UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF A HYBRID MACHINE LEARNING MODEL FOR ROCKFALL SOURCE AND HAZARD ASSESSMENT USING LASER SCANNING DATA AND GIS

ALI MUTAR FANOS

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By

ALI MUTAR FANOS

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Chairman : Professor Shattri Mansor, PhD
Faculty : Engineering

In mountainous and hilly areas such as Malaysia, rockfalls phenomena is a significant and ongoing threat to people and their properties in addition to infrastructure and transportation lines located within steep terrain. This is because such incidence can cause serious injuries and fatalities as well as severe damage to buildings and infrastructure. Therefore, proper and accurate assessment of rockfall sources and hazard is required in order to map and thus understand the characteristics of rockfall catastrophe. The identification of probable rockfall starting regions, the calculation of the rockfall trajectories in complex three-dimensional terrain, and rockfall hazard assessment are three major components of the rockfall research and issues. Although the numerous significant attempts to propose models that can accurately identify potential rockfall source areas, one major problem remain unsolved. This issue is when the focus area contains other types of landslides that have nearly similar geo-morphometric characteristics such as rockfall and shallow landslides. Therefore, this research adopted various methods to investigate, analyze and assess rockfall in terms of sources identification, trajectories modeling and their characteristics, and consequently rockfall hazard. This is based on high-resolution Light Detection and Ranging (LiDAR) techniques both airborne and terrestrial (ALS and TLS). Different machine learning algorithms (Artificial Neural Network [ANN], K Nearest Neighbor [KNN] and Support Vector Machine [SVM]) were tested individually and with various ensemble models (bagging, voting, and boosting) to detect the probability of the landslide and rockfall occurrences. Consequently, a novel hybrid model is developed to identify potential rockfall sources in the presence of shallow landslides. This is based on an integration of Gaussian Mixture Model (GMM) and an ensemble Artificial Neural Network (Bagged ANN -BANN) for automatic detection of potential rockfall sources at Kinta Valley area, Malaysia. Moreover, a developed 3D rockfall model is

employed to derive rockfall trajectories and their characteristics in three different areas within Kinta Valley namely (Gunung Lang, Gua Tambun, and Gunung Rapat) with various scenarios. In addition, a proposed spatial model in combination with fuzzy analytical hierarchy process (fuzzy-AHP) is executed within the geographic information system (GIS) environment to extract rockfall hazard. Mitigation measures are suggested based on the modelling results. Overall, the proposed hybrid model was found to be an efficient method for identifying potential rockfall source areas in the presence of other landslides types with relatively high prediction accuracy and a good generalization performance. GMM could reproduce the slope angle distribution in an accurate way with a coefficient of determination close to 1. The obtained slope thresholds through GMM were (23° to 58°) for landslide and (> 58°) for rockfall. The results of Ant Colony Optimization show that best subset of conditioning factors contains 12 factors of 17 for rockfall with an accuracy of (86%) and 14 factors of 17 for shallow landslide with an accuracy of (82%). The proposed BANN model achieved the best training accuracies of (95%) and best prediction accuracies of (92%) based on testing data compared to other employed methods. This indicates that the model can be generalized and replicated in different regions and the proposed method can be applied in various landslides studies. The result of Fuzzy-AHP revealed the rockfall hazard is highly affected by kinetic energy, frequency, bouncing height, and impact location with weights of (0.48, 0.30, 0.12, and 0.10), respectively. In addition, the proposed spatial model effectively delineates areas at risk of rockfalls. The suggested barriers could effectively reduce the degree of rockfalls hazard. In summary, the proposed methods provide a comprehensive understanding of rockfall hazards that can assist authorities to develop proper management and protection of urban areas and transportation corridors.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMBANGUNAN SEBUAH MODEL PEMBELAJARAN MESIN HIBRID UNTUK SUMBER RUNTUHAN BATU DAN PENAKSIRAN BENCANA MENGGUNAKAN DATA PENGIMBAS LASER DAN GIS

