Measurement of In Situ Shear Strength of Rock Mass

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ABSTRACT

Shear strength parameters are required for stability analysis of dams, slopes and underground structures. The strength parameters are evaluated by conducting a set of in-situ shear tests. This paper deals with methodology for conducting in situ shear test and interpretation of testing data for evaluation of the shear strength parameters for rock to rock and rock to concrete interfaces. The variations in data from different project sites make it necessary to conduct the tests separately at each site/rock type carefully. Angle of internal friction is found to be high at low normal stress range.

Keywords: Shear strength; Cohesion; Friction angle; Rock mass

1. INTRODUCTION

Shear strength characteristics of rock mass is one of the most important parameters being used for the numerical analysis of large concrete gravity dams, underground excavation in rock mass and slope stability problem. In the case of a large concrete gravity dam, the shear strength parameters for the interfaces of rock to rock joints as well as concrete to rock joints are considered for the stability analysis. The shear strength parameters are evaluated by conducting in situ shear tests.

In situ shear test measures peak and residual direct shear strength as a function of stress normal to sheared plane. In situ shear tests should be conducted at least on minimum of five test blocks in the drifts for determining shear strength parameters of rock to rock and concrete to rock interfaces while each test block is sheared at a different but constant normal stress. The inclination of test block and system of loading (normal and shear load) are selected in such a way so that the sheared plane coincides with a plane of weakness in the rock. Based on this large scale in situ shear testing, the shear strength parameters are evaluated and utilized for design.

The shear strength between two planes can be measured by the following equation:

$$\tau = c + \sigma \tan \phi \tag{1}$$

Where,

τ = Shear strength between two planes, MPa
c = Cohesion, MPa
σ = Normal stress acting on two planes, MPa and
ϕ = Angle of internal friction angle, Degrees.

Shear strength parameters i.e. cohesion (c) and frication angles (ϕ) along planes of weakness in rock mass or interfaces between rock to rock and concrete to rock are determined by conducting a set of the direct shear test in the field.

This paper deals with methodology for conducting in situ shear test and interpretation of test data for evaluation of the shear strength parameters (cohesion, c and frication angle, ϕ) for rock to rock and concrete to rock interfaces.

2. IN SITU SHEAR TEST

2.1 Test procedure

The general procedure consisted of bringing the normal load of the specified intensity over test block by loading the system normally and then applying the shear load in increments until the failure occurred. Displacements of block are observed after each increment of load in the directions of normal, lateral and shear. The in situ shear test set-up of rig assembly inside the drift is shown in Fig. 1. The photograph taken during in situ testing inside a drift is shown in Fig. 2.

For conducting this test, the rock surface is prepared by careful manual chiselling. The rock/concrete blocks of size 70 cm x 70 cm x 35 cm are prepared. The base of the test block should coincide with the plane to be sheared. In the case of rock to rock shear test, the rock blocks are prepared by drilling 35 cm deep overlapping holes in such a way that the area of rock block is 70 cm by 70 cm. To avoid any disturbance in the test block during shearing, the block is surrounded by filling concrete around the block with the help of steel frame as shown in Fig. 2 along with an angle of 15 degrees on the upstream side of the block. The same steel frame is used during the testing to avoid any disturbance of the block. Minimum of 5 blocks are prepared for this purpose for one rock type.

In the case of concrete to rock interface, the rock surface is prepared as even as possible by manual chiselling and the concrete mix used for the preparation of blocks is 1:2:4 (cement: coarse aggregate: fine aggregates) by restricting the aggregate size to 20 mm. Minimum of 5 blocks are prepared for this purpose. The concrete blocks are allowed to cure for 28 days.

A channel approximately 20 mm deep and 80 mm wide is cut around the base of the block to allow freedom of shear and lateral displacements. The vertical reaction is taken against a reaction pad cast at the crown. The reaction for shear load is taken against a concrete pad cast at the upstream face of the drift. The direction of the shear load is kept the same as anticipated shearing in the structures, in the case of the water load on the dam i.e. upstream to downstream of the dam.

The normal load is applied using two flat jacks and the shear load is applied using two hydraulic jacks. However, both the flat jacks are connected with single hydraulic pump to inflate and apply pressure. The hydraulic jacks for shearing are set up at an inclination of 15 degrees to the horizontal on the vertical side of the block so that the shearing load passes through the centre of the base of the block without causing any overturning movement (Figs. 1 and 2).

