UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF LANDSLIDE RISK MAPS USING HIGH RESOLUTION AIRBORNE LiDAR DATA

NORBAZLAN MOHD YUSOF

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By

NORBAZLAN MOHD YUSOF

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Engineering

September 2016

DEDICATION

I dedicate my thesis to my family and friends. A special feeling of gratitude to my loving mother, Hjh. Hamidah Bte Hj. Mohd Diah whose words of encouragement and push for tenacity ring in my ears. My beloved wife Hjh. Khadijah Bte Hj. Abdullah who supported me each step of the way and has never left my side. Your love, patience and understanding that allow me to spend most of the time on this thesis. I dedicate this work and give special thanks to my wonderful children Muhammad Danish Zafir, Miza Qistina and Miza Qasrina Faqihah for being my best cheerleaders throughout the entire doctorate program.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Degree of Doctor of Engineering

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Chairman : Associate Professor Helmi Zulhaidi B. Mohd Shafri, PhD
Faculty : Engineering

Landslides are one of the catastrophic that often cause severe property damages, economic loss, and high maintenance costs. Slope failures are a result of multiple triggering parameters, including anthropogenic activities, intense earthquakes, and intense rainfall, and physical properties of unstable surface materials related to geology, land cover, slope geometry, moisture content, and vegetation. This thesis presents a set of novel GIS-based statistical approaches developed for the hazard mapping of rainfall-induced landslides using LiDAR derived data and parameters especially along the highway corridor. These approaches were tested in two areas along the PLUS Expressways Berhad in Perak, Malaysia: (1) Jelapang area (2) Gua Tempurung area.

The objective of this research is firstly aims to identify optimized landslide conditioning parameters that influence the characteristic of landslides and optimise a spatial prediction of landslide hazard areas along the Jelapang and Gua Tempurung area of the North-South Expressway in Malaysia by using two statistical models, namely, logistic regression (LR) and evidential belief function (EBF). The second objective is to design and implement probabilistic (EBF) and statistical (LR) based analysis. LR and EBF determine the correlation between conditioning parameters and landslide occurrence. EBF can also be applied in bivariate statistical analysis. Thus, EBF can be used to assess the effect of each class of conditioning parameters on landslide occurrence. A landslide inventory map with historical landslide locations were recorded using field measurements for both study areas. Subsequently, the landslide inventory was randomly divided into two data sets. Approximately 70 % of the data were used for training the models, and 30 % were used for validating the results. Eight landslide conditioning parameters were prepared for landslide susceptibility analysis: altitude, slope, aspect, curvature, stream power index, topographic wetness index, terrain roughness index, and distance from river. The landslide probability index was derived using both methods (i.e. LR and EBF) and subsequently classified into five susceptible classes by using the quantile method. The

resultant landslide susceptibility maps were evaluated using the area under the curve technique. The success rates of the EBF and LR models in Gua Tempurung were 73.93% and 84.91%, respectively while for Jelapang were 53.95% and 90.12%, respectively. The predicted accuracy rates of EBF and LR models in Gua Tempurung were 67.73% and 83.00%, respectively while Jelapang were 50.1% and 88.78%, respectively. Results revealed the proficiency of the LR method in landslide susceptibility mapping.

The third objective of this research is to produce landslide hazard and vulnerability maps and implement landslide risk assessment which determines the expected degree of loss due to a landslide and the expected number of lives lost, people injured, damage to property and disruption of economic activity. To achieve this objective, the landslide susceptibility maps were transformed into a hazard map considering the main landslide triggering parameter (rainfall) recorded in the landslide inventory database in both study areas. Vulnerability to landslides is also regarded as another main parameter for risk analysis. In order to determine landslide risk in the study areas, the quantitative approach was used. For this purpose, the obtained landslide hazard and vulnerability maps were multiplied to produce risk map and a final landslide risk index map was obtained.

