UNIVERSITI PUTRA MALAYSIA

ROCKFALL HAZARD ASSESSMENT BASED ON AIRBORNE LASER SCANNING DATA AND GIS IN TROPICAL REGION

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

ROCKFALL HAZARD ASSESSMENT BASED ON AIRBORNE LASER SCANNING DATA AND GIS IN TROPICAL REGION

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April 2016

Chairman : Associate Professor Biswajeet Pradhan. PhD
Faculty : Engineering

Rockfall is one of the catastrophes which threaten the human's life and properties in mountainous and hilly regions such as Malaysia with steep and high elevation topography. Prediction and mitigation of such phenomenon can be carried out via the identification of rockfall source areas and modelling of rockfall trajectories and their characteristics. Therefore, a proper rockfall analysis method is required in order to map and thus understand the characteristics of rockfall catastrophe. This research adopted various methods to investigate, analyze and assess rockfall in terms of identification of rockfall source areas, modelling of rockfall trajectories and their characteristics and consequently rockfall hazard map. A portion of North-South Expressways at Jelapang, Malaysia was used as a study area for rockfall hazard assessment. An airborne laser scanner (ALS) was used to gather high-density data point (3-4 pts/m^2). After post-processing in terms of filtration, interpolation and fill, high-resolution DEM (0.5m) was generated. In this study, rockfall source areas were identified using multi-criteria method based on DEM derivates, terrain type or land use/cover (LULC) and high spatial resolution aerial photo (13cm). After the rockfall source areas were identified, rockfall modelling has been done using 3D rockfall model integrated into GIS software. Rockfall modelling processes are carried out through discrete time steps kinematic algorithms that are automatically determined by both particle velocity and cell size. Kinematic algorithms allow rockfall modelling in different motion modes in a 3D frame. Mechanical parameters (coefficients of restitution tangential (Rt) and normal (Rn) and friction angle) were considered to be crucial for rockfall modelling. Multi rockfall scenarios were produced based on a range of mechanical parameters values. Rockfall spatial distribution modelling technique was utilized to display the rockfall spatial distribution frequency, bouncing or flying height and kinetic energy for each scenario according to the outcomes of 3D rockfall process modelling. The hazard map predicting rockfall hazard for each scenario was produced by using of spatial modelling which considers all raster of the rockfall characteristics. Analytic hierarchy process (AHP) was applied in this step to get the weight for each rockfall characteristics raster. The rockfall hazard along the expressway was observed and the hazard percentage was demonstrated. The result shows rockfall behaviour is highly affected by mechanical parameters values. It clears that when the values are big, the rockfall trajectories have the longest stopping distance and more complicated behaviour which result in increasing of rockfall characteristics. This results in rising of the areas affected by

rockfall hazard. In addition, in order to mitigate rockfall hazard, a barrier location was suggested based on less bouncing height and energy. The entire simulation procedure was repeated with a barrier to show the efficiency of barrier eliminating rockfall hazard. The result shows the barrier in suggested location can effectively aid in rockfall hazard mitigation. The outcomes of this study prove the ability of the proposed and applied methods to make valid detection and prediction for rockfall phenomena. The results are expected to not only provide a quick comprehensive assessment of future rockfall hazards and risks but also serve as a guide for barrier designers. The applied methods and information will add a valuable contribution to the rockfall management in the tropical Malaysia.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PENILAIAN BENCANA RUNTUHAN BATU BERDASARKAN DATA IMBASAN LASER DI UDARA DAN SISTEM MAKLUMAT GEOGRAFI DI KAWASAN TROPIKA

Oleh

ALI MUTAR FANOS

April 2016

Pengerusi : Profesor Madya Biswajeet Pradhan, PhD
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Runtuhan batu merupakan salah satu malapetaka yang mengancam kehidupan manusia dan hartanah di kawasan pergunungan dan berbukit-bukau seperti Malaysia yang mempunyai topografi tanah tinggi yang curam dan jauh dari aras laut. Ramalan dan usaha mengurangkan kesan fenomena ini boleh dilakukan dengan mengenal pasti kawasan punca runtuhan batu dan membina model trajektori runtuhan batu dan ciri-cirinya. Oleh itu, kaedah analisis runtuhan batu yang betul diperlukan untuk menyediakan petunjuknya dan dengan itu ciri bencana runtuhan batu dapat difahami. Kajian ini menggunakan pelbagai kaedah untuk mengkaji, menganalisis dan menilai runtuhan batu dari segi pengenalpastian kawasan punca runtuhan batu, model trajektori runtuhan batu dan ciri-cirinya, dan seterusnya petunjuk bencana runtuhan batu. Penyelidikan ini dibahagikan kepada dua sudut umum. Sebahagian daripada Lebuhraya Utara-Selatan di Jelapang, Malaysia telah digunakan sebagai kawasan kajian untuk menilai bencana runtuhan batu. Pengimbas Laser di Udara (ALS) telah digunakan untuk mengumpul data dengan ketumpatan tinggi (3-4 titik / m²). Selepas pascapemprosesan dari segi penapisan, mengisi dan interpolasi, resolusi tinggi DEM (0.5m) telah dijanakan. Dalam kajian ini, kawasan punca runtuhan batu telah dikenal pasti dengan menggunakan kaedah pelbagai kriteria berasaskan hasil DEM, jenis rupa bumi atau penggunaan tanah / perlindungan tanah (LULC) dan gambar ruang dari udara beresolusi tinggi (13cm). Selepas kawasan punca runtuhan batu dikenal pasti, pemodelan runtuhan batu telah disediakan dengan menggunakan model runtuhan batu 3D yang bersepadu dalam perisian GIS. Proses pemodelan runtuhan batu dijalankan melalui masa diskret dengan langkah algoritma kinematik yang ditentu secara automatik oleh kedua-dua faktor, iaitu halaju zarah dan saiz sel. Algoritma kinematik membolehkan pemodelan runtuhan batu dalam mod gerakan yang berbeza dalam rangka 3D. Parameter Mekanikal (pekali pemulangan tangen (Rt) dan biasa (Rn) dan sudut geseran) telah dianggap sebagai penting untuk pemodelan runtuhan batu. Senario pelbagai runtuhan batu telah dihasilkan dengan berdasarkan julat nilai parameter secara mekanikal. Teknik pemodelan ruang serakan runtuhan batu telah digunakan untuk memaparkan kekerapan ruang serakan, lantunan atau ketinggian layangan, dan tenaga kinetik bagi setiap senario mengikut hasil pemodelan proses runtuhan batu 3D. Petunjuk bencana yang meramalkan bencana runtuhan batu untuk setiap senario telah dihasilkan dengan menggunakan pemodelan ruang yang mengambil kira semua gugus

ciri runtuhan batu. Proses hierarki secara analisis (Analytic Hierarcy Process - AHP) telah digunakan bagi langkah ini untuk mengetahui bebanan setiap gugus ciri runtuhan batu. Bencana runtuhan batu di sepanjang lebuhraya diperhatikan dan peratusan bencana dipaparkan. Hasil kajian menunjukkan bahawa lakuan runtuhan batu amat dipengaruhi oleh nilai parameter mekanikal. Ini mencerahkan bahawa apabila nilai parameter mekanikal ini besar, trajektori runtuhan batu akan melalui jarak berhenti paling jauh, dan lebih banyak lakuan rumit hingga menambah ciri runtuhan batu. Ini menyebabkan peningkatan kawasan yang terlibat dengan bencana runtuhan batu. Di samping itu, untuk mengurangkan bencana runtuhan batu, dicadangkan supaya lokasi penghadang disediakan dengan berdasarkan ketinggian lantunan dan tenaga yang kurang. Prosedur simulasi keseluruhan diulang dengan suatu penghadang untuk menunjukkan kecekapan penghadang dalam mengelakkan bencana runtuhan batu. Hasil kajian menunjukkan bahawa penghadang pada lokasi yang dicadangkan menjadi alat yang berkesan untuk mengelakkan bencana runtuhan batu. Hasil kajian ini membuktikan bahawa kaedah yang dicadangkan dan digunakan berupaya untuk mengesan dan meramalkan fenomena kejatuhan batu secara sahih. Keputusan dijangka bukan sahaja dapat menyediakan penilaian komprehensif yang cepat terhadap bencana dan risiko runtuhan batu pada masa hadapan tetapi juga bertindak sebagai panduan untuk mereka bentuk penghadang. Kaedah dan maklumat yang digunakan akan menambah sumbangan bermakna untuk pengurusan runtuhan batu di kawasan tropika Malaysia.

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I certify that a Thesis Examination Committee has met on 29 April 2016 to conduct the final examination of Ali Mutar Fanos on his thesis entitled "Rockfall Hazard Assessment Based on Airborne Laser Scanning Data and Gis in Tropical Region" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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Declaration by graduate student

I hereby confirm that:

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Declaration by Members of Supervisory Committee

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) are adhered to.

