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Deformability of Rock Mass using Plate Jacking Tests and a Comparison with Different Methods

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ABSTRACT

This paper deals with evaluation of modulus of deformation by conducting large size plate jacking test with measurement of displacements inside drill-holes behind loading plates at both sides. An attempt has been made to compare the results of deformability by plate jacking test (PJT) with Goodman jack test (GJT), plate load test (PLT), flat jack test (FLT) on rock mass and laboratory test (LT) on intact rock samples. The results of modulus of deformation using direct measurement by in-situ testing have also been compared with indirect methods such as Q-system and rock mass rating (RMR) for the case study of Pancheshwar Multipurpose Project (PMP). A case study of Yucca Mountain Project (YMP) has also been referred and discussed to show the similarities of results.

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

1. INTRODUCTION

The geological and geotechnical investigations of the Pancheshwar Multipurpose Project (PMP) have been conducted in phases between 1963 and 2016 jointly by erstwhile His Majesty's Government of Nepal (HMG/N) and Government of India under the supervision of Joint Group of Experts (JGE) and Joint Project Office – Pancheshwar Investigation (JPO-PI) and Pancheshwar Development Authority (PDA) constituted in 1978, 1999 and 2015, respectively. Investigations of PMP have been conducted by Water and Power Consultancy Services Limited (WAPCOS) under the guidance of PDA during 2015-2016 to update the Detailed Project Report (DPR).

The WAPCOS in association with the Central Soil and Materials Research Station (CSMRS), New Delhi, took up the work of conducting in-situ and laboratory tests on rock including drilling of NX size (76 mm diameter) drillholes for PJT in the drifts on the left abutment in 1990 at the location of concrete gravity dam axis of Pancheshwar Project. The consulting services for the field investigation works in Nepal territory for PMP was provided by the Pancheshwar Consortium (PACO), California, USA, which was a joint venture of Morrison – Knudsen Engineers Inc. (MKE), Sanfrancisco, USA; Electric Power Development Company Ltd. (EPDC), Tokyo, Japan; Electroconsult SPA (ELC), Milano, Italy; and Monenco Consultants Ltd. (MONENCO), Montreal, Canada. An agreement to this effect was signed and completed successfully between WAPCOS and PACO.

Plate jacking tests and Goodman jack tests were performed at four identified locations in three exploratory drifts on the left bank of river at project site. Laboratory tests were conducted on rock cores at Central Soil and Materials research Station (CSMRS). The results of these investigations are presented in CSMRS report (1990).

This paper presents the comparison of deformability of rock mass by different methods using in-situ plate jacking test (PJT), Goodman jack test (GJT), plate load test (PLT), flat jack test (FLT) on rock mass and laboratory tests (LT) on intact rock. Further, the results have also been compared with indirect methods such as Q system and rock mass rating (RMR). A case study of Yucca Mountain Project (YMP), Nevada constructed by United States Department of Energy for the storage of high level waste has also been discussed to show the comparison of results by different methods for modulus of deformation.

2. THE PROJECT

The PMP is envisaged to construct 311 m high rock-fill main dam across Mahakali river gorge 2.5 km downstream of Sarju-Mahakali confluence near Pancheshwar and two underground powerhouses with installed capacity 6 x 400 MW each on India and Nepal sides with total generation of 4800 MW on both banks. In addition, Rupaligad Re-regulating dam project, 27 km further downstream near Tamli, would consist of 95 m high concrete gravity dam and two underground powerhouses with installed capacity 2 x 60 MW on each bank and with total generation of 240 MW.

The proposed Pancheshwar Multipurpose Project (PMP) is located on the Mahakali River 2.5 km downstream of the confluence of the Sarju River with the Mahakali river, which forms the border between India and Nepal in the far Western development region of Nepal. The site is about 520 km Northwest of Kathmandu, 70 km North of Mahender Nagar and 60 km West of Dadeldhura. Vehicular access by road is possible through India to the right bank of the river which is about 40 km from Lohaghat. From the Nepal side, the project area can only be reached by helicopter or on foot. The PMP IS proposed to harness the hydro-power potential of Mahakali (Sharda) river in Champawat (India) and Baitadi (Nepal). This project is a bi-National endeavour of India and Nepal.

