



UNIVERSITY
OF WOLLONGONG
AUSTRALIA

University of Wollongong
Research Online

University of Wollongong Thesis Collection
1954-2016

University of Wollongong Thesis Collections

1990

Evaluation and updating of slope reliability (with particular reference to optimization and probabilistic analysis)

Shu Zhang
University of Wollongong

UNIVERSITY OF WOLLONGONG

COPYRIGHT WARNING

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site. You are reminded of the following:

This work is copyright. Apart from any use permitted under the Copyright Act 1968, no part of this work may be reproduced by any process, nor may any other exclusive right be exercised, without the permission of the author.

Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material. Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.

Recommended Citation

Zhang, Shu, Evaluation and updating of slope reliability (with particular reference to optimization and probabilistic analysis), Doctor of Philosophy thesis, Department of Civil and Mining Engineering, University of Wollongong, 1990. <http://ro.uow.edu.au/theses/1246>

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au

NOTE

This online version of the thesis may have different page formatting and pagination from the paper copy held in the University of Wollongong Library.

UNIVERSITY OF WOLLONGONG

COPYRIGHT WARNING

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site. You are reminded of the following:

Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material. Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.

EVALUATION AND UPDATING OF SLOPE RELIABILITY

(with particular reference to optimization and probabilistic analysis)

A thesis submitted in fulfilment of the requirements for the award of
the degree

Doctor of Philosophy

from

THE UNIVERSITY OF WOLLONGONG



by

SHU ZHANG, B.E. (Hons)

DEPARTMENT OF CIVIL AND
MINING ENGINEERING

January, 1990

DECLARATION

I, Shu Zhang, declare that the work described in this thesis has not been submitted for a degree to any university or such institution except where specifically indicated. During the research work, the following published or to be published papers are based on this thesis.

Zhang, S. and Chowdhury, R.N. (1989) Identification of critical slope failure surfaces with critical tension cracks. *30th U.S. Symposium on Rock Mechanics*, Morgantown, U.S.A., pp.185-192.

Zhang, S. and Chowdhury, R.N. (1989) Computing techniques for identifying critical failure surfaces in slopes. *Symposium on Computer Systems in the Australian Mining Industry*, Wollongong, Australia, pp.126-132.

Zhang, S. and Chowdhury, R.N. (1990) Optimization Calculations in Back-analysis of Slope Failures. (under review)

Chowdhury, R.N. and Zhang, S. (1988) Prediction of critical slip surfaces. *Proc. 5th Australia - New Zealand Conference on Geomechanics*, Sydney, Australia, pp.451-455.

Chowdhury, R.N. and Zhang, S. (1989) Bayesian updating for open pit slopes. *2nd large Open Pit Conference*, Latrobe Valley, Australia, pp.9-12.

Chowdhury, R.N. and Zhang, S. (1990) Some aspects of convergence related to limit equilibrium slope stability models. *Canadian Geotech. Journal*. (in press)

Shu Zhang

January, 1990

ACKNOWLEDGEMENTS

The author wishes to express his deep gratitude to Associate Professor R.N. Chowdhury, under whose supervision this research work was performed. His invaluable guidance, fruitful discussions and constant encouragements are gratefully acknowledged.

The author also would like to recognize the assistance given by Dr. V.U. Nguyen, especially the help provided by him during the first year of the author's study in the University of Wollongong.

The research work described in this thesis was carried out initially with a scholarship granted by People's Republic of China. The financial assistance provided under this scholarship is sincerely appreciated.

The author is indebted to all members of his family. Special acknowledgement is due to his parents, and his wife, Cuiliang Li, for their constant support and encouragements throughout all the years, and to his lovely son, Hang Zhang, for the fun and happiness he brought to the rather long period of study.

Finally, the author would like to thank all others who have helped him in carrying out this research work. Mr J. St George of New Zealand who, at the request of the author's supervisor (Associate Professor R.N. Chowdhury), made available information about the corrections in the thesis of Stead (1984), a copy of which was kindly provided by Professor R.N. Singh from the University of Nottingham, UK.

ABSTRACT

The research work detailed in this thesis is mainly aimed at two aspects, i.e. (a). assessments of slope reliability considering both deterministic and probabilistic approaches, and (b). updating of slope reliability by reducing the contribution of systematic errors. Currently, the determination of critical slip surfaces within a probabilistic framework and the influence of systematic errors on calculated reliability are areas requiring further development. This research addresses these problems and provides appropriate and systematic approaches in these areas.

Four commonly used deterministic models have been employed in this research. Difficulties in convergence associated with the original Janbu generalized method have been addressed by the proposed modified Janbu method. The convergence of the modified Janbu generalized method developed in this thesis is generally rapid. Based on previously published examples, it is found that the calculation results are in good agreement with those based on other reliable methods. An extra effort made by the writer on the modified method is the determination of the position and depth of tension cracks. The effects of tension cracks on slope stability have been considered during the search for the critical slip surfaces. Critical slip surfaces identified without considering the possible formation of tension cracks are found to be different from those identified when cracks are considered as part of the search process.

Reliability framework for the consideration of inherent variability of geotechnical parameters has been developed on the basis of the adopted deterministic methods and the proposed probabilistic approaches. Two solution techniques for calculating moments of functions of random variables have been employed (i.e. first order second moment approximation and Rosenblueth point estimate method). Three probabilistic models (i.e. lumped parameter model, local average process model

and multi-layer model) have been developed for assessing slope reliability. Spatial variation of shear strength parameters of earth materials has been incorporated in the last two models.

The simplex reflection technique has been used for the determination of critical slip surfaces based either on the factor of safety or on the reliability index. Application of the technique to the search for the critical slip circles has been enhanced. Its extension to the identification of the critical slip surfaces of arbitrary shape has been implemented. Based on the proposed optimization approach, this research work back-analysed some documented failure case histories by searching for the critical slip surfaces and comparing the calculated critical surfaces with the observed failure surfaces. In the back-analysis studies, it is found that only one pair of values of cohesion c and friction angle ϕ can be regarded as reasonable. This is the combination which leads to coincidence or approximate coincidence between the observed failure surface and the optimized critical failure surface.