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Signature: ______________________________
Name of Member of Supervisory Committee: Dr. Azlan A. Aziz

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LIST OF ABBREVIATIONS

RS	Remote Sensing
LiDAR	Light Detection and Ranging
GIS	Geographic Information System
DEM	Digital Elevation Model
ALS	Airborne Laser Scanning
TLS	Terrestrial Laser Scanning
MLS	Mobile Laser Scanning
RADAR	Radio Detection And Ranging
InSAR	Interferometric Synthetic Aperture RADAR
SRTM	Shuttle Radar Topographic Mission
ASTER	Advanced Spaceborne Thermal Emission and Reflectance Radiometer
INS	Inertial Navigation System
IMU	Inertial Measurement Unit
LULC	Land use/cover
AHP	Analytic Hierarchy Process
Rn	Normal coefficient of restitution
Rt	Tangential coefficient of restitutio

CHAPTER 1

INTRODUCTION

1.1 General

In steep mountainous and hilly terrain, rockfalls are natural phenomena. Rockfalls can differ both in magnitude and in the frequency by which they travel down a slope. Such natural phenomenon can pose a serious danger to the transportation corridors which pass through this area. Rockfalls are responsible for delays in goods transportation, damage to both infrastructure and vehicles, and injuries to persons in the region including deadly accidents (Hoek, 2007). While it is true that rockfalls occur naturally, the rockfalls hazard frequency can be increased with more steepening of the rocky slope, high density of rainfall and poor blasted practice that has been used in transportation corridor construction. In both man-made and natural slopes, rockfall hazard identification and mitigation are significant to maintain the functionality and safety of such transportation corridors.

Rockfall occurrence can vary both temporally and spatially along transportation corridors. Therefore, to identify a portion of a transportation corridor as a rockfall hazard is beyond the boundaries of regular engineering analysis. Conventionally, once a rockfall hazard is specified, based on historical information, remedial measures are assessed. The processes in the rockfall analysis have three main stages: (1) location identification of rockfall hazard, (2) location investigation to assign the rockfall source areas, and (3) determination of the geometry characteristics of site that can be used as a boundary condition for the analysis of rockfall. The result from such analysis provides the rockfall characteristics associated with each rockfall event, including the frequency, velocity, bounce height and energy. The factors that affect this result are the parameters that control how the energy is dissipated and absorbed as the falling rock bounces, rolls and slides down the slope surface, and the three-dimensional geometry of terrain that provides the slope characteristics where these processes occur.

1.2 Slope Failure Problem

Rockfalls are a great threat to public transportation networks and properties in hilly regions and rock cutting. However, rockfalls do not present the same degree of economic danger as large-scale failures that can block significant transportation roads for many days at a time, the numbers of the people killed by rockfalls hazard tend to be of the same order as people killed by the other types of rock slope instability. Martin (1988) reported that rockfalls, small rockslides and ravelling are the most frequent problems on transport roads in mountainous regions of North America. Hungr and Evens (1988) observed that there had been 13 rockfall loss of life in the last 87 years in the mountain motorways of British Columbia at Canada. Over the last decades, the increasing slope failure has been observed In Malaysia. Most of them have happened on cut slopes or on embankments alongside roads and highways in mountainous areas

(Pradhan et al., 2010). Shu & Lai (1980) recorded the main rockfall event at Gunung Cheroh, Ipoh, Malaysia, the rockfall included collapsing of the whole face of the cliff as one plate measuring certain weighed 23,000 tonnes and 33 meters in length. Resulting in 40 person deaths and many cattle as well. Amongst these failures was the latest slope failure with the disastrous effect that happened on 7 of August 2011 in Kampung Sungai Ruil, Cameron Highlands, while another main slope failure occurred on 21 May 2011 in Hulu Langat. In addition, Rockfall buried the back part of an illegal factory on the foothills of a limestone hill which occurred in Bercham, Ipoh, Perak, Western Malaysia in December 2004 and caused 2 deaths. There are also some rockfall incidents which generate major inconvenience but without any casualties like Athenaeum Condominium, Ulu Kelang: May 1999 and rocky slope failure at Bukit Lanjan on the New Kelang Valley Expressway: 2003 that resulted in traffic disruption for six months.

1.3 Background of Study

Rockfalls computer simulation programs have become an easy and cost-effective means for rockfall analysis. Various simulation programs have been evolved and implemented in the practical prediction of rockfall over the past two decades. Those programs use simplified parameters to mimic rockfall behavior calculating trajectories and their characteristics and providing handy statistical information for the design of remedial ways. The parameters needed for rockfall simulation including the geometry of slope, slope material characteristics and rock properties, of which the coefficient of restitution (COR) of a slope is the key input and is the most challenging to assess. The Coefficient of Restitution (Rn and Rt) explains the kinetic behavior of a falling rock as it affects against the surface of the slope. Every time the rocks impact against the surface of the slope, the properties by which they move are altered. Hoek (2007) described COR as mathematical expressions of the surface material retardant ability when dealing with the falling rocks. Every slope has unique characteristics, which differ from region to another across the slope. Every falling rock has a unique characteristic as well. It is, therefore, very hard to characterize the coefficient of restitution since each site has a unique set of characteristics. Simplification of this, the coefficient of restitution is generalized to match the behaviors of the similar falling boulders down the slope which have realized parameters. The coefficient of restitution is most commonly identified as the loss of velocity in both directions normal and tangential to the slope surface.

1.4 Scope of Study

Rockfall occurs in steep terrain and determining the slope geometry on which these hazards occur is demanding. Remote survey methods are generally preferred to create the steep rock slope geometry. The remote survey technique that has become quite popular in the last ten years is Light Detection and Ranging (LiDAR). Since airborne LiDAR technique is widely popular these days, it has been widely used for rockfall analysis. In this thesis, airborne LiDAR technique was used to derive three-dimensional digital elevation model (DEM) of slope terrain.

The analyses of rockfall described in this thesis employ 3D physical rockfall modelling process in combination with GIS-based distribution modelling utilized to evaluate the rockfall hazard in regional scale. The achievement of this research has been performed employing 3D rockfall model integrated into GIS which significantly expands the functionality of GIS in the rockfall hazard analysis. Through the use of both vector and raster dataset, the model is able to efficiently handle distribution geometry and mechanical parameters. Raster rockfall distributed modelling approach is utilized to derive the rockfall spatial distribution in terms of rockfall frequency, bouncing height and energy depending on the outcome of 3D rockfall trajectories modelling. The influence of barrier, such as catch net in the advanced rockfall hazard analysis, is also taken into account. The input parameters required for this analysis, such as the slope geometry (slope, aspect and curvature), were derived from high-resolution DEM. The mechanical parameters (coefficient of restitution and friction angle) were obtained from an extensive literature review. Rockfall multi-scenario is conducted based on the minimum and maximum common values of these parameters based on the geological setting and the terrain type of the study area. Finally, a spatial modelling in combination with analytical hierarchy process (AHP) was applied to produce the rockfall hazard map based on rockfall characteristics (frequency, height and energy).

1.5 Problem Statement

Ipoh is one of the main cities in Malaysia. The bedrock geology for Ipoh and surrounding areas are granitic hills, limestone bedrock, and mine. As a result, a lot of engineering geologic issues have been encountered Ipoh and its immediate surroundings, involving rockfalls and landslides. The bedrock of limestone in every region rises over the alluvial plains forming limestone hills with vertical to sub- vertical slopes.

The major trigging factors of rockfalls are ascribed to the rainwater along the crevices and joints exist in the limestone and it is unavoidable that the rock plates will fracture from the cliff where this action is sufficiently decreased its stability. Rockfalls might have also been precipitated by a number of secondary triggers, like vibrations such as low-intensity seismic, mine explosion and passing cars surrounding and oscillation associated with the wind blows through vegetation that growing on cliff faces and lost cohesion due to extended periods of humid weather. Rock blocks and slabs will thus fall down and occasionally even though the time and period of subsequent rockfalls are unpredictable.

The North–South Expressway (NSE) is considered as the longest highway in Malaysia. The highway links several important cities and towns in the west Peninsular Malaysia involving Ipoh, which acts as the 'backbone' of the western coast of Peninsula. The NSE extends from the Malaysian-Thai boundary in the north to the boundary with adjacent Singapore in the south. NSE in Malaysia is contributing to the country economic growth through social, commercial, and the tourism sector. The rockfall incidents are frequently happened along the NSE (Figure 1.1).

Jelapang area is very close to Ipoh and it is a small section of PLUS Highway Berhad in Malaysia, is susceptible to rockfall hazard. PLUS Berhad owns the franchise with a total of 987 kilometers of toll expressways in Malaysia. Currently, the highway considers good in terms of its status and connectivity to each state but some areas requiring urgent attention. Slope stability at these places is of most interest as any instability could cause a hazard to drivers. The slope of the study area is cut slope and categorised as high potential risk. In addition, based on the inventory data the study area had rockfall events in three different regions within the study area (Figure 1.2). Moreover, the study area is located in the direction of two faults (Figure 1.3) that can increase rockfall potential, as stated by Bråtveit et al. (2016), the instability problems are largely related to local faults. Therefore, rockfall hazard evaluation along the NSE is extremely significant. The achievement of this research will be significantly useful to rockfall hazard preparedness and damage reduction to PLUS Highway Berhad.