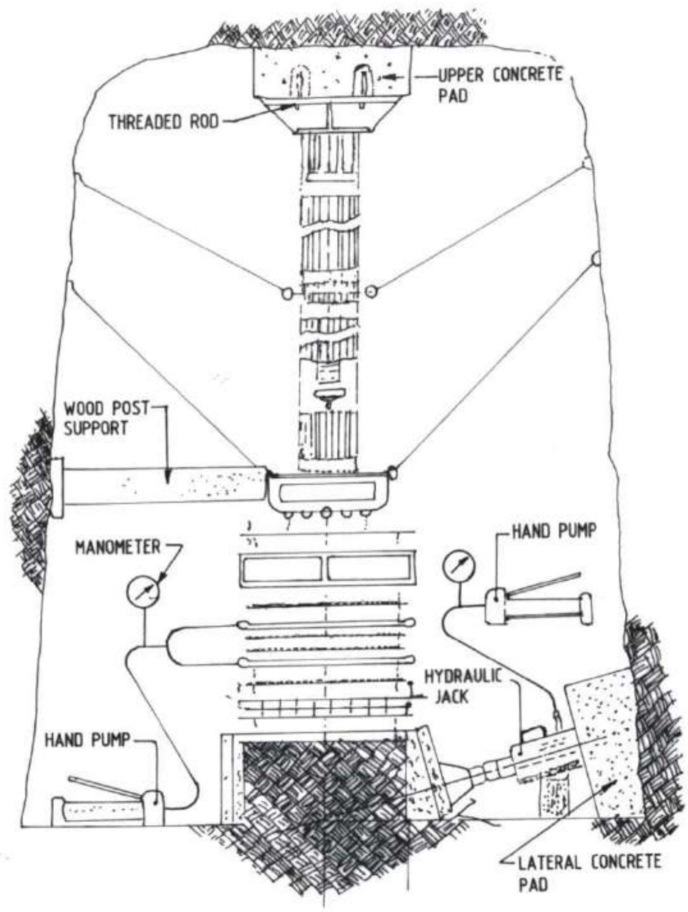

Fig. 1 - In situ shear test assembly inside drift

The displacements are measured in the directions of normal, shear and lateral to the sheared plane. The displacements can be measured either with dial gauges or LVDT (linear voltage differential transducers) with an accuracy of 0.01 mm and a travel of at least 70 mm. The position of dial gauges or LVDT around the block is shown in Fig. 3 as well as in the photograph of Fig. 2.

In the consolidation stage of testing, pore water pressure in the rock and filling material adjacent to the shear plane is allowed to be dissipated under full normal stress before shearing. The consolidation stage is considered to be completed when the rate of change of normal displacement recorded at each of the four normal gauges is less than 0.05 mm in 10 minutes. The consolidation curves are shown in Fig. 4 for all blocks at different normal stress.

