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A review of in-situ testing of rock mechanical parameters in hydropower projects of Nepal

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ABSTRACT

In-situ testing of rock mechanical parameters is essential for rock mass characterisation. The rock mass characterisation is important in design and construction of underground works forming major component of Hydropower projects. The major civil structures of most of the hydropower projects planned in Nepal have to be founded on complex rock formations on fragile geological environments. In-situ rock mechanics tests carried out at various hydropower projects sites are described and the findings are summarised.

INTRODUCTION

Construction of any underground powerhouse, tunnel, or dam requires a thorough understanding of rock mass behaviour of the site. Especially, it is important to know the stress history of the rock mass and its response to imposed and induced loads. The in-situ test results are utilised in deciding the optimum orientation of openings, to design the appropriate support system and also for predicting the deformation in the openings (Hoek 1981).

In-situ stresses are highly heterogeneous at shallow depths. They are affected by the topography of deep and steep river valleys as well as by the discontinuities within the rock mass (Rame Gowda et al 1988). The rock mass contains cracks, fractures, joints, and bedding planes. These planes may be continuous or discontinuous. Consequently, the deformation characteristics of 'jointed' rock mass become considerably different from that of intact one (Sharma 1988, Verma 1985). Hence, a reliable evaluation of the in-situ stress behaviour is essential for the optimum design and construction of safe and economical structures.

For the purpose of obtaining mechanical parameters of the rock mass, various in-situ test methods are used in Nepal. In this paper, an attempt is made to gather various in-situ test results of the rock mass from various parts of the country. The paper gives an idea of the mechanical properties of specific rock types of the Nepal Himalaya and summarises the results of in-situ rock mass testing.

IN-SITU TEST METHODS

A comprehensive in-situ testing method has to be followed to understand the rock mass characteristics and to evaluate the properties of various categories of rock mass (CBIP 1996). In particular, it is important to determine the following:

- Rock mass deformability characteristics, particularly the results of loading in various directions with short and long-time spans;
- State of stress in the rock mass before and after construction;
- Propagation characteristics of elastic waves in the rock mass;
- Rock mass permeability; and
- Rock mass movement.

The in-situ rock mechanics testing was started in Nepal in 1978 during the feasibility study of the Kankai Multipurpose Project (Salzgitter Consult GmbH 1978). After that, the tests were conducted in a number of projects implemented by foreign engineering consulting firms. A list of in-situ rock mechanics tests conducted in Nepal is given in Table 1. Most of the tests were carried

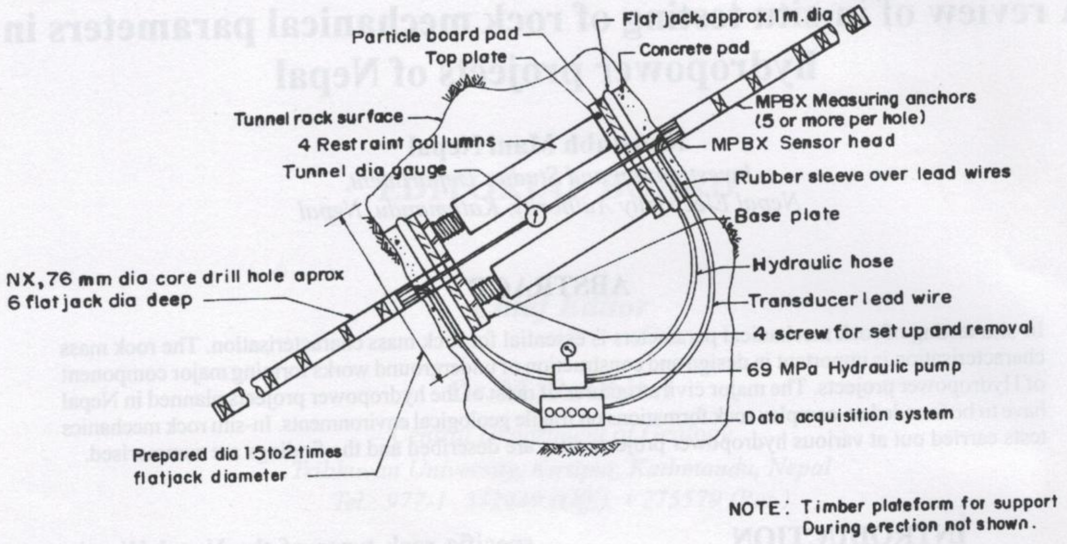

Fig. 1: Borehole plate load test apparatus.

