

# **Comparison of Modulus of Deformation of Rock Mass by Different Methods**

सिपकतु माता मही रसा नः



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## **ABSTRACT**

The modulus of deformation of rock mass is an important engineering parameter required for the stability analysis and design of underground structures. Different equipment and techniques are used to arrive at the design modulus value. Since any error in the estimation of modulus values results in multiplication of its effects in the analysis, it is necessary to know about the reliability of testing equipment and procedures. The different procedures used for direct measurement provide values that often differ from one another by as much as 2 to 3 times depending mostly on the loading area used for a particular test and deformation measured at the surface or inside drillholes. This is inevitable, due to the fact that the rock mass volume stressed differs from one test to another. Also, the parameter is notably sensitive to a scale effect because of the discontinuities. Part of this may arise from the deformation characteristics of discontinuities, which are difficult to analyse. This paper deals with a comparison of deformability of rock mass from different methods by conducting plate loading, plate jacking and Goodman jack tests on a particular site.

**Keywords:** Modulus of deformability of rock mass; Plate loading; Plate jacking; Goodman jack test

## **1. INTRODUCTION**

Deformability of rock mass is characterized by a modulus describing the relationship between the applied load and the resulting deformation. The fact that jointed rock masses do not behave elastically has promoted the usage of the term modulus of deformation rather than modulus of elasticity or Young's modulus. The commission of terminology of the International Society for Rock Mechanics (ISRM) in 1975 has given the following definitions:

**Modulus of elasticity or Young's modulus:** The ratio of stress to corresponding strain below the proportionality limit of a material.

**Modulus of deformation of rock mass:** The ratio of stress to corresponding strain during loading of a rock mass, including elastic and inelastic behavior.

**Modulus of elasticity of rock mass:** The ratio of stress to corresponding strain during loading of a rock mass, only for the elastic behavior.

Since a rock mass contains weakness besides the intact rock material, the modulus values of the latter is in the order of five to twenty times higher than in-situ values. The

difference between laboratory testing on intact rock and in-situ testing of rock mass depends mainly on the joint system and the infilled material in the rock mass. For the rock material, the tangent modulus to the stress-strain curve is taken at the 50% of the failure stress.

All in-situ deformability tests are expensive and difficult to conduct. Initial preparation at test site is particularly time consuming. The interpretation of measured in-situ data is another difficult aspect, which requires experience from those involved. The following in-situ tests are conducted for determination of modulus of deformation:

- Plate jacking test,
- Plate loading test,
- Goodman jack test,
- Flat jack test,
- Cable jacking test,
- Radial jack test, and
- Dilatometer test.

Out of these, first four methods are being used extensively. The plate loading tests, plate jacking tests and Goodman jack tests are described in this chapter. The results of plate loading test, Goodman jack test and plate jacking test with borehole extensometer from the Himalayan region of India, Nepal and Bhutan by the Central Soil and Materials Research Station (CSMRS), New Delhi have been presented by Singh et al. (1992, 1994), Singh and Rajvanshi (1996), Singh and Bhasin (1996), Sharma and Singh (1989) and Sharma et al. (1989, 1990).

Using different equipment and suggested procedures a number of tests were conducted by CSMRS, New Delhi in the same rock mass for the determination of the modulus of deformation. The following test methods were adopted:

- Plate jacking test (PJT) with displacement measurement by borehole extensometers,
- Plate loading test (PLT) with surface displacement measurement, and
- Goodman jack test (GJT) inside drillholes.

The evaluation of deformability characteristics of rock mass by different methods are described in this paper along with a comparison of deformability of rock mass.

## **2. PLATE LOADING TEST**

### **2.1 Test Procedure**

At the selected test site, the rock surface in the bottom and top of the drift is smoothened by chiselling to obtain parallel faces, about 5 cm more than the diameter of the test plate. The test plate of 60 cm diameter is used. A 2 cm thick and 60 cm diameter concrete pad is constructed in the bottom of test plate and about 5 cm thick and 60 cm diameter pad is constructed at the top to take the reaction for loading. Both the pads are kept parallel to each other. The assembly of the plate loading test is shown in Fig. 1.

The testing equipment is installed with 2.5 cm thick and 60 cm diameter plates in the bottom and then 45 cm and 30 cm diameter plates are placed. Then a hydraulic jack of 200 tons capacity is placed centrally at the bottom. Aluminium alloy pipes with a mild steel plate of 2.5 cm thick and 30 cm diameter on the top fills the gap between top pad and jack. The remaining gap is closed by applying seating load or by moving out the plunger of the Jack. The displacement measuring unit is installed by using four extensometers with an accuracy of 0.01 mm.

