

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

SEYED MOHAMMAD MAHDI NIKTABAR



**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
DECEMBER 2016**

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

by

**SEYED MOHAMMAD MAHDI NIKTABAR
DEPARTMENT OF CIVIL ENGINEERING**

Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the



**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

DECEMBER 2016

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.

Dr. Amit Kumar Shrivastava
Associate Professor
Department of Civil Engineering
Delhi Technology University
Shahbad Daultpur, Delhi-110042
INDIA

Dr. K. Seshagiri Rao
Professor
Department of Civil Engineering
Indian Institute of Technology Delhi
Hauz Khas, New Delhi - 110016
INDIA

ACKNOWLEDGEMENTS

I am thankful to God, who made this study possible from the beginning to the end in India.

I would like to appreciate and express my heartfelt gratitude towards my supervisors, Prof. K. Seshagiri Rao, Department of Civil Engineering, IIT Delhi and Dr. Amit Kumar Shrivastava, Department of Civil Engineering, DTU for their inspiring guidance, continuous support and constant encouragement during the research. Their vast experience in the area and willingness to impart their knowledge has helped me during the research. It is because of their great care and exceptional interest that this thesis could be brought to the present form.

I am also thankful to the faculty members of the Geotechnical section, I.I.T. Delhi especially Prof K.G. Sharma during course work and study.

I am grateful to Mr. Jattinder Singh, Managing Director, Hydraulic Engineering and Instrument Company, New Delhi for extending help during the development of the direct shear testing setup.

I express my deep appreciation and sincere thanks to my fellow researchers Ms. Praneeta Surpaneni, Ankesh Kumar, Aditya Singh, Endale Tadele and other GRG members and friends for their valuable discussions and cooperation throughout this program.

Thanks are due to the staff of the Geotechnical and Engineering Geology Laboratories especially, Mr. D. S. Gossain, Mr. Manoj, Mr. D. Biswas, Mr. Alok and others.

Finally no words are adequate to express my gratitude to my parents for all their pains and sufferings to bring me up to this stage. My special thanks are due to my father and mother -in-law, elder brothers Dr. Reza Niktabar and Mr. Ali Niktabar, my sister Dr. Maryam Niktabar and my brother- in- law Ehsan Beshart for their kind hearted support. The acknowledgement will be incomplete without expressing feelings towards the devotion and sacrifice provided by my wife Dr. Azar Besharat. She was always the main source of motivation and encouragement during whole tenure of the research.

Date: December 12th, 2016

Sayed Mohammad Mahdi Niktabar

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 ($K_n=8\text{kN/mm}$) 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, $K_n=16, 32, 64, 128\text{ kN/mm}$. Frequency and amplitude of cyclic shear loads are kept constant at 0.01 Hz and $\pm 8\text{ mm}$ 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 ($K_n=8$ kN/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 joints 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 lie in between the upper and lower boundaries.

Cyclic shear tests performed on unfilled and infilled natural rock joints (hard rock) under CNL and CNS ($K_n=8\text{kN/mm}$) boundary conditions at three different initial normal stresses. In addition, this shear test conducted on unfilled natural rock joints under CNS with $K_n=32\text{kN/mm}$. 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 $K_n=8\text{kN/mm}$. 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 $\sigma_n > c_{\text{infill}}$, is significant under cyclic shear load.

TABLE OF CONTENTS

CERTIFICATE	i
ACKNOWLEDGEMENTS	iii
ABSTRACT	v
TABLE OF CONTENTS	xi
LIST OF FIGURES	xv
LIST OF TABLES	xxiii
LIST OF NOTATIONS	xxv
Chapter 1 INTRODUCTION	1
1.1 General	1
1.2 Motivation of the Thesis (Problem Statement)	2
1.3 Objectives of the Thesis	6
1.4 Organization of the Thesis	7
Chapter 2 LITERATURE REVIEW	11
2.1 General	11
2.2 Static and Cyclic Shear Loads	12
2.3 CNL and CNS Boundary Conditions	14
2.4 Shear Behavior of Unfilled Rock Joints under Static Load	15
2.4.1 Shear Behaviour of Unfilled Joint under CNL Condition	16
2.4.1.1 Linear and Bilinear Models	16
2.4.1.2 Nonlinear and Dilatancy Models	17
2.4.2 Shear Behaviour of Unfilled Joint under CNS Condition	29
2.4.2.1 CNS Models Based on Energy Balance Principles	29
2.4.2.2 Other Mathematical and Analytical Models under CNS	33
2.5 Characterization of Joint Roughness	44
2.5.1 Joint Roughness Coefficient (JRC)	45
2.5.2 Statistical Models	46
2.5.3 Fractal Models	48
2.5.4 Spectral Method	49
2.5.5 Fourier Transform Method	49
2.6 Shear Behaviour of Infilled Rock Joints under Static Loads	50
2.6.1 Shear Strength Models of Infilled Joints under CNL Condition	56
2.6.2 Shear Strength Models of Infilled Joint under CNS Condition	62

