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Stress- Deformation Properties of Rock Material and Rock Mass – An Overview

Hari Dev

Central Soil & Materials Research Station
New Delhi, India

**E-mail: haridev65@gmail.com*

ABSTRACT

Stress-deformation characteristics of rock are very essential for the design of structures on/inside the rock and use of rock in construction, architectural or any other purpose. These properties are influenced and controlled by many factors. It is practically not feasible to exactly assess of impact of these factors on the strength and deformation properties of rock/rock mass. Even though various state of the art techniques are available for characterization of rock and rock mass, but scatter in test results cannot be prevented due to heterogeneity and discontinuities. This paper presents an overview of the deformability characteristics of rock mass.

Keywords:Anisotropy; Modulus of deformation; Modes of failure; Weathering; Machine stiffness

1. INTRODUCTION

Characterization of rock and rock mass faces many challenges. The major challenge in defining the physico-mechanical or chemical properties of rock is geological, mineralogical and environmental variability in the naturally occurring material. The other challenges include sample selection, preparation,size, testing methodology, equipment and interpretation. Arriving at realistic parameters representing all the variations is a herculean task. Soil is normally continuous, homogeneous, isotropic and linearly elastic whereas the rock mass may be generally termed as discontinuous, heterogeneous, anisotropic and non-linearly elastic. There are a number of factors that affect the physical, mechanical and chemical properties of rocks. Forget about the jointed rock mass containing large number of discontinuities; 100 per cent variation in test results can be expected in the intact rock samples collected from close vicinity. Precise quantification of effect of various factors on the physical and mechanical properties of rock is practically impossible. Therefore, interpretation of data needs to take care of all the factors. Recommendation of any parameter depends a lot on the experience of the data analyst.

2. ROCK MATERIAL VERSUS ROCK MASS

Laboratory tests are conducted on samples of rock material with minor or practically no discontinuities and also, tests are carried out on very small-sized samples usually 54 mm diameter cores. Behaviour of anisotropic and jointed rock mass cannot be predicted from the laboratory test results. Hoek and Brown (1980) demonstrated the scale effect with transition from intact rock to heavily jointed rock mass (Figure 1). When the dimensions of the structure supported on the rock mass is sufficiently large than the joint spacing, the rock mass may be assumed to be isotropic. However, no field test can accommodate the effect of all the discontinuities. Whether the discontinuous rock mass can be assumed as continuum, depends on the overall size of the construction element. Therefore, size of individual rock blocks in relation to the size of the structure is important.

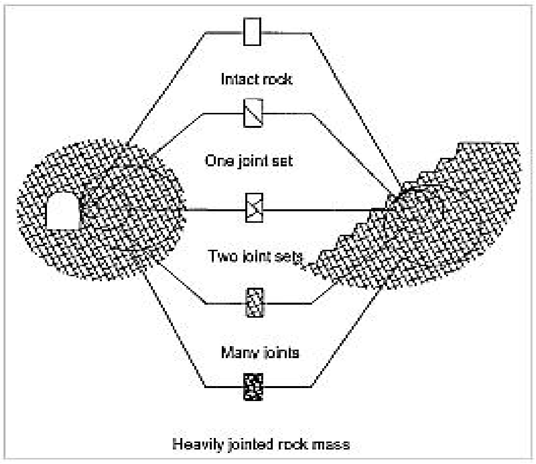


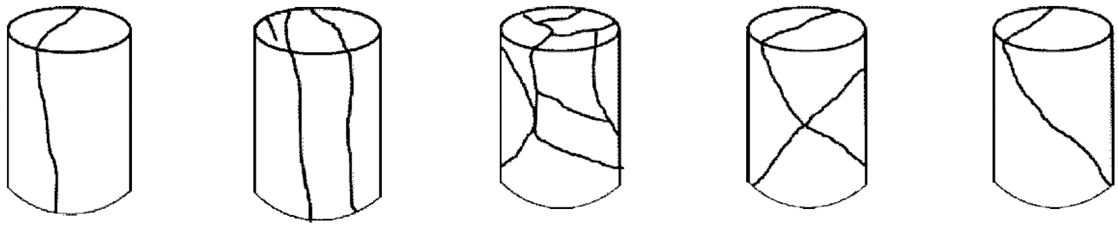
Fig. 1 - Transition from intact rock to heavily jointed rock mass (After Hoek and Brown, 1980)

