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Mechanical Behavior of Rock Joints with Various Kinds of Joint Surface Roughness under Cyclic Direct Shear Loading Conditions

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This study investigates the cyclic shearing behavior of simulated natural rock samples with three kinds of natural joint surface roughness under different confining pressure and shearing rate conditions. The experimental results contribute to the understanding of various mechanical behaviors of the joint for the cyclic case. Mechanical properties, such as the Joint Roughness Coefficient (*JRC*), the shear stiffness, the dilation, the peak and residual stresses, were obtained. The mechanical properties depended on the surface roughness characterized by the *JRC*, the applied normal load, the shearing rate and the loading cycles. These can be helpful in investigating the weak nature of rock slopes under dynamic loading conditions.

Key Words : *rock joints, direct shear test, dilation, damage coefficient, joint surface roughness*

1. INTRODUCTION

The mechanical properties of rock masses are highly affected by the presence of joints. The joints in rock masses are the weakest planes; they have a tendency to slide or to shear over the other planes during the construction of foundations, tunnels and rock slopes[1)]. Joints can cause a significant reduction in the shear strength of rock masses. The shear behavior of rock joints depends upon certain factors, such as the shearing rate (shearing velocity), the joint stiffness, the joint surface roughness, the infilling material and the confining conditions. Hence, it is necessary to carry out a proper evaluation of the mechanical properties of rock joints and to gain a clear understanding, prior to the construction phase.

In this study, a series of cyclic shear tests is carried out for simulated rock joints with various kinds of joint surface roughness under Constant Normal Loading (CNL) as the boundary condition. The cyclic behavior of rock joints is essential in understanding their performance during earthquake. In particular, the stability of a rock slope is discussed through the cyclic behavior of the rock joints. Ground motion during an earthquake can bring the loading and unloading conditions resulting in the cyclic shearing of the joints. Asperity degradation can be a crucial phenomenon during this action. Changes in joint surface roughness or asperity degradation can adversely affect the mechanical properties of the rock joints. A reduction in the mechanical properties, due to the effect of cyclic loading from earthquake ground motion, can bring a fractured rock slope to a vulnerable condition. Since this research deals with cyclic shear tests, the shearing velocity parameter is very essential.

Asperity degradation and the shear strength of rock joints have been found to be functions of the joint surface roughness, the confining pressure, the shearing velocity and the number of cycles[2)]. Barton and Choubey (1977) explained the damage coefficient (*M*). Later, Asadollahi (2010) discussed the coefficient of asperity degradation. Nevertheless, damage coefficient *M* has been not reported in terms of cyclic shear on samples with varying *JRC*. Since the relation for *M* depends upon the *JRC* value and JCS/σ_n, in this study, the damage coefficient has also been taken into consideration in the case of cyclic shear for different joint surface roughness, normal loading and shearing rate conditions. The peak shear displacement, as given by Assadollahi (2010), has also been discussed, as it too depends upon normal loading, shearing rate and the *JRC* values. In this paper, therefore, a study methodology and a discussion of the results are given in order to see the variation in mechanical properties with joint surface roughness, shearing velocity and the confining condition under cyclic loading.

2. Damage Coefficient, *M*

The Joint Roughness Coefficient (*JRC*) is the number that is used to characterize the roughness of a rock joint. Yu and Vayssade (1991) gave an empirical relation for *JRC* that depends upon the measuring intervals and the Z_2 parameter proposed by Tse and Cruden (1979).

$$JRC = 60.32 \times Z_2 - 4.51 \text{ (for 0.25 mm interval)} \quad (1)$$

Barton (1973, 1976) studied the behavior of natural rock joints and proposed that the *JRC* of a rock joint can be calculated through backward calculation, depending upon its peak shear strength during the shear test, from the following equation:

$$JRC = \frac{\arctan\left(\frac{\tau_p}{\sigma_n}\right) - \phi_b}{\log_{10}\left(\frac{JCS}{\sigma_n}\right)} \quad (2)$$

