CYCLIC SHEAR BEHAVIOUR OF JOINTED ROCKS UNDER CNL AND CNS BOUNDARY CONDITIONS

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by

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Dedicated

To

My Wife

CERTIFICATE

This is to certify that the thesis entitled, **' Cyclic Shear Behaviour of Jointed Rocks Under CNL and CNS Boundary Conditions'** being submitted by **Mr. Seyed Mohammad Mahdi Niktabar** 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. Seyed Mohammad Mahdi Niktabar has worked under our supervision for the submission of this thesis, which to our 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

Discontinuities such as joints or fractures, faults and other bedding planes are geological origin and rock masses often have several sets of joints. Joints or rock masses are often subjected to dynamic loads such as earthquake, blasting and vibrations. These dynamic loads can cause shear loads along the joints repeatedly and induce cyclic shear loads on the joints. In this study, cyclic shear behaviour of the joints is investigated under both CNL and CNS conditions.

A new servo controlled direct shear apparatus developed which is capable of conducting tests under both static and cyclic loads at different boundary conditions on rock joints. This shear testing machine can work under different normal stiffness, by feeding value of normal stiffness as input parameter in the software of apparatus. Two model materials selected, as synthetic rock which is casting by plaster of Paris and natural rock which is classified as Jodhpur sandstone. Moreover, infill material selected as combination of 35% plaster of Paris, 15% Clay, 40% Sand and 10% Mica dust which is very close to infill material in the field. Unfilled synthetic rock joints were prepared with regular and irregular asperities such as 0^0-0^0, 15^0-15^0, 30^0-30^0 asperity angles and 30^0-15^0, 15^0-45^0 asperity angles respectively. Unfilled natural rock joints were produced by splitting on the intact rock and saw cut. These joints arranged as three different categories such as planar, smooth and rough joints. Infilled synthetic rock joints were prepared by specific mould with different infill thicknesses of 5 and 10 mm. But infilled natural rock joints were generated only for 5mm infill thickness.

The cyclic shear tests conducted on regular and irregular unfilled synthetic rock joints under CNL and CNS (K_n=8kN/mm) boundary conditions at three different initial normal stresses, i.e. P_i=0.1, 0.5 and 1 MPa. Moreover, cyclic shear tests performed on the same joints (except 0^0-0^0 joint asperity) under CNS with varying normal stiffness, K_n=16, 32,64, 128 kN/mm. Frequency and amplitude of cyclic shear loads are kept constant at 0.01 Hz and ±8 mm respectively.

Test results indicate that there is no effect of number of shear cycles on the peak shear stress for planar (0^0-0^0) joint. Whereas, peak shear stress of non planar joints (15^0-15^0 and 30^0-30^0) reduces with increase in number of shear cycles. The rate of decreasing peak shear stress is more for 30^0-30^0 asperity than 15^0-15^0 asperity with increase in number of cycles. Shear strength of irregular joint is slightly more than regular joint on the same slope of asperity. Irregular joints turned to regular joints after several shear cycles at low P_i=0.1 MPa. Exponential shear stress behaviour is dominated on the joints with increasing normal stiffness, K_n=32, 64, 128 kN/mm at low P_i=0.1 MPa under CNS and cyclic loads. Moreover, normal stress increases several times with respect to P_i. Empirical shear strength model for unfilled rock joints (soft or synthetic rock model) under CNL and CNS boundary conditions proposed based on asperity angles, normal stiffness, number of cycles and different P_i. In this model if both of initial normal stress and asperity angle increased to $0.17\sigma_c$ and 30^0 respectively, shear strength of the joint is same as shear strength of intact sample for first cycle and planar joint for subsequent cycles.

Cyclic shear behaviour of the joint with 30^0-30^0 asperity is investigated under different frequency and amplitude of shear loads. Experimental results indicated that peak shear stress increases with increasing frequency and it has significant effect on first peak shear stress under cyclic loads and this influence decreases with number of shear cycles. Whereas, peak shear stress under different loads amplitude is same at first cycle and for subsequent cycles significant difference is observed.

The cyclic shear tests conducted on infilled synthetic rock joints as 0^0-0^0, 15^0-15^0, 30^0-30^0 asperity with two infill thicknesses of 5 and 10 mm under CNL and CNS (K_n=8kN/mm) boundary conditions at three different initial normal stresses. Test results demonstrate shear strength of infilled planar joints was independent of infill thickness under cyclic shear loads, but for non planar joints with 30^0-30^0 asperity angles are different. No dilation is observed on infilled synthetic rock joints (10mm infill thickness) at P_i= 0.5 and 1 MPa, hence normal stress is constant, i.e. CNS boundary conditions is not effective on infilled joints at these levels of normal stress. Empirical shear strength model for infilled synthetic rock joins under CNL condition is presented based on asperity angles, infill thickness, number of cycles and different P_i.

