MODELLING THE EFFECTS OF SOIL VARIABILITY AND VEGETATION ON THE STABILITY OF NATURAL SLOPES

by

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ABSTRACT

It is well recognised that the inherent soil variability and the effect of vegetation, in particular the effect of tree root reinforcement, have a significant effect on the stability of a natural slope. However, in practice, these factors are not commonly considered in routine slope stability analysis. This is due mainly to the fact that the effects of soil variability and vegetation are complex and difficult to quantify. Furthermore, the available slope stability analysis computer programs used in practice, which adopt conventional limit equilibrium methods, are unable to consider these factors. To predict the stability of a natural slope more accurately, especially the marginally stable one, the effects of soil variability and vegetation needs to be taken into account.

The research presented in this thesis focuses on investigating and quantifying the effects of soil variability and vegetation on the stability of natural slopes. The random finite element method (RFEM), developed by Griffiths and Fenton (2004), is adopted to model the effect of soil variability on slope stability. The soil variability is quantified by the parameters called the *coefficient of variation* (COV) and *scale of fluctuation* (SOF), while the safety of a slope is assessed using *probability of failure*.

In this research, extensive parametric studies are conducted, using the RFEM, to investigate the influence of COV and SOF on the probability of failure of a cohesive slope (i.e. undrained clay slope) with different geometries. Probabilistic stability charts are then developed using the results obtained from the parametric studies. These charts can be used for a preliminary assessment of the probability of failure of a spatially random cohesive slope. In addition, the effect of soil variability on $c'-\phi'$ slopes is also studied. The available RFEM computer program (i.e. *rslope2d*) is limited to analysing slopes with single-layered soil profile. Therefore, in this research, this computer program is modified to analyse slopes with two-layered soil profiles. The modified program is then used to investigate the effect of soil variability on two-layered spatially random cohesive slopes. It has been demonstrated that the spatial variability of soil variability has a significant effect on the reliability of both single and two-layered soil slopes.

Artificial neural networks (ANNs), which are a powerful data-mapping tool for determining the relationship between a set of input and output variables, are used in an attempt to predict the probability of failure of a spatially random cohesive slope. The aim is to provide an alternative tool to the RFEM and the developed probabilistic stability charts because the RFEM analyses are computationally intensive and time consuming. The results obtained from the parametric studies of a spatially random cohesive slope are used as the database for the ANN model development. It has been demonstrated that the ANN models developed in this research are capable of predicting the probability of failure of a spatially random cohesive slope with high accuracy. The developed ANN models are then transformed into relatively simple formulae for direct application in practice.

The effect of root reinforcement caused by vegetation is modelled as additional cohesion to the soils, known as *root cohesion*, c_r. The areas affected by tree roots (i.e. root zone) are incorporated in the finite element slope stability model. The extent of the root zone is defined by the *depth of root zone*, h_r. Parametric studies are conducted and the results are used to develop a set of stability charts that can be used to assess the contribution of root reinforcement on slope stability. Furthermore, ANN models and formulae are also developed based on the results obtained from the parametric studies. It has been demonstrated that the factor of safety of a slope increase linearly with the values c_r and h_r, and the contribution of root reinforcement to a marginally stable slope is significant. In addition, probabilistic slope stability analysis considering both the variability of the soils and root cohesion are conducted using the modified RFEM computer program. It has been demonstrated that the spatial variability of root cohesion has a significant effect on the probability of slope failure.

LIST OF PUBLICATIONS

The following publications have been prepared as a result of this research:

Chok, Y. H., Jaksa, M. B. and Griffiths, D. V., Fenton, G.A., and Kaggwa, W. S. (2007). "A parametric study on reliability of spatially random cohesive slopes." *Australian Geomechanics*, 42(2), 79-85.

Chok, Y. H., Jaksa, M. B. and Griffiths, D. V., Fenton, G.A., and Kaggwa, W. S. (2007). "Effect of spatial variability on reliability of soil slopes." *Proc. 10th Australia New Zealand Conference on Geomechanics*, Brisbane, 2, 584-589.