Joint dilation is the relative movement between the two joint surfaces during shearing. In direct shear tests, it is the vertical movement of one surface (shearing) with respect to the other (non-shearing surface). Dilation can be represented in angular form as the dilation angle given by the following equation:

$$d^{\circ} = \arctan\left(\frac{\delta v}{\delta h}\right) \quad (3)$$

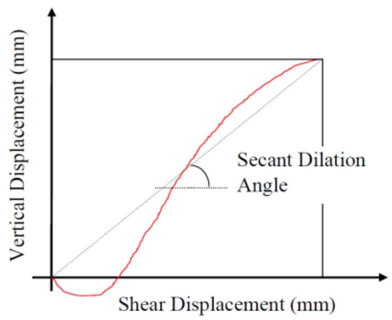


Fig. 1 Secant dilation angle calculation

The empirical equation for the damage coefficient (*M*) is given as follows:

$$M = \frac{JRC}{12.\log_{10}\left(\frac{JCS}{\sigma_n}\right)} + 0.7 \quad (4)$$

Barton (1982) gave an empirical relation for the peak shear displacement that depended on the length of the joint. He did not consider the effect of normal loading in his empirical relation. Later, Asadollahi (2010) proposed an empirical relation for estimating the peak shear displacement as follows:

$$\delta_{peak} = 0.0077 L^{0.45}\left(\frac{\sigma_n}{JCS}\right)^{0.34} \cos\left(JRC.\log_{10}\left(\frac{JCS}{\sigma_n}\right)\right) \quad (5)$$

3. Cyclic direct shear tests of rock joints

After choosing three different kinds of natural joint surfaces (named as surfaces G, H and C), mortar specimens are casted by using impressions of ready-made rubber replicas of natural joint surfaces. The combination ratio of cement, sand and water of 1:2:0.65 is used. High-strength Portland cement and Silica sand number 6 are used. The simulated specimens used are rectangular specimens with a cross section of 120 mm × 120 mm and a height of 60 mm. Likewise, cylindrical samples are also made under the same conditions to carry out the uniaxial compression tests. The specimens are cured in water for 28 days.

To study the mechanical properties, by varying the joint surface roughness condition, the measurement of the roughness profile is important. For this study, the 3-D roughness profiling system, shown in **Fig. 2**, is used. It measures the roughness contour of the specimen before and after the shearing, so that the changes in surface elevation can be traced. The system consists of an X-Y positioning table, with a positioning accuracy of ±10 μm and a repositioning accuracy of ±10 μm. It also consists of a laser scan micrometer with a maximum resolution of 1 μm, a measurement allowance spot dimension of diameter 0.3 mm and a measurement range of ±5 mm . At a point, the spot takes 128 number of data and calculates the average for a precise value of elevation. Based on the digital data of the joint surface roughness, Z_2 parameters were calculated for the surface (each line) using Eq. (6). The average value for Z_2 (following a normal distribution) was adopted to represent for the entire surface. Then the *JRC* before and after shearings were calculate using Eq. (1) and are shown in **Table (1)**.

$$Z_2 = \left[\frac{1}{M-1}\sum_{i=1}^{M-1}\left(\frac{\Delta y}{\Delta x}\right)_i^2\right]^{1/2} \quad (6)$$

Fig. 2 Profiling robot

Fig. 3 MTS direct shear test machine

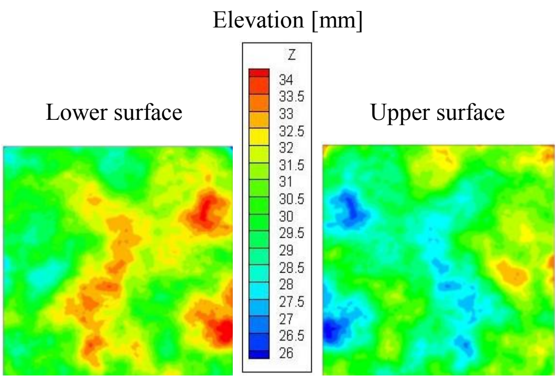
Table 1 *JRC* from roughness profile (example: sample C)

σ_n = 0.5 MPa and shearing rate = 0.1mm/min				
Cyclic condition	*JRC* (upper)	*JRC* (lower)	*JRC* mean	*JRC* from backward calculation
Before shearing	10.58	8.86	9.72	-
After 1st cycle	10.54	8.42	8.98	12.32
After 2nd cycle	9.34	8.39	8.87	9.23
After 3rd cycle	9.35	8.38	8.87	7.71
After 4th cycle	9.37	8.18	8.78	5.90

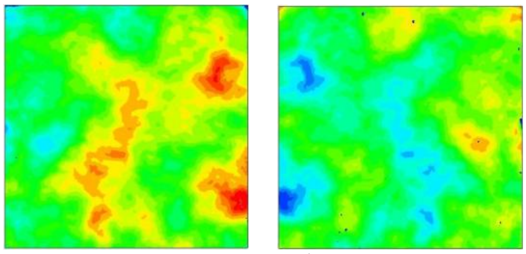
Direct shear tests are conducted under the normal confining conditions of σ_n = 0.5 MPa, 1.0 MPa and 2.0 MPa and the shearing velocity of 0.1 mm/min and 1.0 mm/min. One horizontal dial gauge is used to measure the shear displacement, whereas two vertical dial gauges are used to record the vertical displacement. The shearing was carried out until the maximum displacement of 10 mm. The experimental setup of the machine is shown in **Fig. 3**.