The aim of the rock mechanics investigations was to determine all design parameters by conducting in-situ tests on rock mass at site in the drifts and drillholes and laboratory tests on rock samples selected from drillholes at the locations of dam and powerhouses. All the rock mechanics tests were performed by the CSMRS, New Delhi by using codes and practices of Indian and International standards (ISRM, 1981). The data generated from rock mechanics investigations by the Government of India and the Government of Nepal has been interpreted and presented in this paper.

3. LABORATORY TESTING ON ROCK CORES

Laboratory tests were conducted at the CSMRS laboratory to determine the properties of rock core samples obtained from boreholes drilled for the plate jacking tests. Table 1 summarizes the laboratory investigations. Suggested methods of International Society for Rock Mechanics (ISRM, 1981) were followed in conducting the laboratory tests.

The results of rock mechanics laboratory investigations for drill-holes at plate jacking test (PJT) locations in drifts A-3, A-4 and A-5 at concrete dam site of are given in Table 1 for different types of rock. The modulus of elasticity of 6.0 GPa for augen gneiss rock in drift A-5 (PJT-4) is lower than 17.8 GPa for augen gneiss rock in drift A-4 (PJT-3). Similar results of modulus of deformation of rock mass were observed for plate jacking tests.

4. DEFORMABILITY MEASUREMENT BY PJT AND GJT

Four plate jacking tests (PJT) were conducted under the contract with PACO including two tests in adit (drift) A4 and one test each in adits A3 and A5 on the left bank of river at the location of concrete gravity dam of PMP as shown in Fig. 1. Goodman jack tests (GJT) were conducted perpendicular to boreholes drilled into rock behind plate loading areas for PJT. Table 2 summarizes the in-situ rock mechanics investigations.

Table 1 - Results of rock mechanics laboratory investigations for drillholes in drifts A-3, A-4 and A-5 at concrete dam site

S. No.	Rock parameters		No. of tests	Location and rock type			
				PJT-1 Granite	PJT-2 Mica schist	PJT-3 Augen gneiss	PJT-4 Augen gneiss
1.	Bulk density (dry)	kg/m^3	33	2620	2680	2580	2620
2.	Bulk density (saturated)	kg/m^3	33	2630	2690	2600	2630
3.	Specific gravity	-	33	2.73	2.77	2.73	2.81
4.	Porosity	%	33	0.82	1.37	1.26	1.70
5.	Water absorption	%	33	0.34	0.57	0.49	0.71
6.	Compression wave velocity (dry)	km/s	22	4.03	4.40	3.83	2.86
7.	Shear wave velocity (dry)	km/s	22	2.58	2.80	2.49	1.98
8.	Dynamic modulus of elasticity	GPa	24	36.3	47.2	34.80	15.60
9.	Dynamic Poisson's ratio	-	24	0.24	0.16	0.18	0.10
10.	Uniaxial compressive strength (sat.)	MPa	22	41.20	33.90	45.50	-
11.	Modulus of elasticity (saturated)	GPa	12	30.90	17.60	17.80	6.00
12.	Poisson's ratio (saturated)	-	12	0.13	0.13	0.17	0.15
13.	Slake durability index	%	14	99.04	97.80	94.19	97.80
14.	Apparent cohesion, c	MPa	12	-	3.5	2.5	-
15.	Friction angle φ	Degree	12	-	50	40	-

