PHYSICAL AND NUMERICAL MODELLING OF SHEAR BEHAVIOUR OF JOINTED ROCKS UNDER CNL AND CNS BOUNDARY CONDITIONS

by

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Dedicated
To
My Late Father
and
Family

CERTIFICATE

This is to certify that the thesis entitled, **'Physical and Numerical Modelling of Shear Behaviour of Jointed Rocks Under CNL and CNS Boundary Conditions'** being submitted by **Mr. Amit Kumar Shrivastava** to the Indian Institute of Technology Delhi for the award of the degree of **DOCTOR OF PHILOSOPHY** is a record of the bonafide research work carried out by him. Mr. Amit Kumar Shrivastava has worked under my supervision for the submission of this thesis, which to my knowledge has reached the requisite standard.

The thesis or any part thereof has not been presented or submitted to any other University or Institute for any degree or diploma.

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ABSTRACT

Rock is heterogeneous and discontinuities are inevitable part of the rock masses. The presence of these discontinuities in the rock mass may be in the form of joints, faults, bedding planes or other recurrent planar fractures. The presence of these reduces the shear strength. In addition to joints, shear strength of the rock mass is also influenced by various parameters like, joint roughness, stiffness of the surrounding rock mass, shear rate, condition of the joint i.e. unfilled/ infilled, infill type and their thickness. The correct evaluation of shear strength of rock mass is only possible if all these factors are considered during experimental and analytical studies.

In the past significant research has been carried out on the rock joints in the laboratory using conventional direct shear apparatus where stiffness of the surrounding rock mass is not considered (constant normal load i.e. CNL boundary condition) during testing of unfilled and infilled joints, which is suitable only for planar joints. But rock joints are seldom planar and hence it is important to consider stiffness of the surrounding rock mass (constant normal stiffness i.e. CNS boundary condition) to correctly evaluate the shear behaviour of unfilled and infilled rock joints. This is important for safe and economical design of underground openings in jointed rocks, stability analyis of anchored/ free rock slopes, risk assessment of underground waste disposal, design of foundation on rock and design of rock socketed piles.

These concerns invite accurate quantification of shear strength of unfilled and infilled joints, proper understanding of the basic mechanics of discontinuity and the principles involved in their shear deformation. This can be done through in-situ or laboratory large scale testing on natural rock or laboratory testing on physical model or numerical modelling. In-situ and laboratory large scale testing on natural rocks are practically difficult, time consuming. Numerical methods are easy but need experimental results for their validity

before they can be used. So, physical modelling is preferred in such situations, where this study will be helpful in validating the numerical results and propose a model to determine shear strength of in-situ rock joints.

The laboratory or physical modelling needs testing equipments, but most of the direct shear testing equipment available in the literature are suitable only for CNL conditions. Very few equipments are available for CNS conditions, but these machines have limitations in changing the stiffness according the stiffness of the surrounding rock mass or suitable only for unfilled joints.

Hence, in the present study, a servo controlled large scale direct shear testing machine of capacity 1000 kN is designed and fabricated which has capacity of conducting tests on large, jointed prismatic specimens through friction free rigid platens under CNL and CNS boundary conditions for unfilled and infilled joints. The normal stiffness can be fed in the computer before the test of the specimen according to stiffness of the surrounding rock mass.

Direct shear tests have been performed on physically modeled unfilled rock joints with asperity angle 30^0 - 30^0, 15^0 - 15^0, 30^0 - 15^0 and 0^0 - 0^0 under CNL (k_n= 0 kN/mm) and CNS (k_n= 8 kN/mm) at different P_i ranging from 0.05 to 3.85 MPa to study the effect of normal stiffness and roughness of the rock joints on shear rate, variation of normal stress, dilation, rotation, shear displacement corresponding to peak shear stress (τ_p), strength envelope and sheared area ratio. The additional tests have been performed on 15^0 - 15^0 asperity joint under CNS conditions at k_n= 16 and 32 kN/mm to understand the effect of increasing stiffness on the shear behaviour of rock joints.

Test results indicate that the shearing rates have little or insignificant effect on the peak shear strength for shearing rate ≤ 0.5 mm/ min and for shearing rate > 0.5 mm/ min the peak shear stress increases with increase in shearing rate for both CNL and CNS conditions.

Normal load on the shearing plane is constant under CNL conditions and it increases under CNS conditions during shearing process. A 9 fold increase in the normal load is observed under CNS conditions at P_i= 0.05 MPa and very low increase in the normal stress is observed at $P_i \geq 0.51$ MPa. The variation of normal stress follows the profile of the asperity under CNS condition. Dilation corresponding to peak shear stress is more for CNS conditions than CNL conditions and there is no effect of boundary conditions on dilation at $P_i \geq 0.18\ \sigma_c$. Rotation of the sample is observed only for non planar joints during shearing it is more for CNL than CNS conditions. Shear displacement corresponding to peak shear stress decreases with increase in the in normal stress for both CNL and CNS conditions, but for CNS more shear displacement than CNL is required to reach peak shear stress. There is no effect of boundary conditions on the shear strength of planar joints. The effect of asperity angle is to increase the shear strength with increase in the asperity angle and it is more for CNS than CNL, but the effect is reducing with increase in P_i. At $P_i \geq 0.18\ \sigma_c$ the shear strength under CNL and CNS conditions are almost the same. Asperities with irregular profile have higher shear strength than the regular profile. The strength envelope for planar joint is linear and it changes to curvilinear for non planar joints under both CNL and CNS condition. The curvature of strength envelope increases with increase in the asperity angle and it is more for CNS than CNL condition at $P_i \leq 0.09\ \sigma_{c,}$, at $P_i = 0.09\ \sigma_c$ break in the curvature of strength envelope is observed for all non planar joints indicating shearing of the asperity and there is not much effect of the asperity and boundary conditions after that on the shear strength of joints. It is also observed that asperities were subjected to moderate to high grade damage during shearing process, where CNS condition has more sheared area ratio than the CNL condition and it increases with increase in normal stress and asperity angle.

