

**PHYSICAL AND NUMERICAL MODELING OF
RAINFALL TRIGGERED SHALLOW LANDSLIDES IN
CENTRAL HIGHLANDS, ETHIOPIA**

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**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
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SHALLOW LANDSLIDES IN CENTRAL HIGHLANDS, ETHIOPIA**

by

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DEDICATION TO

MY FATHER, GIDDA GISSILA YAMMA, MY MOM AMARECH AKE CHOLOKA, AND
MY SPOUSE, ZEBIDER MESFIM EMIRU, WITH THANKS.

CERTIFICATE

This is to certify that the thesis entitled “PHYSICAL AND NUMERICAL MODELING OF RAINFALL TRIGGERED SHALLOW LANDSLIDES IN CENTRAL HIGHLANDS, ETHIOPIA” is being submitted by Mr. Biruk Gissila Gidday in the fulfillment for the award of the degree of Doctor of Philosophy to the Indian Institute of Technology Delhi. This is the documentation of his research work, which he completed totally under our supervision and guidance. The research report and results presented in this thesis have not been submitted to any university or institute for the award of any degree or diploma, in part or whole.



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ABSTRACT

Rainfall-triggered Landslides are the most common natural hazard with serious consequences all over the world, including in Ethiopia. Most available methods for predicting rainfall-induced slope instability rely on regional statistical and probabilistic data derived from previous slope failures and rainfall records using GIS tools. Such approaches ignore the underlying effects of many controlling factors, such as variations in rainfall intensity and patterns, as well as geotechnical properties, resulting in subjective and debatable results. Using a physically based model that accounts for hydrogeological and geotechnical parameters to capture the failure mechanism was uncommon, particularly in the Central Highlands of Ethiopia.

The current study developed a numerical model for typical slopes in the region (Adaberga and Jeldu) based on field investigations, geotechnical characterizations, and flume model studies. The unsaturated and saturated soil property models were determined, and the rainfall intensity-duration (ID) threshold was obtained for the use of early warning systems in the region and neighborhood regions of similar characteristics.

In this thesis, a total of eighteen flume experiments were carried out to capture the failure phenomenon and to validate the numerical simulations. The results of the numerical simulation of seepage and slope stability of unsaturated finite slopes (at 25° to 43°) subjected to infiltration (TRIGRS, SEEP/W, and SLOPE/W) are validated with laboratory flume tests on sandy silt soil at identical field density and different rainfall intensities (14 to 47 mm/hr). Empirical correlations are developed based on different combinations of rainfall intensity, slope angles, and a factor of safety from the TRIGRS modeling. Since this soil was derived from a carbonate parent source, the HYDRUS was also used to model solute transport processes such as cation exchange, dissolution, percolation, and precipitation. Analyses were carried out to account for solute transport and the subsequent effects, particularly hydraulic conductivity, which has a significant influence on the rate and magnitude of wetting front advancement into a slope.

XRD and SEM studies were conducted for quantification and the identification of the mineral composition and estimating porosity, respectively.

The rainfall intensity duration thresholds that would cause a landslide (ID plot) are measured in the field and simulated under a controlled environment in the laboratory. The obtained ID plots are used in the numerical simulation with an identical pattern as that of flume experiments. *ImageJ* software was used to observe wetting front advancement based on tracer (potassium permanganate)

movements and sidewall (Flume wall) photo images captured at regular intervals of 10-seconds. Since shallow slope failures account for most occurrences in the regions, only shallow failure mechanisms were considered throughout this thesis.

The GIS framework was utilized to organize, generate, and execute geoprocessing models, and provide interfaces to other ArcGIS components and non-GIS packages dealing with geodata management and visualization.

The flume testing observations revealed that regardless of surface erosion, the failure initiated at the toe of the slope, subsequently extended upslope, displaying columnar failure, and gradually triggered retrogressive shallow slides. From the series of experiments, it was concluded that hydrogeological parameters such as rainfall intensity and slope geometry have a significant influence on the mechanism of slope failure.

The solute transport analysis indicated that concentration increased with depth and time and reached its maximum concentration at nearly about 9 cm below the slope surface. The film layer thickness was determined to be about 3 cm, wherein the peak concentration occurred, and suction was negligible.

The SEEP/W and SLOPE/W analysis revealed that pore pressure development alone is not always responsible for triggering the slope failure, but the loss of suction in the capillary vadose zone can also trigger a shallow landslide.

TRIGRS results after reprocessing were used to map landslide hazard zonation (LHZ). The results of the factor of safety map are validated using ROC/AUC, demonstrating that the model adequately captures the occurrence in terms of both temporal and spatial distribution. The parametric study results using TRIGRS, SEEP/W, and SLOPE/W show that changes in rainfall intensity and hydraulic conductivity have a considerable influence on the factor of safety.

