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Effect of Weathering on the Modulus of Deformation of Gneisses of Peninsular India

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ABSTRACT

Modulus of deformation of rock mass is dependent on many factors such as nature, extent of discontinuities, aperture of joints, joints infilling, grain size distribution and weathering etc. Modulus of rock mass can be determined by in-situ testing, which should be encouraged as these are the most reliable methods. Designers use the indirect methods in the initial planning as the in-situ tests are costly, difficult and time consuming. However, during detailed designing in-situ tests are mandatory. This paper highlights the effect of weathering on the modulus of deformation of gneisses rock mass. The study is based on plate load tests conducted at foundation level of spillway in Precambrian rock known as Eastern Ghat Mobile Belt of Peninsular India.

Keywords: Modulus of deformation; Plate load test; Gneiss; Weathering

1. INTRODUCTION

Rocks normally change their physical characteristics under the action or influence of certain environmental factors viz. biological activity, extreme weather and agents of erosion such as water, wind and ice. These forces influence the continuous breakdown, wearing away and loosening of rocks and soils, thus degrading the engineering properties. Weathering processes are of three main types: mechanical, organic and chemical weathering. The Geological Society, London (1977) classified the different grades of weathering of sedimentary and metamorphic rocks as residual soil (Grade VI), completely weathered (Grade V), highly weathered (Grade IV), moderately weathered (Grade III), slightly weathered (Grade II), faintly weathered (Grade IB) and fresh (Grade IA).

Borrelli et al. (2006) confirmed through quantitative data that the weathering of a rock mass can be assumed as a predisposing factor to the slope instability. Miščević and Vlastelica (2014) studied the effect of weathering on soft rock mass and concluded that temporary stability on untreated slopes is possible in periods ranging from several dozens of days to several years, but the study was inconclusive about the timeline for weathering process to lead loss of strength and ultimately to the sliding and detachment of the slope material.

Relation between engineering properties and weathering grades has been described in detail by Santi (2006). Study by Fehmi and Nihal (2012) on influence of weathering on engineering properties of various grades of weathered dacites (igneous, volcanic rocks) pointed out

dominance of chemical weathering process, whereas fracturing and faulting also play crucial role in the development of weathering profiles.
Atmospheric weathering of residual, coarsely fragmented rock formations leads to a change in their physical properties (Shvets and Gaiduk, 1976). Importance of weathering in rock engineering has been discussed in detail by Goel and Mitra (2015).

Srivastava (2014) noticed the effect of weathering on basalts and concluded that physical and chemical weathering is significant in basaltic area especially upto 7 to 8 m depth. Weathering reduces the joint wall compressive strength (JCS) by 20-25% compared with the fresh porphyritic granite joints and friction angle mainly depends on weathering (Woo et al., 2010). Studies on peak friction angle of granites showed approximately 60° for fresh granites, from 50 to 60° for slightly weathered (SW) granite joints and from 40 to 50° for moderately weathered (MW) joints to highly weathered (HW) granite joints. The residual friction angle is much lower than the peak friction angle. It ranges from 30° to 35° for fresh (F) to SW joint surfaces and from 24° to 27° for MW to HW surfaces. Gurocak and Kilic (2004) studied the effect of weathering on geo-mechanical properties of Miocene basalts in Malatya, Eastern Turkey. The studies indicated that RQD values of the unweathered/ fresh and slightly weathered basalts are 75–100% while those of the moderately and highly or completely weathered basalts are 40–85 and 0–50%. Sener et al. (2008) indicated that p-wave velocity is important parameter for assessment of weathered granitic rock.

2. GEOLOGICAL DETAILS

The rocks exposed in the area belong to Khondalite suite, trending in ENE - WSW direction, of Eastern Ghat Mobile belt of Archean age. The prominent rock types in the area are garnetiferous quartzo-feldspathic gneiss, garnet biotite gneiss, charnockite and migmatite gneiss. The rocks are weathered to fresh, hard and competent in nature. The strike of the foliation in the area trends along NE-SW direction with dip varying from 50^0 to 80^0 towards south-east (i.e. towards downstream and skew to dam alignment). Variation in foliation is also observed at places, which is due to folding. The rock mass is intersected by two prominent joint sets and random joints. The details of prominent joint sets in the area are given in Table 1.

