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# Stress-Deformation Behaviour of Feldspathic Gneisses as Foundation Medium for a 278 m High Concrete Gravity Dam in Eastern Himalayas

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**Abstract.** Deformation modulus of rock is a basic parameter required for the design of any structure involving rock as foundation and abutments. The study of rock behaviour under external stresses is important for the safety analysis of the structure. A multipurpose project involving a 278 m high concrete gravity dam in Eastern Himalayas is under investigation stage. The rock type is mainly feldspathic gneiss with biotite schist. Stresses on foundation rock on account of the proposed dam are expected to be of the order of 6 to 10 MPa. Due to limitations of testing equipment, uniaxial jacking tests could not be performed upto the desired stress level. Hence, in-situ Borehole jack (commonly known as Goodman Jack) tests were preferred wherein stress of the order of 10 MPa was applied for evaluating the modulus of deformation of rock mass. Orientation of stress was varied to study the anisotropic behaviour of rock mass. Deformation modulus of feldspathic gneisses and anisotropic behaviour under different loading directions has been discussed in this paper. The tests were conducted in fresh rock simultaneously with drilling. This enabled to study the stress-deformation behaviour of rock representing the fresh rock without deterioration by way of weathering and other environmental factors.

**Keywords:** Deformation Modulus, Anisotropy, rock discontinuities, weathering.

## 1 Introduction

Rock mass comprises of intact blocks separated by discontinuities namely joints, fractures etc. Pattern and orientations of these fractures mainly govern the properties of the rock mass. Deformability characteristics of rock mass are primarily needed for the design of any structure in or on the rock mass. All the stress analysis theories have been derived assuming the rock mass as continuous, homogeneous, isotropic and linearly elastic (CHILE) material. However, in practice the actual rock mass is discontinuous, inhomogeneous, anisotropic and nonlinearly elastic (DIANE) due to the effect of structural features, thus, necessitating the actual measurement of parameters (Harrison and Hudson, 2000). In order to assess the degree of rock mass anisotropy, field tests are conducted in different directions with respect to the apparent rock mass fabric. A number of methods for measurement of deformation modulus (Bieniawski, Z.T., 1979) of rock mass are available, the important ones are plate jacking test with borehole deformation measurements, plate loading tests with surface deformation measurements, borehole jack with radial deformations inside a drillhole, flat jack tests etc. All these methods have their own benefits and limitations. Borehole jacks or commonly known as Goodman Jack Tests (GJT) are conducted inside NX (76 mm diameter) drillholes. The test involves around 0.15 m3 volume of rock mass and takes into account the effect of a few discontinuities whereas volume of rock mass affected in in plate loading tests (PLT) is much larger. Due to instable nature of drillholes and inability to fix anchors for LVDTs for measurement of deformations in weak and highly jointed rocks, plate jacking tests (PJT) with borehole deformations may not be feasible. Hence, PLT has to be conducted to determine the in-situ deformation modulus. Plate loading tests with deformation at surface of loading plate gives lower modulus values due to the effect of weathering, presence of open joints near the loading surface and ground water conditions. Flat jack tests having similar limitations also give lower modulus values. Therefore, all these methods are bound to provide different modulus values (Palmstrom and Singh, 2001). Hari Dev et al. (2015) compared the modulus values obtained from Goodman jack and plate load tests in pyroclastic rocks. The author's experience shows results of plate load and Goodman jack tests in fresh rocks are quite comparable.

The modulus of deformation primarily depends on sample size; testing conditions; nature and persistence of discontinuities; joint properties and infilling material; water conditions; strength of intact material etc. (Hari Dev 2020). Due to the influence of so many factors, variation in modulus values is observed when even using a single method and that too within close vicinity. Hence, test results need to be interpreted and correlated with structural features of rock and judgement. Shashank et al (2013) suggested statistical approach to interpret results of PLT for providing values of deformation modulus with desired level of confidence.

The method of excavation also affects the modulus. Drill and blast method of excavation leads to fracturing of rock mass around the opening and widening/opening of existing joints. Weathering of rock mass due to water, air and chemical actions etc. are some of the other prominent factors affecting the modulus values. Hari Dev et al., 2017 studied the effect of weathering on the deformation modulus of garnetiferous quartzo-feldspathic gneiss rock mass and 40 % to 60 % decrease in modulus values was reported with alteration from fresh to slightly/moderately weathering.