Figure 1.1 Rockfall Incidents along the North-South Expressway

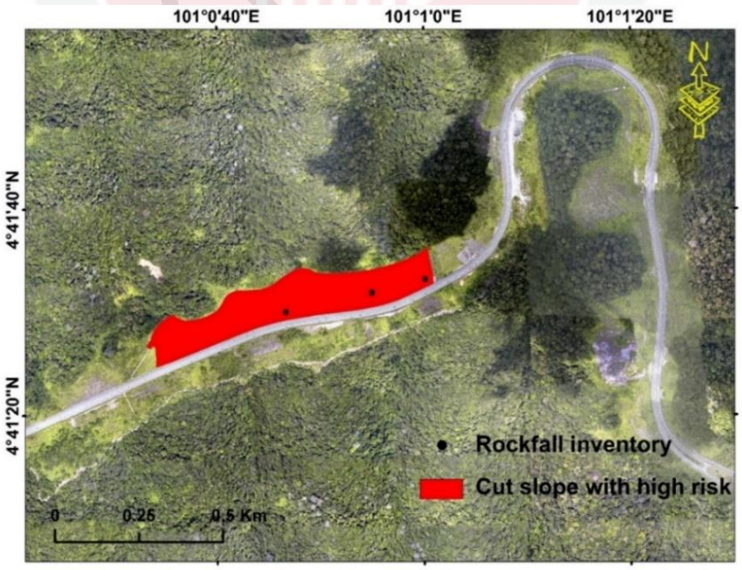

Figure 1.2 Inventory Information of Rockfall Events within the Study Area

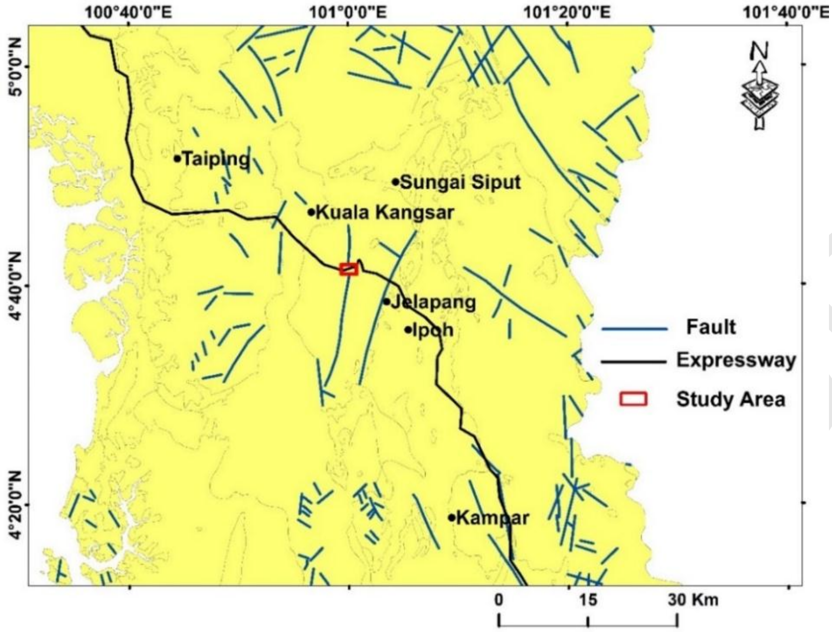

Figure 1.3 The Study Area Located in the Direction of Two Faults

1.6 Research Gaps

There are many studies have been performed regarding characterization of rockfall hazard. However, there is some limitation associated with the implementation of these studies. The main gaps that obtained from extensive literature review are:

1- The use of airborne laser scanning for rockfall hazard assessment is infrequent.
2- The identification of rockfall source areas is the most challenge in rockfall simulation. In addition, most of researchers relied only on slope angle to determine rockfall source areas.
3- A lot of rockfall studies are performed based on 2D rockfall modelling. However, these models are critical to select 2D slope profile and are restricted to provide the spatial distribution of rockfall trajectories and their characteristics. Therefore, they cannot provide realistic assessment results of rockfall hazard.
4- Almost all studies have ignored the uncertainty due to mechanical parameters that strongly affect the outcomes of rockfall modelling.

1.7 Research Objectives

This research proposes some methods that clearly contribute to the gap in the literature. The main research objective of this research is to predict rockfall hazard along a portion of NSE using LiDAR data as:

1- To develop a method of seeder location identification and mechanical characteristics.
2- To derive rockfall characteristic in term of trajectories, frequency, bouncing height, velocity and energy in multi-scenarios.
3- To generate rockfall hazard map for each scenario to delineate area at risk and suggest a barrier location.

1.8 Research Questions

This thesis comprehensively addresses the following research questions:

1- What is the accuracy of digital elevation model (DEM) that can be obtained from using of LiDAR technique?
2- What are the probable sources of rockfall (seeder points)?
3- What are the possible trajectories of falling rocks down the slope?
4- Where do falling rocks stop? Can they be characterized?
5- How can the mechanical parameters affect the rockfall characteristics?
6- What are the regions subject to probable hazard from future rockfalls on the slope under the cliff?
7- What are the possible mitigation ways for rockfall damage?
8- What is the efficiency of mitigation way eliminating rockfall hazard?

1.9 Motivation behind this Research

Nowadays, natural hazards are common in today's life. Increasing amounts of natural catastrophes have proved to the human the vital importance of the natural hazards issues for the safety of the environment, and the populations. Rapid urbanization and climate change are expected to raise the amount of rockfall. The rockfall which occurs in tropical countries, especially Malaysia, emphasizes the extreme in climatic variations. That is why, the topic of rockfall monitoring, mapping, modelling and mitigation are among priority tasks in governments schedule (Kussul et al., 2008). This phenomenon occurs due to the unexpected variation in the state of natural features due to natural forces. In most of the cases, the human is not capable to control and predict these disasters precisely. Main natural catastrophes such as rockfall, landslide, earthquakes, floods and land subsidence when they occur, they lead to affect the human lives, belongings, infrastructure and environment. The influence of natural hazards is varying based on its amount and coverage region.

Rockfalls are the most frequent happening natural catastrophes which influence human and its adjacent environment. Rockfall disaster is more prone to Asia and the Pacific areas which influences the economic and social stability of those countries. Rockfall incidents in Malaysia are very frequent, and have, at times, caused in fatalities as well as destruction for the properties. A typical example of rockfall incidents has been reported by Shu & Lai (1980) and Shu et al. (1981). Attention for providing proper rockfall management has increased over the last centuries. The recent reasons for recurrent falling rocks of some regions are mostly due to un-planned urbanization, construction and deforestation activities. Despite all this its still human participation to control rockfall catastrophe through the enormous use of various technologies. Technology using can facilitate rockfall prevention actions to detect the rockfall areas and to have an early warning for this catastrophe.

This thesis attempts to propose techniques to map the rockfall-prone areas locations and map the rockfall susceptible areas using 3D rockfall modelling integrated into GIS software. The key motivation of this research is to use the generated maps in order to avoid more urbanization in hazardous areas and have a sustainable environment. To reduce the damage and victims in case of a rockfall occurrence, it is critical to locate the susceptible areas. Governments and planners can utilize the produced results by this study to recognize safe regions for citizens, support first responders in emergencies, and update the urban planning strategies. This information can decrease the requirement to perform in-situ investigation by agencies such as surveying departments.

1.10 Research Limitation

The proposed methods for rockfall hazard assessment have been applied and the research objectives have been achieved. However, the environmental elements, like rainfall, are not considered in the simulation of rockfall. Nevertheless, the focus of this study is on assess of rockfall kinematic process and rockfall spatial distribution, thus rockfall hazard. This is based on high-resolution LiDAR data and 3D rockfall model integrated into GIS.

1.11 Thesis Organization

The thesis is split into five chapters. Chapter 1 demonstrates the background of the research problem, the scope of the study, the research objectives and motivation behind this research. Chapter 2 reviews the literature on rockfall hazard analysis. This chapter mainly discusses the general principles and methodology of rockfall hazard analysis including rockfall causes, mechanism, data sources, modelling approaches for rockfall analysis and parameters affect the rockfall simulation.

Chapter 3 presents the methodology and framework of the thesis. This chapter presents and discusses the data are necessary for rockfall hazard analysis. The chapter includes following: deriving digital elevation model (DEM), identify rockfall sources and a 3D modelling approach has been adopted to obtain rockfall trajectories and their spatial distribution and then producing of rockfall hazard map. Chapter 4 presents the collected information and the results of rockfall hazard analysis in term of trajectories, frequency, velocity, bouncing height, energy and hazard map with and without a barrier. Chapter 5 summarizes the research finding, limitations and suggests directions for future work.

REFERENCES

Abellán, A., Jaboyedoff, M., Oppikofer, T., & Vilaplana, J. (2009). Detection of millimetric deformation using a terrestrial laser scanner: Experiment and application to a rockfall event. *Natural Hazards and Earth System Science, 9*(2), 365-372.