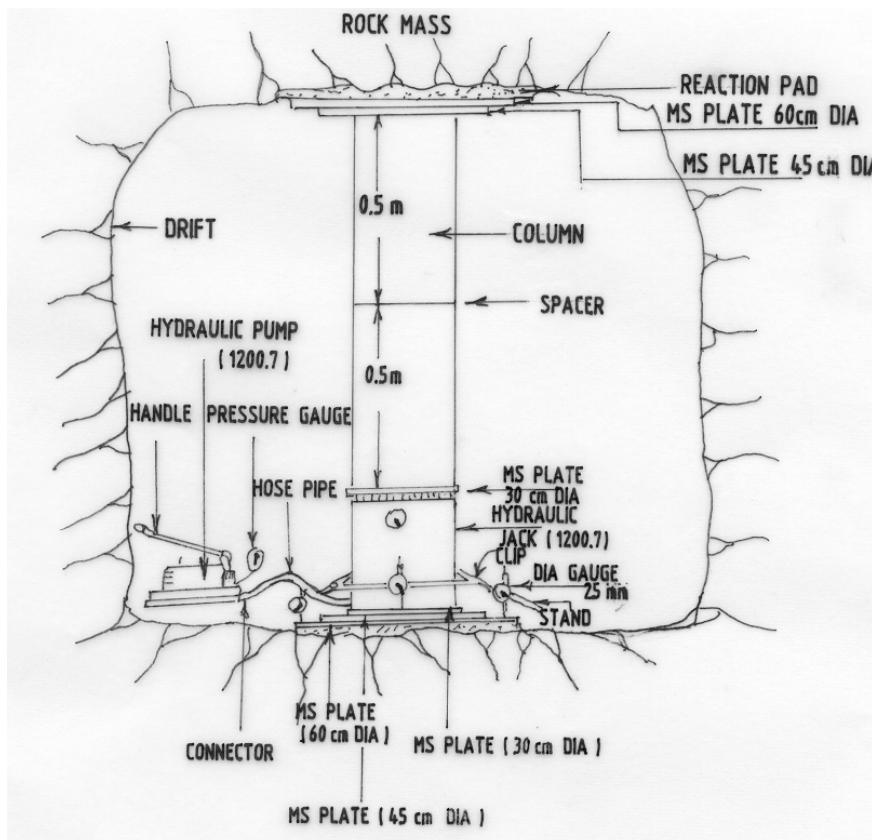


Fig. 1 - Plate loading test assembly inside a testing drift

## 2.2 Calculation

The modulus of deformation ( $E_d$ ) for the loading cycle by considering its total deformation and modulus of elasticity ( $E_e$ ) by considering only elastic deformation or deformation during unloading are calculated by using the following equation:

$$E = \frac{P m (1 - v^2)}{W \sqrt{A}} \quad (1)$$

where,

- E = Modulus of deformation/elasticity in kg/cm<sup>2</sup>,
- P = Applied load in kg,
- v = Poisson's ratio,
- m = Constant depending upon the shape of plate (m= 0.95 for square plate and m = 0.96 for circular plate),
- W = Deformation corresponding to load in cm, and
- A = Area of plate in cm<sup>2</sup>.

For the Poisson's ratio of 0.25 and diameter of the circular plate of 60 cm, Eq. 1 may be reduced to:

$$E = 0.016926 P/W \quad (2)$$

or in terms of applied stress, the above equation can be written as:

$$E = 47.857 \sigma/W \quad (3)$$

where P is load in kg, W is deformation in cm, and  $\sigma$  is stress in kg/cm<sup>2</sup>.

The Eq. 3 can be utilized for determination of modulus of deformation ( $E_d$ ) and modulus of elasticity ( $E_e$ ) based on the total deformation (loading cycle) and elastic deformation (unloading cycle) of a particular cycle, respectively.

### 2.3 Interpretation of Test Results of Plate Loading Test

A minimum of 3 plate loading tests should be conducted to ascertain variation and to average the values inside a drift in one type of rock mass. All the deformability tests are conducted in 5 cycles of loading and unloading. First cycle is normally not considered for interpretation of deformability of rock mass. However, loading and unloading in first cycle may be repeated twice in a condition of low loading. The typical stress versus deformation curve is shown in Fig. 2. The average values of modulii of deformation and modulii of elasticity have been presented in Table 1 along with variation at the applied stress level of 2, 3, 4 and 5 MPa.

Table 1 - Average value of modulus of deformation and elasticity by plate load test

Stress (MPa)	Modulus of Deformation, $E_d$ (GPa)			Modulus of Elasticity, $E_e$ (GPa)			Ratio $E_e/E_d$ Average
	Minimum	Maximum	Average	Minimum	Maximum	Average	
2	0.95	1.45	1.13	1.37	2.28	1.92	1.70
3	1.19	1.58	1.38	1.61	2.61	2.07	1.50
4	1.41	2.20	1.78	1.95	3.04	2.46	1.39
5	1.86	2.28	2.09	2.10	3.63	2.67	1.28

