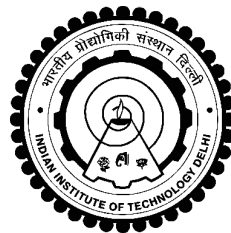


**EFFECT OF RAINFALL AND EARTHQUAKE ON  
LANDSLIDES OF DARJEELING HIMALAYAS**

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**JUNE 2019**

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*by*

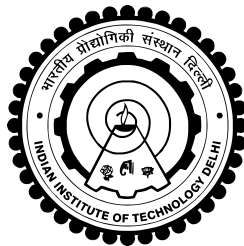
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Submitted

in fulfillment of the requirements of the Degree of Doctor of Philosophy

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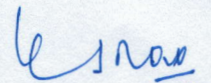
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## Certificate

This is to certify that the thesis entitled, '**Effect of Rainfall and Earthquake on Landslides of Darjeeling Himalayas**' being submitted by **Mr. Prasanta Kumar Kundu** to the Department of Civil Engineering, 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. Prasanta Kumar Kundu 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 of it has not been presented or submitted to any other University or Institute for any degree or diploma.



Dr. K. S. Rao

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**Prasanta Kumar Kundu**

## Abstract

Very high rainfall, long monsoon, high seismicity, young geology and rugged mountains made the Himalayan region contributing to over 70% of global fatal landslides, and majority of devastating landslides in India. Landslides in this region cause havoc during monsoon incurring substantial human and financial losses and disrupting the livelihood of local people. The problem is likely to increase over the years because of over exploitation of natural resources, deforestation, increased developmental activities due to increase in population, hill tourism and climate change.

The main objective of the present study is to understand the root causes and mechanism of landslides in the Himalayan region and develop a simple and quick methodology for the assessment of stability, thereby assisting the planners and designers to take appropriate corrective and preventive actions.

The study has been performed in various phases, e.g., a) site selection, b) geological and geotechnical studies, c) field instrumentation, d) hydrological studies, e) seismic study, f) slope stability analyses and g) formulation of stability analyses model and design charts. Two landslide sites, Tindharia ( $26^{\circ}51'14.55'' N$ ,  $88^{\circ}20'13.12'' E$ ) and Paglajhora ( $26^{\circ}52'16.55'' N$ ,  $88^{\circ}18'16.86'' E$ ), in the Darjeeling Himalayas, Eastern India were selected which were triggered by earthquake and rainfall.

Topographic survey carried out with Total Station and DGPS to develop plan and profile of the study areas followed by Geological and Geotechnical investigation. Available reports and data with regards to Geological and Geotechnical studies carried out by various agencies like SOI, GSI, PWD and JICA were also collected.

A comprehensive hydrological study of the area along with field monitoring has

been carried out with the objective to establish the design rainfall intensity and its' effect on slope stability. Hourly rainfall data of SRRG for over 20 years period comprising of over 200000 records were collected from IMD and Intensity-Duration-Frequency (IDF) analyses carried out using Gumbel's extreme value distribution. Considering long monsoon and frequent high intensity storms in the study area, the effect of raindrop impact force and excess pore pressure generation due to the impact has also been studied. Tipping bucket rain gauge and vibrating wire piezometer were installed to continuously monitor rainfall and pore water pressure. An equipment to measure raindrop impact force has been designed and fabricated to continuously record the impact force. Variation in ground water level was monitored by measuring water level in standpipes using digital water level indicator.

The seismic study has been performed to determine design ground acceleration, to develop seismic hazard curves and to study pore pressure response under seismic loading. Seismotectonic map of the study area has been prepared for the study area identifying all the seismogenic sources. Past earthquake data collected from various sources and a catalogue prepared following standard steps comprising of homogenization, de-clustering and completeness checking. The data was then analysed statistically to obtain G-R recurrence relationship for the region as well as for each identified source.

