DEVELOPMENT OF LANDSLIDE TOLERABLE AND ACCEPTABLE RISK CRITERIA FOR MALAYSIA

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Declaration of Authorship

I, Sim Kwan Ben, hereby declare that the work presented in this thesis is solely mine and it has not been submitted elsewhere for any other degree at this University or any other institution. To the best of my knowledge, the thesis contains no materials from previously published work other than those been cited and acknowledged.

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2024

Abstract

Landslide tolerable and acceptable risk criteria are strongly governed by utilitarian concerns i.e. financial power and the need for development and should be developed locally with historical landslide inventory, public perception, and engineering aspects being considered. The risk criteria of Hong Kong and that of the Australian Geomechanics Society are widely employed in many countries. The present study aims to develop and improve the landslide tolerable and acceptable risk criteria for Malaysia by taking into considerations of qualitative and quantitative inputs from various stakeholders. Based on the compiled landslide inventories, the Frequency-Number of fatalities (F-N) curve of Malaysia established from the present study have a similar slope gradient with those of Italy, Colombia, and Hong Kong. The F-N curve is a graphical tool (typically expressed on a log-log scale) used to depict the level of societal risk associated with a particular activity or project, which, in the present study, is landslides. As for the findings from the questionnaire surveys and interviews with landslide experts, public (non-experts) generally expressed the lowest acceptance in landslide risk for all scenarios (from low to high risk), whereas the experts were willing to accept a higher landslide risk as they understand that an ideal low landslide risk environment is not feasible under the current Malaysian scenario. Gender, occupation and educational level were the significant demographic factors influencing landslide risk acceptability in Malaysia. Modifications were proposed to the existing landslide risk criteria with a lower acceptance towards death upon taking into consideration findings from the present study. To demonstrate the application of the newly developed criterion and runout model, quantitative risk analyses (QRA) were performed to quantify landslide risk for a real-life case study. An important part of QRA concerns the development of a simple yet reliable model for predicting the impact / consequence of a landslide. A new empirical model for landslide runout estimation in Malaysia was proposed based on historical landslide data. The reliability of the proposed model was verified through a reasonable agreement between the actual runout and predicted values. Gumbel analysis was utilized to obtain the extreme rainfall scenario with a 10-year return period. It should be noted that Gumbel analysis is typically conducted for the probability distribution of extreme value in hydrologic studies for prediction of maximum rainfall. Seepage and probabilistic slope stability analyses were carried out to determine the probability of landslide occurrence of the studied slope. Using the

newly developed empirical model, the runout of the landslide was predicted. The outcomes included a quantification of risks posed to elements within the runout path, such as houses and residents. The findings offer a quantitative estimation of the annual probability of fatalities for people. A F-N curve was employed to articulate the societal risk associated with this specific slope in the case study, which was then compared against the newly established risk criterion. These results carry significant societal implications and will furnish decision-makers and regulators with valuable insights for devising risk mitigation strategies for both existing slopes and forthcoming developments.

Acknowledgements

In the grand tapestry of existence, a PhD unfolds as a voyage, transcending the mere confines of a degree or thesis. Verily, my own odyssey has proven to be a formidable, enriching, and awe-inspiring saga. Thus, I extend heartfelt gratitude to those individuals who granted permission, offered assistance, or merely stood as companions on this profound expedition.

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Sim, K.B., Lee, M.L. and Wong, S.Y., 2022. A review of landslide acceptable risk and tolerable risk. Geoenvironmental Disasters, 9(1), pp.1-17 (Awarded Best Paper for the Journal in Year 2022). (Scopus and Emerging Sources Citation Indexed)

Sim, K.B., Lee, M.L., Remenyte-Prescott, R. and Wong, S.Y., 2023. Perception on landslide risk in Malaysia: A comparison between communities and experts' surveys. International Journal of Disaster Risk Reduction, 95, p.103854. (Web of Science indexed, IF 5.00)

Bulletin

Sim, K.B., Lee, M.L., Remenyte-Prescott R and Wong, S.Y., 2023. Societal Risk of Landslides in Malaysia (1961-2022). The Institution of Engineers, Malaysia, (October), pp.16–20.

Conference Proceedings

Sim, K.B., Lee, M.L., Remenyte-Prescott R and Wong, S.Y., 2022. An Overview of Causes of Landslides and Their Impact on Transport Networks. Advances in Modelling to Improve Network Resilience, p.114.

Sim, K. Ben, Lee, M.L. & Wong, S.Y., 2023. An Overview of Socioeconomic Impacts of Landslides. In Proceedings of the IAIA 2023 conference.

Sim, K.B., Lee, M.L., Remenyte-Prescott R and Wong, S.Y., 2024. An Empirical Model for Predicting Landslide Runout Distance in Malaysia. Resilience assessment: Methodological challenges and applications to critical infrastructures, p.245-255

Sim, K.B., Lee, M.L., Remenyte-Prescott R and Wong, S.Y., 2024. Quantitative Assessment of Landslide Risk to Residents on the Slope of a Hazardous Area in Malaysia. From risk imagination to safety intervention –Managing risks with knowledge. *Accepted for publication*

Nomenclature

If required

1. Introduction

1.1 Background

Landslides are one of the major devastating geohazards and claim thousands of lives and create acute economic losses related to property damage every year (Schuster and Highland 2001; Dilley et al. 2005; Petley 2012). The first documented landslide was an earthquake induced landslide dam in Honan Province of China in the year 1767 B.C. (Schuster 1996). International Disaster Database (EM-DAT) of the Centre for Research on the Epidemiology of Disasters reported that landslides caused 17% of the deaths associated with natural hazards worldwide annually (Lacasse and Nadim 2014; Aristizábal and Sánchez 2020). Of the total loss of life resulting from natural hazards worldwide, 5% of it comes from highly developed nations. The remaining 95% of total deaths are from medium and developing countries (Lacasse et al. 2010; Lacasse and Nadim 2014a). According to Dowling and Santi (2014), landslides are catastrophes resulting from social vulnerability.

