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降雨诱发滑坡：稳定分析和概率评价（英文版）

Rainfall-Induced Soil Slope Failure Stability Analysis and Probabilistic Assessment

张璐璐 李锦辉 李 旭 张 洁 朱 虹 著

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内容提要

本书是作者团队十余年来就降雨滑坡问题的科研成果总结、凝练和提升。全书采用英文撰著,主要包括:降雨入渗土坡理论和稳定性评价方法、非饱和土渗流变形耦合理论、基于渗流变形耦合的边坡可靠度分析、裂隙土坡和碎石土坡的降雨入渗和稳定性分析、基于随机场的非均质土坡风险评价、预测模型的概率校准等。

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出版说明

科学技术是第一生产力。21 世纪，科学技术和生产力必将发生新的革命性突破。

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Preface

Rainfall-induced landslides pose a significant threat to the public safety in many parts of the world especially in tropical or subtropical mountainous areas. The research field of rainfall-induced landslides has been developed tremendously during the past 20 years attributed to the advancement of unsaturated soil mechanics. Yet a great number of uncertainties are involved in the analysis of slope stability under rainfall condition. Measured soil properties are subject to inherent spatial variability, measurement error, and statistical error because of a limited number of samples. The predicted performance of a slope from a geotechnical model may deviate from reality because of uncertainties of input parameters and systematic error associated with the prediction model. Using probabilistic approaches, different types of uncertainties can be accounted for in a systematic and quantitative way. The information from various sources can be utilized systematically.

The aim of this book is thus to bring together the perspectives of both geomechanics and reliability to reflect the complicated mechanism and the tremendous uncertainties under-lying the problem of rainfall-induced slope failure. The book clearly presents infiltration analysis and stability analysis methods based on geomechanics approaches. The methods of geotechnical reliability and probability which can be used to address the related uncertainties are also presented. This book is an essential reading for researchers and graduate students who are inter-ested in slope stability, landslides, geohazards, and risk assessment in fields of civil engineering, engineering geology, and earth science. Professional engineers and practitioners in slope engineering and geohazard management can use it as a supplementary reading material. Knowledge of undergraduate soil mechanics, statistics, and probability is a prerequisite for the readers.

This book consists of nine chapters and can be divided into two parts. In the first part (Chapters 2 through 6), we focus on the failure mechanisms of rainfall-induced slope failure. Chapter 2 presents commonly used conceptual models and analytical solutions of rainfall infiltration into the ground and discusses important issues related to the numerical modeling. Chapters 3 and 4 present the stability analysis methods based on limit equilibrium methods and coupled hydromechanical models, respectively. Chapters 5 and 6 focus on the infiltration and stability of natural soil slopes with cracks and colluvium materials, respectively. In the second part of the book (Chapters 7 through 9), the reliability methods and probabilistic approaches are presented. In Chapter 7, the effect of uncertainties of essential soil properties related to the stability of unsaturated soil slopes is characterized. In Chapter 8, the effect of spatial variability of soil properties on an unsaturated soil slope is discussed. Finally, probabilistic model calibration for infiltration and slope stability is presented in Chapter 9.

This book also presents major outcomes of the research conducted by the authors in the past 10 years. We express our highest gratitude to the late Professor Wilson H. Tang (Department of Civil and Environmental Engineering, Hong Kong University of Science & Technology). The authors are grateful to Professor Limin Zhang (Department of Civil and Environmental Engineering, The Hong Kong University of Science & Technology) for his support and help during all these years. We are also grateful to Prof. D. G. Fredlund (Professor Emeritus at the University of Saskatchewan and geotechnical engineering special-ist at Golder Associates) for his great help in our research study.

