Interpretation of deformability of rock mass 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 drill holes and at surface inside drifts at left and right banks of proposed 29 m height concrete gravity dam ofNyera 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 from different methods based on in-situ testing by measuring deformation inside drill holes 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.

1. Introduction:

In–situ rock mechanics tests were conducted for evaluating deformability of rock mass at Nyera Amari Hydropower Project, Bhutan. The proposed Nyera Amari Hydropower Project, Bhutan envisages the construction of a 48 m high concrete gravity dam at EL 1167 m across river Nyera Amari, a 4.2 m diameter and 13.7 km long water conductor system/ head race tunnel (HRT) with intake at EL 1151 m, a 112 MW underground powerhouse with dimensions of 68 m x 20 m x 38.7 m at EL 823 m 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 colour fine grained moderately strong to strong quartzite/ sericitic quartzite. The RMR values at left and right bank drifts are varying from 36 to 43. The Q values of rock mass are varying from 0.82 to 1.65 as per 3-D geological log of the drift. The section of dam along with drifts at both the banks is shown in Fig. 1. The photograph of dam site of Nyera Amari Stage I Hydropower Project is shown in Fig. 2 along with drift portals at left and right banks of dam. Figures 3 and 4 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.

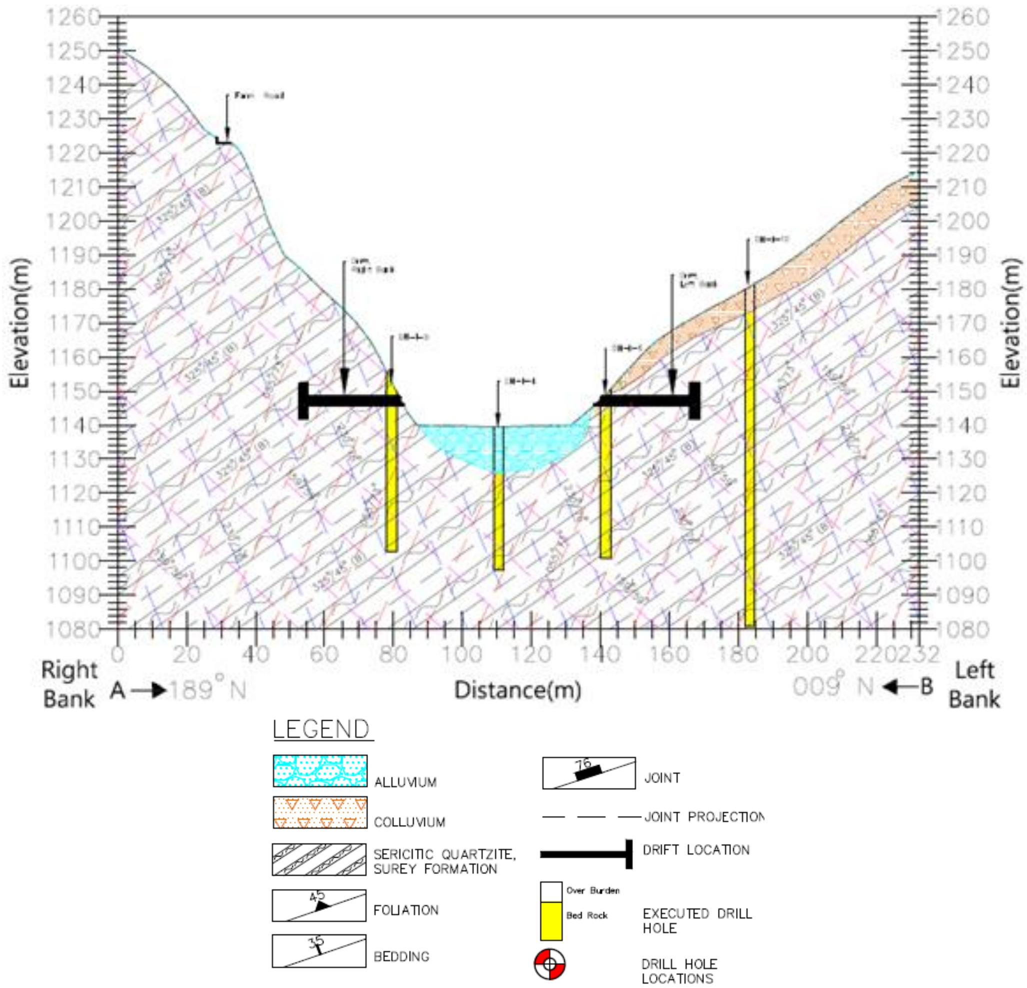

Figure 1 Dam section along with drifts (black colour) at left and right banks

Figure 2Photograph of locations of Nyera Amari dam and drifts

2. Geology of the Project:

Geology along dam axis at both banks comprising panoptic exposures massive to laminated light grey 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 description is massive to laminate in nature, moderately to highly jointed, pale white to gray 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 in the range between 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 observed at dam site except localized/minor folding.