Socioeconomic impacts of landslides are always underestimated because landslides in many countries are always taken as a consequence arising from other triggering processes such as extreme precipitation, typhoons, volcano eruptions or earthquakes. The damage costs from landslides could surpass all other costs from the overall multiple-hazard catastrophes (Froude and Petley 2018; Sultana 2020). Studies have indicated that the EM-DAT database often underestimates the number of fatal landslides by 1400% (Kirschbaum et al. 2015) or 2000% (Petley 2012), and the number of deaths by 331% (Kirschbaum et al. 2015) or 430% (Petley 2012). The under-reporting is caused by the perception of landslides as a secondary hazard, in which the cause of death is normally reported in relation to the primary hazards (e.g. an earthquake rather than a seismically triggered landslide) instead of the actual cause of the loss (Froude and Petley 2018). This underestimation brings about a lower awareness and appreciation regarding landslide risks among regulators, authorities, and the general public.

The most common method used by geotechnical engineers to access a slope is the traditional-based approach or the deterministic approach where Factor of Safety (FoS) of slope against failure is analysed by taking into account established rules as to the design events, loading conditions i.e. precipitation data and soil properties as found in studies conducted by various researchers (Refahi 2006; Soleimani and Asakereh 2014; Holcombe et al. 2016; M. Abbas et al. 2017; Abbas and Mutiny 2018; Suradi 2018). The determined FoS is compared with the minimum required FoS as specified in the established guidelines. Slopes satisfying the stability requirements are assumed to be completely "safe" while those that does not will require mitigation measures such as vegetative root reinforcement (Holcombe et al. 2016). In other words, the method allows quantitative factors of safety to be obtained taking into account for the inconsistency of soil properties if required.

However, the reliability of the traditional approach can no longer be guaranteed due to it being an oversimplified model. What it lacks of is the ability to predict failure probability. FoS is purely just an index: a higher value signifies a lower potential of failure. The 2013 failure of Mt. Polley Tailing dam in British Columbia, Canada despite being designed by competent professional geotechnical engineers with FoS of 1.3 (Hungr 2016) signifies that FoS is not a reliable indication of slope safety. In addition, there are also various inherent uncertainties, such as increased regional precipitation caused by climatic change, rising urbanization in landslide-prone areas, persistent deforestation, etc. Often times, the data requirements for this approach is considered prohibitive and the effectiveness of the models are questioned due to the frequent inability to get the required input data (Dai et al. 2002). The behaviour of landslides is admittedly rather complicated and hence, risk assessments need to be employed to capture the actual hazard and risk level of the area if a landslide were to occur. Landslide risk assessments is studied and employed extensively in developed countries such as Hong Kong (Geothechnical Engineering Office 1999) and Australia (AGS 2007) and in some developing countries but they need to be further improved and validated against other factors so that reliable results can be obtained for future developments and use.

1.2 Problem statement

The currently available landslide risk criteria for Malaysia has a considerably high risk tolerance as compared to other countries. This means that the Malaysian landslide risk criteria is unduly liberal and improvements will have to be made. In addition, the currently available landslide data in Malaysia is rather scattered with some of them are stored in archive of certain database, while some in other authorities such as the Public Works Department, local councils, and etc. Moreover, the concept of landslide risk management is still at its infant stage in Malaysia. Most of the time, engineers will employ the deterministic safety factor method when carrying out designs for new development. There is still no proper landslide risk management in place in Malaysia.

1.3 Aim and objectives

The main aim of this research is to develop landslide tolerable and acceptable risk criteria for Malaysia. To achieve the main aim, several objectives will have to be fulfilled:

I. To evaluate the frequency and impacts of existing landslides in Malaysia by analysing historical landslide inventory data.

II. To analyse the public and experts' perception of landslide risk in the country.

III. To develop landslide tolerable and acceptable risk criteria for Malaysia and compare it with the criteria employed by other countries.

IV. To demonstrate the application of the landslide risk criteria through a case study.

1.4 Scope of research

The first objective of the study is to evaluate the frequency and impact of landsides (in terms of death) in Malaysia in the form of F-N curve (a plot showing the number of fatalities (N) plotted against the cumulative frequency (F) of N on a log-log scale (Dai et al. 2002; Song et al. 2007; Hungr et al. 2016a)). In a simpler term, the F-N Curve compares the number of fatalities (N) of a landslide event with the probability (or frequency) of that event (F). The curve is determined so that one can know the overall societal risk of landslides of the country. To achieve this, historical landslide data collection will have to be made from different sources such as data and reports from the National Slope Master Plan and local councils etc. This is to establish a complete historical landslide inventory data so that a comprehensive F-N curve could be produced.

The second objective is to study the public and experts' perception on the landslide risk in the country. Questionnaire survey studies are carried out among residents in lowlands and those residing near to slopes and landslide prone areas. In addition, interviews are conducted with authorities and landslide experts to obtain professional opinions on the landslide risk problem in Malaysia.

The third objective is to develop landslide risk criterion for Malaysia and compare it with other countries. Every country has its distinct priorities and approaches in dealing with risk management. The risk criteria of every nation is unique to one another and there is a need to take into account the socio-political, economic, and cultural aspects of the nation as society's perception of risks, influenced by factors such as their nature and voluntariness, shape their response to risk (Macciotta and Lefsrud 2018).. The quantitative results from the first objective and the qualitative results from the second objective are used in aiding the risk criterion development. To ensure validity of the proposed risk criteria, comparisons are made with the well-established criteria such as that by Hong Kong.

Lastly, the application of the tolerable and acceptable risk criterion in landslide risk assessment is demonstrated through a case study. To achieve this, a coupled seepage-probabilistic slope stability analysis using Plaxis LE software is conducted to establish probability of slope failures under extreme rainfall condition. Subsequently, runout of the landslide of the case study was predicted using a newly developed empirical model. Quantitative Risk Assessment (QRA) for the effect of landslide on potential fatalities is applied to a selected case study. The overall risk to society is expressed using an F-N diagram to demonstrate the practical implementation of the proposed Malaysian risk criterion. To achieve this, F-N curve of the study area is plotted and compared with the proposed risk criterion. With the F-N curve and the risk criterion established, the landslide risk level of the study can be assessed which forms the basis for making recommendation for the proposed development.