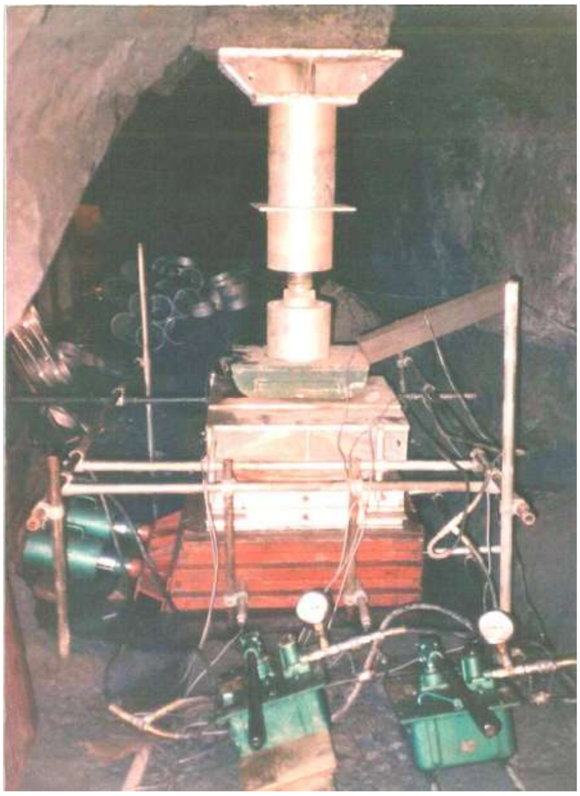

Fig. 2 - Photograph of in situ shear test assembly

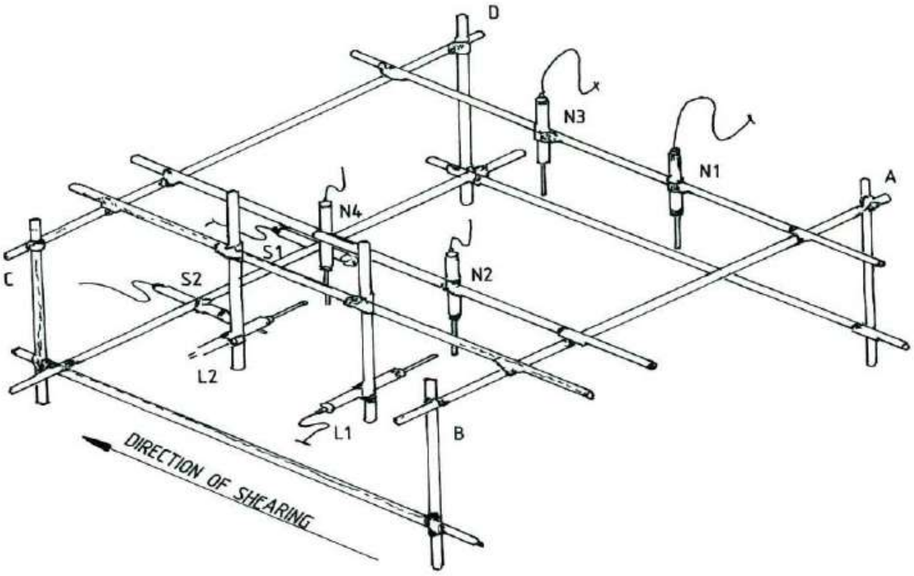

Fig. 3 - Arrangements of displacement gauges, N_1 to N_4 for normal, L_1 to L_2 for lateral and S_1 to S_2 for shear displacements