A total of two hundred and ninety one (291) strong motion data from 52 earthquakes and 113 monitoring stations covering almost entire Himalayan region, except the Nepal Himalaya, have been collected to develop attenuation relationship. The data compared with the available attenuation relationships for the Himalayan region to check their applicability in the present study, however, none found to be suitable and hence a new equation developed for the region. The new attenuation relationship

thus developed and as given below has been used for deterministic and probabilistic seismic hazard analyses.

$$\log_{10}(PGA) = -2.041 + 0.344M - 0.858\log_{10}(R + e^{0.529M}) + \sigma \log \epsilon$$

Since no suitable model for earthquake induced pore water pressure is available for sloping ground, a method for estimating pore water pressure for sloping ground is proposed in this study based on published cyclic triaxial and simple shear test results on isotropically and anisotropically consolidated samples. The method requires the conversion of non-uniform random earthquake loading to equivalent numbers of uniform stress cycles ( $N_{eq}$ ). Based on the analyses of all the 291 earthquake time history records an equation relating earthquake magnitude ( $M_w$ ) to ( $N_{eq}$ ) has been developed as  $N_{eq} = 0.52 * e^{0.49M_w}$ .

The earthquake time histories have also been analysed to develop response spectra for various site classes and compared the same with the spectra in IS 1893 (Part I):2016 and BS EN 1998-1:2004. At high frequencies the spectral amplifications are found to be higher than the IS 1893 (Part I):2016 spectra, however, at lower frequencies it is found to be much covered. Finally, slope stability analyses have been performed for both the sites, by limit equilibrium and numerical methods of analyses, adopting the derived design parameters for various scenarios of rainfall and earthquake. Based on the understanding of the failure mechanism the limit equilibrium equation

$$FOS = \frac{C_n + (1 - r_u^o)(1 - r_u^e - r_u^r) \tan \phi}{\tan \beta + K \cdot \sec \beta + R'_d \sin \beta}$$

is developed for earthquake and rainfall induced shallow landslides in the Eastern Himalayas. Suitable design charts have also been developed for various earthquake magnitudes, PGA, slope angles ( $\beta$ ) and angle of internal friction ( $\phi$ ).

## दार्जिलिंग हिमालय के भूस्खलन पर वर्षा और भूकंप का प्रभाव : सारांश

बहुत अधिक वर्षा, दीर्घ मानसून, महत भूकंपीयता, अल्पवयस्क भूतत्त्व और ऊबड़-खाबड़ पर्वतीय भाग हिमालय क्षेत्र को 70% से अधिक वैश्विक जानलेवा भूस्खलन, और भारत में विनाशकारी भूस्खलन का अधिकांश हिस्से में अपना योगदान प्रदान करवाता है। इस क्षेत्र में मानसून के दौरान भूस्खलन से हुई तबाही से, वास्तविक मानवीय और वित्तीय नुकसान होते हैं और स्थानीय लोगों की आजीविका बाधित होती है। आने वाले वर्षों में प्राकृतिक संसाधनों के दोहन, वनों की कटाई, जनसंख्या वृद्धि के कारण विकासात्मक गतिविधियों में वृद्धि, पहाड़ी पर्यटन और जलवायु परिवर्तन के कारण इस समस्या के बढ़ने की संभावना है। वर्तमान अध्ययन का मुख्य उद्देश्य हिमालयी क्षेत्र में भूस्खलन के मूल कारणों और क्रियाविधि को समझना है और स्थिरता के आकलन के लिए एक सरल और त्वरित कार्यप्रणाली का विकास करना है, जिससे योजनाकारों और डिजाइनर की उपयुक्त सुधारात्मक और निवारक कार्रवाई करने के लिए सहायता की जा सके।

यह अध्ययन विभिन्न चरणों में किया गया है, उदाहरण के लिए, ए) स्थान का चयन, बी) भूवैज्ञानिक और भू-तकनीकी अध्ययन, सी) क्षेत्र साधनविनियोग, डी) हाइड्रोलॉजिकल अध्ययन, ई) भूकंपीय अध्ययन, एफ) असम भूमि स्थिरता विश्लेषण और जी) स्थिरता विश्लेषण मॉडल और डिजाइन चार्ट का निर्माण। दार्जिलिंग हिमालय, पूर्वी भारत में भूकंप और वर्षा से सक्रिय दो भूस्खलन स्थल, टिंधारिया ((26°51'14.55"N, 88°20'13.12"E) और पगलाझोरा ((26°52'16.55"N, 88°18'16.86"E)का चयन किया गया।