Anisotropy is a characteristic of intact foliated metamorphic rocks (slates, gneisses, phyllites, schists). These rocks tend to split into planes due to parallel orientation of microscopic grains of mica, chlorite or other platy minerals. Foliation can also be expressed by alternating layers of different mineral composition such as in gneisses. Non-foliated metamorphic rocks such as marble also show some anisotropy due to preferred orientation of calcite grains. Anisotropy is also the characteristic of intact laminated, stratified or bedded sedimentary rocks such as shales, sandstones, siltstones, limestones, coal, etc. The term transverse isotropy is generally used to indicate that a foliated rock has isotropic geomechanics properties in the foliation plane, i.e. transverse to the axis of rotational symmetry, but has varying geomechanics properties perpendicular to the foliation, i.e. along the axis of rotational symmetry (Wittke, 2014). The properties of the intact rock are different with stress application normal or parallel to the foliation.

Since, analysis is carried out considering the rock mass as completely isotropic, therefore, as per the theory of linear elasticity, rock mass can be characterised by a single value of modulus and Poisson's ratio. But in actual practice, it is almost impossible to assign a unique modulus value to any rock or rock mass.

## 2 Geology of the Project Area

The main geological formations around the project are meta sedimentary rocks of Ithun and Hunli formations of Palaeozoic to Precambrian age. These rocks are intruded by younger granite and pegmatitic rocks having both concordant and discordant relationships with the host rocks. The rocks exposed in the project are massive to jointed quartzo-feldspathic gneiss, amphibolites gneiss/ amphibolites, granitic gneiss with bands of phyllites, volcano-sedimentaries and pegmatites. The different litho units dip towards north, north-east and northwest with varying dips. Light grey coloured feldspathic gneisses with occasional felsic intrusives classified as poor to fair rock class as per RMR have been encountered. The main discontinuities around right bank dam site are given below in Table 1.

**Table 1.** The main discontinuities around right bank dam site

| Set No. | Average Orientation | Spacing (cm.) | Persistence | Condition | Remarks |
|---|---|---|---|---|---|
| $S_1$ | $047^0/66^0$ | Closely spaced (5cm – 15cm) | High | Tight to partly open, rough planer to rough undulatory, Fe-stained | There is reversal of dips from NE to NW direction at higher platform above EL 550m. |
| $S_2$ | $181^0/46^0$ | Moderately spaced (20-50cm) | Medium to high | Tight to partly open, rough, irregular, Fe-stained | |
| $S_3$ | $318^0/45^0$ | Moderately Spaced (25-60cm) | Low to Medium | Tight to partly open, rough irregular to smooth planer | |
| $S_4$ | $270^0/73^0$ | Moderately to widely spaced (50-80cm) | Low | Tight, rough irregular, Fe-stained. | |

## 3 Tests Conducted

A total of 28 tests were carried out in NX size drillholes using Goodman jack in vertical as well as horizontal drillholes (CSMRS 2016a). The transferred stress in the Goodman jack model used in the investigation work is 55% of the applied stress. In view of the expected loading on the foundation due to the proposed dam, the tests were required to be conducted at maximum stress level of 10 MPa. Peak applied stress was kept such that the transferred stress works out to be 1.0, 2.0, 4.0, 6.0, 8.0 and 10.0 MPa. Results from first cycle of 1.0 MPa stress level may not be true representative of the actual rock mass and hence, hence omitted. Modulus values have been determined for the successive five cycles with transferred stress of 2.0 MPa to 10.0 MPa as per the design requirements following suggested methods by International Society of Rock Mechanics (ISRM 2007, Goodman and Tran, 1968).

### 3.1 Anisotropy

To assess the anisotropy in rock mass, orientation of applied stress was varied in different directions. Stress was applied in three mutually perpendicular directions as follows:

1. Along the dam axis (x-axis)
2. Perpendicular to dam axis (y-axis)
3. Normal (Vertical direction) to dam axis (z axis)

Therefore, deformation modulus was determined in all the above orientations with respect to dam axis as depicted in the sketch (Fig. 1).