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Foreword

Several excellent books cover a wide spectrum of unsaturated soil mechanics and its applications to slope engineering, such as "*Unsaturated Soil Mechanics in Engineering Practice*" by Delwyn Fredlund, Harianto Rahardjo and Murray Fredlund published by Wiley and "*Hillslope Hydrology and Stability*" by Ning Lu and Jonathan Godt published by Cambridge University Press. The new book "*Rainfall Induced Soil Slope Failure: Stability Analysis and Probabilistic Assessment*" by Lulu Zhang, Jinhui Li, Xu Li, Jie Zhang and Hong Zhu is a new addition which focuses on rain-induced slope failures from a soil mechanics approach. The authors of the book are all very active young researchers in the field of study.

The new book concisely presents the fundamental mechanics behind rain-induced soil slope failures: infiltration and evapotranspiration in soil slopes, slope stability under rainfall infiltration, and hydro-mechanical coupled deformation. The concepts and analyses are presented clearly from the first principle with a strong physical sense. Some advanced topics, such as plastic analysis of hydro-mechanical coupled seepage and deformation in unsaturated soil slopes, are approached in a plain manner with hand-on tutorials, which is ideal for graduate students. The analysis of the stability of slopes with cracks is an excellent addition—practitioners are aware of the vital importance of cracks but few have the knowhow to quantify cracks on slopes and their effects on slope stability. The book overall provides the fundamental knowledge to deal with climate-slope interactions and resulting slope failures.

The new book also systematically presents the uncertainties involved in the characterization and analysis of rain-induced slope failures. Methods for reliability analysis of slopes under rainfall, including probability concepts, identification of sources of uncertainty, stochastic finite element method and probabilistic model calibration, are introduced. This is a unique feature of the book—it is perhaps the only book that addresses both the mechanics and uncertainties behind rain-induced slope failures.

I believe that *Rainfall Induced Soil Slope Failure: Stability Analysis and*

Probabilistic Assessment will serve as an excellent reference for educators, university graduate students, researchers and practitioners.

Limin Zhang
Professor
Department of Civil and Environmental Engineering
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25 January 2016

List of symbols

B	Variance between the mean values of Markov chains
b_x, b_y, b_z	Body forces in the x-, y-, and z-directions
C	Specific storage capacity of unsaturated soil
C_X	Covariance matrix of X
C_v	Coefficient of consolidation
$C(\ )$	Covariance/autocovariance function
COV	Coefficient of variation
c'	Effective cohesion of a saturated soil
D	Depth of slip surface
$D_{\max}$	Kolmogorov-Smirnov ($K-S$) D statistic
D_w	Depth of the ground water table
$\boldsymbol{D}^{ep}$	Elastoplastic stress-strain matrix
d	Distance from the origin to the limit state surface line in standardized random field space
d	Number of observed data points
df	Degrees of freedom of Student's t distribution
E	Interslice normal force
E	Young's modulus
$E[.]$	Expectation operator
e	Void ratio
F_s	Factor of safety
$F(X)$	Culmulative density function (CDF) of X
$f(\theta)$	Prior density function of θ
$f(\theta \mid \cdot)$	Posterior density function of θ
$f_X()$	Joint probability density function of the random variable vector X
G	Shear modulus
G_s	Specific gravity of soil particle
g	Gravitational acceleration
$g()$	Prediction model