अध्ययन क्षेत्र के पार्श्वचित्र और ढांचा विकसित करने के लिए टोटल स्टेशन और डीजीपीएस के साथ स्थलाकृतिक सर्वेक्षण और उसके उपरांत भूवैज्ञानिक और भू-तकनीकी जांच करी गयी है। भूवैज्ञानिक और भू-तकनीकी अध्ययनों के संबंध में उपलब्ध रिपोर्ट और डेटा एसओआई, जीएसआई, पीडब्ल्यूडी और जेआईसीए जैसी विभिन्न एजेंसियों द्वारा भी एकत्र किया गया था।

क्षेत्र की निगरानी के साथ क्षेत्र का एक व्यापक हाइड्रोलॉजिकल अध्ययन किया गया है जिसका मुख्य उद्देश्य वर्षा की तीव्रता रचना और असम भूमि स्थिरता पर इसका प्रभाव को स्थापित करना है। 20 से अधिक वर्षों

की अवधि के लिए असआरआरजी का प्रति घंटा डेटा जिसमें 200000 से अधिक रिकॉर्ड हैं, आई एम डी से एकत्र किए गए और तीव्रता-अवधि- आवृत्ति विश्लेषण गुम्बल के चरम मूल्य वितरण का उपयोग करके किया गया है। अध्ययन क्षेत्र में लंबे मानसून और लगातार उच्च तीव्रता के तूफानों को देखते हुए, प्रभाव के कारण वर्षावन प्रभाव बल और अतिरिक्त रन्ध्र दबाव उत्पत्ति का प्रभाव का अध्ययन भी किया गया है। टिपिंग बकेट रेन गेज और वाइब्रेटिंग वायर पाईजोमीटर, लगातार बारिश और पानी के दबाव की निगरानी के लिए स्थापित किया गया था। वर्षा के प्रभाव बल को मापने के लिए एक उपकरण का डिजाइन करके गढ़ा गया है जो लगातार प्रभाव बल को रिकॉर्ड करें। भूजल स्तर में भिन्नता की माप की निगरानी डिजिटल वाटर लेवल इंडिकेटर का उपयोग करके स्टैंडपाइप में पानी का स्तर माप कर करी गई ।

भूकंपीय खतरा वक्र विकसित करने के लिए और भूकंप के तहत रन्ध्रयुक्त पानी की दबाव प्रतिक्रिया का अध्ययन भूकंपीय लोडिंग में करने के लिए डिजाइन ग्राउंड त्वरण को निर्धारित करने के लिए भूकंपीय अध्ययन किया गया है। अध्ययन के लिए अध्ययन क्षेत्र का सिस्मोटेक्टोनिक मानचित्र तैयार किया गया है जिसमें सभी भूकंपीय स्रोतों की पहचान करी गयी है। पिछले भूकंप के आंकड़ों को विभिन्न स्रोतों से एकत्र किया गया और निम्नलिखित मानक कदम का उपयोग कर एक सूची तैयार की जिसमें समरूपता, डी-क्लस्टरिंग और पूर्णता जाँच शामिल हैं। फिर डेटा का जीआर पुनरावृत्ति संबंध का उपयोग करके क्षेत्र के साथ-साथ प्रत्येक पहचाना गया स्रोत का सांख्यिकीय रूप से विश्लेषण किया गया ।