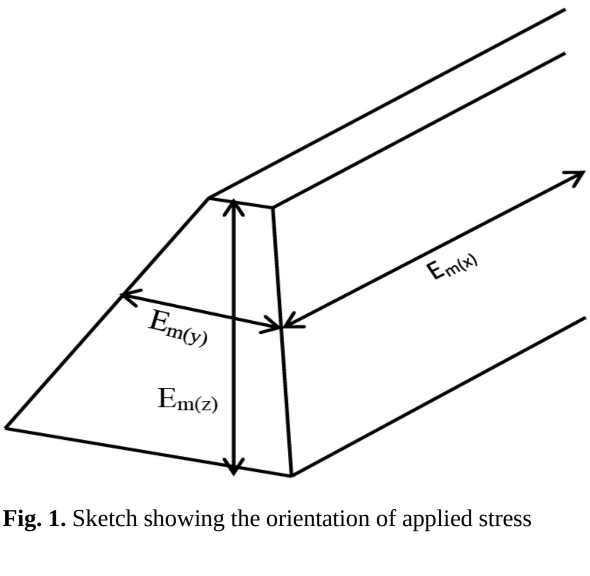


**Fig. 1.** Sketch showing the orientation of applied stress

The GJT tests were conducted in fresh rocks at varying depths from 11.40 m to 42.40 m in five drillholes (2 horizontal and 3 vertical). Results in different loading directions indicated anisotropic behaviour of rock mass. Results were derived in the light of three dimensional data. The deformation modulus was denoted by $E_{m(x)}$, $E_{m(y)}$ and $E_{m(z)}$ in three directions as explained above. Direction of loading was kept oblique to the dam axis (almost 450) also and modulus value has been denoted by $E_{m(o)}$. Similarly, unloading modulus or modulus of elasticity calculated using recovery of deformation during unloading was denoted by $E_{e(x)}$, $E_{e(y)}$, $E_{e(z)}$ and $E_{e(o)}$, in respective directions. All the tests were conducted in fully saturated conditions.

Basic rock type in all the drillholes was found to be feldspathic gneiss. However, the minor geological variations like joint infillings, minor shear seams were noticed. As a result of these geological variations along the drillhole, variation in moduli values was also observed.

The arithmetic mean values of deformation modulus with stress applications in different directions are presented in Table 2. The variation in deformation modulus by GJT has also been graphically shown in Figs. 2 and 3 including correlations between deformation modulus ($E_m$) and applied stress ($\sigma_n$) by drawing trendlines. The anisotropy in rock mass in different loading directions was observed.

Anisotropic study helps in selecting the critical values of parameters for safe design of structures. Deformation modulus values obtained in the present study using Goodman Jack tests with loading in different directions showed anisotropic behaviour of rock mass. Deformation modulus was observed to be lowest with loading in vertical direction. Deformation modulus with stress application in horizontal stress directions viz. along ($E_{m(x)}$), perpendicular ($E_{m(y)}$) and oblique ($E_{m(o)}$) to dam axis were found to be 19.7%, 22.8% and 9.4%, respectively, higher than corresponding values in vertical direction ($E_{m(z)}$).

**Table 2.** Modulus values from Goodman jack tests

| Applied Stress, MPa | 2.0 | 4.0 | 6.0 | 8.0 | 10.0 | Correlation | |
|---|---|---|---|---|---|---|---|
| Orientation of Stress Application | Deformation Modulus, GPa | | | | | Equation | $R^2$ |
| Along Dam Axis ($E_{m(x)}$) | 1.23 | 1.98 | 2.58 | 3.27 | 3.63 | $E_{m(x)} = 0.7691\sigma_n^{0.6814}$ | 1.00 |
| Perpendicular to Dam Axis ($E_{m(y)}$) | 1.78 | 2.54 | 3.14 | 3.47 | 3.73 | $E_{m(y)} = 1.314\sigma_n^{0.4661}$ | 0.99 |
| Vertical Direction ($E_{m(z)}$) | 1.41 | 1.88 | 2.47 | 2.90 | 3.04 | $E_{m(z)} = 0.9902\sigma_n^{0.4980}$ | 0.99 |
| Oblique Direction ($E_{m(o)}$) | 1.00 | 1.72 | 2.11 | 2.86 | 3.32 | $E_{m(o)} = 0.597\sigma_n^{0.7412}$ | 0.99 |