2.7 Shear Behaviour of Rock Joints under Cyclic Shear Loading	71
2.7.1 Experimental Study on Cyclic Shear Behavior of Jointed Rock	72
2.7.2 Models Developed for Cyclic Shear Behaviour of Jointed Rock	79
2.8 Summary	86
Chapter 3 DEVELOPMENT OF SHEAR TESTING MACHINE AND PROFILOMETER	89
3.1 General	89
3.2 Development Large Scale Servo Controlled Direct Shear Apparatus	90
3.2.1 Frame and Loading Unit	90
3.2.1.1 Shear Box	92
3.2.1.2 Load Cells and Linear Variation Displacement Transducers (LVTD's)	93
3.2.1.3 Stopper and Spacer Plates	94
3.2.2 Hydraulic Power Pack with Electro Hydraulic Servo Valve	95
3.2.3 Data Acquisition and Controlling Unit	96
3.2.4 Cooling Unit	98
3.3 Calibration of Direct Shear Apparatus	98
3.4 Large Scale Profilometer Apparatus	100
3.4.1 Frame and Linear Variation Displacement Transducers (LVTD's)	100
3.4.2 Data Acquisition and Processing Unit	102
3.5 Summary	103
Chapter 4 EXPERIMENTAL INVESTIGATIONS	105
4.1 General	105
4.2 Simulation of Natural Joint Roughness	105
4.3 Mould and Asperity Plates for Unfilled Joint	106
4.3.1 Mould and Vibrating Table	107
4.3.2 Asperity Plates	108
4.4 Infilled Mould	108
4.5 Unfilled Joint Model	109
4.5.1 Selection and Characterization of Model Material	109
4.5.2 Preparation of Regular and Irregular Jointed Samples	110
4.6 Preparation of Infilled Joint	111
4.7 Large Intact Sample Shear Test	113
4.8 Joint Deformation Properties	117
4.9 Natural Joint	118
4.9.1 Selection of Rock	118
4.9.2 Preparation of Unfilled Jointed Rock	123
4.9.2.1 Cutting Large Slabs into Blocks	123

4.9.2.2 Making Grooves and Splitting of Rock	125
4.9.2.3 Hard Polishing	125
4.9.3 Infilled Natural Rock Joint	127
4.10 Summary	130
Chapter 5 CYCLIC SHEAR BEHAVIOUR OF UNFILLED SYNTHETIC JOINTS	131
5.1 General	131
5.2 Regular Joint under CNL	131
5.2.1 Joint Asperity 0^0-0^0 (Planar Joint)	132
5.2.2 Joint Asperity 15^0-15^0	132
5.2.3 Joint Asperity 30^0-30^0	133
5.3 Irregular Joint under CNL and Cyclic Shear Loads	137
5.3.1 Joint Asperity 15^0-30^0	138
5.3.2 Joint Asperity 30^0-15^0	139
5.3.3 Joint Asperity 15^0-45^0	139
5.4 Regular and Irregular Joint under CNS and Cyclic Shear Loads	140
5.4.1 Regular Joint (Joint Asperity 15^0-15^0 and 30^0-30^0)	145
5.4.1.1 Shear Behaviour	145
5.4.1.2 Dilation Behaviour	145
5.4.1.3 Variation of Normal Stress	146
5.4.2 Irregular Joint	146
5.4.2.1 Shear Behaviour	146
5.4.2.2 Dilation Behaviour	150
5.4.2.3 Normal Stress Behaviour	150
5.5 Comparison of Shear Strength under CNL and CNS on Regular Joint	154
5.6 Cyclic Shear Behaviour of the Joints under Varying Normal Stiffness	154
5.6.1 Joint Asperity 15^0-15^0	154
5.6.1.1 Shear Behaviour	156
5.6.1.2 Dilation Behaviour	156
5.6.1.3 Normal Stress Behaviour	156
5.6.2 Joint Asperity 30^0-30^0	157
5.6.2.1 Shear Behaviour	157
5.6.2.2 Dilation Behaviour	162
5.6.2.3 Normal Stress Behaviour	162
5.6.3 Joint Asperity 15^0-30^0 (Irregular joint)	168
5.6.3.1 Shear Behaviour	168
5.6.3.2 Dilation Behaviour	168

5.6.3.3 Normal Stress Behaviour	169
5.7 Cyclic Shear Behaviour of the Joints under Different Dynamic Parameters	176
5.7.1 Cyclic Shear Behaviour of the Joints under Varying Frequency	176
5.7.2 Cyclic Shear Behaviour of the Joints under Varying Amplitude	177
5.8 Shear Strength Envelope	182
5.9 Prediction Model	185
5.10 Summary	187
Chapter 6 CYCLIC SHEAR BEHAVIOUR OF INFILLED SYNTHETIC JOINTS	191
6.1 General	191
6.2 Constant Normal Load (CNL) Boundary Condition	191
6.2.1 Planar Infilled Joint	191
6.2.2 Infilled Joint with 15^0 - 15^0 Asperity	192
6.2.3 Infilled Joint with 30^0 - 30^0 Asperity	197
6.3 Constant Normal Stiffness (CNS) Boundary Condition	200
6.3.1 Planar Infilled Joint	200
6.3.2 Non Planar Infilled Joint	200
6.3.2.1 Shear Behaviour on 15^0 - 15^0 Asperity	203
6.3.2.2 Dilation Behaviour on 15^0 - 15^0 Asperity	203
6.3.2.3 Normal Stress Behaviour on 15^0 - 15^0 Asperity	204
6.3.2.4 Shear Behaviour on 30^0 - 30^0 Asperity	204
6.3.2.5 Dilation Behaviour on 30^0 - 30^0 Asperity	208
6.3.2.6 Normal Stress Behaviour on 30^0 - 30^0 Asperity	208
6.4 Comparison of CNL and CNS on Infilled Joint	208
6.5 Shear Strength Envelope	214
6.6 Development of Shear Strength Model for Infilled Joint under Shear Cycles	214
6.7 Prediction Model	216
6.8 Summary	218
Chapter 7 CYCLIC SHEAR BEHAVIOUR OF NATURAL JOINTS	221
7.1 General	221
7.2 Natural Joint Roughness	221
7.3 Quantification of Joint Roughness	222
7.4 Unfilled Natural Joint under CNL	227
7.4.1 Planar Joint	227
7.4.2 Smooth Joint	227
7.4.3 Rough Joint	228
7.5 Unfilled Natural Joint under CNS	234