1.5 Research significance

1.5.1 Raises awareness among the public, local government, and organizations about landslide-associated risks for better preparedness

The first objective of analyzing the frequency and impact of landslides in Malaysia using the F-N curve gives a clear picture of the overall societal risk posed by landslides in Malaysia. By quantifying landslide risks in terms of fatalities and event probability using the QRA framework of objective 4 and benchmarking it against the developed risk criteria of objective 3, this study provides data-driven insights that can be shared with the public, government, and organizations. These insights raise awareness by making the potential loss of life more tangible, thereby fostering a sense of urgency for better preparedness and risk communication across all levels of society. Through the second objective, studying public and expert perceptions on landslide risk reveals how different groups understand and react to these risks. Knowing public and expert perspectives helps to identify gaps in awareness and preparedness that may need addressing, and reveals areas where proactive mitigation efforts would be most beneficial.

1.5.2 Enables foresight of landslide impacts, allowing for proactive mitigation, evacuation, and backup plans.

By using the risk informed approach for either existing slopes and future developments through QRA (objective 4), local governments can foresee likely impacts and design evacuation and backup plans tailored to the societal risk profile of landslides, enhancing proactive response capabilities.

1.5.3 Leads to enhanced design guidelines and more stringent standards for future developments.

The third objective, developing a landslide risk criterion specific to Malaysia, provides a scientific basis for risk-informed policy changes. This criterion could guide local authorities in making decisions when it concerns development near slopes and landslide-prone areas. A tailored risk criterion helps to ensure that design and construction standards reflect the unique socio-political and economic landscape of Malaysia, resulting in safer, and more resilient infrastructure.

1.5.4 Encourages geo-scientists and engineers to incorporate slope risk assessments instead of relying solely on traditional FoS methods.

The fourth objective showcases the practical application of the improved risk criterion of objective 3 through a case study using probabilistic slope stability analysis in Plaxis LE. By demonstrating the benefits of probabilistic methods through QRA over traditional deterministic approaches like Factor of Safety (FoS), this study encourages engineers and geoscientists to adopt quantitative risk assessment methodologies that account for vulnerabilities and uncertainties. This shift supports a more comprehensive and accurate approach to slope safety assessment, ultimately contributing to safer design practices and reducing landslide risk.

1.6 Layout of thesis

This thesis consists of eight chapters in which the contents of each chapter are presented as follows:

- **Chapter 1** introduces the background, aim and objectives, scope, and significance of doing a risk informed approach method for rainfall-induced slope stability assessment.

- **Chapter 2** discusses the cost of life caused by historical landslide events and the economic losses and their quantification around the world. In addition, this chapter also discuss and review the landslide risk acceptance criteria from various nations. Based on literature review, the risk criteria of Hong Kong and that of the Australian Geomechanics Society are widely employed in many countries. The criterion proposed by Malaysia is above the criteria of other nations. It has the highest risk tolerance compared to other countries which is unduly liberal and calls for improvements to be made. Most of the contents from this chapter have been published as (Sim et al. 2022a, b, 2023c).

- **Chapter 3** describes the overall methodology adopted in this project. Historical landslide data were collected from relevant authorities and analysed to form a F-N curve to represent the overall societal risk of landslides in Malaysia. Subsequently, questionnaires are distributed to obtain the public opinion on the landslide problem of Malaysia. Interviews are conducted with authorities and landslide experts to obtain professional opinion on the landslide risk problem of Malaysia. The results from the quantitative study through the F-N curve and the qualitative study from the surveys and interviews have enabled the landslide risk criterion for Malaysia to be established. Utilizing a questionnaire survey and interviews can prove valuable in determining the risk criteria for landslides by collecting opinions from both the communities and experts. The last phase involves the verification of the risk criterion by conducting Quantitative Risk

Assessment (QRA) on a selected case study to demonstrate the practical implementation of the proposed Malaysian risk criterion.

- **Chapter 4** compiles landslide inventories and the number of deaths caused by each landslide event in Malaysia between 1961 and 2022. Based on the data, the trends of landslide occurrences and fatalities are analysed. Subsequently, the F-N curve of landslide hazard in Malaysia is produced and this is compared with that of other nations. Understanding the societal risk level is useful for public authorities to implement appropriate QRA measures for the country. Most of the contents of this chapter have been published as (Sim et al. 2023a, b).

- **Chapter 5** presents the findings from the questionnaire survey and expert interviews to determine the suitable risk criteria for landslides by collecting opinions from both the communities and experts. The demographic factors that govern frequency of acceptability, insurance premium purchase etc. were determined through the independent sample t-test, one-way analysis of variance, and Brown–Forsythe test. Key factors to consider when developing risk evaluation criteria and shortcomings of the previous proposed risk criterion for Malaysia were discussed. Modifications were proposed to the existing landslide risk criterion with a lower acceptance towards death upon taking into consideration findings from the present study. Most of the contents of this chapter have been published as (Sim et al. 2023a).

- **Chapter 6** introduce a new empirical model for runout estimation in Malaysia. Data on landslide events in Malaysia were collected, processed and analysed in order to discuss the efficacy of various influential parameters on the travel distance and to establish its prediction model. The reliability of the proposed model was verified through a reasonable agreement between the actual runout and prediction values. In addition, this model also investigates the understudied yet influential parameter governing landslide travel distance i.e. retrogression distance, paving the way for a more accurate prediction model for Malaysia.

This perspective not only advances the field of landslide prediction but also offers a different approach to enhancing safety and risk management for infrastructures in Malaysia. The contents of this chapter is nowpublished as (Sim et al. 2024).

- **Chapter 7** demonstrates the application of the suggested F-N risk criterion using Quantitative Risk Assessment (QRA). This section specifically focuses on QRA applied to a case study to assess the impact of landslides on residents (potential fatalities) at a hazardous residential area in Malaysia. The runout of the landslide in the case study is forecasted using the empirical model developed in Chapter 6 for this purpose. The risk for elements at risk along the landslide's run-out path is estimated. The overall risk to society is then portrayed using an F-N diagram, demonstrating the practical application of the proposed Malaysian risk criterion from Chapter 5. The contents of this chapter have been accepted in a conference and it is now pending for publication.