Finally, after obtaining risk map through quantitative approach (i.e. LR), a comparison was carried out with risk maps derived from the "TEMAN" for both of study areas. The comparison of the results from TEMAN and LR method for the category of high risk slopes alone for Gua Tempurung and Jelapamg areas have been reduced to 96.2 % and 79%, respectively. The results proved that the method can be significantly effective for an accurate risk assessment for both study areas. Consequently, produced maps in this research may be helpful for planners, decision makers at PLUS, and government agencies in landslide management and planning in the study area.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Kejuruteraan

PEMBANGUNAN PETA RISIKO TANAH RUNTUH MENGGUNAKAN DATA RESOLUSI TINGGI SISTEM UDARA LiDAR

Oleh

NORBAZLAN MOHD YUSOF

September 2016

Pengerusi : Profesor Madya Helmi Zulhaidi B. Mohd Shafri, PhD
Fakulti : Kejuruteraan

Tanah runtuh adalah salah satu bencana yang sering menyebabkan kerosakan teruk harta, kerugian ekonomi, dan kos penyelenggaraan yang tinggi. kegagalan cerun adalah hasil pelbagai parameter mencetuskan termasuk aktiviti antropogenik, gempa bumi yang kuat, dan hujan lebat, dan sifat-sifat fizikal bahan permukaan yang tidak stabil yang berkaitan dengan geologi, penutup tanah, geometri cerun, kandungan kelembapan, dan tumbuh-tumbuhan. tesis ini membentangkan satu set pendekatan statistik berdasarkan GIS-novel dibangunkan untuk pemetaan bahaya tanah runtuh hujan yang disebabkan menggunakan LiDAR diperoleh data dan parameter terutamanya di sepanjang koridor lebuh raya. Pendekatan ini telah diuji di dua kawasan di sepanjang PLUS Expressways Berhad di Perak, Malaysia: (1) Kawasan Jelapang (2) Kawasan Gua Tempurung.

Objektif kajian ini adalah pertama bertujuan untuk mengenal pasti dioptimumkan parameter udara tanah runtuh yang mempengaruhi ciri-ciri tanah runtuh dan mengoptimumkan ramalan spatial kawasan bahaya tanah runtuh di sepanjang kawasan Jelapang dan Gua Tempurung di Lebuhraya Utara-Selatan di Malaysia dengan menggunakan dua model statistik, iaitu regresi logistik (LR) dan fungsi kepercayaan keterangan (EBF). Objektif kedua adalah untuk mereka bentuk dan melaksanakan kebarangkalian (EBF) dan statistik (LR) analisis berasaskan. LR dan EBF menentukan korelasi antara parameter udara dan tanah runtuh berlaku. EBF juga boleh digunakan dalam analisis statistik bivariat. Oleh itu, EBF boleh digunakan untuk menilai kesan setiap kelas parameter udara di kawasan tanah runtuh. A peta tanah runtuh inventori dengan lokasi tanah runtuh sejarah direkodkan menggunakan ukuran padang untuk kedua-dua kawasan kajian. Selepas itu, inventori tanah runtuh itu dibahagikan secara rawak kepada dua set data. Kira-kira 70% daripada data telah digunakan untuk melatih model, dan 30% telah digunakan untuk mengesahkan keputusan. Lapan tanah runtuh parameter udara telah disediakan untuk analisis tanah runtuh kecenderungan: ketinggian, cerun, aspek, kelengkungan, aliran indeks kuasa, indeks kebasahan topografi, indeks muka bumi kasar, dan jarak dari sungai. Indeks tanah runtuh

kebarangkalian telah diperolehi dengan menggunakan kedua-dua kaedah (iaitu LR dan EBF) dan kemudiannya diklasifikasikan kepada lima kelas terdedah dengan menggunakan kaedah quantile. Paduan peta tanah runtuh kerentanan telah dinilai menggunakan kawasan di bawah teknik keluk. Kadar kejayaan EBF dan LR model dalam Gua Tempurung adalah 73,93% dan 84,91%, masing-masing manakala bagi Jelapang masing-masing 53.95% dan 90.12%. kadar ketepatan yang diramalkan daripada EBF dan LR model di Gua Tempurung adalah 67,73% dan 83,00%, manakala Jelapang masing-masing 50.1% dan 88.78%. Hasil kajian menunjukkan tahap penguasaan kaedah LR dalam pemetaan tanah runtuh kecenderungan.