4. Results and discussion

Table 1 presents the fresh *JRC*s of the sample obtained from Eq. (1). Since, there is no significant difference between the *JRC*s of the upper and lower surface joints, it is convenient to use the average of the two for analysis. **Table 1** shows that the *JRC* of the sample decreases with an increase in the shear cycles.



(a) Joint surface C (lower and upper faces), before shearing



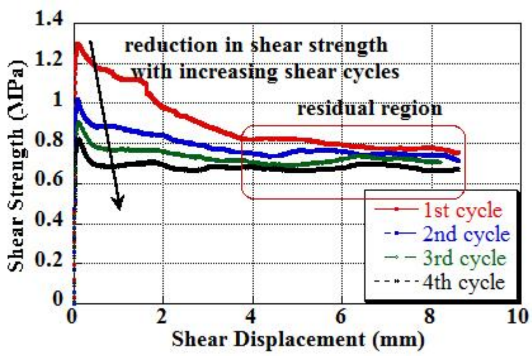
(b) Joint surface C, after 2nd shear cycle

Fig. 4 Contour of joint surface roughness

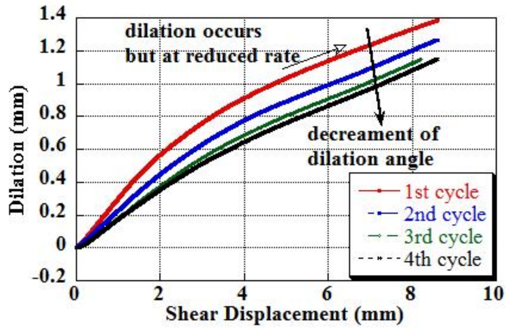
shearing and to the asperities becoming smoother than they were previously. For the latter cycles, there is no significant change in *JRC*. A notable difference is seen between the *JRC*s found from Barton's backward calculation and from the Z_2 of the roughness profile. There is a drastic change in the *JRC*s calculated from Barton's backward analysis (**Table 1**), because it incorporates the potential shaved off regions during shear. However, the *JRC*s calculated from the surface roughness profiles incorporate entire points of the joint surface. Changes in the surface of the joint before and after cyclic shear are shown in **Fig. 4**. From the profile data for the *JRC*, there is only a slight change in the *JRC* after shear.

Fig. 5 shows the relation between shear stress, shear displacement and dilation for a sample with normal load of σ_n = 1.0 MPa and the shearing rate of 0.1 mm/min. The reduction in shear strength of the sample with increasing the shearing cycles, is shown in **Fig. 5(a)**, while the graphical representation for the dilation vs. shear displacement is shown in **Fig. 5(b)**. It is seen that the joint dilates until the peak strength. After the peak strength of the joint is reached, dilation continues, but at a reduced rate.

This is due to the lower degree of the overriding of the asperities which decreases after the breakage. Upon increasing the shearing cycles, the dilation of the joint attenuates.



(a) Shear stress vs. shear displacement



(b) Dilation vs. shear displacement

Fig. 5 Examples of shear stress, shear displacement and dilation graph respectively for sample H

The reduction in peak shear strength for different kinds of joints is shown in **Fig. 6**. This can be made analogous to **Fig. 7**, it is seen that most of the crucial shearing of the asperities have occurred during the first cycle. After the first cycle, there is no significant change in the weight of the gouge material. The sheared volume is calculated based on the weight of gouge material measured after the shearing and density of the sample. For the sample with a high *JRC*, under a low normal load, crucial shearing does not always occur in the first cycle. The peak stress is seen to be decreasing in **Fig. 6**, but with a steep decent (for sample C). However, for the samples with lower *JRC*, the peak stress reaches a nearly constant level from the same cycle.

