Shear Strength of Rock Mass - Interpretation and Analysis

Hari Dev
Central Soil and Materials Research Station, New Delhi

Abstract

Rock is a discontinuous, inhomogeneous, anisotropic and non-linearly elastic. The properties of rock mass largely depend on the behaviour of discontinuities under various natural and induced stresses. Mechanical properties of rock mass can be best represented by in-situ tests because of over estimation by laboratory tests. In some cases like weak, fractured or sheared rock mass, in-situ tests are the only option available. Shear strength is one of the important parameters essentially required for the design of structures involving rock. This paper discusses the importance of interpretation of in-situ shear test data for finalisation of shear strength parameters of rock mass for the design of gravity dams in the light of some case histories.

1. Introduction:

Rock mass is defined as an aggregate of blocks separated by fractures (Goodman et al., 1968). Strength of rock mass is mainly governed by the behaviour of these discontinuitiesand planes of weakness. The discontinuities may be with or without the infilling material. Additionally, the type and characteristics infilling material may also vary. The frequency of joints,their orientation with respect to the engineeringstructures and the roughness of the joint havea significant impact on stability of rock structures.Shear strength of rock mass is greatly influenced by the variation in strength of beddings and shearing takes place along the weakest zone (HariDev et al. 2013).The effect of joint intensity on engineering behaviour of rock mass has also been studied by various researchers (Goldstein et al., 1966; Hayashi, 1966; Walker, 1971; Lama, 1974; Arora, 1987). In-situ characterisation of strength and deformationbehaviour of rock mass is very important for safe andeconomical design of structures involving rocks suchas dams, bridge abutments, tunnels, undergroundpowerhouse etc. In-situ tests are used to measure the primary and residual stresses; deformation properties; shear strength parameters; anchor capacities and permeability characteristics of rock mass. Theseparameters help the designers to carry out basic design and stability analysis of structures involving rock.

Selection of site, number of tests, care during site preparations, type of testing equipment, accuracy of the testing equipment, normal load consideration, direction of loading as actually anticipated, precision in testing, interpretation, consideration of the geological conditions are some of the points which affect the final results to a large extent. Above all, judgement and experience of the investigator play a major role in realistic assessment of rock properties.

2. Stability of Gravity Dams:

Gravity dams can fail in overturning, shear and tension and should primarily satisfy the following stability criteria:

- Safety against sliding on any plane within the dam, at the base, or at any plane below it (foundation).

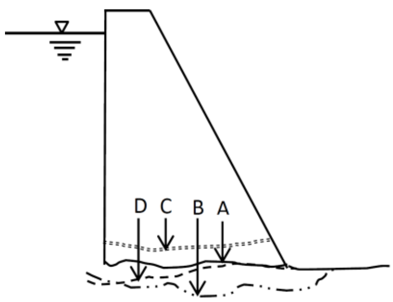
- Unit stresses in the concrete or masonry or in the foundation material should not exceed the safe limits.

Shear strength parameters of rock mass is the basic parameter for design of dam foundations. Though in-situ shear strength is difficult to be measuredand time consuming, these are essentially required to verify the stability of any water retaining structures. Shear strength parameters comprise two components, viz. cohesion ‘c’ and friction angle ‘ϕ’. The interpretation of in-situ shear strength though looks simple; is in fact very complex.

The gravity dams may fail in shear along any or combination of the following planes (Fig. 1):

1. Failure along concrete to rock interface
2. Failure along rock to rock interface
3. Failure along any concrete joint
4. Composite failure along rock and concrete interfaces

In concrete gravity dams, major destabilising forces are horizontal and these are resisted by frictional or shearing force along horizontal or nearly horizontal planes. These planes can either be within the body of the dam or the foundation on which the dam is seated. As the construction of dam is done in lifts, the joints between successive lifts may also act as possible planes of weakness. Shear failure is possible along these concrete joints or concrete to rock interface. Similarly, weak rock joints/shear seems within the foundation rock mass may also act as failure planes. Composite failure along the concrete to rock interface and weak rock joints is also occur.The various possible modes of failure of concrete gravity dams in shear have been described in Fig. 1:



A. Failure along concrete to rock interface
B. Failure along rock to rock interface
C. Failure along concrete joint
D. Composite failure along rock and concrete