Objektif ketiga kajian ini adalah untuk menghasilkan tanah runtuh bahaya dan keterdedahan dan melaksanakan penilaian risiko tanah runtuh yang menentukan tahap jangkaan kerugian akibat tanah runtuh dan jangkaan bilangan nyawa yang hilang, orang cedera, kerosakan kepada harta dan gangguan aktiviti ekonomi. Untuk mencapai objektif ini, tanah runtuh peta kecenderungan diubah menjadi sebuah peta bahaya memandangkan tanah runtuh utama mencetuskan parameter (hujan) direkodkan dalam pangkalan data tanah runtuh inventori dalam kedua-dua kawasan kajian. Pendedahan kepada tanah runtuh juga dianggap sebagai satu lagi parameter utama untuk analisis risiko. Dalam usaha untuk menentukan risiko tanah runtuh di kawasan kajian, pendekatan kuantitatif telah digunakan. Untuk tujuan ini, tanah runtuh bahaya dan keterdedahan yang diperolehi didarabkan untuk menghasilkan peta risiko dan akhir peta indeks risiko tanah runtuh telah diperolehi.

Akhirnya, setelah mendapat peta risiko melalui pendekatan kuantitatif (iaitu LR), perbandingan telah dijalankan dengan peta risiko berasal dari "TEMAN" bagi kedua-dua kawasan kajian. Perbandingan keputusan dari kaedah TEMAN dan LR bagi kategori cerun berisiko tinggi semata-mata untuk Gua Tempurung dan Jelapamg kawasan telah dikurangkan kepada 96.2% dan 79% masing-masing. Keputusan membuktikan bahawa kaedah ini boleh menjadi ketara berkesan untuk penilaian risiko yang tepat untuk kedua-dua kawasan kajian. Oleh itu, peta yang dihasilkan dalam kajian ini boleh membantu untuk perancang, pembuat keputusan di PLUS, dan agensi-agensi kerajaan dalam pengurusan tanah runtuh dan perancangan di kawasan kajian

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This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfillment on the requirement for the degree of Doctor of Engineering. The member of the Supervisory Committee were as follows:

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This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

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LIST OF ABBREVIATIONS

PMB	PLUS Malaysia Berhad
PLUS	Projek Lebuhraya Usahasama Berhad
UEM	United Engineers Malaysia Berhad
MHA	Malaysian Highway Authority
ARSM	Malaysian Remote Sensing Agency
MMCGDI	Malaysian Centre for Geospatial Data Infrastructure
MMD	Department of Metrological Malaysia
DGMM	Department of Geoscience & Mineral Malaysia
DSMM	Department of Survey and Mapping Malaysia
PWD	Public Works Department
SPDH	Seremban Port Dickson Highway
KLBK	Konsortium Lebuhraya Butterworth - Kulim
ELITE	North-South Expressway Central Link
TERAS	Teras Teknologi Sdn Bhd
PHS	PLUS Helicopter Services Sdn Bhd
TRL	Transport Research Laboratory, United Kingdom
PBSB	Penang Bridge Sdn Bhd
NKVE	New Klang Valley Highways
LINKEDUA	Laluan Kedua-Malaysia Singapore
NSE	North-South Expressways
GIS	Geographical Information System
RS	Remote Sensing
BOT	Build Operate Transfer
TEMAN	Total Expressway Maintenance Management System
EsMAS	Slope Maintenance Management System
PMMS	Pavement Maintenance Management System
DMMS	Drainage Maintenance Management System
BMMS	Bridge Maintenance Management System

TMMS	Tunnel Maintenance Management System
SgIS	Signboard Inventory System
BgIS	Building Inventory System
CsID	Consultants Information Database
CtID	Contractors Information Database
3pID	3rd Party Access Applications
EIS	Executive Information System
PORS	PLUS Online Registration System
RSA	Rest and Service Area
OBR	Overhead Bridge Restaurant
LiDAR	Light Detection and Ranging
InSAR	Interferometric Synthetic Aperture Radar
BSA	Bivariate Statistical Analysis
MSA	Multivariate Statistical Analysis
LSMs	Landslide Susceptibility Maps
Ps	Spatial Probability
PT	Temporal Probability
TWI	Topographic Wetness Index
SPI	Stream Power Index
TRI	Terrain Roughness Index
ArcGIS	The Name of the Group of Geographic Information System Software Product Lines Produced by ESRI
NDVI	Normalised Difference Vegetation Index
EBF	Evidential Belief Function
Bel	Degree of Belief Map
Dis	Degree of Bisbelief Map
Unc	Degree of Uncertainty Map
Pls	Degree of Plausibility Map
FR	Frequency Ratio
LR	Logistic Regression

AUC	Area Under Curve
AHP	Analytic Hierarchy Process
DTM	Digital Terrain Model
DEM	Digital Elevation Model
WGS84	World Geodetic System 1984
GDM2000	Geoid Datum Malaysia 2000