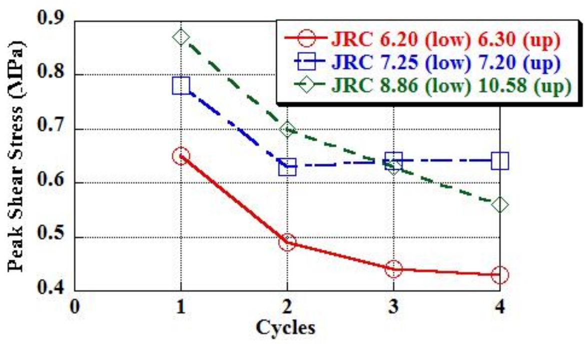


Fig. 6 Peak stress vs. shear cycles

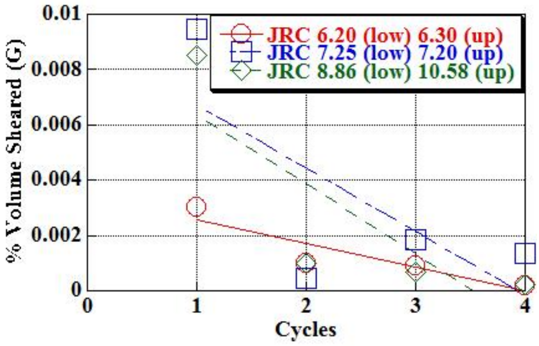


Fig. 7 Percentage volume sheared vs. shear cycles

Due to the undisturbed fresh asperities, more friction is induced owing to higher shear strength.

Fig. 8 shows the reduction in shear stress on increasing the shearing velocity. It can be due to the less time of contact between the asperities to dilate on higher shear velocity. It can be also credited to the fact that, on increasing the shear velocity, time for heat dissipation is lessened resulting in slight melting of the asperity contacts causing reduction in frictional resistance[10].

Along with the other mechanical properties, **Table 2** also shows the residual strength of the samples after cyclic shear. There is no significant variation in the residual strength of a sample after cycles of shearing. Asperity degradation can be visualized from the decrease in dilation angle. Similar to *JRC*, asperity degradation happens in mainly the 1st or 2nd shear, while it attenuates for later cycles. The general trend in the decrement of the dilation angle and the effect of the asperity height and the inclination in dilation can be compared to the tests carried out by Chern et al. (2012). After a comparison, it can be clarified that for higher *JRC*, at a lower normal load, crucial shearing does not always occur in the first cycle and the degradation of the asperities continues.

In a similar manner, the effect of cyclic shear on shearing stiffness (k_s) can also be seen. Shear stiffness diminishes with the increasing shear cycles. This is because the teeth break and the surface smoothens after consecutive shearing. The increase in stiffness is seen in some cases; this was due to errors in the reseating of the two halves in the same original position[11].

In the case of the damage coefficient, as given by Eq.(4), results can be seen in **Table 2**. The sample with the higher *JRC* suffers more damage than the other two. For the low *JRC* samples and under a lower normal load, the damage coefficient decreases and the values remain steady after the 1st or 2nd cycle. However, in the case of higher *JRC*, the damage is prolonged and takes more cycles to attain a steady position.

