Shear strength characterization of a natural rock joint developed in Peridotite deposits

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ABSTRACT: The shear behavior of open rock joints in Peridotite rock, igneous in nature, is studied. These joints are open, random, with the most frequent aperture of 1-2 mm, filled with serpentinite, magnesite, chlorite, asbestos, and talk. Roughness are characterized as rough, smooth, undulating, planar, stepped, stepped/smooth plane, rough stepped, stepped undulating, polished, planer rough, and others. Direct shear test at three constant normal load are carried out, and joint characteristic curves are developed to determine their mechanical properties. All joint sample was collected from different boreholes of 75 mm diameter from depth ranging from 13.18 m to 555.78 m. Further, joints basic friction angle, JRC, JCS are determined. Based on these test results, the dilation and peak shear displacement models are developed and compared with existing shear strength models.

Keywords: Open rock joint, CNL, Direct shear test, Dilation.

1 INTRODUCTION

Development of any mining, civil, or petroleum engineering structure in rock mass, especially for those within a few hundred meters from the earth's surface, behaves as discontinuum. The behavior of these discontinuities under given conditions plays an important role in defining the stability of rock structures. It is, therefore, essential that both the structure of a rock mass and the nature of its discontinuities are carefully studied in addition to the lithological description of the rock type (Anon, 1981). For this purpose, eighty-five sets of joint samples of peridotite are collected from boreholes coring of 75 mm diameter core obtained from a depth ranging from 13.18 m to 555.78 m with an average depth of 271.3 m. Peridotite is a country rock for the chromite deposit of Sukinda valley, Odisha, India. These joints are open/ filled, with the most frequent aperture of < 1 mm up to 15 mm, filled with cohesive materials like serpentinite, magnesite, chlorite, asbestos, talk and no indication of prior shearing. Geologically roughness of the joints are classified as rough, smooth, undulating, planar, stepped, stepped/smooth plane, rough stepped, stepped undulating, polished, planer rough, and others.

The direct shear test in constant normal load (CNL) condition is carried out on these specimens at three normal stresses of 1 MPa, 2 MPa, and 3 MPa. From the standard plots cohesion (0 to 520.43

kPa), angle of internal friction (0.37 to 17.34 kPa), peak shear strength (1660.54 kPa), peak shear displacement (9 mm), dilation angle (13.98), residual cohesion (460 kPa), residual friction angle (15.1°) are determined. Basic friction angle (30°) is determined by tilt test. The nature of shear stress vs. shear displacement curve is mostly elasto-perfectly-plastic, whereas three types of dilation curves are observed, which represents weak joint, weak-to-strong joint, and strong joint surface. It is found that mostly weak-to-strong joint surface is dominating, followed by weak surface, and for very few instances, strong joint surface are notices. With the increase in normal stress the dilation behaviour is decreasing.

1.1 Site geology

The Sukinda Ultramafic complex forms a part of the unfossiliferous metamorphosed Pre-Cambrians of peninsular India and one of the most important ultramafic complexes with huge deposit of chromite, located near the east coast of India in the tri-junction of Jajpur, Keonjhar and Dhenkanal districts in Odisha state, India. The chromite bearing ultramafics of Sukinda area have intruded into the Precambrian metamorphites in the form of a lopolith. The intrusive has a width of 2-5 km and extends for about 20 kms in a ENE-WSW direction from Kansa in the east to Maruabil and beyond in the west and situated between latitude 20° 57’ 38’’ N to 21° 04’ 58’’ N and longitude 85° 38’ 36’’ E to 85° 52’ 18’’ E featuring in Survey of India Toposheet No. 73 G/12, G/16, H/9 and H/13, The area is bounded by Daitari hill ranges in the north and Mahagiri hills in the south as shown in Figure 1. The ultramafic body is consisting essentially of magnesite rich Dunite-Peridotite with chromite bands and sub-ordinate amount of pyroxenite which is devoid of chromite mineralization (Chakraborty & Chakraborty, 1984).

