

**PHYSICAL AND NUMERICAL MODELING ON
SHEAR BEHAVIOUR OF NATURAL ROCK JOINTS**

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INDIAN INSTITUTE OF TECHNOLOGY DELHI
OCTOBER 2019**

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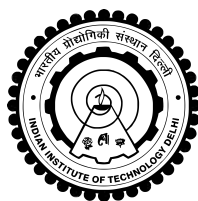
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Submitted

in fulfillment of the requirement of the degree of Doctor of Philosophy

to the



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

MAY 2019

**This research is dedicated to my father, mother, sister, brother, my wife and our two
sons**

CERTIFICATE

This is to certify that the thesis titled **“Physical and Numerical Modeling on Shear Behaviour of Natural Rock Joints”** being submitted by **Sandeep Bhardwaj**, to the Indian Institute of Technology, Delhi, for the award of degree of **Doctor of Philosophy**, is a bona fide record of the research work done by him under my supervision. Mr.Sandeep Bhardwaj has worked under my supervision for the submission of this thesis, which to the best of my knowledge has reached the requisite standard. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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Date: 16th May 2019

ACKNOWLEDGEMENTS

I am thankful to almighty Lord Krishna who made me to complete this research. I like to give sincere thanks to my supervisor Prof. K. Seshagiri Rao without which this high quality research will not be possible. I express my deep appreciation and sincere thanks to my teachers , who provide me timely help during the initial study of the research. I would also like to thanks Institute technicians for giving me an opportunity to work in Engineering Geology, Rock Engineering and Soil Engineering Laboratories.

Finally, my father Late Mr. Rajvir Sharma hard-work comes to an end, to bring out this thesis to present form. All throughout my stay and research work at IITDelhi my wife Dr. Rupali Sharma and my sons master Himank Bhardwaj and master Nakshatra Bhardwaj provide me the strength and wisdom for successful completion of this thesis. Lastly, my full gratitude to my parent institute Chaudary Charan Singh Haryana Agricultural University, Hisar, Haryana who gave me an opportunity to complete this Doctoral Thesis and also thanks to All India Council of Technical Education(AICTE) for providing me sponsorship through Quality Improvement Programme (QIP) fellowship to complete this degree program.

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Date: 16th May 2019

ABSTRACT

The presence of rock joints in the rock mass reduces the shear strength of the rock mass. These natural rock joints influenced by the joint roughness, stiffness of the surrounding rock mass, rate of shearing and seepage condition of the rock joint. The strength parameters of the natural rock joint were simulated for two types of boundary condition viz. constant normal load(CNL) and constant normal stiffness(CNS). It is challenging to measure the pore water pressure in the direct shear environment so that saturated state of natural rock joints was studied.

Splitting of the Kota sandstone blocks was planned and performed in the lab. With a planned groove of 2 cm on all edges in a $300mm \times 300mm \times 125mm$ sized Kota sandstone blocks made. This way split and matched Kota sandstone joints were carved out from this natural rock block. Total eighty of Kota sandstone blocks used for creating a split. These split specimens prepared for roughness measurement and shear strength testing.

A profilometric study was conducted for the estimation of the joint roughness of split Kota sandstone. These split specimens placed on the Profilometer table, which can be moved horizontally in both directions that is forward and backward. The longitudinal distance measured with a sampling interval of 10 mm and a transverse distance measured with a sampling interval of 5 mm. Vertical distance(height) measured with the help of a data acquisition system consisting of an LVDT of length 20 cm. This entire arrangement makes the 240 mm square grid inside the joint surface after leaving 2 cm space on all four edges of the split sandstone, in this square grid mesh, each element having a size of $10mm \times 5mm$. After that vertical distance at every corner of these rectangular elements also measured.

Primarily two algorithms were used for the analysis of Joint Roughness Coefficient(JRC). These two JRC estimation algorithms were the root mean square derivative method (Z2) by

Tse and Cruden(1979) and the roughness profile index(Rp) method by Maerz et al. (1990). The correlations of Z2 and Rp parameters with JRC used for estimation of roughness. Based on these JRC values, Analysis of Variance applied for statistical determination for identification of the group within which particular JRC ranges existed, and plotting of these ranges done in the form of interval plot. Based on this analysis, joint roughnesses of splits sandstone categorized into four ranges. The first range is for the values of less than ten JRC (Barton, 1973) scale of 10 cm, which symbolizes the very smooth roughness. The second range is from eleven to fourteen which implies smooth roughness. The third range which is the most prevailing of all is between fifteen and nineteen on JRC scale which means medium rough joint and lastly very rough is the fourth range which is above nineteen.