इथियोपिया सहित पूरी दुनिया में वर्षा-प्रेरित भूस्खलन सबसे आम प्राकृतिक खतरा है जिसके गंभीर परिणाम होते हैं। वर्षा-प्रेरित ढलान अस्थिरता की भविष्यवाणी करने के लिए अधिकांश उपलब्ध तरीके जीआईएस उपकरणों का उपयोग करके पिछले ढलान विफलताओं और वर्षा रिकॉर्ड से प्राप्त क्षेत्रीय सांख्यिकीय और संभाव्य डेटा पर निर्भर करते हैं। इस तरह के दृष्टिकोण कई नियंत्रित कारकों के अंतर्निहित प्रभावों की उपेक्षा करते हैं, जैसे वर्षा की तीव्रता और पैटर्न में भिन्नता, साथ ही साथ भू-तकनीकी गुण, जिसके परिणामस्वरूप व्यक्तिपरक और बहस योग्य परिणाम होते हैं। शारीरिक रूप से आधारित मॉडल का उपयोग करना जो विफलता तंत्र को पकड़ने के लिए हाइड्रोजियोलॉजिकल और भू-तकनीकी पैरामीटरों के लिए खाता है, विशेष रूप से इथियोपिया के केंद्रीय हाइलैंड्स में असामान्य था।

वर्तमान अध्ययन ने क्षेत्र की जांच, भू-तकनीकी लक्षण वर्णन और प्लूम मॉडल अध्ययन के आधार पर क्षेत्र (एडाबरगा और जेल्डु) में विशिष्ट ढलानों के लिए एक संख्यात्मक मॉडल विकसित किया। असंतृप्त और संतृप्त मिट्टी की संपत्ति के मॉडल निर्धारित किए गए थे, और समान विशेषताओं वाले क्षेत्र और पड़ोस के क्षेत्रों में प्रारंभिक चेतावनी प्रणाली के उपयोग के लिए वर्षा की तीव्रता-अवधि (आईडी) सीमा प्राप्त की गई थी।

इस थीसिस में, विफलता की घटना को पकड़ने और संख्यात्मक सिमुलेशन को मान्य करने के लिए कुल अठारह प्लूम प्रयोग किए गए थे। घुसपैठ (TRIGRS, SEEP/W, और SLOPE/W) के अधीन असंतृप्त परिमित ढलानों (25° से 43° पर) के टपका और ढलान स्थिरता के संख्यात्मक सिमुलेशन के परिणाम समान स्तर पर रेतीली गाद मिट्टी पर प्रयोगशाला के प्रवाह परीक्षणों के साथ मान्य हैं। क्षेत्र घनत्व और विभिन्न वर्षा तीव्रता (14 से 47 मिमी/घंटा)। वर्षा की तीव्रता, ढलान कोण और TRIGRS मॉडलिंग से सुरक्षा के एक कारक के विभिन्न संयोजनों के आधार पर अनुभवजन्य सहसंबंध विकसित किए गए हैं। चूंकि यह मिट्टी एक कार्बोनेट मूल स्रोत से प्राप्त की गई थी, इसलिए हाइड्रस का उपयोग विलेय परिवहन प्रक्रियाओं जैसे कि राशन विनिमय, विघटन, छिद्रण और वर्षा के मॉडल के लिए भी किया गया था। विलेय परिवहन और उसके बाद के प्रभावों, विशेष रूप से हाइड्रोलिक चालकता के लिए विश्लेषण किया गया, जिसका ढलान में सामने की ओर बढ़ने की दर और परिमाण पर महत्वपूर्ण प्रभाव पड़ता है।

XRD और SEM अध्ययन क्रमशः परिमाणीकरण और खनिज संरचना की पहचान और सरंध्रता का आकलन करने के लिए आयोजित किए गए थे।

बारिश की तीव्रता की अवधि की सीमाएं जो भूस्खलन (आईडी प्लॉट) का कारण बनती हैं, उन्हें क्षेत्र में मापा जाता है और प्रयोगशाला में नियंत्रित वातावरण के तहत अनुकरण किया जाता है। प्राप्त आईडी भूखंडों का

उपयोग संख्यात्मक सिमुलेशन में फ्लूम प्रयोगों के समान पैटर्न के साथ किया जाता है। ImageJ सॉफ्टवेयर का उपयोग ट्रेसर (पोटेशियम परमैंगनेट) आंदोलनों और 10-सेकंड के नियमित अंतराल पर कैप्चर की गई साइडवॉल (फ्लूम वॉल) फोटो छवियों के आधार पर गीलापन की उन्नति का निरीक्षण करने के लिए किया गया था। चूंकि उथली ढलान विफलताएँ क्षेत्रों में अधिकांश घटनाओं के लिए जिम्मेदार होती हैं, इस थीसिस में केवल उथली विफलता तंत्र पर विचार किया गया था।