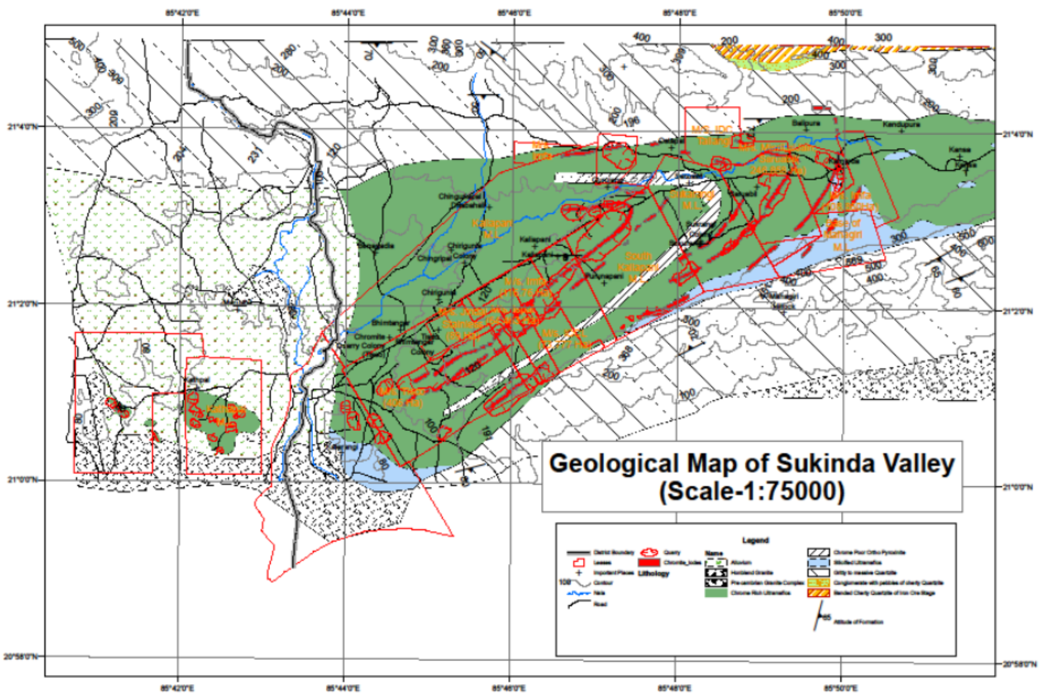


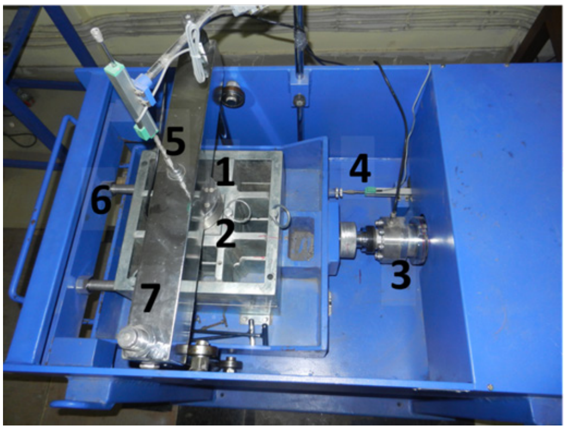
Figure 1. Geological map of Sukinda valley (as per GSI).

1.2 Rock joint sample

The rock joint samples of eighty-five sets are collected from 75 mm core, drilled at various location from different depths ranging from 13.18 m to 555.78 m in the Sukinda valley. Samples from each lithological units are wrapped, packed and transported to the laboratory for direct shear test (Muralha et al., 2013).

2 LABORATORY EXPERIMENT

Direct shear test is conducted on the electro-mechanical direct shear machine, as shown in Figure 2, by casting the jointed samples in 100 mm x 100 mm x 50 mm mold and 150 mm x 150 mm x 50 mm mold depends on the size of the shear plane. Casting is done by using white cement with sand are cured in a humidity chamber for 21 days. This apparatus consists of shear box of dimension (100~300 mm×100~300 mm×100~300 mm) loading unit, and data acquisition system. Loading units includes normal and shear load cells of capacity 50 kN each. Normal stress is allowed to stabilize before the shear force is applied. Shear displacement and vertical displacement are measured by LVDT with measuring range of ±50 mm and accuracy of 0.01 mm. All direct shear tests are performed up to 10 mm of shear displacement at shearing rate 0.2 mm/min.