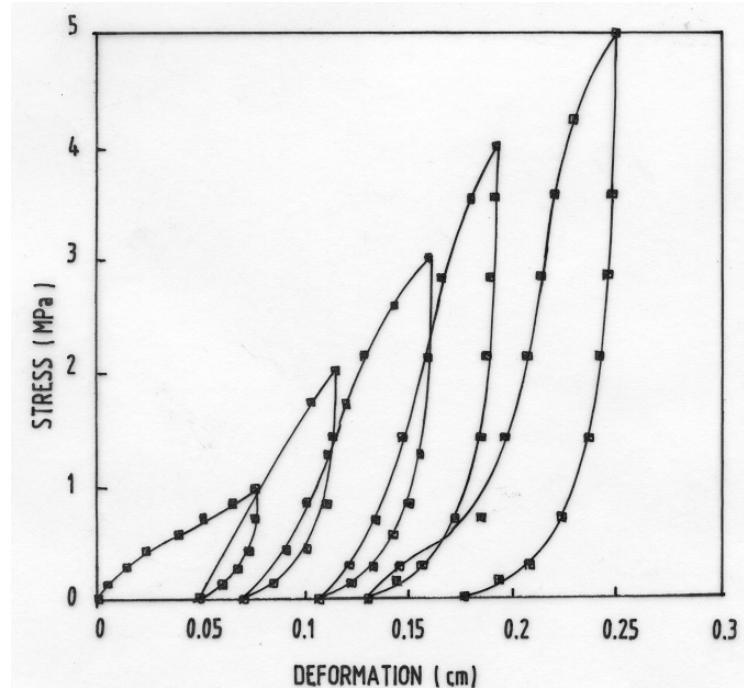


Fig. 2 - Stress versus deformation curve from plate loading test

The modulus value increases and the ratio of  $E_e/E_d$  decreases with the increase in stress level. It is, therefore, very essential to know the magnitude of loading of the structure to be constructed on or inside rock mass. The stress due to structure may be multiplied by a factor of 1.5 times to determine the deformability of rock mass.

The value of modulus of deformation shows variation from 1.86 GPa to 2.28 GPa with an average value of 2.09 GPa at 5 MPa stress level and the modulus of elasticity varies from 2.10 GPa to 3.63 GPa with an average value of 2.67 GPa (Table 1).

The ratio of modulii of elasticity and deformation ( $E_e / E_d$ ) is 1.70 at an applied stress level of 2 MPa and decreases to 1.28 at an applied stress level of 5 MPa. The ratio  $E_e/E_d$  shows the amount of jointing in the rock mass. In a homogenous good quality of rock mass, the ratio  $E_e/E_d$  is almost one in the last cycle. The decrease in modulii ratio shows the closing of joints at high applied stress.

### 3. GOODMAN JACK TEST

#### 3.1 Goodman Jack and Test Procedure

The drillhole jack designed by Goodman, Harlomoff and Horning and licensed by Slope Indicator Co., Seattle, USA, has been used in the investigation. It consists of two curved rigid bearing plates of angular width of 90 degrees, which can be forced apart by a number of pistons. The device is used inside an NX size (76 mm diameter) drillhole. Two LVDTs mounted at either end of the 20 cm long bearing plates measure the displacement. Two return pistons retract the bearing plates to their original position. The total piston travel of the equipment is about 12.5 mm and the LVDTs have a linear range of 5 mm. Pressure of the order of 70 MPa can be applied by the jacks. The volume of rock affected by the jack is about  $0.028 \text{ m}^3$  and extends to about 114 mm into the rock away from the drillhole walls. One problem with borehole deformability tests is that they affect a relatively small volume

of rock and therefore contain an incomplete sample of fracture system (Goodman 1989). However, the Goodman jack has the unique advantage of giving an indication of the range of properties of the rock mass remote from the surface at an early stage of field investigation. Large scale field test requires drifts and is more expensive and time consuming. The large scale field test can be carried out for final construction of structure. Goodman jack along with pump is shown in Fig. 3 and Goodman jack inside a drillhole is shown in Fig. 4.



Fig. 3 - Goodman jack along with hydraulic pump

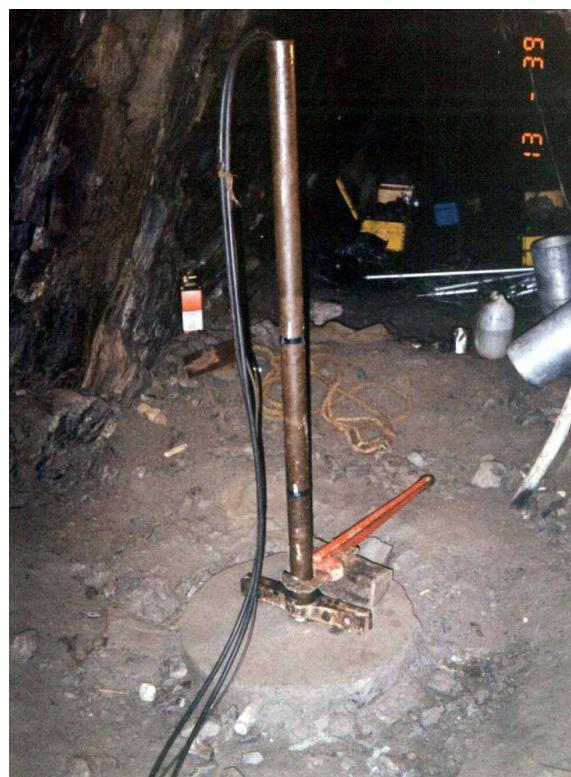


Fig. 4 - Goodman jack inside drillhole

Stress transferred to the drillhole walls depends upon the particular model used for the tests. Two types of Goodman jacks are used to determine the modulus of deformation of rock mass depending upon the type of rock mass. For hard rocks the Goodman jack model 52101 is used in which the stress transferred to the drillhole walls is 93 % of the applied stress. Whereas for soft rocks, the model 52102 is used in which the stress transferred to the drillhole walls is 55 % of the applied stress. The Goodman jack of soft rock model was used to obtain the data presented herein. At each location, tests were conducted in two mutually perpendicular directions.