Table 1: Characteristics of prominent joint sets

Sl. No.	Strike of Joints	Dip Amount	Spacing of Joints	Orientation with reference to dam axis
1.	N $10^0 - 25^0$W S$10^0 - 25^0$E	Vertical or near vertical	Random	Almost perpendicular
2.	N$65^0 - 80^0$ E S$65^0 - 80^0$ W	$40^0 - 80^0$ dipping due S$25^0 - 10^0$E (i.e. downstream)	0.50 to 2.0 m	Parallels to dam axis.
3.	N10^0E – S10^0W	Steep dips or vertical	Random	Perpendicular to dam axis
4.	N80^0W – 5$80^0$E	Vertical	-do-	Parallel to dam axis

The joints, in general, are tight to slightly open, moderately to widely spaced, rough, planar, irregular, continuous to discontinuous and straight to curvilinear in nature. UCS of the fresh rock varies from 80 to 100 MPa in both dry and saturated conditions. Weathering is commonly observed in the area and varies from highly weathered to slightly weathered. However at places weathering is so intense that the rock is converted into reddish brown silty clay soil. The rock in the area also consists of pegmatite bands/veins of varying thickness ranging from few centimeters to a meter. It is also noticed that wherever these pegmatite bands/veins exist, generally they are sheared and crushed, affecting the adjoining rock mass.

3. MODULUS OF DEFORMATION OF ROCK MASS

Commission of Terminology of the International Society for Rock Mechanics (ISRM) defined modulus of deformation of rock mass in 1975.

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

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

Modulus of elasticity of rock mass: The ratio of stress to corresponding strain during unloading of a rock mass, including only the elastic behaviour.

The modulus of rock mass is denoted in terms of modulus of deformation rather than modulus of elasticity, because rock mass contain joints and during loading permanent deformations occur because of closing of the joint openings.

4. OBJECTIVE OF PLATE LOAD TESTS

Since the area of interest encompasses various degrees of weathering (fresh to highly weathered) of rock mass, it is important to determine the modulus of deformation as acceptable founding material. Accordingly, 7 plate load tests (PLT) were conducted along the spillway axis between chainage 60m to 380m (RL 9.567 m to 10.345 m) as given in Fig. 1.

Figure 1: Layout plan showing the plate load test locations

5. TEST METHODOLOGY

Surface preparation for the plate load tests was done carefully using electrically operated small cutting machines, grinders, chisels and hammers. The surface was made smooth with undulations less than 5 mm. Rock powder from grinding was used for smoothening the minor undulations.

Excavator weighing 120 tonnes was used for providing the desired loading (Fig. 2). For this, a beam consisting of ISMB 300 sections, stiffeners and flange plates was designed and fabricated in the project workshop and the same was welded on the bottom plate of the excavator with its center matching with the center of gravity of the excavator. Hence, this mobile excavator of 120 tonnes weight was considered adequate for providing ultimate load of 72 tonnes during testing. Ramps were provided on both sides of the test location to make head room for installation of loading assembly and deformation measuring setup. This mobile loading arrangement was helpful in conducting as many as 7 tests in shortest possible time of 5 working days.

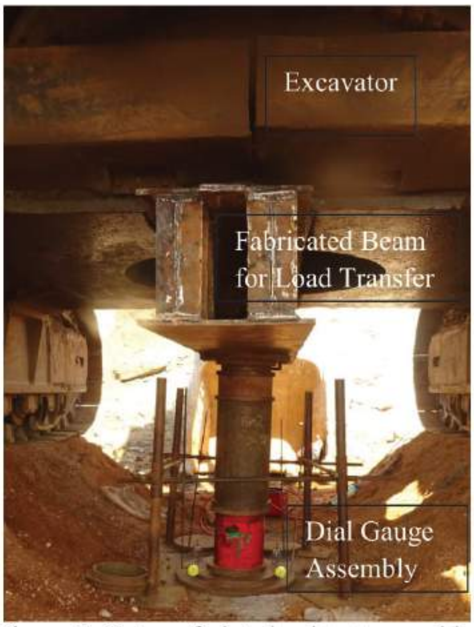

Figure 2: Setup of plate load test assembly

Two sets of plate load tests as per the requirements of the project were carried out at foundation level of the spillway. Accordingly, the results were analyzed and the deformability characteristics have been recommended.

