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Deformability of Rock Mass by Plate Jacking Test at Dam Site of Nyera Amari Hydropower Project in Bhutan

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ABSTRACT

The modulus of deformation of rock mass was determined by conducting 12 plate jacking tests with measurement of deformations inside drillholes and at surface inside drifts at left and right banks of proposed 48 m height concrete gravity dam of Nyera Amari hydropower project, Bhutan. Six plate jacking tests were conducted 3 in horizontal and 3 in vertical directions inside each drifts at left and right banks of dam site, respectively. The modulus values have been compared with different methods based on in-situ testing by measuring deformation inside drillholes and at surface. The modulus of deformation from in-situ tests has also been compared with indirect methods based on RMR and Q system of rock mass classification.

Keywords: Modulus of deformation; Rock mass; Drift; Plate jacking test; Indirect methods

1. INTRODUCTION

In–situ rock mechanics tests were conducted for evaluating deformability of rock mass at Nyera Amari Hydropower Project, Bhutan. The proposed project envisages the construction of a 48m high concrete gravity dam at EL 1167m across river Nyera Amari, a 4.2m diameter and 13.7km long water conductor system/ head race tunnel (HRT) with intake at EL 1151m, a 112 MW underground powerhouse with dimensions of 68m x 20m x 38.7m at EL 823m and a tail race tunnel (TRT) with normal tail water level (TWL) at 814 m.

The geology of dam complex mainly comprises of whitish to greenish white-coloured fine grained moderately strong to strong quartzite/ sericitic quartzite. The RMR and Q-values in the drifts were observed to be 36-43 and 0.82-1.65 respectively as per 3-D geological log of the drift. Figures 1 and 2 show the jointing of rock mass at the entrance of drifts at left and right banks of the dam, respectively.

The present paper includes the interpretation of 12 plate-jacking tests conducted inside two drifts at proposed concrete gravity dam of Nyera Amari hydropower project, Bhutan. The modulus of deformation evaluated from field tests have been compared with indirect methods of RMR and Q-system from both the drifts at left and right banks of dam. The detail of testing and evaluation procedure has been discussed in the paper.

2. GEOLOGY OF PROJECT

Geology along dam axis at both banks comprises of panoptic exposures massive to laminated light gray to pale white coloured quartzite with thin bands of phyllite. The topography in the area exhibits moderately steep to very steep slope conditions with moderate to thick vegetation cover. Rock mass is massive to laminate in nature, moderately to highly jointed, pale white to grey coloured, fine-grained quartzite with presence of three joint sets. The uniaxial compressive strength (UCS) of the rock mass on the basis of Schmidt hammer rating and relative density was found to be in the range of 200–350 MPa. No signs of weathering have been observed in the rock mass along and near dam axis except minor surface staining at few places. No prominent geological structure has been observedat dam site except localized/minor folding.

Fig. 1 - Jointing at portal of left bank drift

Fig. 2 - Jointing at portal of right bank drift

The rock mass across both sides of stream is dissected by three prominent joint sets with similar pattern and average orientations (dip amount/dip direction) of bedding joint J1, J2 and J3 are 51°/310°, 58°/091° and 69°/195° respectively. The physical properties and rock mass characteristics of quartzite in the area have been described in Table 1.

Table 1 - Rock mass characteristics and properties at dam site

Quartzite	Joint Characteristics						
Joint Type	Orientation	Joint Surface	Weathering	Aperture (mm)	Persistence (m)	Spacing (cm)	Infillings
J1 (Bedding)	45–51°/ 295–315°	Slightly Rough/ planer	Un–weathered	<0.1–1	5–20	20–60	None
J2	58–64°/ 085–105°	Slightly Rough/ planer	Un–weathered	<0.1–1	2–15	15–40	None
J3	65–72°/ 185–212°	Slightly Rough/ planer	Un–weathered	<0.1–1	1–10	15–20	None

3. DEFORMABILITY OF ROCK MASS BY PLATE JACKING TEST (PJT)

The 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 drillholes at both sides of loading plates. The plate jacking set up in vertical and horizontal directions along with concrete pad are shown in Figs. 3 and 4, respectively. It 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.