Table 1: In-situ rock mechanics tests carried out in Nepal

Project Name	Name of Test	No. of Tests
Pancheshwar Multipurpose Project (WAPCOS and CSMRS 1990)	Plate load Dilatometer (Goodman jack)	4 16
Karnali Multipurpose Project (Himalayan Power Consult 1989)	Plate Load Dilatometer Overcoring Hydraulic jacking	3 31 2 4
Kaligandaki 'A' Hydropower Project (Shah Consult International 1994)	Dilatometer Hydrofracture Temperature Profile Convergence Measurement	17 22 two adits 2
Middle Marsyandi Hydropower Project (Lahmeyer International 1997)	Dilatometer Small Flat Jack	5 6
Kankai Multipurpose Project (Salzgitter Consult GmbH 1978)	Dilatometer	8
Sapt Gandaki Hydropower Project (JICA 1983)	Plate Load Shear Test	3 15
Arun III Hydroelectric Project (Joint Venture Arun III Consulting Services 1990)	Dilatometer Small flat jack Overcoring	45 20 15

out in accordance with the method suggested by the International Society of Rock Mechanics (ISRM 1975).

DEFORMABILITY CHARACTERISTICS OF ROCK MASS

In the hydropower projects of Nepal, the deformability characteristics of the rock mass were determined by applying various methods (Table 1) such as plate jacking (surface loading), flat jack, Goodman jack, and dilatometer (loading inside the boreholes). A short summary of the various methods is presented below.

Plate Load Test (Surface Loading)

The plate load test (Fig. 1) is generally performed in test adits to measure the deformation characteristics of the rock mass. Two areas, each approximately 1 m in diameter, are loaded simultaneously by jacks positioned across the adit or tunnel. The rock deformation is measured inside the boreholes behind each of the loaded area. The data available from incremental and cyclic loading are used for calculation of elastic deformation unloading modulii. The creep phenomena of rock mass are also determined from the displacement-time graph (ISRM 1975).

The plate load tests were carried out in the Karnali and Pancheshwor Multipurpose Projects. Similarly, in the Sapta Gandaki Hydroelectric Development Project, the deformation of rock mass was measured by the method described by Japanese National Committee on Large Dams (1971) *the Design Criteria for Dams* prepared by. The typical deformability test results and graphs are presented respectively in Table 2.

Goodman Jack Test

The Goodman Jack test is carried out in two directions: parallel and perpendicular to the axis of the test adit. It was used for measuring the deformability of rock mass in the Pancheshwor Multipurpose Project. It is an advanced method, where a maximum pressure of 350 kg/cm² can be applied, and the borehole deformation can be measured to the accuracy of 0.01 mm.

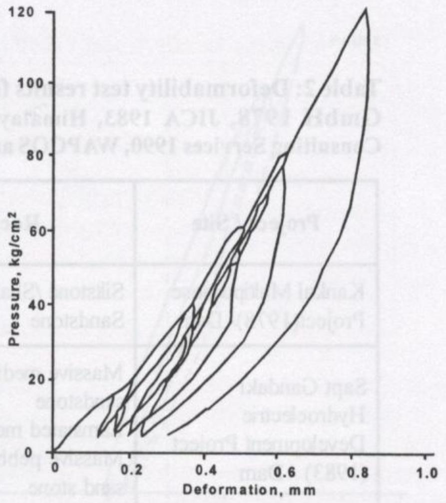

Fig. 2: Typical pressure versus diametral deformation curves for the Goodman Jack test

In the Pancheshwor Multipurpose Project, the tests were conducted up to a maximum load of 120 kg/cm² with five load cycles of peak loads of 20, 40, 60, 80, and 120 kg/cm² (WAPCOS and CSMRS, 1990). The typical test results and pressure-deformation curves are shown respectively in Table 2 and Fig. 2.