Table 2 - Summary of rock mechanics tests

Adit no.	Location	Elevation (m)	Chainage (m)	Rock type	Test	
					PJT	GJT
A3	Concrete Dam	419.90	25.60	Granite	PJT-1	GJT-1.1 GJT-1.2 GJT-1.3 GJT-1.4
A4	Concrete Dam	453.10	19.00	Mica Schist	PJT-2	GJT-2.1 GJT-2.2 GJT-2.3 GJT-2.4
A4	Concrete Dam	453.10	33.00	Augen Gneiss	PJT-3	GJT-3.1 GJT-3.2 GJT-3.3 GJT-3.4
A5	Concrete Dam	423.10	66.50	Augen Gneiss	PJT-4	GJT-4.1 GJT-4.2 GJT-4.3 GJT-4.4

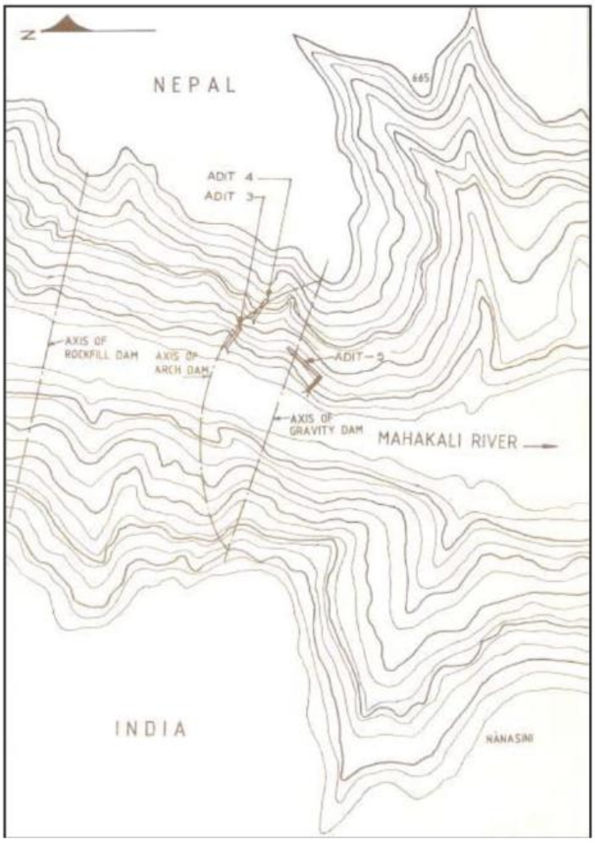

Fig. 1 - Location plan of proposed concrete gravity, arch and rock-fill dams along with adits (drifts) A-3, A-4 and A-5 at left bank of Pancheshwar multipurpose project

The results of four plate jacking tests and 16 Goodman jack tests conducted inside 3 drifts (Adit-3, Adit-4 and Adit-5 as shown in Fig. 1) are given in Tables 3 and 4, respectively. The creep factor of rock mass by PJT is also given in Table 3.

Table 3 - Results of plate jacking test (PJT)

Test Location	Rock type	Adit No.	RD m	Up/ down	Applied stress MPa	Modulus of deformation (E_d), GPa	Average modulus of deformation (E_d), GPa	Creep factor %
PJT1	Granite	A3	25.6	Up	5	19.2	16.1	37.08
				Down		13.0		56.52
PJT2	Mica Schist	A4	19.0	Up	5	08.5	12.6	8.65
				Down		16.9		9.09
PJT3	Augen Gneiss	A4	33.0	Up	5	09.7	15.8	14.58
				Down		21.8		18.42
PJT4	Augen Gneiss	A5	66.5	Up	3	06.5	5.5	14.57
				Down		04.6		6.43

The results of PJT-4 location corresponds to a maximum pressure of 3 MPa (Table 3) due to failure of concrete pad whereas the results at other locations correspond to the applied pressure of 5 MPa.

Modulus of deformation by PJT-4 is the lowest among 4 tests due to low applied pressure of 3 MPa and failure of concrete pad during testing. The lowest value of modulus of elasticity was observed for PJT-4 in laboratory testing and Goodman jack tests also. Hence, the modulus of deformation by in-situ PJT varied from 12.6 GPa to 16.1 GPa (Table 3) at applied stress of 5 MPa for this project site. However, modulus of deformation by in-situ GJT varied from 1.7 GPa to 2.9 GPa at applied stress of 5 MPa (Table 4).

