method may be used very cautiously based on sufficient experience and may be compared by conducting plate jacking tests for a particular rock mass. The modulus by rock mass classification approach appears to be reliable and very close to in-situ test in the present case study.

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