Based on the developed models and approaches, the case and example studies have allowed a comprehensive analysis of the contributions of different uncertainties to the location of critical slip surfaces and the evaluation of slope reliability. The difference between conventional and reliability based critical slip surfaces have been explored. It is found that a conventional critical slip surface is not always close to the corresponding reliability based critical slip surface. Under certain conditions the reliability based critical slip surfaces are much deeper than the conventional critical slip surfaces; in other situations conventionally determined critical surfaces are deeper.

In addition to the inherent variability of shear strength parameters and pore water pressure and the intrinsic random measurement error, there are two systematic errors involved in the evaluation of slope stability, i.e. statistical estimation error

and measurement bias. These systematic errors do not follow the averaging rule and can not be expected to cancel out. They introduce uncertainties in the estimation of the statistical parameters (mean and standard deviation) and thus the evaluation of slope stability. However, these errors are not the inherent characteristics of the natural world and can be reduced on the basis of additional information. In the case of slope stability study, this information could be the performance of a soil or rock slope. The performance (e.g. failure or success) could be considered associated with each stage of construction or operation. An approach based on Bayes' theorem has been developed in this thesis to update slope reliability. The performance of a slope is regarded as a full scale field test based on this approach. The approach provides new prospects for the application of probability theory to slope stability analysis. It can be employed for a major project at any stage of its construction or operation. The approach can result in an enhanced appreciation of risk and reliability and may lead to significant cost savings for a project. The application of this approach has been demonstrated for modeling, analysis and updating of slope stability for both failed and survived slopes.

TABLE OF CONTENTS

	Page No.
Title Page.....	-i-
Declaration.....	-ii-
Acknowledgements.....	-iii-
Abstract.....	-iv-
Table of Contents.....	-vii-
List of Figures.....	-xiv-
List of Tables.....	-xxiv-
Notation.....	-xxvii-
CHAPTER 1. INTRODUCTION AND SCOPE.....	1-1
1.1 General Remarks.....	1-1
1.2 Objectives and Scope of This Research work.....	1-2
1.3 Research Approach and Outline of the Thesis.....	1-3
CHAPTER 2. PROBABILISTIC APPROACH IN SLOPE	
STABILITY STUDY (a brief review).....	2-1
2.1 General Remarks.....	2-1
2.2 Background of Probabilistic Study of Slope Stability.....	2-2
2.2.1 Uncertainties and Modelling of Inherent Variability.....	2-2
2.2.2 Probabilistic Approaches.....	2-4
2.3 Advantages of Probabilistic Study of Slope Stability.....	2-8
2.4 Requirements for the Further Use of Probabilistic Studies in Slope Stability.....	2-10

PART ONE.
DEVELOPMENT OF BASIC MODELS

CHAPTER 3. DETERMINISTIC BASIS.....	3-1
3.1 General Remarks.....	3-1
3.2 Basic Assumptions.....	3-3
3.2.1 Geometry Mode.....	3-3
3.2.2 Process of Deformation.....	3-4
3.3 Proposed Methods of Slope Stability Study.....	3-5
3.3.1 The Ordinary Method of Slices.....	3-5
3.3.2 Bishop's Simplified Method.....	3-7
3.3.3 Janbu Generalized Method.....	3-10
3.3.4 Difficulties of Convergence and False Convergence Associated with Janbu Generalized Method.....	3-13
3.3.5 Janbu Simplified Method.....	3-20
3.4 Modification of Janbu Generalized Method.....	3-22
3.5 Location of Critical Tension Crack in Slope Stability Analysis....	3-26
3.5.1 Available Methods for Determination of Tension Cracks.....	3-26
3.5.2 Determination of Tension Crack Using the Modified Janbu Method.....	3-33
3.5.3 Physical Interpretation of the Development of Tension Crack	3-35
3.6 Summary.....	3-37
 CHAPTER 4. PROBABILISTIC FRAMEWORK.....	 4-1
4.1 General Remarks.....	4-1
4.2 Description of Basic Parameters.....	4-4
4.3 Probability of Failure and Reliability Index.....	4-6

4.4	Probabilistic Analysis Using Ordinary Method of Slices.....	4-8
4.4.1	Solution Technique for Explicit Functions of Random Variables: First Order Second Moment Expansion.....	4-8
4.4.2	Probabilistic Formulation of Ordinary Method of Slices...	4-10
4.5	Probabilistic Analysis Using Bishop and Janbu Methods.....	4-12
4.5.1	Difficulty Arising from a Non-explicit Function for Factor of Safety.....	4-12
4.5.2	Solution Technique for Non-explicit Functions of Random Variables: Point Estimate Approximation.....	4-18
4.5.3	Application of Point Estimate Approximate.....	4-22
4.6	Spatial Variation of Strength Parameters.....	4-25
4.6.1	Introduction.....	4-25
4.6.2	Description of Spatial Variation of Strength Parameters....	4-26
4.6.3	Simulation of Spatial Variation of Strength Parameters in this Research.....	4-32
4.6.3.1	Lumped Parameter Model.....	4-32
4.6.3.2	Local Average Process.....	4-33
4.6.3.3	Multi-layer Model.....	4-44
4.7	Summary.....	4-46

CHAPTER 5. OPTIMIZATION APPROACH TO SLOPE

	STABILITY.....	5-1
5.1	General Remarks.....	5-1
5.2	The State-of-the-art of Optimization Methods in Slope Stability Analysis.....	5-3
5.2.1	Conventional Methods Based on Repeated Trials.....	5-3
5.2.2	Direct Search Methods.....	5-8
5.2.3	Combination of Conventional Repetitive Search and Direct Search.....	5-13