Based on the series of tests conducted on different asperities joints under CNL and CNS conditions a new model for predicting the shear strength of unfilled joints is presented. The general proposed equations are as given below:

$$\tau_p = P_n \tan(\varphi_b + i') \quad (1)$$

$$P_n = 0.6(k_n/i) \quad (2)$$

$$\frac{i'}{i} = 1.25 e^{-9.86\frac{P_n}{\sigma_c}} \quad (3)$$

where, τ_p is peak shear stress in MPa, P_n is normal stress in MPa, i' is effective asperity angle in degree, σ_c is unconfined compressive strength in MPa, i is initial asperity angle in degree, k_n is normal stiffness of joint in kN/mm and φ_b is basic friction angle in degree.

Direct shear tests have also been performed on physically modeled infilled rock joints to study the influence of boundary conditions and thickness of the infill material (*t*) on shear strength , shear displacement corresponding to peak shear stress (δ_{sp}), variation of normal stress, dilation and strength envelope for different asperity joints (0^0 - 0^0, 30^0 - 30^0 and 15^0 - 15^0).

Test results indicate that the variation of normal stress on the shearing plane of infilled joint for different infill thickness (*t*) and asperity height (*a*) ratio i.e. *t/a*, under CNL and CNS conditions are similar to that of unfilled joints. The presence of the infill material cause positive dilation (compression) of the sample for all range of P_i and it increases with increase in infill thickness for both CNL and CNS conditions. Shear displacement corresponding to peak shear stress (δ_{sp}) initially increases for *t/a* ≤ 1.4 and after that it decreases sharply to a minimum value when t/a approaches to (*t/a*) =2, it is more for CNS than CNL conditions. The shear strength of the joint decreases sharply with addition of infill material but reduction is more for planar joint than non planar joints. At low *t/a* ratio the combined effect of the basic friction angle and joint asperity angle is pronounced but it diminishes with increase in *t/a* ratio. When shear strength of infill material (τ_{infill}) alone is compared with shear strength of infilled rock joint ($\tau_{pinfill}$) a rapid reduction in shear strength is observed with increase in *t/a* ratio and at *t/a=2* the shear strength of the joint approaches the shear strength of infill material alone and this ratio is defined as the critical ratio. The strength envelope for planar infilled joint is linear where as influence of infill material on non planar joint is to change the strength envelope from curvilinear to bilinear for unfilled to infilled joints for both CNL and CNS cases. The strength envelopes changes from bilinear to linear for *t/a* ratio ≥ $(t/a)_{cr}$. Peak shear stress is more for CNS conditions than CNL conditions for all level of P_i at different *t/a*, due to increased normal stress on shearing plane under CNS condition. The peak shear stress also increases with increase in the asperity angle for non planar joints.

A new shear strength model for infilled joint is developed based on observations made during the experimental investigations. The equation is as given below:

$$\tau_{p\text{infill}} = P_n \tan\left(\varphi_b + i'_{\text{infill}}\right) \tag{4}$$

$$P_n = P_i + 0.04k_n \tag{5}$$

For nonplanar joints

$$i'_{\text{infill}}/i = x\ln(P_n/\sigma_c) + y \tag{6}$$

For planar joints

$$\varphi/\varphi_b = x\ln(P_n/\sigma_c) + y \tag{7}$$

where, i'_{infill} is effective asperity angle of infilled joint in degree, *i* is initial asperity angle in degree, P_n is normal stress corresponding to peak shear stress in MPa, σ_c is unconfined compressive strength in MPa, φ is effective friction angle of infill joint in degree, φ_b is basic friction angle in degree, x and y are coefficients, the value of which depends upon *t/a* ratio and asperity angle. The new model for unfilled and infilled joints successfully describes the shear strength of the modeled joint.

A UDEC model with different asperity unfilled and infilled joints have been created to evaluate its applicability to replicate the shear strength and displacement behaviour of same joints tested in the laboratory under CNL and CNS conditions. It is observed that the existing joint models in UDEC like Coulomb slip and continuous yielding joint model is not well capable of predicting the shear behaviour of unfilled and infilled joints with different asperity under CNL and CNS conditions. It is due to improper modelling of asperity degradation due to increase in the normal stress on the shearing plane for the unfilled joints under CNS conditions and reduction in frictional angle due to reduced rock to rock contact with increase in infill thickness in case of infilled joints. Hence, modification in the existing model is made to incorporate in the proposed new models for asperity degradation and reduction in friction angle for unfilled and infilled joints respectively in predicting the shear strength. It is observed that the modified model is capable of predicting well the shear strength but shear displacement is over predicted for unfilled and infilled joints when compared with experimental results under CNL and CNS conditions for all asperity angle and P_i values.

The application of the proposed model in predicting the shear strength of all types of rocks ranging from soft to hard rock joints under CNL and CNS conditions, whose experimental results are available in the literature is also investigated and it is found that the proposed model successfully describes the shear strength of all the joints under both CNL and CNS conditions.

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