Table 4 - Results of Goodman jack test (GJT)

Test no.	Adit no.	RD m	Up/ down hole	Parallel/ perpendicular to adit axis	Applied stress MPa	Modulus of deformation Ed, GPa	Average modulus of deformation Ed, GPa	Rock type
GJT1.1	A3	25.6	Up	Parallel	5	1.5	2.2	Granite
GJT1.2				Perpendicular		2.3		
GJT1.3		25.6	Down	Parallel	5	2.7		
GJT1.4				Perpendicular		2.4		
GJT2.1	A4	19.0	Up	Parallel	5	2.1	2.1	Mica schist
GJT2.2				Perpendicular		1.5		
GJT2.3		19.0	Down	Parallel	5	2.4		
GJT2.4				Perpendicular		2.3		
GJT3.1	A4	33.0	Up	Parallel	5	1.9	2.9	Augen gneiss
GJT3.2				Perpendicular		3.0		
GJT3.3		33.0	Down	Parallel	5	3.4		
GJT3.4				Perpendicular		3.4		
GJT4.1	A5	66.5	Up	Parallel	5	2.5	1.7	Augen gneiss
GJT4.2				Perpendicular		0.8		
GJT4.3		66.5	Down	Parallel	5	1.9		
GJT4.4				Perpendicular		1.5		

The results of 4 plate jacking tests and 16 Goodman jack tests conducted inside 3 drifts (A3, A4 and A5) have been summarised in Table 5 along with creep factor of rock mass by PJT. The magnitudes of modulus of deformation by Goodman jack tests are very low due to small loading surface as compared to plate jacking tests and discussed by Palmstrom and Singh (2001).

Table 5 - Modulus of deformation of rock mass by PJT and GJT

S. No.	Test	Modulus of deformation, GPa Method and rock type			
		PJT-1 Granite	PJT-2 Mica schist	PJT-3 Augen gneiss	PJT-4 Augen gneiss
1.	Plate jacking tests (PJT)	16.1	12.6	15.8	5.5
2.	Goodman jack tests (GJT)	2.2	2.1	2.9	1.7
4.	Ratio PJT/GJT	7.3	6.0	5.4	3.2

In general, modulus of deformation by GJT is 2 to 4 times lower than PJT as discussed by Palmstrom and Singh (2001), Singh (2009, 2011, 2014, 2015, and 2016) and Singh and Garg (2017). However, the modulus by GJT is 3.2 to 7.3 times lower than PJT in this case study as given in Table 4. Similar results have been presented by George et al. (1999) where the modulus of deformation by GJT is 3.3 to 5.9 times lower than PJT.

In view of above, it is, therefore, recommended to utilize the modulus of deformation determined by large size PJT in the analysis and design. The concrete dam axis is about 290 m downstream of proposed rock-fill dam axis. Hence, the data obtained is within the foundation for rockfill dam in the vicinity of underground powerhouse and same data can be utilised for rockfill dam and powerhouse also.

5. DEFORMABILITY MEASUREMENT BY FJT

The CSMRS conducted in-situ rock mechanics tests by using flat jack method on the right bank of PMP. Flat jack tests (FJT) were conducted to determine modulus of deformation of rock mass and in-situ stresses in horizontal and vertical directions in the drift D-2 at the location of underground powerhouse. The 115m long drift D-2 is located at EL 425m. The rock mass in the drift and test area was granite quartzite. The results of 30 cm diameter flat jack tests are given in Tables 6 for deformability of rock mass and in-situ stresses, respectively.