Comprehensive shear strength envelope is proposed for cyclic condition on any rock model. Shear strength envelope of intact model and planar joints are plotted in such that the maximum and minimum boundaries for shear strength envelope of non planar joints under cyclic shear loads. The shear strength envelope of any non planar joints will lies in between the upper and lower boundaries.

Cyclic shear tests performed on unfilled and infilled natural rock joints (hard rock) under CNL and CNS (K_n=8kN/mm) boundary conditions at three different initial normal stresses. In addition, this shear test conducted on unfilled natural rock joints under CNS with K_n=32kN/mm. Each natural joint surface quantified before any shear test based on developed large scale profilometer. Experimental results indicated, no dilation is observed on planar or saw cut natural joint, hence CNS boundary condition is not effective on this type of joints. But dilation is dominated on non planar joints specifically on rough joints. Peak shear stress on non planar rock joint at first cycle is remarkable. This peak shear stress is related to interlocking of the rock grains and second order asperities. But, peak shear stress is not changed for subsequent cycles significantly. First peak shear stress is independent on smooth and rough joints (first order asperities) at low $\frac{\sigma_n}{\sigma_c}$ and depends on second order asperities or interlocking of the rock grains. Hardening strain behaviour (except first cycle) is observed under CNS condition with K_n=8kN/mm. With increasing normal stiffness to 32kN/mm, exponential shear stress behaviour is dominated on unfilled natural rock joints under cyclic loads. In contrast to unfilled natural rock joint, dilation is not observed for infilled joints (natural rock) at P_i= 0.5 and 1 MPa, Hence, boundary condition is not effective on infilled rock joint. First peak shear stress is not appeared on infilled joint because of no interlocking between second order asperities (except at low P_i). The difference of first peak shear stress between unfilled and infilled rock joint where $\sigma_n > c_{infill}$, is significant under cyclic shear load.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF NOTATIONS AND ABBRIVATIONS

CNL	Constant normal load
CNS	Constant normal stiffness
JRC	Joint roughness coefficient
JCS	Joint compressive strength
UCS	Uniaxial compressive strength of intact sample
τ_P	Peak shear stress
τ_{P_N}	Peak shear stress at cycle number N
i	Asperity angle
λ	Asperity base length
j_α	Interlocking factor
i'	Change of asperity angle by the shear cycles
P_n	Normal stress
P_i	Initial normal stress
K_n	Normal stiffness
Δy	Peak dilation
σ_c	Uniaxial compressive strength of intact sample
N	Number of cycles
ϕ_b	Basic friction angle
ϕ_i	Intact friction angle
$\sigma_{c_{infill}}$	Uniaxial compressive strength of infill material
c_{infill}	Cohesion of infill material
ϕ_i	Intact friction angle of infill material
a	Asperity amplitude
t	Thickness of infill material
Δu	Shear displacement along joint
$\Delta\sigma_n$	Change in normal stress
c	Cohesion
c_a	Apparent cohesion
c_{s1}	Cohesion of rock for asperity sliding
c_{sh}	Cohesion for shearing
dL_c	Critical base length
e	Exponential
i’	Effective asperity angle
i_o	Dilation angle at zero normal load

$i_{\tau p}$	Total dilation angle at peak shear stress under CNS condition
K	Spring stiffness
k_i	Coefficient derived from the tensile strength of the material
KNEFF	Stiffness of the adjacent structure
k_{ni}	Initial normal stiffness of the joint
k_{nn}	Joint tangent normal stiffness
k_s	Shear stiffness of joint
L	Joint length
M	Damage coefficient
P_i	Initial normal stress
φ	Friction angle
φ_r	Residual friction angle
φ_μ	Sliding resistance between mineral grains
$\varphi_{\mu r}$	Residual friction angle at large shear displacement
ψ	Dilation angle which represents the surface roughness
$\Phi^p{}_{sh}$	Peak friction angle in shearing
$\Phi^p{}_{sl}$	Peak friction angle in sliding
P_T	Transitional normal stress
qu	Uniaxial compressive strength
S_F	Force required for sliding over the asperities
S_r	Force required for shear through the asperities
T_p	Peak shear force
u_p	Horizontal displacement at the peak
v_p	Vertical displacement of the average joint plane at the peak
Y- Y’	Dilation resisted by the surrounding rock mass
γ	Inclination of mean shear plane with pre-existing cracks
δ_{sp}	Shear displacement corresponding to peak shear stress
δ_v	Joint dilation
Δy_1	Dilation caused by shear displacement
η	Interlocking factor
μ	Coefficient of friction
μ_p	Factor representing the plough resistance
σ_{ci}	Uniaxial compressive strength of intact rock
σn_o	Normal stress at initial condition
σ_t	Tensile strength

τ_{infill}	Shear strength of infill material alone
$\tau_{pinfill}$	Shear strength of infill joint
τ_{rock}	Shear strength of intact rock

*Symbols and Abbreviations if not presented here are described where ever it appears in the text