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Modulus of Deformation and Shear Strength Parameters of Rock Material and Rock Mass in Underground Powerhouse

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ABSTRACT

The modulus of deformation of rock mass was determined by conducting 10 plate jacking tests (PJT) with measurement of deformations inside drillholes in vertical and horizontal directions. It was observed that, the modulus of deformation increased and modulus ratio decreased with the increase in applied stress level. The rock mass is anisotropic as the modulus of deformation in horizontal direction (19.22 GPa) is higher than in vertical direction (14.06 GPa) by PJT in powerhouse drift. Further, the magnitudes of modulus of deformation by direct methods using PJT have been compared with indirect methods based on Q and RMR. Shear strength parameters (cohesion and friction angle) were determined by conducting in-situ shear tests on rock joints inside drift of underground powerhouse. The cores, extracted from drilling for PJT, were utilized to determine engineering properties of rock in the laboratory. A comparison has been given to evaluate and differentiate the properties of rock and rock mass. The modulus of elasticity of intact rock tested in the laboratory is 2 to 15 times higher than modulus of deformation of rock mass evaluated by conducting large size in-situ plate jacking test. The cohesion and friction angle of intact rock were observed to be higher about 10 to 35 times and about 1.2 times respectively than that of rock mass. The difference is much higher in case of cohesion of intact rock and it is insignificant in case of friction angle.

Keywords:In-situ tests; Modulus of deformation; RMR and Q; Shear strength parameters; Laboratory tests

1. INTRODUCTION

The Chenab Valley Power Projects Limited (CVPP) has undertaken the construction of PakalDul Hydro Electric Project, Jammu & Kashmir. It was decided to conduct the in–situ and laboratory tests of rock for underground powerhouse of the project. In–situ tests at the project site were conducted for evaluating modulus of deformation of rock mass, shear strength parameters of rock joints and laboratory testing to determine engineering properties of rock. The Client, M/s CVPP Limited has entrusted M/s Indian Geotechnical Services, New Delhi, India to conduct in-situ testing at proposed powerhouse.

The present paper includes the comprehensive field tests based on geological information from drilling and surface mapping of drifts and interpretations of the test results for rock and rock mass inside powerhouse drift. The modulus of deformation of rock mass was determined by conducting plate jacking tests (PJT) with measurement of deformations inside drillholes. The modulus of deformation from in-situ tests was compared with indirect methods based on rock quality (Q) system and rock mass rating (RMR). Shear strength parameters (cohesion and friction angle) were determined by conducting in-situ shear tests on rock joints inside powerhouse drift. The cores, extracted from drilling for PJT, were utilised to determine engineering properties of rock in the laboratory. The results from all methods have been compared to evaluate the properties of rock and rock mass.

2. THE PROJECT

The project envisages construction of 167 m high concrete face rock-fill dam (CFRD) on river Marusudar at Dangduru in Tehsil Kishtwar. The river bed level at the dam site is about 1540 m corresponding to FRL of 1700 m. The gross storage capacity of Drangdhuran reservoir is 125.4 Mcm and area under submergence is 228 Ha. Diversion of water shall be done through two head race tunnels (HRT) each of 10 km length and 7.2 m finished diameter. An underground powerhouse with dimensions (166 m x 20.2 m x 50.8 m) is proposed on the right bank of river Chenab. The maximum gross head of 417 m between the dam site at Dangduru and powerhouse at Dul is to be utilized for power generation of 1000 MW with four units of 250 MW each. The project will generate 3330.18 million units in a 90% dependable year. The Chenab Valley Power Projects Limited (CVPPL) has undertaken the construction of PakalDul Hydroelectric Project in Jammu and Kashmir.

After power generation, the water from the powerhouse would be discharged through 4 numbers of 125 m long, 5.5 m diameter horse-shoe-shaped tail race tunnels (TRT) in the reservoir of Dulhasti Hydroelectric Project in river Chenab. The regulated flows of water from PakalDul project would enhance the generation of Dulhasti Hydroelectric Power Station.

The layout plan of the project is shown in Fig. 1. The layout plan of the drift with respect to project is shown in Fig. 2 along with marking of test locations.

Marusudarriver originates from Nun-kun glacier in Warwan valley from higher Himalayas and joins Chenab at Bhandarkot. The project area lies in inner 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 Bhandarkot to Palimahal and beyond that mule path exists.

Topography of the area is characterized by rugged steep cliffs and deep fascinating gorges with elevations ranging from 1500 m to 4500 m. Right bank is almost rocky with steep escarpments whereas left bank is generally covered under slope wash material. Because of relatively gentle slope the left bank is easily approachable and also where most of the villages are present.

3. GEOLOGY OF THE POWERHOUSE

Geologically the project area lies in inner Lesser Himalayas under Kishtwar group of rocks. Dam and appurtenant structures and part of HRT lie in Kiber Gneiss formation of Kishtwar group of rocks, whereas the powerhouse complex and remaining part of HRT are housed in low grade metamorphics of Dul formation (schist, phyllite and quartzite). Detailed investigations have been carried out for constructing the underground powerhouse and appurtenant structures on right bank of river Chenab at upstream of DulHasti dam. The rocks exposed on this bank are alternate sequence of quartzite and phyllite.