CHAPTER 1

INTRODUCTION

1.1 General

Natural hazards such as earthquakes, tsunamis, floods, and landslides are severe and climatic events that occur naturally worldwide, but some regions are more vulnerable to certain hazards than others. Any type of natural hazard can be considered a possible danger to human lives and properties; the threat of a naturally occurring event negatively affecting the humans. Landslides principally entail massive failures to infrastructures, properties, and agricultural lands (Promper et al., 2012). Owing to extensive deforestation actions and urban expansion, landslide events will continuously occur in the future because of climate change (Bellugi et al., 2011). Considering the vast coverage of landslide failures, decision makers and planners need to detect landslide-prone locations to design relief procedures (Pradhan, 2011). Landslide susceptibility evaluation relies on the applied technique as well as on the scale and feature of the conditioning parameters (Cortes and Vapnik, 1995). The quality of landslide susceptibility maps depends on the quality and quantity of dataset and the selection of proper analysis technique (Ayalew and Yamagishi, 2005).

Landslides are a disastrous event and a kinetic procedure that may transform and destruct a certain landscape (Lee and Pradhan, 2006). Different natural and anthropogenic agents activate landslides (Guzzetti et al., 2005). Meteorological changes such as heavy rainfall and tectonic forces such as seismic activity are the primary triggering parameters that initiate the landslides (Huang et al., 2012). The combination of natural phenomena, including precipitation and anthropological operations, can also activate landslides (Guadagno et al., 2003). The damages caused by landslides can be mitigated through landslide susceptibility as well as hazard and risk assessment (Pradhan and Buchroithner, 2010). The first phase in landslide hazard and risk evaluation is landslide susceptibility, which ascertains the estimated probability value of event in a certain area (Pradhan et al., 2011; Pradhan and Youssef, 2010). Landslide susceptibility assessment comprises the determination of landslide-prone areas and the estimation of landslide probability in a given location (Pourghasemi et al., 2012a). Landslide susceptibility is characterized using relative quantitative and qualitative studies of the conditioning parameters and historical landslide locations (Domínguez-Cuesta et al., 2007). Dissimilarities between the individualities of each parameter should be appraised to yield a landslide susceptibility map that applies different conditioning parameters. The characteristics of these parameters vary in every region; hence, the first step in creating susceptibility maps is to evaluate the significance of each parameter (Nefeslioglu et al., 2010). Constructing the conditioning parameters is a difficult task (Jibson and Keefer, 1989), and no particular instructions are used to express how many conditioning parameters are adequate for an explicit susceptibility analysis. In addition, no structure exists for the selection of such parameters. These parameters are usually selected based on expert opinion (Nefeslioglu et al., 2008). In the last decade, different approaches for landslide susceptibility mapping have been developed owing to the extreme popularity of geographic information system (GIS) and remote sensing (RS) techniques (Yao et al., 2008). In susceptibility analysis, the landslide conditioning parameters dataset is an essential requirement; thus, landslide-related spatial dataset should first be made. In this regard, different studies have used diverse sorts of conditioning parameters. These parameters can be selected based on the knowledge achieved from field investigations and literature (Smith and Ward, 1998). The construction of landslide-related spatial dataset is critical because certain conditioning parameters may influence the landslide occurrence for a given area, but the identical parameters may be ineffective for other regions. The accuracy of resultant maps relies not only on the adopted approach but also on the quality of the conditioning parameters. The performance of resultant susceptibility maps can be improved through high quality data (Pradhan, 2013b). Full datasets that comprise topological, environmental, geological, and hydrological information can hardly be accessed for every country. Consequently, this study aims to use light detection and ranging (LiDAR)-derived conditioning parameters in landslide susceptibility mapping to examine the efficiency of high-precision conditioning parameters in modeling.