Dilatometer Test

The test uses dilatometer (expanding probe) to exert pressures up to 100 kg/cm² in borehole walls. Water is used as the pressure medium. The resulting deformation of the borehole is measured by a displacement transducer housed inside the probe. It measures the resulting deformation of the hole. The modulus of deformation of the rock mass at the dilatometer location is calculated from the relationship between the pressure and deformation. The typical test results and pressure - deformation curves are given respectively in Table 2 and Fig. 3.

In-situ Stress Measurements

In-situ stress measurements are necessary for designing underground and surface excavation works. The measured values are used for optimisation of the cavity, orientation of the cavern, and for the prediction of its deformation pattern (Mehrotra et al. 1988, Ramamurthy 1996). Generally, there is a variation in the results obtained by various in-situ

Table 2: Deformability test results from various projects (Sources: Salzgitter Consult GmbH 1978, JICA 1983, Himalayan Power Consult 1989, Joint Venture Arun III Consulting Services 1990, WAPCOS and CSMRS 1990, and Lahmeyer International 1997)

Project / Site	Rock Type	Deformation Modulus (MPa)	Type of Test
Kankai Multipurpose Project(1978)/ Dam	Siltstone /Shale	513	Dilatometer
	Sandstone	454	
Sapt Gandaki Hydroelectric Development Project (1983) / Dam	Massive medium sandstone	730	Plate load
	Laminated medium sandstone	10881	
	Massive pebbly sand stone	069	
Karnali Multipurpose Project (1989) / Dam	Sandstone	5590	Plate Load
	Mudstone	4609	
	Siltstone	11376	
	Sand stone	3595	Dilatometer
	Mudstone	1316	
	Siltstone	5250	
	Sedimentary Breccia	3308	
Arun - III Hydroelectric Project (1990) / Dam	Augen gneiss	4200	Dillatometer
	Mica / Quartzitic schist	1955	
		10500	Small Flat Jack
Head race tunnel	Mica schist	2450	Dilatometer
Surge Tank	Granitic gneiss	1910	
Power house	Augen gneiss	11000	
	Augen gneiss	10500	Small Flat jack
Pancheshwor Multipurpose Project (1990) /Dam	Granite	1568	Plate Jack
		1764	Goodman jack
	Gneiss	5490	Plate Jack
		1421	Goodman Jack
	Augen Gneiss	6470	Plate Jack
		2157	Goodman Jack
	Quartzite Band	931	Goodman Jack
Middle Marshyangdi Hydroelectric Project (1997) / Power House	Quartzitic Phyllite	2600	Dilatometer
		750	

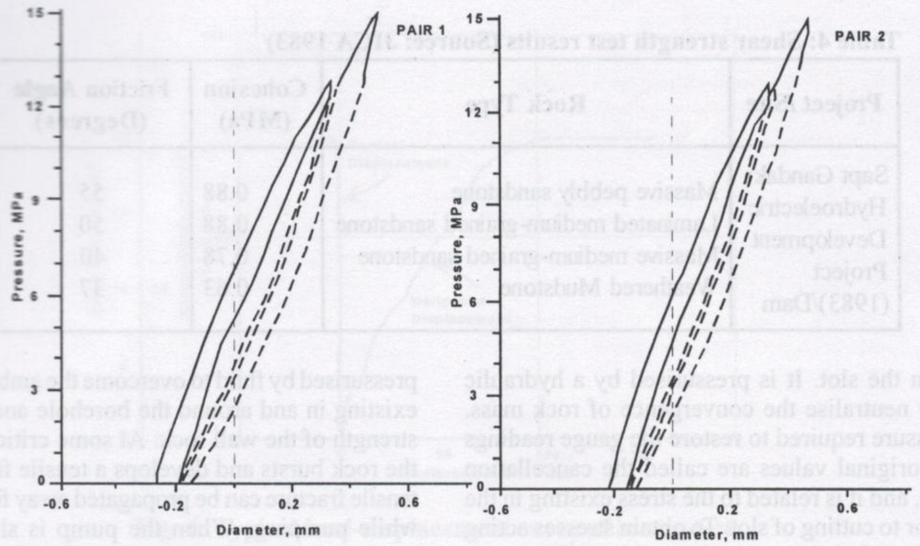

Fig. 3: Typical pressure versus diametral deformation curves for the dilatometer test