Fig. 3 - PJT in vertical direction

Fig. 4 - PJT in horizontal direction

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 1, 2, 3, 4 and 5 MPa of loading and unloading the pressure every time to zero. The modulus values were calculated for the cycles of 1, 2, 3, 4 and 5 MPa. The first cycle was considered carefully 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 minute at the stage of initial loading, incremental loading and maximum loading, while the intermediate load increments were maintained for one minute. The tests were conducted according to the method suggested by ISRM (1979, 1981).

$$W_z = 2\frac{P(1-\nu^2)}{E}\left[(a^2+z^2)^{\frac{1}{2}} - z\right] - \frac{Pz(1+\nu)}{E}\left[z(a^2+z^2)^{\frac{1}{2}} - 1\right] \qquad (1)$$

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 = applied pressure (in MPa),

A = outer radius of flat jack (cm),

ν = Poisson's ratio, and

E = modulus of rock mass (MPa).

After substituting the appropriate values of a, z and ν , the Eq. 1 can be written as

$$W = \frac{P}{E}(K_z) \tag{2}$$

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

$$E_d = P\left[\frac{K_{z1} - K_{z2}}{W_{z1} - W_{z2}}\right] \tag{3}$$

where, K_{z1} and K_{z2} are constants at depth z1 and z2, respectively. Similarly, W_{z1} and W_{z2} are deformations measured between depths z1 and z2. The Eq. 3 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.

4. TEST LOCATIONS AT DAM SITE

The 12 plate jacking tests (6 each in vertical and horizontal directions) were conducted inside left and right bank drifts of dam site. These 12 tests were conducted by applying loading in vertical as well as in horizontal direction in both the drifts. Twelve PJT were conducted in vertical and horizontal directions inside drift at left and right banks with details given in Table 2. The test locations are given in Fig. 5.

Table 2 - Details of PJT in left and right bank drifts at dam site

S. No.	Test No.	Location	RD, m	RMR value	Q-value
Whitish to greenish white-coloured fine grained moderately strong to strong quartzite/ sericitic quartzite					
1	PJT1V	Cross cut U/S Side	1.73	36-43	0.82-1.65
2	PJT2V	Cross cut D/S Side	3.45	36-43	0.82-1.65
3	PJT3V	Main drift	23.55	36-43	0.82-1.65
4	PJT4H	Cross cut D/S Side	3.45	36-43	0.82-1.65
5	PJT5H	Main drift	23.55	36-43	0.82-1.65
6	PJT6H	Main drift	13.20	36-43	0.82-1.65
7	PJT7V	Cross cut U/S Side	2.80	36-43	0.83-1.24
8	PJT8V	Cross cut D/S Side	3.50	36-43	0.83-1.24
9	PJT9V	Main drift	22.50	36-43	1.24
10	PJT10H	Cross cut D/S Side	3.50	36-43	0.83-1.24
11	PJT11H	Main drift	22.50	36-43	1.24
12	PJT12H	Main drift	16.80	36-43	1.24

Note: *In test numbers, suffix V and H are vertical and horizontal respectively*

The average value of RMR at left and right bank drifts is 39.50 (say 40) with the variation from 36 to 43. The average value of RMR at PJT location is 40 with variation from 36 to 43. The average value of *Q* at left and right bank drifts is 1.235 with the variation from 0.82 to 1.65.