7.5.1 Non Planar Joint under CNS with $K_n = 8 \text{ kN/mm}$	234
7.5.1.1 Shear Behaviour	234
7.5.1.2 Dilation Behaviour	234
7.5.1.3 Normal Stress Behaviour	235
7.5.2 Non Planar Joint under CNS with $K_n = 32 \text{ kN/mm}$	235
7.6 Comparison CNL and CNS on Unfilled Natural Joint	241
7.7 Infilled Natural Joint under CNL	242
7.8 Infilled Natural Joint under CNS	243
7.9 CNL and CNS Comparison on Infilled Joint	243
7.10 Summary	251
Chapter 8 SUMMARY AND CONCLUSIONS	253
8.1 General	253
8.2 Laboratory Equipments and Specimens	254
8.3 Results on Unfilled Synthetic Rock Joint	254
8.3.1 Cyclic Shear Load under CNL	254
8.3.2 Cyclic Shear Load under CNS with Constant Normal Stiffness	255
8.3.2.1 Shear Behaviour	255
8.3.2.2 Dilation and Normal Stress Behaviours	256
8.3.3 Shear Strength Envelope	256
8.3.4 Cyclic Shear Load under CNS with Varying Normal Stiffness	256
8.3.4.1 Shear Behaviour	256
8.3.4.2 Dilation and Normal Stress Behaviours	257
8.3.5 Cyclic Shear Load under Varying Frequency and Amplitude	257
8.3.6 Proposed Shear Strength Model	258
8.4 Results on Infilled Synthetic Rock Joint	259
8.4.1 Cyclic Shear Load under CNL	259
8.4.2 Cyclic Shear Load under CNS	259
8.4.2.1 Shear Behaviour	259
8.4.2.2 Dilation and Normal Stress Behaviours	260
8.4.3 Shear Strength Envelope	260
8.4.4 Proposed Shear Strength Model	260
8.5 Results on Unfilled Natural Rock Joint	261
8.5.1 Cyclic Shear Load under CNL	261
8.5.2 Cyclic Shear Load under CNS	262
8.5.2.1 Shear Behaviour	262
8.5.2.2 Dilation and Normal Stress Behaviours	262
8.6 Results on Infilled Natural Rock Joint	262

8.6.1 Cyclic Shear Load under CNL and CNS	262
8.6.1.1 Shear Behaviour	262
8.6.1.2 Dilation and Normal Stress Behaviours	263
8.7 Suggestions for Future Study	263
REFERENCES	265
Appendix A Design Details of Direct Shear Facility and Profilometer	277
Appendix B Comprehensive Shear Strength Envelope	283
Appendix C Comparison between Proposed Model and Experimental Results for Unfilled Synthetic Joint	289
Appendix D Comparison between Proposed Model and Experimental Results for Infilled Synthetic Joint	303

LIST OF FIGURES

Fig. 1.1 Vajont Dam and Town of Longarone after Flood	4
Fig. 1.2 Malpasset and The St. Francis Concrete Dam 1928, after Failure	4
Fig. 1.3 Slope Failures in Himalayan Region and Taiwan	4
Fig. 1.4 Caopo and Dankanliangzi Tunnels after Earthquake in China	5
Fig. 1.5 Tunnel in Taiwan before and after Earthquake	5
Fig. 1.6 Chediguan Tunnel in China and Wanazu Tunnel in Japan after Earthquake	5
Fig. 2.1 Joints in Rock mass Surajkund, Delhi, India (2014)	11
Fig. 2.2 Load Direction and Joint Movement under Cyclic Condition	13
Fig. 2.3 (a) Cyclic Shear Loads, Shear Stress vs. Horizontal Displacement. (b) Static or Monotonic Shear loads, Equal with Forward Advance of First Shear Cycle (FA ₁).	14
Fig. 2.4. Schematic Sketch of Rock mass under CNL and CNS Boundary Conditions. Unreinforced Rock Slope under CNL Condition and the Rest of Rock mass under CNS condition.	15
Fig. 2.5 Comparing the Rock Joint Strength Envelopes (Patton's and Jaeger's)	17
Fig. 2.6 Roughness Profiles and Range of JRC Values Associated with Each Profile (after Barton, 1976).	20
Fig. 2.7 Type of Model Joint Specimens (Yang and Chiang, 2000)	27
Fig. 2.8 Photograph of Shear Testing Device (Jiang, 2004)	42
Fig. 2.9 Large Scale Direct Shear Test with Three Main Components 1) Loading units 2) Hydraulic Power Pack with Servo valve 3) Data acquisition and Controlling unit (Shrivastava and Rao 2013)	43
Fig 2.10 Rough Discontinuity Surface with First-order and Second-order Asperities (Patton and Deere)	45
Fig. 2.11 Estimation of JRC form Measurement of Surface Roughness Amplitude (Barton, 1982)	47
Fig 2.12 Presence of Infill Material in Discontinuities Rock mass 18 km Away from Srinagar in Garhwal Himalaya, India (Sinha and Singh, 2000).	51
Fig. 2.13 Layers and Movement of Grains of Infill (Pereira, 1990)	53
Fig. 2.14 Four Categories of Discontinuity in Filling Thickness (Barton, 1974)	55
Fig. 2.15 Shear Coefficient vs. Discontinuity Width or Filling Thickness (Fishman, 2004)	61
Fig. 2.16 Direct Shear Apparatus (Indraratna et al. 1998)	63
Fig. 2.17 Shear Strength Model for Infilled Joints Showing the Role of Φ_{fill} and Φ_b (Welideniya, 2005)	70
Fig 2.18 Simple Hysteresis of Rock Joint under CNL and Cyclic Load Conditions (Coulomb model)	72
Fig 2.19 Servo-Controlled Direct Shear Testing Machine for Cyclic Loading Condition (Huang et al., 1993)	74
Fig. 2.20 Average Asperity Angle i (Normalized by Initial Asperity or i_0) vs. Sliding Work on Artificial Joint at Moderate Normal Stress during 20 cycle Displacement (Huang et al., 1993).	74