### 3.2 Calculation

The modulus of deformation is calculated using the following relationship given by Goodman and Van (1968) and Goodman et al. (1972):

$$E = 0.86 \frac{\Delta P}{\frac{\Delta D}{D}} K(\nu, \beta) \quad (4)$$

where,

$E$  = Modulus of deformation/elasticity ( $\text{kg}/\text{cm}^2$ ),

$\Delta P$  = Pressure increment ( $\text{kg}/\text{cm}^2$ ),

$\Delta D$  = Diametral displacement increment (cm),

$D$  = Diameter of drillhole (cm), and

$K(\nu, \beta)$  = Constant depending upon Poisson's ratio ( $\nu$ ) and angle of loaded arc ( $\beta$ ).

The percentage of applied stress transferred to the drillhole walls is 55 % (as per manufacturer). The provision of 55% was included in the applied stress. The modulus of deformation for Poisson's ratio of 0.25 and loaded arc of 45 degrees has been calculated using the following relationships:

$$\begin{aligned} E &= 0.86 \times 7.6 \times 1.254 \frac{\Delta P}{\Delta D} \\ &= 7.6224 \frac{\Delta P}{\Delta D} \end{aligned} \quad (5)$$

where,

0.86 = 3-D Effect

0.55 = Hydraulic Efficiency, 55 % for Soft Rock Jack (not included in Eq. (#. 5) as the stress applied was 55% higher),

7.6 = Diameter of NX size Drillhole, and

1.254 =  $K(\nu, \beta)$  for  $\nu = 0.25$  and  $\beta = 45^\circ$  using Goodman's chart.

### 3.3 Interpretation of Test Results of Goodman Jack Test

A total of 15 Goodman jack tests (GJT) were conducted inside 3 NX size drillholes down to a depth of 6m each (one horizontal drillhole and 2 vertical drillholes in upward and downward direction in a drift). The vertical direction and horizontal direction were oriented parallel and perpendicular to the axis of the drift. This is the main advantage with GJT to conduct the tests in the desired direction to know the anisotropy of rock mass. The typical stress versus deformation curve is shown in Fig. 5.

### 3.3.1 Vertical deformability

The average values of modulus of deformation and modulus of elasticity in vertical loading direction i.e. GJT1 to GJT4 are presented in Table 2 at the applied stress levels of 3, 4.5, 6 and 7.5 MPa. The modulus value increases and the ratio of  $E_e/E_d$  decreases with the increase in stress level. The average value of modulus of deformation increases from 1.98 GPa to 4.98 GPa with an average value of 3.60 GPa at 7.5 MPa stress level. The modulus of elasticity varies from 2.08 GPa to 5.42 GPa with an average value of 3.99 GPa. The ratio of modulii of elasticity and deformation ( $E_e/E_d$ ) is 1.26 at an applied stress level of 3.0 MPa and decreases to 1.11 at an applied stress level of 7.5 MPa.

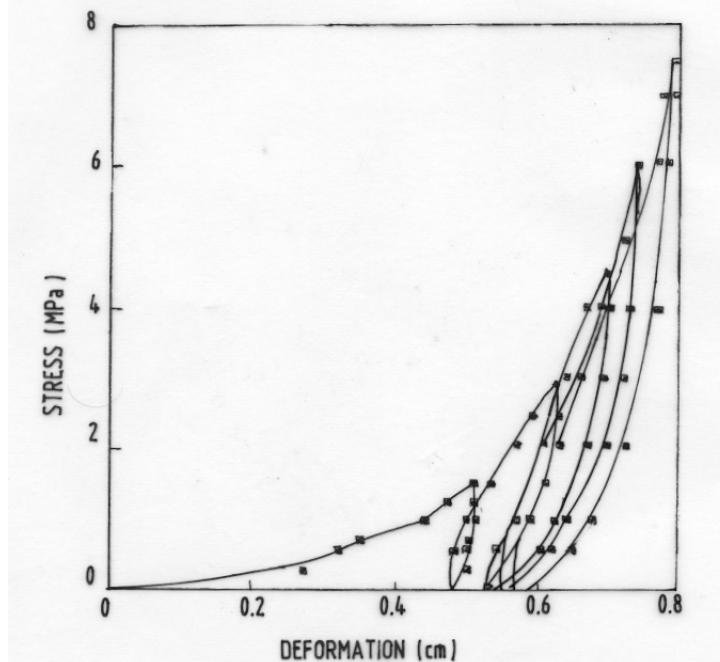


Fig. 5 - Stress versus deformation curve from Goodman jack test

Table 2 - Average modulii values in vertical direction by GJT

Stress (MPa)	Modulus of Deformation, $E_d$ (GPa)			Modulus of Elasticity, $E_e$ (GPa)			Ratio $E_e/E_d$ Average
	Minimum	Maximum	Average	Minimum	Maximum	Average	
3.0	1.25	2.62	2.22	1.47	3.83	2.80	1.26
4.5	1.53	3.56	2.02	1.70	3.74	3.06	1.52
6.0	1.78	3.83	3.25	1.92	5.25	3.54	1.09
7.5	1.98	4.98	3.60	2.08	5.42	3.99	1.11

