

LB/DON/10/02

✓  
2

**APPLICATION OF FUZZY SETS AND OTHER  
STATISTICAL TECHNIQUES IN LANDSLIDE HAZARD  
ZONATION MAPPING**

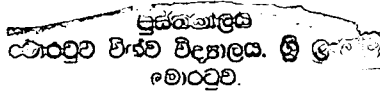
by

Kumari Mala Weerasinghe



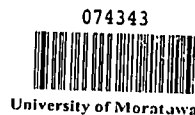
University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)

This thesis was submitted to the department of Civil Engineering of the University of Moratuwa in partial fulfillment of the requirements for the Degree of Master of Engineering in Geotechnical Engineering



Department of Civil Engineering  
University of Moratuwa  
Sri Lanka

August, 2001



74343  
624 "01"  

---

624.131.31

74343

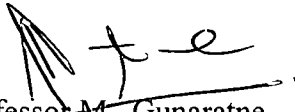
TH

## DECLARATION

I Kumari Mala Weerasinghe do honestly and truly declare that the work included in this thesis in part or whole has not been submitted for any other academic qualification at any institution.

Kumari Mala Weerasinghe  
Candidate for the Degree of Master of Engineering in Geo-technical Engineering.

## CERTIFIED BY



Professor M. Gunaratne  
Department of Civil and Environmental Engineering  
University of South Florida, USA

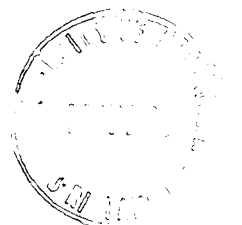


University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)  
Dr. H.G.P.A. Ratnaweera  
Senior Lecturer & Head of the Department of Civil Engineering  
The Open University of Sri Lanka



Dr. U.G.A. Puswewela  
Senior Lecturer  
Department of Civil Engineering  
University of Moratuwa, Sri Lanka

Mr. N.M.S.I. Arambepola  
Director, Landslide Studies & Services Division  
National Building Research Organisation,  
99/1 Jawatta Road  
Colombo 05, Sri Lanka



# APPLICATION OF FUZZY SETS AND OTHER STATISTICAL TECHNIQUES IN LANDSLIDE HAZARD ZONATION MAPPING

by

**Kumari Mala Weerasinghe**

An abstract of the thesis submitted to the Department of Civil Engineering at the University of Moratuwa, in partial fulfillment of the requirements for the degree of Master of Engineering in Geotechnical Engineering.

**August, 2001**

The objectives of this research are, (1). establish a methodology that quantifies the severity levels of causative factor attributes that are rated subjectively, and (2). optimize weights and severity levels of the causative factor attributes in order to achieve maximum agreement between the predicted landslide hazard potential and the actual landslide intensities observed in the field.



University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)

The landslide hazard potential is evaluated based on a decision tree consisting of two levels of attributes identified as primary and secondary. It is assumed that the primary and secondary attributes have independent contributions towards the final result. The relative importance of each component attribute (factor) among the other factors that are connected to a nodal point of this tree is indicated by a subjective (or linguistic) description. Fuzzy sets mathematics which is an effective tool for mathematical representation of subjective expressions such as “quite high”, “medium” or “not that high” etc. are used to describe the relative importance of component attributes. Moreover, linguistic ratings used to describe the severity of each secondary factor are also considered as fuzzy numbers in order to account for the vagueness or the subjectivity in the rating procedure.

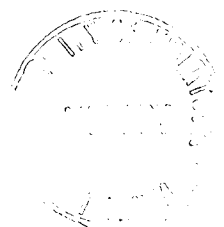
Computer routines are developed to express the fuzzy sets that describe the subjective ratings and weights and then manipulate them using a technique resembling the Monte-Carlo simulation in order to determine the overall hazard potential of a given site. Eventually, the resulting overall degree of hazard, which itself is a fuzzy set, is

converted back to an appropriate linguistic scale containing 'very high', 'high', 'medium', 'low', or 'very low' designations, in order to interpret the overall landslide potential of the site. Once the hazard potential estimates are predicted for every zone demarcated on a selected study area, they are compared with actual landslide intensities estimated for the same zones based on available field data. Then, through an iterative procedure the initially assigned weights of the primary and secondary attributes are systematically adjusted until the field observed landslide intensity matches at a satisfactory level with the predicted hazard potential.

When the developed methodology is applied to the remaining study areas in Sri Lanka, and weights are refined further, it would become an effective tool in accurate landslide hazard zonation.



University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)



## *ACKNOWLEDGEMENT*

It is my pleasure to thank my supervisors, Prof. M. Gunaratne, Dr. H.G.P.A. Ratnaweera, Dr. U.G.A. Puswewela, and Mr. N.S.M.I. Arambepola for their valuable advise, guidance and encouragement during the course of this research.