Abellán, A., Vilaplana, J., & Martínez, J. (2006). Application of a long-range terrestrial laser scanner to a detailed rockfall study at vall de núria (eastern pyrenees, spain). *Engineering Geology, 88*(3), 136-148.

Abellán, A., Calvet, J., Vilaplana, J. M., & Blanchard, J. (2010). Detection and spatial prediction of rockfalls by means of terrestrial laser scanner monitoring. *Geomorphology, 119*(3), 162-171.

Agliardi, F., & Crosta, G. (2003). High resolution three-dimensional numerical modelling of rockfalls. *International Journal of Rock Mechanics and Mining Sciences, 40*(4), 455-471.

Ahmad, M., Umrao, R., Ansari, M., Singh, R., & Singh, T. (2013). Assessment of rockfall hazard along the road cut slopes of state highway-72, maharashtra, india. *Geomaterials, 3*(1), 15-23.

Akin, M., Topal, T., & Akin, M. K. (2013). Evaluation of the rockfall potential of kastamonu castle using 3-D analysis. *Landslide science and practice* (335-340) Springer.

Allen, S., & Huggel, C. (2013). Extremely warm temperatures as a potential cause of recent high mountain rockfall. *Global and Planetary Change, 107*, 59-69.

Ansari, M., Ahmad, M., & Singh, T. (2014). Rockfall hazard analysis of ellora cave, aurangabad, maharashtra, india. *International Journal of Science and Research (IJSR), 3*(5), 427-431.

Antoniou, A., Papadimitriou, A., & Tsiambaos, G. (2008). A geographical information system managing geotechnical data for athens (greece) and its use for automated seismic microzonation. *Natural Hazards, 47*(3), 369-395.

Antoniou, A. A. (2013). GIS-based evaluation of rockfall risk along routes in greece. *Environmental Earth Sciences, 70*(5), 2305-2318.

Antoniou, A. A., & Lekkas, E. (2010). Rockfall susceptibility map for athinios port, santorini island, greece. *Geomorphology, 118*(1), 152-166.

Arbanas, Ž., Grošić, M., Udovič, D., & Mihalić, S. (2012). Rockfall hazard analyses and rockfall protection along the adriatic coast of croatia. *J Civ Eng Arch David Publishing Company, 6*(3), 344-355.

Armesto, J., Ordóñez, C., Alejano, L., & Arias, P. (2009). Terrestrial laser scanning used to determine the geometry of a granite boulder for stability analysis purposes. *Geomorphology, 106*(3), 271-277.

Assali, P., Grussenmeyer, P., Villemin, T., Pollet, N., & Viguier, F. (2014). Surveying and modeling of rock discontinuities by terrestrial laser scanning and photogrammetry: Semi-automatic abgpproaches for linear outcrop inspection. *Journal of Structural Geology, 66*, 102-114.

Asteriou, P., Saroglou, H., & Tsiambaos, G. (2012). Geotechnical and kinematic parameters affecting the coefficients of restitution for rock fall analysis. *International Journal of Rock Mechanics and Mining Sciences, 54*, 103-113.

Ayalew, L., & Yamagishi, H. (2005). The application of GIS-based logistic regression for landslide susceptibility mapping in the kakuda-yahiko mountains, central japan. *Geomorphology, 65*(1), 15-31.

Ayalew, L., Yamagishi, H., & Ugawa, N. (2004). Landslide susceptibility mapping using GIS-based weighted linear combination, the case in tsugawa area of agano river, niigata prefecture, japan. *Landslides, 1*(1), 73-81.

Azzoni, A., La Barbera, G., & Zaninetti, A. (1995). Analysis and prediction of rockfalls using a mathematical model. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 32.* (7), 709-724.

Baltsavias, E. P. (1999). Airborne laser scanning: Basic relations and formulas. *ISPRS Journal of Photogrammetry and Remote Sensing, 54*(2), 199-214.

Barbarella, M., Fiani, M., & Lugli, A. (2013). Application of lidar-derived dem for detection of mass movements on a landslide. *ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 1*(3), 89-98.

Basson, F. (2012). Rigid body dynamics for rock fall trajectory simulation. *46th US Rock Mechanics/Geomechanics Symposium, ARMA 12–267.*

Bater, C. W., & Coops, N. C. (2009). Evaluating error associated with lidar-derived DEM interpolation. *Computers & Geosciences, 35*(2), 289-300.

Berry, J. K. (1993). Cartographic modeling: The analytical capabilities of GIS. *Environmental Modeling with GIS*, 58-74.

Berry, P., Garlick, J., & Smith, R. (2007). Near-global validation of the SRTM DEM using satellite radar altimetry. *Remote Sensing of Environment, 106*(1), 17-27.

Besl, P. J., & McKay, N. D. (1992). Method for registration of 3-D shapes. *Robotics-DL Tentative, 14.* (2), 239-256.

Bitelli, G., Dubbini, M., & Zanutta, A. (2004). Terrestrial laser scanning and digital photogrammetry techniques to monitor landslide bodies. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 35*(Part B 5), 246-251.

Blahut, J., Klimeš, J., & Vařilová, Z. (2013). Quantitative rockfall hazard and risk analysis in selected municipalities of the české švýcarsko national park, northwestern czechia. *Geografie, 118*(3), 205-220.

Bornaz, L., Lingua, A., & Rinaudo, F. (2002). Engineering and environmental applications of laser scanner techniques. *International Archives of Photogrammetry Remote Sensing and Spatial Information Sciences, 34*(3/B), 40-43.

Bozzolo, D., & Pamini, R. (1986). Simulation of rock falls down a valley side. *Acta Mechanica, 63*(1-4), 113-130.

Bråtveit, K., Bruland, A., & Brevik, O. (2016). Rock falls in selected Norwegian hydropower tunnels subjected to hydropeaking. *Tunnelling and Underground Space Technology, 52,* 202-207.

Brideau, M., Yan, M., & Stead, D. (2009). The role of tectonic damage and brittle rock fracture in the development of large rock slope failures. *Geomorphology, 103*(1), 30-49.

Buckley, S. J., Howell, J., Enge, H., & Kurz, T. (2008). Terrestrial laser scanning in geology: Data acquisition, processing and accuracy considerations. *Journal of the Geological Society, 165*(3), 625-638.

Bühler, Y., Glover, J., Christen, M., & Bartelt, P. (2014). Digital elevation models in numerical rockfall simulations. *EGU General Assembly Conference Abstracts, 16,* 2109-2114.

Burns, W. J., Coe, J. A., Kaya, B. S., & Ma, L. (2010). Analysis of elevation changes detected from multi-temporal LiDAR surveys in forested landslide terrain in western oregon. *Environmental & Engineering Geoscience, 16*(4), 315-341.

Carrara, A., Bitelli, G., & Carla, R. (1997). Comparison of techniques for generating digital terrain models from contour lines. *International Journal of Geographical Information Science, 11*(5), 451-473.

Chai, B., Tang, Z., Zhang, A., Du, J., Su, H., & Yi, H. (2015). An uncertainty method for probabilistic analysis of buildings impacted by rockfall in a limestone quarry in fengshan, southwestern china. *Rock Mechanics and Rock Engineering, 48*(5), 1981-1996.

Chai, S., Yacoub, T., Charbonneau, K., & Curran, J. (2013). The effect of rigid body impact mechanics on tangential coefficient of restitution. *Geo Montreal.*

Chang, H., Ge, L., Rizos, C., & Milne, T. (2004). Validation of DEMs derived from radar interferometry, airborne laser scanning and photogrammetry by using GPS-RTK. *Geoscience and Remote Sensing Symposium, 2004. IGARSS'04. Proceedings. 2004 IEEE International, 5,* 2815-2818.

Chau, K., Wong, R., & Wu, J. (2002). Coefficient of restitution and rotational motions of rockfall impacts. *International Journal of Rock Mechanics and Mining Sciences, 39*(1), 69-77.

Chen, G., Zheng, L., Zhang, Y., & Wu, J. (2013). Numerical simulation in rockfall analysis: A close comparison of 2-D and 3-D DDA. *Rock Mechanics and Rock Engineering, 46*(3), 527-541.

Chen, H., Chen, R., & Huang, T. (1994). An application of an analytical model to a slope subject to rockfalls. *Bulletin of the Association of Engineering Geologists, 31*(4), 447-458.

Chen, Y., Yeh, C., & Yu, B. (2011). Integrated application of the analytic hierarchy process and the geographic information system for flood risk assessment and flood plain management in taiwan. *Natural Hazards, 59*(3), 1261-1276.

Chiessi, V., D'Orefice, M., Mugnozza, G. S., Vitale, V., & Cannese, C. (2010). Geological, geomechanical and geostatistical assessment of rockfall hazard in san quirico village (abruzzo, italy). *Geomorphology, 119*(3), 147-161.

Crosta, G., & Agliardi, F. (2004). Parametric evaluation of 3D dispersion of rockfall trajectories. *Natural Hazards and Earth System Science, 4*(4), 583-598.