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ALI MUTAR FANOS

Ogos 2019

Pengerusi : Profesor Shattri Mansor, PhD
Fakulti : Kejuruteraan

Di kawasan bergunung-ganang dan berbukit-bukit seperti Malaysia, fenomena runtuhan batu adalah signifikan dan merupakan ancaman yang berterusan kepada manusia dan harta benda mereka, juga pada infrastruktur dan jalan pengangkutan yang terletak di terain yang cerun. Hal ini disebabkan fenomena ini boleh mengakibatkan kecederaan yang serius dan juga kematian di samping kerosakan yang teruk pada bangunan dan infrastruktur. Oleh sebab itu, penaksiran yang wajar dan tepat mengenai sumber runtuhan batu dan bencana adalah perlu bagi pemetaan dan dengan itu dapat memahami ciri katastrofi runtuhan batu. Pengenalpastian kawasan bermulanya runtuhan batu yang mungkin terjadi, pengiraan trajektori runtuhan batu di terain tiga dimensi yang kompleks dan penaksiran bencana runtuhan batu merupakan tiga komponen utama dalam penyelidikan dan masalah runtuhan batu. Walaupun pelbagai percubaan yang signifikan bagi mengesyorkan model yang secara tepat dapat mengenal pasti kawasan sumber runtuhan batu yang berpotensi, satu masalah utama masih belum dapat diselesaikan. Isu ini ialah apabila kawasan fokus mengandungi pelbagai jenis tanah runtuh lain yang mempunyai ciri geomorfometrik yang seakan-akan sama seperti runtuhan batu dan tanah runtuh yang cetek. Oleh sebab itu, penyelidikan ini menerima pakai pelbagai kaedah bagi menyelidiki, menganalisis dan menilai runtuhan batu dari segi pengenalpastian sumber, modeling trajektori dan ciri mereka, dan seterusnya bencana runtuhan batu. Hal ini berdasarkan teknik Penjulatan dan Pengesanan Cahaya beresolusi tinggi (LiDAR) yang meliputi kedua-dua udara dan darat (ALS dan TLS). Algoritma pembelajaran mesin yang berbeza (Rangkaian Neural Artifisial [ANN], K Jiran Terdekat [KNN], dan Mesin Vektor Bantuan [SVM]) telah diuji secara individu dan dengan pelbagai model ensembel (pengantungan, pengundian, dan penggalakan) bagi mengesan kebarangkalian kewujudan kejadian tanah runtuh dan runtuhan batu. Akibatnya, suatu model hibrid yang

