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Anisotropic Deformation Behaviour of Augen Gneiss

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ABSTRACT

Modulus of deformation of rock mass is essential parameter required for the design and performing stability analysis of surface and subsurface structures. The rocks are anisotropic which can be accredited mainly to the geological variability and in particular the nature and extent of discontinuities; mineralogical variations and many more reasons. Anisotropy in foliated rocks can be studied by stress application parallel and perpendicular to the foliations and reasonable degree of variations are observed in stress-deformation characteristics. Deformability test is performed on intact cores as well as on in-situ rock mass. Uniaxial jacking tests (UJT) is one of the methods used for determination of modulus of deformation of rock mass. The test can be conducted by applying uniaxial stress in vertical, horizontal or in any inclined direction and response of the rock mass to applied stress is recorded in terms of deformations. Anisotropy in augen gneiss of powerhouse drift at Pancheshwar multipurpose project, India/Nepal was studied by conducting UJT with stress application in nearly parallel and perpendicular to foliation joints striking parallel to drift and dipping vertically/sub-vertically. Compared with stress application parallel to foliation, around 30-40% increase in values of modulus were observed with stress application perpendicular to foliation plane.

Keywords: Anisotropic; Foliation joints; Deformation modulus; Uniaxial jacking tests

1. INTRODUCTION

Foliated rocks like slates, gneisses, phyllites, schists etc. exhibit anisotropy. Due topresence of parallel orientation of microscopic grains of mica, chlorite or other thin sheets like platy minerals. Such rocks have tendency to split along these week planes. The rocks like gneisses can also have alternating layers of different mineral compositions. Sedimentary or stratified rocks like sandstones, siltstones, shales, limestones also show anisotropic behaviour. 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). On the contrary, behaviour of rock and rock mass is assumed to be linearly elastic in analytical models.

Deformation modulus of rock mass can be assessed by plate load/plate jacking test (known as uniaxial jacking test), bore hole jacking test, flat jack jests, dilatometer and radial jacking tests. Goodman jack test is the easiest and the fastest method to determine anisotropic behaviour of the rock mass. (Singh, 2009). Rock mass deformability is scale and stress dependent and usually shows strong anisotropy (Zhang, 2017). Ramana et al. (2016) studied stress-deformation anisotropy in biotitic rocks with stress application in 3 mutually perpendicular directions. This paper discusses anisotropy in augen gneisses rock mass based on studying stress-deformation characteristics by uniaxial jacking tests. The stress was applied nearly parallel and perpendicular to foliations.

2. UNIAXIAL JACKING TEST

Uniaxial jacking test involves application of stress on two parallel flat surfaces and measurement of resulting deformation. Expected stresses on the foundation due to the proposed structure forms the basis for deciding the maximum stress to be applied. The stress is applied in five cycles of loading and unloading. The resulting deformations in each cycle are used to evaluate the moduli of deformation and elasticity corresponding to the applied stress. Evaluation of deformation modulus is based on rigid plate pressed into semi-infinite elastic medium using the Eq. 1. (IS 7317).

$$E_d = \frac{Pm(1-\upsilon^2)}{\delta\sqrt{A}} \tag{1}$$

where

E_d	= modulus of deformation,
P	= total load on the test plate,
m	= constant depending upon the shape of plate (0.96 for circular plate)
υ	= Poisson's ratio of the rock (0.25 for gneissic rocks),
δ	= total deformation of the test plate during loading cycle, and
A	= area of test plate.

On substituting, δ = Recovered deformation during unloading, Eq.1 would determine value of elastic modulus (E_e) or unloading modulus instead of deformation modulus (E_d).

3. GEOLOGY OF EXPLORATORY DRIFT

The Pancheshwar multipurpose project, India/Nepal has been envisaged across Mahakali river for power generation, irrigation and flood regulation purposes. Investigations were done in exploratory drift (D2) on the right bank powerhouse. The total length of drift is 118m with 46m straight stretch along N65°W. Major type of rock encountered in the drift is augen gneiss. Foliation plane strikes in N70°W direction with 80° dip amount. Uniaxial jacking tests (UJT) were conducted between 23.5m to 34m. Rock mass rating (RMR) varies in the range from 43 to 63 and Q-value ranges between 3.3 and 6.5. Minor shear seams were observed between 30m to 38m on the crown. 3D-log of drift with test locations (marked as box shape) is shown in Fig.1.