### 3.3.2 Horizontal deformability parallel to drift

The average values of modulus of deformation and modulus of elasticity in the horizontal loading direction parallel to drift axis are presented in Table 3 at applied stress levels of 3, 4.5, 6 and 7.5 MPa. The modulus value increases and ratio of  $E_e/E_d$  decreases with the increase in stress level. The average value of modulus of deformation shows increase from 2.83 GPa to 7.33 GPa with an average value of 3.74 GPa at 7.5 MPa stress level. The modulus of elasticity varies from 2.04 GPa to 8.31 GPa with an average value of 4.37 GPa. The ratio of modulii of elasticity and deformation ( $E_e/E_d$ ) is 1.29 at an applied stress level of 3.0 MPa and decreases to 1.17 at an applied stress level of 7.5 MPa. The modulii values in horizontal direction parallel to drift are slightly higher than modulii values in vertical direction.

Table 3 - Average modulii values in horizontal direction (parallel to drift) by GJT

Stress (MPa)	Modulus of Deformation, $E_d$ (GPa)			Modulus of Elasticity $E_e$ (GPa)			Ratio $E_e/E_d$ Average
	Minimum	Maximum	Average	Minimum	Maximum	Average	
3.0	1.61	2.93	2.31	1.85	4.98	2.98	1.29
4.5	2.41	5.75	3.36	2.41	6.80	3.78	1.13
6.0	2.49	7.12	3.75	2.77	7.12	4.02	1.07
7.5	2.83	7.33	3.74	2.04	8.31	4.37	1.17

### 3.3.3 Horizontal deformability perpendicular to drift

The average values of modulus of deformation and modulus of elasticity in horizontal loading direction parallel to drift axis are presented in Table 4 for applied stress levels of 3, 4.5, 6 and 7.5 MPa. The modulus value increases from 3.12 GPa to 4.98 GPa with an average value of 3.82 GPa at 7.5 MPa stress level. The modulus of elasticity varies from 3.12 GPa to 4.79 GPa with an average value of 3.82 GPa. The ratio of modulii of elasticity and deformation ( $E_e/E_d$ ) is 1.21 at an applied stress level of 3.0 MPa and decreases to 1.00 at an applied stress level of 7.5 MPa. The rock mass has behaved perfectly elastic in this case. The modulii values in the horizontal direction perpendicular to drift axis are slightly higher than modulii values in the vertical direction as well as in the horizontal direction parallel to drift axis.

Table 4 - Average modulii values in horizontal direction (perpendicular to drift) by GJT

Stress (MPa)	Modulus of Deformation, $E_d$ (GPa)			Modulus of Elasticity, $E_e$ (GPa)			Ratio $E_e/E_d$ Average
	Minimum	Maximum	Average	Minimum	Maximum	Average	
3.0	1.92	2.77	2.17	1.85	3.56	2.63	1.21
4.5	2.41	3.94	3.02	2.41	4.40	3.16	1.05
6.0	2.49	4.15	3.21	2.77	4.47	3.43	1.07
7.5	3.12	4.98	3.82	3.12	4.79	3.82	1.00

### 3.3.4 Modulii values by GJT

Based on 15 Goodman jack tests (GJT) conducted inside 3 NX size drillholes in the drift, the average values of modulii of deformation and modulii of elasticity are given in Table 5 at applied stress level of 3, 4.5, 6 and 7.5 MPa. The average modulus value increases and the ratio of  $E_e/E_d$  decreases with the increase in the stress level.

The average value of the modulus of deformation increases from 1.98 GPa to 7.33 GPa with a final average value of 4.06 GPa at 7.5 MPa stress level. The average modulus of elasticity varies from 2.04 GPa to 8.31 GPa with a final average value of 4.24 GPa. The ratio of average values of modulii of elasticity and deformation ( $E_e / E_d$ ) is 1.35 at an applied stress level of 3.0 MPa and decreases to 1.04 at an applied stress level of 7.5 MPa.

Table 5 - Average modulii values by GJT

Stress (MPa)	Modulus of Deformation, Ed (GPa)			Modulus of Elasticity, Ee (GPa)			Ratio $E_e/E_d$ Average
	Minimum	Maximum	Average	Minimum	Maximum	Average	
3.0	1.00	3.83	2.33	1.19	5.54	3.14	1.35
4.5	1.47	5.75	3.16	1.53	6.80	3.48	1.10
6.0	1.78	7.12	3.60	1.78	7.12	3.92	1.09
7.5	1.98	7.33	4.06	2.04	8.31	4.24	1.04

## 4. PLATE JACKING TEST

The schematic diagram of the plate jacking set up is shown in Fig. 6 along with a typical illustration of installation of anchors and extensometers inside the drillhole. It comprises of a hand pumps, hydraulic jacks, flat jacks, multiple point borehole extensometers with anchors and the measuring system with displacement transducers and a 12-channel digital readout unit with an accuracy of 0.001 mm. The capacity of the system is 7 MPa uniaxial pressure.