5.2.4	Dynamic Programming.....	5-14
5.3	The Extension of the Simplex Method for this Research Work....	5-18
5.3.1	Basic Formulation.....	5-19
5.3.2	Adaptation of Simplex Technique.....	5-26
5.3.3	Extension of Simplex Technique to Search for Critical Slip Circles (Based on F_m or on β_{rm}).....	5-36
5.3.4	Extension of Simplex Technique to Search for Critical Slip Surfaces of Arbitrary Shape (Based on F_m or on β_{rm}).....	5-38
5.4	Summary.....	5-42

CHAPTER 6. BAYESIAN UPDATING OF SLOPE STABILITY

	(reducing the influence of systematic errors).....	6-1
6.1	General Remarks.....	6-1
6.2	Systematic Errors.....	6-2
6.2.1	Errors Due to Statistical Estimation.....	6-2
6.2.2	Errors Due to Measurement Bias.....	6-5
6.3.	Distinguishing Inherent Randomnesses from Systematic Errors.....	6.9
6.4	Bayesian Updating Approach for Reducing the Influence of Systematic Errors.....	6-13
6.4.1	Bayesian Approach.....	6-13
6.4.2	Previous Work Concerning Use of Bayesian Approach in Updating Slope Stability.....	6-15
6.4.3	Proposed Updating Approach Based on a Single Random Variable.....	6-16
6.4.3	Updating Evaluation of Slope Stability Involving Multiple Random Variables.....	6-23
6.5	Discussion and Summary.....	6-30

PART TWO
CASE AND EXAMPLE STUDIES

**CHAPTER 7. APPLICATIONS OF PROPOSED MODIFIED
JANBU GENERALIZED METHOD OF SLICES
(with particular reference to determination of
location and depth of critical tension cracks)..... 7-1**

7.1 General Remarks..... 7-1

7.2 Examples from Previous Publications..... 7-2

7.3 Comparisons among Various Alternatives Based on
Janbu Methods..... 7-7

7.4 Evaluation of Depth of Critical Tension Crack..... 7-12

7.5 Parametric Studies Concerning Tension Crack and
Its Influence on Slope Stability..... 7-19

7.6 Discussions and Summary..... 7-24

7.6.1 Discussion..... 7-24

7.6.2 Summary..... 7-26

**CHAPTER 8. APPLICATIONS OF PROPOSED
OPTIMIZATION APPROACH
(search for critical slip surfaces associated
with minimum factor of safety)..... 8-1**

8.1 General Remarks..... 8-1

8.2 Examples from Previous Publications..... 8-2

8.3 Application to Back-Analyses of Open-pit Mining Slopes
(Documented Failure Cases)..... 8-6

8.3.1 Cases of Circular Slip Surfaces..... 8-7

8.3.2 Cases of Slip Surfaces of Arbitrary Shape..... 8-24

8.4 Discussion and Summary..... 8-35

8.4.1 Discussion.....	8-35
8.4.2 Summary.....	8-37

**CHAPTER 9. EVALUATIONS OF SLOPE STABILITY
BASED ON MINIMUM FACTOR OF
SAFETY & MINIMUM RELIABILITY**

INDEX.....	9-1
9.1 General Remarks.....	9-1
9.2 Application of Lumped Parameter Model.....	9-3
9.2.1 Evaluation of Critical Slip Surface on Case History: Green Creek Slide.....	9-3
9.2.2 Parametric Analyses Based on INGHAM SIDEWALL.....	9-18
9.3 Application of Local Average Process Model.....	9-46
9.4 Analyses for Slope Stability under “ $\phi = 0$ ” condition (Multi-layer Model Used).....	9-57
9.5 Discussion.....	9-62
9.5.1 Consideration of Reliability Index Based on Fellenius Method.....	9-62
9.5.2 Consideration of Negative Values of Reliability Index.....	9-67
9.5.3 Consideration of the Case with $\beta_{rm} = 0$	9-72
9.5.4 Some Correspondence between Deterministic and Probabilistic Solutions.....	9-72
9.5.5 Consideration of Type of Parameter Uncertainties.....	9-73
9.5.6 Consideration of Limit Equilibrium Methods Used.....	9-74
9.6 Summary.....	9-75

CHAPTER 10. STUDIES OF RELIABILITY UPDATING.....	10-1
10.1 General Remarks.....	10-1
10.2 Illustrative Example: Application to an Open Pit Mine (Survival Case).....	10-2
10.3 Application to a Failure Case History: Congress Street Open Cut.	10-16
10.4 Illustrative Example: Application to Coal Stock Piles: (Sensitivity Study for Survival Case).....	10-22
10.5 Discussions and Summary.....	10-38
10.5.1 Discussion.....	10-38
10.5.2 Summary.....	10-39
 CHAPTER 11. SUMMARY AND CONCLUSIONS.....	 11-1
11.1 Summary.....	11-1
11.2 Main Conclusions.....	11-4
11.3 Recommendations for Further Development.....	11-8
 REFERENCES.....	 R-1
 APPENDIX: “SRFSS” USER GUIDE.....	 A-1
A.1 Features of “SRFSS”.....	A-1
A.2 Input Data Instructions.....	A-4
A.3 Illustrative Examples.....	A-14

LIST OF FIGURES

Figure No.	Page No.
Fig.(1.1) Simplified Flow Chart of SRFSS.....	1-5
Fig.(3.1) Terms of the Ordinary Method of Slices.....	3-6
Fig.(3.2) Forces Acting on a Single Slice (Bishop's Method).....	3-8
Fig.(3.3) Equilibrium Consideration in Janbu Method.....	3-10
Fig.(3.4) Flow Chart of Janbu Generalized Method of Slice	3-14
Fig.(3.5a) Locus of Function of Factor of Safety for Slip Surface with Reverse Slope at the Toe.....	3-16
Fig.(3.5b) Locus of Function of Factor of Safety for Slip Surface without Reverse Slope at the Toe.....	3-17
Fig.(3.6) Correction Factor (After Janbu, 1973).....	3-21
Fig.(3.7) General Procedure of Modified Janbu Method Proposed by the Writer.....	3-24
Fig.(3.8) Illustration of Interslice Effective Normal Stress Distribution.....	3-28
Fig.(3.9a) Illustration of Effect of Dry Crack within Tension Zone on Calculation of Factor of Safety.....	3-30
Fig.(3.9b) Illustration of Effect of Dry Crack beyond Tension Zone on Calculation of Factor of Safety.....	3-31
Fig.(3.9c) Illustration of Effect of Wet Crack beyond Tension Zone on Calculation of Factor of Safety.....	3-32
Fig.(3.10) Illustration for Creation of Interslice Tension Force.....	3-36
Fig.(4.1) A Simple Example Shows Effect of Spatial Variation on Stability Assessment.....	4-2
Fig.(4.2) Flow Chart of the Calculations of Probability of Failure based on Back Analysis of Slope Stability.....	4-15
Fig.(4.3) Flow Chart of Applications of Monte Carlo Simulation to Probabilistic Study of Slope Stability.....	4-17