Portal of exploratory drift depicting the foliation joint orientation is shown in Fig. 2. It can be seen that foliation joints are thinly foliated with some random joints. The entire drift is in saturated condition and dripping at number of places.

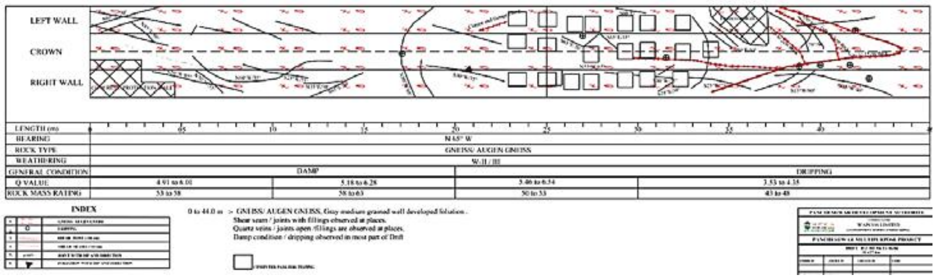


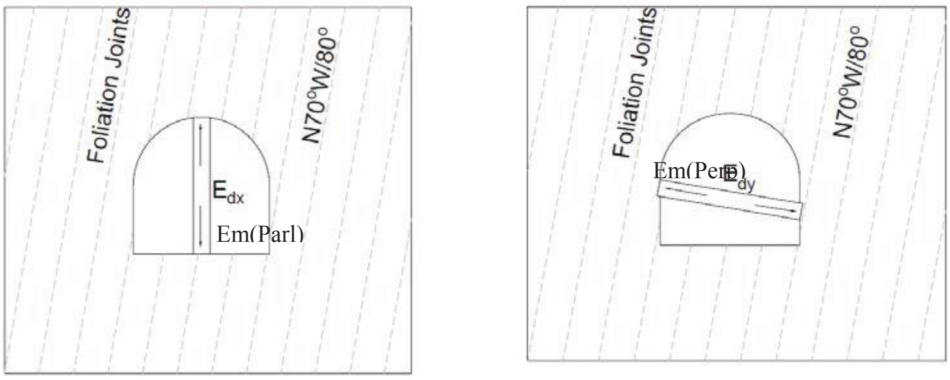
Figure 1 - 3D Log of exploratory drift D2

Figure 2 - Drift portal and inside view

4. TEST METHOD TO STUDY ANISOTROPY BEHAVIOUR

In order to assess the degree of rock mass anisotropy, field tests were conducted in different directions with respect to the apparent rock mass fabric. As the foliations are vertical/sub-vertical, the in-situ tests were planned with stress application in nearly parallel and perpendicular directions to foliation joints so as to assess the anisotropic behaviour. The modulus of deformation obtained from the test results was denoted by:

a) $E_{m(Parl)}$ - Deformation modulus with stress application nearly parallel to foliation plane (Fig. 3a)
b) $E_{m(Perp)}$ - Deformation modulus with stress application perpendicular to foliation plane (Fig. 3b)



(a) Applied stress nearly parallel to foliation (10°)

(b) Applied stress perpendicular to foliation

Figure 3 -Stress directions to study anisotropy in deformation modulus

The tests were conducted in accordance with the provisions laid in Indian Standard - Code of practice (IS: 7317). Test setup showing the equipment assembly is shown in Fig.4.

a) Stress nearly parallel to foliation (b) Stress perpendicular to foliation

Figure 4–Photographs showing the test setup

5. IN-SITU TEST RESULTS

Total 11 number of tests (6 nearly parallel to foliation and 5 perpendicular to foliation plane) were conducted between 23.5m to 34m and the details are given in Table 1. Deformations were measured at bottom plate in case of vertical uniaxial jacking tests whereas in horizontal uniaxial jacking tests, deformations were measured on both the loading surfaces i.e. upstream and downstream walls. Maximum stress of 6MPa was applied in all the tests and modulus values were calculated considering average deformations from all the dial gauges (CSMRS, 2016).