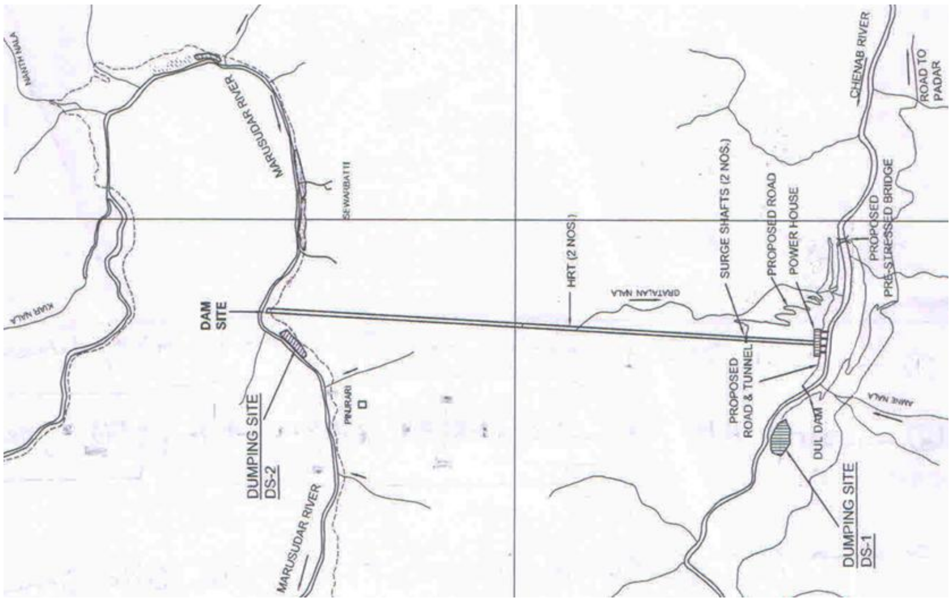

Fig. 1 - The layout plan of PakalDul hydroelectric project

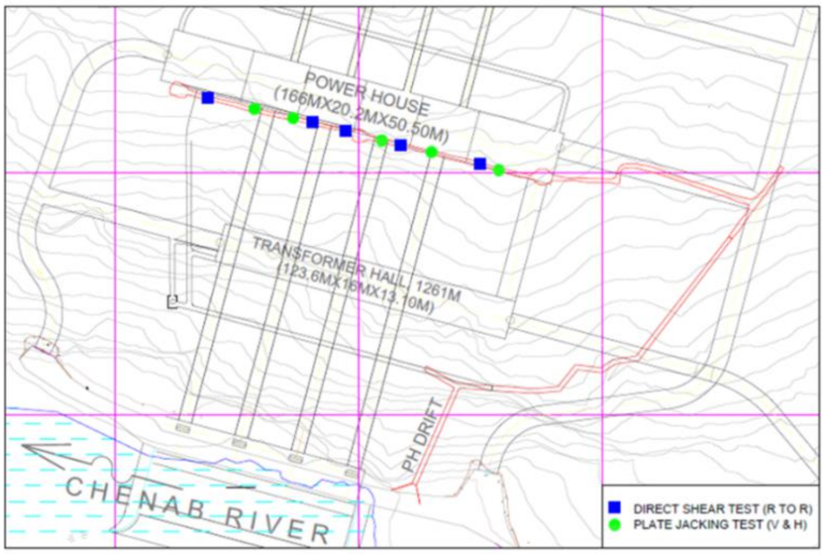

Fig. 2 - Layout plan of the powerhouse drift with locations of in-situ tests

Strong quartzite is the dominating rock type in the underground powerhouse area and weak to very weak chloriticphyllite is present in the core and outer shell of the folded structure, as the trace of the foliation depict presence of major recumbent folding. Apart from the foliation planes, rock mass is dissected by mainly other three sets of joints and intensity of jointing increase towards the hinge of the fold in this area. Subvertical joints either dipping towards upstream or downstream are prominently developed & observed to be quite persistent.

The underground powerhouse cavern shall be located mainly within strong quartzite rock forming lower limb of a recumbent fold. Weak to very weak chloriticphyllite is present in the core and outer shell portion of recumbent at places. Ground water seepage is anticipated to be the significant aspect during construction of the powerhouse. The rock cover above the machine and transformer caverns will be around 160 m and 120 m, respectively.

4. GEOTECHNICAL INVESTIGATIONS

Following was the scope of the present investigation work:

- Conducting plate jacking tests (PJT) for determination of modulus of deformation of rock mass by uniaxial loading technique in powerhouse drift as per standard specifications.
- Conducting in-situ rock shear tests (SHT) to determine the in-situ shear strength of rock joints inside powerhouse drift.
- Exploratory core drilling of NX (54 mm) diameter in rock mass for plate jacking tests.
- Conducting laboratory tests on selected rock core samples as per standard specifications to get the engineering properties of rock in obtained from underground powerhouse.

This paper includes the evaluation of laboratory and in-situ properties for underground powerhouse complex for rock and rock mass, respectively.

5. IN-SITU SHEAR TEST IN POWER HOUSE DRIFT

5.1 Test Procedure

In-situ shear tests were conducted to determine the shear strength parameters as discussed by IS 7746:1991, ISRM: 1981, CBIP: 1988, Ramamurthy (2014), Singh (2009, 2014a), Singh and Garg (2017a), Singh and Sarwade (2016) and Sarwade et al. (2017).

A set of blocks of rock mass is made for testing purpose. Diamond wheel cutter, chisel and hammer were used to separate the rock mass of block size (70 cm x 70 cm x 35 cm) from parent rock. Steel frame of 20 mm thickness MS plates is placed over the block and filled with cement grout. 20 mm thick MS plates were used to prepare side and top reaction pads, strengthen by RCC. The care was taken to keep the top and side reaction pads concentric with the block.

Each block was sheared at constant but different normal load. Vertical load was applied by 200 tons capacity hydraulic jack and MS cylinders were used to fill up the gap between the top reaction pad and the hydraulic jack. The shear load was applied by another 300 tons capacity hydraulic jack from the side reaction pad at an angle of 15^o with the horizontal in order that the resultant force passed through the centre of the test block. The shear stress was applied at 15^o angle with the horizontal to avoid the overturning of blocks during shearing. This was achieved by two wooden wedges placed across the jack. The application of shear force was kept until the peak and residual shear stresses were attained.

Five such blocks were sheared. Each block was tested for a particular normal stress which was kept constant during the test. The shear force and shear displacement of block were measured and recorded during the test. The vertical, horizontal and lateral displacements of the block, produced during the test were measured by eight dial-gauges (four for normal displacement, two for shear displacement and two for lateral displacement) each of 0.01 mm least-count. The observations were recorded till failure and continued even after the failure to the extent possible to get the information regarding residual frictional resistance.

5.2 Calculations

Normal stress and shear stress are obtained from normal load and shear load recorded during the in-situ test. The shear stress and normal stresses are calculated from the following equations:

Shear Stress, τ $$= \frac{P_s}{A} = \frac{P_{sa} \cos\alpha}{A} \qquad (1)$$

Normal stress, σ_n $$= \frac{P_n}{A} = \frac{P_{na} + P_{sa} \sin\alpha}{A} \qquad (2)$$

where

P_{sa} = applied shear load,
P_s = total shear force,
P_n =total normal force,
A =area of test block,
P_{na} = applied normal load,
α = inclination of applied shear load at an angle of 15° from horizontal plane.

As α is 15° in this case, the applied normal force is reduced after each increase in shear force by an amount P_{sa} sinα in order to maintain the normal stress approximately constant. The peak and residual shear stresses are obtained from a plot of shear stress versus shear displacement. At failure (peak) and after failure (residual), the shear stress is plotted against the normal stress and the "curve of best fit" is drawn using linear regression analysis. From the equation of straight line obtained, the intercept on the Y- axis gives cohesion 'c' of the rock mass and the slope of the line gives the friction angle 'φ' of the rock mass.

5.3 In-situ Shear Test in Powerhouse Drift

One set of in-situ shear tests (SHT) was conducted consisting of five blocks (SHT1 to SHT5) with dimensions of 70 cm x 70 cm x 35 cm for each block. The descriptions of shear test locations are given in Table 1 for all five blocks in power house drift.