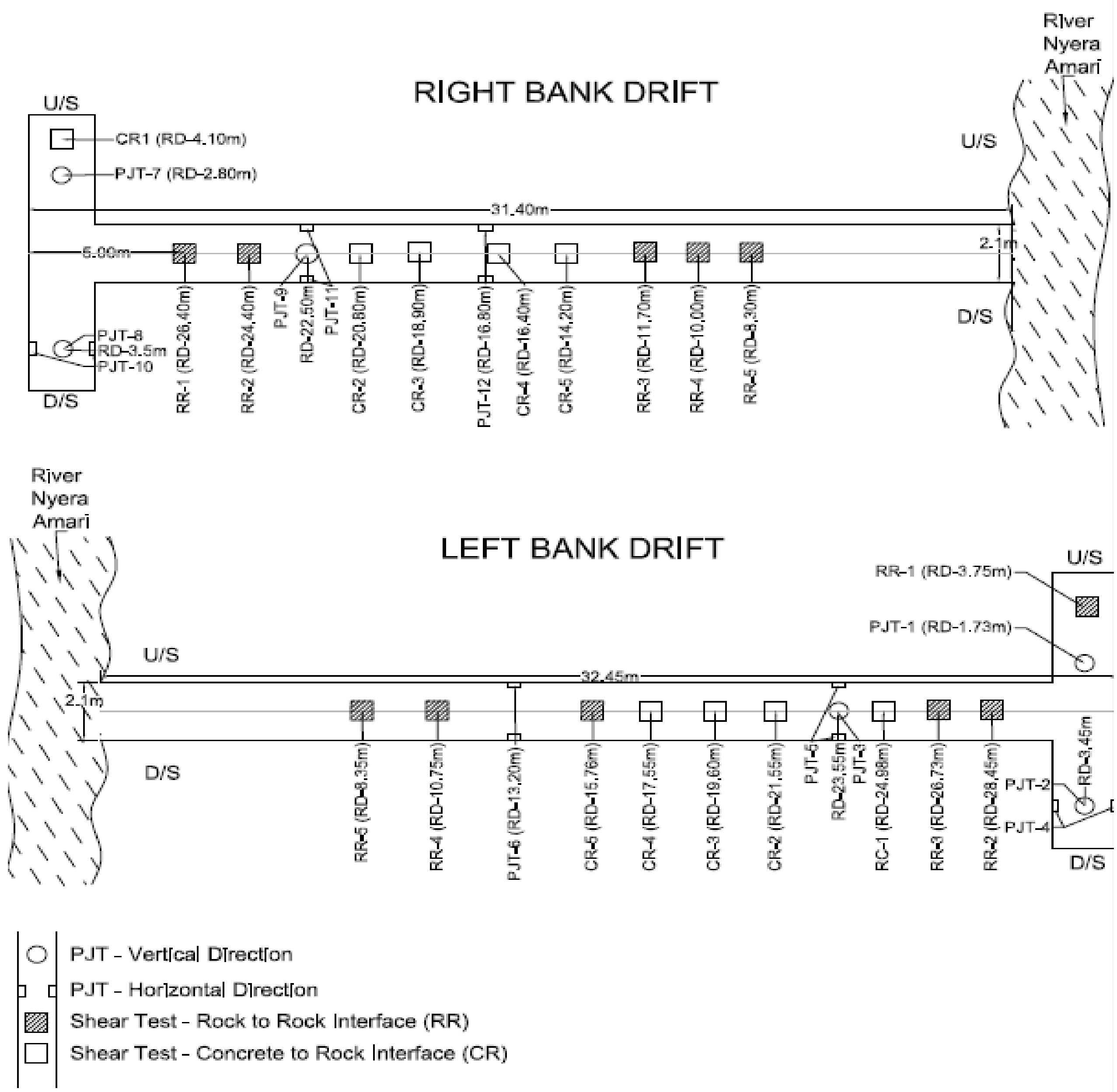

Fig. 5 - Locations of PJT in left and right bank drifts at dam site

5. RESULTS AND DISCUSSIONS

The 12 plate jacking tests (6 each in vertical and horizontal directions) were conducted inside left and right bank drifts of dam site with details given in Table 2 and Fig. 5. All the results of 12 PJT have been discussed for each test separately in Report (2017).

5.1 Modulus of Deformation (E_d)and Elasticity (E_e) for PJT5H in Left Bank Drift

For giving example in this paper and to show the trends, results of three PJTs have been presented in horizontal direction inside drift at left bank with details given in Table 2 from PJT4H to PJT6H. The typical stress versus deformation curves are shown in Fig.6 in upstream and downstream directions, respectively. The test results have been summarised in Table 3. The minimum, maximum and average magnitudes of modulus of deformation (E_d) and modulus of elasticity (E_e) at applied stresses varying from 1 MPa to 5 MPa are given in Table 4 from 3 PJTs conducted in left bank drift.

Table 3 - Moduli of deformation (E_d)and elasticity (E_e) for PJT5H in left bank drift

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
Horizontal upstream						
1	25 - 583	0.0080	0.0060	4.42	5.89	1.33
2	25 - 583	0.0155	0.0125	4.56	5.66	1.24
3	25 - 583	0.0201	0.0175	5.28	6.06	1.15
4	25 - 583	0.0236	0.0215	5.99	6.58	1.10
5	25 - 583	0.0253	0.0241	6.99	7.34	1.05
Horizontal downstream						
1	28 - 582	0.0085	0.0050	3.92	6.66	1.70
2	28 - 582	0.0169	0.0110	3.94	6.05	1.54
3	28 - 582	0.0250	0.0201	4.00	4.97	1.24
4	28 - 582	0.0312	0.0266	4.27	5.01	1.17
5	28 - 582	0.0355	0.0335	4.69	4.97	1.06

With increase in applied stress, the modulus of deformation (E_d) increases and moduli ratio (E_e / E_d) decreases. The modulus in upstream direction (6.99GPa) is higher than downstream direction (4.69GPa) as given in Table 3.