Deformation modulus of rock mass is not a constant parameter and depends on applied stress level (IS: 7317, 2010; Palmström and Singh, 2001; Pathak et al., 2013, Pathak etal., 2015, and Senthil etal., 2019) till the applied stress does not cause any fractures. The rock mass deformability characteristics largely depend on two factors such as applied stress and scale effect (Dev, 2020). The deformation modulus values at different stress levels have been presented and analysed in this study. First loading cycle being non-representative of actual rockmass behaviour, the results are omitted from the final recommendations.

Table 1- In-situ test location details

Location & stress orientation				Applied stress (MPa)	Rock type	Rock mass grade	
RD m	Parallel to foliation plane	RD m	Perpendicular to foliation plane			Q	RMR
23.5	UJT-1	-	-	1 to 6	Medium grained augen gneiss Drift was un-supported.	5.5-6.5	50 to 53
25.0	UJT-2	25.0	UJT-7	1 to 6 /1 to 5		5.5-6.5	50 to 53
27.5	UJT-3	27.5	UJT-8	1 to 6		5.5-6.5	50 to 53
29.5	UJT-4	29.5	UJT-9	1 to 6		5.5-6.5	50 to 53
30.5	UJT-5	30.5	UJT-10	1 to 5		3.5-4.4	43 to 48
-	-	32.8	UJT-11	1 to 6		3.5-4.4	43 to 48
34.0	UJT-6	-	-	1 to 6		3.5-4.4	43 to 48

5.1 Stress Orientation -Nearly Parallel to Foliation Plane

To facilitate in-situ test, stress direction was kept at 10^o away from the foliation planes. Variation of deformation modulus values with applied stress obtained from six tests with stress application parallel to foliation plane is given in Table 2 and the same are graphically presented in Fig. 5. On inspection of test data, UJT-3 being an outlier, results have not been considered while averaging. The low modulus values in UJT-5 and UJT-6 are attributed to the presence of minor shear at the test location, which has also reflected in RMR and Q-values. Modulus values increase with applied stress level. Average $E_{m(Parl)}$ corresponding to 6MPa stress level was found to be 1.2GPa.

Table 2 - Variation in modulus values ($E_{m(Parl)}$) with applied stress

Stress Level (MPa)	UJT-1	UJT-2	UJT-3	UJT-4	UJT-5	UJT-6	Average $E_{m(Parl)}$
2	0.8	0.6	1.4	0.6	0.3	0.3	0.5
3	1.2	0.8	1.9	0.8	0.5	0.4	0.7
4	1.5	1.2	2.2	1.0	0.7	0.5	1.0
5	1.6	1.4	2.6	1.2	0.8	0.7	1.1
6	1.7	1.5	2.7	1.3	0.9	0.8	1.2