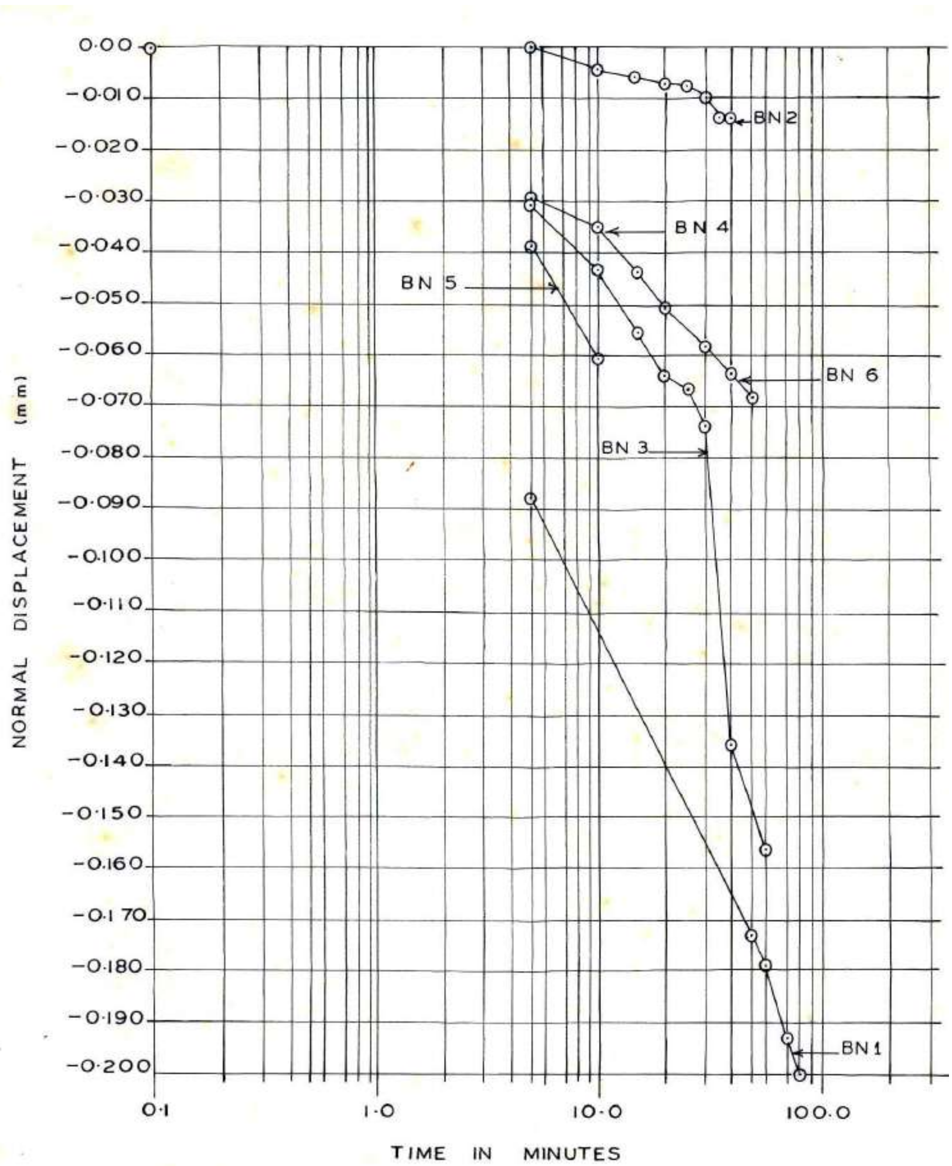

Fig. 4 - Consolidation curves for six blocks at different normal stresses

The shear loading is applied after the consolidation of the block (to be sheared). The normal stress is kept constant for each block and shearing stress is applied in small increments and corresponding horizontal shear displacement of the block is noted to an accuracy of 0.01 mm with the help of dial gauges/LVDT along with displacements in normal as well lateral dial gauges.

The rate of shear displacement should be less than 0.1 mm/min in 10 minute before taking a set of reading. This rate may be increased to 0.5 mm/min between sets of reading provided that the peak strength is adequately recorded (ISRM 1981). After reaching peak strength, reading should be taken at increment of shear displacement from 0.5 mm to 5 mm. The residual strength value is achieved when the block is sheared at a constant normal stress and at least 4 consecutive sets of reading are obtained which show not more than 5 % variation in shear stress over a shear displacement of 1 cm. The observations are continued till failure and continued even after the failure to the extent possible to get the information regarding residual frictional resistance. A sheared test block is shown in Fig. 5 after the testing.

Fig. 5 - Shear test block after shearing

After first value of residual stress is established, it is possible to obtain more values of residual stress from the same block. However, only one peak stress is obtained from one block. The normal stress on the block is either reduced or increased and another new value of residual stress is obtained against new normal stress by repeating the test. The block should be consolidated under each normal stress before shearing.

Out of a set of 5 test blocks, each block is tested for different but constant normal stress. After the completion of test on each block, the shear block is overturned to measure the correct contact shear area as shown in Fig. 6. The corrected area is measured by taking a section at every 10 cm in the directions of shear and perpendicular to the shear to measure accurately the average length and width of the sheared block.

2.2 Calculations

The plots of shear stress versus horizontal displacement (Fig. 7) and normal stress versus shear stress (Fig. 8) observed at all locations are plotted. The failure envelopes corresponding to the peak and the residual strength are also drawn.

The displacements recorded during the test are averaged to obtain mean values of shear, lateral and normal displacements. The shear and lateral displacements are taken into account while computing the corrected contact area. The shear area of the block is measured after the test by overturning the sheared block as shown in Fig. 6. Shear and normal stresses are computed as follows:

Fig. 6 - Measurement of shear surface for correct shear area calculation

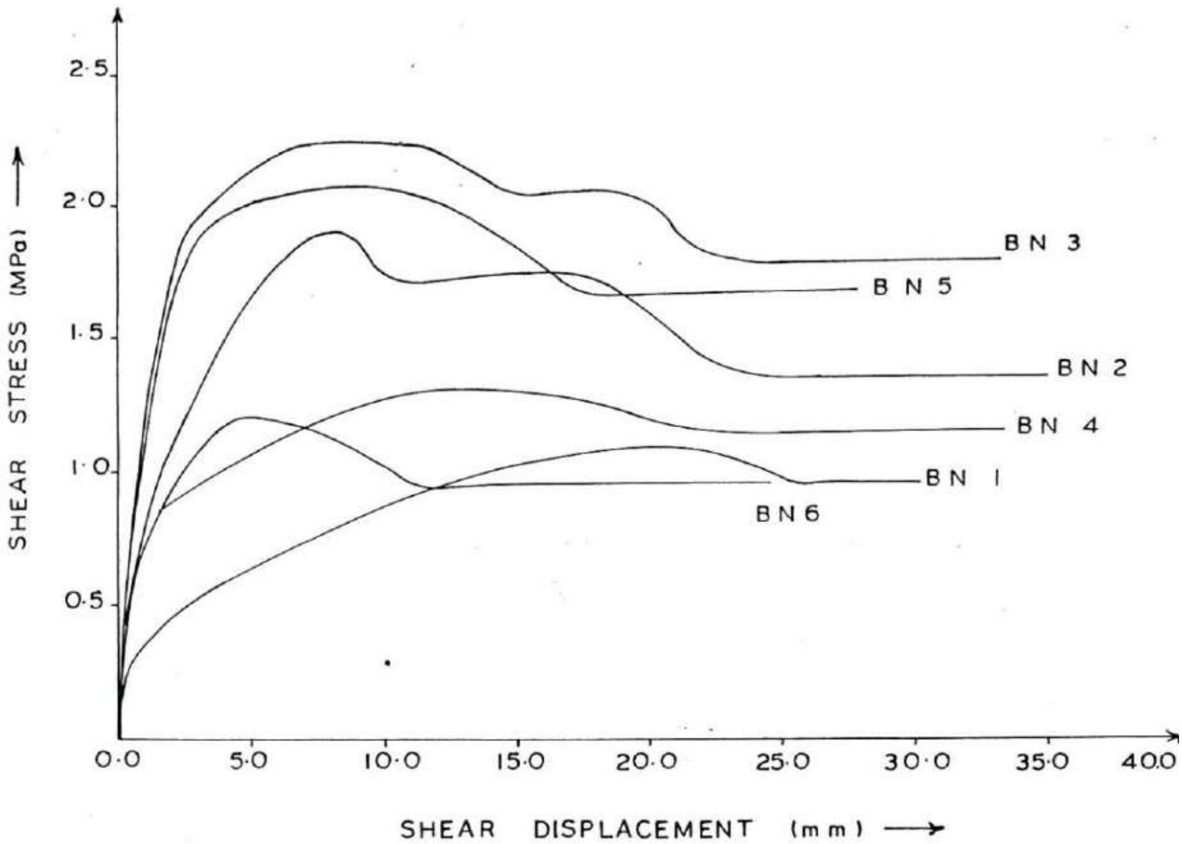

Fig. 7 - Shear stress versus shear displacement curves

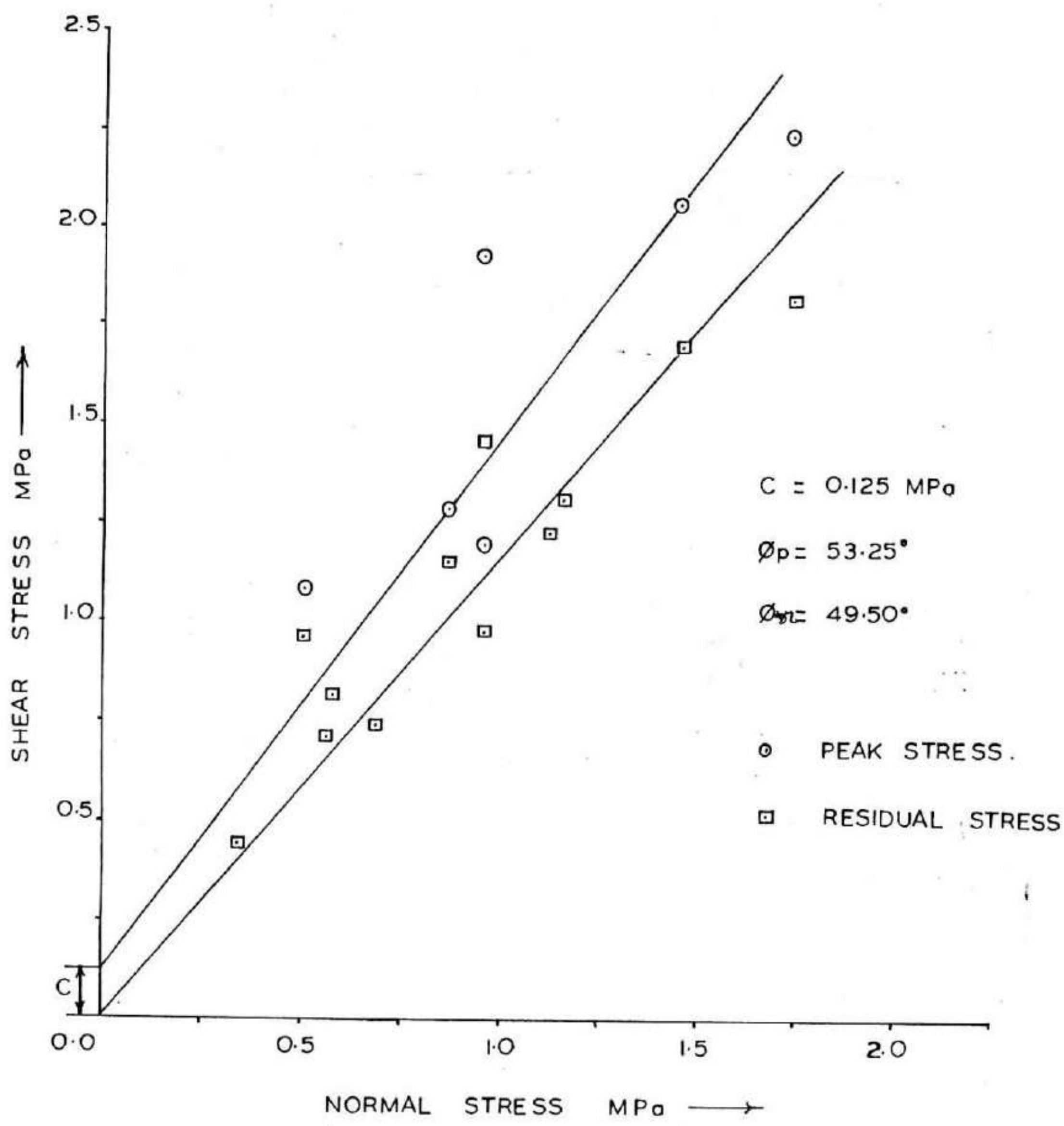

Fig. 8 - Shear stress versus normal stress curve

$$\text{Shear Stress} = \frac{P_s}{A} = \frac{P_{sa}\ \text{Cos}\alpha}{A} \qquad (2)$$

$$\text{Normal Stress} = \frac{P_n}{A} = \frac{P_{na} + P_{sa}\ \text{Sin}\,\alpha}{A} \qquad (3)$$

where,

P_s = Total shear force in kg (or kN),

P_n = Total normal force in kg (or kN),

A = Area of shear surface (overlap) corrected to account for shear and lateral displacements in cm^2,

α = Inclination of the applied shear force to the shear plane in degrees (15 degrees),
P_{sa} = Applied shear force in kg (or kN), and
P_{na} = Applied normal force in kg (or kN).

The applied normal stress is reduced after each increment in shear stress by an amount P_{sa} Sin α in order to maintain the normal stress approximately constant during in situ shear test.

2.3 Evaluation of Shear Strength

In situ shear tests are conducted for the determination of shear strength parameters of rock to rock and concrete to rock interfaces. Tests are conducted at a location of similar rock mass. For each set of tests, generally 5 to 6 blocks are sheared by varying the normal stress on each block. The rock type is noted. The test location should be marked on a map of drift along with geology (RMR and Q values) of the location. The peak and residual values of shear stress with reference to each block are noted from a shear stress versus shear displacement curve. The normal stresses from all blocks are plotted corresponding to peak and residual shear stresses. The shear strength parameters are evaluated from lines of best fit by linear regression analysis for peak and residual stresses.