Eight numbers of flat jack tests were conducted to determine deformability characteristics of rock mass and in-situ stresses in the underground powerhouse. The modulus of deformation of rock mass varied from 0.21 GPa to 1.90 GPa with the variation of applied stress from 3.4 MPa to 9.0 MPa (Table 6). The applied stress should have been constant to take the average value of modulus of deformation. The tests for deformability should have been conducted in 5 loading/unloading cycles. The magnitudes of modulus of deformation were very low as the tests were conducted at disturbed surface of weathered rock mass in the drift.

Table 6 - Deformability data and results by FJT

S. no.	Type of slot	Cycle no.	Applied stress MPa	Gross defor-mation cm	Elastic defor-mation cm	Modulus of defor-mation Ed GPa	Modulus of elastic-city Ee GPa	moduls Ratio Ee/Ed
1.	Horizontal	III	9.0	0.125	0.057	1.40	3.09	2.2
2.	Vertical	II	7.2	0.074	0.042	1.90	3.33	1.8
3.	Horizontal	III	7.5	0.194	0.108	0.75	1.35	1.8
4.	Vertical	II	7.7	0.088	0.042	1.70	3.56	2.1
5.	Horizontal	II	4.5	0.110	0.048	0.79	1.82	2.3
6.	Vertical	II	3.4	0.310	0.150	0.21	0.44	2.1
7.	Horizontal	III	7.0	0.238	0.145	0.57	0.94	1.7
8.	Vertical	II	4.0	0.291	0.142	0.27	0.55	2.0

6. DEFORMABILITY OF ROCK MASS BY PLT

Plate loading tests (PLT) were conducted by CSMRS in the drift D-2. The test results from all the 6 tests in vertical direction and 5 PLT in horizontal direction have been summarized in Table 7.

Rock mass was classified using classification methods of Q and RMR. Major rock type encountered in the drift was well developed gneiss/ augen gneiss, in the strike direction of N70°W-S70°E. The dip amount of the foliation is 80°. Six plate loading tests were conducted in vertical direction and 5 in horizontal direction. Stress application in vertical plate loading tests was almost parallel to the foliation whereas the same was perpendicular to foliation plane in case of horizontal plate loading tests. Deformations were measured at the bottom plate in case of vertical plate loading tests whereas it was recorded at both the loading surfaces namely upstream side and downstream side walls in horizontal tests.

The modulus of deformation of rock mass varied from 1.277 GPa to 2.703 GPa with an average value of 1.807 at applied stress 5 MPa (Table 7) in vertical direction. The modulus of deformation of rock mass varied from 1.355 GPa to 1.980 GPa with an average value of 1.684 at applied stress 5 MPa (Table 7) in horizontal direction.

Table 7 - Moduli of deformation and elasticity in drift D-2 by PLT

Pressure MPa	Modulus of deformation (E_d), GPa			Modulus of elasticity (E_e), GPa			Average modulus ratio, E_e/E_d
	Minimum	Maximum	Average	Minimum	Maximum	Average	
Vertical direction, parallel to foliation, Rock type: gneiss/ augen gneiss							
2	0.576	1.367	0.835	0.894	3.412	1.624	1.94
3	0.820	1.872	1.192	0.567	2.672	1.671	1.40
4	0.990	2.203	1.477	0.766	2.904	1.914	1.30
5	1.180	2.607	1.696	1.002	3.257	2.095	1.24
6	1.277	2.703	1.807	1.167	3.168	2.137	1.18
Horizontal direction, perpendicular to foliation, Rock type: gneiss/ augen gneiss							
2.0	0.477	0.923	0.705	1.232	2.570	1.714	2.43
3.0	0.712	1.422	1.069	1.409	2.556	1.942	1.82
4.0	1.060	1.616	1.349	1.832	2.440	2.209	1.64
5.0	1.135	1.818	1.550	1.857	2.430	2.298	1.48
6.0	1.355	1.980	1.684	1.960	2.483	2.282	1.36

7. COMPARISON OF ROCK MECHANICS INVESTIGATIONS

7.1 Case Study of Pancheshwar Multipurpose Project (PMP)

Summary of rock mechanics tests is given in Table 8. The minimum, maximum and average values of modulus of deformation by in-situ plate jacking and Goodman jack tests and static modulus of elasticity, dynamic modulus and compressive strength in dry and saturated state by laboratory tests have been given to have an idea of different rock mass and rock properties.