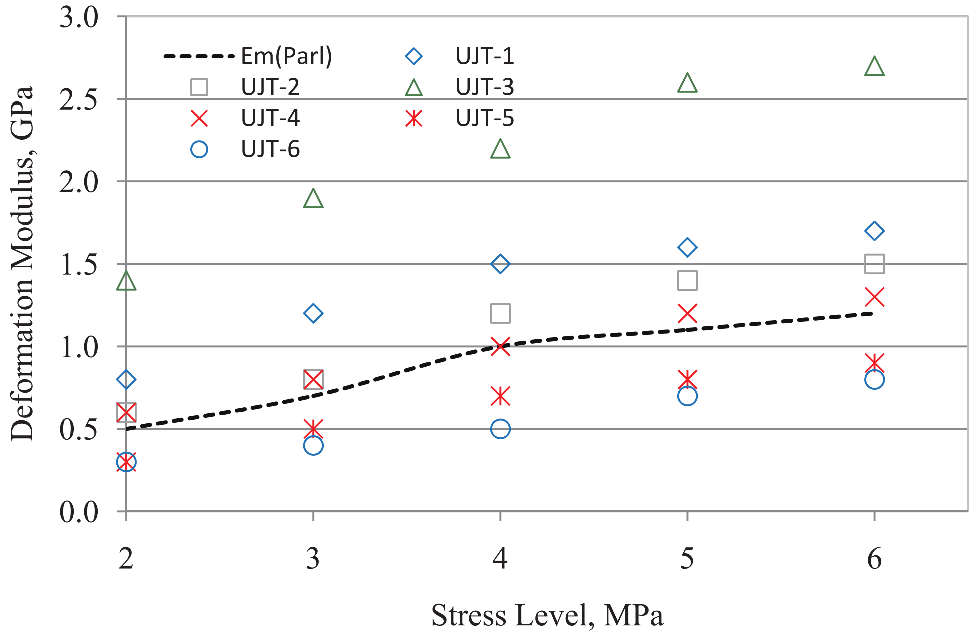


Figure 5 - Test results - $E_{m(Parl)}$ with different stress level

5.2 Stress Orientation - Perpendicular to Foliation Plane

Deformation values arrived from five tests conducted with stress application perpendicular to foliation plane are presented in Table 3 and plotted in Fig. 6. Modulus values increases with applied stress level. Average $E_{m(Perp)}$ corresponding to 6 MPa stress level was found to be 1.7GPa.

Table 3 - Variation of modulus values ($E_{m(Perp)}$) with applied stress

Stress Level (MPa)	UJT-7	UJT-8	UJT-9	UJT-10	UJT-11	Average $E_{m(Perp)}$
2	0.9	0.5	0.6	0.9	0.6	0.7
3	1.1	0.7	1.0	1.4	1.2	1.1
4	1.4	1.1	1.3	1.6	1.3	1.3
5	1.7	1.1	1.5	1.8	1.6	1.5
6	1.8	1.4	1.7	2.0	1.7	1.7

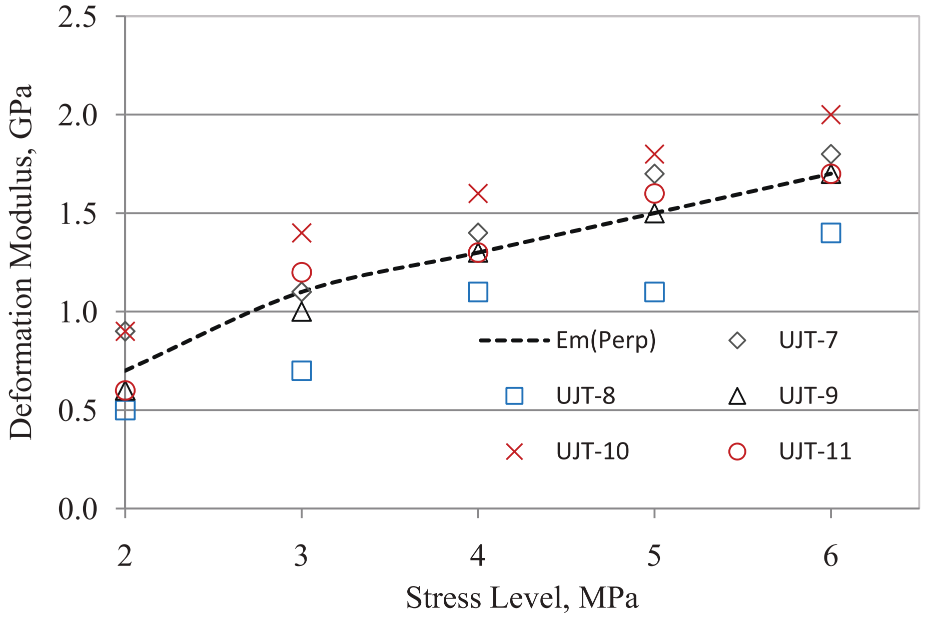
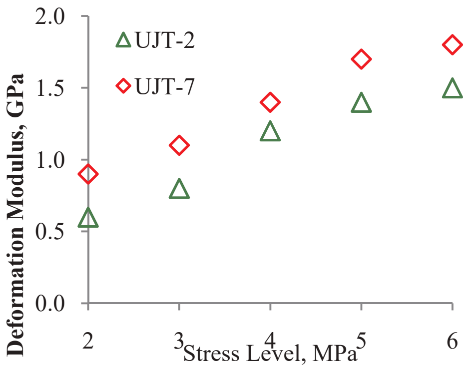