क्षीणन संबंध विकसित करने के लिए, 52 भूकम्पों और 113 निगरानी स्टेशन, नेपाल हिमालय को छोड़कर लगभग पूरे हिमालयी क्षेत्र से कुल दो सौ इक्क्यानवे (291) मजबूत गति डेटा को एकत्र किया गया है। वर्तमान अध्ययन में प्रयोज्यता की जांच करने के लिए, हिमालयी क्षेत्र के लिए उपलब्ध क्षीणन संबंधों की तुलना वर्तमान डेटा से करी गयी हालांकि, कोई भी उपयुक्त नहीं पाया गया और इसलिए इस क्षेत्र के लिए एक नया समीकरण विकसित हुआ। नए क्षीणन संबंध ,इस प्रकार विकसित और जैसा कि नीचे दिया गया है, नियतात्मक और संभाव्य के भूकंपीय खतरे का विश्लेषण करता है।

$$\log_{10}(\text{PGA}) = -2.041 + 0.344M - 0.858\log_{10}(R + e^{0.529M}) + \sigma\log\epsilon$$

चूंकि असम भूमि के लिए, भूकंप प्रेरित रन्ध्र जल दबाव के लिए कोई उपयुक्त मॉडल उपलब्ध नहीं है, असम भूमि के लिए रन्ध्र दबाव उत्पत्ति के आकलन करने के लिए एक विधि, समदैशिक और अनिसोट्रोपिक समेकित नमूनों पर चक्रीय त्रिअक्षीय और सरल कतरनी परीक्षण समेकित प्रकाशित परिणाम के आधार पर इस अध्ययन में प्रस्तावित है। इस विधि में गैर-समान यादृच्छिक भूकंप के रूपांतरण को एकसमान तनाव चक्र ( $N_{eq}$ ) में बराबर संख्या में लोड करने की आवश्यकता है। सभी 291 भूकंप इतिहास के समय के विश्लेषण के आधार पर एक समीकरण ( $M_w$ ) को ( $N_{eq}$ ) से संबंधित करने के लिए,  $N_{eq} = 0.52 \cdot 10^{0.49M_w}$  के रूप में विकसित करा गया है।

प्रतिक्रिया स्पेक्ट्रा विकसित करने के लिए विभिन्न साइट वर्गों के भूकंप के समय के इतिहास का विश्लेषण किया गया है और इसकी तुलना आईएस 1893 में (भाग I): 2016 और बीएस एन 1998-1:2004 स्पेक्ट्रा के साथ करी गयी। उच्च आवृत्तियों पर वर्णक्रमीय प्रवर्धन आईएस 1893 (भाग I): 2016 से अधिक पाया गया है, हालांकि, कम आवृत्तियों पर है बहुत कम पाया गया।

अंत में, दोनों साइटों के लिए असम भूमि स्थिरता विश्लेषण, सीमा संतुलन और विश्लेषण के संख्यात्मक तरीकों से, वर्षा और भूकंप के विभिन्न परिदृश्यों के लिए व्युत्पन्न डिज़ाइन पैरामीटर को अपनाते हुए निष्पाद किया गया है।

$$FOS = \frac{C_n + (1 - r_u^o) (1 - r_u^e - r_u^r) \tan \phi}{\tan \beta + K \cdot \sec \beta + R'_d \sin \beta}$$

विफलता क्रियाविधि की समझ पर आधारित, पूर्वी हिमालय क्षेत्र में भूकंप और वर्षा उत्प्रेरित उथले भूस्खलन के लिए, सीमा संतुलन समीकरण विकसित किया गया है।

विभिन्न भूकंपों की तीव्रता के लिए, पीजीए, ढलान कोण और आंतरिक घर्षण का कोण उपयुक्त डिज़ाइन चार्ट भी विकसित किए गए हैं।

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## List of Abbreviations

The following list defines the principal Abbreviations and their definitions as used in the thesis. Abbreviations not listed here are defined as they appear in the text.