novel telah dibangunkan bagi mengenal pasti sumber runtuhan batu yang berpotensi dengan kewujudan tanah runtuh yang cetek. Hal ini berdasarkan Model Percampuran Gaussan (GMM) dan Rangkaian Neural Artifisial yang diensembel (Kantung ANN -BANN) bagi pengesanan automatik bagi sumber runtuhan batu yang berpotensi di kawasan Lembah Kinta, Malaysia. Tambahan pula, model runtuhan batu 3D yang berpotensi telah digunakan bagi mendapatkan trajektori runtuhan batu dan ciri mereka di tiga kawasan yang berbeza di Lembah Kinta, iaitu (Gunung Lang, Gua Tambun, dan Gunung Rapat) dengan pelbagai senario. Di samping itu, suatu model spatial yang disyorkan berkombinasi dengan proses hierarki analitikal fuzi (fuzzy-AHP) telah digunakan dalam persekitaran sistem maklumat geografik (GIS) bagi mengekstrak bencana runtuhan batu. Pengukuran mitigasi telah disyorkan berdasarkan dapatan modeling. Keseluruhannya, model hibrid yang disyorkan didapati sebagai suatu kaedah yang efisien bagi mengenal pasti kawasan sumber runtuhan batu yang berpotensi di samping kewujudan jenis tanah runtuh lain dengan ketepatan ramalan yang secara relatif adalah tinggi dan suatu prestasi generalisasi yang baik. GMM dapat menghasilkan semula penyebaran sudut lereng dengan cara yang tepat dengan koefisien determinasi hampir pada 1. Ambang lereng diperoleh melalui GMM ialah (23° hingga 58°) bagi tanah runtuh dan (> 58°) bagi runtuhan batu. Dapatan Pengoptimisasian Koloni Semut menunjukkan bahawa subset faktor pelaziman terbaik mengandungi 12 faktor, iaitu 17 bagi runtuhan batu dengan ketepatan (86%) dan 14 faktor daripada 17 bagi tanah runtuh dengan ketepatan (82%). Model BANN yang disyorkan memperoleh ketepatan latihan terbaik sebanyak (95%) dan ketepatan ramalan terbaik (92%) berdasarkan data pengujian berbanding dengan kaedah lain yang digunakan. Dapatan ini memperlihatkan model tersebut dapat digeneralisasi dan direplikatkan di kawasan yang berbeza dan kaedah yang disyorkan dapat diaplikasikan dalam pelbagai kajian mengenai runtuhan batu. Dapatan Fuzzy-AHP memperlihatkan bencana runtuhan batu amat disebabkan oleh tenaga kinetik, kekerapan, ketinggian lantunan, dan lokasi impak dengan keberatan masing-masing (0.48, 0.30, 0.12, dan 0.10). Di samping itu, model spatial yang disyorkan secara efektif dapat menghalang kawasan yang berisiko runtuhan batu. Penghalang yang disyorkan secara efektif dapat mengurangkan kadar bencana runtuhan batu. Kesimpulannya, kaedah yang disyorkan dapat memberikan pemahaman yang komprehensif mengenai bencana runtuhan batu yang seterusnya dapat membantu pihak berkuasa membangunkan pengurusan dan perlindungan yang sesuai terhadap kawasan bandar dan koridor pengangkutan.

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Declaration by graduate student

I hereby confirm that:

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Signature: ____________________
Name of Member of Supervisory Committee: Dr. Zainuddin bin Md Yusoff

Signature: ____________________
Name of Member of Supervisory Committee: Dr. Ahmad Fikri bin Abdullah

Signature: ____________________
Name of Member of Supervisory Committee: Professor Dr. Biswajeet Pradhan

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LIST OF ABBREVIATIONS

LiDAR	Light Detection and Ranging
DTM	Digital Terrain Model
ALS	Airborne Laser Scanning
TLS	Terrestrial Laser Scanning
GMM	Gaussian Mixture Model
ANN	Artificial Neural Network
KNN	K Nearest Neighbour
SVM	Support Vector Machine
ACO	Ant Colony Optimization
BANN	Bagged Artificial Neural Network
ROC	Receiver Operating Curves
MCC	Multiscale Curvature Algorithm
LULC	Land Use / Land Cover
SPI	Stream Power Index
STI	Sediment Transport Index
TRI	Topographic Roughness Index
TWI	Topographic Wetness Index
AUC	Area Under the Curve
Rn	Normal Coefficient of Restitution
Rt	Tangential Coefficient of Restitution
AHP	Analytic Hierarchy Process

CHAPTER 1

INTRODUCTION

1.1 General

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. Rockfall is categorized as one of the landslides types that composes of a boulder detachment or many isolated blocks from a sub-vertical or vertical cliffs followed by fast downslope movement with different motion mode: flying or free-falling, impact and bouncing, sliding and rolling (Varnes, 1978). Rockfall is extraordinarily fast process and can run long distance. Although rockfall has a low risk level on economic in comparison with large scale landslide, the high velocity correlated with rockfall results in the same fatalities number as the number of people killed by all other landslide types on the same order of magnitude (Hoek, 2007). While a rockfall event is happening, people are normally incapable to take an evasive behavior because of the rapid movement. Therefore, the risks of injuries and loss of lives is excessively high. Thus, rockfall incidents are the main reason of landslides casualties, even when elements with lower exposure degree are included like traffic along transportation ways (Fanos and Pradhan, 2018). Moreover, rockfall can cause serious damage to lifelines buildings and infrastructure. An efficient and simple way to minimize probable destruction from natural hazard, such as rockfall is to make better land management via accurate land use (LU) designing relying on hazards delineation maps (Hungr, 2018). This is significant for the selection and setting priorities of proper mitigation processes (Wohlers et al., 2017). Utilizing hazard zoning and mapping methods has become essential for the planning of land management for two major causes. First, the recent obvious changes in the climatic have excessively increased rockfall frequency events. Second, growth of population results in urban sprawl and a subsequent increase in the number of regions at risk (Ravanel and Deline, 2011).