Figure 1 Different modes of shear failure in concrete gravity dams

In gravity dams, weight of dam is the main resisting force, whereas the horizontal force due to head of water is the prime force responsible for destabilization. Factor of safety (FOS) against sliding can be evaluated from the following relationship:

FOS against sliding = $\frac{\mu.\Sigma V}{\Sigma H}$ (1)

Where μ = co-efficient of friction between two surfaces
$\sum V$ = sum of vertical forces acting on dam
$\sum H$ = sum of horizontal forces acting on dam

Hence, determination of shear strength parameters of both concrete to rock and rock to rock interfaces becomes essential. Interpretation of shear strength parameters account for geological variation in the foundation material apart from the measured field data from direct shear tests. Many a times, we do not get failure along the bedding planes or rock joints as anticipated. In case of concrete blocks, it is not necessary to get failure along the probable concrete to rock interface. In such cases, role of the interpretation and experience comes into force.

3. Shear Strength of Rock:

The relationship between the peak shear strength (τ) and the normal stress (σ) can be represented by the Mohr-Coulomb equation:

$$\tau = \sigma \tan\phi + c \tag{2}$$

where c is the cohesive strength of the shearing interface and $\emptyset$ is the angle of friction.

Barton (1973) suggested a criterion to estimate the peak shear strength by joint roughness coefficient (JRC) and the joint wall strength (JCS), as functions of the normal stress.

Furthermore, Barton and Choubey (1977) replaced basic friction angle with residual friction angle as it takes into account the influence of saturated and weathered fracture surface.

$$\tau = \sigma_n' \, .\tan[JRC \, .log_{10}\frac{JCS}{\sigma_n'} + \emptyset_{res}] \tag{3}$$

Where,

$\emptyset_{res}$ is residual friction angle

The Hoek – Brown Strength Criterion Hoek and Brown (1980) represented the shear strength of rock as a curved Mohr envelope and later new elements were introduced incorporating practical problems (Hoek et al., 2002).

4. Case Studies:

Some typical case studies based on in-situ direct shear test on rock to rock and concrete to rock interfaces (IS 7746:1991, ISRM: 2006) have been discussed in detail.

4.1 Case Study-1:

This case study is based on 8 shear tests, four each on rock to rock (R/R) and concrete to rock interface (C/R) carried in quartz mica schist rock mass in middle Himalayas. In case of C/R interface, in 3 out of 4 tests, shearing was observed below the C/Rinterface (Fig. 2a,2b and 2c), i.e. along the rock joints. Thus, indicatinghigher shear resistancealong the interface of concrete and rockthan within the rock. Hence, during interpretation, results from these 3 C/R interface tests were analysed alongwith R/R interface data (Fig. 3a, 3b, 3c and 3d). Thus normal stress versus shear stress plot (Fig. 4) for seven tests (4 R/R and 3 C/R interfaces) was drawn to determine critical shear strength parameters for design of concrete gravity dam.

a) b) c)

Figure2 Shear failure in concrete to rock interface blocks

a) b) c) d)