In upstream direction (Table 4), the average value of modulus of deformation is 6.64GPa with variation from 4.92GPa to 8.03GPa at applied stress of 5MPa. The average value of modulus of elasticity is 6.94GPa with variation from 5.04GPa to 8.43GPa at applied stress of 5 MPa in upstream direction. The modulus of deformation (E_d) increases from 4.28GPa to 6.64 GPa with the increase in applied stress from 1 MPa to 5 MPa and moduli ratio (E_e / E_d) decreases from 1.38 to 1.04 in upstream direction.

In downstream direction, the average value of modulus of deformation is 3.77GPa with variation from 3.22GPa to 4.69GPa at applied stress of 5MPa. The average value of modulus of elasticity is 3.99GPa with variation from 3.47 GPa to 4.97GPa at applied stress of 5MPa in downstream direction (Table 4). The modulus of deformation (E_d) increases from 3.23GPa to 3.77GPa with the increase in applied stress from 1MPa to 5MPa and moduli ratio (E_e / E_d) decreases from 1.50 to 1.06 in downstream direction.

Table 4 - Average values of Moduli of deformation (E_d)and elasticity (E_e) for left bank drift in horizontal direction (PJT4H to PJT6H)

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	
Horizontal tests in upstream direction							
1	3.76	4.66	4.28	4.66	7.21	5.92	1.38
2	3.92	4.59	4.36	4.95	5.84	5.48	1.26
3	4.70	5.28	5.03	5.00	7.16	6.07	1.21
4	4.76	6.45	5.74	5.07	7.36	6.34	1.10
5	4.92	8.03	6.64	5.04	8.43	6.94	1.04
Horizontal tests in downstream direction							
1	2.28	3.92	3.23	3.88	6.66	4.83	1.50
2	2.90	3.94	3.31	3.29	6.05	4.65	1.41
3	2.90	4.00	3.32	3.19	4.97	3.87	1.17
4	3.04	4.27	3.48	3.21	5.01	3.91	1.12
5	3.22	4.69	3.77	3.47	4.97	3.99	1.06