1.2 Background of Study

Rockfalls are rock movement from a very steep slope that the rock continually moving down the slope. Rockfall is a frequent phenomenon on steep terrain or excavated/constructed slopes that are exposed to erosion and weathering. Rockfall includes free fall or flying, bouncing, rolling, and sliding causing one of the main geologic hazard in Malaysia (Simon et al., 2015). Rockfalls occurrence is high in Kinta Valley which is characterized by steep slopes of few hundred meters.

Most of the rockfalls in Kinta Valley that result in serious damage involves massive beds of limestone and granite (Lai et al., 2017). Rockfalls pose a massive risk to traffic safety, cause maintenance issues, and exert a continual exertion on the available limited maintenance funds amount. This produced a considerable agreement of management-related and scientific interest, and the current thesis is one of this situation outcome. This research aims to develop a novel model for rockfall source identification in presence of the other landslide types. In addition, this research strives to calibrate and test a sophisticated 3D rockfall model to provide a reliable tool for future rockfall hazard assessment. The first research of rockfall behavior has been carried out by Ritchie (1963) for the Washington State Highway Commission. Since then many researches have been performed in several countries to define the rockfall trajectories and their characteristics and to design the rockfall mitigation processes as well.

Rockfall has developed into a topic with enormous economic significance, especially for the agencies of transportation. The economic attention combines with extraordinary growth in the capability of the rockfall phenomenon evaluation and the modern techniques for designing and constructing rockfall mitigation measures, has resulted in the necessity of a much more comprehensive assessment of rockfall phenomenon than in earlier researches. Developed understanding of such physical process assists engineers and scientists to improve accurate analytical models for rockfall evaluation as a hazard to people and their properties (Hungr, 2005), that decision makers can thus combine in land-use planning for the risk minimizing.

Landslide and rockfall controlled by various conditioning factors. On the other hand, the distribution of rockfall trajectories and deposits is highly controlled by topography, block physical properties (size, shape, and geology), the dynamics of block (velocity, impact, and bounce height) (Wyllie, 2014). Rockfall 3D models to some extent can consider all the above mentioned processes through an algorithm, normally parameterized in a user interface where the effects of specific site can be calibrated. Algorithms calibration to reality is a fundamental process that can be done through field checks and user expertise or back analysis based on historical data (Dorren and Berger, 2005).

In last decades, the topographic data both acquisition and analysis have seen a remarkable development in terms of methodologies and technologies related to the use of LiDAR technique. LiDAR technique is essentially designed for general geospatial data collection and terrain mapping. This technique is able of gathering huge amounts of accurate 3D data point and has been widely utilized in recent years, not just in the field of photogrammetry and remote sensing, but also in a vast difference of applications such as preservation of sculptures and historical buildings and assisting in the navigation of unmanned vehicles (Yan et al., 2015).

1.3 Problem Statement

Rockfall source areas are needed to be detected through proper method in order to be used in rockfall modeling and prediction. Furthermore, traditional rockfall forcasting methods contain some weak points interms of solpe geometry representation and sources identification which can be solved through the colletion of accurate data and the use of a novel ensemble model in addition to proper modeling of rockfall hazard assessment.