Table 8 - Summary of rock mechanics tests

S. No.	Rock parameter	Mini-mum	Maxi-mum	Ave-rage	Test
1	PJT-Modulus of deformation (GPa)	12.6	16.1	14.8	Plate jacking tests (3 tests)
2	GJT-Modulus of deformation (GPa)	1.7	2.9	2.3	Goodman jack tests
3	PLT-Modulus of deformation (GPa)	1.3	2.7	1.8	Plate load test
4	FJT- Modulus of deformation (GPa)	-	-	1.9	Flat jack test
5	Static modulus of elasticity (GPa)	14.8	46.0	25.3	Laboratory tests
6	Q-system (Q=6, Qc=2.42 for UCS=40.3)	-	-	13.4	Indirect method
7	Rock mass rating (RMR=49)	-	-	12.6	Indirect method
8.	Dynamic modulus (GPa)	19.0	49.1	36.5	Laboratory tests
9.	Unconfined compressive strength, Dry (MPa)	33.2	107.7	65.0	Uniaxial compression tests
10.	Unconfined compressive strength, Sat. (MPa)	18.4	71.1	40.3	Uniaxial compression tests

The results of rock mechanics laboratory investigations for drill holes at plate jacking test (PJT) locations in drifts A-3, A-4 and A-5 at concrete dam site of Pancheshwar Multipurpose Project, India/Nepal are given in Table 5 for different types of rock. The modulus of elasticity of 6.0 GPa for augen gneiss rock in drift A-5 (PJT-4) was lower than 17.8 GPa for augen gneiss rock in drift A-4 (PJT-3). Similar results of modulus of deformation of rock mass were observed for plate jacking tests.

The average values by different methods are given in Table 9. The results included from plate jacking test (PJT), plate load test (PLT), Goodman jack test (GJT), flat jack test (FJT), Q-system, Rock mass rating (RMR) and laboratory test (LT).

Table 9 - Comparison of PJT with other methods

S. No.	Methods	Modulus of deformation GPa	Ratio PJT/Other method	Remarks
1	Plate jacking test (PJT)	14.8	1.0	PJT
2	Plate load test (PLT)	1.8	8.2	PJT/PLT
3	Goodman jack test (GJT)	2.3	6.4	PJT/GJT
4	Flat jack test (FJT)	1.9	7.8	PJT/FJT
5	Q (Singh and Bhasin, 1996)	17.5	0.8	PJT/Q
6	Q-system (Barton, 1983)	35.0	2.4	PJT/Q
7	Q-system (Barton, 2002)	13.4	1.1	PJT/Q
8	Rock mass rating (RMR)	12.6	1.2	PJT/RMR
9	Laboratory test (LT)	25.3	0.6	LT/PJT=1.7

The modulus of deformation determined by PJT is 8.2, 6.4 to 7.8 times higher than PLT, GJT and FJT, respectively. Similar results have been given by US report by George et al. (1999) wherein PJT is 3.3 to 5.9 times higher than GJT. The PJT is 1.1 and 1.6 times higher than Q-system and RMR, respectively. However, the modulus of intact rock tested in the laboratory is 1.7 times higher than PJT. Farmer and Kemeny (1992) found that the deformation modulus on intact rock samples is in the order of 5 to 20 times higher than in situ values.