Fig. 2.21 Shear Stress - Shear Displacement on Natural Joint (Dolomite) at Normal stress of 4.5 MPa under 20 Cyclic Displacement (Huang et al., 1993)	75
Fig 2.22 Shear Strength of Regular Undulated Joint under CNS ($P_i = 2$ MPa, $K_n = 2$ MPa/mm) and Cyclic Conditions (Homand et al.1999)	76
Fig 2.23 Direct Shear System with Normal and Horizontal Brushless Servo-Motors (Jafari et al. 2003)	78
Fig 2.24 Transformation Stress Between Microscopic and Macroscopic Stresses (Plesha, 1987)	81
Fig. 3.1 Photograph of Shear Testing Machine (a) Loading Unit (b) Hydraulic Power Pack with Servo Valve (c) Data Acquisition and Controlling Unit and (d) Cooling Unit	91
Fig. 3.2 Close Up View of Conjunction between Shear Box and Piston	93
Fig. 3.3 Close Up View of New LVTDs Holders	94
Fig. 3.4 Close Up View of Stopper	95
Fig. 3.5 Software Environment for Static and Cyclic Shear Mode Respectively	97
Fig. 3.6 Close Up View of Cooling Unit such as (a) Cooling Tower for Decreasing Water Temperature (b) and (c) Water Circulation for Decreasing Temperate of Hydraulic Power Pack	99
Fig. 3.7 Photograph of Large Scale Profilometer (a) Frame and LVTD's (b) Data Acquisition and Processing Unit	100
Fig. 3.8 Close Up View of Frame and LVTD's	101
Fig. 3.9 3D View of Joint Surface after Using Profilometer	102
Fig. 4.1 Two Different Models for Asperity (a) Asperity Angle Changes Based on Variation of Asperity Base length or L , and Keeping Constant Amplitude or A . (b) Asperity Angle Changes Based on Variation of Asperity Amplitude and Keeping Constant Base Length	106
Fig. 4.2 Varying of Amplitude and Base Length on Barton and Choubey (1977) Profiles	107
Fig. 4.3 Steps of Sample Preparation (a) Prepare Suitable Mixer (b) Mix the Plaster of Paris and Water Prepare Paste (c) Moulds and Asperity Plates fixed on the Table Vibration (d) Make flat on the Mould Surface (e) Photograph of Samples with Regular Asperity 0° - 0° , 15° - 15° , 30° - 30° Respectively	112
Fig. 4.4 (a) Photograph of Samples with Irregular Asperity 15° - 30° and 15° - 45° Respectively (b) Samples for Air Curing at Room Temperature	113
Fig. 4.5 Photograph of (a and b) for Processing of Infilled Joint Sample Preparation. (c) Infilled Joints (5mm and 10 mm infill thickness) for 0° - 0° , 15° - 15° and 30° - 30° Asperity Angles	114
Fig. 4.6 Samples for Air Curing at Room Temperature	115
Fig. 4.7 Preparations of Large Intact Samples	115
Fig. 4.8 Shear Stress vs. Horizontal Displacement (Part A) and Normal Displacement vs. Horizontal Displacement (Part B) for Intact Samples at Three Different Normal Stresses 0.1, 0.5 and 1 MPa Respectively (Static Shear Loads)	116
Fig. 4.9 Shear Strength Envelope of Intact Model	117
Fig. 4.10 Normal Stiffness vs. Depths (Jiang et al., 2009)	117
Fig. 4.11 (a) Normal Stiffness Test and (b) Normal Stress vs. Normal Displacement Curve	118

Fig. 4.12 Large Slab of Jodhpur Sandstone	119
Fig. 4.13 X Ray Diffraction (XRD) for Jodhpur Sandstone	119
Fig. 4.14 Scanning Electron Microscope (SEM) for Jodhpur Sandstone	120
Fig. 4.15 Preparation of Intact Jodhpur Sandstone for Characterization	120
Fig. 4.16 Uniaxial Compressive Strength vs. Anisotropy Angles	123
Fig. 4.17 Tensile Strength vs. Anisotropy Angles	123
Fig. 4.18 Apparatus for Rock Joint Preparation (a) Cutter with large Blade (b) Portable Cutter, Polisher, Chisel and Hammer	124
Fig. 4.19 Rock Blocks Cut Parallel to Stratification from Large Slab of Jodhpur Sandstone	125
Fig. 4.20 The Process of Sample Preparation such as, a) Cutting Cubic Form of Rock as Large Size b) Make Groove Along the Stratification c) Make Tension Force on the Grooves by Chisels d) Polishing for Creating Exact Size and Reduce of Margin Thickness	126
Fig. 4.21 Photograph of Unfilled Rock Joint	127
Fig. 4.22 Preparation of Infilled Rock Joint	128
Fig. 4.23 Photograph of Infilled Rock Joints for Curing	128
Fig. 4.24 Flow Chart of Experimental Program on Synthetic Rock	129
Fig. 4.25 Flow Chart of Experimental Program on Natural Rock	130
Fig. 5.1 Shear Stress (Part A) and Normal Displacement (Part B) vs. Horizontal Displacement on 0° - 0° Asperity Joint (Planar Joint) at Three Different Normal Stresses 0.1, 0.5 and 1 MPa Respectively under CNL for Thirty Cyclic Shear Load	134
Fig. 5.2 Shear Stress (Part A) and Normal Displacement (Part B) vs. Horizontal Displacement on 15° - 15° Asperity Joint at Three Different Normal Stresses 0.1, 0.5 and 1 MPa Respectively under CNL for Thirty Cyclic Shear Load.	135
Fig. 5.3 Shear Stress (Part A) and Normal Displacement (Part B) vs. Horizontal Displacement on 30° - 30° Asperity Joint at Three Different Normal Stresses 0.1, 0.5 and 1 MPa Respectively under CNL for Thirty Cyclic Shear Load	136
Fig. 5.4 Regular Joint after Cyclic Shear Test at Different Normal Stress under CNL Condition	137
Fig. 5.5 Shear Stress (Part A) and Normal Displacement (Part B) vs. Horizontal Displacement on 15° - 30° Asperity Joint at Three Different Normal Stresses 0.1, 0.5 and 1 MPa Respectively under CNL for Thirty Cyclic Shear Load.	141
Fig. 5.6 Shear Stress (Part A) and Normal Displacement (Part B) vs. Horizontal Displacement on 30° - 15° Asperity Joint at Three Different Normal Stresses 0.1, 0.5 and 1 MPa Respectively under CNL for Thirty Cyclic Shear Load.	142
Fig. 5.7 Shear Stress (Part A) and Normal Displacement (Part B) vs. Horizontal Displacement on 15° - 45° Asperity Joint at Three Different Normal Stresses 0.1, 0.5 and 1 MPa Respectively under CNL for Thirty Cyclic Shear Load.	143
Fig. 5.8 Irregular Joint after Cyclic Shear Test at Different Normal Stress under CNL Condition and Close View of Irregular Joint at $P_i = 0.1$ MPa	144
Fig. 5.9 Shear Stress, Normal Displacement and Normal Stress vs. Horizontal Displacement of Joint Asperity 15° - 15° (Part A) and Joint Asperity 30° - 30° (Part B) Respectively at $P_i = 0.1$ MPa, under CNS for Thirty Cyclic Shear Loads	147