Fig.(4.4)	Flow Chart of Applications of Point Estimate Approximation to Slope Stability Study.....	4-23
Fig.(4.5)	Statistically Homogeneous Model.....	4-28
Fig.(4.6)	Statistically Homogeneous Model with Lumped Parameters.....	4-28
Fig.(4.7)	Models Show Non-constant Mean Value and Constant Variance..	4-31
Fig.(4.8)	Models Show Non-constant Mean Value and Non-constant Variance.....	4-32
Fig.(4.9)	A Simple Example Shows Effect of Correlation Distance Parameter on Stability Assessment.....	4-34
Fig.(4.10)	Simple Example Shows Different Correlation Parameters and Different Domains over which Variation is Averaged.....	4-39
Fig.(4.11)	A Simple Example Shows the Decrease of Variance with the Increase of Area over which the Random Variable is Averaged....	4-40
Fig.(4.12)	Variance Reduction Factor for One Dimensional Averages.....	4-41
Fig.(4.13)	Multi-layer Model.....	4-45
Fig.(5.1)	Grid-search Method.....	5-4
Fig.(5.2)	Random Search Scheme.....	5-7
Fig.(5.3)	Star Technique.....	5-9
Fig.(5.4)	Alternating Variable Method.....	5-10
Fig.(5.5)	Search Scheme Employed in Dynamic Programming (After Baker, 1980).....	5-15
Fig.(5.6)	The General Minimization Scheme of Baker's Dynamic Programming (after Baker, 1980).....	5-17
Fig.(5.7)	The Basic Operations of Simplex Method for a Problem of Two Variables.....	5-23
Fig.(5.8)	Flow Diagram of Simplex Reflection Method.....	5-25
Fig.(5.9)	A Two Dimensional Transition Operation Employed by Parkinson and Hutchinson (1972) to Keep the Shape of the Simplex Unchanged after an Expansion.....	5-27

Fig.(5.10a)	The Expansion Operation Adopted by Nelder and Mead (1965)...	5-29
Fig.(5.10b)	The Expansion Operation Adopted by Parkinson and Hutchinson (1972).....	5-30
Fig.(5.10c)	The Expansion Operation Adopted by the Writer.....	5-31
Fig.(5.11)	Comparison of Simplex Methods with Different Expansion Operation Techniques (Length L_s in meters).....	5-33
Fig.(5.12)	Comparison of Simplex Methods with Different Expansion Operation Techniques (Length L_s in feet).....	5-34
Fig.(5.13)	Application of Simplex Reflection Technique to a Two Dimensional Problem.....	5-37
Fig.(5.14)	Coordinates for Simulating Arbitrary Slip Surfaces in Using Simplex Reflection Method Adopted by the Writer.....	5-41
Fig.(6.1)	Sources of Parameter Uncertainties Involved in Slope Stability Study.....	6-10
Fig.(6.2)	Uncertainties Associated with Sample Mean of Cohesion.....	6-12
Fig.(6.3)	Excavation and Stripping Sequences in an Open Pit Mine.....	6-18
Fig.(6.4)	Discrete Values of Sample Mean \bar{C}	6-20
Fig.(7.1)	Illustration of Modified Janbu's Method Based on Examples from Janbu's Work.....	7-3
Fig.(7.2)	Illustration of Modified Janbu's Method Based on Examples from Spencer's Work.....	7-4
Fig.(7.3)	Failures of Weathered Rock Slopes with Calculated Critical Slip Surface (after Sancio & Goodman, 1979).....	7-5
Fig.(7.4)	Comparisons among Different Alternatives based on Janbu Method.....	7-9
Fig.(7.5)	Depth of Tension Crack vs. Cohesion & Density	7-14
Fig.(7.6)	Depth of Tension Crack vs. Cohesion & Internal Friction.....	7-15
Fig.(7.7)	Comparison of Different Ways to Estimate Depth of Tension Crack. Case I: $r_u = 0.3$, $\phi' = 32.21^\circ$	7-16

Fig.(7.8)	Comparison of Different Ways to Estimate Depth of Tension Crack. Case II: $r_u = 0.0$, $\phi' = 36^\circ$	7-17
Fig.(7.9)	Comparison of Different Ways to Estimate Depth of Tension Crack. Case III: $r_u = 0.5$, $\phi' = 36^\circ$	7-18
Fig.(7.10)	Crack Water vs. Tension Crack.....	7-20
Fig.(7.11)	Groundwater Condition vs. Tension Crack.....	7-21
Fig.(7.12)	Slope Inclination vs. Tension Crack.....	7-22
Fig.(7.13)	Slope Height vs. Tension Crack.....	7-23
Fig.(8.1)	A Slope Stability Problem.....	8-2
Fig.(8.2)	Spoil Pile Failure.....	8-6
Fig.(8.3)	Back-analysis Results for Glyn Glas Highwall Failure.....	8-7
Fig.(8.4)	Calculated and Observed Failure Surfaces for Glyn Glas Failure ($r_u = 0$).....	8-8
Fig.(8.5)	Calculated and Observed Failure Surfaces for Glyn Glas Failure ($r_u = 0.2$).....	8-9
Fig.(8.6)	Calculated and Observed Failure Surfaces for Glyn Glas Failure ($r_u = 0.4$).....	8-10
Fig.(8.7)	Back-analysis Results for Coalfield Farm Sidewall Failure, IDB 61.....	8-11
Fig.(8.8)	Calculated and Observed Failure Surfaces for Coalfield Farm IDB 61 Failure ($r_u = 0$).....	8-11
Fig.(8.9)	Calculated and Observed Failure Surfaces for Coalfield Farm IDB 61 Failure ($r_u = 0.2$).....	8-12
Fig.(8.10)	Calculated and Observed Failure Surfaces for Coalfield Farm IDB 61 Failure ($r_u = 0.4$).....	8-13
Fig.(8.11)	Back-analysis Results for Coalfield Farm Sidewall Failure, IDB 106.....	8-14
Fig.(8.12)	Calculated and Observed Failure Surfaces for Coalfield Farm IDB 106 Failure ($r_u = 0$).....	8-15