1.2 PLUS Expressways

The PLUS Expressways, also known as PLUS Malaysia Berhad (PMB) or Projek Lebuhraya Usaha Sama Berhad (PLUS), is the largest highway concessionary or build-operate-transfer operator company in Malaysia. A member of the United Engineers Malaysia Berhad (UEM) Group, the company is also the largest toll expressway operator in Southeast Asia and the eighth largest in the world. The company was founded on 27 June 1986 as Highway Concessionnaires Berhad, which was eventually changed into PLUS on 13 May 1988. On 29 January 2002, PLUS Expressways Berhad (PEB) was incorporated in Malaysia as a public company. On 29 November 2010, PMB was incorporated and became involved in investment holding. On 29 November 2011, PLUS completely acquired the PEB assets and liabilities. Pursuant thereto, PMB became the holding company of Projek Lebuhraya Utara-Selatan Berhad, Expressway Lingkaran Tengah Sdn Bhd (ELITE), Linkedua (Malaysia) Berhad, Konsortium Lebuh Raya Butterworth-Kulim Sdn Bhd, Teras Teknologi Sdn Bhd, and PLUS Helicopter Services Sdn Bhd as well as the substantial shareholder of Touch ‘n Go Sdn Bhd. In addition, PMB acquired Penang Bridge Sdn Bhd from UEM Builders Berhad.

PLUS, a wholly-owned subsidiary of PMB, was incorporated on 27 July 2011 to consolidate all highway concessionaires acquired under a single entity. The acquisition of all five highway concession assets was completed on 12 January 2012. With the completion of its acquisition, PMB is then considered the largest toll expressway operator in Malaysia and one of the largest in Southeast Asia.

Table 1.1 : Total alignment of PLUS Expressways

Company Name	Date of Establishment	Highway Operator
Projek Lebuhraya Utara-Selatan Berhad (PLUS)	1986	North-South Expressway New Klang Valley Expressway Federal Highway Route 2
Expressway Lingkaran Tengah Sdn Bhd (ELITE)	1993	North-South Expressway Central Link
Linkedua Malaysia Berhad (LINKEDUA)	1994	Malaysia-Singapore Second Link and Second Link Expressway
Seremban–Port Dickson Highway (SPDH) Sdn Bhd	1994	Seremban-Port Dickson Highway
Konsortium Lebuhraya Butterworth-Kulim (KLBK) Sdn Bhd	1993	Butterworth-Kulim Expressway
Penang Bridge Sdn Bhd (PBSB)	1994	Penang Bridge

1.3 Problem statement

Numerous landslides have been activated recently along the east coast and north–south highways in Peninsular Malaysia. The mountainous areas along the north–south highways in the states of Perak, Pahang, and Johor are the hardest hit areas. These landslides cost millions of ringgit to PLUS Highway Berhad. The extent of damage can be reduced or minimized if long-term hazard and risk maps, which predict landslide-prone areas, have been developed and are implemented.

PLUS have in total 6908 number of slopes inventory registered in Total Expressway Maintenance Management System (TEMAN) in which 607 slopes are ranked very high and high risk (PLUS Network Maintenance Report 2015). The hazard and risk ranking for slopes that were established by Transport Research Laboratory (TRL) in the year 2000 and have never been visited since then. The engineering appraisals for hazard and risk maps shall be carried out in every two years as suggested by TRL (Heath, 1996). The landslides that occurred in the New Klang Valley Expressway (NKVE) in 2003 have alerted highway authorities and other organizations toward the seriousness of landslide management and prevention. The memory of the October 2002 landslide in Kuala Lumpur remains fresh in the consciousness of people because it severely destroyed a number of houses and killed six people. The landslides that occur in Malaysia are mainly triggered by tropical rainfall and flash floods, which cause failure in the rock surface along the fracture, joint, and cleavage planes. The geology of the country is relatively stable, but its continuous development and urbanization leads to deforestation and weathering; the erosion of the covered soil masses seriously threatens the slopes.

Earthquake is a serious source of landslides in mountainous terrain. Although Malaysia does not belong to the seismic zone of the world unlike Japan, which experiences earthquake every hour, it is surrounded by earthquake-prone areas. Thus, the probability of transmitted mild shocks remains as experienced in the western parts of the country in 2006.