Rockfalls vary both spatially and temporally and it is challenging to predict or eliminate such incidents worldwide. This phenomenon is widely occurred in limestone and granitic areas with high and steep terrain. Kinta Valley is one of the main districts in Malaysia. The bedrock geology for Kinta Valley and surrounding areas are granitic hills, limestone bedrock, and it is mining area. As a result, a lot of engineering geologic issues have been encountered Kinta Valley and its immediate surroundings, involving rockfalls and landslides. The bedrock of limestone in Kinta Valley rises over the alluvial plains forming limestone hills with vertical to sub- vertical slopes (Simon et al., 2015).

The major triggering 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 grows 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.

Although the aforementioned studies (Losassoet al., 2017; Messenzehl et al. 2017; Mote et al., 2019) have made significant attempts to propose models that can accurately identify potential rockfall source areas using photogrammetry or laser scanning data, one major problem still remain unsolved. This issue is when the focus area contains other types of landslides that have nearly similar geo-morphometric characteristics such as rockfall and shallow landslides. Thus, this research proposes a hybrid model for identifying potential rockfall source areas from airborne laser scanning data. The proposed model is based on two main algorithms: a Gaussian Mixture Model (GMM) and bagging Artificial Neural Networks (BANN).

In addition, despite the numerous studies in rockfall hazard assessment, information about impact location and time factor are rarely discussed or presented in the literature. However, the impact location is the most significant factor in rockfall risk assessment and designing of a mitigation process.

Moreover, the time element is not considered or demonstrated in these studies, which a key element in early warning processes.

1.4 Research Gaps

There are many studies have been performed regarding the identification of rockfall source areas and characterization of rockfall hazard. However, there are some limitations associated with the implementation of these studies. The main gaps obtained from extensive literature review are:

1. The identification of rockfall source areas is the most challenge in rockfall modeling. However, most of researchers rely only on slope angle (which specified based on their experience) to determine rockfall source areas. Therefore, the uncertainty associated with this method is quite high (Agliardi et al., 2016).
2. Most of researchers applied a single machine learning algorithm for producing rockfall probability, nevertheless, they did not apply or test an ensemble model that can produce better accuracy and consistency (Pham et al., 2017).
3. Most of the rockfall studies used limited conditioning factors whereas rockfall phenomenon controlled by various conditioning factors. In addition, factors optimization was not performed in these studies or optimized individually (Kavzoglu et al., 2015).
4. In most of the studies that use machine learning algorithms, the hyperparameters of the machine learning algorithms were not optimized. However, these parameters highly affect the performance of machine learning algorithms (Klein et al., 2016).
5. In order to obtain accurate rockfall hazard maps, factors such as the rockfall runout and distribution, frequency, probability, and intensity should be taken into account at each position and over the trajectory. However, just a few methodologies of rockfall hazard assessment fulfill all of these demanding (Ferrari et al., 2016).
6. 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 (Li and Lan, 2015).
7. Even the existing 3D rockfall model most of them are based on lumped mass approach which neglects rock properties (shape and size) and considers a rock as a point mass (Li and Lan, 2015).

1.5 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, LiDAR technique was used to derive three-dimensional digital terrain model (DTM) of slope terrain. In geohazard application, the concern is the bare earth or DTM. Therefore, a filtering algorithm to filter non-ground points from ground points is required. The identification of rockfall sources areas is a key element in rockfall hazard assessment. Therefore, in this research, a novel model based on machine learning algorithms within GIS environment was utilized to identify rockfall source regions. This based on Gaussian Mixture Model (GMM) and Bagged Artificial Neural Network (BANN). The assessment of rockfall trajectories described in this thesis employs 3D physical rockfall modelling process to evaluate the rockfall characteristics and hazard. The achievement of this research has been performed employing a 3D rockfall model to efficiently handle the distribution geometry and the mechanical parameters. This was carried out in three different study areas namely: Gunung Lang, Gua Tambun, and Gunung Rapat. The influence of barrier, such as concrete wall or 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 DTM. The factors included morphological, hydrological, anthropogenic, soil and vegetation factors were also considered in this research. The mechanical parameters (coefficient of restitution and friction angle) were calibrated based on historical data. Rockfall trajectories and their characteristics in three study areas were derived through 3D rockfall modeling process with three different scenarios. A developed spatial modelling was then applied to produce the rockfall hazard maps based on rockfall characteristics (frequency, height, impact, and kinetic energy).