Static direct shear tests done for split Kota sandstone specimens under dry and saturated conditions. Both conditions suggest shear strength was influenced by normal stress more as compared to joint roughness for low order JRC ranges. Higher order JRC specimens show a sharp peak in shear strength envelope despite low normal stress. Peak shear stress also increases with the increase of normal stress in all cases. However joint roughness has a lesser role as compared to normal stress. High JRC values have more influence in CNS boundary condition as compared to CNL boundary condition. Analysis of static direct shear data was consistent in RocData 5.0. and Power Law strength criteria found to be giving satisfactory peak shear strength estimation in CNL and CNS boundary condition under static direct shear.

For cyclic shear, frequency 0.05 Hz chosen for testing the split Kota sandstone specimens under three normal stresses, i.e., 0.1, 0.5 and 1MPa. Split sandstone specimens were tested only for 4 mm amplitude for simplicity and generalization of the shear strength criteria. Significant variation in peak shear strength of natural rock joints under cyclic loading is only visible for low normal stresses.

During cyclic testing of split specimens, as the JRC range increases the peak shear stress

also increases. As the number of shear cycle increases, peak shear stress decreased. Cyclic direct shear tests conducted on split sandstone, under dry and saturated states. In CNL conditions the forward and reverse shear peaks are regular for low normal stresses. In CNS condition during cyclic shearing, the forward shear peak becomes sharper and sharper with increasing normal stresses. Under CNL condition, forward shear and reverse shear cycles were asymmetrical whereas in CNS condition forward shear is more dominant as compared to reverse shear which means lesser asperity degradation in reverse cycle. Maximum peak shear stress obtained in the first or second cycle which means the first order asperity was sheared off in these cycles.

With saturation in cyclic shear, shear strength envelope shows flat shape for CNL and CNS boundary condition. It happens during only in low normal stress and the maximum peak shear strength obtained in low normal stresses in saturation. However, when normal stress increases, peak shear stress decreasing and resulted in flat shape peak in shear strength envelope. If no volume change is allowed in the direct shear box, then this causes negative pore pressure in the direct shearing causes natural jointed rock specimens to dilate. So, as a result, this flat shape is obtained during shearing.

In saturation state, only forward shear cycle obtained. In this, the first order asperities sheared off completely in forwarding cycles due to which reverse shear cycle is near to axis. Peaks obtained where the amplitude of the cycle finished, before that it was linear. It is due to the shearing of asperities before and after backward advance (BA) stage of the cycle. Peak shear stress versus several cycles follows the simple exponential curve for both CNL and CNS boundary condition In CNL condition, for low normal stress, it is near to axis, and it follows the simple exponential fit with 95 percent confidence index. In CNS condition, the peak shear stress versus several cycles also follow the simple exponential fit, but it is more curvilinear with increasing normal stress in the dry and saturated state. It happens due to change(increase) in normal stress while restriction in dilation is in place during cyclic shear

in the dry and saturated state.

सार

रॉक द्रव्यमान में रॉक जोड़ों की उपस्थिति रॉक द्रव्यमान की कतरनी ताकत को कम करती है। इन प्राकृतिक रॉक जोड़ों को संयुक्त खुरदरापन, आस-पास के रॉक द्रव्यमान की कठोरता, रॉक जॉइंट की कतरनी और रिसने की स्थिति से प्रभावित किया जाता है। प्राकृतिक रॉक जोड़ों की शक्ति मापदंडों को दो प्रकार की सीमा स्थितियों के लिए अनुकरण किया गया था। निरंतर सामान्य भार (CNL) और निरंतर सामान्य कठोरता (CNS)। यह प्रत्यक्ष कतरनी वातावरण में प्राकृतिक रॉक जोड़ों पर संतृप्ति प्रभाव को मापने के लिए चुनौतीपूर्ण है ताकि प्राकृतिक रॉक जोड़ों की संतृप्त अवस्था का अध्ययन किया गया।