Generally, field tests are conducted either in exploratory drifts or in open trench. For true representation of rock mass behaviour, the tests should be conducted in fresh and undisturbed rock. Preparation of undisturbed samples is a major concern. The excavation methodology used in exploratory drifts or trenches also affects the deformability properties of the surrounding rock mass. Even with adoption of controlled blasting techniques, disturbance to the adjacent mass cannot be averted. Of course, it can be minimized to a certain extent. Rock mass being anisotropic in nature; strength and deformation properties varies with the change in orientation of loading apart from magnitude of applied stress. The joint properties like frequency, spacing, roughness, alteration, filling material, continuity, in-situ stress, geological history govern the rock mass properties (Obert and Duvall, 1967; Bieniawski, 1968; Jaeger and Cook, 1976). Similarly, hydraulic conductivity also plays a key role in stress-strain behaviour of rock mass. In addition, deformation modulus depends on the stiffness of the testing machine/equipment also (Hudson and Harrison, 1997). Based on the available data, Heuze (1980) concluded that deformation modulus of rock mass is 20 to 60 per cent of the intact rock specimens.

Szwedzicki (2007) demonstrated some possible failure modes in intact rocks (Fig. 2). The failure in intact rocks under uniaxial stress occurs along the foliations and the minor discontinuities or in other words along the weakest planes.

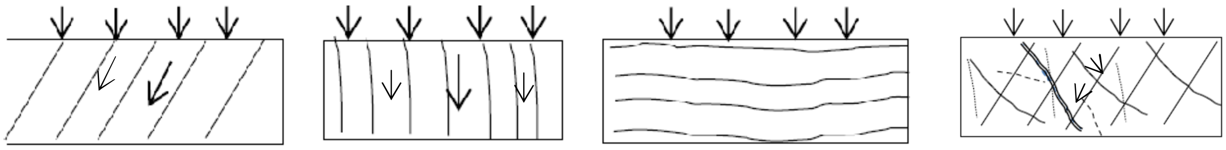
Deformation or failure pattern in jointed rock masses may be attributed to the discontinuities and strength of intact rock as demonstrated in Fig. 3:

- sliding along single discontinuity, or
- sliding through a path of several discontinuities or
- a combination of fracturing of rock mass and sliding along discontinuities.



Simple extension | Multiple extension | Multiple fracturing | Multiple Shear | Simple shear

Fig. 2 - Common modes of failure in rock sample under compression (Szwedzicki, 2007)



a) Oblique | b) Vertical or sub-vertical | c) Horizontal or sub-horizontal | d) Several discontinuities

Joint/Discontinuity	Symbol	Joint/Discontinuity	Symbol
J1		J2	
J3		Random	
Shear			

Fig. 3 - Failure in rock mass containing discontinuities

Therefore, under uniaxial stress, intact rock may fail in shear or fracturing in single or multiple planes whereas substantial part of the deformations in rock mass is due to the closing of joint spaces and sliding along discontinuities. Fracturing of the rock depends on the applied stress and the confinement. Though failure mechanism in intact rocks can be defined to a certain extent, it is difficult to simulate the exact mode of failure in jointed rock mass.

The resultant deformation on account of stress shall mostly be due to sliding along the discontinuity as shown in Figs. 3a and 3b whereas Fig. 3c indicates that the substantial deformation can be attributed to closing of the joint spaces and crushing/compaction of the infilling material. In case of several discontinuities (Fig. 3d), resultant deformation will be the combination of sliding, closing of joint spaces, compaction of the joint infilling material and fracturing of the rock fabric. Apart from this, rock mass may also contain the discontinuities in the form of folding, faulting, mineralogical variations, presence of bands or intrusions in any rock. Hence, deformation or failure mechanism of rock mass is complex.

For understanding the stress-deformation behaviour of intact rock and rock mass, deformation modulus of intact rock and rock mass pertaining to different rock types based on the actual testing have been tabulated in Table 1. The Table 1 presents deformation modulus of rock at 50 per cent of the yield stress or appearance of first crack whereas the deformation modulus of rock mass corresponds to applied stress levels of 3 to 6 MPa. The deformation modulus of intact rock may be 2 to 10 times the rock mass with some exceptions (Table 1). It is important to mention that rock mass at this stress level did not witness any fracture or crushing effect. Hence, the actual in-situ deformation modulus may be higher than reported, however due to practical difficulties and limitations of testing methodologies, it is impossible to denote it by a unique value.

