I would like to dedicate this thesis to people living in hills

CERTIFICATE

It is certified that the work contained in the thesis titled ***"LANDSLIDE HAZARD ASSESSMENT OF RESIDUAL SOIL SLOPE USING NUMERICAL SIMULATION"*** submitted by ***Mr. ARUNAVA RAY*** (Registration No. 16151003) has been carried out under our supervision and that this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy and SOTA for the award of PhD. Degree.

Dr. Rajesh Rai
(Supervisor)
Associate Professor
Department of Mining Engineering
IIT(BHU), Varanasi

Prof. T. N. Singh
(Co-supervisor)
Professor
Department of Earth Sciences
IIT Bombay

DECLARATION BY THE CANDIDATE

I, ***ARUNAVA RAY***, certify that the work embodied in this thesis is my bona fide work and carried out by me under the supervision of ***Dr. Rajesh Rai*** and Co-supervision of ***Prof. T. N. Singh*** from **July-2016** to **Dec-2021,** at the ***Department of Mining Engineering***, Indian Institute of Technology (BHU), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not will fully copied any other's work, paragraphs, text, data, results, etc., reported in journals, books, magazines, reports dissertations, theses, etc., or available at websites and have not included them in this thesis and have not cited as my own work.

Date:

Place: Varanasi (Arunava Ray)

CERTIFICATE BY THE SUPERVISOR (s)

It is certified that the above statement made by the student is correct to the best of my knowledge.

Dr. Rajesh Rai
(Supervisor)
Associate Professor
Department of Mining Engineering
IIT(BHU), Varanasi

Prof. T. N. Singh
(Co-supervisor)
Professor
Department of Earth Sciences
IIT Bombay

Prof. Piyush Rai
(Head, Department of Mining Engineering)

COPYRIGHT TRANSFER CERTIFICATE

Title of the Thesis: **Landslide Hazard Assessment of Residual Soil Slope Using Numerical Simulation**

Name of the Student: **Arunava Ray**

COPYRIGHT TRANSFER

The undersigned hereby assigns to the Indian Institute of Technology (Banaras Hindu University), Varanasi all rights under copyright that may exist in and for the above thesis submitted for the award of the **"Doctor of Philosophy"**.

Date:

Place: Varanasi (Arunava Ray)

ACKNOWLEDGEMENT

First of all, I am very much thankful to the almighty God and my Parents, who gives this opportunity to express my acknowledgements. I would like to express my deep sense of gratitude to Dr. Rajesh Rai and Prof. T. N. Singh for their invaluable suggestions, meticulous guidance, and continuous encouragement in carrying out the PhD work. I feel fortunate to work under their guidance and really enriched the quality discussions I had with them during my entire research period. I would like to express my deep gratitude to Prof. Piyush Rai, Head, Mining Engineering Department for the support provided for carrying out various laboratory works in the department. I would like to express my sincere appreciation to Dr. Ashok Jaiswal and Dr. P. B. Ramudu for serving on my doctoral scrutiny committee members. I am also very thankful to Prof. S. Gupta, Prof. B. K. Shrivastva, Prof. Surya Parkash and Dr. Manoj Khandelwal for their valuable suggestions. I am also grateful to Library In-charge, Mining Engineering Library IIT(BHU) for allowing me to access vast literature resources. I am also grateful to the Laboratory In-charge and technicians of Geotechnical Lab, Civil Engineering Department IIT(BHU); Rock Mechanics Lab, Mining Engineering Department IIT(BHU); Computer Lab, Mining Engineering Department IIT(BHU) and Workshop, Mining Engineering Department IIT(BHU) for allowing and helping me in performing laboratory works.

I am also thankful to my senior Mr. Ashish Vishwakarma, batchmates (Mr. Ashutosh Kumar Bharati and Mr. Gaurav Verma) and juniors (Mr. R.E.S. Chaitanya Kumar, Mr. Ankit Raj, Mr. Vikas Kumar and Mr. Harshal Verma) who helped me in completing my PhD work.

Lastly, the most important person whom I admire most, my better half Mrs. Sweta Ray who gave me motivation, encouragement, caring and strength to be firm in tough situations during my PhD work.

(Arunava Ray)

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

LHZ	Landslide Hazard Zonation
GIS	Geographical Information System
ML	Machine Learning
ANN	Artificial Neural Network
GSI	Geological Survey of India
CRED	Centre for Research on the Epidemiology of Disasters
FOS	Factor of Safety
LEM	Limit Equilibrium Method
FEM	Finite Element Method
FDM	Finite Difference Method
SSR	Shear Strength Reduction
SRF	Strength Reduction Factor
PSSA	Probabilistic Slope Stability Analysis
MCSM	Monte Carlo Sampling Method
LSZ	Landslide Susceptibility Zonation
SMR	Slope Mass Rating
CSMR	Chinese Slope Mass Rating
CoSMR	Continuous Slope Mass Rating
RMR	Rock Mass Rating
UCS	Uniaxial Compressive Strength
SD	Spacing of Discontinuities
CD	Condition of Discontinuities
GD	Groundwater Condition
RQD	Rock Quality Designation
SSZ	Shyok Suture Zone
ITSZ	Indus Tsangpo Suture Zones

HMB	Himalayan Metamorphic Belt
MCT	Main Central Thrust
MBT	Main Boundary Thrust
MFT	Main Frontal Thrust
IMD	India Meteorological Department
JJAS	June, July, August and September
ISRM	International Society for Rock Mechanics
XRD	X-ray diffraction
ASTM	American Society for Testing Materials
ISSCS	Indian Standard Soil Classification System
WC	Water Content
SDI	Slake Durability Index
PDF	Probability Density Function
CDF	Cumulative Distribution Function
StD	Standard Deviation
RMSE	Root Mean Square Error
VAF	Variance Accounted For
MLP	Multilayer Perceptron
BFGS	Broyden-Fletcher-Goldfarb-Shanno
DEM	Distinct Element Method
PFC	Particle Flow Code
MSL	Mean Sea Level

LIST OF SYMBOLS

φ	Friction angle
c	Cohesion
ξ	Slope height factor
λ	Discontinuity factor
H	Slope Height
e	Void ratio
w	Water content
G	Specific gravity
S	Degree of saturation
$F_0(x)$	CDF of the hypothesised distribution
$F_{data}(x)$	Empirical distribution function of your observed data
D	Kolmogorov-Smirnov test statistic
f	Transfer function or activation function for the neuron
p_i	i^{th} input in ANN network
w_i	i^{th} weight in ANN network
b	Bias in ANN network
a	Output of a neuron
O_i	Output corresponding to the i^{th} data point in the training set
I_i	Actual output as considered in the target set
n	Number of data points
j	Neurons within the hidden layer
Qi	Relative importance of the i^{th} input variable on the output
$OW_{j,i}$	Weight of output variable for the j^{th} neuron
$IW_{j,I}$	Weight of j^{th} neuron from the i^{th} input variable of hidden layer
K_s	Shear stiffness
K_n	Normal stiffness