Fig. 5.10 Shear Stress, Normal Displacement and Normal Stress vs. Horizontal Displacement of Joint Asperity 15°-15° (Part A) and Joint Asperity 30°-30° (Part B) Respectively at $P_i=0.5$ MPa, under CNS for Thirty Cyclic Shear Loads	148
Fig. 5.11 Shear Stress, Normal Displacement and Normal Stress vs. Horizontal Displacement of Joint Asperity 15°-15° (Part A) and Joint Asperity 30°-30° (Part B) Respectively at $P_i=1$ MPa, under CNS for Thirty Cyclic Shear Loads	149
Fig. 5.12 Shear Stress, Normal Displacement and Normal Stress vs. Horizontal Displacement of Joint Asperity 15°-30° (Part A) and Joint Asperity 15°-45° (Part B) Respectively at $P_i=0.1$ MPa, under CNS for Thirty Cyclic Shear Loads	151
Fig. 5.13 Shear Stress, Normal Displacement and Normal Stress vs. Horizontal Displacement of Joint Asperity 15°-30° (Part A) and Joint Asperity 15°-45° (Part B) Respectively at $P_i=0.5$ MPa, under CNS for Thirty Cyclic Shear Loads	152
Fig. 5.14 Shear Stress, Normal Displacement and Normal Stress vs. Horizontal Displacement of Joint Asperity 15°-30° (Part A) and Joint Asperity 15°-45° (Part B) Respectively at $P_i=1$ MPa, under CNS for Thirty Cyclic Shear Loads	153
Fig. 5.15 Peak Shear Stress, vs. Number of Cycle on Different Joints under CNL (Part A) and CNS Conditions (Part B) at $P_i=0.1, 0.5$ and 1 MPa Respectively for Thirty Cyclic Shear Loads	155
Fig. 5.16 Shear Stress, Normal Displacement and Normal Stress vs. Horizontal Displacement of Joint Asperity 15°-15° at $P_i=0.1$ MPa (Part A) and $P_i=0.5$ MPa (Part B) Respectively under CNS with $K_n=16$ kN/mm for Thirty Cyclic Shear Loads	158
Fig. 5.17 Shear Stress, Normal Displacement and Normal Stress vs. Horizontal Displacement of Joint Asperity 15°-15° at $P_i=0.1$ MPa (Part A) and $P_i=0.5$ MPa (Part B) Respectively under CNS with $K_n=32$ kN/mm for Thirty Cyclic Shear Loads	159
Fig. 5.18 Shear Stress, Normal Displacement and Normal Stress vs. Horizontal Displacement of Joint Asperity 15°-15° at $P_i=0.1$ MPa (Part A) and $P_i=0.5$ MPa (Part B) Respectively under CNS with $K_n=64$ kN/mm for Thirty Cyclic Shear Loads	160
Fig. 5.19 Shear Stress, Normal Displacement and Normal Stress vs. Horizontal Displacement of Joint Asperity 15°-15° at $P_i=0.1$ MPa (Part A) and $P_i=0.5$ MPa (Part B) Respectively under CNS with $K_n=128$ kN/mm for Thirty Cyclic Shear Loads	161
Fig. 5.20 Shear Stress, Normal Displacement and Normal Stress vs. Horizontal Displacement of Joint Asperity 30°-30° at $P_i=0.1$ MPa (Part A) and $P_i=0.5$ MPa (Part B) Respectively under CNS with $K_n=16$ kN/mm for Thirty Cyclic Shear Loads	164
Fig. 5.21 Shear Stress, Normal Displacement and Normal Stress vs. Horizontal Displacement of Joint Asperity 30°-30° at $P_i=0.1$ MPa (Part A) and $P_i=0.5$ MPa (Part B) Respectively under CNS with $K_n=32$ kN/mm for Thirty Cyclic Shear Loads	165
Fig. 5.22 Shear Stress, Normal Displacement and Normal Stress vs. Horizontal Displacement of Joint Asperity 30°-30° at $P_i=0.1$ MPa (Part A) and $P_i=0.5$ MPa (Part B) Respectively under CNS with $K_n=64$ kN/mm for Thirty Cyclic Shear Loads	166
Fig. 5.23 Shear Stress, Normal Displacement and Normal Stress vs. Horizontal Displacement of Joint Asperity 30°-30° at $P_i=0.1$ MPa (Part A) and $P_i=0.5$ MPa (Part B) Respectively under CNS with $K_n=128$ kN/mm for Thirty Cyclic Shear Loads	167
Fig. 5.24 Shear Stress, Normal Displacement and Normal Stress vs. Horizontal Displacement of Joint Asperity 15°-30° at $P_i=0.1$ MPa (Part A) and $P_i=0.5$ MPa (Part B) Respectively under CNS with $K_n=16$ kN/mm for Thirty Cyclic Shear Loads	170