Day, R. W. (1997). Case studies of rockfall in soft versus hard rock. *Environmental & Engineering Geoscience, 3*(1), 133-140.

Demir, N., Bayram, B., Alkis, Z., Helvaci, C., Çetin, I., Vogtle, T., et al. (2004). Laser scanning for terrestrial photogrammetry, alternative system or combined with traditional system? *International Archives of Photogrammetry and Remote Sensing, 35*, 193-197.

Dorren, L. K. (2003). A review of rockfall mechanics and modelling approaches. *Progress in Physical Geography, 27*(1), 69-87.

Dorren, L. K., & Seijmonsbergen, A. C. (2003). Comparison of three GIS-based models for predicting rockfall runout zones at a regional scale. *Geomorphology, 56*(1), 49-64.

Douglas, G. (1980). Magnitude frequency study of rockfall in co. antrim, N. ireland. *Earth Surface Processes, 5*(2), 123-129.

Duong, H., Pfeifer, N., & Lindenbergh, R. (2006). Full waveform analysis: ICESat laser data for land cover classification. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 36*(Part 7), 30-35.

Dussauge-Peisser, C., Helmstetter, A., Grasso, J., Hantz, D., Desvarreux, P., Jeannin, M., et al. (2002). Probabilistic approach to rock fall hazard assessment: Potential of historical data analysis. *Natural Hazards and Earth System Science, 2*(1/2), 15-26.

Erismann, T. (1986). Flowing, rolling, bouncing, sliding: Synopsis of basic mechanisms. *Acta Mechanica, 64*(1-2), 101-110.

Evans, I. S. (1977). The selection of class intervals. *Transactions of the Institute of British Geographers, 2*(1), 98-124.

Evans, S., & Hungr, O. (1993). The assessment of rockfall hazard at the base of talus slopes. *Canadian Geotechnical Journal, 30*(4), 620-636.

Fanti, R., Gigli, G., Lombardi, L., Tapete, D., & Canuti, P. (2013). Terrestrial laser scanning for rockfall stability analysis in the cultural heritage site of pitigliano (italy). *Landslides, 10*(4), 409-420.

Feng, Q., Sjögren, P., Stephansson, O., & Jing, L. (2001). Measuring fracture orientation at exposed rock faces by using a non-reflector total station. *Engineering Geology, 59*(1), 133-146.

Ferrari, F., Giani, G. P., & Apuani, T. (2013). Why can rockfall normal restitution coefficient be higher than one? *Rendiconti Online Società Geologica Italiana, 24,* 122-124.

Firpo, G., Salvini, R., Francioni, M., & Ranjith, P. (2011). Use of digital terrestrial photogrammetry in rocky slope stability analysis by distinct elements numerical methods. *International Journal of Rock Mechanics and Mining Sciences, 48*(7), 1045-1054.

Fish, M., & Lane, R. (2002). Linking new hampshire's rock cut management system with a geographic information system. *Transportation Research Record: Journal of the Transportation Research Board,* (1786), 51-59.

Florinsky, I. V. (1998). Accuracy of local topographic variables derived from digital elevation models. *International Journal of Geographical Information Science, 12*(1), 47-62.

Francioni, M., Salvini, R., Stead, D., & Litrico, S. (2014). A case study integrating remote sensing and distinct element analysis to quarry slope stability assessment in the monte altissimo area, italy. *Engineering Geology, 183*, 290-302.

Frattini, P., Crosta, G. B., Agliardi, F., & Imposimato, S. (2013). Challenging calibration in 3D rockfall modelling. *Landslide science and practice* (169-175) Springer.

Frattini, P., Crosta, G., Carrara, A., & Agliardi, F. (2008). Assessment of rockfall susceptibility by integrating statistical and physically-based approaches. *Geomorphology, 94*(3), 419-437.

Fritz, A., Kattenborn, T., & Koch, B. (2013). UAV-based photogrammetric point clouds-tree stem mapping in open stands in comparison to terrestrial laser scanner point clouds. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XL, 1*, W2.

Froese, C. R., Moreno, F., Jaboyedoff, M., & Cruden, D. M. (2009). 25 years of movement monitoring on south peak, turtle mountain: Understanding the hazard. *Canadian Geotechnical Journal, 46*(3), 256-269.

Gallay, M. (2013). Direct acquisition of data: Airborne laser scanning. *Geomorphological Techniques, British Society for Geomorphology,* 1-17.

Gallay, M., Lloyd, C. D., McKinley, J., & Barry, L. (2013). Assessing modern ground survey methods and airborne laser scanning for digital terrain modelling: A case study from the lake district, england. *Computers & Geosciences, 51*, 216-227.

Gardner, J. (1983). Rockfall frequency and distribution in the highwood pass area, canadian rocky mountains. *Zeitschrift Für Geomorphologie, 27*(3), 311-324.

Gigli, G., Frodella, W., Mugnai, F., Tapete, D., Cigna, F., Fanti, R., et al. (2012). Instability mechanisms affecting cultural heritage sites in the maltese archipelago. *Natural Hazards and Earth System Sciences, 12*, 1883-1903.

Gigli, G., Morelli, S., Fornera, S., & Casagli, N. (2014). Terrestrial laser scanner and geomechanical surveys for the rapid evaluation of rock fall susceptibility scenarios. *Landslides, 11*(1), 1-14.

Giordan, D., Manconi, A., Facello, A., Baldo, M., Allasia, P., & Dutto, F. (2014). Brief communication" the use of UAV in rock fall emergency scenario". *Natural Hazards and Earth System Sciences Discussions, 2*(6), 4011-4029.

Glenn, N. F., Streutker, D. R., Chadwick, D. J., Thackray, G. D., & Dorsch, S. J. (2006). Analysis of LiDAR-derived topographic information for characterizing and differentiating landslide morphology and activity. *Geomorphology, 73*(1), 131-148.

Glover, J., Bartelt, P., Christen, M., & Gerber, W. (2015). Rockfall-simulation with irregular rock blocks. *Engineering geology for society and territory-volume 2* (1729-1733) Springer.

Guerin, A., Hantz, D., Rossetti, J., & Jaboyedoff, M. (2014). Brief communication" estimating rockfall frequency in a mountain limestone cliff using terrestrial laser scanner". *Natural Hazards and Earth System Sciences Discussions, 2*(1), 123-135.

Günther, A. (2003). SLOPEMAP: Programs for automated mapping of geometrical and kinematical properties of hard rock hill slopes. *Computers & Geosciences, 29*(7), 865-875.

Guzzetti, F., Crosta, G., Detti, R., & Agliardi, F. (2002). STONE: A computer program for the three-dimensional simulation of rock-falls. *Computers & Geosciences, 28*(9), 1079-1093.

Haarbrink, R., & Eisenbeiss, H. (2008). Accurate DSM production from unmanned helicopter systems. *The International Archives of the Photogr Ammetry, Remote Sensing and Spatial Information Sciences., 37*, 1259-1264.

Haneberg, W. C. (2007). Directional roughness profiles from three-dimensional photogrammetric or laser scanner point clouds. *E. Eberhardt, D. Stead, &T. Morrison (Eds.), Rock Mechanics: Meeting Society's Challenges and Demands,* 101-106.

Harding, D. (2009). Pulsed laser altimeter ranging techniques and implications for terrain mapping. *Topographic Laser Ranging and Scanning Principles and Processing,* 173-194.

Hassani, H., Gholinezhad, M., & Tehrani Moghadas, S. (2014). Rock fall zonation map of doroud-andimeshk railway track using GIS. *Amirkabir Journal of Civil and Environmental Engineering, 45*(2), 97-104.

Heckmann, T., & Schwanghart, W. (2013). Geomorphic coupling and sediment connectivity in an alpine catchment—Exploring sediment cascades using graph theory. *Geomorphology, 182*, 89-103.

Hegg, C., & Kienholz, H. (1995). Determining paths of gravity-driven slope processes: The 'Vector tree model'. *Geographical information systems in assessing natural hazards* (79-92) Springer.

Hengl, T., Heuvelink, G., & Van Loon, E. (2010). On the uncertainty of stream networks derived from elevation data: The error propagation approach. *Hydrology and Earth System Sciences, 14*(7), 1153-1165.

Herzfeld, U. C., & Merriam, D. F. (1995). Optimization techniques for integrating spatial data. *Mathematical Geology, 27*(5), 559-588.

Hétu, B., & Gray, J. T. (2000). Effects of environmental change on scree slope development throughout the postglacial period in the chic-choc mountains in the northern gaspé peninsula, québec. *Geomorphology, 32*(3), 335-355.

Heywood, I., Oliver, J., & Tomlinson, S. (1995). Building an exploratory multi-criteria modelling environment for spatial decision support. *Innovations in GIS, 2*, 127-136.

Hoek, E. (2007). Analysis of rockfall hazards, practical rock engineering. *Electronic Document,* 115-136.