Minimal work has been performed on regional landslide hazard and risk analysis along the PLUS expressway in Malaysia. Pradhan and Lee (2010a) conducted landslide hazard and risk analysis for Penang Island using a frequency ratio (FR) and logistic regression (LR) model. Althuwaynee et al. (2012) evaluated the landslide susceptibility in Kuala Lumpur and its surrounding areas using an evidential belief function (EBF) model. Another research was conducted in the Kuala Lumpur metropolitan area and surrounding areas for landslide hazard assessment through rainfall threshold analysis (Althuwaynee et al., 2014). These models failed to provide the weightage for landslide causative parameters. Weight determination can only be conducted through artificial neural network (ANN) and fuzzy logic models, among others. Ali and Hui (2005) developed a real-time GPS-based transmitter (i.e., EWarns) to monitor rainfall information for certain stretches of highways and tourism locations in Cameron Highland. In the last few years, various researchers in different countries have conducted landslide hazard evaluation using GIS and data mining such as fuzzy logic and ANN (Ercanoglu and Gokceoglu, 2002; Pistocchi et al., 2002). However, the result of these works cannot be directly used in the Malaysian landslide hazard analysis because of the changes in the geographical environment set up, litho types, different climatic conditions, and so on. Local geographical settings cause different landslide types based on completely different mechanisms and are incomparable.

1.4 Research motivation

Landslides are the most commonly occurring natural catastrophe that influences humans and their adjacent environment. Asia and the Pacific regions are particularly vulnerable to such calamity, and their social and economic stabilities are greatly affected. Pradhan (2010a) indicated that approximately 90% of the destruction related to natural catastrophes in Malaysia is produced by landslide. In fact, the average annual landslide damage is as high as USD 10 million (Shaluf et al., 2003). Thus, the attention devoted to providing proper landslide management has risen over the past several years. Recurrent landslides occur in certain regions mostly because of un-planned urbanization, construction, and deforestation. Nonetheless, landslide disasters can be governed by human involvement using geospatial technology. Such technology can facilitate landslide prevention actions to detect the landslide areas and to attain an early warning system for this catastrophe.

Table 1.2 : Maintenance data extracted from Total Expressway Maintenance Management System (TEMAN) database from year 2001 – 2012

Total no of slopes	No of slopes affected	No of repair works	Total no of slopes ranked Very High and High
6908	4616	42,794	High (421) Very High (186) 607

The key motivation of this research is to identify exact location of hazardous and risk areas that could trigger danger to motorist and PLUS' assets and use generated maps to implement preventive maintenance along the North–South Expressway (NSE) for a sustainable environment. There are 6908 number of slopes registered and maintained by PLUS and 607 of them are ranked as very high and high risk, as tabulated in table 1.2. The number of maintenance work are very high at 42,794 times spreading at various locations along North-South Expressways prompt high interest within PLUS to identify in which location of maintenance work shall be intensified. The areas susceptible to landslides should be identified to reduce the damage and larger maintenance work. To recognize such areas, landslide inventory maps should be generated as a basis for landslide susceptibility mapping. In addition to inventory and susceptibility mapping, the optimization of conditioning parameters is of great interest as well. Governments and planners can use the findings of this study to support the first responders in emergencies and to update the urban planning strategies. Such data can decrease the requirements to perform field surveys by agencies such as the departments of surveying.

The Total Expressway Maintenance Management System (TEMAN) has been used by PLUS since 2000. In TEMAN, a sub-system called the Expressway Slope Maintenance Management System (ESMaS) has been designed to cater for all the activities for slope maintenance. Hazard and risk ranking was established by the Transport Research Laboratory (United Kingdom) in 2000 in ESMaS for all 6716 individual slopes along the NSE. The frequency of periodic inspections was then derived. However, PLUS failed to retrieve and re-execute the methodology used to establish the hazard and risk. Therefore, PLUS failed to identify the latest conditioning parameters that could trigger landslides from the macroscopic view, with the exception of the current conditions that can be visualized from walkthrough inspection activities as the source of evidence for maintenance activities.

1.5 Research objectives

This research mainly aims to develop models for the identification of landslide hazards, vulnerability, and risk areas in the proposed study area using high-resolution airborne LiDAR data and GIS tools.

The main objectives of this project are as follows:

1- To identify optimized landslide conditioning parameters that influence the characteristics of landslides, particularly in a selected stretch of North-South Expressways;
2- To design and implement probabilistic-based EBF and statistical-based LR models for landslide susceptibility and hazard analysis for North-South Expressways;
3- To produce landslide hazard and risk maps for both pilot study areas as well as to establish a comprehensive methodology for landslide analysis in order to improve the existing TEMAN system.