Fig.(8.13)	Calculated and Observed Failure Surfaces for Coalfield Farm IDB 106 Failure ($r_u = 0.2$).....	8-16
Fig.(8.14)	Calculated and Observed Failure Surfaces for Coalfield Farm IDB 106 Failure ($r_u = 0.4$).....	8-17
Fig.(8.15)	Back-analysis Results for Bursnip's Road Lowwall Failure, IDB 190.....	8-18
Fig.(8.16)	Calculated and Observed Failure Surfaces for Bursnip's Road IDB 190 Failure ($r_u = 0$).....	8-18
Fig.(8.17)	Calculated and Observed Failure Surfaces for Bursnip's Road IDB 190 Failure ($r_u = 0.2$).....	8-19
Fig.(8.18)	Calculated and Observed Failure Surfaces for Bursnip's Road IDB 190 Failure ($r_u = 0.4$).....	8-20
Fig.(8.19)	Back-analysis Results for Springfield Loosewall Failure, IDB 199.....	8-21
Fig.(8.20)	Calculated and Observed Failure Surfaces for Springfield Loosewall Failure ($r_u = 0$).....	8-22
Fig.(8.21)	Calculated and Observed Failure Surfaces for Springfield Loosewall Failure ($r_u = 0.2$).....	8-23
Fig.(8.22)	Calculated and Observed Failure Surfaces for Springfield Loosewall Failure ($r_u = 0.4$).....	8-24
Fig.(8.23)	Back-analysis Results for Tir-Y-Gof Pavement Failure, IDB 7.....	8-25
Fig.(8.24)	Calculated and Observed Failure Surfaces for Tir-Y-Gof Pavement Failure ($r_u = 0$).....	8-25
Fig.(8.25)	Calculated and Observed Failure Surfaces for Tir-Y-Gof Pavement Failure ($r_u = 0.2$).....	8-26
Fig.(8.26)	Calculated and Observed Failure Surfaces for Tir-Y-Gof Pavement Failure ($r_u = 0.4$).....	8-27

Fig.(8.27)	Back-analysis Results for Remiltoun Highwall Failure, IDB 12.....	8-28
Fig.(8.28)	Calculated and Observed Failure Surfaces for Remiltoun Highwall Failure ($r_u = 0$).....	8-29
Fig.(8.29)	Calculated and Observed Failure Surfaces for Remiltoun Highwall Failure ($r_u = 0.2$).....	8-30
Fig.(8.30)	Calculated and Observed Failure Surfaces for Remiltoun Highwall Failure ($r_u = 0.4$).....	8-31
Fig.(8.31)	Back-analysis Results for St. Aidans Highwall Failure, IDB 35.....	8-32
Fig.(8.32)	Calculated and Observed Failure Surfaces for St. Aidans Highwall Failure ($r_u = 0$).....	8-32
Fig.(8.33)	Calculated and Observed Failure Surfaces for St. Aidans Highwall Failure ($r_u = 0.2$).....	8-33
Fig.(8.34)	Calculated and Observed Failure Surfaces for St. Aidans Highwall Failure ($r_u = 0.4$).....	8-34
Fig.(9.1)	Comparison of Different Critical Slip Surfaces for Green Creek Slide ($V_c = 0.3, V_t = 0.15, V_{ru} = 0.67$).....	9-6
Fig.(9.2)	Comparison of Different Critical Slip Surfaces for Green Creek Slide ($V_c = 0.5, V_t = 0.5, V_{ru} = 0$).....	9-9
Fig.(9.3)	Comparison of Different Critical Slip Surfaces for Green Creek Slide ($V_c = 0.1, V_t = 0.1, V_{ru} = 0$).....	9-11
Fig.(9.4)	Comparison of Different Critical Slip Surfaces for Green Creek Slide ($V_c = 0.5, V_t = 0.1, V_{ru} = 0$).....	9-13
Fig.(9.5)	Comparison of Different Critical Slip Surfaces for Green Creek Slide ($V_c = 0.1, V_t = 0.5, V_{ru} = 0$).....	9-15
Fig.(9.6)	Comparison of Different Critical Slip Surfaces for Green Creek Slide ($V_c = 0.1, V_t = 0.5, V_{ru} = 0$, Homogeneous material -- no bedrock below slope).....	9-17