The results of PJT versus GJT/PLT/FJT were much higher than that discussed by Singh (2009, 2011, 2014, 2015 and 2016) and Palmstrom and Singh (2002). The modulus of deformation by PJT (14.8 GPa) is close to the equations derived for Q (13.4 GPa) by Barton (2002) and RMR (12.6 GPa) by Serafim and Periera (1983). Hence, it is necessary to conduct PJT to arrive at a suitable magnitude of the modulus of deformation of rock mass. Benson et al. (1970) presented modulus testing of rock at the Churchill falls underground powerhouse and concluded to conduct large size plate jacking test for determination of modulus of rock mass.

The modulus of deformation in vertical direction (1.8 GPa) was slightly higher than in horizontal direction (1.6 GPa) as determined by PLT. The maximum value of the modulus of deformation in vertical direction (1.9 GPa) was slightly higher than in horizontal direction (1.4 GPa) as determined by FJT. The modulus of deformation in horizontal direction parallel to the drift (2.3 GPa) was slightly higher than in horizontal direction perpendicular to the drift (2.2 GPa) as determined by GJT. Hence, the rock mass was moderately anisotropic due to different results in vertical and horizontal directions.

7.2 Case Study of Yucca Mountain Project (YMP)

George et al. (1999) discussed to determine potential changes in the rock mass modulus resulting from thermally induced closure of the fractures for the Yucca Mountain Project (YMP), Nevada constructed by United States Department of Energy for the storage of high level waste. A plate loading niche was constructed near the drift such that one side of the niche would be near ambient temperature and the other side was heated to≥ 10 0° C. The plate loading test with measurement of displacement by borehole extensometer (PJT) and Goodman jack tests were conducted in both sides of the drift at temperatures of ambient and 100° C. The test parameters for ambient side and heated sides are given in Table 10.

The results of plate loading and Goodman tests suggest that modulus on heating side was about 2 to 2.5 times higher than ambient side despite the fact that the Q value of 4.03 on heating side was lower than 7.7 on ambient side. The modulus from plate jacking test was about 3.3 to 5.9 times higher than Goodman jack test. The difference was high on heating side. The modulus value using indirect methods by Bieniawski (1978), Serafim and Periera (1983), Barton (1983) was much higher than plate loading and Goodman jack tests at ambient temperature and lower side at heating side. However, modulus (11.1 GPa) by Singh and Bhasin (1996) was very close to PJT (12 GPa) at ambient side. The modulus of elasticity (36.8 GPa) of intact rock was about 3 times higher than 12 GPa of rock mass by large size PJT.

Table 10 - Comparison of different methods (after George et al., 1999)

S. No.	Parameters	Ambient side	Heated side
1	Average rock mass quality, Q	7.70	4.03
2	Average rock mass rating, RMR	66.8	64.7
3	Ed (GPa) based on Bieniawski, 1978	33.6	29.4
4	Ed (GPa) based on Serafim and Periera, 1983	26.3	23.3
5	Ed (GPa) based on Barton, 1983	22.2	15.1
6	Ed (GPa) based on Barton, 2002	19.7	15.9
7	Ed (GPa) based on Singh and Bhasin, 1996	11.1	7.6
8	Ed (GPa) by plate jacking test	12.0	30.0
9	Ed (GPa) by Goodman jack test	3.3	5.9
10	Ed Ratio PJT/GJT	3.6	5.1
11	Ed (GPa) based on intact rock	36.8	-

7.3 Present Case Study

The data presented by Palmstrom and Singh (2001) and further testing and compilation by Singh (2009, 2011, 2014, 2015, and 2016), Singh and Garg (2017) and George et al. (1999) has been updated in Table 11 based on in-situ testing and indirect methods. Singh and Rajvanshi (1996) discussed the effect of blasting on modulus of deformation due to excavation of test drift.

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.

Based on experience at CSMRS and testing at other projects, this may be explained by:

- Plate jacking test (PJT) with borehole extensometer measurement: Here, the deformations are measured inside the drillhole away from the damaged zone and towards the undisturbed rock masses.
- Plate loading test (PLT) with surface measurement: The lower deformation modulus measured at the rock surface in these tests can be explained by the fact that these measurements are made in the damaged zone from blasting.
- Flat jack test (FJT): The lower modulus of deformation measured near the rock surface in these tests can be explained by the fact that these measurements are made in the damaged zone from blasting.