### 4.1 Site Preparation

The plate jacking test is conducted by applying load in the direction normal to drift axis. The rock surface of the drift at the test locations are carefully prepared by removing all loose rock material by chiselling within a diameter of 150 cm around the drillholes. The loading surfaces are kept concentric. NX size (76 mm diameter) instrumentation drillholes of about 6 m depth are drilled at the prepared surfaces along with extraction of cores. All the cores are preserved properly in wooden core boxes. Both the drillholes are aligned carefully so that they are normal to surface and are in line with each other. Concrete pads using rich mix are cast around the drillholes to ensure smooth transfer of load from the flat jacks to the rock mass. The pads are allowed to cure for about seven days to obtain sufficient strength prior to commencement of the test.

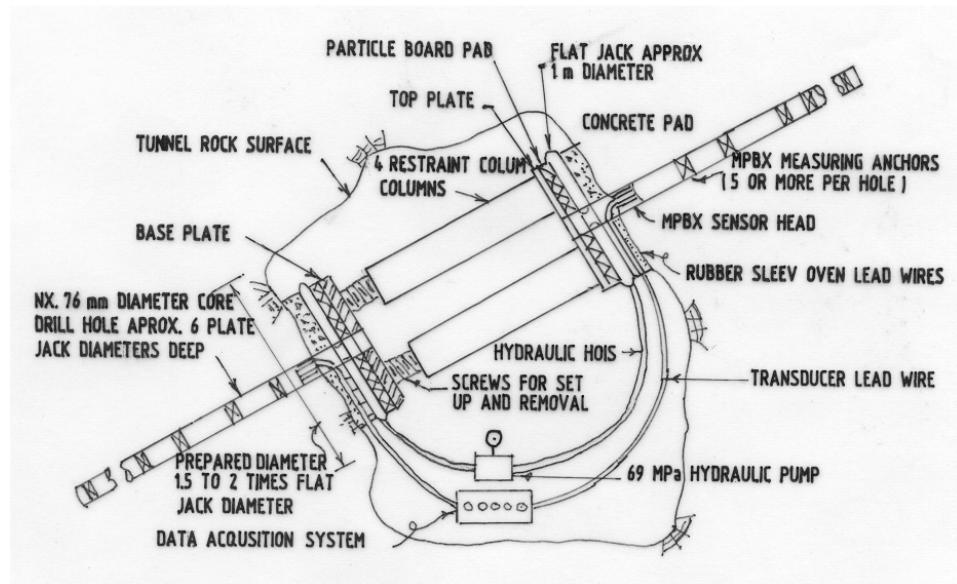


Fig. 6 - Schematic diagram of the plate jacking test set up

#### 4.2 Equipment Installation

The extensometers with the help of anchors are installed at suitable locations inside the drillholes. The location of anchors is decided after careful examination and logging of drillhole cores. Care is taken so that the anchors are not placed on joints. The last anchor in the drillhole is kept about 20 - 40 cm below the rock surface just to avoid blasting effects in the drift. The deepest anchor is located at a depth of 480 cm (about 6 times the diameter of the flat jack) from the rock surface in order to provide a fixed point to which the movement of all the extensometers can be referred. In all six to seven anchors are installed in each instrumentation drillhole, which accommodate five to six extensometers. The gap between the flat jack assembly and base and the top plates is filled up by special particle board made of wooden chips and resin, fabricated to accommodate the flat jack configuration on one side and the base plate on the other side. The flat jack assembly on top and bottom of restraining columns are shown in Fig. 7 along with screw jacks for tightening the loading assembly before applying the load with pump.

#### 4.3 Test Procedure

After all the components are installed, the system is checked for the actual test. The loading is applied through the flat jack system by manually operated hydraulic pump. It is 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. However, the modulus values are calculated for the cycles of 2, 3, 4 and 5 MPa. The first cycle is not considered for evaluation of deformability as the closing of joints due to blasting and some settlement of loading assembly takes place during loading and unloading. The load is maintained for 5 minutes at the stage of initial loading, incremental loading and maximum loading, while the intermediate load increments are maintained for one minute. The test is conducted according to the suggested method by ISRM (1979). Time dependent deformability characteristics of rock mass can also be determined as per guideline of ISRM (1979).



Fig. 7 - Plate jacking test loading assembly

#### 4.4 Calculation

Deformation measurements for various load cycles are utilized to compute modulus of deformation according to appropriate formula. The modulus of deformation is calculated for each cycle of loading and unloading. The equation utilized for this purpose is given below:

$$W_z = \frac{2 P (1 - \nu^2)}{E} \left[ (a^2 + z^2)^{\frac{1}{2}} - z \right] - \frac{P z (1 + \nu)}{E} \left[ z (a^2 + z^2)^{\frac{1}{2}} - 1 \right] \quad (6)$$

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 (MPa),
- $A$  = Outer radius of flat jack (cm),
- $\nu$  = Poisson's ratio, and
- $E$  = Modulus of rock mass (MPa).

After substituting the appropriate values of  $a$ ,  $z$  and  $\nu$ , the Eq. 6 can be written as:

$$W_z = \frac{P}{E} (K_z) \quad (7)$$

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

$$E_d = P \left[ \frac{K_{z1} - K_{z2}}{W_{z1} - W_{z2}} \right] \quad (8)$$

where,  $K_{z1}$  and  $K_{z2}$  are constants at depth  $z_1$  and  $z_2$ , respectively. Similarly,  $W_{z1}$  and  $W_{z2}$  are deformations measured between depths  $z_1$  and  $z_2$ , respectively. The Eq. 8 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 (unloading cycle) of particular cycle, respectively.