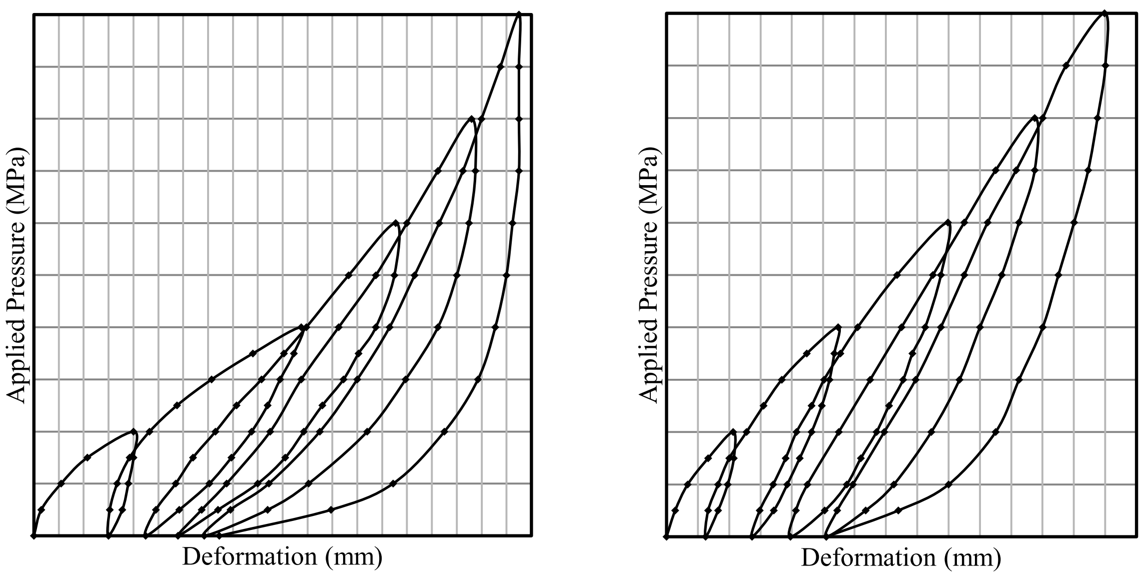

Fig. 6 - Stress versus deformation curve for PJT5H upstream and downstream

5.2 Summary of PJT Results in Horizontal Direction

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 1MPa to 5MPa have been summarised in Table 5 for 6 PJT results of dam drifts at left bank and right bank in upstream and downstream horizontal directions.

The average value of modulus of deformation is 7.45GPa with variation from 3.22GPa to 11.08 GPa at applied stress of 5 MPa. The average value of modulus of elasticity is 7.95 GPa with variation from 3.47GPa to 12.18GPa at applied stress of 5MPa in horizontal direction with E_e/E_d ratio of 1.07.

The average value of modulus of deformation is varying from 5.90GPa to 7.45GPa with the variation of applied stress from 1MPa to 5MPa respectively along with variation of E_e/E_d ratio from 1.40 to 1.07.

5.3 Summary of PJT Results in Vertical Direction

Based on 6 PJT results of dam drifts at left and right banks in vertical direction at applied stresses varying from 1 to 5 MPa, overall minimum, maximum and average magnitudes of modulus of deformation (E_d) and modulus of elasticity (E_e) have been summarised in Table 5.

The average value of modulus of deformation is 7.32GPa with variation from 2.02GPa to 12.01GPa at an applied stress of 5 MPa. The average value of modulus of elasticity is 7.73GPa with variation from 2.12GPa to 12.71GPa at an applied stress of 5MPa in vertical direction with E_e/E_d ratio of 1.06.

Table 5 - Summary of PJT results in horizontal and vertical directions at dam site

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
Modulus of deformation in horizontal direction							
1	2.28	10.03	5.90	3.88	13.37	8.24	1.40
2	2.90	10.28	6.26	3.29	13.37	7.95	1.27
3	2.90	10.55	6.69	3.19	13.37	7.98	1.19
4	3.04	10.96	7.09	3.21	12.14	7.83	1.11
5	3.22	11.08	7.45	3.47	12.18	7.95	1.07
Modulus of deformation in vertical direction							
1	1.78	11.33	7.08	1.97	17.29	9.99	1.41
2	1.15	11.04	6.58	1.66	15.72	9.06	1.38
3	1.63	11.13	6.81	1.80	14.82	8.34	1.23
4	1.79	11.33	7.04	1.92	12.48	7.73	1.10
5	2.02	12.01	7.32	2.12	12.71	7.73	1.06

The average value of modulus of deformation is increasing from 6.58GPa to 7.32GPa with the variation of applied stress from 1MPa to 5MPa, respectively, along with decrease in E_e/E_d ratio from 1.41 to 1.06.The average modulus of deformation represents the overall modulus of deformation of a heterogeneous rock mass.

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 (7.45GPa) is slightly higher than in vertical direction (7.32GPa) as seen from Table 5. The rock mass is moderately anisotropic.

6. MODULUS OF DEFORMATION BY INDIRECT 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 (2001) and Singh (2009, 2011) 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 (Ramamurthy, 2007).

On perusal of test results from PLT, it is seen that the average value of deformation modulus, E_d is 1.10GPa at 5MPa stress level. Accordingly, the deformation modulus for PJT, corresponding to the value of 1.10GPa obtained in PLT, works out to be 2.75GPa (1.10 x 2.5) as discussed by Singh (2009). The modulus of deformation of 7.32 GPa determined by PJT is about 6.7 times higher than evaluated from PLT (1.10 GPa) in vertical direction along with PJT. Similar results were discussed by Singh (2019) and Finley et al. (1999).