Fig. 5.25 Shear Stress, Normal Displacement and Normal Stress vs. Horizontal Displacement of Joint Asperity 15^0 - 30^0 at $P_i=0.1$ MPa (Part A) and $P_i=0.5$ MPa (Part B) Respectively under CNS with $K_n= 32$ kN/mm for Thirty Cyclic Shear Loads	171
Fig. 5.26 Shear Stress, Normal Displacement and Normal Stress vs. Horizontal Displacement of Joint Asperity 15^0 - 30^0 at $P_i=0.1$ MPa (Part A) and $P_i=0.5$ MPa (Part B) Respectively under CNS with $K_n= 64$ kN/mm for Thirty Cyclic Shear Loads	172
Fig. 5.27 Shear Stress, Normal Displacement and Normal Stress vs. Horizontal Displacement of Joint Asperity 15^0 - 30^0 at $P_i=0.1$ MPa (Part A) and $P_i=0.5$ MPa (Part B) Respectively under CNS with $K_n= 128$ kN/mm for Thirty Cyclic Shear Loads	173
Fig. 5.28 Joint with 15^0 - 15^0 Asperity Angle after Cyclic Shear Test at Different Normal Stiffness under $P_i= 0.1$ MPa (Low Initial Normal Stress)	174
Fig. 5.29 Peak Shear Stress vs. Normal Stiffness for Joints with Different Asperity Angle at First Cyclic and $P_i= 0.1$ MPa	175
Fig. 5.30 Shear Stress (Part A) and Normal Displacement (Part B) vs. Horizontal Displacement of Joint Asperity 30^0 - 30^0 for Different Frequency 0.1, 0.05 and 0.01 Hz Respectively at $P_i=0.1$ MPa under CNL and Thirty Cyclic Shear Test	178
Fig. 5.31 Shear Stress (Part A) and Normal Displacement (Part B) vs. different Horizontal Displacement (or Amplitude = 4, 6 and 8mm respectively) of Joint Asperity 30^0 - 30^0 at $P_i=0.1$ MPa under CNL and thirty cyclic shear test	179
Fig. 5.32 Peak Shear Stress vs. Number of Cycles for Joint with 30^0 - 30^0 Asperity Angle under Varying Frequency at $P_i= 0.1$ MPa and CNL Condition	180
Fig. 5.33 Peak Shear Stress vs. Number of Cycles for Joint with 30^0 - 30^0 Asperity Angle under Varying Amplitude at $P_i= 0.1$ MPa and CNL Condition	180
Fig. 5.34 Joint with 30^0 - 30^0 Asperity Angle after Cyclic Shear Test at Different Amplitude under $P_i= 0.1$ MPa	181
Fig. 5.35 Shear Strength Envelopes of Non Planar Joint (15^0 - 15^0) Between Intact Sample and Planar Joint Shear Envelopes under CNL	183
Fig. 5.36 Shear Strength Envelopes of Non Planar Joint (30^0 - 30^0) Between Intact Sample and Planar Joint Shear Envelopes under CNL	183
Fig. 5.37 Shear Strength Envelopes of Non Planar Joint (15^0 - 30^0) Between Intact Sample and Planar Joint Shear Envelopes under CNL	184
Fig. 5.38 Shear Strength Envelopes of Non Planar Joint (15^0 - 45^0) Between Intact Sample and Planar Joint Shear Envelopes under CNL	184
Fig. 5.39 Shear Strength Envelopes of Non Planar Joint (30^0 - 30^0) Between Intact Sample and Planar Joint Shear Envelopes under CNS	185
Fig. 5.40 Peak Shear Stress vs. Number of Cycles for 30^0 - 30^0 Asperity at $P_i=0.1$ MPa for both Model and Experimental Results under (a) CNL and (b) CNS ($k_n=8$ kN/mm) Conditions	187
Fig. 6.1 Shear Stress and Normal Displacement vs. Horizontal Displacement on Infilled Planar Joints (0^0 - 0^0 Asperity) with Infill Thickness of 5mm at $P_i =0.1, 0.5$ and 1 MPa Respectively under CNL and Cyclic Shear Loads	193
Fig. 6.2 Shear Stress and Normal Displacement vs. Horizontal Displacement on Infilled Planar Joints (0^0 - 0^0 Asperity) with Infill Thickness of 10mm at $P_i =0.1, 0.5$ and 1 MPa Respectively under CNL and Cyclic Shear Loads	194