Figure 6 - Test results - $E_{m(Perp)}$ with different stress level

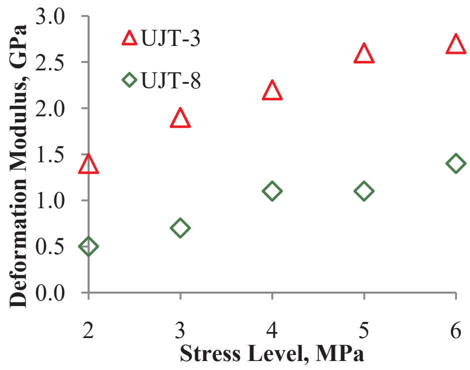
6. ANISOTROPIC BEHAVIOUR

Results of UJT with stress application in parallel and perpendicular direction to foliation plane were compared and analysed to study the anisotropy. Tests at four locations were conducted exactly in both directions i.e. RD25m, RD27.5m, RD29.5m and RD 30.5m and comparative deformation modulus-stress curves are shown in Fig. 7. It can be seen that deformation modulus values with applied stress perpendicular to foliation is higher than those in parallel direction. The mean values of modulus at different stress levels have also been plotted in Fig. 8. Trendlines drawn show perfect correlation between stress and modulus values. The deformation modulus in stress orientation perpendicular to the foliation ($E_{m(Perp)}$) was found to be 1.7GPa at stress level of 6MPa whereas the corresponding value with stress direction parallel to foliation ($E_{m(Parl)}$) was 1.2GPa, thus confirming the anisotropic behaviour of rock mass.

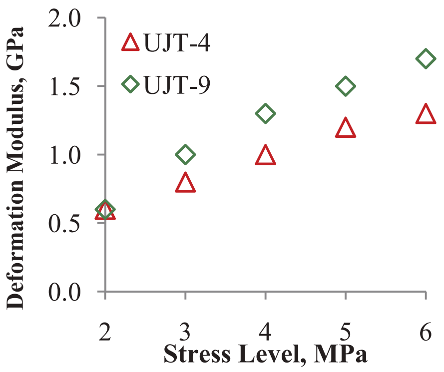
Under the application of stress in jointed rocks, most of the deformation is attributed to i) closing of joint spaces, ii) sliding along the joints and iii) compaction of infilling material. In the present case study, the augen gneisses are thinly foliated (Fig. 2). Foliation joints are tight and stability of drift without any artificial support confirms the compact nature of foliations. Due to applied stress, thin foliations gets compressed whereas, due to compact nature of the foliations, deformations are restricted with stress application normal to foliation planes. This is the main reason for higher values of deformation modulus with stress direction perpendicular to foliations.



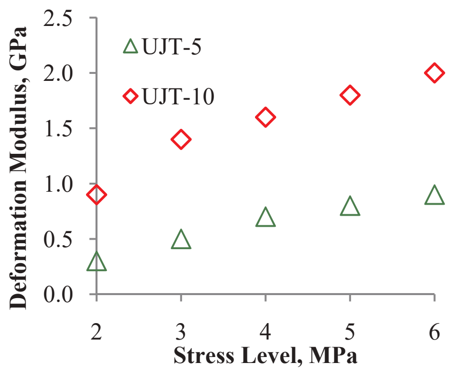
a) RD25 m



b) RD 27.5
c)