Table 1 -Comparison of deformation modulus of intact rock and rock mass

Rock Type	Deformation modulus		Ratio E_r/E_m
	Rock mass (E_m)	Intact rock (E_r)	
Dolomitic limestone	4.0	16	4.0
*Jointed quartzites	2.37	40	16.9
Granite gneiss	3.20	18	5.63
Augen gneiss	4.86	11	2.3
Quartz mica schist	2.71	10	3.69
Augen gneiss (crushed and closely jointed)	2.65	16	6.04
#Gneisses, mica schist, banded quartzitic gneisses	1.61	21	13.04
Leucogranite with pegmatite veins	3.70	35	9.46
$Leucogranite with biotite gneiss	1.97	25	12.69

Notations:*- Closely jointed, #- Joint volume =12-15, $- 4+ random joint sets

3. FACTORS INFLUENCING DEFORMABILITY CHARACTERISTICS

Deformability of intact rock and discontinuous rock mass may be broadly described by modulus of deformation. Applied stress level; orientation of stress in relation to foliation/bedding/stratification; number and orientation of discontinuities; persistence and extent of discontinuities, joint properties such as alteration; roughness, asperities, properties of infilling material; water conditions; weathering grade, in-situ stresses are the prominent factors affecting the deformability of rock mass.

Modulus of deformation of rock mass is directly proportional to loading area and the applied stress. Rock and rock mass being anisotropic, its mechanical properties vary with stress orientation. More number of discontinuities and lesser spacing of joints lead to reduction in the deformation modulus of rock mass. Further, the condition of joints also plays a vital role in defining the deformation modulus as the various types of infilling material have varied degrees of deformational characteristics. The rock contains minerals and certain types of minerals have the tendency of reacting with water which results in reduction in strength, thus affecting the deformability. Shales, sandstones and other similar rocks are susceptible to changes in strength with moisture content (Hoek and Marinos, 2000). Clay as infilling material may have swelling characteristics too. Modulus of fresh rock is always higher than that exposed to weathering. Modulus of rock mass also depends on the prevailing in-situ stresses.

3.1 Influence of Weathering

Weathering in rock mass influences its deformation modulus significantly. Ground water alters the properties of infilling material and flow of water may result in erosion of joint infilling material too. Goel and Mitra (2015) discussed and highlighted the importance of weathering in rock and concluded that intact rock strength, spacing of discontinuities and condition of discontinuities are adversely affected by weathering. The authors further recommends that weathering of joint roughness (J_r) and Joint alteration (J_a) be taken into account while computing Q-value for long-term support pressure for tunnels through soft and jointed rock masses charged with ground water. Strength losses of 30 to 100 % occur in many rocks as a result of chemical deterioration of the cement or clay binder (Broch, 1974).

Hari Dev and Gupta (2017) conducted in-situ plate load tests on fresh to moderately weathered garnetiferousquartzo-feldspathic gneiss rock and inferred that transformation from fresh to slight and moderate weathering may lead to reduction in modulus of deformation by 40 % to 60 %. Figure 4 presents variation in modulus of deformation in relation to weathering.