Fig.(9.7)	Comparison of Different Critical Slip Surfaces for INGHAM SIDEWALL ($r_u = V_{ru} = 0$).....	9-25
Fig.(9.8)	Some Extreme Positions of Reliability Based Critical Slip Surfaces ($r_u = V_{ru} = 0$).....	9-26
Fig.(9.9)	Comparison of Different Critical Slip Surfaces for INGHAM SIDEWALL (Based on Fellenius Method $V_{ru} = 0$).....	9-28
Fig.(9.10)	Comparison of Different Critical Slip Surfaces for INGHAM SIDEWALL (Based on Bishop Simplified Method $V_{ru} = 0$).....	9-29
Fig.(9.11)	Comparison of Different Critical Slip Surfaces for INGHAM SIDEWALL (Based on Janbu Simplified Method $V_{ru} = 0$).....	9-30
Fig.(9.12)	Comparison of Different Critical Slip Surfaces for INGHAM SIDEWALL (Based on Modified Janbu Generalized Method $V_{ru} = 0$).....	9-31
Fig.(9.13)	Comparison of Different Critical Slip Surfaces for INGHAM SIDEWALL (Based on Fellenius Method $V_c = 0, V_t = 0$).....	9-33
Fig.(9.14)	Comparison of Different Critical Slip Surfaces for INGHAM SIDEWALL (Based on Bishop Simplified Method $V_c = 0, V_t = 0$).....	9-34
Fig.(9.15)	Comparison of Different Critical Slip Surfaces for INGHAM SIDEWALL (Based on Modified Janbu Generalized Method $V_c = 0, V_t = 0$).....	9-35
Fig.(9.16)	Comparison of Different Critical Slip Surfaces for INGHAM SIDEWALL (Based on Fellenius Method $r_u = 0.1, V_c = 0.1$).....	9-38
Fig.(9.17)	Comparison of Different Critical Slip Surfaces for INGHAM SIDEWALL (Based on Fellenius Method $r_u = 0.1, V_t = 0.1$).....	9-39

Fig.(9.18)	Comparison of Different Critical Slip Surfaces for INGHAM SIDEWALL (Based on Bishop Simplified Method $r_u = 0.1, V_c = 0.1$).....	9-40
Fig.(9.19)	Comparison of Different Critical Slip Surfaces for INGHAM SIDEWALL (Based on Bishop Simplified Method $r_u = 0.1, V_t = 0.1$).....	9-41
Fig.(9.20)	Comparison of Different Critical Slip Surfaces for INGHAM SIDEWALL (Based on Janbu Simplified Method $r_u = 0.1, V_c = 0.1$).....	9-42
Fig.(9.21)	Comparison of Different Critical Slip Surfaces for INGHAM SIDEWALL (Based on Janbu Simplified Method $r_u = 0.1, V_t = 0.1$).....	9-43
Fig.(9.22)	Comparison of Different Critical Slip Surfaces for INGHAM SIDEWALL (Based on Modified Janbu Generalized Method $r_u = 0.1, V_c = 0.1$).....	9-44
Fig.(9.23)	Comparison of Different Critical Slip Surfaces for INGHAM SIDEWALL (Based on Modified Janbu Generalized Method $r_u = 0.1, V_t = 0.1$).....	9-45
Fig.(9.24)	Comparison of Different Critical Slip Surfaces Based on Local Average Process (by Bishop's Simplified Method).....	9-48
Fig.(9.25)	Comparison of Different Critical Slip Surfaces Based on Local Average Process (by Janbu's Simplified Method).....	9-49
Fig.(9.26)	Factors of Safety from Different Critical Surfaces vs. Correlation Distances (by Bishop's Simplified Method).....	9-50
Fig.(9.27)	Reliability of Different Critical Surfaces vs. Correlation Distances (by Bishop's Simplified Method).....	9-51
Fig.(9.28)	Sliding Mass of Different Critical Surfaces vs. Correlation Distances (by Bishop's Simplified Method).....	9-52

Fig.(9.29)	Factors of Safety from Different Critical Surfaces vs. Correlation Distances (by Janbu's Simplified Method).....	9-53
Fig.(9.30)	Reliability of Different Critical Surfaces vs. Correlation Distances (by Janbu's Simplified Method).....	9-54
Fig.(9.31)	Sliding Mass of Different Critical Surfaces vs. Correlation Distances (by Janbu's Simplified Method).....	9-55
Fig.(9.32)	Influence of Autocorrelation of Strength Parameters on Probability of Failure of Green Creek Slide.....	9-56
Fig.(9.33)	Comparison of Different Critical Slip Surfaces Based on Multi-Layer Model.....	9-60
Fig.(9.34)	Different Layering Models and Their Associated Critical Slip Surfaces.....	9-61
Fig.(9.35)	Influence of Slope Inclination on Determination of Reliability Based Critical Slip Surface ($V_c = 0.5, V_t = 0.1$).....	9-65
Fig.(9.36)	Influence of Slope Inclination on Determination of Reliability Based Critical Slip Surface ($V_c = 0.1, V_t = 0.5$).....	9-66
Fig.(9.37)	Location of Reliability Based Critical Slip Surface vs. Minimum Factor of Safety < 1 (Glyn Glas Failure Geometry, $r_u = 0$).....	9-68
Fig.(9.38)	Location of Reliability Based Critical Slip Surface vs. Minimum Factor of Safety < 1 (Glyn Glas Failure Geometry, $r_u = 0.4, V_{ru} = 0.2$).....	9-69
Fig.(9.39)	Location of Reliability Based Critical Slip Surface vs. Minimum Factor of Safety < 1 (Geometry of Coalfield Farm IDB 61 Failure, $r_u = 0.2, V_{ru} = 0.2$).....	9-70
Fig.(9.40)	Location of Reliability Based Critical Slip Surface vs. Minimum Factor of Safety < 1 (Geometry of Bursnip's Road IDB 190 Failure, $r_u = 0$).....	9-71