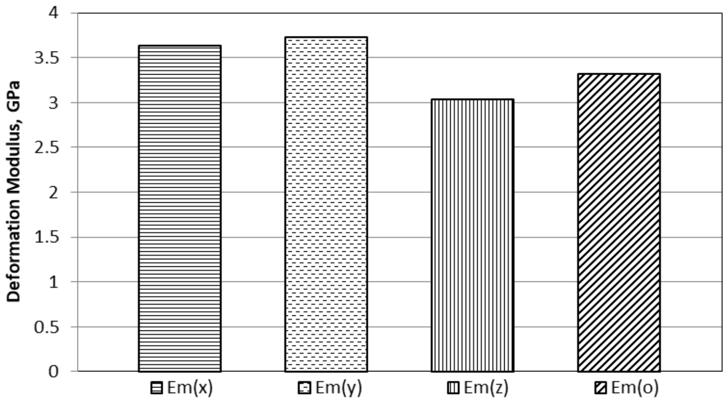


**Fig. 2.** Anisotropy in deformation modulus at applied stress 10 MPa

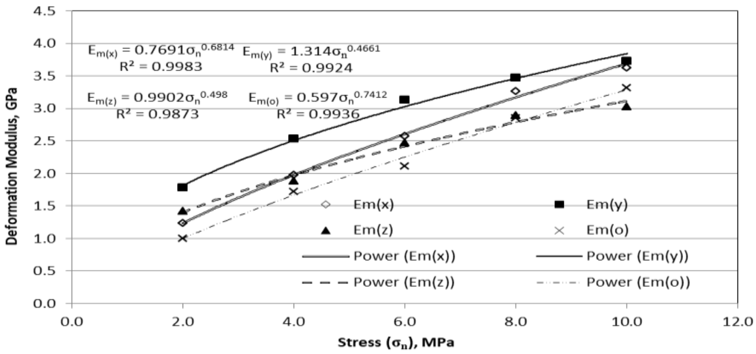


**Fig. 3.** Variation in deformation modulus with variation in stress

### 3.2 Comparison of GJT and PLT

Plate load tests (PLT) were also conducted in left and right abutment drifts (5 tests in left and right abutment drifts). Deformation modulus of rock mass was found to be 1.535 GPa at 5 MPa applied stress (CSMRS 2015) and 2.140 GPa at 6 MPa applied stress (CSMRS 2016b) in right and left bank drifts, respectively. The average modulus of deformation from PLT has been presented in Table 3. Though 10 MPa stress application is possible in GJT, stress levels of 5-6 MPa could be applied in PLT due to limitations of testing equipment. Unless tested at the desired stress level, the stress-deformation behaviour cannot be assumed to be similar. However, for the sake of comparison, deformation modulus vs applied stress curve for all data from all the PLTs was drawn and a trend line was drawn to estimate the deformation modulus at stress levels equivalent to GJT (Fig. 4). For this, the upper and lower bound curves were drawn to exclude the outliers or the odd results. The correlation $E_m=0.2703\ \sigma_n^{1.0357}$ was derived by omitting the outliers. The extrapolated deformation modulus of rock mass by PLT at 10 MPa stress level was estimated to be 3.5 GPa which is in coherence with corresponding values of 3-3.7 GPa obtained by GJT.

**Table 3.** Results of plate load tests

| Applied Stress, MPa | 2.0 | 3.0 | 4.0 | 5.0 | 6.0 | 10.0 (Ex-trapolated) | Correlation Equation |
|---|---|---|---|---|---|---|---|
| Modulus of Deformation ($E_m$), GPa | 0.50 | 0.80 | 1.06 | 1.38 | 1.50 | 3.5 | $E_m = 0.2703\ \sigma_n^{1.0357}$ |