Figure 3Jointing at portal of left bank drift

Figure 4 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 Massby 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 drill holes at both sides of loading plates.The plate jacking set up in horizontal and vertical directions along with concrete pad and installation of anchors and extensometers in drill holes are shown in Figs. 5 to 10. 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.

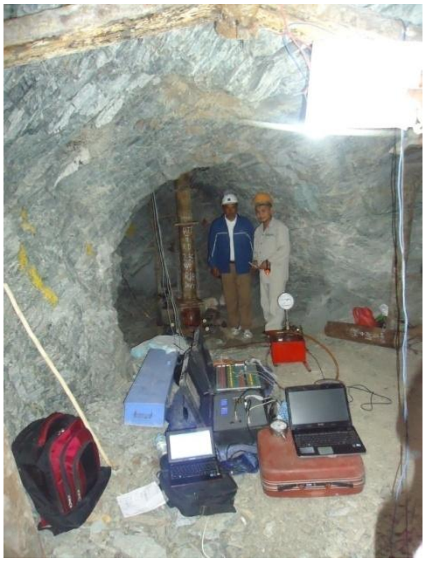

Figure 5 PJT in vertical direction

Figure 6 PJT in horizontal direction

Figure 7 Concrete pad for PJT

Figure 8 Installation of anchor and extensometer

Figure 9 Data acquisition system for PJT

Figure 10 Extensometer with anchors setting tools

The plate jacking tests were conducted by applying load in the direction normal to drill holes. The rock surface of the drift at the test locations were carefully prepared by removing all loose rock material by chiseling 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 6 m depth were drilled at the prepared surfaces.

The extensometers with the help of anchors were installed at suitable locations inside the drill holes. Care was taken so that the anchors were not placed on joints. The last anchor in the drill hole was kept about 30 - 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 retrained columns.

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 minutes 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 suggested method by ISRM (1979, 1981).

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

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

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:

$$W_z = \frac{P}{E}(K_z) \qquad (2)$$

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 utilized 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. 12 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. 11.

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

S. No.	Test No.	Direction of PJT	Location	RD, m	RMR	Q value	Rock type
1	PJT1V	Vertical	Cross cut U/S Side	1.73	41-43	0.82-1.65	Whitish to greenish white color fine grain moderately strong to strong Quartzite/Sericitic Quartzite
2	PJT2V	Vertical	Cross cut D/S Side	3.45	41-43	0.82-1.65	
3	PJT3V	Vertical	Main drift	23.55	41-43	0.82-1.65	
4	PJT4H	Horizontal	Cross cut D/S Side	3.45	41-43	0.82-1.65	
5	PJT5H	Horizontal	Main drift	23.55	41-43	0.82-1.65	
6	PJT6H	Horizontal	Main drift	13.20	41-43	0.82-1.65	
7	PJT7V	Vertical	Cross cut U/S Side	2.80	41 - 43	0.83-1.24	Whitish to greenish white color fine grain moderately strong to strong Quartzite/Sericitic Quartzite
8	PJT8V	Vertical	Cross cut D/S Side	3.50	41 - 43	0.83-1.24	
9	PJT9V	Vertical	Main drift	22.50	41 - 43	1.24	
10	PJT10H	Horizontal	Cross cut D/S Side	3.50	41 - 43	0.83-1.24	
11	PJT11H	Horizontal	Main drift	22.50	41 - 43	1.24	
12	PJT12H	Horizontal	Main drift	16.80	42 - 43	1.24	

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.