Fig.(9.41)	Location of Reliability Based Critical Slip Surface vs. Minimum Factor of Safety < 1 (Geometry of Bursnip's Road IDB 190 Failure, $r_u = 0.2$, $V_{ru} = 0.2$).....	9-71
Fig.(10.1)	A Slope in an Open Pit Mine.....	10-3
Fig.(10.2)	Distributions of Expected Values of Strength Parameters Before and after Updating (Normal Distribution Initially).....	10-11
Fig.(10.3)	Distributions of Expected Values of Strength Parameters Before and after Updating (Uniform Distribution Initially).....	10-12
Fig.(10.4)	Congress Street Open Cut.....	10-16
Fig.(10.5)	Coal Stockpile.....	10-23
Fig.(10.6)	Updated Mean Value of \bar{t}' vs. Number of Intervals of Prior Probability Distribution.....	10-27
Fig.(10.7)	Updated Mean Value of \bar{t}' vs. Updating Times.....	10-28
Fig.(10.8)	Initial Distribution of \bar{t}'	10-29
Fig.(10.9)	Distribution of \bar{t}' after 10 Times Updating Calculations.....	10-30
Fig.(10.10)	Distribution of \bar{t}' after 30 Times Updating Calculations.....	10-31
Fig.(10.11)	Distribution of \bar{t}' after 150 Times Updating Calculations.....	10-32
Fig.(10.12)	Updating Calculations Associated with Random S_t^2 and Deterministic S_t^2 (Mean of \bar{t}' vs. Updating Times).....	10-33
Fig.(10.13)	Updating Calculations Associated with Random S_t^2 and Deterministic S_t^2 (P_f vs. Updating Times).....	10-34
Fig.(10.14)	Updating Calculations Associated with Random S_t^2 and Deterministic S_t^2 (β_r vs. Updating Times).....	10-35
Fig.(10.15)	Updating Calculations Associated with Random S_t^2 and Deterministic S_t^2 (F_m vs. Updating Times).....	10-36
Fig.(10.16)	Standard Deviation of t' (S_t) vs. Updating Times.....	10-37
Fig.(A.1)	Illustrative Example to Show Input Data for the Specification of the Depth of Crack Water.....	A-5
Fig.(A.2)	Descriptions of the Input Profile Data.....	A-7

Fig.(A.3)	Example 1: Search for Slip Surface with Minimum Factor of Safety.....	A-17
Fig.(A.4)	Example 2: Search for Slip Surface with Minimum Reliability Index.....	A-21
Fig.(A.5)	Example 3: Search for Slip Surface with Minimum Factor of Safety and Minimum Reliability Index.....	A-25
Fig.(A.6)	Example 4: Bayesian Updating Calculations along a Fixed Slip Circle.....	A-30

LIST OF TABLES

Table No.		Page No.
Table (4.1)	One-dimensional Functions for Autocorrelation Coefficient & Correlation Distance Parameter.....	4-29
Table (4.2)	One-dimensional Functions for Reduction Factor.....	4-37
Table (5.1)	Brief Summary of Some Commonly Used Optimization Methods in Slope Stability Study.....	5-4
Table (7.1)	Input and Output for the Analyses of Failures of Weathered Rock Slopes.....	7-6
Table (7.2)	Calculation Results based on Proposed Modified Janbu Method for the Failures of Weathered Rock Slopes.....	7-7
Table (7.3)	Comparisons among Different Alternatives Based on Janbu Method.....	7-10
Table (8.1)	Comparison of Factors of Safety for the Example from Baker (After Donald & Giam, 1988).....	8-3
Table (8.2)	Critical Values of Factors of Safety Obtained in this Study	

	for the Example from Baker.....	8-4
Table (8.3)	Input and Output for Glyn Glas Failure ($r_u = 0$).....	8-8
Table (8.4)	Input and Output for Glyn Glas Failure ($r_u = 0.2$).....	8-9
Table (8.5)	Input and Output for Glyn Glas Failure ($r_u = 0.4$).....	8-10
Table (8.6)	Input and Output for Coalfield Farm IDB 61 Failure ($r_u = 0$).....	8-12
Table (8.7)	Input and Output for Coalfield Farm IDB 61 Failure ($r_u = 0.2$)....	8-13
Table (8.8)	Input and Output for Coalfield Farm IDB 61 Failure ($r_u = 0.4$)....	8-14
Table (8.9)	Input and Output for Coalfield Farm IDB 106 Failure ($r_u = 0$).....	8-15
Table (8.10)	Input and Output for Coalfield Farm IDB 106 Failure ($r_u = 0.2$)..	8-16
Table (8.11)	Input and Output for Coalfield Farm IDB 106 Failure ($r_u = 0.4$)..	8-17
Table (8.12)	Input and Output for Bursnip's Road IDB 190 Failure ($r_u = 0$)....	8-19
Table (8.13)	Input and Output for Bursnip's Road IDB 190 Failure ($r_u = 0.2$).	8-20
Table (8.14)	Input and Output for Bursnip's Road IDB 190 Failure ($r_u = 0.4$).	8-21
Table (8.15)	Input and Output for Springfield Loosewall Failure ($r_u = 0$).....	8-22
Table (8.16)	Input and Output for Springfield Loosewall Failure ($r_u = 0.2$).....	8-23
Table (8.17)	Input and Output for Springfield Loosewall Failure ($r_u = 0.4$).....	8-24
Table (8.18)	Input and Output for Tir-Y-Gof Pavement Failure ($r_u = 0$).....	8-26
Table (8.19)	Input and Output for Tir-Y-Gof Pavement Failure ($r_u = 0.2$).....	8-27
Table (8.20)	Input and Output for Tir-Y-Gof Pavement Failure ($r_u = 0.4$).....	8-28
Table (8.21)	Input and Output for Remiltoun Highwall Failure ($r_u = 0$).....	8-29
Table (8.22)	Input and Output for Remiltoun Highwall Failure ($r_u = 0.2$).....	8-30
Table (8.23)	Input and Output for Remiltoun Highwall Failure ($r_u = 0.4$).....	8-31
Table (8.24)	Input and Output for St. Aidans Highwall Failure ($r_u = 0$).....	8-33
Table (8.25)	Input and Output for St. Aidans Highwall Failure ($r_u = 0.2$).....	8-34
Table (8.26)	Input and Output for St. Aidans Highwall Failure ($r_u = 0.4$).....	8-35
Table (9.1)	Comparison of Different Critical Surfaces for Green Creek Slide ($V_c = 0.3$, $V_t = 0.15$, $V_{ru} = 0.67$).....	9-5
Table (9.2)	Comparison of Different Critical Surfaces for Green Creek Slide ($V_c = 0.5$, $V_t = 0.5$, $V_{ru} = 0$).....	9-8