Chok, Y. H., Kaggwa, W. S., Jaksa, M. B. and Griffiths, D. V. (2004). "Modelling the effects of vegetation on stability of slopes." *Proc. 9th Australia New Zealand Conference on Geomechanics*, Auckland, 1, 391-397.

STATEMENT OF ORIGINALITY

This thesis contains no material which has been accepted for the award of any other degree or diploma at any university or other tertiary institution and, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference has been made in the text.

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NOTATION

A	total cross-sectional area of the soil
A_r	total cross-sectional area occupied by roots
ANNs	artificial neural networks
a_i	mean cross-sectional area of roots in size class i
$C_{y_j d_j}$	covariance between the model output (y_j) and the desired output (d_j)
COV	coefficient of variation
$\mathrm{Cov}[\ldots]$	covariance operator
c	cohesion
c'	drained or effective cohesion
c_0	autocovariance at lage 0
c_k	autocovariance
c_r	root cohesion
c_{Total}	total cohesion
c_u	undrained cohesion
D	depth factor of a slope
d	root diameter
$\bar{d}$	mean of desired output (d_j)
d_j	desired actual output of node j
E	global error function
E_s	Young's modulus
$\mathrm{E}[\cdots]$	expectation operator
F_s	factor of safety
FEM	finite element method
FOS	factor of safety
FOSM	first order second moment method

$f(I_j)$	transfer function of node j
$f(x)$	continuous function of x
$G(x)$	standard normal random field
H	height of slope
h_r	depth of root zone
I	number of input variables
k	lag distance
k_0	autocorrelation distance
L_{min}	minimum root length
LAS	local average subdivision
MAE	mean absolute error
MLPs	multi-layer perceptrons
MCS	Monte Carlo simulation
MSE	mean squared error
Median_X	median of variable X
Mode_X	mode of variable X
N_s	stability coefficient
n	number of data points
n_f	number of realisation reaching failure
n_{sim}	number of realisations
P_f	probability of failure
PEM	point estimation method
PDF	probability density function
RAR	root area ratio
RFEM	random finite element method
RMSE	root mean squared error
r	coefficient of correlation
S_w	surcharge due to weight of vegetation
SOF	scale of fluctuation
s	soil shear strength
s_u	undrained shear strength
T	averaging domain

T_r	mean tensile strength of roots
t_i	deterministic trend component
u	pore water pressure
u_a	pore air pressure
$\mathrm{Var}[\ldots]$	variance operator
W	total weight of slice
w_{ji}	connection weight between nodes i and j
X	random variable
$\overline{X}$	average value of variable X
x	input variables
x_i	input from node i
x_{max}	maximum value of input variable x
x_{min}	minimum value of input variable x
x_n	scaled value of input variable x
Y	random variable
$\overline{Y}$	average value of variable Y
$\bar{y}$	average value of variable y
y_j	predicted output of node j
α	shear distortion angle
β	slope angle
Γ^2	variance function
γ	bulk unit weight
Δw_{ji}	weight increment from node i to node j
ε_i	residual component
η	learning rate
θ	scale of fluctuation
θ_j	bias for node j
μ	mean value
μ_X	mean value of variable X
μ_Y	mean value of variable Y
$\mu_{\ln X}$	mean of the normally distributed ln(X)

ν	Poisson's ratio
ρ	correlation coefficient
ρ_k	autocorrelation coefficient
ρ_{XY}	coefficient of correlation of variables *X* and *Y*
σ	standard deviation
σ^2	point variance
σ_n	normal stress
σ_T^2	variance of the soil property spatially averaged over an averaging domain T
σ_X	standard deviation of variable *X*
σ_Y	standard deviation of variable *Y*
σ_{d_j}	standard deviation of desired output d_j
σ_{y_j}	standard deviation of model output y_j
$\sigma_{\ln X}$	standard deviation of the normally distributed ln(*X*)
τ_b	limiting bond stress between the root and the soil
ϕ	friction angle
ϕ^b	friction angle of the soil with respect to changes in matric suction
ϕ'	drained or effective friction angle
ψ	dilation angle