The maximum load was decided on the basis of stresses expected on the foundation and the provisions of IS 7317:1993. Considering height of spillway dam /spillway above the foundation level as 44m, the maximum stress works out to be 1.10 MPa due to the weight of the proposed structure. Keeping a factor of safety of 1.5, the stresses work out to be 1.65 MPa. Further, IS 7317:1993 suggests the applied stress to be kept as 1.2 to 1.5 times the stresses expected on the foundation due to proposed structure. Based upon the above criteria, maximum stress level of 2.5 MPa was arrived at. Since cyclic loading is specified for the plate load tests, the loading cycles were decided as 0.5, 1.0, 1.5, 2.0, and 2.5 MPa. Based on this, maximum stress level of 2.5 MPa, ultimate load of 72 tonne was applied using 60 cm diameter base plate.

The load was applied by means of jack and pump and the test was completed in five loading and unloading cycles as per ISRM (2007) and IS 7317:1993. The deformations were recorded using four dial gauges with an accuracy of 0.01 mm, installed diagonally on the bottom plate.

The modulus of deformation for the loading cycle has been calculated by considering total deformation during a particular cycle, whereas, modulus of elasticity has been calculated by considering elastic deformation for the same cycle using the Eq. 1.

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

where

E = modulus of deformation/elasticity,
P = applied load,
ν = Poisson's ratio of rock mass (ν = 0.20 for the granite rock mass),
m = constant depending upon the shape of plate (m = 0.96 for circular plate),
δ = deformation corresponding to load, and
A = area of loading plate.

Considering the Poisson's ratio of the rock mass as 0.20 and the 60 cm diameter circular plate used in the investigation, Eq. 1 reduces to:

$$E = \frac{0.00173319P}{\delta} \tag{2}$$

The Eq. 2 was used to calculate the values of moduli of deformation and elasticity using the total deformation of the loading cycle and elastic deformation of unloading cycles, respectively.

6. RESULT AND DISCUSSIONS

Seven plate load tests were conducted in rock mass comprising garnetiferous quartzo-feldspathic gneiss with varying degree of weathering, jointing and water seepage conditions. Exposed rock mass at all the locations is shown in Figs. 3 to 8.

Figure 3: Exposed rock mass around chainage 60 m (PLT-1)

Figure 4: Exposed rock mass around chainage 100 m (PLT-2)

Figure 5: Exposed rock mass around chainage 200 m (PLT-3)

Figure 6: Exposed rock mass around chainage 310 m (PLT-4)

Figure 7: Exposed rock mass around chainage 350 m and 360 m (PLT-5 and PLT-6)

Figure 8: Exposed rock mass around chainage 380 m (PLT-7)

The modulus of deformation of rock mass was determined at applied stress levels varying from 1.0 MPa to 2.5 MPa. Stress-deformation plot for PLT-1 (fresh rock), PLT-4 (fresh to moderately weathered rock) and PLT-7 (moderately weathered rock) is shown in Fig. 9, 10 and 11, respectively. Rock mass conditions at various test locations alongwith modulus values have been summarized in Table 2.