Table 1- Description of shear test locations in power house

Test No.	RD, m	Rock type	Description of surface						Ground water condition
			Roughness	Filling material	Dip Direction, degree	Dip amount (S-1), degree	Persistence, m (S-1)	Spacing of set (S-1) (cm)	
SHT-1	115	Quartzite with thin phyllitic intercalations	Rough planar (irregular)	Tightly healed, hard, non-softening, impermeable filling (at places: slightly altered joint walls. non-softening mineral coatings; sandy particles, clay-free disintegrated rock)	40	15-25	3-10m	20-60cm	Dry
SHT-2	153				40	15-25	3-10m	20-60cm	Dry
SHT-3	176				35	15-25	3-10m	20-60cm	Dry
SHT-4	192				40	15-25	3-10m	20-60cm	Dry
SHT-5	237				30	15-25	3-10m	20-60cm	Dry

The location of shear test blocks in the powerhouse drift is shown in Fig. 2. The in-situ shear test assembly is shown in Fig. 3. The overturned blocks after the completion of in-situ shear test are shown in Fig. 4 at RDs of 115 m to 237 m. Each block was overturned after the test to measure the corrected sheared area.

One set of in-situ shear test consisting of five blocks was conducted for rock to rock interface. The shear stress versus shear displacement curves for all 5 blocks is shown in Fig. 5 to determine peak and residual shear stresses. The values of peak and residual shear stresses for all 5 blocks at different normal stresses are given in Table 2.

(A) (B)

Fig. 3 - View of direct in-situ shear test on rock to rock interface

SHT-1 SHT-2 SHT-3 SHT-4 SHT-5

Fig. 4 - View of the overturned sheared blocks from SHT-1 to SHT-5

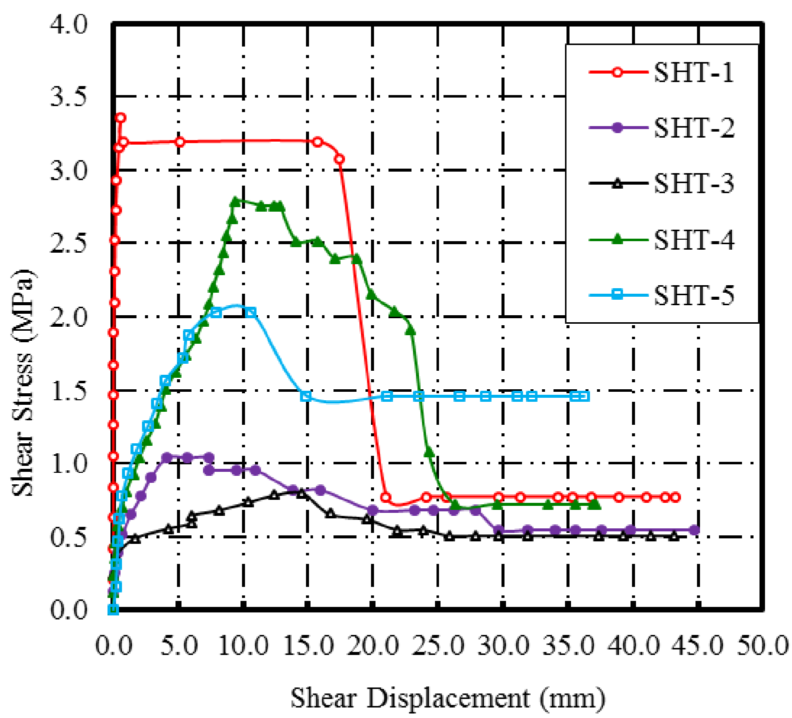

Fig. 5 - Shear stress versus shear displacement curve for rock to rock interface

Table 2 - Peak and residual values of shear stress for different normal stress in powerhouse drift for shear test

S. no.	Block no.	Normal stress (MPa)	Normal settlement (mm)	Peak shear stress (MPa)	Residual shear stress (MPa)
1	SHT-3	0.218	1.21	0.785	0.508
2	SHT-2	0.433	1.18	1.040	0.550
3	SHT-1	0.637	0.20	3.360	0.773
4	SHT-4	0.810	1.36	2.787	0.719
5	SHT-5	1.041	1.38	2.033	1.457

Based on the data of in-situ shear test using 5 blocks as given in Table 2, the plots of shear stresses (peak and residual) versus normal stress are shown in Fig. 6.

The data of blocks 1 and 4 was not utilised due to very high peak stress applied to shear the blocks. Shear stress is applied at an angle of 15° to avoid overturning of blocks during shearing. A vertical component of shear stress is decreased during shearing from applied normal stress by an amount of P_{sa}Sin15° for all increment of shear stress in order to maintain the normal stress constant during shear test. In blocks SHT-1 and SHT-4, vertical component of the applied shear stress attained a value of more than applied normal stress. Hence, the normal stresses of blocks SHT-1 and SHT-4 could not be kept constant during in-situ shear tests due to very high shear stress. It was, therefore, decided to use the data of blocks SHT-2, SHT-3 and SHT-5 in the plot of shear stress versus normal stress.

For peak shear strength parameters as determined from Fig. 6, the cohesion, c and friction angle, φ are 0.42 MPa and 57.02°, respectively. The cohesion, c and friction angle, φ for residual shear strength parameters of rock to rock interface are 0.14 MPa and 50.84°, respectively.

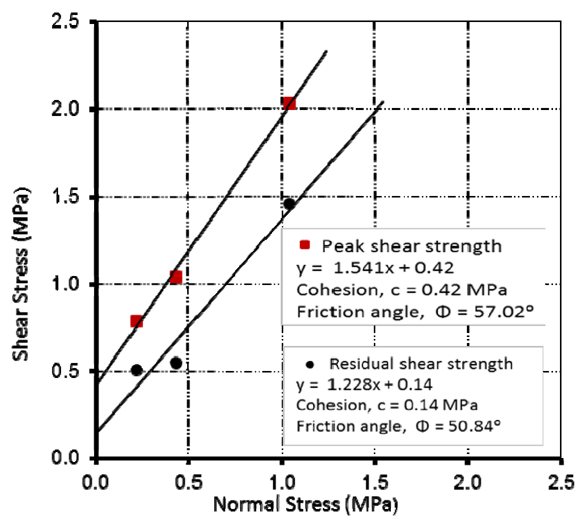

Fig. 6 - Shear stress versus normal stress curve for in-situ shear test

5.4 Recommendations of Shear Strength Parameters

The recommended shear strength parameters of rock to rock interface as given in Table 3 based on Fig. 6, cohesion and friction angle are 0.42 MPa (c) and 57.02° (φ), and 0.14 MPa (c_r) and 50.84° (φ_r) for peak and residual shear strength of rock mass, respectively.

The recommended shear strength parameters of intact rock based on triaxial tests in the laboratory as given in Table 3, cohesion and friction angle are 14.05 MPa (c) and 67.71° (φ_r), respectively.