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:

$$E_d\ (GPa) = 2\,RMR - 100 \tag{4}$$

The Eq. 4 is valid for rock masses having a RMR value greater than 50. Serafim and Pereira (1983) extended the above equation to cover also the lower values of modulus where RMR is lesser than 50 as given below:

$$E_d\ (GPa) = 10^{\frac{RMR-10}{40}} \tag{5}$$

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:

$$E_d\ (GPa) = 10Q_c^{\frac{1}{3}} \tag{6}$$

The correlation to convert RMR from Q value or vice versa was determined from the following equation (Barton and Beiniawaski, 2008):

$$\text{RMR} = 15 \log \text{Q} + 50 \tag{7}$$

Hoek and Brown 1980) suggested the use of both the Q-system and the RMR-system in a joint assessment of modulus of deformation. This may be done even using approximate relationship between Q and RMR given by Bieniawski (1989). However, Barton and Bieniawski (2008) mentioned to utilize both methods independently to determine the modulus of deformation.

In the present study, both methods Q and RMR have been evaluated independently to determine the modulus of deformation according to Barton and Bieniawski (2008). Based on mean value of RMR as 40 from Table 2 and the Q value was 1.235. Q_c was 1.235 with UCS = 100 MPa.

The magnitudes of modulus of deformation by plate jacking tests (PJT), plate loading test (PLT) and indirect methods using Q and RMR at dam are given in Table 6.

Average value of RMR at dam is 40 as per 3D Geological log of the drift. The modulus value from RMR cannot be computed due to RMR<50 based on Eq. 4 given by Bieniawski (1978). The modulus values from RMR is 5.62 GPa based on Eq. 5 given by Serafim and Pereira (1983). The modulus values based on Q is 10.73 GPa based on Eq. 6 given by Barton (2002) and assuming UCS of 100 MPa.

The average value of modulus of deformation from 6 PJT in vertical direction increases from 2.02 GPa to 12.01 GPa at stress level of 5 MPa in the drifts at left and right banks with an overall average of 7.32 GPa. The value of 7.32 GPa is higher than 5.62 GPa evaluated from RMR and is lower than 10.73 GPa evaluation from Q as given in Table 6.

Table 6 - Comparison between direct and indirect methods for modulus of deformation

RMR mean value	Q_c mean value	Modulus of deformation, GPa				
		Serafim and Pereira (1983)	PLT	Singh (2009)	Barton 2002	PJT
40	1.235	5.62	1.10	3.30	10.73	7.32

The modulus of deformation equal to 7.32GPa determined by PJT is about 6.7 times higher than evaluated from PLT (1.10GPa) in vertical direction along with PJT. It is also higher than the ratio of 2 to 3 predicted by Singh (2009). The similar type of large difference between PJT and PLT has been presented by Singh (2019) and between PJT and GJT has been discussed by Finley et al. (1999). It is, therefore, recommended to conduct plate jacking test to evaluate correct and appropriate value for modulus of deformation of rock mass.

Based on above discussions, it is recommended to utilise a value of 7.32GPa for modulus of deformation of rock mass determined by PJT.

7. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are inferred for dam site of Nyera Amari Hydropower Project, Bhutan on the basis of large scale in-situ rock mechanics testing at site and a comparison with indirect methods:

The following conclusions and recommendations are inferred for dam site of Nyera Amari Hydropower Project, Bhutan on the basis of large scale in-situ rock mechanics testing at site and a comparison with indirect methods:

- 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 (7.45GPa) is slightly higher than in vertical direction (7.32GPa). The rock mass is moderately anisotropic.
- The modulus values in upward directions are higher than downward direction in vertical plate jacking tests. The modulus values in right bank drift are higher than left bank drift which is saturated throughout the length. The modulus values in fresh rock in T-section of the drifts are higher than in the main drift.
- The average value of modulus of deformation from 6 PJT in vertical direction increases from 2.02GPa to 12.01GPa at stress level of 5MPa in the drifts at left and right banks with an overall average of 7.32GPa.
- The modulus value of 7.32GPa is higher than 5.62GPa evaluated from RMR and is lower than 10.73GPa evaluation from Q_c.
- The modulus of deformation of 7.32GPa determined by PJT is about 6.7 times higher than evaluated from PLT (1.10GPa) at surface in vertical direction along with PJT.
- Based on above discussions, it is recommended to utilise a value of 7.32GPa for modulus of deformation of rock mass determined by PJT at dam site.
- It is therefore recommended to conduct plate-jacking test to evaluate correct and appropriate design value for modulus of deformation of rock mass. There are large variations in modulus values determined from both drift. Hence, minimum of 4 PJT must be conducted inside a drift to determine a suitable optimum value of modulus of deformation of rock mass.

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