Höfle, B., & Rutzinger, M. (2011). Topographic airborne LiDAR in geomorphology: A technological perspective. *Zeitschrift Für Geomorphologie, Supplementary Issues, 55*(2), 1-29.

Hofton, M., Dubayah, R., Blair, J. B., & Rabine, D. (2006). Validation of SRTM elevations over vegetated and non-vegetated terrain using medium footprint lidar. *Photogrammetric Engineering & Remote Sensing, 72*(3), 279-285.

Hungr, O., & Evans, S. (1988). Engineering evaluation of fragmental rockfall hazards. *Proceedings of the Fifth International Symposium on Landslides, Lausanne, AA Balkema, Rotterdam, Netherlands,* 685-690.

Hutchinson, M. F., & Gallant, J. C. (2000). Digital elevation models and representation of terrain shape. *Terrain Analysis: Principles and Applications*, 29-50.

Ishizaka, A., & Labib, A. (2009). Analytic hierarchy process and expert choice: Benefits and limitations. *OR Insight, 22*(4), 201-220.

Jaboyedoff, M., & Labiouse, V. (2011). Technical note: Preliminary estimation of rockfall runout zones. *Natural Hazards and Earth System Science, 11*(3), 819-828.

Jaboyedoff, M., Oppikofer, T., Locat, A., Locat, J., Turmel, D., Robitaille, D., et al. (2009). Use of ground-based LIDAR for the analysis of retrogressive landslides in sensitive clay and of rotational landslides in river banks. *Can Geotech J, 46*, 1379-1390.

Jaboyedoff, M., Choffet, M., Derron, M., Horton, P., Loye, A., Longchamp, C., et al. (2012). Preliminary slope mass movement susceptibility mapping using DEM and LiDAR DEM. *Terrigenous mass movements* (109-170) Springer.

Jaboyedoff, M., Couture, R., & Locat, P. (2009). Structural analysis of turtle mountain (alberta) using digital elevation model: Toward a progressive failure. *Geomorphology, 103*(1), 5-16.

Jaboyedoff, M., Dudt, J., & Labiouse, V. (2005). An attempt to refine rockfall hazard zoning based on the kinetic energy, frequency and fragmentation degree. *Natural Hazards and Earth System Science, 5*(5), 621-632.

Jaboyedoff, M., Oppikofer, T., Abellán, A., Derron, M., Loye, A., Metzger, R., et al. (2012). Use of LIDAR in landslide investigations: A review. *Natural Hazards, 61*(1), 5-28.

James, L. A., Watson, D. G., & Hansen, W. F. (2007). Using LiDAR data to map gullies and headwater streams under forest canopy: South carolina, USA. *Catena, 71*(1), 132-144.

Janeras, M., Navarro, M., Arnó, G., Ruiz, A., Kornus, W., Talaya, J., et al. (2004). Lidar applications to rock fall hazard assesment in vall de núria. *Proceedings, 4th ICA Mountain Cartography Workshop, Vall De Núria, Catalonia, Spain,* 1-14.

Janke, J. R. (2013). Using airborne LiDAR and USGS DEM data for assessing rock glaciers and glaciers. *Geomorphology, 195*, 118-130.

Jibson, R. W. (1996). Use of landslides for paleoseismic analysis. *Engineering Geology, 43*(4), 291-323.

Jomelli, V., & Francou, B. (2000). Comparing the characteristics of rockfall talus and snow avalanche landforms in an alpine environment using a new methodological approach: Massif des ecrins, french alps. *Geomorphology, 35*(3), 181-192.

Kemeny, J., & Post, R. (2003). Estimating three-dimensional rock discontinuity orientation from digital images of fracture traces. *Computers & Geosciences, 29*(1), 65-77.

Kenner, R., Bühler, Y., Delaloye, R., Ginzler, C., & Phillips, M. (2014). Monitoring of high alpine mass movements combining laser scanning with digital airborne photogrammetry. *Geomorphology, 206*, 492-504.

Keskin, İ. (2013). Evaluation of rock falls in an urban area: The case of boğaziçi (Erzincan/Turkey). *Environmental Earth Sciences, 70*(4), 1619-1628.

Keylock, C., & Domaas, U. (1999). Evaluation of topographic models of rockfall travel distance for use in hazard applications. *Arctic, Antarctic, and Alpine Research, 31*(3), 312-320.

Kil, S. H., Lee, D. K., Kim, J. H., Li, M. H., & Newman, G. (2016). Utilizing the Analytic Hierarchy Process to Establish Weighted Values for Evaluating the Stability of Slope Revegetation based on Hydroseeding Applications in South Korea. *Sustainability, 8*(1), 58.

Kirkby, M., & Statham, I. (1975). Surface stone movement and scree formation. *The Journal of Geology, 83*(3), 349-362.

Ku, C. (2012). Assessing rockfall hazards using a three-dimensional numerical model based on high resolution DEM. *The Twenty-Second International Offshore and Polar Engineering Conference,* 790-796.

Kussul, N., Shelestov, A., & Skakun, S. (2008). Grid system for flood extent extraction from satellite images. *Earth Science Informatics, 1*(3-4), 105-117.

Lan, H., Derek Martin, C., & Lim, C. (2007). RockFall analyst: A GIS extension for three-dimensional and spatially distributed rockfall hazard modeling. *Computers & Geosciences, 33*(2), 262-279.

Lan, H., Martin, C. D., Zhou, C., & Lim, C. H. (2010). Rockfall hazard analysis using LiDAR and spatial modeling. *Geomorphology, 118*(1), 213-223.

Lato, M., Hutchinson, J., Diederichs, M., Ball, D., & Harrap, R. (2009). Engineering monitoring of rockfall hazards along transportation corridors: Using mobile terrestrial LiDAR. *Natural Hazards and Earth System Sciences, 9*(3), 935-946.

Lato, M., Kemeny, J., Harrap, R., & Bevan, G. (2013). Rock bench: Establishing a common repository and standards for assessing rockmass characteristics using LiDAR and photogrammetry. *Computers & Geosciences, 50*, 106-114.

Lato, M., Diederichs, M. S., Hutchinson, D. J., & Harrap, R. (2009). Optimization of LiDAR scanning and processing for automated structural evaluation of discontinuities in rockmasses. *International Journal of Rock Mechanics and Mining Sciences, 46*(1), 194-199.

Lato, M. J., Diederichs, M. S., Hutchinson, D. J., & Harrap, R. (2012). Evaluating roadside rockmasses for rockfall hazards using LiDAR data: Optimizing data collection and processing protocols. *Natural Hazards, 60*(3), 831-864.

Lee, K., & Elliott, G. (1998). Rockfall: Application of computer simulation to design of preventive measures. *Planning, Design and Implementation of Debris Flow and Rockfall Hazards Mitigation Measures, Association of Geo-Technical Specialists & Hong Kong Institution of Engineers, Hong Kong,* , 47-65.

Leine, R., Schweizer, A., Christen, M., Glover, J., Bartelt, P., & Gerber, W. (2013). Simulation of rockfall trajectories with consideration of rock shape. *Multibody System Dynamics, 32*(2), 1-31.

Li, L., & Lan, H. (2015). Probabilistic modeling of rockfall trajectories: A review. *Bulletin of Engineering Geology and the Environment, 74*(4), 1163-1176.

Lichti, D. D. (2007). Error modelling, calibration and analysis of an AM–CW terrestrial laser scanner system. *ISPRS Journal of Photogrammetry and Remote Sensing, 61*(5), 307-324.

Lopez-Saez, J., Corona, C., Eckert, N., Stoffel, M., Bourrier, F., & Berger, F. (2016). Impacts of land-use and land-cover changes on rockfall propagation: Insights from the Grenoble conurbation. *Science of The Total Environment*, *547*, 345-355.

Loye, A., Jaboyedoff, M., & Pedrazzini, A. (2009). Identification of potential rockfall source areas at a regional scale using a DEM-based geomorphometric analysis. *Natural Hazards and Earth System Science, 9*(5), 1643-1653.

Luckman, B. (1976). Rockfalls and rockfall inventory data: Some observations from surprise valley, jasper national park, canada. *Earth Surface Processes, 1*(3), 287-298.

Ma, G., Matsuyama, H., Nishiyama, S., & Ohnishi, Y. (2011). Practical studies on rockfall simulation by DDA. *Journal of Rock Mechanics and Geotechnical Engineering, 3*(1), 57-63.

Macciotta, R., Cruden, D., Martin, C., & Morgenstern, N. (2011). Combining geology, morphology and 3D modelling to understand the rock fall distribution along the railways in the fraser river valley, between hope and boston bar. *BC International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering, Vancouver, BC, Canada.*

Macciotta, R., Martin, C. D., & Cruden, D. M. (2014). Probabilistic estimation of rockfall height and kinetic energy based on a three-dimensional trajectory model and monte carlo simulation. *Landslides, 12*(4), 1-16.

MacEachren, A. M. (1994). *Some truth with maps: A primer on symbolization and design* Assn of Amer Geographers.

