

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

by

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## ABSTRACT

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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

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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

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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

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$A$	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
$\text{Cov}[\dots]$	covariance operator
$c$	cohesion
$c'$	drained or effective cohesion
$c_0$	autocovariance at lag 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
$E[\dots]$	expectation operator
$F_s$	factor of safety
FEM	finite element method
FOS	factor of safety
FOSM	first order second moment method

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$f(I_j)$	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 <sub><math>x</math></sub>	median of variable $X$
Mode <sub><math>x</math></sub>	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

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$T_r$	mean tensile strength of roots
$t_i$	deterministic trend component
$u$	pore water pressure
$u_a$	pore air pressure
$\text{Var}[\dots]$	variance operator
$W$	total weight of slice
$w_{ji}$	connection weight between nodes $i$ and $j$
$X$	random variable
$\bar{X}$	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
$\bar{Y}$	average value of variable $Y$
$\bar{y}$	average value of variable $y$
$y_j$	predicted output of node $j$
$\alpha$	shear distortion angle
$\beta$	slope angle
$\Gamma^2$	variance function
$\gamma$	bulk unit weight
$\Delta w_{ji}$	weight increment from node $i$ to node $j$
$\varepsilon_i$	residual component
$\eta$	learning rate
$\theta$	scale of fluctuation
$\theta_j$	bias for node $j$
$\mu$	mean value
$\mu_X$	mean value of variable $X$
$\mu_Y$	mean value of variable $Y$
$\mu_{\ln X}$	mean of the normally distributed $\ln(X)$

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$\nu$	Poisson's ratio
$\rho$	correlation coefficient
$\rho_k$	autocorrelation coefficient
$\rho_{XY}$	coefficient of correlation of variables $X$ and $Y$
$\sigma$	standard deviation
$\sigma^2$	point variance
$\sigma_n$	normal stress
$\sigma_T^2$	variance of the soil property spatially averaged over an averaging domain $T$
$\sigma_X$	standard deviation of variable $X$
$\sigma_Y$	standard deviation of variable $Y$
$\sigma_{d_j}$	standard deviation of desired output $d_j$
$\sigma_{y_j}$	standard deviation of model output $y_j$
$\sigma_{\ln X}$	standard deviation of the normally distributed $\ln(X)$
$\tau_b$	limiting bond stress between the root and the soil
$\phi$	friction angle
$\phi^b$	friction angle of the soil with respect to changes in matric suction
$\phi'$	drained or effective friction angle
$\psi$	dilation angle