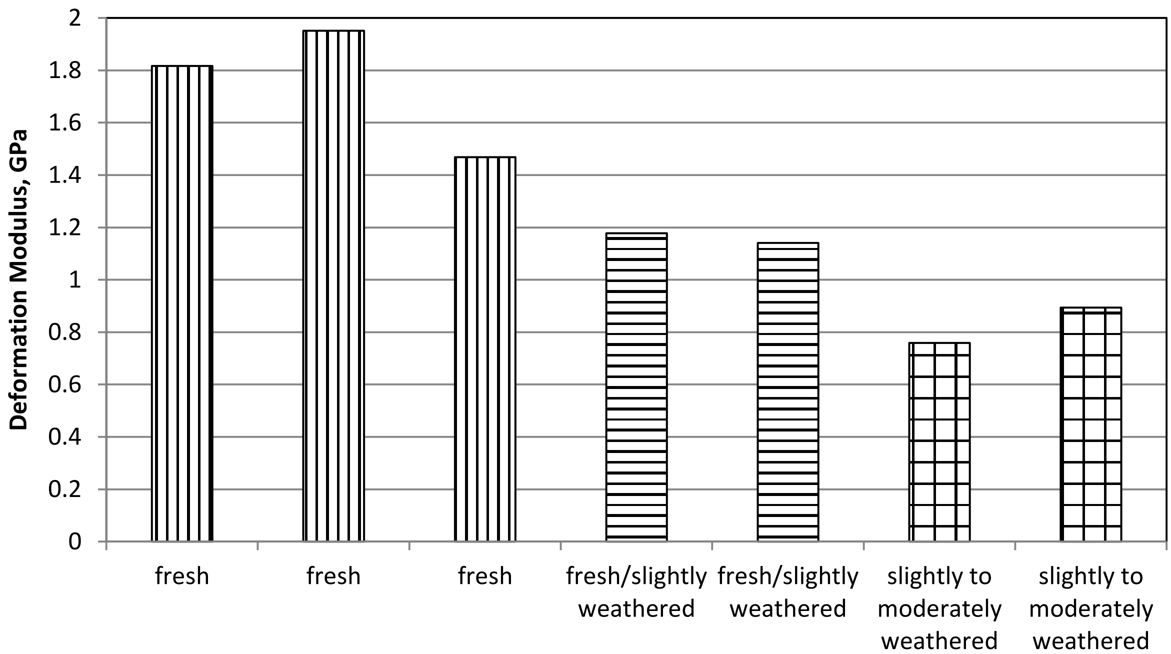


Fig. 4 - Variation of modulus of deformation with weathering grade

3.2 Effect of Repetitive Loading

Modulus of deformation also depends on repeatability of loading cycles. Rock mass deformability is strongly scale and stress dependent and usually shows strong anisotropy (Zhang, 2017). Applying repetitive loading in plate loading tests, Senthil et al. (2019) concluded that rock mass gets stiffer and tends to behave elastically. With repetition of loading cycles, permanent deformation reduces and recovery of deformation during unloading increases. Permanent deformation in jointed rock mass occurs due to the closing of joint spaces and compression of infilling material. More repeated 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 (Pathak et al., 2014). Figure 5 can be referred to understand the effect of repetitive loading in granite gneiss (medium to coarse grained). Reduction in plastic deformation and increase in elastic recovery while unloading is clearly visible.