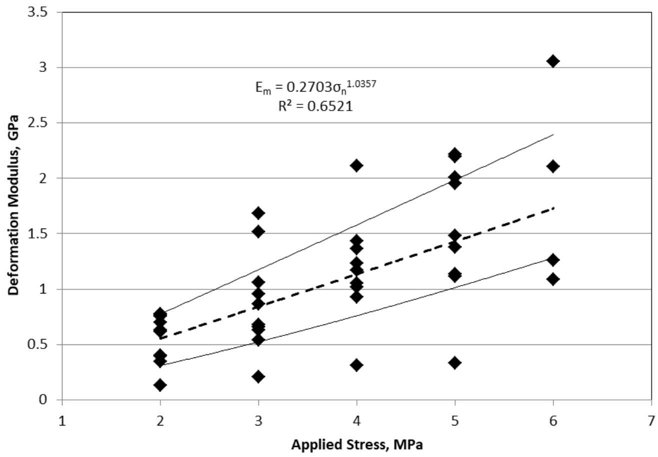


**Fig. 4.** Variation of deformation modulus by PLT

## 3.3 Comparison of Modulus of Intact Rock ($E_r$) and Rock Mass ($E_m$)

*Bieniawski (1989) wrote that "Unfortunately, few projects to date have featured a sufficient number of different tests to allow a meaningful comparison of in situ test data. Very different in situ results may be obtained depending on the test method. Under these circumstances, it is not helpful to discuss the precision of in situ methods. Even in an extensive in situ test program in fairly uniform and good quality rock mass conditions, deformability data may feature a deviation of 25% or as much as 10 GPa for an average in situ modulus of 40 GPa. The tests involving full scale prototype behaviour (tunnel relaxation) give different results by comparison with other in situ tests. The choice of the design value for the in situ modulus of deformation thus becomes a matter of engineering judgement. This means that it is difficult to rely on any one in situ method alone; two or more methods should be used to crosscheck the results."*

Therefore, variations in test results are obvious and has to be interpreted using own wisdom and experience. Further, no in-situ method is capable of providing unique characteristic value of in-situ modulus of deformation due to limitations of capacity of testing equipment and the wide ranging geological variations (Hari Dev, 2020). Deformations of rock mass in field tests is mainly the result of closing of joint spaces, compaction of joint infilling material and sliding along the discontinuities. For assigning deformation modulus ($E_m$) a unique or specified value, the rock mass has to be tested upto failure. But due to restricted capacity of testing system and to involve all the discontinuities, it is impractical.

At the project site, in-situ modulus of deformation was evaluated using two different methods and an attempt has been made to compare $E_r$ and $E_m$ based on extrapolation of observed field test data. Average modulus ($E_r$) of intact feldspathic gneiss rock tested in laboratory was observed to be 34 GPa with variation from 24 GPa to 46 GPa and average uniaxial compressive strength (UCS) has been reported as 33.1 GPa (ISM 2011). The in-situ modulus ($E_m$) at applied stress of 10 MPa was of the order of 3-4 GPa which is about 1/10$^{th}$ of value of $E_r$. Since, the measured values of modulus of deformation of rock mass ($E_m$) corresponds to certain stress levels actually tested and it is not the unique value of modulus of rock mass; comparison of $E_r$ and $E_m$ as such may not be justified. For comparison, the deformation modulus of rock mass should be corresponds to UCS. Therefore, the deformation modulus vs applied stress plots have to be extrapolated. Hence, likewise PLT (Fig. 4), deformation modulus values by GJT were also plotted against the applied stress. Upper bound and lower bound curves were drawn to filter the exceptionally low and high values. Considering the remaining results within the lower and upper bound, trendline was drawn (Fig. 5). The following correlations for PLT (Eq. 1) and GJT (Eq. 2) were arrived at and used to estimate the deformation modulus at stress levels corresponding to UCS. The comparison of $E_r$ and $E_m$ (Extrapolated using the correlation) is given in Table 4.

$$E_m = 0.2703\ \sigma_n^{1.0357} \qquad (1)$$

$$E_m = 0.9416\ \sigma_n^{0.5788} \qquad (2)$$

Therefore, for the sake of comparison, the $E_m$ was estimated using the trendline equations for PLT and GJT (given above) to the stress levels corresponding to UCS. Modulus of rock mass using the correlations was estimated to be of the order of 10 GPa and 7 GPa for PLT and GJT at stress level equivalent to UCS. Therefore, ratio of $E_r$ to $E_{m(estimated)}$ using the correlations worked out to be 3.4 and 4.8 for PLT and GJT, respectively. These estimates authenticate the remarks by Bieniawski (1989). Volume of rock mass affected in in-situ tests is much large as compared to intact rock. Further, the extent of rock mass affected varies with the test method employed.

In the absence of field tests, $E_m$ is generally estimated by dividing $E_r$ with a factor of 2.5. In-situ deformation modulus is primarily dependent on the discontinuities present in the rock mass. Hence, it is advisable to assess $E_m$ due to different testing methods as well as influence of various geological and environmental factors.