Fig. 6.3 Shear Stress and Normal Displacement vs. Horizontal Displacement on Infilled Joints with 15°-15° Asperity and 5mm Infill Thickness at $P_i=0.1, 0.5$ and 1 MPa Respectively under CNL and Cyclic Shear Loads	195
Fig. 6.4 Shear Stress and Normal Displacement vs. Horizontal Displacement on Infilled Joints with 15°-15° Asperity and 10 mm Infill Thickness at $P_i=0.1, 0.5$ and 1 MPa Respectively under CNL and Cyclic Shear Loads	196
Fig. 6.5 Shear Stress and Normal Displacement vs. Horizontal Displacement on Infilled Joints with 30°-30° Asperity and 5 mm Infill Thickness at $P_i=0.1, 0.5$ and 1 MPa Respectively under CNL and Cyclic Shear Loads	198
Fig. 6.6 Shear Stress and Normal Displacement vs. Horizontal Displacement on Infilled Joints with 30°-30° Asperity and 10 mm Infill Thickness at $P_i=0.1, 0.5$ and 1 MPa Respectively under CNL and Cyclic Shear Loads	199
Fig. 6.7 Close View of Infilled Joints after Cyclic Shear Test at $P_i=0.1$ MPa under CNL	201
Fig. 6.8 Close View of Infilled Joints after Cyclic Shear Test at $P_i=0.5$ MPa under CNL	202
Fig. 6.9 Shear Stress, Normal Displacement and Normal Stress versus Horizontal Displacement of Infilled 15°-15° Joint Asperity for $t/a=1$ (Part A) and $t/a=2$ (Part B) Respectively under CNS ($K_n=8$ kN/mm) at $P_i=0.1$ MPa for Thirty Cyclic Shear Loads	205
Fig. 6.10 Shear Stress, Normal Displacement and Normal Stress versus Horizontal Displacement of Infilled 15°-15° Joint Asperity for $t/a=1$ (Part A) and $t/a=2$ (Part B) Respectively under CNS ($K_n=8$ kN/mm) at $P_i=0.5$ MPa for Thirty Cyclic Shear Loads	206
Fig. 6.11 Shear Stress, Normal Displacement and Normal Stress versus Horizontal Displacement of Infilled 15°-15° Joint Asperity for $t/a=1$ (Part A) and $t/a=2$ (Part B) Respectively under CNS ($K_n=8$ kN/mm) at $P_i=1$ MPa for Thirty Cyclic Shear Loads	207
Fig. 6.12 Shear Stress, Normal Displacement and Normal Stress versus Horizontal Displacement of Infilled 30°-30° Joint Asperity for $t/a=1$ (Part A) and $t/a=2$ (Part B) Respectively under CNS ($K_n=8$ kN/mm) at $P_i=0.1$ MPa for Thirty Cyclic Shear Loads	209
Fig. 6.13 Shear Stress, Normal Displacement and Normal Stress versus Horizontal Displacement of Infilled 30°-30° Joint Asperity for $t/a=1$ (Part A) and $t/a=2$ (Part B) Respectively under CNS ($K_n=8$ kN/mm) at $P_i=0.5$ MPa for Thirty Cyclic Shear Loads	210
Fig. 6.14 Shear Stress, Normal Displacement and Normal Stress versus Horizontal Displacement of Infilled 30°-30° Joint Asperity for $t/a=1$ (Part A) and $t/a=2$ (Part B) Respectively under CNS ($K_n=8$ kN/mm) at $P_i=1$ MPa for Thirty Cyclic Shear Loads	211
Fig. 6.15 Close View of Infilled Joint with $t/a=1$ after Cyclic Shear Test at $P_i=0.1$ MPa under CNS	212
Fig. 6.16 Close View of Infilled Joint with $t/a=2$ after Cyclic Shear Test at $P_i=0.1$ MPa under CNS	212
Fig. 6.17 Peak Shear Stress of Infilled Joints vs. Number of cycles for (a) 30°-30° and 15°-15° (b) Asperity Angle with $t/a=1$ and 2 at $P_i=0.1$ MPa under CNL and CNS Condition	213
Fig. 6.18 Peak Shear Stress of Infilled Joints vs. Number of cycles for (a) 30°-30° and 15°-15° (b) Asperity Angle with $t/a=1$ and 2 at $P_i=0.5$ MPa under CNL and CNS Condition	214
Fig. 6.19 Shear Strength Envelopes of Non Planar Joint (30°-30°) with $t/a=0$, Between Intact Sample and Planar Joint Shear Envelopes under CNS	215
Fig. 6.20 Shear Strength Envelopes of Non Planar Infilled Joint (30°-30°) with $t/a=1$, Between Intact Sample and Infilled Planar Joint Shear Envelopes under CNS	215