Figure3Shear failures in rock to rock interface blocks

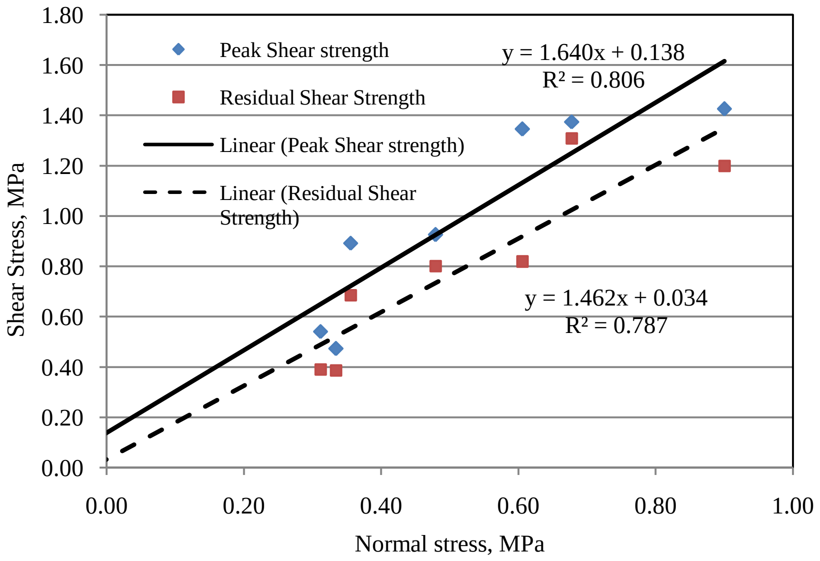
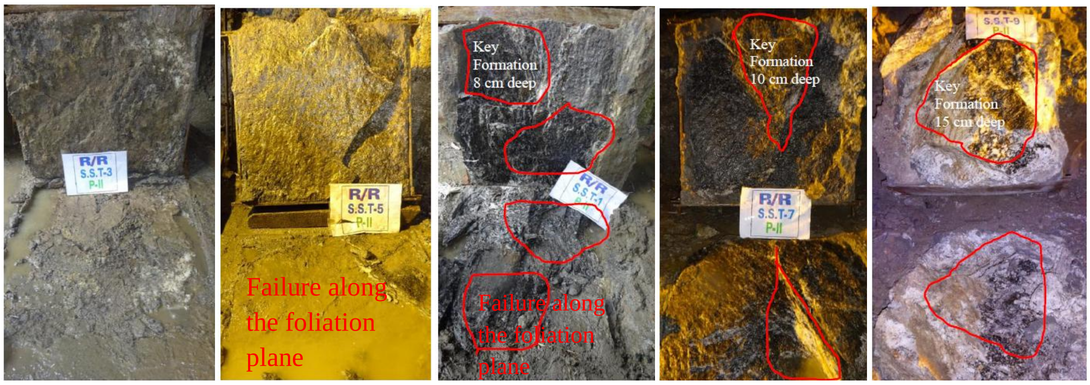


Figure 4 Normal versus shear stress plot

Therefore, considering the shear failure within the rock mass in all these seven blocks, shear strength parameters were evaluated using linear regression method. The values of peak shear strength parameters viz. cohesion ‘c’ and friction angle ‘φ’ were recommended as 0.139 MPa and 58.63^0 respectively whereas the corresponding values for residual shear strength were found to be0.034 MPa and 55.63^0, respectively.

4.2 Case Study 2:

This case study pertains to shear strength parameters of quartzo-feldspathic gneiss. A total of 10 shear tests, 5 each on R/R and C/R interfaces were carried out.Photographs of the all the inverted blocks after the test showing the failure pattern aregiven in Fig. 5.

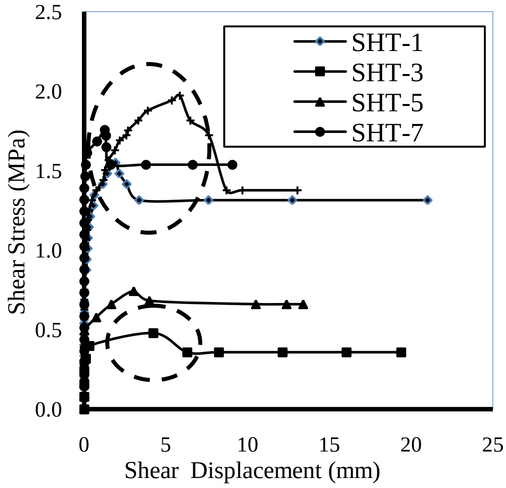


a. b. c. d. e.

Figure 5Failure pattern in R/R Interface

Uniform pattern of shearing of rock blocks could not beobservedin all the tests. Failure in two tests was observed along the foliation plane (Figs. 5a and 5b) whereas in remaining three tests, key formation due to intersection of rock joints (Figs. 5c, 5d and 5e)beneath the probable failure plane was observed which resulted into sliding of the block up on the asperities.Shear stress versus displacement plot as shown in Fig. 6

indicates two different modes of failure.Shear stress was observed to be lower than the normal stress in case of failure along the foliation plane whereas in other 3 tests the shear stresswas much higher than normal stress (Fig. 7). However, failure in C/R interface was observed to be along the interface of concrete with rock.