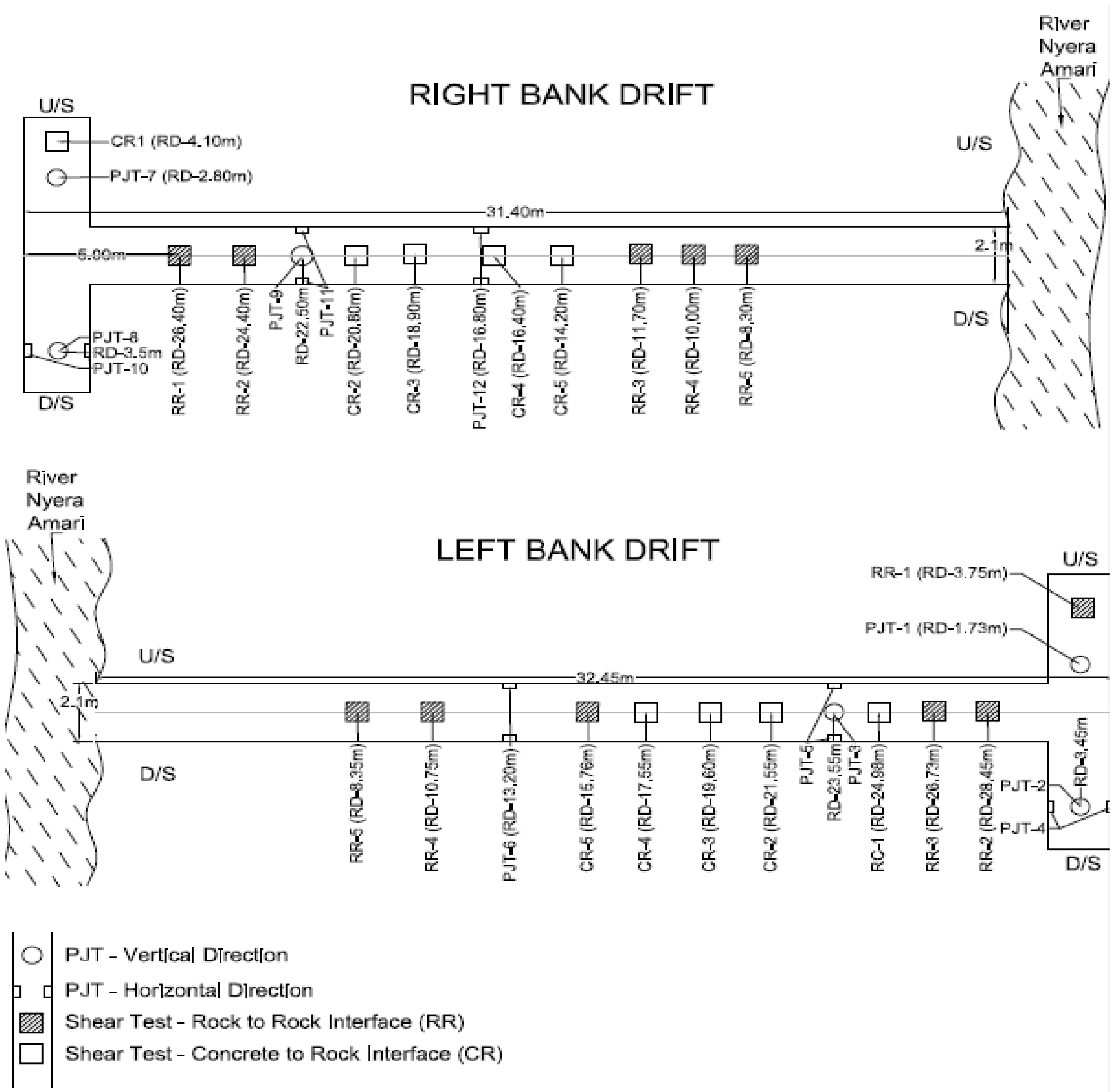

Figure11Locations of PJT in left and right bank drifts at dam site

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. 11. All the results of 12 PJT have been discussed for each test separately in Report (2017).

For giving example in this paper and to show the trends, three PJT 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. 12 in upstream and downstream direction, respectively. The test results for PJT5H have been summarized 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 PJT (PJT4H to PJT6H) conducted in left bank drift.

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June-December 2017

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

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

Table 4
Average values of Moduli of deformation ($E_{d)}$ and elasticity (E_e)
forleft bank driftin horizontal direction (PJT4H to PJT6H)

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	
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

In upstream direction (Table 4), the average value of modulus of deformation is 6.64 GPa with variation from 4.92 GPa to 8.03 GPa at applied stress of 5 MPa. The average value of modulus of elasticity is 6.94 GPa with variation from 5.04 GPa to 8.43 GPa at applied stress of 5 MPa in upstream direction. The modulus of deformation (E_d) increases from 4.28 GPa 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 3.77 GPa with variation from 3.22 GPa to 4.69 GPa at applied stress of 5 MPa. The average value of modulus of elasticity is 3.99 GPa with variation from 3.47 GPa to 4.97 GPa at applied stress of 5 MPa in downstream direction (Table 4). The modulus of deformation (E_d) increases from 3.23 GPa to 3.77 GPa with the increase in applied stress from 1 MPa to 5 MPa and moduli ratio (E_e/E_d) decreases from 1.50 to 1.06 in downstream direction.