c) RD 29.5 m



d) RD 30.5 m

Figure 7 -Location wise comparison of $E_{m(Parl)}$ and $E_{m(Perp)}$

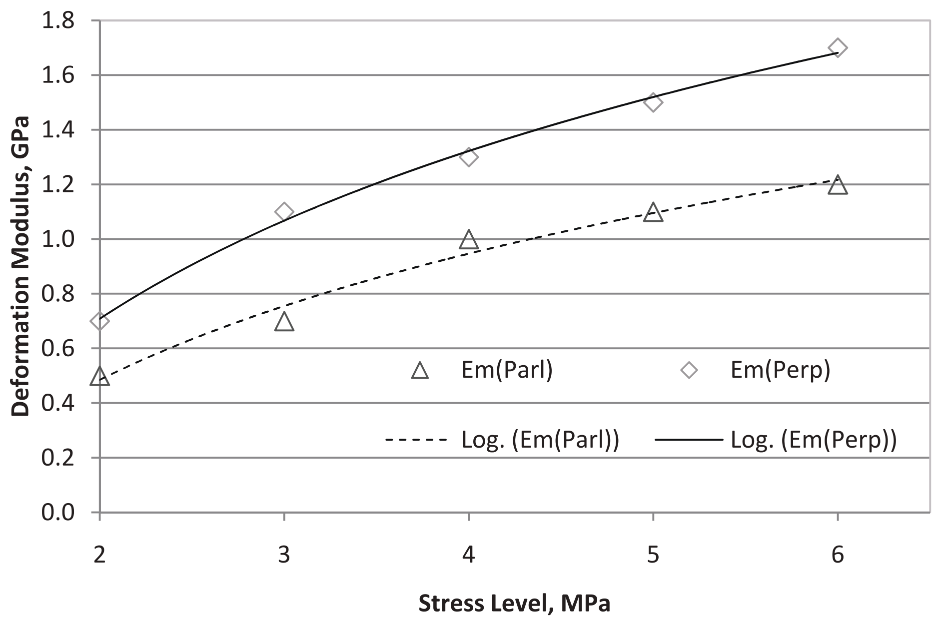


Figure 8 - Stress vs average values of deformation modulus ($E_{m(Parl)}$ and $E_{m(Perp)}$)

Average deformation modulus values in both directions were correlated with stress level. Logarithmic equation best fits to the test data with following equations:

$$E_{m(Parl)} = 0.67 \ln(\sigma) + 0.024 \quad (R^2 = 1.0) \tag{2}$$

$$E_{m(Perp)} = 0.89 \ln(\sigma) + 0.095 \quad (R^2 = 0.98) \tag{3}$$

where $E_{m(Parl)}$ and $E_{m(Perp)}$ are deformation modulus in stress directions parallel and perpendicular to foliations respectively; σ is applied stress.

The laboratory tests on intact cores revealed deformation modulus (E_r) as 11.67GPa. Modulus of deformation of rock mass is stress dependent and varies with applied stress. Secondly, due to large size of the loading area and limitations due to capacity of the testing equipment, rarely sufficient stress is applied to cause fractures in the rock mass to have a unique value of its deformation modulus. Hence, it will not be advisable to compare the modulus of intact rock with that of the rock mass at certain stress level (Dev et al., 2020).

Hence, an attempt was made to estimate the modulus of rock mass by extrapolating the test results to the applied stress corresponding to 45.5 MPa (UCS of intact cores) pertaining to the same rock from the same project site. Therefore, using the trend line equations 2 and 3, the deformation modulus of rock mass were estimated at 45.5 MPa stress level. The extrapolated values of modulus ($E_{m(Parl)}$ and $E_{m(Perp)}$) at stress level corresponding to UCS were estimated to be 2.58GPa and 3.49GPa. Comparing these values with modulus of intact rock, the modulus ratios (E_m/E_r) come out to be 4.52 and 3.34. In the absence of field tests, the modulus of deformation of rock mass is normally assumed to be 1/4th of the modulus of intact rock. The modulus ratios evaluated from the present study are in close conformity of this assumption. For design purpose, the deformation modulus shall be taken corresponding to stress level expected due to the proposed structure or stress expected in the vicinity of underground excavations.

7. CONCLUSIONS

Based on this study, the following conclusions are drawn:

- Modulus of deformation of rock mass is stress related. Because of anisotropy, the modulus values vary with direction of loading, particularly with respect to the foliation or bedding planes. Present study based on in-situ uniaxial jacking tests on augen gneiss with foliation joint (N70^{o}W/80^o) striking parallel to drift and dipping vertically/sub-vertically reveals anisotropy in rock mass. Stress was applied in parallel and perpendicular directions to foliation plane. Compared with stress application parallel to foliation, around 30-40% increase in values of modulus were observed with stress application perpendicular to foliation plane.
- Recommended modulus values in the loading directions; nearly parallel and perpendicular to foliation were 1.2 GPa and 1.7 GPa, respectively after omitting the outliers.
- The values of modulus of deformation of rock mass were also compared with modulus of intact rock. For rational comparison, the tests data was extrapolated to estimate the field modulus at the stress level corresponding to the unconfined compressive strength (UCS) of intact rock

samples. Deformation modulus of intact rock was found to be about 4 times than that of the estimated rock mass at extrapolated stress level corresponding to UCS of intact rock.

- Uniaxial jacking tests with 60 cm diameter of rigid plates cover large volume of rock and the effect of discontinuities. However, site preparation needs utmost care such that disturbance to the parent rock is minimal. Thus, field tests are expensive and time consuming as compared to the laboratory tests. Though, correlations between field modulus and intact rock modulus have been suggested by researchers, but there is no substitute for actual testing at site.
- It is also suggested that any in-situ test shall be planned considering the local geological features and the design requirements.

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