- **Chapter 8** summarizes the final findings, contributions of the project, and provides recommendations for future endeavours.

2. Literature review

This chapter reviews the socioeconomic impacts of landslides worldwide and the landslide risk criteria adopted by various countries. Firstly, the factors causing landslides worldwide, namely triggering factors and contributing factors are discussed. Secondly, the socioeconomic impacts of landslides worldwide in terms of fatalities from the past centuries to the recent events as well as economic losses are discussed to give an insight about the severity of the landslide issue worldwide. Subsequently, the concept of landslide risk assessment is explained and followed by a discussion of the concept of acceptable and tolerable risks as well as risk curves of landslides of various countries. Finally, the tolerable risk criteria of landslides of different countries are reviewed.

2.1 Factors affecting landslides

According to Griffiths (1999), a slope can undergo failure due to many contributing factors i.e. geological, morphological, human and physical, but there is only one trigger that triggers the landslides at the moment of failure. By definition a trigger is an external stimulus i.e. extreme precipitation, storm waves, earthquake shaking, volcanic eruption, or rapid stream erosion that results in near-immediate reaction in the form of a landslide through the rapid rise in the stresses or through the reduction of the strength of slope properties. In certain scenarios, landslides could transpire without any evident attributable trigger due to assortment or combination of causes, such as chemical or physical weathering of materials, that progressively take the slope to failure (Wieczorek 1996). The triggering and contributing factors that causes landslides will be discussed in this section.

2.1.1 Triggering factors

According to Highland and Bobrowsky (2008), the most common landslides triggering factors are such as extreme rainfall, rapid snowmelt, volcanic eruption, earthquake shaking, change in water level i.e. rapid drawdown. Other common triggering factors is change in slope geometry and erosion (Ng 2012; Akter et al. 2019). The distribution of triggering factors worldwide is plotted in Figure 2-1. Statistic showed that precipitation followed by water level change are the leading triggering factors of landslides worldwide (Ng 2012). A comprehensive review of landslide studies by Sassa et al. (2009) found the majority of papers (54.2%) dealt with landslides disasters triggered by precipitation. A comprehensive review by Sassa et al. (2009) found that the majority (54.2%) of landslide studies that can be found on current available literature dealt with rainfall induced landslide. A documented study by Froude and Petley (2018) stated that rainfall has always been the main trigger of landslides all around the world amounting to approximately 3841 landslide disasters worldwide between 2004 to 2016. Globally, rainfall induced landslides have resulted in nearly 90% of deaths (Haque et al. 2016; Sultana 2020). 41% of rainfall induced landslides worldwide were contributed by the Asian continent notably China, Nepal and India.

Extreme precipitation contributed to 73% of all fatal landslides in Latin America and Caribbean (Sepúlveda and Petley 2015) Brazil and Colombia together contribute to 67% of all rainfall triggered landslides in Latin America amounting to 37% and 32%, respectively, with most of the disasters concentrated around south-east Brazil and central region of Colombia. A distribution of triggering factors of landslides in Colombia are as follows: rainfall 87%, Human activity 10%, seismic excitation 0.6% and 0.1% for volcano eruption (Aristizábal and Sánchez 2020).

From the statistics in Figure 2-2, it is clear that China alone contributes 81% of all rainfall triggered landslides of the whole East Asia due to the summer Monsoon season. Moreover, it is documented that China alone contributes to 15% of all the rainfall induced landslides worldwide (Froude and Petley 2018).

In South Asia, the summer Monsoon has also result in a rise in landslide disasters in India, Nepal, Pakistan and Bangladesh. Nepal and India contribute to 26% of the world rainfall induced landslides at 10% and 16%, respectively. It is stated by Sultana (2020) that 83% of landslide occurrence in Bangladesh have been attributed to extreme precipitation.

Most of the rainfall triggered landslide disasters in South East Asia are from Indonesia and Philippines at 46% (42% caused by typhoons) and 32%, respectively. It is further stated by (Froude and Petley 2018) that 22% of rainfall triggered landslides in the south-east Asian region and 5% worldwide is brought about by typhoons.

Strauch et al. (2015) found that climate change is altering rainfall patterns, leading to less frequent but more intense rain events. In a case study in Hawaii, they observed that the lower average annual rainfall is linked to higher rain intensities and more dry days. In Southeast Asia, monsoon seasons are projected to be delayed by 15 days, with rainfall dropping to 70% below usual levels (Loo et al. 2015). However, in areas with certain topography, like mountains or islands, rainfall intensity may increase, resulting in more extreme weather, including severe flooding in some regions and intense drought in others.

The IPCC (Intergovernmental Panel on Climate Change), founded in 1988, projected that from 1990 to 2100, average global temperatures may increase by 1.4°C to 5.8°C resulting in the alteration of rainfall patterns, making them more intense but less frequent (Kristo et al. 2017). The main causes of global warming that highlight the significant impact of human activity including a 40% rise in carbon dioxide emissions from fossil fuel combustion in power plants and transportation; methane emissions from livestock and agriculture; deforestation of tropical forests, and increased use of chemical fertilizers (Picarelli et al. 2021). The change in rainfall patterns owing to these scenarios can significantly affect soil moisture and groundwater, weakening soil stability bringing about landslide disasters as a consequence (Dhanai et al. 2022). Extreme weather events, which are expected to occur with greater frequency in the future, will likely lead to flooding and subsequent impacts on slope stability, as well as trigger rapid landslides (Picarelli et al. 2021).