- Goodman jack test (GJT) performed inside the drill hole: Also the Goodman jack tests have been found to give lower values of the moduli because, in hard rock, the loading platens deform and the loading is being applied on a very small area as compared to large size PJT.

From the measurements performed by CSMRS the ratio between these types of deformation measurements are given in Table 11, where also some experience published by other authors is shown.

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 CSMRS. 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.

Table 11- Ratio between plate jacking test (PJT) and other tests for modulus of deformation, compiled from Palmstrom and Singh (2001), Bieniawski (1989), Singh (2009, 2011, 2014, 2015, 2016), George et al. (1999), Goodman et al. (1968), and Singh and Garg (2017)

S.No.	Name of project/author	Ratio						
		PJT/ PLT	PJT/ FJT	PJT/ GJT	PJT/ Q	PJT/ RMR1	PJT/ RMR2	LT/ PJT
1	Lakhwar	1.9	1.75	2.05	-	-	-	14.6
2	Jamrani	-	-	2.6	-	-	-	-
3	Tala	4.0	-	2.4	-	-	-	-
4	Pancheshwar	8.2	7.8	6.4	-	-	-	-
5	Bursar	2.4	-	3.5	0.99	0.94	0.95	4.3
6	Yucci Mountain[1]	-	-	3.3	0.61	0.36	0.46	3.1
7	Yucci Mountain[2]	-	-	5.1	1.89	1.02	1.29	-
8	Bieniawski, 1989	2-3	2-3	2-3	-	-	-	-
9	CSMRS, 1990	2-8	2-8	2-6	-	-	-	-
10	Palmstrom and Singh (2001)	2.5	2.5	2.5	-	-	-	-
11	Singh (2016)	2.5	2.5	2.5	-	-	-	2-18

Notations: Yucci Mountain[1]- Ambient temperature side; Yucci Mountain2 - Heated side by George et al. (1999); PJT= Plate jacking test; PLT= Plate loading test; GJT= Goodman jack test; FJT= Flat jack test; LT = Laboratory test; RMR1 = Bieniawski, 1978; RMR2 = Serafim and Periera, 1983

8. CONCLUSIONS

The following conclusions are drawn based on rock mechanics investigations at site and laboratory:

- The modulus of deformation of undisturbed rock mass was 14.8 GPa with a variation from 12.6 GPa to 16.1 GPa by large size in-situ plate jacking tests.
- The modulus of deformation of rock mass by plate jacking test was 3 to 6 times higher than Goodman jack test. This was also comparable to US report wherein modulus by PJT was about 3.3 to 5.9 times higher than GJT.

- In general, the modulus of intact rock is 2 to 15 times higher than rock mass. This difference is dependent on jointing in rock mass. The difference is large for highly jointed rock mass. The intact rock sample tested in the laboratory is the strongest part of the rock mass without any joints or minor fissures.
- The rock mass is anisotropic as the modulus of deformation in vertical direction is different than horizontal direction.
- The modulus of deformation of rock mass may be utilised for the analysis rockfill dam and underground powerhouse also as the dam foundation is within this zone and location of powerhouse is also very near to the drifts used for conducting large size in-situ plate jacking tests.
- The magnitudes of modulus of deformation based on indirect methods of Q and RMR were slightly on lower side as compared to plate jacking test (Table 9). Hence, indirect methods may be utilised on a particular project after comparison and confirmation of results of in-situ plate jacking test.
- Based on this study and earlier work published by many researchers, it is recommended to conduct large size plate jacking tests for the determination of modulus of deformation of rock mass. The test results by other methods such as plate loading test, flat jack test, Goodman jack test and dilatometer test shall be multiplied by a minimum factor of 2.5 to arrive at a reasonable value of modulus of deformation.

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