जीआईएस ढांचे का उपयोग जियोप्रोसेसिंग मॉडल को व्यवस्थित करने, उत्पन्न करने और निष्पादित करने के लिए किया गया था, और अन्य आर्कजीआईएस घटकों और जियोडाटा प्रबंधन और विजुअलाइज़ेशन से निपटने वाले गैर-जीआईएस पैकेजों के लिए इंटरफेस प्रदान किया गया था।

फ्लूम परीक्षण टिप्पणियों से पता चला है कि सतह के कटाव की परवाह किए बिना, ढलान के पैर की अंगुली पर शुरू की गई विफलता, बाद में विस्तारित उत्थान, स्तंभ की विफलता को प्रदर्शित करती है, और धीरे-धीरे प्रतिगामी उथली स्लाइडों को ट्रिगर करती है। प्रयोगों की श्रृंखला से, यह निष्कर्ष निकाला गया था कि हाइड्रोजियोलॉजिकल पैरामीटर जैसे कि वर्षा की तीव्रता और ढलान ज्यामिति का ढलान विफलता के तंत्र पर महत्वपूर्ण प्रभाव पड़ता है।

विलेय परिवहन विश्लेषण ने संकेत दिया कि गहराई और समय के साथ एकाग्रता में वृद्धि हुई और ढलान की सतह से लगभग 9 सेमी नीचे इसकी अधिकतम सांद्रता तक पहुंच गई। फिल्म की परत की मोटाई लगभग 3 सेमी निर्धारित की गई थी, जिसमें चोटी की सघनता थी, और चूषण नगण्य था।

SEEP/W और SLOPE/W विश्लेषण से पता चला है कि ढलान की विफलता को ट्रिगर करने के लिए अकेले ताकना दबाव विकास हमेशा जिम्मेदार नहीं होता है, लेकिन केशिका वैडोज़ ज़ोन में सक्शन का नुकसान भी उथले भूस्खलन को ट्रिगर कर सकता है।

पुनर्प्रसंस्करण के बाद TRIGRS परिणाम भूस्खलन खतरा क्षेत्र (LHZ) को मैप करने के लिए उपयोग किए गए थे। सुरक्षा मानचित्र के कारक के परिणाम आरओसी/एयूसी का उपयोग करके मान्य किए जाते हैं, यह प्रदर्शित करते हुए कि मॉडल अस्थायी और स्थानिक वितरण दोनों के संदर्भ में घटना को पर्याप्त रूप से पकड़ लेता है। TRIGRS, SEEP/W, और SLOPE/W का उपयोग करते हुए पैरामीट्रिक अध्ययन के परिणाम बताते हैं कि वर्षा की तीव्रता और हाइड्रोलिक चालकता में परिवर्तन का सुरक्षा के कारक पर काफी प्रभाव पड़ता है।

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LIST OF NOTATIONS AND ABBREVIATIONS

AEV	Air Entry Value
AMCSD.....	American Mineralogist Crystal Structure Database
AUC	Area Under Curve
DEM	Digital Elevation Model
EM-DAT	Emergency Events Database
ESRI	Environmental Systems Research Institute
FAO	Food and Agriculture Organization
FEM	Finite Element Method
FRV	Frequency Ratio Values
FS	Factor of Safety
GIS	Geographic Information System
HCF	Hydraulic Conductivity Function
I-D	Intensity-Duration threshold
Ks.....	Saturated permeability
LEM	Limit Equilibrium Method
LHZ	Landslide Hazard Zonation
MC	Mohr Columb
NSNR	Non-Seismic Non-Rainfall
PFMT.....	Preliminary Flume Model Test
PSD	Particle Size Distribution
PTF	Pedo Transfer Function
PWT_C.....	Pore Water Pressure Channel
RETC.....	Retention curve
REV	Representative Elementary Volume
RFC.....	Rainfall combinations
ROC	Receiver Operating Characteristic
S12	Series 12
SEM	Scanning Electron Microscopy
SS	Suction Sensor
SWCC	Soil Water Characteristic Curve
VWC	Volumetric Water Content

XRD	X-ray diffractometry
α_s	Slope angle
θ	volumetric water content function
$u_a - u_w$	Suction Stress
$\sigma_n - u_a$	Net Normal stress
Δp	Change in pore water pressure