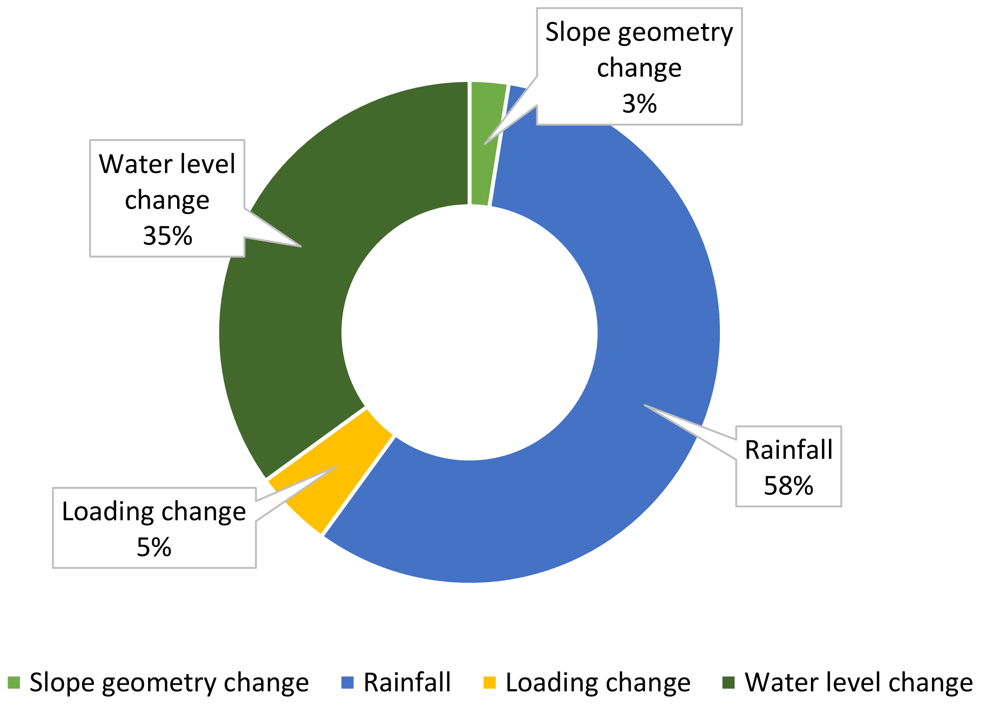


Figure 2-1 Distribution of landslide triggering factors around the world (Ng 2012)

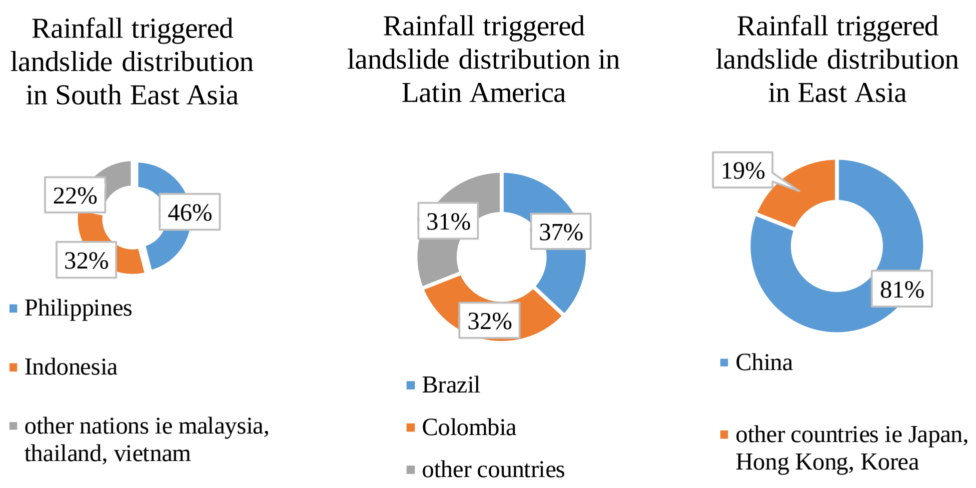


Figure 2-2 Distribution of rainfall induced landslides across different regions. Source: (Froude and Petley 2018)

2.1.2 Contributing factors

Geological conditions, geo-morphological conditions, physical, and manmade factors are the main contributing factors to landslides (Griffiths 1999). According to Ng (2012), numerous studies have been conducted to determine landslide contribution factors distribution taking into accounts countries such as China, Italy, Thailand, Russia, Taiwan, Germany, Korea, Japan, and Australia. Figure 2-3 distribute the contributing factors of landslides worldwide. Similar distribution is found in Akter et al. (2019). It is clearly shown in the chart that ground conditions and human causes are the main contributing factors of landslide failures on a global scale. Furthermore, the landslides disaster also occurs from the mismanagement of land use due to the rise in population and the demand for agricultural activities that consequently force the population to stay in regions susceptible to landslides (Soralump 2010). More than 97% of climate scientists who actively researching in climate change agree that human activities play a major role in altering global average temperatures (Doran and Zimmerman 2009; Kristo et al. 2017). It is stated by Cloutier et al. (2017) that in Québec, Canada, approximately

40% of the landslides requiring government assistance are linked to human activities. They further stated that the direct influence of human actions on landslides may be more substantial than projections based solely on climate change impacts. In addition to future human-induced changes like deforestation and urban expansion, land cover changes related to climate change, including those in the biosphere and cryosphere, are currently happening and are anticipated to persist which will further aggravate the situation there. A documented study by (Froude and Petley 2018) states that human activities such as construction and mining has contributed to approximately 770 landslide disasters with 3725 deaths between 2004 to 2016. The distribution is plotted in Figure 2-4. Globally, majority of landslides disasters occurring from construction activities occurred in India (28 %), followed by China (9 %), then Pakistan (6 %), the Philippines (5 %), Nepal (5%) and Malaysia (5 %) (Froude and Petley 2018). On average, construction induced landslides claim 3 lives per occurrence. In China, 52% of disasters occur in urban construction sites, while landslides along roads are scarce (7 %). A more recent case study by Li et al. (2020) state that road construction has heightened landslide susceptibility at the Three Gorges area in China. Along older roads, this increased risk is brought about by added slope load from passing vehicles and rainfall infiltration. In contrast, susceptibility near newly built roads is primarily due to slope cutting and excavation. Additionally, the expansion of agricultural land, artificial plantations, and construction activities have also contributed to higher landslide susceptibility, as these activities often involve the excavation, loosening, and accumulation of materials on slopes. As for India and Nepal, road construction contributes to 30% and 43% of landslide disasters, respectively (Froude and Petley 2018). (Petley et al. 2007; Chaudhary et al. 2017) states that the rise in landslides disasters in the Himalayan region has always been associated with road construction due to the poor engineering design, route choice and spoils management (Hearn and Shakya 2017). From the chart in Figure 2-4 it is seen that landslide disasters due to mining are driven from the rise in illegal or unregulated extraction. Globally, the nations that give rise to landslides from mining activities are India (12 %), followed by

Indonesia (11.7 %), then China (10 %), Pakistan (7%) and Philippines (7%) (Froude and Petley 2018).