$g(X)$	Performance function
$g'(X)$	Response surface function to approximate the performance function $g(X)$
H	Total head or hydraulic head
H	Slope height
H_B	Elastic modulus for soil structure with respect to pore-water pressure in Biot (1941) coupled formulation
H'_B	Coefficient of pore-water content change due to normal stresses in Biot (1941) coupled formulation
H_F	Elastic modulus for soil structure with respect to a change in matric suction in Fredlund and Rahardjo (1993) coupled formulation
H_m	Elevation difference between the starting point and the lowest point of deposition of the mass movement
$\boldsymbol{h}$	Vector of nodal pressure heads
h	Pore pressure head
h_s	Suction head
I	Cumulative infiltration
I	Rainfall intensity in I–D threshold curve equation
$\boldsymbol{I}$	Unit matrix
I_p	Cumulative infiltration at the moment of ponding
I_p	Plasticity index
I_s	Cumulative infiltration on a sloping ground
$I(x)$	Indicator function of the Monte Carlo simulation
i	Infiltration rate or capacity
$J(\cdot\|\cdot)$	Jumping distribution or transition kernel of the Markov chain
$\boldsymbol{k}$	Tensor of coefficient of permeability
k	Coefficient of permeability
k	Normalization constant for the posterior density function in Bayesian theory
k_s	Saturated coefficient of permeability
k_w	Coefficient of permeability in the wetted zone of the Green-Ampt model
L	Total depth of a soil
$\boldsymbol{L}$	Lower triangular decomposed matrix of the covariance matrix ($\boldsymbol{LL}^T = \boldsymbol{C}$)
$L(\cdot\|\cdot)$	Likelihood function
L_c	Length of the aperture
L_m	Horizontal distance between the starting point and lowest point of deposition of the mass movement

M	Slope of the critical state line
M	Number of Markov chains
M_{col}	Slope of collapse surface
m_1^s	Coefficient of volume change of soil skeleton with respect to a change in $(\sigma_{mean} - u_a)$ in Fredlund and Rahardjo (1993) coupled formulation
m_2^s	Coefficient of volume change of soil skeleton with respect to a change in $(u_a - u_w)$ in Fredlund and Rahardjo (1993) coupled formulation
m_1^w	Coefficient of volume change of pore water with respect to a change in $(\sigma_{mean} - u_a)$ in Fredlund and Rahardjo (1993) coupled formulation
m_2^w	Coefficient of volume change of pore water with respect to a change in $(u_a - u_w)$ in Fredlund and Rahardjo (1993) coupled formulation
N	Normal force on the base of the slice
N_{chain}	Length or number of samples of a Markov chain
N	Intercept of normal consolidation line in the v-$\overline{p}$ plane
n	Porosity of the soil
n	Number of segments along the slip surface
n	Dimension of the input model parameter vector θ
n_c	Crack porosity
P_{clay}	Percentage of clay
P_{sand}	Percentage of sand
p	Mean total stress
p_f	Probability of failure
$\hat{p}_f$	Estimation of the probability of failure p_f
p'	Mean effective stress
p_{at}	Atmospheric pressure
p'_{cs}	Mean effective stress at the critical state
p^c	Reference stress
p_s	Intercept of the ellipse of yield surface at the $\overline{p}$ axis at suction s
$\overline{p}$	Mean net stress
$\overline{p}_0$	Preconsolidation stress
Q	Load
q	Rainfall intensity
q	Deviator stress
R	Radius or the moment arm of a circular slip surface
R	Resistance

R_B	Coefficient of pore-water content change due to pore-water pressure in Biot (1941) coupled formulation
R_{stat}	Gelman-Rubin convergence diagnostic
S	Degree of saturation
$S(.)$	Spectral density function of a random field
S_e	Effective degree of saturation
S_m	Mobilized shear force at the base of a slice
S_r	Residual degree of saturation
s	Scale of the inverse chi-square distribution
s_f	Suction head at the wetting front of the Green-Ampt model
$s(x)$	Sampling function of the importance sampling method
$\boldsymbol{T}$	Diagonal and upper matrix of triangular Cholesky decomposition of the covariance matrix
T_s	Surface tension of water
t	Time
t_{debris}	Thickness of debris
t_p	Time of ponding
U	Random number from a uniform distribution
u	Displacement components along the x-direction
u_a	Pore-air pressure
u_w	Pore-water pressure
$(u_a - u_w)$	Matric suction
V	Vulnerability
V_m	Volume of the sliding mass
v	Vector of flow rate
v	Displacement components along the y-direction
v	Specific volume of a soil
var[.]	Variance operator
W	Total weight of the slice
W	Average of the within-chain variances of Markov chains
W^{ep}	Elastoplastic suction-strain matrix
w	Displacement components along the z-direction
w_w	Gravimetric water content
$w(x)$	Weighting function of the importance sampling method
X	Interslice shear forces
X	Random variable
X	Vector of random variables
x	Location coordinates vector or the vector of a spatial variable
x^*	Design point in the original random variable space
Y	Vector of model output