<b>ADC</b>	Analog-to-Digital Converter
<b>ASCE</b>	American Society of Civil Engineers
<b>ASTM</b>	American Society for Testing and Materials
<b>BEM</b>	Boundary Element Method
<b>BH</b>	Borehole
<b>BS EN</b>	British Standard European Norm
<b>CAV</b>	Cumulative Absolute Velocity
<b>CCGC</b>	Central Crystalline Gneissic Complex
<b>CDF</b>	Cumulative Density Function
<b>CEUS</b>	Central and Eastern United States
<b>CSR</b>	Cyclic Stress Ratio
<b>CUVI</b>	Cumulative Visual Interpretation
<b>CVR</b>	Critical Void Ratio
<b>DBE</b>	Design Basis Earthquake
<b>DEM</b>	Digital Elevation Modelling
<b>DG</b>	Darjeeling Gneiss
<b>DHR</b>	Darjeeling Himalayan Railway
<b>DSD</b>	Drop Size Distribution
<b>DSHA</b>	Deterministic Seismic Hazard Analysis
<b>DSS</b>	Direct Simple Shear
<b>DST</b>	Department of Science and Technology
<b>ENA</b>	Eastern North America
<b>FC</b>	Fine Contents

<b>FDM</b>	Finite Difference Method
<b>FEM</b>	Finite Element Method
<b>FS/FOS</b>	Factor of Safety
<b>FTB</b>	Fold- Thrust Belt
<b>GLE</b>	General Limit Equilibrium
<b>GMPE</b>	Ground Motion Prediction Equation
<b>GSI</b>	Geological Survey of India
<b>GWT</b>	Ground Water Table
<b>IBC</b>	International Building Code
<b>IDF</b>	Intensity Duration Frequency
<b>IMD</b>	Indian Meteorological Department
<b>IPCC</b>	Intergovernmental Panel on Climate Change
<b>IS</b>	Indian Standard
<b>ISC</b>	International Seismological Centre
<b>ISR</b>	Institute of Seismological Research
<b>JICA</b>	Japan International Cooperation Agency
<b>LEM</b>	Limit Equilibrium Method
<b>MAP</b>	Mean Annual Precipitation
<b>MBT</b>	Main Boundary Thrust
<b>MCE</b>	Maximum Considered Earthquake
<b>MCT</b>	Main Central Thrust
<b>MoRTH</b>	Ministry of Road Transport and Highways
<b>MSF</b>	Magnitude Scaling Factor
<b>MSRF</b>	Munger Sahasra Ridge Fault
<b>MSRMF</b>	Munger Sahasra Ridge Marginal Fault
<b>NCEER</b>	National Center for Earthquake Engineering Research
<b>NEHRP</b>	National Earthquake Hazards Reduction Program
<b>NGA</b>	New Generation Attenuation

<b>NH</b>	National Highway
<b>NIC</b>	National Informatics Centre
<b>NICNET</b>	Nation Information Centre Network
<b>NZS</b>	New Zealand Standard
<b>OCR</b>	Over Consolidation Ratio
<b>PDF</b>	Probability Density Function
<b>PEC</b>	Pseudo Energy Capacity
<b>PESMOS</b>	Program for Excellence in Strong Motion Studies
<b>PGA/pg<sub>a</sub></b>	Peak Ground Acceleration
<b>PGV</b>	Peak Ground Velocity
<b>PLI</b>	Point Load Index
<b>PSA</b>	Peak Spectral Acceleration
<b>PSHA</b>	Probabilistic Seismic Hazard Analysis
<b>PWD</b>	Public Works Department
<b>PWP/pw<sub>p</sub></b>	Pore Water Pressure
<b>RBM</b>	River Borne Material
<b>RIF</b>	Raindrop Impact Force
<b>RMR</b>	Rock Mass Rating
<b>RQD</b>	Rock Quality Designation
<b>SA</b>	Spectral Acceleration
<b>SDA</b>	Serial Data
<b>SEI</b>	Software Engineering Institute
<b>SOI</b>	Survey of India
<b>SPT</b>	Standard Penetration Test
<b>SRR</b>	Structural Response Recorder
<b>SRRG</b>	Self Recording Rain Gauge
<b>SS</b>	Slightly weathered Sandstone
<b>SSSR</b>	Static Shear Stress Ratio

<b>SWAN</b>	State Wide Area Network
<b>SWC</b>	Soil Water Characteristics
<b>TX</b>	Triaxial
<b>UCS</b>	Unconfined Compressive Strength
<b>UHRS</b>	Uniform Hazard Response Spectra
<b>USGS</b>	United States Geological Survey
<b>USLE</b>	Universal Soil Loss Equation
<b>VWP</b>	Vibrating Wire Piezometer
<b>WB-PWD</b>	West Bengal Public Works Department

## List of Notations

The following list defines the principal symbols and their brief definition as used in the thesis. Symbols not listed here are defined as they appear in the text.