1.6 Research questions

This thesis comprehensively addresses the following research questions:

1. What are the most applicable conditioning parameters in landslide susceptibility assessment especially for highway corridor?
2. How effective are the number of conditioning parameters on the accuracy of the results derived from the susceptibility models?
3. How can the hydrological, geological, and morphological circumstances influence the landslides in the case studies especially in tropics?
4. Which methods are the most suitable for the spatial analysis for landslide susceptibility assessment in both study areas?
5. What type of spatial and non-spatial data is prerequisite and available for conducting landslide hazard and risk assessment in the case study areas?
6. What categories of spatial analysis tools and techniques can be used for processing data and generating hazard and vulnerability indicators?
7. How are the landslide hazards, vulnerability, and risk distributed over the study areas?
8. How can the results of landslide risk contribute to hazard reduction designs and early warning systems over both study areas?
9. How can the resultant landslide hazard, vulnerability, and risk maps improve the existing TEMAN at PLUS?

1.7 Scope of research

This study aimed to detect and predict landslide-prone areas only in selected stretches of NSE using LiDAR and GIS techniques applicable for tropical countries such as Malaysia. The proposed methodology was developed by deriving the landslide conditioning parameters from remote sensing resources and historical landslide inventory maps produced from onsite inspection data. Prediction models were constructed based on bivariate and multivariate statistical-based methods and were then applied in two study areas. All resultant maps were evaluated for accuracy using success and prediction rate curves. A hazard map was developed by integrating precipitation (triggering parameters) and spatial probabilities, and a risk map was used to assess the affected elements of landslide risk. Landslide susceptibility models as well as hazard and risk prediction assessment can serve as the primary keys in developing a warning system and managing mitigation plans. Figure 1.1 shows a framework of the research scope.

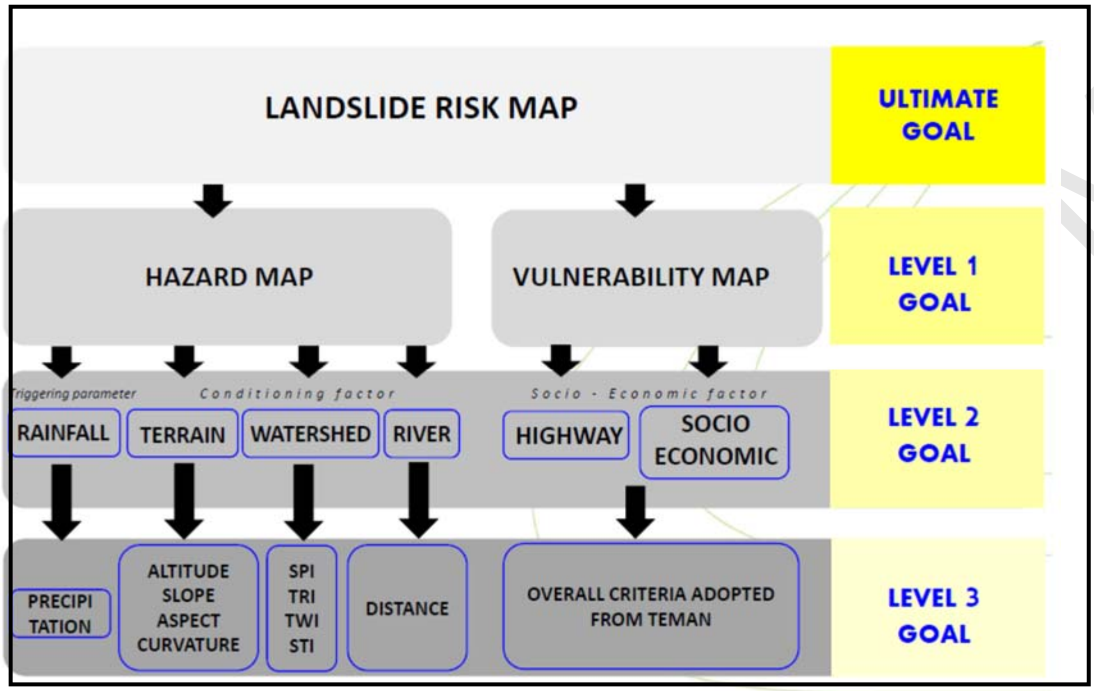

Figure 1.1 : A framework of the scope of research

1.8 Thesis outline

This thesis is organized into five chapters. The summary of each chapter is given in the succeeding paragraphs.

i. Chapter one: Introduction

This chapter discusses the problem statement, objectives, and the scope of the study. In addition, this chapter presents the research questions.