stress measurement methods. Therefore, several test methods are recommended by ISRM for the determination of the in-situ stresses of a particular site. In Nepal, the following methods are used in hydropower projects.

The principle of **Flat Jack Test** is based on balancing in-situ stress by externally applied pressure. For this purpose, a slot is cut into the rock surface. The slot relieves the stresses that originally existed across it. Because of the stress relief, sides of the slot converge. The convergence of slot is measured between previously established two references. For this purpose, a Demec gauge is installed on either side of the proposed slot.

The flat jack consists of two metal plates welded together along their edges. The jack is filled with liquid and attached with the pressure regulation and monitoring devices. Then, the flat jack is embedded

Table 3: In-situ stress measurement results from various projects (Sources: Himalayan Power Consult 1989, Shah Consult International (P) Ltd. 1994, Lahmeyer International 1997, and Joint Venture Arun III Consulting Services 1990)

Project /Site	σ_1	σ_2	σ_3	K	Type of Test
Karnali Multipurpose Projcet (1989) / Dam	6.55	3.27	2.89	2.6	Over-coring
Kali Gandaki "A" Hydroelectric Projcet (1994)/Powerhouse	4.5	3.0	3.0	1.5	Hydro-fracturing
Middle Marshyangdi Hydroelectric Project (1997) / Powerhouse	5.5	3.75	2.75	2.0	Small Flat Jack
Arun III Hydroelectric Project (1990)/Headrace Tunnel and Powerhouse site	8.710.3	2.73.2	2.93.1	3.13.3	Over-coring and Small Flat Jack

Table 4: Shear strength test results (Source: JICA 1983)

Project /Site	Rock Type	Cohesion (MPa)	Friction Angle (Degrees)
Sapt Gandaki Hydroelectric Development Project (1983)/Dam	Massive pebbly sandstone	0.88	55
	Laminated medium-grained sandstone	0.88	50
	Massive medium-grained sandstone	0.78	40
	Weathered Mudstone	0.63	37

tightly in the slot. It is pressurised by a hydraulic pump to neutralise the convergence of rock mass. The pressure required to restore the gauge readings to their original values are called the cancellation pressure, and it is related to the stress existing in the rock prior to cutting of slot. To obtain stresses acting perpendicular to the slot, the cancellation pressure is corrected for the influences of slot size, reference point gauges, and the stress acting parallel to the major axis of the slot. The results of flat jack tests in the Middle Marshyangdi and Arun III projects are presented in Table 2.

Over-coring Technique is suitable for rock masses not having closely spaced joints or bedding, and which do not react chemically with water. It is one of the stress relief techniques, which is commonly used. This method determines the magnitude and directions of three principal stresses acting at a point. Hence, it is an absolute stress measuring method. This method was used in the Karnali Multipurpose Project (Himalayan Power Consult 1989). The Unites States Bureau of Mines (USBM) deformation gauge was used to measure the deformation. An initial AX-size hole was drilled and the strain-measuring instrument incorporated with USBM deformation gauges were installed. The entire length of borehole was over-cored by using 150 mm diameter diamond bit to produce a stress relieved concentric rock annuals. The instruments measured the strains resulting form the over-coring (Table 3). The initial stress conditions were then simulated from the strain measurements in a separate bi-axial modulus chamber to determine the original stress field.