कोटा बलुआ पत्थर ब्लॉकों के विभाजन की योजना बनाई गई थी और प्रयोगशाला में प्रदर्शन किया गया था। \$ 300 मिमी \ गुना 300 मिमी \ गुना 125 मिमी के सभी किनारों पर 2 सेमी की योजनाबद्ध नाली के साथ कोटा सैंडस्टोन ब्लॉक बनाए गए थे। इस तरह से विभाजित और कोटा बलुआ पत्थर के जोड़ों का मिलान इस प्राकृतिक रॉक ब्लॉक से किया गया था। कोटा सैंडस्टोन ब्लॉकों के कुल अस्सी का उपयोग विभाजन बनाने के लिए किया गया था। ये विभाजन नमूने खुरदरापन माप और कतरनी शक्ति परीक्षण के लिए तैयार किए गए थे।

विभाजन सैंड सैंडस्टोन की संयुक्त खुरदरापन के अनुमान के लिए एक प्रोफिलोमेट्रिक अध्ययन किया गया था। इन विभाजित नमूनों को प्रोफिलोमीटर टेबल पर रखा गया था, जो आगे और पीछे दोनों दिशाओं में क्षैतिज रूप से स्थानांतरित हो सकते हैं। अनुदैर्घ्य दूरी को 10 मिमी के नमूने अंतराल के साथ और एक अनुप्रस्थ दूरी को 5 मिमी के नमूने अंतराल के साथ मापा गया था। वर्टिकल डिस्टेंस (ऊंचाई) को 20 सेमी क्षमता के LVDT से युक्त डाटा अधिग्रहण प्रणाली की मदद से मापा गया। यह पूरी व्यवस्था विभाजित सैंडस्टोन के सभी चार किनारों पर 2 सेमी जगह छोड़ने के बाद संयुक्त सतह के अंदर 240 मिमी वर्ग ग्रिड बनाती है, इस वर्ग ग्रिड जाल में, प्रत्येक तत्व का आकार \$ 10 मिमी \ गुना 5 मिमी \$ है। उसके बाद इन आयताकार तत्वों के हर कोने पर ऊर्ध्वाधर दूरी भी मापी गई।

मुख्य रूप से संयुक्त एल्गोरिदम गुणांक (JRC) के विश्लेषण के लिए दो एल्गोरिदम का उपयोग किया गया था। ये दो JRC आकलन एल्गोरिदम जड़ थे वर्गाकार व्युत्पन्न विधि (Z2) Tse और Cruden (1979) और Maerz एट अल द्वारा खुरदरापन सूचकांक (Rp) विधि। (1990)। जेआरसी के साथ जेड 2 और आरपी मापदंडों के संबंध खुरदरापन का अनुमान लगाने के लिए उपयोग किए जाते हैं। इन JRC मूल्यों के आधार पर, Variance का विश्लेषण उस समूह की पहचान के लिए सांख्यिकीय निर्धारण के लिए लागू किया गया था जिसके भीतर विशेष JRC श्रेणियां मौजूद थीं, और इन श्रेणियों की साजिश अंतराल साजिश के रूप में की गई थी। इस विश्लेषण के आधार पर, विभाजन बलुआ पत्थर के संयुक्त खुरदरेपन को चार श्रेणियों में वर्गीकृत किया गया था। पहली सीमा 10 सेमी के पैमाने पर दस जेआरसी (बार्टन, 1973) से कम के मूल्यों के लिए है, जो बहुत चिकनी खुरदरापन का प्रतीक है। दूसरी सीमा ग्यारह से चौदह तक है जिसका अर्थ है मोटे जोड़। तीसरी

श्रेणी जो सभी में सबसे अधिक प्रचलित है, जेआरसी पैमाने पर पंद्रह और उन्नीस के बीच है जिसका मतलब मध्यम मोटा संयुक्त है और अंतिम रूप से बहुत मोटा चौथा है जो उन्नीस से ऊपर है।

शुष्क और संतृप्त परिस्थितियों में विभाजित कोटा सैंडस्टोन नमूनों के लिए मोनोटोनिक स्थिर प्रत्यक्ष कतरनी परीक्षण किए गए थे। दोनों स्थितियों से पता चलता है कि कतरनी ताकत सामान्य तनाव से प्रभावित थी, जो कि कम क्रम वाले जेआरसी रैंज के लिए संयुक्त खुरदरापन की तुलना में अधिक थी। उच्च क्रम JRC नमूने, कम सामान्य तनाव के बावजूद कतरनी ताकत लिफाफे में तेज चोटी दिखाते हैं। और पीक कतरनी ताकत लिफाफा उच्च क्रम JRC में उच्च सामान्य तनाव के लिए प्राप्त किया गया था। पीक कतरनी तनाव भी सभी मामलों में सामान्य तनाव की वृद्धि के साथ बढ़ता है। सीएनएल सीमा स्थिति की तुलना में उच्च जेआरसी मूल्यों का सीएनएस सीमा स्थिति में अधिक प्रभाव है। RocData 5.0 की मदद से मोनोटोनिक प्रत्यक्ष कतरनी डेटा का विश्लेषण किया गया था। और पावर लॉ शीयर स्ट्रेंथ मानदंड को मोनोटोनिक स्टैटिक डायरेक्ट शीयर के तहत सीएनएल और सीएनएस सीमा स्थिति में संतोषजनक पीक शीयर शक्ति का आकलन करने के लिए पाया गया था।