#### 4.5 Interpretation of Test Results by Plate Jacking Test

It was possible to conduct only one plate jacking test (PJT) with borehole extensometers inside drift at this project site where plate loading and Goodman jack tests were also conducted at the same location. The stress versus deformation curve is shown in Fig. 8 for all the five cycles. The variation of deformation with depth from different extensometers is shown in Fig. 9.

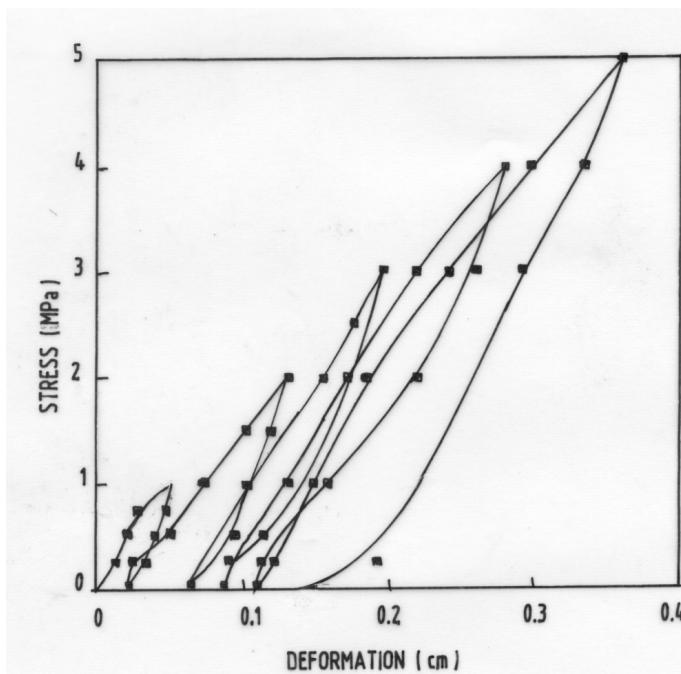


Fig. 8 - Stress versus deformation curve from plate jacking test

The extensometers were installed in both the vertical downward and upward drillholes and the loading was applied in both the directions by flat jacks on the top and bottom of the loading assembly. The modulii values were calculated for the downward vertical drillhole. However, modulii values can be interpreted simultaneously from both the drillholes in plate jacking test.

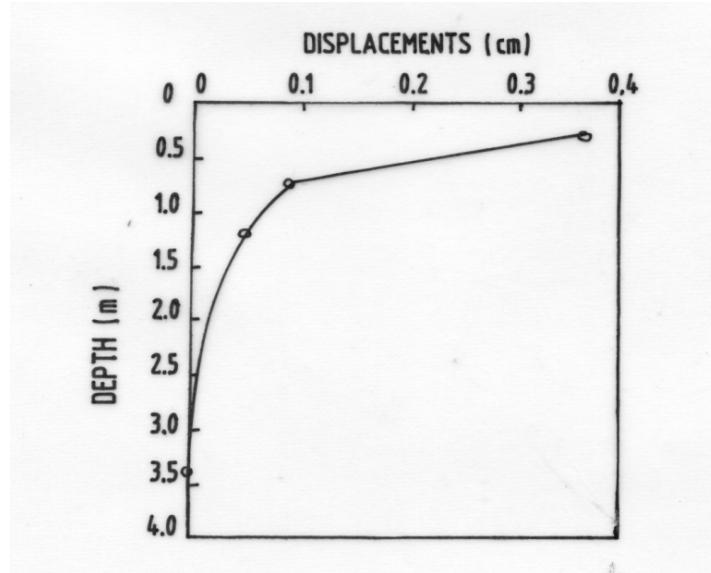


Fig. 9 - The variation of displacements with depth in PJT

The values of modulus of deformation and modulus of elasticity have been estimated at the applied stress level of 1, 2, 3, 4, and 5 MPa and are given in Table 6. The magnitude of modulus of deformation is 8.70 GPa and the modulus of elasticity is 10.14 GPa at a stress level of 5 MPa. The ratio of modulii of elasticity and deformation ( $E_e/E_d$ ) is 1.76 at an applied stress level of 1 MPa and decreases to 1.12 at an applied stress level of 5 MPa. As observed in other tests, ratio of  $E_e/E_d$  decreases with the increase in stress level.

Table 6 - Modulii of deformation and elasticity for plate jacking test

Stress (MPa)	Total Deformation (cm)	Elastic Rebound (cm)	$E_d$ (GPa)	$E_e$ (GPa)	Ratio $E_e/E_d$
1	0.051	0.029	8.63	15.17	1.76
2	0.107	0.067	8.22	13.13	1.59
3	0.135	0.110	9.78	12.00	1.23
4	0.194	0.173	9.07	10.17	1.12
5	0.253	0.217	8.70	10.14	1.12

## 5. COMPARISON OF DEFORMABILITY BY DIFFERENT METHODS

The experience is that different procedures used for in-situ measurements provide values that often differ from one another by as much as 100%. This is inevitable, due to the fact that the volume of rock mass structure differs from one test to another particularly in terms of degree of jointing. As the modulus is notably sensitive to the presence of joints, the rock mass conditions at each test site should be carefully described as part of the test procedure. By comparing the variations in rock mass quality, some of the difference in test results may be explained.