Hydrofracturing technique is extensively used for the measurement of both magnitude and direction of in-situ stresses (Rummel 1995). It is very simple in operation where a sealed off borehole section is pressurised by fluid to overcome the ambient stresses existing in and around the borehole and the tensile strength of the wall rock. At some critical pressure, the rock bursts and develops a tensile fracture. The tensile fracture can be propagated away from the hole while pumping. When the pump is shut off with hydraulic circuit kept closed a "shut-in" pressure is recorded. In-situ stress magnitudes are determined from critical and shut-in pressures. An impression packer is used to get the inclination and orientation of the fracture.

The tests can be carried out down to the depth of 300 m, used in elastic and visco-elastic rocks, and done as a routine test for stress gradient (Gowd 1996). Nowadays the hydrofracturing stress measurement technique is an integral part of geo-technical site investigations for hydropower projects, tunnelling, underground space utilisations, as well as for geo-science research projects such as plate dynamics. The test results and typical pressure - flow curves are presented respectively in Table 3.

In-situ Shear Tests

The information of shear strength of rock mass is necessary because it gives an idea of about the overall stability. The test measures peak and residual shear strengths as a function of normal stress to the sheared plane. The output is employed in limit equilibrium analysis of slope stability problems or for stability analysis of dam foundation.

Both the inclination of test block and system of applied loads are usually selected so that the sheared plane coincides with the discontinuity plane or with the interface between rock / soil or concrete and rock.

In applying the test results, the pore water pressure condition and possibility of progressive

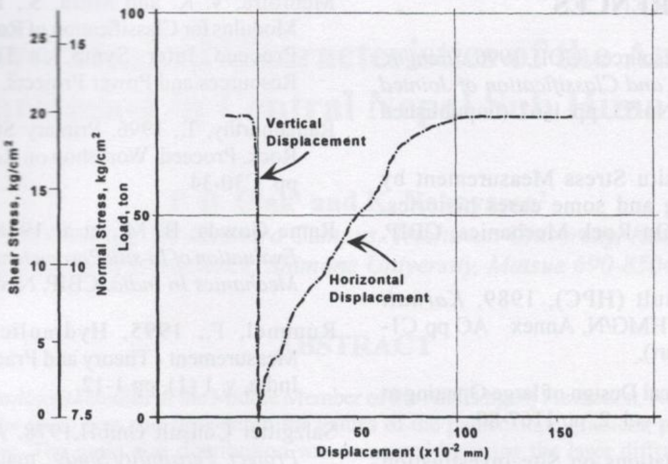

Fig. 4: Typical load-displacement curve of in-situ test

failure must be assessed for the design case as they may differ from test conditions.

Fifteen in-situ shear tests were carried out in the Sapta Gandaki Hydroelectric Power Development Project in various types of the Siwalik sandstones. The tests were executed according to the standards for geological investigation of dam foundations proposed by Japanese National Committee on Large Dams (1971). One of the test results and pressure - displacement curves are presented in Table 4 and Fig. 4, respectively.

Permeability of Rock Mass

In this method, water is injected between packers or below a packer in a borehole. In both cases, a length of water injection section of 5 m is usually adopted and Lugeon[*] value is determined by the rate of flow of water into the strata under 10kg/cm^2 pressure, after stabilisation of the injection volume. This test is used to determine the local apparent equivalent permeability of the rock mass. Calculation assumes that the cavity is entirely below the water table (in saturated rock), that flow is perpendicular to the borehole and that steady state condition has been achieved.

CONCLUSIONS

In-situ stress measurements are essential for designing the underground structures with appropriate support. The deformability characteristics, permeability, in-situ stress parameters, and in-situ shear test results presented in this paper give an idea of the complex mechanical properties of the Himalayan rocks. These results can be used as the guidelines for estimating the mechanical properties of the Himalayan rock mass. However, precise results may be obtained only by measuring the in-situ stresses at a specific site. The choice of the method as well as the number of measurements to be taken depends on urgency of the problem, the availability of underground access, and the cost involved in the projects.

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[*] When the water loss under a pressure of 10 kg/cm^2 is 1litre/min./m length of borehole, the permeability is said to be 1 Lugeon, 1 Lu.

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