The cohesion of intact rock is about 33 times higher than rock mass and friction angle of intact rock is about 1.2 times higher than peak friction angle of rock mass. The difference is much higher in case of cohesion of intact rock and it is insignificant in case of friction angle, as the rock mass has discontinuities.

Table 3 -Shear strength parameters of rock mass and intact rock in powerhouse drift

Rock to rock interface of rock mass				Intact rock	
Peak shear strength parameters		Residual shear strength parameters		Shear strength parameters	
Cohesion, c (MPa)	Friction angle, φ (°)	Cohesion, c_r (MPa)	Friction angle, φ_r(°)	Cohesion, c (MPa)	Friction angle, φ (°)
0.42	57.02	0.14	50.84	14.05	67.71

Designers should realize that the mobilized actual peak cohesion in the deep cavern is likely to be one order of magnitude more than the measured value of cohesion from direct shear test. There is a significant strength enhancement due to the intermediate principal stress along the cavern axis, constrained dilatancy on all the sides except the face of excavation and lesser lengths of rock joints in a deep cavern. So, the 3DEC software is the ideal choice for design of the support system for caverns. Further, the angle of internal friction is likely to decrease with the increase in the confining pressure. Even the residual angle of internal friction is likely to reduce with increasing confining pressure.

6. DEFORMABILITY OF ROCK MASS

6.1 Deformability Tests by Plate Jacking Test

6.1.1 Introduction

The plate jacking tests (PJT) is conducted to determine the modulus of deformation of rock mass. In PJT, the stress is applied at the surface of the drift and deformations are measured through multipoint borehole extensometers installed inside drill-holes at both sides of loading plates.

6.1.2 Plate jacking test

The plate jacking test set up in vertical and horizontal directions along with concrete pad and installation of anchors and extensometers in drill-holes, data acquisition system and extensometers with anchor and installation tools are shown in Figs. 7 to 12. PJT assembly comprises of hand pumps/electric pump, hydraulic jacks, multiple point borehole extensometers with anchors and the measuring system with displacement transducers and a multi-channel digital readout unit alone with automatic data acquisition system with an accuracy of 0.001 mm.

6.1.3 Site preparation

The plate jacking tests were conducted by applying load in the directions normal to loading surface. The rock surface of the drift at each test location was carefully prepared by removing all loose rock material by chiselling within a diameter of 150 cm around the drill holes. The loading surfaces were kept concentric. NX size (76 mm diameter) instrumentation drill holes of about 5 to 6 m depth were drilled at the prepared surfaces. Both the drill holes were aligned carefully so that they were normal to surface and were in line with each other. Concrete pads using rich mix were cast around the drill holes to ensure smooth transfer of loading from the jack to the rock mass. The pads were allowed to cure for at least seven days to obtain sufficient strength prior to commencement of the test.

Fig. 7- PJT in vertical direction

Fig. 8 - PJT in horizontal direction

Fig. 9 - Concrete pad for plate jacking test

Fig. 10 - Installation of anchors and extensometers

Fig. 11 - Data acquisition system for PJT

Fig. 12 - Extensometer with anchors setting tools

6.1.4 Equipment installation

The extensometers with the help of anchors were installed at suitable locations inside the drill-holes. The locations of anchors were decided after careful examination and logging of drill-hole cores. Care was taken so that the anchors were not placed on joints. The last anchor in the drill-hole was kept about 50 - 80 cm below the rock surface just to avoid blasting effects in the drift. The deepest anchor was located up to a depth of 600 cm from the rock surface in order to provide a fixed point to which the movement of all the extensometers can be referred. In all, five to seven anchors were installed in each instrumentation drill-hole, which accommodated four to six extensometers in each drill hole. The gap between the plate jacking assembly and the top plates was filled up by restrained columns of different length.

6.1.5 Test procedure

After all the components were installed, the system was checked for the actual test. The loading was applied through the hydraulic jack system by manually operated hydraulic pump. It was tried to maintain the rate of loading as 0.4 MPa/min and the load was applied in cycles of 2, 4, 6, 8 and 10 MPa of loading and unloading the pressure every time to zero. The modulus values were calculated for the cycles of 2, 4, 6, 8 and 10 MPa. The first cycle was not considered for evaluation of deformability as the closing of joints due to blasting and some settlement of loading assembly takes place in loading and unloading. The load was maintained for 5 minutes at the stage of initial loading, minimum and maximum loading, while the intermediate load increments were maintained for one minute. The tests were conducted according to the suggested method by ISRM (1979, 1981).

6.1.6 Calculations

Deformation measurement for the various load cycles are utilised to compute deformation modulus according to appropriate formula. The modulus of deformation has been calculated for each cycle of loading and unloading. The equation utilised for this purpose is given below by utilising the following formula:

$$W_z = \frac{2\,P\,(1-\upsilon^2)}{E}\left[(a^2+z^2)^{1/2} - z\right] - \frac{P\,z\,(1+\upsilon)}{E}\left[z\,(a^2+z^2)^{1/2} - 1\right] \tag{3}$$

where

- W_z = displacement in the direction of applied pressure (cm),
- Z = distance from the loaded surface to the point where displacement is measured (cm),
- P = dpplied pressure (in MPa),
- A = duter radius of flat jack (cm),
- υ = Poisson's ratio, and
- E = dodulus of rock mass (MPa).

After substituting the appropriate values of a, z andυ, the Eq. 3 can be written as:

$$W_z = \frac{P}{E}(K_z) \tag{4}$$

The modulus of deformation (Ed) can be determined by the following formula:

$$E_d = P\left[\frac{K_{z1}-K_{z2}}{W_{z1}-W_{z2}}\right] \tag{5}$$

Where, K_{z1} and K_{z2} are constants at depth z_1 and z_2, respectively. Similarly, W_{z1} and W_{z2} are deformations measured between depths z_1 and z_2. The Eq. 5 can be utilised for the determination of modulus of deformation (E_d) and modulus of elasticity (E_e) based on the total deformation (loading cycle) and elastic deformation/rebound (unloading cycle) of particular cycle, respectively.

6.2 Test Locations at Powerhouse Drift

The 10 plate jacking tests (5 each in vertical and horizontal directions) were conducted inside powerhouse drift. These 10 tests were conducted by applying loading in vertical as well as in horizontal direction. 10 PJT were conducted in vertical and horizontal directions inside powerhouse drift with details given in Table 4. The test locations are shown in Fig. 2.

The average value of RMR at PJT location is 66 with variations from 55 to 84. The average value of Q is 21.39 with the variations from 11.66 to 37.77.