ii. Chapter two: Literature review

This chapter provides an overview of the landslide status in various regions as well as the previous work of using remote sensing and GIS for landslide detection and susceptibility mapping. This chapter also discusses both the traditional and the innovative and emerging techniques for detecting landslide-prone areas. In addition, the methodology used for landslide inventory and susceptibility mapping using qualitative and quantitative analysis is discussed, and the validation methods for assessing the accuracy of the developed maps are summarized. This chapter also depicts the main parameters of landslide risk analysis.

iii. Chapter 3 : Materials and methodology

This chapter describes in detail about the characteristic of the study area and presents the data, methodology and framework applied in this research. This chapter also discusses further the GIS-based modelling for landslide susceptibility, the validation of susceptibility maps, hazard analysis, as well as vulnerability and risk analysis using various GIS techniques and LiDAR data.

iv. Chapter 4: Results and discussion

This chapter focuses on the results obtained from the analysis on landslide susceptibility, hazard analysis, as well as vulnerability and risk analysis. These findings are supported by diagrams, tables, equations and charts for both study areas.

v. Chapter 5: Conclusion and recommendation

Recommendations

This chapter provides the research conclusions as well as the recommendation for future research for the study area.

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LIST OF PUBLICATIONS

Journals Articles

Norbazlan, M. Y., Pradhan, B., Helmi Zulhaidi M.S, Mustafa Naemah J. & Zainuddin Y. 2015. Spatial Landslide Hazard Assessment Along the Jelapang Corridor of the North-South Expressway in Malaysia using High Resolution Airborne LiDAR Data. *Arabian Journal of Geosciences*, pp 9789-9800

Norbazlan, M. Y., Pradhan, B., Helmi Zulhaidi M.S, Mustafa Naemah J. & Zainuddin Y. 2016. Slope Vulnerability and Risk Assessment along the North-South Expressway (Gua Tempurung) in Malaysia using high-resolution Digital Elevation Model (DEM). PLOS One. (under review).

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Norbazlan, M. Y. 2012. The PLUS GIS: A New Perspective in Map Visualisation at Asia Geospatial Forum 2012 from 17 to 19 September 2012 at Milea Hotel, Hanoi Vietnam.

Norbazlan, M. Y. 2013. Web-Based TEMAN (Total Expressway Maintenance Management System) with Street level Panoramic Imagery at World Geospatial Forum, from 13 to 16 May 2013 at Beurs World Trade Centre, Rotterdam, the Netherlands.

Norbazlan, M. Y. 2013. Web-Based TEMAN (Total Expressway Maintenance Management System) with Street level Panoramic Imagery at Asia Geospatial Forum, from 24 to 26 September 2013 at Putra World Trade Centre, Kuala Lumpur.

Norbazlan, M. Y., Pradhan, B., Helmi Zulhaidi & Zainuddin Y. 2013. Landslide Analysis along the Expressways using Remote Sensing and Geographic Information System on 15 November 2013 at CIHTMB (Chartered Institution of Highways and Transportation) Technical Talk, Persada PLUS, Kuala Lumpur.

Norbazlan, M. Y., Pradhan, B., Helmi Zulhaidi, & Zainuddin Y. 2014. Landslide Susceptibility Mapping along PLUS Expressways in Malaysia using Probabilistic Based Model in GIS IGRSM 2014 at Berjaya Times Square Hotel, Kuala Lumpur 21-22 April 2014 (Scopus).

Norbazlan, M. Y., Pradhan, B., Helmi Zulhaidi & Zainuddin Y. 2015. Landslide Susceptibility Mapping along PLUS Expressways in Malaysia using Probabilistic Based Model in GIS Geospatial World 2014 at Centre International Conferences Geneva, Switzerland from 06 to 09 May 2014.

Norbazlan, M. Y., Pradhan, B., Helmi Zulhaidi & Zainuddin Y. 2015. Landslide Hazard Analysis at Jelapang of North-South Expressway in Malaysia Using High Resolution Airborne LiDAR Data at Geospatial World Forum 2015, Portugal from 25 to 29 May 2015.

Honours & Awards

Asia Geospatial Excellence Award for application of Geospatial Technology in Roads and Highways to PLUS Berhad by Norbazlan Mohd Yusof for Total Expressways Maintenance Management System, a decision support tool to facilitate management control of highway inventories or assets, their condition and related maintenance activities. This helps identify high-risk slopes that would pose a hazard in the event of failure based on the criteria such as slope height and distance from the carriageway.

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