Malczewski, J. (2000). On the use of weighted linear combination method in GIS: Common and best practice approaches. *Transactions in GIS, 4*(1), 5-22.

Manetti, L., & Steinmann, G. (2007). 3DeMoN ROBOVEC—integration of a new measuring instrument in an existing generic remote monitoring platform. *7th International Symposium on Field Measurements in Geomechanics*, 24-27.

Martin, D. C. (1988). Rockfall control: An update (technical note). *Bull. Assoc. Eng'g. Geol., 13*(14), 329-335.

Masuya, H., Amanuma, K., Nishikawa, Y., & Tsuji, T. (2009). Basic rockfall simulation with consideration of vegetation and application to protection measure. *Natural Hazards and Earth System Science, 9*(6), 1835-1843.

Meng, X., Currit, N., & Zhao, K. (2010). Ground filtering algorithms for airborne LiDAR data: A review of critical issues. *Remote Sensing, 2*(3), 833-860.

Michoud, C., Derron, M., Horton, P., Jaboyedoff, M., Baillifard, F., Loye, A., et al. (2012). Rockfall hazard and risk assessments along roads at a regional scale: Example in swiss alps. *Natural Hazards and Earth System Sciences*, *12*(3), 615-629.

Mignelli, C., Pomarico, S., & Peila, D. (2012). Multicriteria analysis model for the comparison of different rockfalls protection devices. *EGU General Assembly Conference Abstracts, 14.* 9303.

Mikoš, M., Petje, U., & Ribičič, M. (2006). Application of a rockfall simulation program in an alpine valley in slovenia. *Disaster Mitigation of Debris Flows, Slopes, Failures and Landslides*, 199-211.

Monserrat, O., & Crosetto, M. (2008). Deformation measurement using terrestrial laser scanning data and least squares 3D surface matching. *ISPRS Journal of Photogrammetry and Remote Sensing, 63*(1), 142-154.

Nelson, A., Reuter, H. I., & Gessler, P. (2009). DEM production methods and sources. *Developments in Soil Science, 33*(0), 65-85.

Niethammer, U., James, M., Rothmund, S., Travelletti, J., & Joswig, M. (2012). UAV-based remote sensing of the super-sauze landslide: Evaluation and results. *Engineering Geology, 128*, 2-11.

Niethammer, U., Rothmund, S., James, M., Travelletti, J., & Joswig, M. (2010). UAV-based remote sensing of landslides. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 38*(Part 5), 496-501.

Olaya, V. (2009). Chapter 6 basic land-surface parameters. *Developments in Soil Science, 33*(0), 141-169.

Oppikofer, T., Jaboyedoff, M., Blikra, L., Derron, M., & Metzger, R. (2009). Characterization and monitoring of the åknes rockslide using terrestrial laser scanning. *Natural Hazards and Earth System Science, 9*(3), 1003-1019.

Oppikofer, T., Jaboyedoff, M., & Keusen, H. (2008). Collapse at the eastern eiger flank in the swiss alps. *Nature Geoscience*, *1*(8), 531-535.

Papathanassiou, G., Marinos, V., Vogiatzis, D., & Valkaniotis, S. (2013). A rock fall analysis study in parnassos area, central greece. *Landslide science and practice* (67-72) Springer.

Petrie, G., & Toth, C. K. (2008). Introduction to laser ranging, profiling, and scanning. *Topographic Laser Ranging and Scanning: Principles and Processing*, 1-28.

Pfeiffer, T. J., & Bowen, T. (1989). Computer simulation of rockfalls. *Bulletin of the Association of Engineering Geologists, 26*(1), 135-146.

Pradhan, B., Mansor, S., Ramli, A. R., Sharif, Abdul Rashid B Mohamed, & Sandeep, K. (2005). LIDAR data compression using wavelets. *Remote Sensing*, pp. 598305-598305-12.

Pradhan, B. (2010). Remote sensing and GIS-based landslide hazard analysis and cross-validation using multivariate logistic regression model on three test areas in malaysia. *Advances in Space Research, 45*(10), 1244-1256.

Pradhan, B., Abokharima, M. H., Jebur, M. N., & Tehrany, M. S. (2014). Land subsidence susceptibility mapping at kinta valley (malaysia) using the evidential belief function model in GIS. *Natural Hazards, 73*(2), 1019-1042.

Pradhan, B., Latif, Z. A., & Aman, S. N. A. (2012). Application of airborne LiDAR-derived parameters and probabilistic-based frequency ratio model in landslide susceptibility mapping. *Applied Mechanics and Materials*, *225,* 442-447.

Pradhan, B., & Lee, S. (2010). Regional landslide susceptibility analysis using back-propagation neural network model at cameron highland, malaysia. *Landslides, 7*(1), 13-30.

Pradhan, B., Mansor, S., Pirasteh, S., & Buchroithner, M. F. (2011). Landslide hazard and risk analyses at a landslide prone catchment area using statistical based geospatial model. *International Journal of Remote Sensing, 32*(14), 4075-4087.

Pradhan, B., OHb, H., & Buchroithner, M. (2010). Use of remote sensing data and GIS to produce a landslide susceptibility map of a landslide prone area using a weight of evidence model. *Assessment*, *11*, 13.

Raaflaub, L. D., & Collins, M. J. (2006). The effect of error in gridded digital elevation models on the estimation of topographic parameters. *Environmental Modelling & Software, 21*(5), 710-732.

Rammer, W., Brauner, M., Dorren, L., Berger, F., & Lexer, M. (2010). Evaluation of a 3-D rockfall module within a forest patch model. *Natural Hazards and Earth System Sciences, 10*(4), 699-711.

Rayburg, S., Thoms, M., & Neave, M. (2009). A comparison of digital elevation models generated from different data sources. *Geomorphology, 106*(3), 261-270.

Reuter, H. I., Hengl, T., Gessler, P., & Soille, P. (2009). Chapter 4 preparation of DEMs for geomorphometric analysis. *Developments in Soil Science, 33*(0), 87-120.

Richards, L. (1988). Rockfall protection: A review of current analytical and design methods. *Secondo Ciclo Di Conferenze Di Meccanica Ed Ingegneria Delle Rocce, MIR, Politecnico Di Torino, 11*, 1-13.

Ritchie, A. M. (1963). Evaluation of rockfall and its control. *Highway Research Record,* (17), 13-28.

Rodriguez, E., Morris, C. S., & Belz, J. E. (2006). A global assessment of the SRTM performance. *Photogrammetric Engineering & Remote Sensing, 72*(3), 249-260.

Rosser, N., Lim, M., Petley, D., Dunning, S., & Allison, R. (2007). Patterns of precursory rockfall prior to slope failure. *Journal of Geophysical Research: Earth Surface (2003–2012), 112*(F4), 1-14.

Ruff, M., & Czurda, K. (2008). Landslide susceptibility analysis with a heuristic approach in the eastern alps (vorarlberg, austria). *Geomorphology, 94*(3), 314-324.

Ruiz, J., Diaz-Mas, L., Perez, F., & Viguria, A. (2013). Evaluating the accuracy of DEM generation algorithms from UAV imagery. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 40*, 333-337.

Rychkov, I., Brasington, J., & Vericat, D. (2012). Computational and methodological aspects of terrestrial surface analysis based on point clouds. *Computers & Geosciences, 42*, 64-70.

Saaty, T. L. (1977). A scaling method for priorities in hierarchical structures. *Journal of Mathematical Psychology, 15*(3), 234-281.

Saaty, T. The analytic hierarchy process, McGraw-hill, new york, 1980.

Sabatakakis, N., Depountis, N., & Vagenas, N. (2015). Evaluation of rockfall restitution coefficients. *Engineering geology for society and territory-volume 2* (2023-2026) Springer.

Salvini, R., Francioni, M., Riccucci, S., Bonciani, F., & Callegari, I. (2013). Photogrammetry and laser scanning for analyzing slope stability and rock fall runout along the Domodossola–Iselle railway, the italian alps. *Geomorphology, 185*, 110-122.

Samodra, G., Chen, G., Sartohadi, J., Hadmoko, D., & Kasama, K. (2014). Automated landform classification in a rockfall-prone area, gunung kelir, java. *Earth Surface Dynamics, 2*(1), 339-348.

Samodra, G., Sartohadi, J., Chen, G., & Kasama, K. (2013). Application of supervised landform classification of 9-unit slope model for preliminary rockfall risk analysis in gunung kelir, java. *Geo Morphometry.Org*, O-8-1-O-8-4.

Shary, P. A., Sharaya, L. S., & Mitusov, A. V. (2002). Fundamental quantitative methods of land surface analysis. *Geoderma, 107*(1), 1-32.

Shu, Y., Chow, W., & Zakaria, M. (1981). Rockfall danger related to limestone hills in the kinta valley, perak. *1981 Annual Report, Geological Survey Malaysia,* 184-197.

Shu, Y., & Lai, K. (1980). Rockfall at gunung cheroh, Ipoh. *Geological Survey Malaysia, Geological Papers, 3*, 1-9.