Table 4 - Details of PJT in powerhouse drift

S. No.	Test no.	RD, m	RMR	Q value	Rock type
1	PJT1V and PJT1H	108	84	37.77	Quartzite with thin phylliticintercalations
2	PJT2V and PJT2H	136	55	11.66	
3	PJT3V and PJ31H	157	61	18.75	
4	PJT4V and PJT4H	197	62	18.75	
5	PJT5V and PJT5H	214	70	20.00	
Average Value			66	21.39	

6.2.1 PJT in powerhouse drift (vertical direction)

Five PJT were conducted in vertical direction inside powerhouse drift with details given in Table 4 from PJT1V to PJT5V. The stress versus deformation curves for PJT4V are shown in Figs. 13 to 14 in upward and downward directions, respectively. The test results have been summarised in Table 5 for PJT4V.

Table 5 - Moduli of deformation (E_d) and elasticity (E_e) for PJT4V

Applied stress MPa	Depth cm	Total deformation, W_d cm	Elastic rebound, W_e cm	E_d GPa	E_e GPa	Ratio E_e / E_d
Vertical Upward						
2	57 - 459	0.0073	0.0036	5.22	10.58	2.03
4	57 - 459	0.0070	0.0051	10.89	14.94	1.37
6	57 - 459	0.0088	0.0079	12.99	14.47	1.11
8	57 - 459	0.0115	0.0113	13.25	13.49	1.02
10	57 - 459	0.0140	0.0140	13.61	13.61	1.00
Vertical Downward						
2	58 - 349	0.0060	0.0036	5.93	9.88	1.67
4	58 - 349	0.0104	0.0082	6.84	8.68	1.27
6	58 - 349	0.0142	0.0122	7.51	8.75	1.16
8	58 - 349	0.0151	0.0145	9.42	9.81	1.04
10	58 - 349	0.0158	0.0152	11.26	11.70	1.04

The value of modulus of deformation is increasing from 5.22 GPa to 13.61 GPa with the variation of applied stress from 2 MPa to 10 MPa, respectively, along with decrease of E_e/E_d ratio from 2.03 to 1.00 in upward direction for PJT4V (Table 5).

The value of modulus of deformation is increasing from 5.93 GPa to 11.26 GPa with the variation of applied stress from 2 MPa to 10 MPa, respectively, along with decrease of E_e/E_d ratio from 1.67 to 1.04 in downward direction for PJT4V (Table 5).

The minimum, maximum and average magnitudes of modulus of deformation (E_d) and modulus of elasticity (E_e) for all 5 PJT conducted in vertical direction (PJT1V to PJT5V) at applied stresses varying from 2 MPa to 10 MPa are given in Table 6.

Table 6 - Average values of Moduli of deformation (E_d) and elasticity (E_e) in vertical direction (PJT1V to PJT5V)

Stress level, MPa	Modulus of deformation, E_dGPa			Modulus of elasticity, E_eGPa			Modulus ratio E_e/E_d
	Minimum	Maximum	Average	Minimum	Maximum	Average	
Vertical test at drift crown in upward direction							
2	5.09	11.15	7.57	8.24	18.71	13.68	1.81
4	9.23	20.73	13.74	11.17	25.91	17.70	1.29
6	10.93	19.85	14.68	13.32	22.75	16.45	1.12
8	12.54	20.06	14.84	13.16	21.45	15.73	1.06
10	11.94	21.60	14.98	12.24	22.21	15.46	1.03

Vertical test at drift invert in downward direction							
2	4.99	7.43	6.08	6.59	12.86	10.52	1.73
4	6.84	12.95	10.24	8.68	16.05	12.51	1.22
6	7.51	14.00	10.98	8.75	17.17	13.38	1.22
8	9.42	15.14	11.90	9.81	16.72	13.02	1.09
10	11.05	17.01	13.13	11.70	17.60	13.57	1.03

The average value of modulus of deformation (E_d) is 14.98 GPa with variation from 11.94 GPa to 21.6 GPa at applied stress of 10 MPa in upward direction (Table 6). The average value of modulus of elasticity is 15.46 GPa with variations from 12.24 GPa to 22.21 GPa (Table 6) at applied stress of 10 MPa in upward direction.

The average value of modulus of deformation (E_d) is 13.13 GPa with variations from 11.05 GPa to 17.01 GPa at applied stress of 10 MPa (Table 6). The average value of modulus of elasticity (E_e) is 13.57 GPa with variations from 11.7 GPa to 17.6 GPa at applied stress of 10 MPa in downward direction.

Overall minimum, maximum and average magnitudes of modulus of deformation (E_d) and modulus of elasticity (E_e) in vertical direction at applied stresses varying from 2 MPa to 10 MPa have been summarised in Table 7 for results of 5 PJT (PJT1V to PJT5V) of powerhouse drift in vertical upward and downward directions.

The average value of modulus of deformation is 14.06 GPa with variations from 11.05 GPa to 21.6 GPa (Table 7) at an applied stress of 10 MPa. The average value of modulus of elasticity is 14.51 GPa with variations from 11.7 GPa to 22.21 GPa (Table 7) at an applied stress of 10 MPa in vertical direction with E_e/E_dratio of 1.03.

The average value of modulus of deformation is increasing from 6.82 GPa to 14.06 GPa (Table 7) with the variations of applied stress from 2 MPa to 10 MPa, respectively, along with decrease in E_e/E_d ratio from 1.77 to 1.03.

It was observed that the modulus of deformation increased and modulus ratio (E_e/E_d) decreased with increase in applied stress level. The modulus of deformation in horizontal direction is 19.22 GPa (Table 6), which is higher than 14.06 GPa in vertical direction (Table 7). *The rock mass is moderately anisotropic.*

Table 7 - Summary of PJT results in vertical direction at powerhouse

Stress level, MPa	Modulus of deformation, E_d GPa			Modulus of elasticity, E_e GPa			Modulus ratio
	Minimum	Maximum	Average	Minimum	Maximum	Average	E_e/E_d
2	4.99	11.15	6.82	6.59	18.71	12.10	1.77
4	6.84	20.73	11.99	8.68	25.91	15.11	1.26
6	7.51	19.85	12.83	8.75	22.75	14.92	1.16
8	9.42	20.06	13.37	9.81	21.45	14.37	1.07
10	11.05	21.60	14.06	11.70	22.21	14.51	1.03