Table (9.3)	Comparison of Different Critical Surfaces for Green Creek Slide ($V_c = 0.1, V_t = 0.1, V_{ru} = 0$).....	9-10
Table (9.4)	Comparison of Different Critical Surfaces for Green Creek Slide ($V_c = 0.5, V_t = 0.1, V_{ru} = 0$).....	9-12
Table (9.5)	Comparison of Different Critical Surfaces for Green Creek Slide ($V_c = 0.1, V_t = 0.5, V_{ru} = 0$).....	9-14
Table (9.6)	Comparison of Different Critical Surfaces for Green Creek Slide ($V_c = 0.1, V_t = 0.5, V_{ru} = 0$ and no restriction under the slope)...	9-16
Table (9.7)	Comparison of Different Critical Slip Surfaces for INGHAM SIDEWALL ($V_c/V_t = 0.25, r_u = V_{ru} = 0$).....	9-20
Table (9.8)	Comparison of Different Critical Slip Surfaces for INGHAM SIDEWALL ($V_c/V_t = 0.50, r_u = V_{ru} = 0$).....	9-21
Table (9.9)	Comparison of Different Critical Slip Surfaces for INGHAM SIDEWALL ($V_c/V_t = 1, r_u = V_{ru} = 0$).....	9-22
Table (9.10)	Comparison of Different Critical Slip Surfaces for INGHAM SIDEWALL ($V_c/V_t = 2.0, r_u = V_{ru} = 0$).....	9-23
Table (9.11)	Comparison of Different Critical Slip Surfaces for INGHAM SIDEWALL ($V_c/V_t = 2.5, r_u = V_{ru} = 0$).....	9-24
Table (9.12)	Comparison of Different Critical Slip Surfaces for INGHAM SIDEWALL (Based on Janbu's Simplified Method $V_c = V_t = 0$)..	9-36
Table (9.13)	Spatial Variation of London Clay.....	9-57
Table (10.1)	Calculated Values of Factor of Safety, Reliability Index, Probability of Failure for Open Pit Slope.....	10-5
Table (10.2)	Calculations of Factor of Safety and Probability of Failure for Excavation Depth of 65m Considering Saturation Due to Rainfall.....	10-6
Table (10.3a)	Revised Calculations Considering Updated Values (Uniform Distributions for Parameters to be Updated).....	10-7
Table (10.3b)	Revised Calculations Considering Updated Values (Symmetric	

Triangular Distributions for Parameters to be Updated).....	10-9
Table (10.3c) Revised Calculations Considering Updated Values (Normal Distributions for Parameters to be Updated).....	10-10
Table (10.4) Calculations Based on Updating after Each Step of Excavation ...	10-14
Table (10.5) Calculations Based on Updating after Each Step of Excavation (Under the Assumption that $\overline{F} \leq 1$ then $P_f = 1$).....	10-15
Table (10.6) Updating Calculations along the Observed Failure Surface of Congress Street Open Cut (I).....	10-19
Table (10.7) Updating Calculations along the Observed Failure Surface of Congress Street Open Cut (II).....	10-19
Table (10.8) Updating Calculations along the Calculated Critical Failure Surface of Congress Street Open Cut (I).....	10-21
Table (10.9) Updating Calculations along the Calculated Critical Failure Surface of Congress Street Open Cut (II).....	10-21
Table (A.1) Input Limitations for Geometry Data.....	A-8

NOTATION

α	Inclination of slice
α_s	Reflection coefficient in simplex method
b	Width of slice
β	Slope inclination
β_r	Reliability index
β_{rm}	Minimum reliability index
β_s	Contraction coefficient in simplex method
c	Cohesion

C	Cohesion as a random variable
c'	Effective cohesion
\bar{c} or \overline{c}	Sample mean of cohesion
\overline{C} or \overline{C}	Sample mean of c as a random variable
$\text{COV}[x, y]$	Covariance between x and y
D_t	Depth of tension crack
E	Normal force on slice interface
ΔE	Increment of E
$E(\cdot)$	Mean value of (\cdot)
f_0	Correction factor for Janbu's simplified method
F	Factor of safety
F_m	Minimum factor of safety
γ	Density of earth mass
γ_s	Expansion coefficient in simplex method
H	Total height of slope
l	Length of slice base
L_s	Length of the initial simplex side
L_t	Horizontal distance from slope crest to tension crack location
μ_x	Population mean value of x
$N(\mu, \sigma)$	Normal distribution with mean μ and standard deviation σ
P	Normal force on slice base
P_f	Probability of failure
P_m	Maximum probability of failure
P_{sv}	Probability of survival
$P_{i\pm}$	Coefficients of point concentrations or weighting factors in Rosenblueth's method
θ_c	Correlation distance parameter for c
θ_t	Correlation distance parameter for $\tan\phi$
r_u	Pore water pressure ratio

$\rho[x, y]$	Correlation coefficient between x and y
s	Shear force on slice base
s_c	Sample standard deviation of c
s_t	Sample standard deviation of $\tan\phi$
S_c	Sample standard deviation of c as a random variable
S_t	Sample standard deviation of $\tan\phi$ as a random variable
SM	Safety margin
σ_x	Population standard deviation of x
T	Shear force on slice interface
ΔT	Increment of T
t	$\tan\phi$ as a random variable
\bar{t} or \overline{t}	Sample mean of $\tan\phi$ as a random variable
t_i	$\tan\phi_i$
$\tan\phi$	Internal friction
$\tan\phi'$	Effective internal friction
$\overline{\tan\phi}$	Sample mean of $\tan\phi$
u	Pore water pressure at the base of slice
Var[.]	Variance of [.]
V_c	Global coefficient of variation of cohesion
V_{cp}	Point coefficient of variation of cohesion
V_t	Global coefficient of variation of $\tan\phi$
V_{tp}	Point coefficient of variation of $\tan\phi$
v_x	Skewness coefficient of x
w	Weight of slice
W_{Fm}	Weight of sliding mass involved by critical slip surface of F_m
$W_{\beta m}$	Weight of sliding mass involved by critical slip surface of β_m
ζ_c	Reduction factor for V_{cp}
ζ_t	Reduction factor for V_{tp}