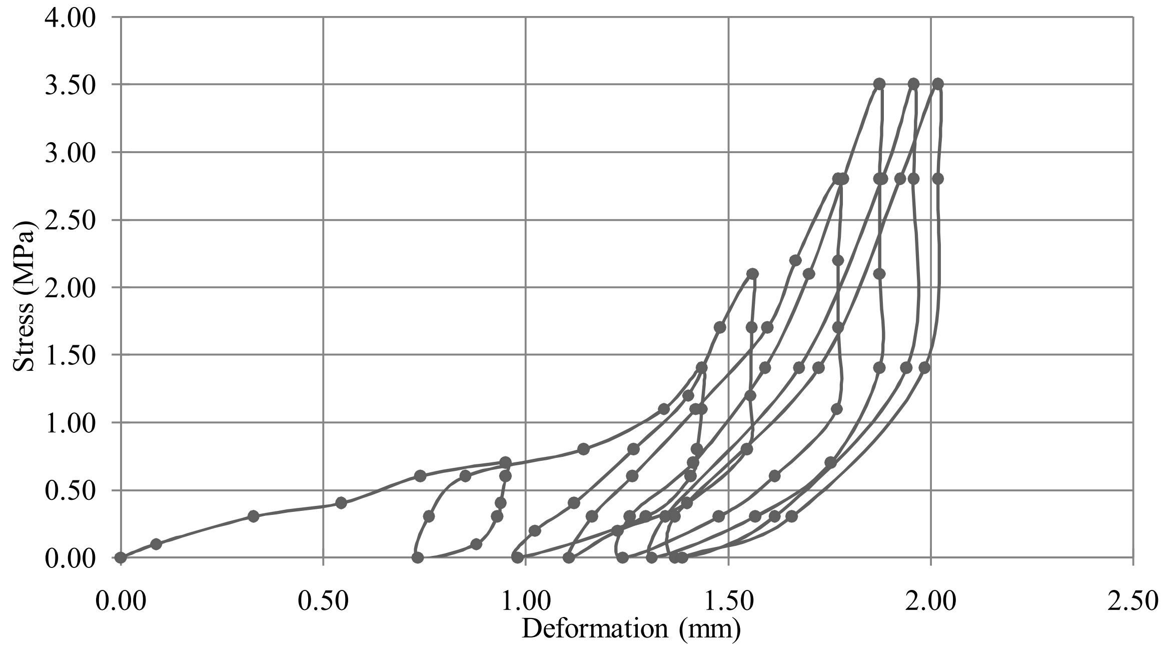


Fig. 5 - Effect of repetitive loading in granite gneiss rock mass

3.3 Anisotropy in Rock Mass

Direction of applied stress with respect to the major discontinuities also affects its strength and deformability characteristics. Anisotropy in rocks is basically related to variations in formation stages and mainly depends on the texture and fabric of the principal rock-forming minerals or the microscopic fabric (Ullemeyer et al., 2006). All igneous, metamorphic or sedimentary rocks exhibit anisotropy. The reason for anisotropy in foliated metamorphic rocks may be because of orientation of flat/long minerals whereas in stratified sedimentary rocks, it may be attributed to the sedimentation process with different minerals and varying grain size. Igneous rocks have rare possibility of anisotropy, but in some cases, the anisotropy may be found due to layering when lava flows and moves as highly viscous masses immediately before the consolidation such as granite (Wahlstrom, 1973).

Ramana et al. (2016) on the basis of Goodman jack tests inside the drillholes studied the effect of anisotropy on deformation modulus of leucogranite rock mass by stress application in three orthogonal directions i.e. along, perpendicular and normal (vertical) to the orientation of power house (PH) and tail race tunnel (TRT) as depicted in 3-D sketch (Fig. 6). The modulus of deformation was denoted by E_{dx}, $E_{dy}$and E_{dz}, respectively in the directions along, across and normal (Vertical) to PH/TRT.

Variation in modulus of deformation with change in orientation of stress in the power house was noticed from ± 2-17% at applied stress of 5 MPa whereas the tail race tunnel the variation was observed to be ± 12 to 21 (Fig. 7). Hence, significant anisotropic variation in modulus was noticed and this anisotropic nature must be accounted in design.