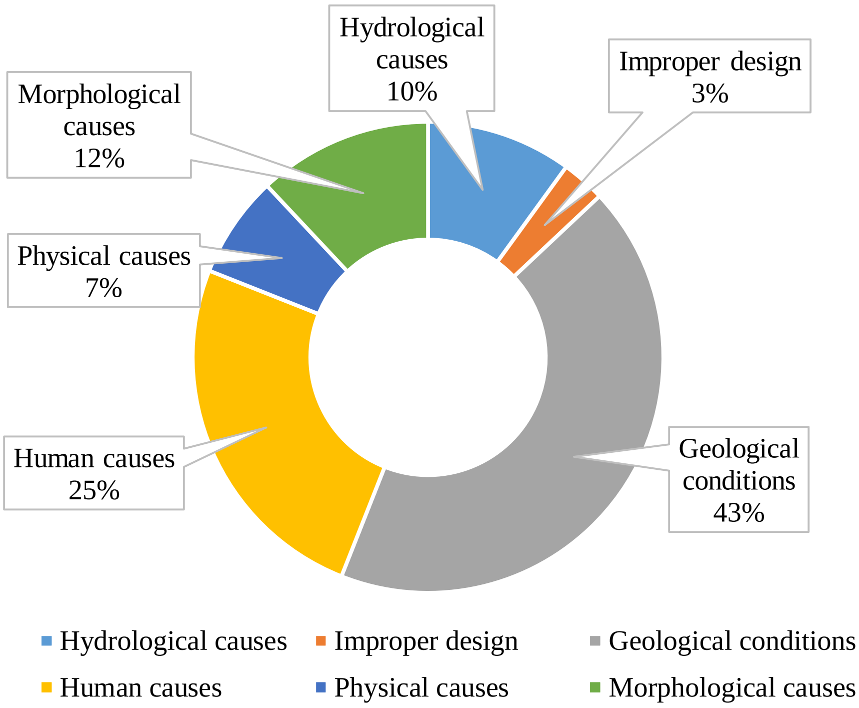


Figure 2-3 Distribution of landslide contributing factors around the world (Ng 2012; Kazmi et al. 2016; Akter et al. 2019)

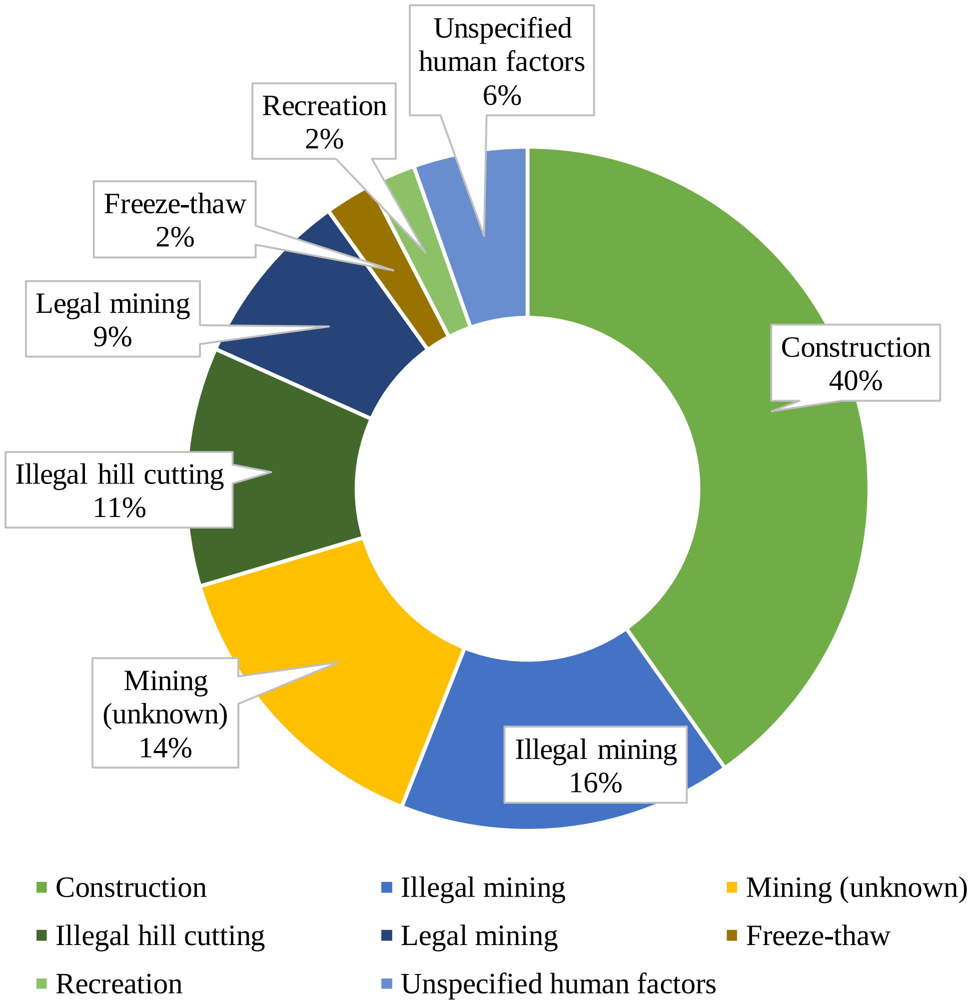


Figure 2-4 distribution of landslides resulting from human factors worldwide (Froude and Petley 2018)

2.2 Fatalities caused by landslides

2.2.1 In the past centuries

Since centuries ago, many nations across the globe have suffered deaths and economic losses due to landslides and the impact is still on the rise until now. According to Schuster (1996), the first documented landslides was a landslide dam that formed due to a seismic event in Honan Province of China from the year 1767 B.C.. Landslides not only result in casualties to both humans and animals but destroy the quality of water quality of streams and rivers as well as the destruction of structural and infrastructural developments.