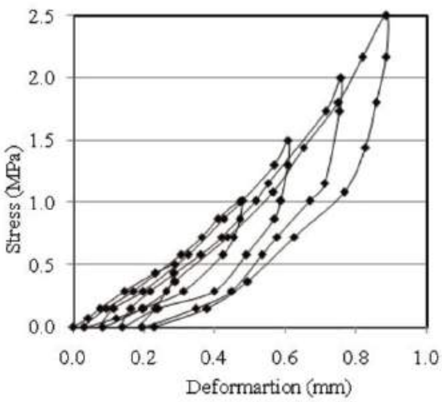

Figure 9: Stress-deformation plot for PLT-1

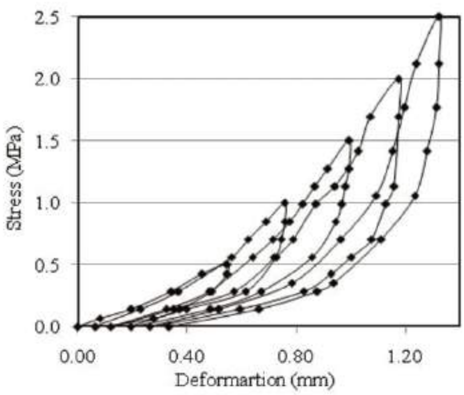

Figure 10: Stress-deformation plot for PLT-4

Clear trend in values of modulus of deformation with geological variations at various locations along the spillway axis was observed. Massive rock mass with wider spacing of joints and almost dry conditions at test locations 1 and 2 (between chainage 60 to 100 m) indicated higher modulus of deformation. The rock conditions deteriorates in respect of weathering, joints, water, fracturing and presence of shear seams from left flank to 380 m chainage towards right flank. Effect of these factors on the modulus of deformation can be seen (Table 2).

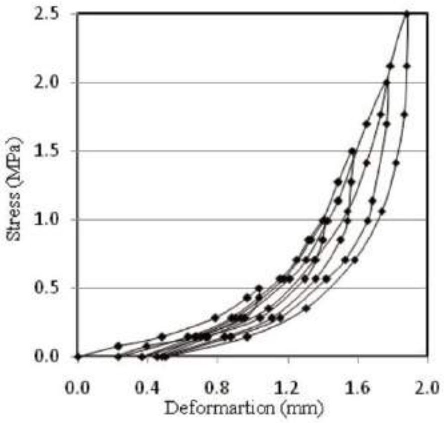

Figure 11: Stress-deformation plot for PLT-7

Table 2: Rock mass conditions and variations in modulus values

Item	Test No.						
	PLT-1	PLT-2	PLT-3	PLT-4	PLT-5	PLT-6	PLT-7
No. of Joint Sets	3	3	4	2	2	2	2
Spacing of Foliation Joint, S1	very wide	very wide	closely spaced	moderately to very wide	wide	moderately to highly jointed	moderately to closely jointed
Spacing of Joint Set, S2	very wide	very wide	very wide	wide	wide	wide	moderately to closely jointed
Roughness	rough planar	rough planar	rough planar	rough irregular	rough irregular	rough irregular	rough irregular
Opening/ Infilling	tight to open	tight to partly open	tight to partly open	tight	partly open	partly open	highly jointed and fractured
Rock Class	I	II	III	I	III	III	IV
Dry/wet	dry	generally dry	dry	damp to water seepage conditions	damp to water seepage conditions	damp to water seepage conditions	moist to dipping
Weathering around test locations (above 10 RL)	fresh	fresh	fresh	fresh/slightly weathered	fresh/slightly weathered	slightly to moderately weathered	slightly to moderately weathered
Modulus of Deformation (E_d) at 2.5 MPa stress	1.817	1.951	1.469	1.178	1.141	0.759	0.894
*Total Deformation, mm	0.88	0.89	0.95	1.32	1.20	2.43	1.88
*Elastic Deformation, mm	0.65	0.61	0.83	0.99	1.08	1.50	1.38
*Plastic Deformation, mm	0.23	0.28	0.12	0.33	0.12	0.93	0.50