I also thank the faculty and the visiting faculty of the Civil Engineering Department of the University of Moratuwa for enriching my subject knowledge.

I highly acknowledge the support of Eng. Godwin Vithana, the Director General of the NBRO, and Mr. C.H. de Tissera, the former Director General of the NBRO, for granting me leave to attend lectures at the University of Moratuwa. I also thank for their approval of using published and unpublished data that belong to the Landslide Hazard Mapping Project of the NBRO.

I am grateful to the Research Committee of the NBRO, and the UNDP for facilitating my research with necessary approvals and financial support.

I deeply appreciate the continued interest of Dr. R.K.Bhandari, the former Chief Technical Adviser to the NBRO, and the Head of the International Science and Technology Directorate, India, in the field of landslide hazard investigations and for his guidance for performing this research.

I am grateful to Mr. R.M.S. Bandara, Mr. M.I.D.H. Wijewickrama, Mr. P.P.D.H. Pallewela, Mr. M. Somaratne, Mr. H.A.G. Jayatissa, Mr. K.N. Bandara, Ms. H.M.R. Manike, Mr. Ajith Ratnayaka, and Mr. Sunil Jayaweera, Mr. T. Rasarupan, and late Mr. V.S. Jayaratne of the Landslide Hazard Mapping Project for their prompt attention in providing necessary data and for the benefit of discussions.

I also appreciate the assistance of Mr. P.N. Aluthwela, Mr. D.M.L. Bandara, Ms. Dharshika Perera, and Ms. Buddhimala Rodrigo in computer related executions of my work.

I always remember the valuable advise, guidance and encouragement of my father late Mr. L.S. Arachchi throughout my life. I am indebted to my mother, Ms. M.S. Arachchi, my husband, Dr. M.S.S. Weerasinghe, and my son, Uditha Weerasinghe for the sacrifice they made while I was spending most of my time on this research. Thank you!

Kumari Mala Weerasinghe

August 22, 2001



# Table of Contents

DECLARATION	II
ABSTRACT	III
ACKNOWLEDGEMENT	V
CHAPTER 1	1
INTRODUCTION	1
1.1 LAYOUT OF THE THESIS	3
CHAPTER 2	5
STABILITY OF NATURAL SLOPES	5
2.1 TYPES OF LANDSLIDES	5
2.2 ENGINEERING PROPERTIES THAT AFFECT LANDSLIDES	6
2.3 IMPACT OF RAIN FALL ON SLOPE INSTABILITY	7
CHAPTER 3	9
CURRENT METHODOLOGY FOR LANDSLIDE HAZARD MAPPING	9
3.1 FACTORS CAUSING LANDSLIDES	9
3.1.1. <i>Bedrock Geology</i>	9
3.1.2. <i>Surface Deposits</i>	12
3.1.3. <i>Hydrology and Drainage</i>	13
3.1.4. <i>Slope Range and Category</i>	14
3.1.5. <i>Land Use</i>	14
3.1.6. <i>Landform</i>	14
3.2 QUANTIFYING THE RELATIVE IMPORTANCE OF CAUSATIVE FACTORS	14
3.2.1. <i>Ad-hoc Approach</i>	15
3.2.2. <i>Sighted approach</i>	15
3.2.3. <i>Overlay Approach</i>	15
3.3 CRITERIA FOR RATING A SITE AGAINST SUB-FACTOR ATTRIBUTES	15
3.4 IMPACT OF RAIN FALL ON SLOPE INSTABILITY	16
CHAPTER 4	18
APPLICATION OF FUZZY SET THEORY	18
4.1 THE EXTENSION PRINCIPLE	19
4.2 EVALUATION OF LANDSLIDE POTENTIAL USING FUZZY SETS	20
4.3 MONTE CARLO SIMULATION TECHNIQUE:	22
CHAPTER 5	24
METHODOLOGY FOR ANALYSING THE HAZARD POTENTIAL	24
5.1 INTEGRATION OF FACTOR ATTRIBUTES	24
CHAPTER 6	34
RESULTS AND DISCUSSION	34
CHAPTER 7	57
CONCLUSIONS	57
REFERENCES	59

APPENDIX I	61
APPENDIX II	68
APPENDIX III	76



University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)