1- Shear box
2- Normal load cell
3- Shear load cell
4- Horizontal LVDT
5- Vertical LVDT
6- Loading frame
7- Loading yoke

Figure 2. Direct shear apparatus.

For the casting of sample, molds of Plywood are prepared, as shown in Figure 3. To prepare the laboratory experiments, the rock specimens are set inside the molds and then are encapsulated to ensure a solid fit. For this purpose, rock sample is kept at the centre of mold and fixed with casting material. Casting material is a mixture of sand, cement, and water in 1: 1.5: proper ratio and then molds are tightened. After natural curing in the mold for 24 h, the molded cement sample are placed in the humidity chamber for 21 days for curing. Finally, the samples are de-molded and used for direct shear test.

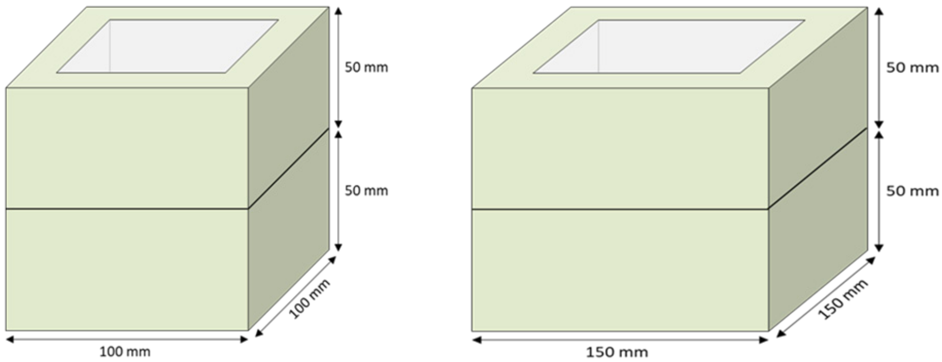


Figure 3. Dimension of the casting mold.

Figure 4 shows the steps for sample preparation from borehole core (Figure 4(a)), condition of sample before and after the direct shear test. Borehole core is cut up to the required length so as to fit inside the mold, the casted mold are shown in Figure 4(b). Figure 4(c) shows the upper and lower block of the casted sample before test, whereas Figure 4(d) shows the sheared blocks. The test results are measured in terms of shear stress vs. shear displacement plots at different normal stress of 1 MPa, 2 MPa, and 3 MPa.

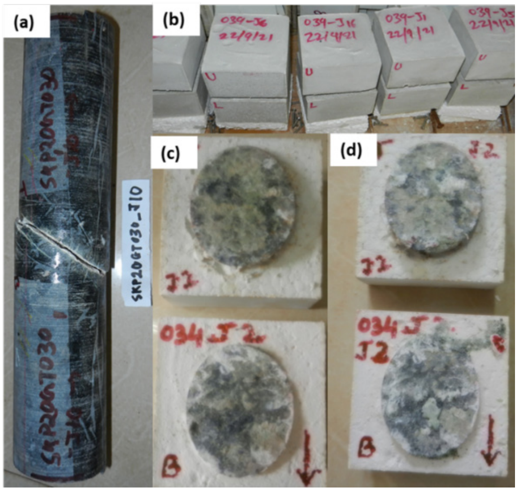


Figure 4. Sample preparation an test procedure for direct shear test.

3 RESULTS AND DISCUSSION

For each set of direct shear strength test, four graph are plotted as shown in Figure 5 and the results are summarized in Table 1.