$\hat{Y}$	Vector of observed response
Y_i	Standardized (dimensionless/reduced) random variable of the random variable X_i
y^*	Design point in the standardized random variable space
Z	Correlated standard normal random field
z	Elevation head; coordinate of elevation; vertical coordinate
z_w	Depth of wetting front
α_B	Coefficient measures the ratio of the water volume squeezed out to the volume change of the soil in Biot (1941) coupled formulation
α_c	Biot's hydromechanical coupling coefficient
α_c	Angle of contact between water and soil particle
α_s	Slope angle
α_{slice}	Angle between the tangent to the base of slice and the horizontal direction
β	Reliability index
β_w	Compressibility of water
Γ	Intercept of the critical state line in the $v - \ln p'$ plane
$\Gamma^2(.)$	Variance reduction factor function
γ_t	Total unit weight of the soil
γ_w	Unit weight of water
$\gamma(.)$	Semivariogram
γ_{xy}, γ_{yx}, γ_{yz}, γ_{zy}, γ_{xz}, γ_{zx}	Components of the shear strain tensor
δ	Scale of fluctuation
δ	Coefficient of variation
ε	Strain tensor
ε	Vector of residual errors
ε_v	Volumetric strain
ε_x, ε_y, ε_z	Normal strain components along the x-, y-and z-directions
κ	Unloading stiffness parameter due to net stress loading
κ_s	Swelling stiffness parameter due to suction unloading
λ	Slope of the critical state line in the $v - \ln p'$ plane
μ	Mean value
μ_X	Mean value vector of X
Θ_d	Dimensionless water content
θ	Vector of random input model parameters
θ_r	Residual volumetric water content
θ_s	Saturated volumetric water content
θ_w	Volumetric water content
σ	Total stress tensor

σ	Total stress
σ	Standard deviation
$(\sigma - u_a)$	Net normal stress
σ_{mean}	Mean total normal stress
$\sigma_{\mathrm{mean}} - u_a$	Mean net normal stress
σ_n	Total normal stress on the slip surface
$\sigma_n - u_a$	Net normal stress on the slip surface
σ_x	Standard variation of the variable x
σ_x, σ_y, σ_z	Normal stresses in the x-, y-, and z-directions
σ'	Effective stress
σ^s	Suction stress
τ	Lag or separation distance between two spatial locations
τ_{f}	Shear strength
τ_{n}	Mobilized shear stress parallel to the segment
τ_{xy}, τ_{xz}, τ_{yx}, τ_{yz}, τ_{zx}, τ_{zy}	Components of the shear stress tensor
ν	Poisson's ratio
π	Osmotic suction
ρ	Correlation coefficient
ρ_w	Density of water
ρ_X	Correlation matrix of X
Φ	Matric flux potential
Φ_s	Steady-state matric flux potential
$\Phi(\cdot)$	Cumulative distribution function (CDF) of the standard normal distribution.
ϕ'	Effective friction angle of a soil
ϕ^b	An angle indicating the rate of increase in shear strength related to matric suction
ϕ'_{col}	Friction angle of the collapse surface
ϕ'_{cs}	Friction angle of the critical state line
$\phi()$	Probability density function(PDF) of the standard normal distribution $N(0, 1)$
χ	The parameter with the value between zero and unity in Bishop's effect stress for unsaturated soils
ψ	Soil suction
ψ_{aev}	Air-entry value (AEV) of the soil
ψ_{r}	Residual suction
ω	Angular frequency
∇^2	Laplace operator or Laplacian

Contents