Among the world's most critical natural disasters, landslides stands at third place(Perera et al. 2018) and its crisis is still rising as mentioned earlier predominantly due to investments as well as developments in landslide-prone areas. Landslides approaches in a big range of velocities and most of the time without warning, causing little to no window for evacuation. During the 1970s, casutlaties caused by landslides amounted close to 600 with aproximately 90 percent of the casualties occuring in the Ring of Fire region. In Japan, 150 deaths were recorded annually for 16 years from 1967 due to landslides while the annual casualties of landslides USA were not less than 25. There were scarcity of landslide records for developing countries such as those in the South America continent, China, Russia, Nepal and Indonesia unfortunately (Schuster and Fleming 1986).

Figure 2-6 summarize the loss of lives due to landslides in the 20th century. It can be seen from Figure 2-6 that American continent suffered the most deaths due to landslides in the 20th century, followed by Europe and then Asia with deaths of around 21,000, 15,000 and 16,000 respectively. Inside Europe, Italy face the highest human and economic losses owing to landslides (Sidle and Ochiai 2006; Lacasse and Nadim 2014) while for Asia, high death rates comes from China, Nepal, India and Japan (Sidle and Ochiai 2006). In the American continent, high death rates have been coming since the 1960s from developing countries in the latin American Region particularly among the steep hillslopes around Rio de Janeiro, Brazil due to the growth of favela (slums) in the region (Jones 1974; Fernandes et al. 2004; Sidle and Ochiai 2006). In the context of landslides during the 1960s, Malaysia (a Southeast Asian country with a tropical climate similar to that of Latin America) experienced its first recorded landslide tragedy in 1961, resulting in the loss of 16 lives following its independence (Ali and Chua 2023). Since then, numerous other fatal landslide incidents have been documented, with a significant number occurring in urban regions particularly in the Ulu Klang area. The aforementioned area has experienced several major landslides since December 1993, when Block 1 of the Highland Towers collapsed, claiming 48 lives and causing economic losses amounting to millions of ringgit (Sim et al. 2023c). The Highland Towers comprises three 12-storey blocks, constructed between 1975 and 1979 at the bottom of a very steep slope which was later terraced thoroughly in the beginning of 1980s. Today abandoned remains of Block 2 and Block 3 were restricted from public access, and the site have fallen from vandalism and became a haven for criminal activities. The many factors that brought about this catastrophe are extracted from various reports (Gue and Liong 2007; Gul et al. 2017; Rahman and Mapjabil 2017) and they are as follows: (i) Unsuitable construction of building on the edge of hill; (ii) Building apartment on hillside is against Land Conservation Act 1960 which prohibits development on hillsides with slope exceeding 18 degrees; (iii) Report by Ampang Jaya Town Council in 1994 - inadequate drainage, design deficiencies (safety factor less than 1.0); (iv) In 1991, a new housing development project, known as Bukit Antarabangsa Development Project, commenced construction on the hilltop behind Highland Towers. The hill was cleared of trees and other landcovering plants, exposing the soil to land erosion that lead to the catastrophe.

Figure 2-5 (A) Collapse of Block 1 of Highland Towers in 1993 due to catastrophic landslide (Krishnan 2023)**; (B) Remains of Block 2 and 3 of Highland Towers** (Gul et al. 2017)

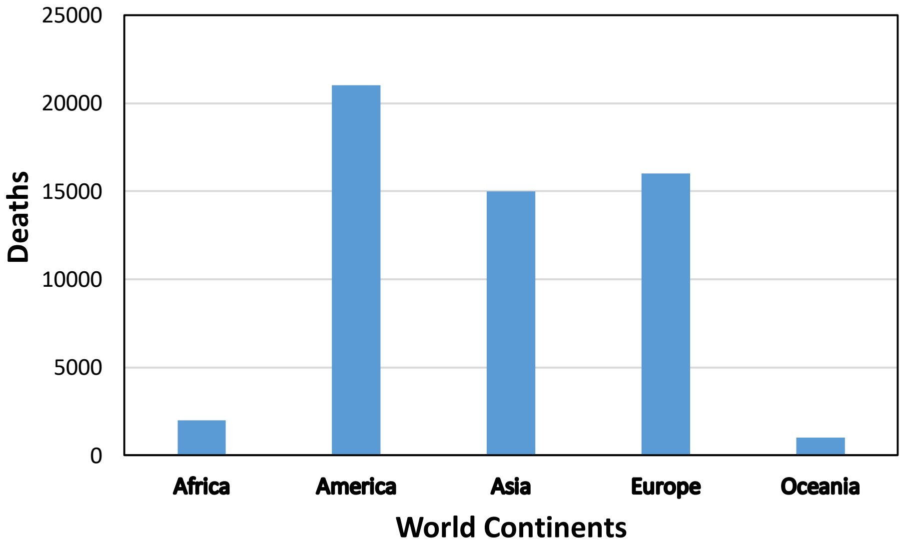


Figure 2-6 Summary of landslide deaths of different continents worldwide (1903 - 2004). Source: (EM-DAT, OFDA/CRED International Disaster database) as seen in (Lacasse and Nadim 2014)

2.2.2 In the new millennium

However, as the the world enters a new millenium, technology advances and with the advent of the World Wide Web, data regarding landslides socioeconomic impact in developed countries and especially developing countries become more complete and available. The world wide landslide database in the new millenium have demonstrated the extent where landslides impact on population and identified regions with the highest risk. It should be noted in Figure 2-7 that landslides mainly cluttered in tropical regions mainly across China, Nepal and India. This is due to the climate conditions of these regions that is frequently raining. In addition, tropical countries are highly susceptible to landslides disasters due to the destabilizing effect of groundwater pressures of soil or rock slopes subjected to exceptional precipitation (Turner 2018). As mentioned by (Dowling and Santi 2014; Froude and Petley 2018), rainfall is the main triggering factor of landslides (see Figure 2-1). Heavy rainfall is the main trigger for mudflows, the most lethal and destructive of all types of landslides (Lacasse and Nadim 2014). A documented study by Froude and Petley (2018) states that over the interval of 13 years from 2004 to 2016, a total of 4862 landslide events strucked the world not taking into account seismically triggered landslides. The fatalities from the 4862 disasters amounted to 55,997 lives loss with the Asia continent being the dominant region (75% of the 4862 events). 95% of the disasters comprise of the failure of a single slope and the highly clustered regions are:

- Carribean islands
- Central America region between South Mexico and Costa Rica
- South America
    - Around the states of Rio de Janeiro and Sao Paolo of Brazil
    - Mount Andes covering the region between Bolivia and Venezuela and Chile to a certain degree
- Eastern Africa
    - The borders surrounding Congo, Uganda, Burundi, Kenya, Rwanda and Tanzania.