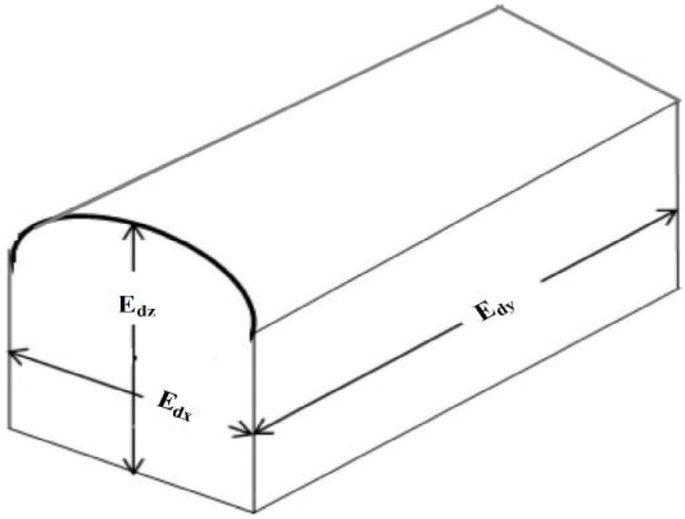


Fig. 6 - 3D sketch showing the stress application

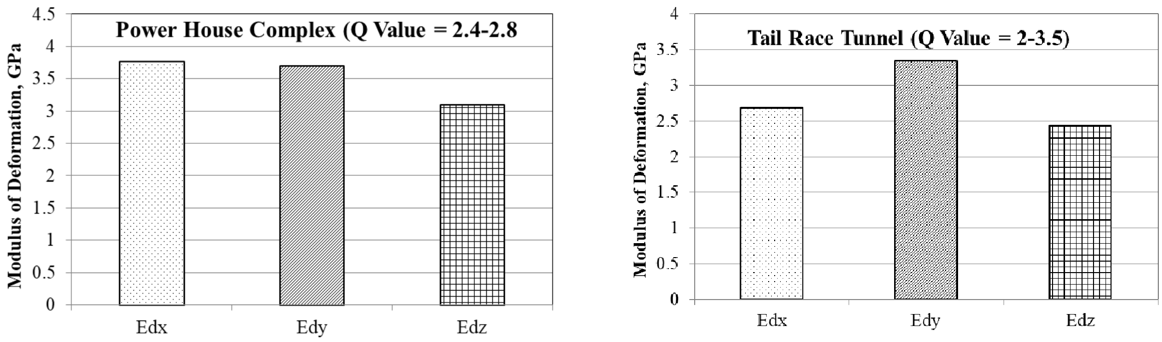


Fig. 7 - Anisotropy in rock mass at 5 MPa applied stress level

4. DEFORMABILITY AS A FUNCTION OF MEASURING TECHNIQUE

The available methods for the determination of properties are having their own limitations. The choice of method needs to be based on the extent of discontinuities. Large variations are also observed using a single method of testing and even when the rock mass is uniform (Bieniwaski, 1978). The variation in results with change in method of measurement has been observed. The stress distribution and volume of rock mass affected also varies with testing method. Researchers have pointed out that plate loading test with deformation measurements at the surface of bearing plate gives about 2-3 times lower values of modulus of deformation as compared to plate jacking tests with deformation measurements inside the drill-holes i.e. away from the disturbed mass (Palmstrom and Singh, 2001; Hari Dev and Gupta, 2017). Deformation modulus is stress dependent and cannot be defined by a unique value. Therefore, these are the rough estimates as the measured values of modulus by different methods correspond to certain stress level and that too using different sized loading plates. The rigidity or stiffness of the loading system is also important. It is difficult to ascertain the ultimate values of in-situ deformation modulus due to limitation of testing methodology, assumptions and complexities of deformation in rock mass.

A comprehensive laboratory and field rock mass study on thinly foliated augen gneiss rock was carried with actual data in the Himalaya. The foliation was vertical to sub vertical. In-situ plate loading tests (PLT) for the determination of modulus of deformation with surface measurements were conducted with deformation measurements by stress application parallel and perpendicular to foliation. Modulus of deformation of augen gneisses was found to be 1.12 GPa with loading parallel to foliation and 1.55 GPa when loading in perpendicular direction; thus recording about 35% increase with loading direction perpendicular to foliation as compared with parallel to foliation plane. The phenomenon may be attributed to the fact that crushing of thin foliations occurs in parallel loading case whereas lesser deformations were recorded in loading direction perpendicular to compact foliations. Modulus values from plate jacking tests (PJT) with deformation measurements inside the drillhole were found to be 4.86 GPa at same applied stress level. The PJT indicated deformation modulus 2 to 4 times than PLT. This is due to the disturbance of rock mass or the weathering effects at the surface. Modulus of elasticity from laboratory testing on NX core samples (54 mm diameter) was found to be 11.67 GPa which is about 7 to 10 times the deformation modulus by PLT and 2.4 times by PJT (Bharti et al., 2017).

The volume of rock mass affected by loading also plays a vital role in evaluation of strength and deformability. In Goodman jack or borehole jack test, about 0.15 m^3 of rock mass is affected whereas plate jacking or plate loading testemploys load bearing plates of 60-80 cm in diameter. Due to small size of loading platens in borehole jack, the rock mass affected may be assumed to be intact rock in case of massive rocks wherein joints are widely spaced. In flat jack tests, jacks of different size and shape can be used to determine the modulus of deformation of rock mass. The number of discontinuities under the loading area varies, thereby affecting the modulus value. Modulus of deformation of rock mass is stress dependent and increases with increase in stress level within the linear elastic limit.