Fig. 6.21 Shear Strength Envelopes of Non Planar Infilled Joint (30^0 - 30^0) with $t/a=2$, Between Intact Sample and Infilled Planar Joint Shear Envelopes under CNS	216
Fig. 6.22 Peak Shear Stress vs. Number of Cycles for 30^0 - 30^0 Asperity at $P_i=0.1$ MPa under CNL Condition for (a) $t/a=1$ ($t=5$ mm) (b) $t/a=2$ ($t=10$ mm)	218
Fig. 6.23 Peak Shear Stress vs. Number of Cycles for 30^0 - 30^0 Asperity at $P_i=1$ MPa under CNL Condition for (a) $t/a=1$ ($t=5$ mm) (b) $t/a=2$ ($t=10$ mm)	218
Fig. 7.1 (a) Photograph and (b) 3D view of Joint Roughness of Planar Joint from Jodhpur Sandstone	223
Fig. 7.2 (a) Photograph and (b) 3D View of Joint Roughness of Smooth Joint from Jodhpur Sandstone	224
Fig. 7.3 (a) Photograph and (b) 3D View of Joint Roughness of Rough Joint from Jodhpur Sandstone	225
Fig. 7.4 Shear Stress (Part A) and Normal Displacement (Part B) vs. Horizontal Displacement on Planar Joint at Three Different Normal Stresses 0.1, 0.5 and 1 MPa Respectively under CNL for Thirty Cyclic Shear Load	229
Fig. 7.5 Shear Stress (Part A) and Normal Displacement (Part B) vs. Horizontal Displacement on Smooth Joint at Three Different Normal Stresses 0.1, 0.5 and 1 MPa Respectively under CNL for Thirty Cyclic Shear Load	230
Fig. 7.6 Shear Stress (Part A) and Normal Displacement (Part B) vs. Horizontal Displacement on Rough Joint at Three Different Normal Stresses 0.1, 0.5 and 1 MPa Respectively under CNL for Thirty Cyclic Shear Load	231
Fig. 7.7 Rock Joint after Cyclic Shear Test at Different Normal Stress under CNL Condition	232
Fig. 7.8 Rough Joint Surface after Cyclic Shear Test at $P_i=1$ MPa	233
Fig. 7.9 Smooth Joint Surface after Cyclic Shear Test at $P_i=1$ MPa	233
Fig. 7.10 Shear Stress, Normal Displacement and Normal Stress versus Horizontal Displacement of Smooth (Part A) and Rough Joint (Part B) Respectively at $P_i=0.1$ MPa, under CNS ($K_n=8$ kN/mm) for Thirty Cyclic Shear Loads	236
Fig. 7.11 Shear Stress, Normal Displacement and Normal Stress versus Horizontal Displacement of Smooth (Part A) and Rough Joint (Part B) Respectively at $P_i=0.5$ MPa, under CNS ($K_n=8$ kN/mm) for Thirty Cyclic Shear Loads	237
Fig. 7.12 Shear Stress, Normal Displacement and Normal Stress versus Horizontal Displacement of Smooth (Part A) and Rough Joint (Part B) Respectively at $P_i=1$ MPa, under CNS ($K_n=8$ kN/mm) for Thirty Cyclic Shear Loads.	238
Fig. 7.13 Rock Joint at Different Normal Stress under CNS Condition after Cyclic Shear Test	239
Fig. 7.14 Shear Stress, Normal Displacement and Normal Stress versus Horizontal Displacement of Smooth (Part A) and Rough Joint (Part B) Respectively at $P_i=0.1$ MPa, under CNS ($K_n=32$ kN/mm) for Thirty Cyclic Shear Loads	240
Fig. 7.15 Peak Shear Stress of Natural Rock Joint vs. Number of Cycles at Three Different P_i under CNL and CNS Conditions for Smooth Joint Roughness	241
Fig. 7.16 Peak Shear Stress of Natural Rock Joint vs. Number of Cycles at Three Different P_i under CNL and CNS Conditions for Rough Joint Roughness	242

- Fig. 7.17 Shear Stress and Normal Displacement vs. Horizontal Displacement on Infilled Natural Smooth Joints with 5 mm Infill Thickness at $P_i=0.1, 0.5$ and 1 MPa Respectively under CNL and Cyclic Shear Loads 244
- Fig. 7.18 Shear Stress and Normal Displacement vs. Horizontal Displacement on Infilled Natural Rough Joints with 5 mm Infill Thickness at $P_i=0.1, 0.5$ and 1 MPa Respectively under CNL and Cyclic Shear Loads 245
- Fig. 7.19 Shear Stress, Normal Displacement and Normal Stress versus Horizontal Displacement of Infilled Natural Joint for smooth (Part A) and Rough (Part B) Respectively with 5mm Infill Thickness under CNS ($K_n= 8$ kN/mm) at $P_i=0.1$ MPa for Thirty Cyclic Loads 246
- Fig. 7.20 Shear Stress, Normal Displacement and Normal Stress versus Horizontal Displacement of Infilled Natural Joint for smooth (Part A) and Rough (Part B) Respectively with 5mm Infill Thickness under CNS ($K_n= 8$ kN/mm) at $P_i=0.5$ MPa for Thirty Cyclic Loads 247
- Fig. 7.21 Shear Stress, Normal Displacement and Normal Stress versus Horizontal Displacement of Infilled Natural Joint for smooth (Part A) and Rough (Part B) Respectively with 5mm Infill Thickness under CNS ($K_n= 8$ kN/mm) at $P_i= 1$ MPa for Thirty Cyclic Loads 248
- Fig 7.22 Peak Shear Stress of Unfilled and Infilled Natural Rock Joints vs. Number of Cycles at Three Different P_i under CNL Condition for Smooth Joints 249
- Fig 7.23 Peak Shear Stress of Unfilled and Infilled Natural Rock Joints vs. Number of Cycles at Three Different P_i under CNL Condition for Rough Joints 249
- Fig 7.24 Peak Shear Stress of Unfilled and Infilled Natural Rock Joints vs. Number of Cycles at Three Different P_i under CNS Condition for Smooth Joints 250
- Fig 7.25 Peak Shear Stress of Unfilled and Infilled Natural Rock Joints vs. Number of Cycles at Three Different P_i under CNS Condition for Rough Joints 250

LIST OF TABLES

Table 3.1 Components Designed and Modified for Direct Shear Apparatus	92
Table 4.1 Physico-Mechanical Properties of the Model Material	110
Table 4.2 Physico-Mechanical Properties of the Jodhpur Sandstone	121
Table 4.3. Classification of Anisotropy (Sing et al., 1989)	122
Table 4.4. The Results of UCS Test on Jodhpur Sandstone at Different Angles	122
Table 5.1 First Peak Normal Stress and Shear Stress Based on Increasing Normal Stiffness on the Joint with 30 ⁰ -30 ⁰ Asperity	163
Table 6.1 First Peak Shear Stress of Joint with 30 ⁰ -30 ⁰ Asperity at Different t/a Ratio under CNL and CNS Conditions	212
Table 7.1 Max Amplitude, JRC and Category for Unfilled Natural Joints	226
Table 8.1 Max Amplitude, JRC and Category for Infilled Natural Joints	226

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_{sl}	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_{tp}	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
Φ_{sh}^p	Peak friction angle in shearing
Φ_{sl}^p	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
σ_{n_0}	Normal stress at initial condition
σ_t	Tensile strength

τ_{infill}	Shear strength of infill material alone
τ_{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