RELATIONSHIP BETWEEN INPUT AND OUTPUT: A SYSTEMATIC STUDY OF THE STABILITY OF HIGHLY FRACTURED ROCK SLOPES USING THE HOEK-BROWN STRENGTH CRITERION

by

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ABSTRACT

Rock slope stability is a particularly important topic in rock engineering. The circular failure of highly fractured rock slopes is a critical failure mode that can cause severe damage. Over the past decades, significant research has been devoted to soil slopes and failure modes of rock slopes controlled by discontinuities. However, there have been few attempts to systematically study the circular failure mode of rock slopes.

Circular failure is controlled by the strength of the rock mass. While the strength of a rock mass is difficult to measure directly, the Hoek-Brown (HB) strength criterion has proved effective and convenient for its estimation.

This research presents a systematic study of the stability of highly fractured rock slopes using the HB strength criterion. Both deterministic analyses and probabilistic analyses are included. The relationship between the input (GSI, m_i, σ_{ci}, and their variability) and the output, Factor of Safety (FS) and Probability of Failure (PF), is investigated. *Slide6.0* and a limit equilibrium model programmed in *Matlab* are used for FS calculations; Monte Carlo simulations are applied for PF calculations.

The deterministic analysis aims to characterise the sensitivity of FS to the changes in HB parameters (FS sensitivity). A sensitivity graph analysis and an equation fitting analysis are developed. The sensitivity graph analysis displays the relationship between HB parameters and FS directly. The equation fitting analysis fits a large amount of data generated by *Slide6.0* with an equation connecting HB parameters and FS, and then determines FS sensitivity from the derivatives of this equation with respect to HB parameters. It is found that slopes with the same geometry and the same FS (but different combinations of HB parameters) can have quite different sensitivity and GSI is the most critical parameter in this respect. With the increase in GSI, FS becomes increasingly sensitive to the change in GSI and that in σ_{ci}.

The probabilistic analysis investigates the relationship between the variability of HB parameters (quantified by the coefficient of variation COV and scale of fluctuation θ) and PF. Its effectiveness in assessing the impact of FS sensitivity on slope stability is also studied. A series of parametric studies are implemented. It is found that there is a strong relationship between FS sensitivity and PF: for slope cases with identical FS and the same COV of input HB parameters, a slope of higher FS sensitivity has a higher PF, indicating a higher risk. The relative contributions of the variability of HB parameters to PF are also compared. It is found that when the COV of GSI, m_i, and σ_{ci} are identical, the variability of GSI makes the largest contribution; however, when these COV are set to their upper-limit values observed in engineering practice, the high variability of σ_{ci} makes the largest contribution. Finally, the investigation demonstrates that spatial variability of HB parameters (applicable to m_i and σ_{ci} in this study) has significant influences on slope stability. For a slope with FS > 1, the PF increases as the scale of fluctuation θ of HB parameters increases. Also, larger θ makes the effect of FS sensitivity on slope stability more significant.

STATEMENT OF ORIGINALITY

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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NOTATION (OTHER THAN DEFINED LOCALLY WITHIN EQUATIONS)

a	range of influence
$a_1, \ldots, a_9$	coefficients for the equation fitting
$\boldsymbol{a}$	coefficient matrix for the equation fitting
$\boldsymbol{A}$	HB parameter matrix for the equation fitting
ARD	absolute relative difference
b	width of a slice
c	cohesion
$\mathbf{C}$	covariance matrix
C_0	nugget variance
C	a parameter, when added to C_0, represents the *sill* of a variogram
COV	coefficient of variation
CSS	critical slip surface
$C(\tau)$	covariance between the data of two points separated by distance τ
D	rock mass disturbance factor
DF	driving force
E_L; E_R; X_L; X_R	normal and shear forces acting on both sides of a slice
FORM	first order reliability method
FOSM	first order second moment method
FS	factor of safety
GSI	Geological Strength Index
h_r	height of a slice
h_w	height of the water table

H	height of the slope
HB	Hoek-Brown
i	increment factor for HB parameters in sensitivity graphs
Is_{50}	point load index
LEM	limit equilibrium method
m_b; s; a	Hoek-Brown constants for the rock mass
m_i	Hoek-Brown constant for the intact rock
M	number of times that the system fails in a Monte Carlo simulation
MC	Mohr-Coulomb
MCS	Monte Carlo simulation
MPa	Mega-Pascal
N; N'	normal and effective normal forces acting on the base of a slice
N	total number of iterations in a Monte Carlo simulation
PDF	probability density function
PEM	point estimate method
PF	probability of failure
PF-GSI	probability of failure when only GSI is modelled as a random variable
PF-m_i	probability of failure when only m_i is modelled as a random variable
PF-σ_{ci}	probability of failure when only σ_{ci} is modelled as a random variable
PSSA	probabilistic slope stability analysis
r_r	unit weight of the soil/rock material
r_w	unit weight of water
RD	relative difference
RFEM	random finite element method
RF	resisting force
r_s	Spearman correlation coefficient

t	location in a random field
T	local averaging distance
u	water pressure along the slip surface
UCS	uniaxial compressive strength (= σ_{ci})
W	weight of a slice
x	an arbitrary parameter or a random variable (often serves as input)
x_1; x_2; x_3	GSI, m_i, and σ_{ci} representations in the equation fitting
y	an arbitrary parameter or a random variable (often serves as output)
$\boldsymbol{y}$	FS matrix for the equation fitting
α	base angle of a slice
β	slope face angle
β_r	reliability index
β_{HL}	Hansfor and Lind’s reliability index
θ	scale of fluctuation
γ_h	variogram (semivariogram)
γ_h^*	experimental variogram
γ(T)	variance function
λ	parameter for demonstrating the concept of spatial variability
μ	mean
σ	standard deviation
σ_1	major principal stress
σ_3	minor principal stress
σ^2	variance
σ’	effective normal stress acting on the base of a slice
σ_{ci}	uniaxial compressive strength (= UCS)
σ_n	normal stress

τ	shear stress
τ_f	shear strength
σ_t	tensile strength of the intact rock
$\sigma^2{}_{\mathrm{T}}$	variance of the locally averaged random field (over distance T)
$\rho(\tau)$	correlation function
φ	angle of friction