Most often, remarkable variation in rock mass can be seen in geological conditions in close vicinity. The condition of joints whether tight, open or having infilling material, plays a key role in its stress-deformation behaviour. Minor and major shear seams increases the plasticity in jointed rock mass when subjected to stress. Further, the behaviour of rock may be entirely different in dry and saturated ground conditions. The strength of oven dried sandstones may be reduced by 50% when in saturated state (Hoek, 1983). Abdullah and Singh (2010) conducted study on five variants of quartzites. Variations of the order of 66% and 100% were recorded in uniaxial compressive strength and modulus of elasticity, respectively in saturated states in different variants of quartzites belonging to the same grades of UCS.

The best way to interpret the data of in-situ tests would be simulation of the in-situ test and the drift in 3DEC software for the back-calculation of the joint stiffness etc., taking into account nearby shear zone, fault and in-situ stresses. Then the same software and geotechnical data may be used to design the rock structures. All the repeated loading and unloading cycles need to be simulated to understand the non-linear behavior of rock joints and anisotropy of rock mass.

5. ESTIMATION OF DEFORMATION MODULUS FROM INDIRECT METHODS

Based on some case studies, researchers have suggested numerous correlations of deformation modulus of rock mass with other properties of intact rock and empirical rock mass classifications like RQD, RMR, Q value, GSI, etc. (Bieniawski, 1978;Serafim and Pereira, 1983; Barton, 1983;Grimstad & Barton, 1993;Clerici, 1993;Palmstrom, 1995; Hoek and Brown, 1998;Ramamurthy, 1993; Hoek and Brown, 1998, Hoek and Diederichs, 2006;Zhang and

Einstein,2004). It is difficult to predict the behaviour of rock mass precisely due to complexities in resultant deformations of jointed/discontinuous rock mass.

These empirical correlations using theoretical and mathematical procedures have been suggested for estimation of the deformation modulus assuming regular dispersion of discontinuities which in fact is practically not true (Amadei and Goodman, 1981; Gerrard, 1982a& b;Fossum, 1985).

Zhang (2017) discussed various empirical methods for estimation of modulus of deformation of rock mass and concluded that it is hard or impossible to decide the most accurate method as the sources of databases are different.

Further, there are certain questions that need to be answered. Is there any method which can define the modulus of rock mass by a unique value when it is stress dependent?

Deformation modulus of rock mass increases with increase in stress, but upto what stress level?

With regard to our engineering structures, we are concerned about the behaviour of rock and rock mass at certain applied stress levels i.e. stresses anticipated on account of superstructure. Empirical correlations have been developed over a period of time using the data from the actual testing and empirical rock mass classifications. The grading assigned to rock mass using empirical classification approaches is also judgmental, based on certain parameters and depends on the experience of the user. Hence, determination of ultimate modulus of deformation is not feasible. Therefore, there is considerable probability of error in estimating the deformability using empirical correlations. Hence, empirical correlations are only indicative and should be used with caution for preliminary planning and design of structures only.

6. DISCUSSIONS AND CONCLUSIONS

Stress-deformation characteristics of rock and rock mass are the vital parameters required for the design of any structure in or on the rock mass. Rock mass behaviour depends on a number of factors and it is difficult to assess the impact of each factor individually due to complexities in resultant deformation. Deformation modulus varies with method as well as with loading area. As far as possible, the tests should be conducted in fresh rocks as weathering affects the deformability. In weak rock masses weathering results in deterioration of deformability properties at a fast rate. Apart from various other factors, the complete stress-strain tests on rock cores are also influenced by the stiffness of testing machine.

The correlations between the intact rock and rock mass properties suggested by researchers are mainly site/project specific. The excavation methodology also influences the deformation characteristics of discontinuous rock mass. Engineering rock mass classifications are empirical and judgmental in nature. Since, discontinuities are not regularly dispersed, the test results may vary even in close vicinity. Hence, no indirect method can replace the actual test results. Stress and scale are the two factors on which rock mass deformability characteristics largely depend. Another factor of prime importance is anisotropy which means the orientation of stress has a great bearing on the rock mass deformability. No correlation is capable of taking into account the effect of stress, scale and anisotropy.

Therefore, the factors like geological variability; heterogeneity; limitations of indirect methods; large variation in intact rock and rock mass properties; complex stress-deformational behaviour; stress/scale dependency; anisotropy etc. urges the need for actual determination of deformability characteristics. Even in case of actual testing, proper interpretation of test data is needed before recommending the design parameters.

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