चक्रीय कतरनी के लिए, आवृत्ति 0.05 हर्ट्ज को तीन सामान्य तनावों के तहत विभाजित कोटा सैंडस्टोन नमूनों के परीक्षण के लिए चुना गया था, अर्थात्, 0.1, 0.5 और 1 एमपीए। स्प्लिट बलुआ पत्थर के नमूनों का परीक्षण केवल 4 मिमी आयाम के लिए सादगी और कतरनी शक्ति मानदंड के सामान्यीकरण के लिए किया गया था। चक्रीय लोडिंग के तहत प्राकृतिक रॉक जोड़ों की चोटी कतरनी ताकत में महत्वपूर्ण भिन्नता केवल कम सामान्य तनावों के लिए दिखाई देती है।

विभाजन नमूनों के चक्रीय परीक्षण के दौरान, जेआरसी सीमा बढ़ने के साथ-साथ शिखर कतरनी तनाव भी बढ़ जाता है। जैसे-जैसे कतरनी चक्र की संख्या बढ़ती है, शिखर कतरनी तनाव कम हो जाता है। सूखे और संतृप्त राज्यों के तहत, विभाजित बलुआ पत्थर पर चक्रीय प्रत्यक्ष कतरनी परीक्षण किए गए थे। सीएनएल स्थितियों में आगे और पीछे की कतरनी चोटियाँ निम्न सामान्य तनावों के समान हैं। चक्रीय कतरनी के दौरान सीएनएस की स्थिति में, आगे के कतरे शिखर सामान्य तनाव बढ़ने के साथ तेज और तेज हो जाते हैं। सीएनएल स्थिति के तहत, आगे के कतरनी और रिवर्स कतरनी चक्र विषम थे, जबकि सीएनएस स्थिति में आगे कतरनी रिवर्स कतरनी की तुलना में अधिक प्रभावी होती है, जिसका अर्थ है रिवर्स चक्र में कम asperity गिरावट। पहले या दूसरे चक्र में अधिकतम शिखर कतरनी तनाव प्राप्त किया गया था जिसका मतलब है कि इन चक्रों में पहले क्रम की असमानता को दूर कर दिया गया था।

चक्रीय कतरनी में संतृप्ति के साथ, कतरनी शक्ति लिफाफा सीएनएल और सीएनएस सीमा स्थिति के लिए सपाट आकार दिखाता है। विभाजन का यह संतृप्त राज्य कोटा बलुआ पत्थर कम सामान्य तनाव में मनाया गया और संतृप्ति में अधिकतम शिखर कतरनी ताकत देखी गई। हालांकि, जब सामान्य तनाव बढ़ता है, तो पीक कतरनी तनाव घटता पाया गया और परिणामस्वरूप शीयर स्ट्रेंथ लिफाफे में सपाट आकार की चोटी हो गई। यदि प्रत्यक्ष कतरनी बॉक्स में किसी भी मात्रा में परिवर्तन की अनुमति नहीं है, तो यह प्रत्यक्ष कतरनी में नकारात्मक छिद्र दबाव का कारण बनता है प्राकृतिक संयुक्त रॉक नमूनों को पतला करने का कारण बनता है। तो, परिणामस्वरूप, यह समतल आकृति कतरनी के दौरान प्राप्त की जाती है।\ par संतृप्त अवस्था में, केवल आगे का कतरनी चक्र प्राप्त किया गया था। इसमें, पहले क्रम की असमानताएं पूरी तरह से आगे के चक्रों में बंद हो गईं, जिसके कारण रिवर्स कतरनी चक्र कम कतरनी दिखा रहा है। चोटियों को प्राप्त किया गया जहां