1.6 Research Objectives

This research proposes some methods that clearly contribute to the gaps in the literature. The main research objective of this research is to predict and assess rockfall sources and hazard using LiDAR data and the specific objectives are:

1- To develop and test a hybrid model to automatically identify rockfall source areas in the presence of other landslide types based on machine learning algorithms.
2- To predict rockfall trajectories and derive their distribution and characteristics (velocity, bouncing height, kinetic energy, and impact

locations), based on the identified sources using a developed 3D rockfall kinematic model.
3- To develop a spatial model for rockfall hazard assessment based on the obtained rockfall characteristics integrated with fuzzy-AHP and suggest mitigation processes.

1.7 Research Questions

This thesis comprehensively addresses the following research questions:

1- What is the accuracy of digital terrain model (DTM) that can be obtained from the using of LiDAR technique?
2- What are the probable sources of rockfall (seeder points)?
3- How can differentiate rockfall from other landslide types?
4- What are the possible trajectories of falling rocks down the slope? Can they be characterized?
5- Where do falling rocks stop?
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?

1.8 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 and landslide incidents in Malaysia are very frequent, and have, at times, caused in fatalities as well as destruction for the properties (Pradhan and Lee, 2010). A typical example of rockfall incidents has been reported by Simon et al., (2015). 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 rainfall, un-planned urbanization, construction, and deforestation activities. Despite all this, it is 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 and map the rockfall susceptible areas using a developed hybrid model for the identification of rockfall source areas and a 3D rockfall modelling for rockfall trajectories distribution and their characteristics. 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.

1.9 Research Limitation

The proposed methods for rockfall sources and hazard assessment have been applied and the research objectives have been achieved. However, the temporal factor was not considered in this research. This is because of uncompleted inventory data of landslides incidents in terms of time. Nevertheless, the focus of this study is on identifying rockfall source areas and assessment of rockfall kinematic process and spatial distribution, thus rockfall hazard. This is based on high-resolution LiDAR data and a developed 3D rockfall model in addition to a novel hybrid model.

1.10 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 assessment. This chapter mainly discusses the general principles and methodology of rockfall hazard assessment including rockfall causes, mechanism, rockfall sources identification parameters and methods, modelling approaches for rockfall analysis and parameters affect the rockfall simulation. Some of machine learning algorithms are also presented in this chapter.

Chapter 3 presents the methodology and framework of the thesis. This chapter presents and discusses the data which necessary for rockfall sources identification and hazard analysis. The chapter includes the following: deriving digital terrain model (DTM), 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 maps.

Chapter 4 presents the collected information and the results of rockfall source identification and hazard assessment in term of trajectories, frequency, velocity, bouncing height, kinetic energy, impact points, and hazard maps. Chapter 5 summarizes the research finding, limitations and suggests directions for future work.

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BIODATA OF STUDENT

Ali Mutar Fanos was born on 28th January 1987 in Baghdad, Iraq. He received his Bachelor in surveying engineering from University of Baghdad, Iraq in 2008. He obtained his MSc in GIS and Geomatic Engineering from Universiti Putra Malaysia (UPM) in 2016. Apart from this, he worked as a senior engineer with State Commission on Survey, Ministry of water resources, in different projects in Iraq from 2008 to 2014. Currently, he is a PhD candidate in the field of Geographic Information System (GIS) in the Faculty of Engineering, Universiti Putra Malaysia.

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Fanos, A. M., & Pradhan, B. (2019). A novel rockfall hazard assessment using laser scanning data and 3D modelling in GIS. *CATENA*, *172*, 435-450.

Fanos, A. M., Pradhan, B., Mansor, S., Yusoff, Z. M., & bin Abdullah, A. F. (2018). A hybrid model using machine learning methods and GIS for potential rockfall source identification from airborne laser scanning data. *Landslides*, *15*(9), 1833-1850.

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