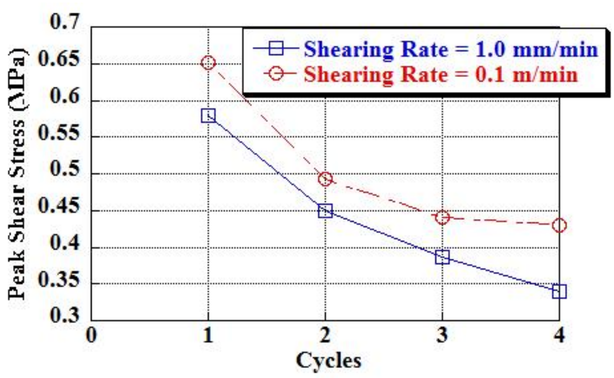


Fig. 8 Peak shear stress vs. shear cycles

Table 2 Mechanical properties of the samples after cyclic shearing

Uniaxial compressive strength 34.97 MPa, Base friction angle (ϕ_b) = 37.5 $^\circ$					
Normal load (σ_n) = 0.5 MPa and shearing rate = 0.1 mm/min					
Sample Initial *JRC* (up) Initial *JRC* (low)	Shear cycle	Residual stress [MPa]	Secant dilation angle	Shearing stiffness (*ks*) [per mm]	Experimental peak shear displacement [mm]
		JRC (backward calculation)	Average dilation angle	Damage Coefficient (*M*)	Asadollahi's peak shear displacement [mm]
G 6.20 6.30	1	0.36	8.11	4.70	0.273
		8.11	8.15	1.06	0.675
	2	0.29	8.16	4.18	0.196
		3.84	8.16	0.87	0.694
	3	0.30	7.03	18.30	0.059
		2.08	6.91	0.79	0.698
	4	0.30	7.41	16.00	0.024
		1.37	7.30	0.76	0.699
H 7.20 7.25	1	0.51	14.20	1.36	0.854
		10.69	16.89	1.18	0.658
	2	0.49	14.07	1.16	0.571
		7.52	15.36	1.03	0.679
	3	0.57	9.60	0.55	1.147
		7.83	12.24	1.05	0.677
	4	0.56	9.00	0.49	0.953
		7.78	11.42	1.05	0.677
C 10.58 8.86	1	0.38	17.09	4.36	0.449
		12.32	18.49	1.25	0.645
	2	0.39	17.13	3.36	0.026
		9.23	17.04	1.12	0.669
	3	0.31	15.46	4.31	0.154
		7.71	16.48	1.04	0.678
	4	0.33	17.09	4.73	0.124
		5.90	17.46	0.96	0.686
Normal load (σ_n) = 1.0 MPa and shearing rate = 0.1 mm/min					
H 7.20 7.25	1	0.75	9.05	44.62	0.071
		9.63	8.37	1.21	0.856
	2	0.71	8.32	25.62	0.078
		5.21	7.89	0.98	0.876
	3	0.70	7.91	19.80	0.109
		3.07	7.76	0.86	0.882
	4	0.67	7.59	18.70	0.092
		1.33	7.36	0.77	0.885
Normal load (σ_n) = 0.5 MPa and shearing rate = 1.0 mm/min					
G 6.20 6.30	1	0.35	8.18	4.45	0.173
		6.36	8.27	0.98	0.685
	2	0.31	7.45	5.25	0.119
		2.43	7.60	0.80	0.697
	3	0.31	6.88	5.62	0.122
		0.13	7.18	0.70	0.699
Normal load (σ_n) =2.0 MPa and shearing rate = 1.0 mm/min					
H 7.20 7.25	1	0.96	9.57	23.29	0.16
	2	11.96	9.55	1.50	1.08

5. CONCLUSIONS

Cyclic shearing has a significant effect on the mechanical properties of rock joints. The shear strength of rock joints decreases after consecutive shearing. This is attributed to the breakage of the asperities, which eventually become smoother. The joints with higher *JRC*s have a greater degree of interlocking and asperity height, which causes more friction during shearing, and that results in higher shear strength. An increment in normal loading requires more force to overcome the internal resistance during shearing leading to a rise in shear strength. Whereas, the internal resistance decreases leading to reduction in shear stress on increasing the shearing velocity. Due to the rougher surface morphology, the shearing is accompanied by a higher degree of dilation. It was found to be suppressed with the increase in normal load and shearing velocity, because of the resistance provided to the vertical movement and less time for asperity contact and overriding respectively. The descending trend for the asperity degradation can be seen from the decrease in dilation angle. With an increasing number of shear cycles, the joints become smoother or plane due to the breakage of teeth. Owing to this mechanism, properties like *JRC* and the shearing stiffness decrease. *JRC* and σ_n notably affect the value of *M*. Higher values of *JRC* and σ_n result in higher damage in the sample whereas, damage is less for higher shearing rate. As the surface roughness becomes smoother with the number of shear cycles, the value *M* decreases and finally reaches a constant level. The peak shear displacement depends on *JRC* and σ_n. As a consequence of the smooth surface morphology, the lower *JRC* sample has a higher value for the peak shear displacement. The parameter increases with the increasing normal load whereas, shearing velocity has no significant effect. But, further test might draw some clearer conclusion on it.

Future works will include changes in the experimental conditions for the shearing rate, 2.0 mm/min. Further studies on the degradation of asperities during shearing will be done based on the dilation angle and the sheared volume. These conditions will help in the investigation of the changes they bring upon the mechanical properties of rock joints.

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APPENDIX

τ_p is the peakshear strength of the joint [MPa].
σ_n is the normal confining stress [MPa].
ϕ_b is the basic friction angle.
JCS is the joint wall compressive strength [MPa].
d° is the secant dilation angle.
δv is the vertical displacement [mm].
δh is the horizontal displacement [mm].
L is the joint length [m].
M is the measuring lines
Δx is the measuring interval [mm] (0.25 in this study)
Δy is the asperity height [mm]

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