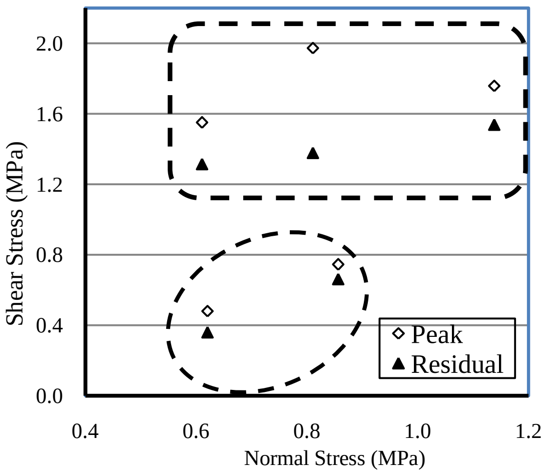
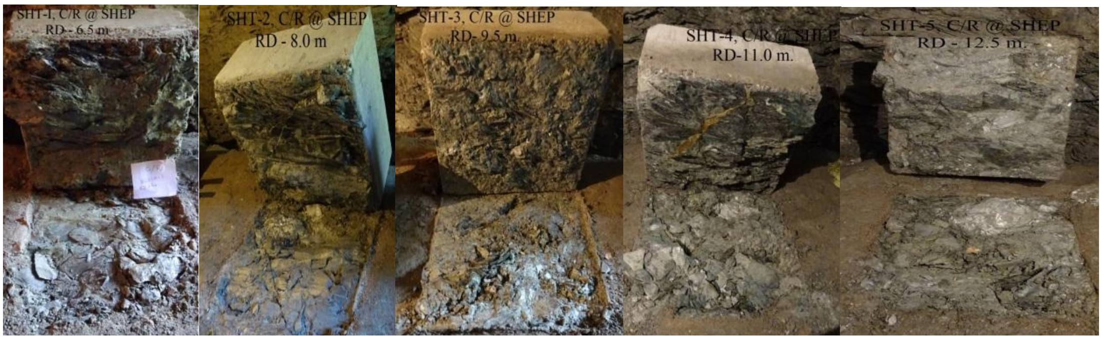


Figure6 Shear stress - displacement plotFigure7 Shear stress - normal stress plot

Analysis of data from all the five tests on R/R interface resulted in higher shear resistance (for the given range of normal stress) as compared to C/R interface, and therefore, for rock to rock interface also, it was recommended to adopt the shear strength parameters of concrete to rock interface in the design.Therefore, C/R interface shear test results for recommended for use in design.Hence, cohesion ‘c’ and friction angle were recommended as ‘ϕ’ 0.10 MPa and 45.57^0, respectively. Similarly, residual shear strength parameters ‘c_r’ and friction angle ‘ϕ_r’ were found to be 0.03 MPa and 39.92^0, respectively.

4.3 Case Study 3:

Case study 3 pertains to shear strength parameters of phyllitic-quartzite and highly puckered phyllite (dominance of highly jointed, clay filled) rock mass. The shear tests on concrete to rock interface revealed that shearing has occurred along the weak foliation plane below the C/R interface (Figs. 8a, 8b, 8c, 8d and 8e) similar to R/R interface shear tests (Figs. 9a, 9b, 9c, 9d and 9e). Such phenomenon may be observed in thinly foliated or highly jointed/fractured rocks.



a. b. c. d. e.

Figure 8Shear failure in C/R interface blocks

a. b. c. d. e.

Figure 9Shear failure in R/R interface blocks

The phenomenon was attributed to the fact that shear strength of foliation joint is lower than C/R interface. Presence of saturated clay as joint infilling material seems to be another probable cause behind this type of behaviour. Phyllite rock mass was observed to stratified and containing several parallel failure planes within the rock mass. Crushing/shearing through the asperities was also observed.Therefore in view of the observed data, it was decided to plot all the test results together and carry out the combined analysis for interpretation of shear strength parameters of rock mass to be adopted for design purpose(Fig. 10).