The shear stress versus shear displacement curves for various normal stresses are shown in Fig. 7. The peak and residual shear stress versus normal stress plots are plotted and shown in Fig. 8. The peak and residual stresses are obtained from Fig. 7 at different normal stresses for respective blocks and are given in Table 1.

Table 1 - Peak and residual stresses against different normal stresses at shear blocks

Block Numbers	Normal Stress MPa	Peak Shear stress MPa	Residual Shear Stress MPa
BN1	0.506	1.081	0.951
BN4	0.872	1.286	1.153
BN2	0.961	1.926	1.453
BN6	0.961	1.196	0.974
BN5	1.453	2.066	1.687
BN3	1.744	2.238	1.813

In general, shear stress increases with the increase in normal stress. However, there are exception due to change in rock profile as also seen from Table 1 for block numbers 2 and 6 at same magnitude of normal stress, there are different peak and residual shear stresses.

The shear strength parameters were evaluated from Fig. 8 for concrete to rock interface. The peak shear strength parameters of cohesion and friction angle were 0.125 MPa and 53.25 degrees, respectively. The residual shear strength parameters of cohesion and friction angle were 0.0 MPa and 49.50 degrees, respectively. The peak shear strength parameters were evaluated based on 6 values from 6 blocks. However, 12 residual values were obtained from 6 blocks as plotted in Fig. 8.

After first value of residual stress was established, it was possible to obtain more values of residual stress from the same block. However, only one peak stress was obtained from one block. The normal stress on the block was either reduced or increased and another new value of residual shear stress was obtained against new normal stress by repeating the test. The block was consolidated under each normal stress before shearing.

3. SHEAR STRENGTH PARAMETERS FROM DIFFERENT PROJECTS

The shear strength parameters obtained from 20 different project sites in India and Bhutan are given in Table 2 for rock to rock and concrete to rock interfaces based on data from Singh and Sharma (1989), Singh et al. (2000a), Singh et al. (2000b), Singh (2007) and reports from CSMRS.

The data shows a large variations among the shear strength parameters i.e. cohesion and friction angle. There are also variations in peak and residual shear strength parameters. The variations are mainly due to change in rock mass properties from one project to another project and orientation of rock mass bedding planes at a particular site. There are variations at one project site with same rock type on left and right bank. However, the shear strength parameters are almost similar in magnitude on the left bank and the right bank of Tala hydroelectric project in Bhutan for both rock to rock and concrete to rock interfaces (Table 2).

The variations in the magnitudes of shear strength parameters and average values have also been given in Table 2 based on this limited test data from 20 sites in Himalayan region.

The average values of peak shear strength parameters of cohesion and friction angle on rock to rock interface were 0.48 MPa and 58.4 degrees with a variation from 0.11 to 1.20 MPa and 38 to 70 degrees, respectively. The average residual shear strength parameters of cohesion and friction angle were 0.22 MPa and 49.6 degrees with a variation from 0.0 to 0.76 MPa and 37.5 to 69 degrees, respectively (Table 2).

On concrete to rock interface, the average value peak shear strength parameters of cohesion and friction angle were 0.35 MPa and 55.8 degrees with a variation from 0.12 to 0.79 MPa and 41 to 64 degrees, respectively. The average residual shear strength parameters of cohesion and friction angle were 0.15 MPa and 52 degrees with a variation from 0.0 to 0.48 MPa and 40 to 64 degrees, respectively (Table 2).

In general, the average values of shear strength parameters of cohesion and friction angle on rock to rock interfaces were higher than on concrete to rock interfaces. These friction angles are very high due to low normal stresses.

The variations are also due to change in direction of shearing in same rock type and same project. It is, therefore, necessary to conduct in situ shear test on different rock interfaces as well as on concrete to rock interface at all project sites. The data from one project with similar rocks should not be applied to another project.