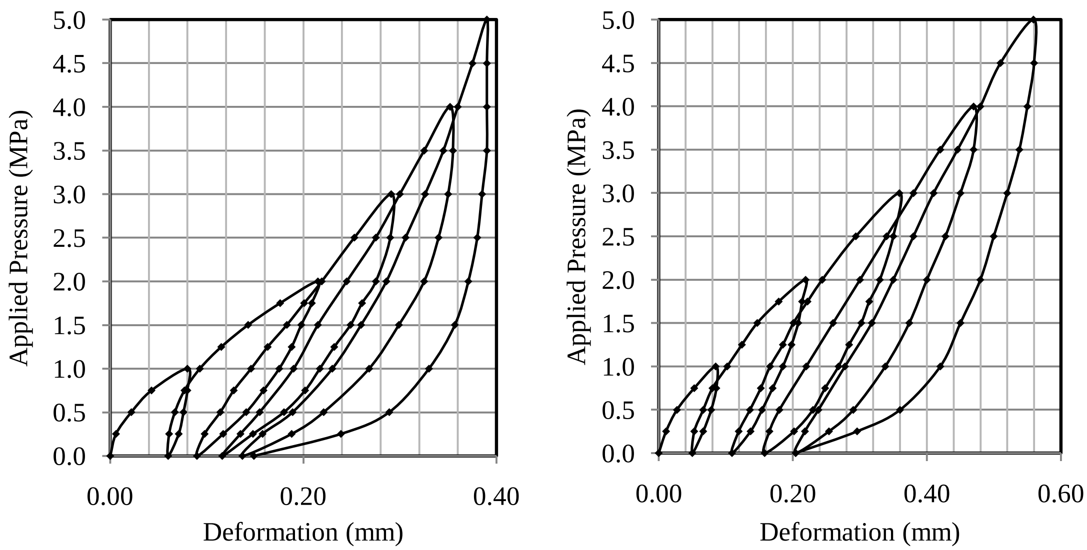

Figure 12 Stress versus deformation curve for PJT5H in upstream and downstream

5.1 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 1 MPa to 5 MPa have been summarized in Table 5 for6 PJT results of dam drifts at left (3 PJT) and right (3 PJT) banksin upstream and downstream horizontal directions.

The average value of modulus of deformation is 7.45 GPa with variation from 3.22 GPa to 11.08 GPa at applied stress of 5 MPa. The average value of modulus of elasticity is 7.95 GPa with variation from 3.47 GPa to 12.18 GPa at applied stress of 5 MPa in horizontal direction with E_e/E_d ratio of 1.07. There are large variations in modulus values at dam site due to variations in joint parameters. Hence, minimum of 4 tests must be conducted inside a drift to include the variations in rock mass properties.

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

5.2 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 summarized in Table 5.

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

The average value of modulus of deformation is increasing from 6.58 GPa to 7.32 GPa with the variation of applied stress from 2 MPa to 5 MPa, respectively, along with decrease in E_e/E_d ratio from 1.38 to 1.06. Sometimes, misleading results are obtained in first cycle due to the closing of joints during first loading.

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

Table 5
Summary of PJT results in horizontal direction 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

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.

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.

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 (2007, 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 in Table 10.8 –Comparison of test results as discussed by Ramamurthy (2007).

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 lower values of modulus where RMR is lesser than 50 also 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:

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

The RMR and Q valuescan be correlatedin the following equation:

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

Based on mean value of RMR as 40 from Table 2, the average Q value was 1.235 and Q_c was 1.235 with UCS = 100 MPa.

The modulus of deformation by direct methods of measurements using plate jacking tests (PJT) and plate loading tests (PLT), and indirect methods at dam is 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				
		Direct methods		Indirect methods		
		PJT	PLT	Singh (2009)	Q- Barton 2002	RMR-Serafim and Pereira (1983)
40	1.235	7.32	1.10	3.30	10.73	5.62

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 Z.T. (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) with 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.

On perusal of test results from PLT, it is seen that the values of deformation modulus, E_d varies from 4.05 to 4.63 GPa with an average value of 4.32 GPa at 10 MPa stress level. Accordingly, the deformation modulus for PJT, corresponding to the value of 4.32 GPa obtained in PLT, works out to be 10.80 GPa (4.32 x 2.5) as discussed by Singh (2009).

The modulus of deformation equal to 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. It is also higher than the ratio of 2 to 3 predicted by Singh (2009). 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 utilize a value of 7.32 GPa for modulus of deformation of rock mass determined by PJT.

7. Conclusions and Recommendations:

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

- 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 (7.45 GPa) is slightly higher than in vertical direction (7.32 GPa). 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 2.02 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 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 withmeasurement at surfacein PJT. It is, therefore, recommended to conduct plate jacking test to evaluate correct and appropriate design value for modulus of deformation of rock mass.
- The modulus values from RMR is 5.62 GPa and based on Q is 10.73 GPa. There are large variations between two established indirect methods. The value of 7.32 GPa from PJT is higher than 5.62 GPa evaluated from RMR and is lower than 10.73 GPa evaluated from Q.
- Based on above discussions, it is recommended to utilise a value of 7.32 GPa for modulus of deformation of rock mass determined by PJT at dam site.
- 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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