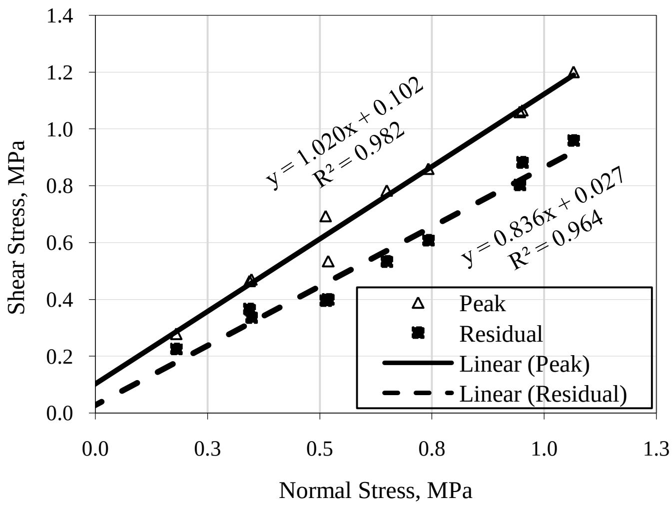


Figure 10 Shear stress versus normal stress plot

Values of peak shear strength parameters for C/R interface viz. cohesion ‘c’ and friction angle ‘ϕ’ were found as 0.306 MPa and 46.3^0, respectively whereas the corresponding values of residual shear strength parameters i.e. ‘c_r’ and friction angle ‘ϕ_r’ were found to be 0.087 MPa and 40.6^0, respectively.

5. Conclusions:

Based on the above case studies, the following conclusions can be drawn:

In-situ tests best represent the properties of rock mass as these take into account the effect of discontinuities. Moreover, in-situ tests takes care the effect of geological features, environmental conditions, direction of loading as envisaged etc. However, utmost care is required during site preparations. The blocks need to be prepared using chisels and small hammers or cutting devices so as keep it intact and undisturbed.

Since, gravity dams are liable to failure along weak rock joint or concrete to rock interface in particular, direct shear tests on both R/R and C/R interfaces are essential for deciding the critical shear strength parameters to be used in design. Before concreting, the rock surface at the foundation needs to be properly cleaned and dried for good bonding.

Interpretation of data and experience plays a significant role in finalisation of shear strength parameters due to variation in testing data.Each and every detail recorded during the field tests like nature of shear failure, measuring the actual area under shear, photographs of the inverted blocks, geological details including rock class etc. helps in proper interpretation.

References

1. Arora, V.K. (1987). Strength and deformation behaviour of jointed rocks.PhD thesis, IIT Delhi, India.
2. Barton, N.R., 1973. Review of a new shear-strength criterion for rock fractures. *Engineering geology*, Vol. 7, Nr. 4, pp. 287-332.
3. Barton, N.R., Choubey, V., 1977. The shear strength of rock fractures in theory and practice. *Rock Mechanics*, Vol. 10, pp. 1-54.
4. Goldstein, M., Goosev, B., Pyrogovsky, Tulinov, R., and Turovskaya A. (1966)."Investigations of mechanical properties of cracked rock." Proc., 1st Congress of Society of Rock Mechanics, Lisbon, I, 521-524.
5. Goodman, R.E., Talyor R.L., Brekke T.L., 1968. A model for the mechanics of fractured rock.*Journal of the Soil Mechanics and Foundations Division*, Vol. 94, pp. 637-660.
6. HariDev, Rajbal Singh and J.K. Yachu (2013), "Shear Strength Parameters of Pyroclast Rock Mass", Indorock-2013, 29-31 May 2013, Solan, Himachal Pradesh
7. Hayashi, M., (1966). Strength and dilatancy of brittle jointedmass.The extreme stochastic and anisotropic failure mechanism. Proc., 1st Int. Congress on Rock Mechanics, Lisbon, I, 295-302.
8. Hoek, E. and Brown, E.T. (1980). Underground excavations in rock: London Institute of Mining and Metallurgy, London, UK, p. 527.
9. Hoek, E., Carranza-Torres, C. and Corkum, B. (2002).Hoek–Brown failure criterion - 2002 edition. Procedure of the 5th North American Rock Mechanics Symposium, Toronto, Canada, Vol. 1, July 2002, pp. 267–273.
10. IS 7746 (1991): Indian Standard code of practice for In-situ Shear test on rock, Bureau of Indian Standards, New Delhi.
11. ISRM (2006): "The Complete ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 1974-2006", Edited by ReşatUlusay and John A. Hudson.
12. Lama, R.D. (1974): Uniaxial compressive strength of jointed rock. Institute of soil mechanics and rock mechanics, P-Muller Festschrift.ed., Karlsruhe, Germany, 67- 77.
13. Walker, Orville C., Jr. (1971). The Effects of Learning on Bargaining Behaviours. In Fred C. Alvine (ed.).*1971 Combined Proceedings* (pp. 194–199). Chicago: American Marketing Association.