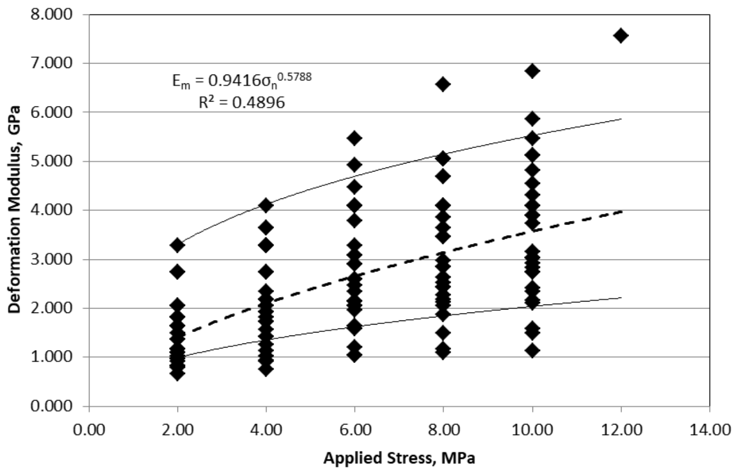


**Fig. 5.** Variation of deformation modulus by GJT

**Table 4**. Comparison of $E_r$ and $E_m$

| Uniaxial Compressive Strength of intact rock (UCS), MPa | Deformation Modulus of intact rock, $E_r$ (GPa) | Extrapolated Deformation modulus of rock mass $E_m$ (GPa) | | Ratio $E_r/E_m$ | |
|---|---|---|---|---|---|
| | | PLT | GJT | PLT | GJT |
| 33.1 | 34 | 10.1 | 7.1 | 3.4 | 4.8 |

### 3.4 Elasto-plastic nature of rock

Similarly, modulus of unloading also denoted by modulus of elasticity ($E_e$) was calculated from the stress-deformation curve using recovery of deformation during unloading. Modulus ratio ($E_e/E_m$) was plotted against the varying applied stress (Fig. 6). During loading, the rock mass deforms, and some of this deformation becomes irrecoverable, generally denoted by plastic or permanent deformation whereas a part of this total deformation recovers while unloading which is usually known as elastic rebound. The magnitude of plastic and elastic deformation depends mainly on the properties of joints and joint volume. Ratio of modulus of elasticity to modulus of deformation ($E_e/E_m$) in GJT was observed to be 1.19 at 10 MPa applied stress whereas in PLT, modulus ratio was observed to be 2.43 and 1.57 in right and left bank at stress level of 5 and 6 MPa, respectively. Stress-deformation curves for one of the GJT and PLT are shown in Figs. 7 and 8 to compare the behaviour of rock under stress in different testing methods. From results of GJT (Fig. 7), the rock mass look to be elastic. In fact, it is due scale effect. Elasticity or plasticity in rock mass is directly proportional to aperture size and number of joints/discontinuities and properties of joints under the influence of loading platens. GJT affects lesser loading area (two rigid curved plates 20.3 cm x 6 cm); thereby involving lesser number of discontinuities whereas PLT influences large volume of rock mass (usually 60 cm or higher diameter rigid plate used in loading). Also, as seen in Figs. 7 and 8, there is substantial difference in total deformation in GJT and PLT even though 10 MPa stress was applied in GJT compared with 5 MPa in PLT.