## List of Figures

Figure 1.1 Decision tree used for evaluation of fuzzy landslide hazard potential. ....	2
Figure 1.2 Proposed Methodology for Evaluation of Landslide Hazard Potential using Subjective Weights and Severity Levels. ....	3
Figure 3.1 NBRO's present methodology for landslide hazard zonation mapping .....	10
Figure 3.2 Landslide hazard zonation map generated according to NBRO's present methodology .....	17
Figure 4.1 Representation of the fuzzy set "approximately 5" .....	18
Figure 4.2 Membership functions of relative importance (weight) fuzzy sets. ....	21
Figure 4.3 Graphical illustration of Monte Carlo simulation technique. ....	22
Figure 5.1 Preliminary hazard map of a study area .....	25
Figure 5.2 Computer routine developed for execution of the proposed evaluation methodology .....	26
Figure 5.3 Overall landslide hazard potential fuzzy sets of sites <i>A</i> , <i>B</i> , & <i>C</i> .....	27
Figure 5.4 Conversion of overall landslide hazard potential fuzzy sets of sites <i>A</i> , <i>B</i> , & <i>C</i> into subjective terms. ....	28
Figure 5.5 Integrated membership function of the fuzzy sets shown in Figure 5.3 plotted against the evaluation function. ....	30
Figure 5.6 Landslide hazard zonation map generated by fuzzy sets based integration. ....	32
Figure 6.1 Computer routine developed for numerically optimize the weights assigned for different causative factors. ....	35
Figure 6.1a Impact of weights assumed for bedrock geology on cumulative hazard potential . .....	37
Figure 6.2b Impact of weights assumed for surface deposits (overburden) on cumulative hazard potential .....	37
Figure 6.2c Impact of weights assumed for slope range and category on cumulative hazard potential .....	38
Figure 6.2d Impact of weights assumed for hydrology and drainage on cumulative hazard potential .....	38
Figure 6.2e Impact of weights assumed for land use and management on cumulative hazard potential .....	39
Figure 6.2f Impact of weights assumed for landform on cumulative hazard potential .....	39
Figure 6.3 Optimized weights assigned for causative factors on the decision tree. ....	40
Figure 6.4 Increase of reliability of predicted hazard with revised weights.....	40
Figure 6.5 Landslide hazard zonation map generated by fuzzy sets based integration with revised weights .....	42



Figure 6.6a	Number of landslides observed in different bedrock geology sub-factor, lithology .....	45
Figure 6.6b	Relative ranking of lithology mapping units according to the criteria suggested in the NBRO user manual (1995). .....	45
Figure 6.6c	Number of landslides observed in different extents of surface deposits.....	46
Figure 6.6d	Relative ranking of surface deposits mapping units according to the criteria suggested in the NBRO user manual (1995).....	46
Figure 6.6e	Number of landslides observed in different slope range and category mapping units.....	47
Figure 6.6f	Relative ranking of slope category mapping units according to the criteria suggested in the NBRO user manual (1995).....	47
Figure 6.6g	Number of landslides observed in different relief amplitude mapping units.....	48
Figure 6.6h	Relative ranking of relief amplitude mapping units according to the criteria suggested in the NBRO user manual (1995).....	48
Figure 6.6i	Number of landslides observed in different land use mapping units .....	49
Figure 6.6j	Relative ranking of land use mapping units according to the criteria suggested in the NBRO user manual (1995).....	49
Figure 6.6k	Number of landslides observed in different land form mapping units.....	50
Figure 6.6l	Relative ranking of land form mapping units according to the criteria suggested in the NBRO user manual (1995). .....	50
Figure 6.6m	Number of landslides observed in different hydrological map unit areas.....	51
Figure 6.6n	Number of landslides observed in different hydrological map unit shapes. ....	51
Figure 6.6o	Number of landslides observed in different drainage densities. ....	52
Figure 6.7	Landslide hazard zonation maps generated by fuzzy sets based integration with revised weights and rating criteria. ....	54
Figure 6.8	Increase in reliability with revised weights and rates .....	56


 University of Moratuwa, Sri Lanka  
 Electronic Theses & Dissertations  
[www.nbro.mrt.ac.lk](http://www.nbro.mrt.ac.lk)



## List of Tables

Table 3.1 Criteria for relative ranking of mapping attributes.....	11
Table 4.1: Conversion of linguistic values into subjective ratings or weights. ....	20
Table 5.1 Hazard ratings of sites <i>A, B, and C</i> .....	27
Table 5.2 Overall landslide hazard potentials of sites <i>A, B, and C</i> .....	29
Table 5.3 Reliability analysis of the hazard potential values predicted for the study area.....	33
Table 6.1 Increase of reliability of the predicted hazard with revised weights .....	41
Table 6.2 Back analysis on attributes of sites where landslide have been occurred....	43
Table 6.3 Criteria for relative ranking of mapping attributes with refined weights and revised ratings. ....	53
Table 6.3 Increase of reliability of the predicted hazard with revised weights and ratings.....	55



University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)