Singh, P., Wasnik, A., Kainthola, A., Sazid, M., & Singh, T. (2013). The stability of road cut cliff face along SH-121: A case study. *Natural Hazards, 68*(2), 497-507.

Siqiao, Y., Hongmei, T., Hongkai, C., & Hui, Z. (2010). Stability evaluation of rockfall based on AHP-fuzzy method. *Fuzzy Systems and Knowledge Discovery (FSKD), 2010 Seventh International Conference on, 3.* 1369-1373.

Slater, J., Heady, B., Kroenung, G., Curtis, W., Haase, J., Hoegemann, D., et al. (2009). Evaluation of the new ASTER global digital elevation model. *Avalible Online at: Http://earth-Info.Nga.mil/GandG/elevation.*

Slob, S., Hack, H., & Turner, A. K. (2002). An approach to automate discontinuity measurements of rock faces using laser scanning techniques. *Proceedings of ISRM EUROCK, 2002*, 87-94.

Spadari, M., Kardani, M., De Carteret, R., Giacomini, A., Buzzi, O., Fityus, S., et al. (2013). Statistical evaluation of rockfall energy ranges for different geological settings of new south wales, australia. *Engineering Geology, 158*, 57-65.

Spang, R., & Rautenstrauch, R. (1988). Empirical and mathematical approaches to rockfall protection and their practical applications. *5th International Symposium on Landslides*, 1237-1243.

Statham, I., & Francis, S. Influence of scree accumulation and weathering on the development of steep mountain slopes, abrahams AD, hillslope processes, 1986, 245-267.

Stephenne, N., Frippiat, C., Veschkens, M., Salmon, M., & Pacyna, D. (2014). Use of a lidar high resolution digital elevation model for risk stability analysis. *Earsel Eproceedings, 13*(S1), 24-29.

Stock, G. M., Bawden, G. W., Green, J. K., Hanson, E., Downing, G., Collins, B. D., et al. (2011). High-resolution three-dimensional imaging and analysis of rock falls in yosemite valley, california. *Geosphere, 7*(2), 573-581.

Strozzi, T., Delaloye, R., Kääb, A., Ambrosi, C., Perruchoud, E., & Wegmüller, U. (2010). Combined observations of rock mass movements using satellite SAR interferometry, differential GPS, airborne digital photogrammetry, and airborne photography interpretation. *Journal of Geophysical Research: Earth Surface (2003–2012), 115*(F1).

Sturzenegger, M., & Stead, D. (2009). Quantifying discontinuity orientation and persistence on high mountain rock slopes and large landslides using terrestrial remote sensing techniques. *Natural Hazards and Earth System Science, 9*(2), 267-287.

Sturzenegger, M., Yan, M., Stead, D., & Elmo, D. (2007). Application and limitations of ground-based laser scanning in rock slope characterization. *Proceedings of the First Canadian US Rock Mechanics Symposium, 1*, 29-36.

Tatone, B. S., & Grasselli, G. (2009). A method to evaluate the three-dimensional roughness of fracture surfaces in brittle geomaterials. *Review of Scientific Instruments, 80*(12), 110-125.

Temme, A. J. A. M., Heuvelink, G. B. M., Schoorl, J. M., & Claessens, L. (2009). Chapter 5 geostatistical simulation and error propagation in geomorphometry. *Developments in Soil Science, 33*(0), 121-140.

Tonini, M., & Abellan, A. (2014). Rockfall detection from terrestrial LiDAR point clouds: A clustering approach using R. *Journal of Spatial Information Science*, (To appear JOSIS issue 8), 95-101.

Tonini, M., & Abellan, A. (2015). Rockfall detection from terrestrial LiDAR point clouds: A clustering approach using R. *Journal of Spatial Information Science*, (8), 95-110.

Topal, T., Akin, M., & Ozden, U. A. (2007). Assessment of rockfall hazard around afyon castle, turkey. *Environmental Geology, 53*(1), 191-200.

Uddin, W. (2002). Evaluation of airborne lidar digital terrain mapping for highway corridor planning and design. *Proc. Pecora, 15*, 10-15.

Vaidya, O. S., & Kumar, S. (2006). Analytic hierarchy process: An overview of applications. *European Journal of Operational Research, 169*(1), 1-29.

Varnes, D. J. (1978). Slope movement types and processes. *Transportation Research Board Special Report,* (176), 11-33.

Varnes, D. J. (1984). Landslide hazard zonation: A review of principles and practice, 64.

Veneziano, D., Souleyrette, R., & Hallmark, S. (2002). Evaluation of lidar for highway planning, location and design. *Proc. Pecora, 15.*

Vidrih, R., Ribičič, M., & Suhadolc, P. (2001). Seismogeological effects on rocks during the 12 april 1998 upper soča territory earthquake (NW slovenia). *Tectonophysics, 330*(3), 153-175.

Vijayakumar, S., Yacoub, T., Ranjram, M., & Curran, J. (2012). Effect of rockfall shape on normal coefficient of restitution. *46th US Rock Mechanics/Geomechanics Symposium.*

Vijayakumar, S., Yacoub, T., & Curran, J. H. (2011). On the effect of rock size and shape in rockfall analyses. *Proceedings of the US Rock Mechanics Symposium (ARMA) San Francisco CA, USA.*

Voegtle, T., Schwab, I., & Landes, T. (2008). Influences of different materials on the measurements of a terrestrial laser scanner (TLS). *Proc. of the XXI Congress, the International Society for Photogrammetry and Remote Sensing, ISPRS2008, 37,* 1061-1066.

Volkwein, A., Schellenberg, K., Labiouse, V., Agliardi, F., Berger, F., Bourrier, F., et al. (2011). Rockfall characterisation and structural protection-a review. *Natural Hazards and Earth System Sciences, 11*, 2617-2651.

Wang, I., & Lee, C. (2012). Simulation and statistical analysis of motion behavior of a single rockfall. *International Journal of Civil and Environmental Engineering, 61*, 853-862.

Wang, X., Frattini, P., Crosta, G., Zhang, L., Agliardi, F., Lari, S., et al. (2014). Uncertainty assessment in quantitative rockfall risk assessment. *Landslides, 11*(4), 711-722.

Webster, T. L., & Dias, G. (2006). An automated GIS procedure for comparing GPS and proximal LiDAR elevations. *Computers & Geosciences, 32*(6), 713-726.

Wehr, A., & Lohr, U. (1999). Airborne laser scanning—an introduction and overview. *ISPRS Journal of Photogrammetry and Remote Sensing, 54*(2), 68-82.

Wieczorek, G. F., Snyder, J. B., Waitt, R. B., Morrissey, M. M., Uhrhammer, R. A., Harp, E. L., et al. (2000). Unusual july 10, 1996, rock fall at happy isles, yosemite national park, california. *Geological Society of America Bulletin, 112*(1), 75-85.

Williams, K., Olsen, M. J., Roe, G. V., & Glennie, C. (2013). Synthesis of transportation applications of mobile LiDAR. *Remote Sensing, 5*(9), 4652-4692.

Wilson, J. P. (2012). Digital terrain modeling. *Geomorphology, 137*(1), 107-121.

Wilson, J. P., AGGETT, G., & Yongxin, D. (2008). Water in the landscape: A review of contemporary flow routing algorithms. *Advances in digital terrain analysis* (213-236) Springer.

Wilson, J. P., & Burrough, P. A. (1999). Dynamic modeling, geostatistics, and fuzzy classificaiton: New sneakers for a new geography? *89*(4), 736-746.

Wise, S. (2000). Assessing the quality for hydrological applications of digital elevation models derived from contours. *Hydrological Processes, 14*(11-12), 1909-1929.

Wise, S. (2000). Assessing the quality for hydrological applications of digital elevation models derived from contours. *Hydrological Processes*, *14*(11-12), 1909-1929.

Wise, S. (2011). Cross-validation as a means of investigating DEM interpolation error. *Computers & Geosciences*, *37*(8), 978-991.

Wyllie, D. C. (2014). Calibration of rock fall modeling parameters. *International Journal of Rock Mechanics and Mining Sciences*, *67*, 170-180.

Yoshimatsu, H., & Abe, S. (2006). A review of landslide hazards in japan and assessment of their susceptibility using an analytical hierarchic process (AHP) method. *Landslides, 3*(2), 149-158.

Youssef, A. M., Pradhan, B., Al-Kathery, M., Bathrellos, G. D., & Skilodimou, H. D. (2015). Assessment of rockfall hazard at al-noor mountain, makkah city (saudi arabia) using spatio-temporal remote sensing data and field investigation. *Journal of African Earth Sciences*, *101*, 309-321.

Yusof, N. M., Pradhan, B., Shafri, H. Z. M., Jebur, M. N., & Yusoff, Z. (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, 8*(11), 1-12.

Zandbergen, P. (2008). Applications of shuttle radar topography mission elevation data. *Geography Compass*, *2*(5), 1404-1431.

Zinggeler, A., Krummenacher, B., & Kienholz, H. (1991). Steinschlagsimulation in gebirgswäldern. *Berichte Und Forschungen, 3*, 61-70.