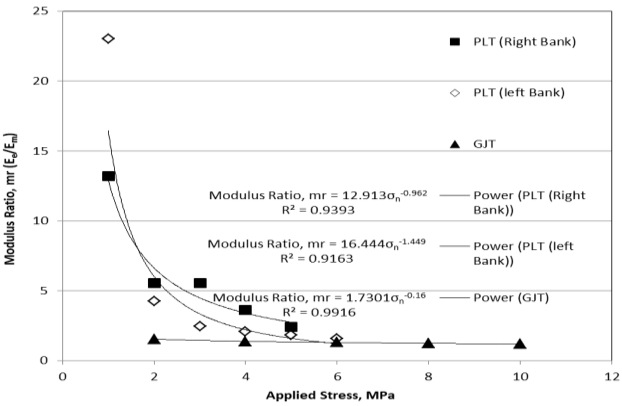


**Fig. 6.** Modulus ratio vs applied stress curve

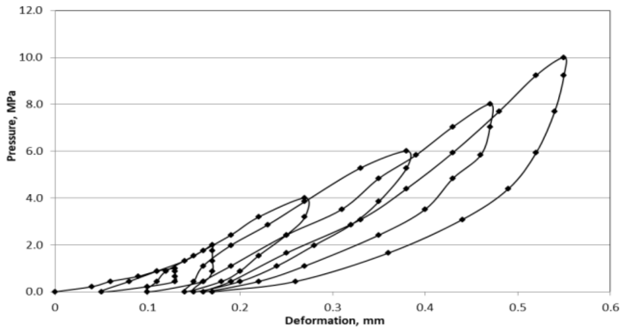


**Fig. 7.** Stress-deformation plot for GJT

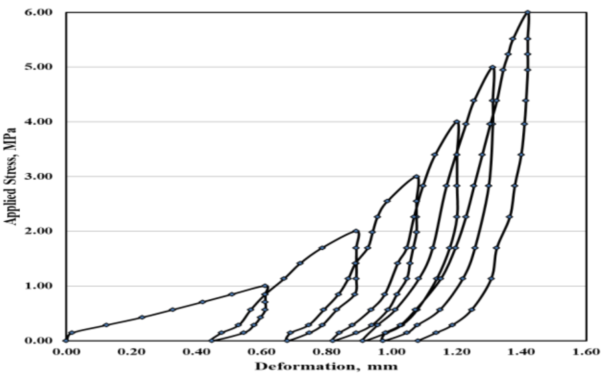


**Fig. 8.** Stress-deformation plot for PLT

## 4 Conclusions

Based on this study, the following conclusions can be drawn:

For reliable assessment of deformation modulus of rock, the tests should be carried out in fresh rock as weathering leads in significant reduction in modulus values.

Deformation modulus increases with applied stress. However, due to excessive deformations or fracturing of weak rock mass fabric, higher applied stress may not necessarily yield the increase in modulus. Repeated or sustained loading tends to strengthen the rock mass and improves the deformability behaviour given the condition that repeated loading does not cause formation of additional fractures or crushing of rock material.

Rock mass being anisotropic material, deformation modulus varies with application of stress orientation. In the present study, feldspathic gneisses showed anisotropy. Modulus of deformation by GJT at 10 MPa stress level with loading directions along, perpendicular, vertical and oblique directions with respect to dam axis was found to be 3.630 GPa ($E_{m(x)}$), 3.725 GPa ($E_{m(y)}$), 3.033 GPa ($E_{m(z)}$) and 3.317 ($E_{m(o)}$) GPa, respectively. Thus, the variation in deformation modulus was observed to be of the order of 9.4% to 22.8% when compared with vertical loading direction. Deformation modulus in vertical loading direction ($E_{m(z)}$) was found to be 3.033 GPa at 10 MPa stress level and observed to be the lowest. Hence, the anisotropic studies can be helpful in safe design of structures using critical modulus values.

The estimated modulus by PLT at 10 MPa stress through extrapolation of PLT data worked out to be 3.5 GPa which is in well coherence with modulus values of the order of 3-3.7 GPa measured using GJT at same stress level.

Comparison of intact rock modulus ($E_r$) with rock mass modulus ($E_m$) can be done if the latter is tested upto failure. However, no in-situ test method is capable of providing unique value of $E_m$, but an attempt was made to estimate the ultimate modulus of rock mass by extrapolating the field test data upto the stress level corresponding to UCS. $E_r$ was found to be 3.4 and 4.8 times the in-situ modulus $E_m$ by PLT and GJT, respectively. Therefore, it is always advisable to measure the in-situ modulus rather than assuming it using the correlations in view of influence of geology, environmental factors and test method.

Behaviour of rock mass whether elastic, plastic or elasto-plastic depends mainly on the number of joints, their spacing, orientations, joint properties and properties of infilling material. In cyclic tests, recovery of deformations during unloading increases in stress in successive cycles. This may be attributed to the closing of joint spaces in successive loading cycles and strain hardening of the material. With increased number of loading cycles, behaviour of rock mass shifts towards elastic nature. Due to the involvement of more number of discontinuities under the loading platens, plasticity/elasticity of rock mass is represented better in PLT in comparison with GJT.

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