Table 2 - Shear strength parameters from different projects in India and Bhutan

S. No.	Name of the Project	Rock Type	Shear Strength Parameters							
			Rock to Rock Interface				Concrete to Rock Interface			
			Peak Values		Residual Values		Peak Values		Residual Values	
			C MPa	ϕ^0	C_r MPa	ϕ_r^0	C MPa	ϕ^0	C_r MPa	ϕ_r^0
Hydroelectric Projects in India										
1.	Lakhwar Dam	Trap	0.68	42.0	0.58	40.0	-	-	-	-
2.	Chamera Dam Project	Phillites	-	-	-	-	0.13	53.3	0.00	49.5
3.	Hibra Hydroelectric Project	Phillitic Quartzite	-	-	-	-	0.10	56.5	0.00	55.1
4.	Srinagar Dam (Left Bank) Main drift T-Section	Quartzite	 0.50 1.20	 68.0 59.0	 0.15 0.60	 60.0 58.0	 0.25 -	 58.5 -	 0.22 -	 45.0 -
5.	Srinagar Dam (Right Bank) Main drift T-Section	Quartzite	 - -	 - -	 - -	 - -	 0.44 0.40	 59.0 64.0	 0.00 0.00	 51.0 64.0
6.	Srinagar Dam (Right Bank) Main drift	Metabasic	0.76	46.0	-	-	0.16	41.0	0.10	40.0
7.	Greater Shillong Dam	Phyllites	0.27	70.0	0.01	69.0	0.25	66.0	0.01	62.0
8.	Nathpa Jhakri Dam	Mica Schist	0.25	57.5	0.13	50.3	-	-	-	-
9.	Kalpong Dam	Ultra Basic	-	-	-	-	0.12	59.0	0.01	46.0
10.	Rupsiabagar Khasipara (Left Bank)	Quartz Biotite Schist	0.99	58.8	0.76	40.5	0.32	55.8	0.23	53.5
11.	Rupsiabagar Khasipara (Right Bank)	Quartz Biotite Schist	-	-	-	-	0.37	60.6	0.35	59.4
12.	Vishnugad Pipalkothi (Left Bank)	Quartzite	-	-	-	-	0.79	54.8	0.48	49.1
13.	Vishnugad Pipalkothi (Right Bank)	Quartzite	-	-	-	-	0.30	58.8	0.22	57.1
14.	Kotlibhel Dam (Left bank)	Quartzitic Sandstones	0.35	67.9	0.22	65.4	0.42	54.3	0.26	53.5
15.	Kotlibhel Dam (Right bank)	Quartzitic Sandstones	0.31	65.0	0.24	52.0	0.34	54.0	0.13	50.0
Hydroelectric Projects in Bhutan										
16.	Bunakha Dam	Biotite Gneiss	-	-	-	-	0.65	62.0	0.38	61.0
17.	Sankosh Main Dam	Phyllites	0.17	60.0	0.00	57.0	-	-	-	-
18.	Sankosh Lift Dam	Sandstone	0.11	38.0	0.00	37.5	0.13	52.0	0.00	48.0
19.	Tala Dam (Right Bank)	Biotite Gneiss	0.37	62.9	0.025	57.1	0.50	49.0	0.08	46.0
20.	Tala Dam (Left Bank)	Biotite Gneiss	0.35	63.8	0.14	57.4	0.54	46.0	0.16	45.0
Variations in values			0.11-1.20	38-70	0.00-0.76	37.5-69	0.12-0.79	41-64	0.00-0.48	40-64
Average values			0.48	58.4	0.22	49.6	0.35	55.8	0.15	52.0

4. CONCLUSIONS

Based on this study on in-situ shear test and the shear strength parameters data from 20 projects, the following conclusions are drawn:

- The shear strength parameters should be evaluated by conducting in-situ shear test at rock to rock and concrete to rock interfaces by constructing minimum of 5 blocks.

- It is possible to obtain only one value of peak shear stress from one block. However, 1 to 2 additional values of residual shear stress can be obtained by increasing or reducing normal stress on each block after getting first value of residual stress. The actual sheared area of each block should be determined accurately by overturning the block after shearing.

- The average values of shear strength parameters of cohesion and friction angle on rock to rock interfaces were higher than on concrete to rock interfaces.

- Due to variations in rock mass properties, the data from one project with similar rocks should not be applied at another project. There are changes in values from one bank to another bank at same dam site. There are also changes due to change in direction of shearing.

- Strength parameters are useful for stability of rock slopes and concrete dam foundations.

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