* After 5 cycles of loading, i.e. 2.5 MPa applied stress Level

To study the behaviour of rock mass, ratio of elastic deformation to total deformation (δ_e/δ_d) in various cycles of loading was plotted against applied stress (Fig. 12). First cycle was intentionally omitted here as the deformations occurring during the first cycle may not be true due to initial packing and adjustments of minor undulations of the rock below the plate. The recovery of deformation during unloading was observed to vary between 89.9 to 95.5 percent with variation in stress level from 1.0 MPa to 2.5 MPa. From Fig. 12, it can be seen that recovery in deformation increases with increase in applied stress. This means average plastic deformation in fifth cycle of loading i.e. at applied stress level of 2.5 MPa was of the order of 4.5% of the total deformation occurred. This is due to the closure of joint openings at higher normal stress. A trendline was also drawn and the coefficient of correlation (R^2) was found to be 0.99 (almost 1.0). The following correlation between ratio of elastic deformation to total deformation (δ_e/δ_d) and applied stress (P) was obtained:

$$\delta_e/\delta_d = 0.9\,P^{0.07} \tag{3}$$

where

δ_e = elastic deformation during unloading,
δ_d = total deformation during loading, and
P = applied stress level in MPa.

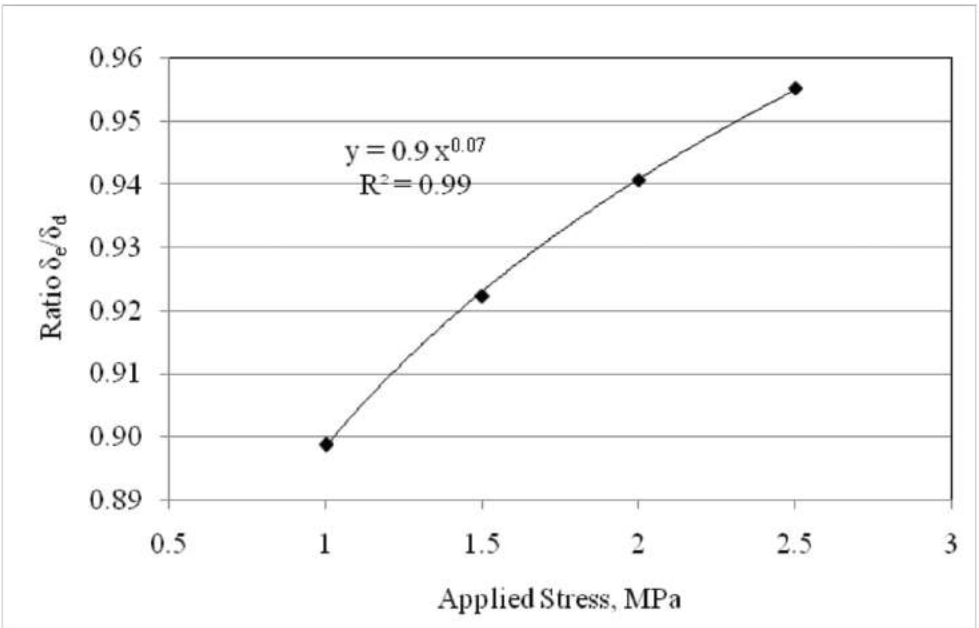

Figure 12: Percentage recovery of deformation versus applied stress

8. CONCLUSIONS

- Fresh to slightly/moderately weathered jointed gneisses rock mass of Peninsular India with dry to dripping conditions have been tested in-situ for modulus of deformation. Broadly, with deterioration in rock mass condition because of weathering, the declining trend in modulus values was observed.

- The modulus of deformation values were obtained as 1.817 GPa, 1.951 GPa and 1.469 GPa in fresh rock conditions (PLT-1, PLT-2 and PLT-3); 1.178 GPa and 1.141 GPa in fresh to slightly weathered rock conditions (PLT-4 and PLT-5); 0.759 GPa and 0.894 GPa in slightly to moderately weathered rock conditions (PLT-6 and PLT-7). Therefore, vis-à-vis, the fresh rocks, the decrease in modulus values of the order of 41.5 % and 61% was observed from fresh to slightly weathered and to moderately weathered rock, respectively. However, the behaviour of rock mass was observed to be trending towards elastic with recovery of deformations during unloading (5^{th} cycle) as high as 95% of the total deformation occurred during loading at 2.5 MPa applied stress level. A correlation was also derived between ratio of elastic deformation to total deformation and applied stress ($\delta_e/\delta_d = 0.9\ P^{0.07}$) with correlation coefficient R^2 as 0.99. This is also equal to the ratio between modulus of deformation and the modulus of elasticity which increases with the applied stress on the plate.

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