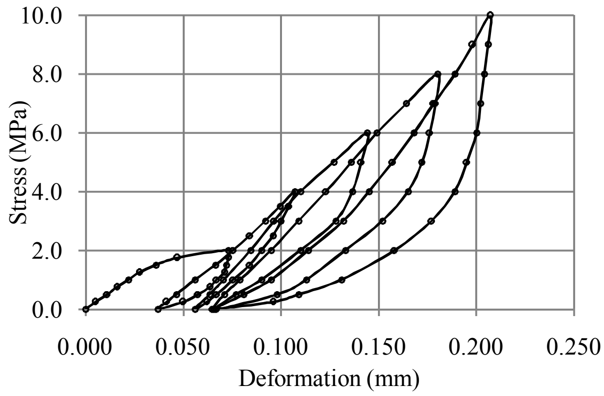

Fig. 13 - Stress versus deformation curve for PJT4V-U/W

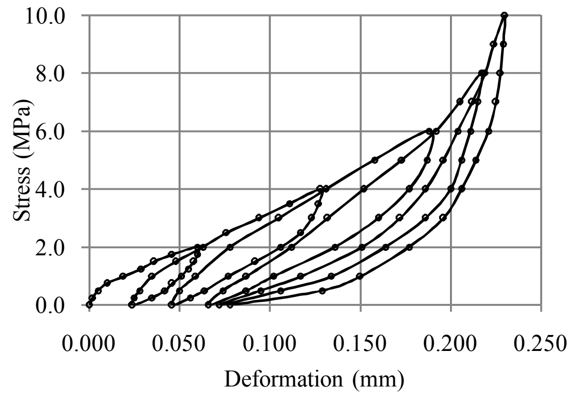

Fig. 14 - Stress versus deformation curve for PJT4V-D/W

6.2.2 PLT in vertical downward direction inside powerhouse drift

The magnitude of modulus of deformation based on surface measurement for plate loading test (PLT) while conducting PJT (PLT4V) inside powerhouse drift has been given in Table 8. The applied stress versus deformation curves for PLT4V have been shown in Fig. 15. This additional work was done by IGS is to compare the results of PJT with PLT at surface measurement.

The value of modulus of deformation is increasing from 0.73 GPa to 4.15 GPa with the variation of applied stress from 2 MPa to 10 MPa, respectively, in vertical downward direction for PLT4 (Table 8). The value of modulus of elasticity is increasing from 2.76 GPa to 4.20 GPa with the variation of applied stress from 2 MPa to 10 MPa, respectively, along with decrease of E_e/E_d ratio from 3.80 to 1.01 in vertical downward direction for PLT4 (Table 8).

Table 3 - Moduli of deformation (E_d) and elasticity (E_e) for PLT4V

Applied Stress, MPa	Total deformation, W_d (cm)	Elastic deformation, W_e (cm)	E_d GPa	E_e GPa	Modulus ratio E_e/E_d
2	0.1348	0.0355	0.73	2.76	3.80
4	0.1130	0.0490	1.73	4.00	2.31
6	0.1323	0.0817	2.22	3.60	1.62
8	0.1655	0.0985	2.37	3.98	1.68
10	0.1180	0.1168	4.15	4.20	1.01

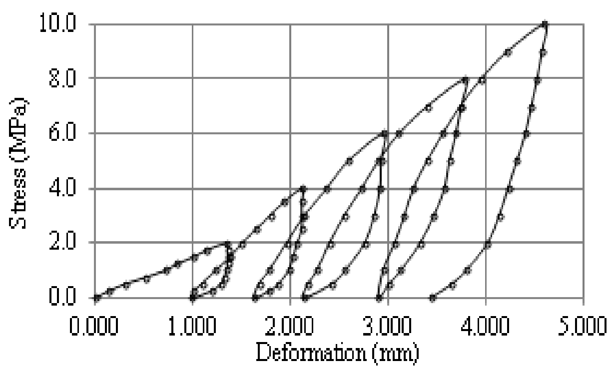

Fig. 15 - Stress versus deformation curve for PLT4

The average values based on 5 plate loading test (PLT) have been summarised in Table 9 along with variations of minimum and maximum. The average value of modulus of deformation (E_d) is

3.24 GPa with variations from 1.75 GPa to 4.62 GPa at applied stress level of 10 MPa. The modulus of elasticity (Ee) is 4.04 GPa with variations from 2.09 GPa to 6.51 GPa (Table 9).

Table 9 - Moduli of deformation and elasticity for PLT

Applied Stress, MPa	Modulus of deformation, Ed GPa			Modulus of elasticity, EeGPa			Modulus ratio E_e/E_d
	Minimum	Maximum	Average	Minimum	Maximum	Average	
2	0.33	1.81	0.81	0.72	2.93	2.06	2.56
4	0.70	2.32	1.46	1.02	5.19	3.14	2.16
6	1.01	3.46	2.04	1.33	4.15	2.97	1.46
8	1.31	3.58	2.42	1.81	5.42	3.65	1.51
10	1.75	4.62	3.24	2.09	6.51	4.04	1.24

The average values of modulus of deformation (E_d) increases from 0.81 GPa to 3.24 GPa (Table 9) with the increase in stress level from 2 MPa to 10 MPa, respectively. The ratio of E_e/E_d decreases from 2.56 to 1.24 (Table 9), in general, with the increase in stress level from 2 MPa to 10 MPa, respectively.

The overall average value of modulus of deformation in vertical downward direction from PJT is 14.06 GPa (Table 7) which is about 4.3 times higher than 3.24 GPa (Table 9) determined by PLT with surface measurement of displacement at applied stress level of 10 MPa. This ratio of PJT/PLT is higher than 2.5 as recommended by Palmstrom and Singh (2001). This is due to the blasting effect at the surface of the drift.

6.2.3 PJT in powerhouse drift (horizontal direction)

Five PJT were conducted in horizontal direction inside powerhouse drift with details given in Table 4 from PJT1H to PJT5H. The stress versus deformation curves are shown in Figs. 16 and 17 in upstream and downstream directions, respectively. The test results have been given in Table 10 for PJT4H.

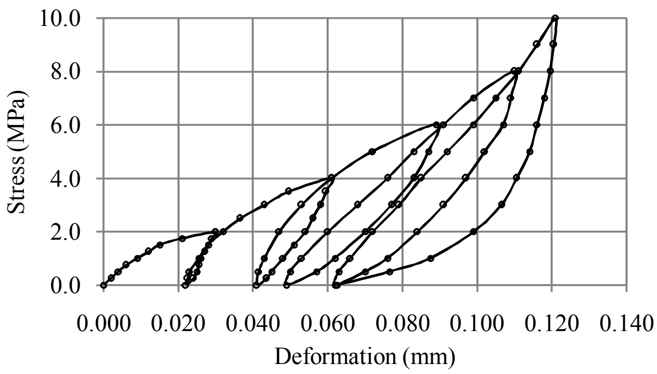

Fig. 16 - Stress versus deformation curve for PJT4H-U/S

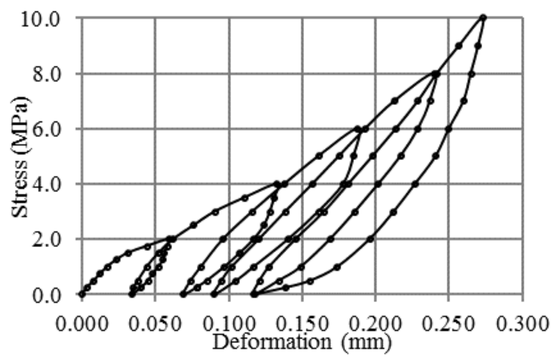

Fig. 17 - Stress versus deformation curve for PJT4H-D/S

The value of modulus of deformation is increasing from 5.73 GPa to 14.56 GPa with the variation of applied stress from 2 MPa to 10 MPa, respectively, along with decrease of Ee/Ed ratio from 3.75 to 1.00 in upstream direction for PJT4H (Table 10).