The CSMRS has performed in-situ deformation tests with the Goodman jack and plate jacking during the last two decades at most of the important river valley projects in India, Nepal, and Bhutan. The procedures and suggested method of the International Society of Rock Mechanics (ISRM, 1979) have been closely followed for conducting all the tests. From the test results, it has been possible to compare and correlate the in-situ measurement, as given in Table 7.

As earlier pointed out by several researchers (Bieniawski, 1979; Heuze and Amadei, 1985), the value obtained by the various in-situ deformation tests will not give the same deformation modulus. Based on CSMRS experience this may partly be explained by:

- (i) In plate jacking test (PJT) with drillhole extensometer measurement: the deformations are measured inside the drillhole from the damaged zone towards the undisturbed rock mass.
- (ii) In plate loading test (PLT) with surface measurement: larger deformations measured at the rock surface in these tests include the top damaged zone.
- (iii) Goodman jack test (GJT) performed inside the drillhole: gave lower values of the moduli because, in hard rock, the loading platens deform. Thus, the displacement devices record the increase in drillhole diameter plus deformation of the loading plates. Further, the stress is applied on a very small area as compared to large size plate jacking test.

Table 7 - Ratio between plate jacking test (PJT) and other types of field deformation measurements, compiled from Singh et al. (1994), Sharma et al. (1989), Bieniawski (1979), CSMRS (1999), Singh and Dhawan (1999), Palmstrom and Singh (2001)

Ratio	Measurements in Hydropower Projects			Experience by		Suggested Ratio between in-situ Measurements
	Lakhwar	Jamrani	Tala	Bieniawski	CSMRS	
PJT/PLT	1.9		4.0		2 - 3	2.5
PJT/FJT	1.75				2 - 3	2.5
PJT/GJT	2.05	2.6	2.4	approx. 2	2 - 3	2.5

Notation: PJT= Plate jacking test, PLT= Plate loading test; GJT= Goodman jack test; FJT= Flat jack test

From the measurements carried out, the ratio between these types of deformation measurements is given in Table 7, where in the results of Bieniawski (1979) are also given.

Bieniawski (1979) 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. The PJT is less sensitive to the variations in the pressure distribution than displacements directly under the loaded area. The measurements of deformation in drillholes at various depths

provide a check against any gross errors (blunders) of the measurements. The PJT also allows a better assessment of the properties at depth as the displacements outside loaded area are influenced to a much greater extent by the behavior of rock.

The low modulus value by GJT is due to the fact that loaded area in GJT is much smaller than PJT as also concluded by Singh et al. (1994) and Sharma et al. (1989). Heuze and Amadei (1985) have suggested an trial and error method for improving the modulii values obtained by borehole jack method. They tried to increase the value of constant K factor (Eq. 4), which was also discussed by Singh et al. (1994). Beiniawski (1989) tried to compare the rock deformability by GJT with Petite Seismique and flat jack methods.

It is, therefore, suggested that the results obtained by plate loading and Goodman jack tests may be multiply by a factor of 2.5 to arrive at a reasonably good value. This factor can be derived for a particular site by conducting plate jacking and Goodman jack tests.

## 6. CONCLUSIONS

Based on evaluation of deformability of rock mass from different methods, the following conclusions are drawn:

- The modulus of deformation of rock mass is calculated by taking total deformation of loading cycle at a particular applied stress level. The modulus of elasticity of rock mass is calculated by considering deformation of unloading cycle at a particular applied stress level.
- The modulus value increases in general with increase in stress level. It is, therefore, essential to know the magnitude of loading due to structure to be constructed on or inside the rock mass. The stress due to structure may be multiplied by a factor of 1.5 times to determine application of maximum stress during test for evaluation of the deformability of rock mass. The deformability tests are conducted in five cycles of loading and unloading and maximum stress is applied in the fifth cycle.
- Ratio of  $E_e/E_d$  decreases with the increase in stress level in all the methods. The decrease in modulii ratio shows the closing of joints at high stress level. In good rock mass condition, modulii ratio becomes almost one in fifth cycle of loading and unloading.
- The modulii values in the horizontal direction perpendicular to drift axis could be different than the modulii values in the vertical direction as well as in the horizontal direction parallel to drift axis. The variation in modulus values in all the three direction by Goodman jack test show anisotropy of the rock mass. Goodman jack test is the easiest and the fastest method to determine anisotropic behavior of the rock mass.
- There are variations in the modulus values determined by different methods. Sometimes these variations are due to the change in the rock mass properties also. The results of deformability measurements must be analysed by experts working in the field. The experience obtained at one project site with the same rock type cannot be utilized at another project site with the same type of rock mass. Therefore, the deformability of rock mass must be determined by any available method.

- It is recommended to utilize large size plate jacking test with borehole deformation measurements to arrive at a final design value of any project. However, the modulus of deformation of rock masses obtained by plate loading tests and Goodman jack tests may have to be multiplied by a factor of 2.5 to arrive at a reasonably good representative value. This factor may be derived accurately for a particular site by conducting in-situ tests.

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