चक्र का आयाम समाप्त हो गया, इससे पहले यह रैखिक था। यह चक्र के पहले और पिछड़े अग्रिम (बीए) चरण के बाद asperities के बाल काटना के कारण है। पीक कतरनी तनाव बनाम चक्रों की संख्या सीएनएल और सीएनएस सीमा स्थिति दोनों के लिए सरल घातीय वक्र का अनुसरण करती है। सीएनएल स्थिति में, कम सामान्य तनाव के लिए, यह अक्ष के पास है, और यह 95 प्रतिशत आत्मविश्वास सूचकांक के साथ सरल घातीय फिट का अनुसरण करता है। सीएनएस स्थिति में, चक्र कतरनी तनाव बनाम चक्रों की संख्या भी सरल घातीय फिट का पालन करती है, लेकिन शुष्क और संतृप्त अवस्था में सामान्य तनाव बढ़ने के साथ यह अधिक वक्रता है। यह सामान्य तनाव में परिवर्तन (वृद्धि) के कारण होता है जबकि सूखे और संतृप्त अवस्था में चक्रीय कतरनी के दौरान फैलाव में प्रतिबंध होता है।

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ABBREVIATIONS

CNL	Constant Normal Load
CNS	Constant Normal Stiffness
JRC	Joint Roughness Coefficient
JMC	Joint Matching Coefficient
JCS	Joint Compressive Strength
ISRM	International Society of Rock Mechanics
PR	Persistence Ratio
DL	Length of Discontinuity
RBL	Length of Rock Bridge
RQD	Rock Quality Designation
P-wave	Primary or Longitudinal Wave
FA	Forward Advance
FR	Forward Reverse
BA	Backward Advance
BR	Backward Reverse
UCS	Uniaxial Compressive Strength
SRF	Strength Reduction Factor
OCR	Over Consolidation Ratio
PoP	Plaster of Paris
CD	Consolidated Drained
BB	Barton and Bandis
MC	Mohr-Coloumb
PW	Power Law
ANOVA	Analysis of Variance
QIP	Quality Improvement Programme

NOTATIONS

s_j	Joint Spacing
λ	Joint Frequency
V_p	P-wave Velocity
μ_l	Mean Area
k_a	Correlation Factor
γ_i	Angles between the Discontinuity Sets
V_b	Block Volume
e_h	Hydraulic Aperture
τ	Shear Strength
τ_{clean}	Shear Strength of Clean Joint
τ_j	Average Shear Stress
τ_p	Shear Strength of the Joint
τ_s	Shear Stress
τ_{ult}	Ultimate Shear Strength
τ_n	Shear Strength of the Joint at Normal Stress
D	Fractal Number
Z^2	Second Root Mean Square Derivative
R_p	Roughness Profile Sinuosity
i_p	Peak Dilatancy Rate
σ_1	Major Principal Stress
σ_2	Intermediate Principal Stress
σ_3	Minor Principal Stress
σ_c	Uniaxial Compressive Strength
σ_{ci}	Intact Rock Uniaxial Compressive Strength
σ_{cj}	Jointed Rock Uniaxial Compressive Strength
σ_{cr}	Rock Mass Uniaxial Compressive Strength
σ_{dev}	Deviatoric Stress
σ_m	Mean Principal Stress
σ_n	Normal Stress
σ_{ni}	Initial Seating Pressure
σ_{nj}	Normal Stress of the Joint
σ_{no}	Initial Normal Stress
σ_t	Tensile Stress
σ_{static}	Static Normal Stress
σ_{dyn}	Dynamic Normal Stress
σ_j	Average Normal Stress
δ_n	Vertical Deformation
δ_{peak}	Deformation at Peak Normal Stress
δ_s	Horizontal Deformation
K_n	Normal Stiffness
K_s	Shear Stiffness
ν	Poisson's Ratio
u_{nc}	Joint Closure Deformation under Normal Stress
u_n	Joint Deformation under Normal Stress
E	Elastic Modulus

E_i	Intact Rock Elastic Modulus
E_j	Jointed Rock Elastic Modulus
J_f	Joint Factor
J_n	Number of Joints per meter Depth
n	Critical Joint Inclination
r	Sliding Joint Strength
β_n	Joint Orientation in Degrees
ϕ_b	Base Rock Angle of Internal Friction
ϕ_{fill}	Angle of Internal Friction of Infill
ϕ_{io}	Angle on Internal Friction of Intact Rock under low Confining Pressure
ϕ_j	Angle of Internal Friction between Joints
ϕ_r	Residual Friction Angle
c_j	Joint Cohesion
a_j	Contact Areas of Asperities