The value of modulus of deformation is increasing from 6.08 GPa to 11.50 GPa with the variation of applied stress from 2 MPa to 10 MPa, respectively, along with decrease of Ee/Ed ratio from 2.36 to 1.01 in downstream direction for PJT4H (Table 10).

Table 10 - Moduli of deformation (E_d) and elasticity (E_e) for PJT4H

Applied stress MPa	Depth (cm)	Total deformation, W_d (cm)	Elastic rebound W_e (cm)	E_d GPa	E_e GPa	Modulus Ratio E_e/E_d
Horizontal - upstream						
2	115 - 429	0.0030	0.0008	5.73	21.48	3.75
4	115 - 429	0.0039	0.0020	8.81	17.19	1.95
6	115 - 429	0.0048	0.0040	10.74	12.89	1.20
8	115 - 429	0.0061	0.0048	11.27	14.32	1.27
10	115 - 429	0.0059	0.0059	14.56	14.56	1.00
Horizontal - downstream						
2	60 - 429	0.0059	0.0025	6.08	14.35	2.36
4	60 - 429	0.0099	0.0064	7.25	11.21	1.55
6	60 - 429	0.0119	0.0098	9.04	10.98	1.21
8	60 - 429	0.0150	0.0123	9.56	11.66	1.22
10	60 - 429	0.0156	0.0155	11.50	11.57	1.01

Overall minimum, maximum and average magnitudes of modulus of deformation (E_d) and modulus of elasticity (E_e) in horizontal upward and downward directions at applied stresses varying from 2 MPa to 10 MPa have been summarised in Table 11 for results of 5 PJT (PJT1H to PJT5H) conducted in powerhouse drift.

The average value of modulus of deformation is 18.94 GPa with variations from 11.43 GPa to 27.69 GPa at applied stress of 10 MPa (Table 11). The average value of modulus of elasticity is 19.66 GPa with variation from 12.06 GPa to 29.27 GPa at applied stress of 10 MPa in upstream direction along with decrease of Ee/Ed ratio from 2.22 to 1.04.

The average value of modulus of deformation is 19.50 GPa with variation from 11.50 GPa to 27.83 GPa at applied stress of 10 MPa in downward direction (Table 11). The average value of modulus of elasticity is 20.30 GPa with variation from 11.57 GPa to 29.43 GPa at applied stress of 10 MPa in downstream direction along with decrease of Ee/Ed ratio from 1.82 to 1.04.

Table 11 - Average values of Moduli of deformation (E_d) and elasticity (E_e)
in horizontal direction (PJT1H to PJT5H)

Stress level, MPa	Modulus of deformation, E_dGPa			Modulus of elasticity, E=GPa			Modulus ratio E_e/E_d
	Minimum	Maximum	Average	Minimum	Maximum	Average	
Horizontal tests in upstream direction							
2	4.47	8.42	7.04	10.79	22.30	15.59	2.22
4	8.70	14.33	11.69	11.87	19.52	16.64	1.42
6	9.55	20.07	14.44	12.52	23.15	17.54	1.22
8	10.74	26.44	16.96	12.86	28.26	19.03	1.12
10	11.43	27.69	18.94	12.06	29.27	19.66	1.04
Horizontal tests in downstream direction							
2	3.04	9.33	5.69	5.20	14.35	10.35	1.82
4	7.25	16.11	11.18	11.21	21.11	14.88	1.33
6	9.04	22.96	14.65	10.98	24.82	17.36	1.18
8	9.56	26.05	16.92	11.66	27.83	18.98	1.12
10	11.50	27.83	19.50	11.57	29.43	20.30	1.04

Overall minimum, maximum and average magnitudes of modulus of deformation (E_d) and modulus of elasticity (E_e) in horizontal direction at applied stresses varying from 2 MPa to 10 MPa have been summarised in Table 12 for results of 5 PJT in powerhouse drift including the data of upstream and downstream horizontal directions.

Table 12 - Summary of PJT results in horizontal direction

Stress level, MPa	Modulus of deformation, E_d GPa			Modulus of elasticity, E_e GPa			Modulus ratio
	Minimum	Maximum	Average	Minimum	Maximum	Average	E_e/E_d
2	3.04	9.33	6.36	5.20	22.30	12.97	2.04
4	7.25	16.11	11.43	11.21	21.11	15.76	1.38
6	9.04	22.96	14.54	10.98	24.82	17.45	1.20
8	9.56	26.44	16.94	11.66	28.26	19.00	1.12
10	11.43	27.83	19.22	11.57	29.43	19.98	1.04

The average value of modulus of deformation is 19.22 GPa with variations from 11.43 GPa to 27.83 GPa at applied stress of 10 MPa (Table 12). The average value of modulus of elasticity is 19.98 GPa with variation from 11.57 GPa to 29.43 GPa at applied stress of 10 MPa in horizontal direction with modulus ratio (E_e/E_d) of 1.04.

The average value of modulus of deformation is increasing from 6.36 GPa to 19.22 GPa with the variation of applied stress from 2 MPa to 10 MPa, respectively, along with decrease of E_e/E_d ratio from 2.04 to 1.04.

In general the modulus of deformation is increasing and modulus ratio (E_e/E_d) is decreasing with the increase in applied stress level. The modulus of deformation in horizontal direction is 19.22 GPa (Table 12), which is higher than 14.06 GPa in vertical direction (Table 7). Hence, the rock mass is moderately anisotropic.

6.3 Comparison between Direct (PJT and PLT) and Indirect (Q and RMR) Methods

The modulus of deformation of rock mass 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.

Palmstrom and Singh (2002) and Singh (2009b, 2011, 2014, 2014b, and 2016), and Singh and Garg (2017b) proposed to multiply by a factor of 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 Table 10.8. Ramamurthy (2014) has also discussed comparison of test results of moduli obtained by various field tests. George et al. (1999) conducted in-situ PJT and GJT and discussed the ratio of PJT/GJT to be varying from 3.3 to 5.5.

Bieniawski (1978) has stated that the flat jack test is the least reliable due to difficulties with the interpretation of the results as well as the small volume of rock tested near to the rock surface. Benson et al. (1970) suggested that the modulus values must be obtained from PJT measurements. This is also the experience of Central Soil and Materials Research Station (CSMRS), New Delhi, India. They are less sensitive to variations in pressure distribution than displacements directly under the loaded area. The measurements of deformation in boreholes at various depths provide a check against any gross errors (blunders) of the measurements. They also allow a better assessment of the properties at depth as the displacements outside the loaded area are influenced to a much greater extent by the behaviour of rock mass.