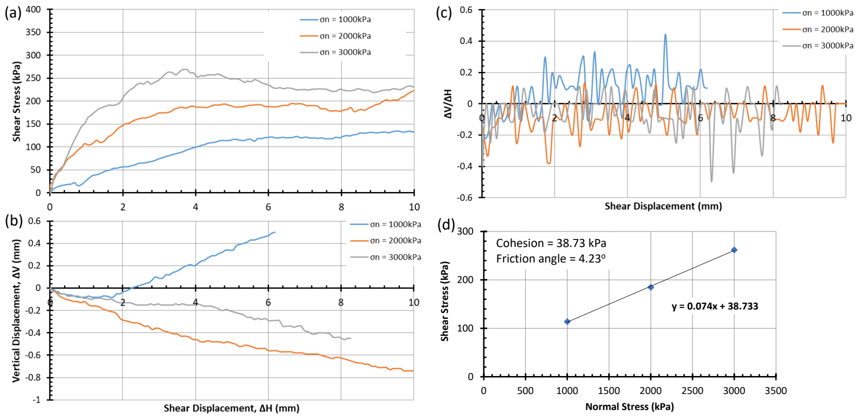


Figure 5. Plots from direct shear test.

Table 1. Summary of direct shear test results.

Statistical parameters	C (kPa)	φ (°)	Res. C (kPa)	Res. φ (°)	k (MPa/m)	JRC	δ_{hp} (mm)	d_n (°)	JCS (MPa)
Minimum	0.00	0.88	0.00	0.29	0.01	1.00	0.90	0.17	19.00
Maximum	543.54	21.54	15.10	15.10	0.36	18.50	9.00	13.98	40.40
Mean	127.34	8.64	7.85	7.85	0.12	6.30	3.94	5.02	32.02
SD	138.42	5.85	4.70	4.70	0.08	3.52	1.94	3.10	5.38

C: Cohesion; φ: friction angle; Res.: Residual; k: shear stiffness; SD: Standard Deviation; JRC: Joint roughness coefficient; δ_{hp}: Peak horizontal displacement; d_n: Dilation angle; JCS: Joint compressive strength

Figure 6 typically shows three post failure behaviour (1) elastic-perfectly plastic, (2) elastic-hardening-perfectly plasticity, (3) elastic-softening-perfectly plasticity. Out of all tests the dominant behaviour is shown by hardening and softening characteristics. The peak failure state is at the yield point where the slope of the curve decreases to zero. This maximum stress point is marked as point C in Figure 6. At this point, unstable crack propagation starts, and cracks intersect each other and start forming a major failure plane resulting into failure of asperities. The testing system should be stiffer than the specimen to develop the post failure behaviour curve. If the testing system is not stiff, the test will be terminated by brittle failure of the asperities at point C. Different names like post-failure state, plastic state, post-peak state, and strain-softening or -hardening region exist for the description plastic region. In this state, the slope of the curve is negative for the softening behavior, zero for perfectly plastic and positive for hardening behaviour. In softening behaviour, asperities loses their ability to resist or sustain load with increasing shear deformation.

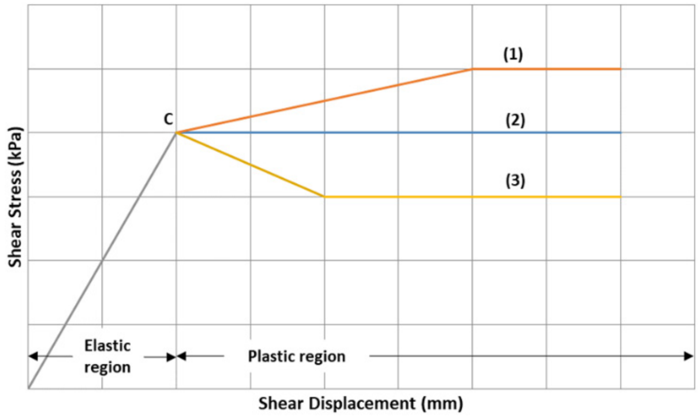


Figure 6. Classification of shear stress vs shear strain curve on post failure behaviour.