$\tau_{cyc}$	Amplitude of cyclic shear stress
$\phi$	Angle of internal friction
$A$	Area
$P_a$	Atmospheric pressure
$\tau_f$	Average shear strength at failure
$\tau_d$	Average shear stress developed along failure surface
$M_D$	Body wave magnitudes
$R_{JB}$	Closest horizontal distance to the surface projection of the fault plane from site/ Joyner-Bore distance
$K_s$	Co-efficient of permeability
$c$	Cohesion
$M_c$	Completeness magnitude
$\sigma_3$	Confining pressure
$h_c$	Critical depth
$z_w$	Depth of water table
$\delta$	Deflection
$S$	Degree of saturation
$h_w$	Depth of wetting front
$Q$	Discharge
$R$	Distance from the earthquake source to the site
$\gamma_{cyc}$	Double amplitude of cyclic shear strain
$\phi'$	Effective angle of internal friction
$c'$	Effective cohesion

$\sigma'_{oct}$	Effective consolidation stress
$P_e$	Effective cumulative precipitation
$\sigma'_{vo}$	Effective overburden pressure
$\Delta u(1)$	Excess pore water pressure after first cycle
$\Delta u(N)$	Excess pore water pressure after N cycles
$L_f$	Fault length
$S_f$	Final degree of saturation
$F$	Force
$K_T$	Frequency factor corresponding to return period T
$X$	Hypo-central distance from the source
$i$	Infiltration per unit cross-sectional area of soil
$S_o$	Initial degree of saturation
$\alpha$	Initial static shear stress ratio
$\theta_i$	Initial water content
$r_{u,lim}^e$	Limiting porewater pressure due to earthquake loading
$M_w$	Moment magnitude
$\lambda_c$	Macroscopic capillary length
$m$	Mass
$h_f$	Matric head
$E$	Modulus of elasticity
$E_d$	Deformation Modulus of elasticity (Mass)
$c_n$	Normalised effective cohesion
$W_s$	Normalised unit energy
$N_I$	Normalized rainfall intensity
$N_{50}$	Number of cycles to develop pore water pressure equal to 50% of the confining pressure
$N_{eq}$	Number of equivalent loading cycles
$N_{liq}$	Number of uniform cycles required for liquefaction of soils
$I_p$	Plasticity index

$\mu$	Poisson's ratio
$u_a$	Pore air pressure
$u_{cy}$	Pore pressure under cyclic loading
$u_w$	Pore water pressure
$r_u^o$	Static pore pressure ratio
$r_u^r$	Pore pressure ratio due to raindrop impact
$n$	Porosity
$P$	Pressure
$R_d$	Raindrop impact pressure
$T_r$	Rainfall Duration
$I_r$	Rainfall intensity
$\lambda_m$	Rate of earthquakes per year with magnitudes greater than $m$ per year
$k_c$	Ratio of consolidation stresses
$D_r$	Relative density
$r_u^e$	Pore pressure ratio due to earthquake loading
$r_d$	Rigidity factor
$K_{sat}$	Saturated permeability
$\theta_s$	Saturated water content
$V_s$	Shear-wave velocity
$\beta$	Slope angle
$M_s$	Surface wave magnitudes
$V$	Terminal velocity of raindrop
$I_{r(thr)}$	Threshold rainfall intensity
$t$	Time
$\sigma_n$	Total normal stress
$\sigma_{vo}$	Total overburden pressure
$H$	Total head
$\gamma'$	Effective unit weight

$\gamma_w$	Unit weight of water
$v$	Velocity
$\sigma'$	Vertical or the octahedral effective consolidation stress
$e$	Void ratio