As earlier pointed out by several researchers (Bieniawski, 1978; Heuze and Amadei, 1985; Heuze and Salem 1977), the value obtained by the various in situ deformation tests will not give the same deformation modulus.

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:

$$E_d\ (GPa) = 2RMR - 100 \tag{6}$$

The Eq. 6 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 also as given below:

$$E_d\ (GPa) = 10^{\frac{RMR-10}{40}} \tag{7}$$

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:

$$E_d\ (GPa) = 10 Q_c^{\frac{1}{3}} \tag{8}$$

Q_c in Eq. 7 is Barton's Q normalised with 100MPa UCS.

The modulus of deformation by direct methods using plate jacking test (PJT), plate loading test (PLT) and indirect methods based on RMR and Q in powerhouse drift are given in Table 13.

Average value of RMR at power house drift is 66 with variations from 55 to 84. The average value of Q is 21.39 with variations from 11.66 to 37.77. The modulus value from RMR is 32.80 based on Eq. 6 given by Bieniawski (1978) and 30.91 GPa based on Eq. 7 given by Serafim and Pereira (1983). The modulus values based on Q is 26.82 GPa based on Eq. 8 given by Barton (2002) and taking average UCS of 95 MPa.

The average value of modulus of deformation from 5 PJT in vertical direction is 14.06 GPa at stress level of 10 MPa. The value of 14.06 GPa is much lower than values evaluated from RMR and Q as given in Table 13.

Table 13 - Modulus of deformation by plate jacking tests (PJT) and indirect method

RMR mean value	Barton Qmean value	Q_c mean value (UCS = 95 MPa)	Modulus of deformation, GPa					
			Bieniawski (1978)	Serafim and Pereira (1983)	Barton 2002	LT	PLT	PJT
66	21.39	20.32	32.8	30.91	26.82	79.49	3.24	14.06

The modulus of deformation equal to 14.06 GPa determined by PJT is about 4.34 times higher than evaluated from PLT (3.24 GPa) in vertical direction. It is also higher than the PJT/PLT ratio of 2.5 predicted by Singh (2009b, 2011). The deformation modulus of intact rock (79.49 GPa) is about 5.65 times higher than modulus of rock mass (14.06 GPa).

Considering this modulus of deformation values indicated by PJT is more reliable than PLT (due to blasting effect). The modulus of deformation determined by PLT shall be multiplied by a minimum factor of 2.5 to arrive at a reasonable design value as discussed by Palmstrom and Singh (2001) and Singh (2009b, 2011). Hence, value determined by PJT is recommended.

Based on above discussions, it is recommended to utilise a value of 14.06 GPa for modulus of deformation of rock mass in vertical direction determined by PJT and 19.22 GPa in horizontal direction in powerhouse drift. The results are based on direct measurement by conducting PJT in the drift along the length of the underground powerhouse. Further, the in-situ tests were conducted by applying a very high stress level of 10 MPa in vertical and horizontal directions in the drift of underground powerhouse.

7. LABORATORY INVESTIGATIONS OF ROCK

7.1 Details of Tests and IS Codes

This paper covers the following investigations of the rock and recommendations rock properties and parameters, determined as per IS Codes and ISRM Suggested Methods (ISRM 1981), CBIP (2010):

- Identification and index properties
  - Density, water content, apparent porosity (IS: 13030-1991),
  - Slake durability index (IS: 10050 – 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),
- Indirect tensile strength - Brazilian, (IS: 10082 – 1981).

Summary of rock properties based on laboratory tests in powerhouse drift are given in Table 14 including water related properties, strength and deformability characteristic in uniaxial compression in saturated condition, shear strength parameters and tensile strength.

Table 14: Summary of rock properties based on laboratory tests at powerhouse drift

Rock parameter	Quartzite		
	Minimum	Maximum	Average
Index properties			
Density, γ (g/cc)	2.62	2.69	2.66
Water absorption (%)	0.52	0.72	0.60
Specific gravity	2.74	2.76	2.75
Porosity (%)	1.8	4.2	2.8
Strength and deformability in uniaxial compression in saturated condition			
Uniaxial compressive strength (MPa)	61.18	133.54	95.74
Modulus of elasticity, E (GPa)	57.07	115.56	79.49
Poisson's ratio, μ	0.15	0.25	0.20
Shear strength parameters			
Apparent cohesion, c (MPa)	11.69	17.14	14.05
Friction angle, φ (Degree)	64.00	66.97	65.71
Indirect tensile strength (MPa)	11.46	15.26	13.07

8. CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations for underground powerhouse drift of PakalDul Hydroelectric Project, Jammu & Kashmir on the basis of laboratory and in-situ rock mechanics testing at site for rock mass of quartzite with thin phyllitic intercalations are as follows:

- The recommended shear strength parameters of rock to rock interface cohesion (c) and friction angle (φ) are 0.42 MPa and 57.02° respectively, where as peak residual shear strength (c_r) and friction angle (φ_r) are 0.14 MPa and 50.84° respectively.
- The recommended shear strength parameters of intact rock based on triaxial tests in the laboratory, cohesion and friction angle are 14.05 MPa and 67.71° respectively.

- The cohesion of intact rock is about 33 times higher than rock mass and friction angle of intact rock is about 1.2 times higher than peak friction angle of rock mass. The difference between rock and rock mass is much higher in case of cohesion and it is insignificant in case of friction angle.
- In general, the modulus of deformation is increasing and modulus ratio (E_e/E_d) is decreasing with the increase in applied stress level.
- The rock mass is anisotropic as the modulus of deformation in horizontal direction (19.22 GPa) is higher than in vertical direction (14.06 GPa). The modulus values in crown are higher than invert in vertical plate jacking tests.
- The average value of modulus of deformation from 5 PJT in vertical direction is 14.06 GPa which is much lower than values evaluated from RMR (32.80/ 30.91 GPa) and Q (26.82 GPa). Hence, indirect method should be used cautiously to evaluate modulus of deformation.
- The modulus of deformation equal to 14.06 GPa determined by PJT is about 4.34 times higher than evaluated from PLT (3.24 GPa). Considering this, modulus of deformation of rock mass determined by PJT is more reliable than PLT due to blasting effect.
- It is recommended to utilise a value of 14.06 GPa for modulus of deformation of rock mass in vertical direction determined by PJT and 19.22 GPa in horizontal direction.
- It is recommended to utilise a large size PJT for determination of modulus of deformation of rock mass.
- The modulus of elasticity and shear strength parameters for intact rock are higher than modulus of deformation and shear strength parameters for rock mass as the intact rock sample collected for laboratory test is the strongest part of the rock mass.

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