3.1 Peak shear displacement model

Figure 7 shows the linear relationship between the normalised JRC and normalised peak shear displacement. This relation can be used to predict the maximum shear displacement of the joint as shown by Equation 1.

$$\frac{d_p}{L} = \frac{1}{0.07}\frac{JRC^{0.94}}{L} \tag{1}$$

In general form, the Equation 1 can be expressed as shown in Equation 2, where constant A and B represents the surface morphology, i.e., roughness and joint strength.

$$\frac{d_p}{L} = \frac{1}{A}\left(\frac{JRC}{L}\right)^B \tag{2}$$

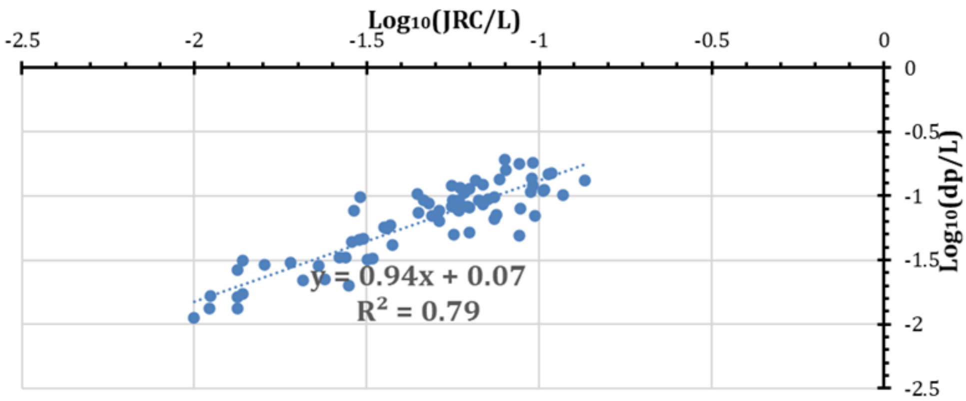


Figure 7. Normalized JRC with normalised maximum shear displacement.

3.2 *Effect of normal stress on dilatancy*

The effect of normal stress on dilation behaviour is shown in Figure 10. If specimen subjected to higher normal stresses as 0.7 MPa, 1.0 MPa, 2 MPa, and 3.0 MPa the dilatancy decreases because a greater proportion of the asperities becomes damaged during shearing. Based on the dilation curve, the joint plane of the rock joint can be classified as (1) weak joint surface, (2) weak to strong joint surface, and (3) strong joint surface. For the weak surface there is continuous downward increase in vertical deformation while shearing, indicating the weak joint surface, which may be due to weathering of the joint surface or weak joint material. For weak to strong joint surface, dilation curve shows downward increase of vertical deformation followed by upward movement, signifies weak surface deformation at the start of the shearing followed by riding of asperities. Similarly, for strong surface the dilation is asperities are riding on each other with the shearing of the joint. Although, this is limited to only three specimens.

$$d_n = 21.61e^{-32.58\left(\frac{\sigma_n}{\sigma_c}\right)} \tag{3}$$

In general form, the equation (5) can be written as equation (6) where, constant A and B are signifies the roughness of the asperities.

$$d_n = Ae^{-B\left(\frac{\sigma_n}{\sigma_c}\right)} \tag{4}$$

4 CONCLUSIONS

The experimental results are analysis and the findings from this analysis is as follows:

- From direct shear test, it is found that the cohesion (0 to 520.43 kPa), angle of internal friction (0.37 kPa to 17.34 kPa), peak shear strength (1660.54 KPa), peak shear displacement (9 mm), dilation angle (13.98), residual cohesion (460 KPa), residual friction angle (15.1^o) are determined. It is found that the JRC varies from 1 to 18.5, and basic friction angle varies from 28^o to 30^o.
- The nature of shear stress vs. shear displacement curve is mostly elasto-perfectly-plastic in nature. whereas three types of dilation curves are observed i.e., weak joint, weak-to-strong joint, and strong joint surface. It is found that mostly weak-to-strong joint surface is dominating, followed by weak surface, and for very few instances, strong joint surface are notices. With the increase in normal stress the dilation behaviour is decreasing.
- A ratio of peak shear displacement to the joint length is a linear function of the ratio of JRC and joint length.
- Dilation model is developed, which is an exponential function, and it decreases with the increase in the ratio of normal stress and joint compressive strength.

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