- Asia (region with three quarters of the total landslides) with a high occurrence in
    - Himalayas in the regions throughout India and the south east region of China
    - Bangladesh
    - South east asian counties : Myanmar, Laos, Phillipines and Indonesia
- Turkey
- Iran
- The Alps in the European continent

Similar reporting is seen in (Perkins 2012; Petley 2012). In addition, it is stated in a paper by Nadim and Kjekstad (2009) that Colombia, Tajikistan, India, and Nepal are the countries with the highest risk of fatal landslides where the annual landslide death per 100 km^2 exceeds one.

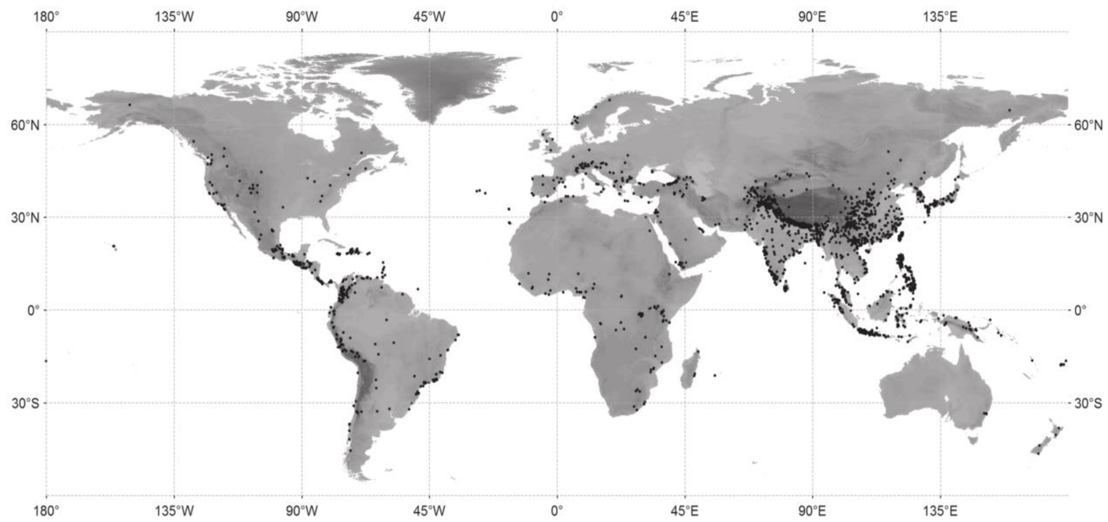


Figure 2-7 Global distribution of fatal landslides (each dot represents a single landslide) (Petley 2012)

2.2.3 Recent events

The landslides costs on lives for the year 2020 is plotted in Figure 2-8. It should be noted the data obtained only focus on deaths occurred in the most vulnerable nations (European Commission 2021). The distribution of landslide deaths is clearly heterogeneously distributed with Asia prevailing again as the continent with most landslide fatalities (around 79%, a percentage that tallied to the percentage of deaths from 2004 to 2016 which is 75%). Figure 2-9 distribute the landslides deaths in countries with high vulnerability within the interval of 5 months (August 2020 to December 2020) which are:

- Central America region with San Salvador, El Salvador reporting 42 deaths on 29th October 2020.
- South America with Anqioquia, Colombia 18 deaths reported on 23th November 2020
- European continent with Eastern Norway and Lombardy, Italy recorded 10 deaths with 1,010 missing persons on 30th December 2020 and 3 deaths on 12th August 2020 respectively.
- Asia
    - 45 districts in Nepal reported 136 deaths
    - Cebu Province of Philipines reported 10 deaths on 21th December 2020.
    - Gilgit-Balistan region of Pakistan reported 16 deaths on 18th October 2020.
    - Kerala state of India on 7th August 2020 reported 70 deaths.
    - North Kalimantan Province of Indonesia reported 11 deaths on 28th september 2020
    - Central Province of Papua New Guinea reported 13 deaths on 29th December 2020.

- Hanyuan County, Sichuan Province, China on August 21, 2020 reported 9 deaths due to landslides caused by extreme rainfall (He et al. 2021).

It should be noted that the landslide deaths data for 2020 from European Commission (2021) is very restricted and does not completely report on the total global landslide fatalities for 2020. For example, the deaths that resulted from a landslide from extreme rainfall in state capital of Minas Gerais, Belo Horizonte, Brazil in January 2020 is not included. Although the data does not cover all the deaths in 2020, it does indicate strongly that the trend of fatal landslides still remains the same i.e. clustered around developing countries such as Nepal, India, Indonesia and developed countries such as Norway and Italy since the past centuries till today. By reffering to global landslide map in Figure 2-9, it is clear that fatal landslides clustered in southwestern eastern Asia, Central America, India, and the Caribbean region. Similar reporting is seen in (Perkins 2012; Petley 2012; Froude and Petley 2018).

By referring to Figure 2-10 it is clear that most of these countries have comparatively low Gross National Income (GNI) and that the landslides conglomerate at cities of these low GNI countries at highly susceptible areas according to the evaluation of the physical characteristics of those “hotspots” by (Kirschbaum et al. 2012) which are frequently subjected to extreme rainfall. During the write-up of this section, another tragedy unfolded as a landslide hit the Kandy District of Sri Lanka, damaging 618 houses and affecting not less than 44,153 people on the 13^{th} May 2021.

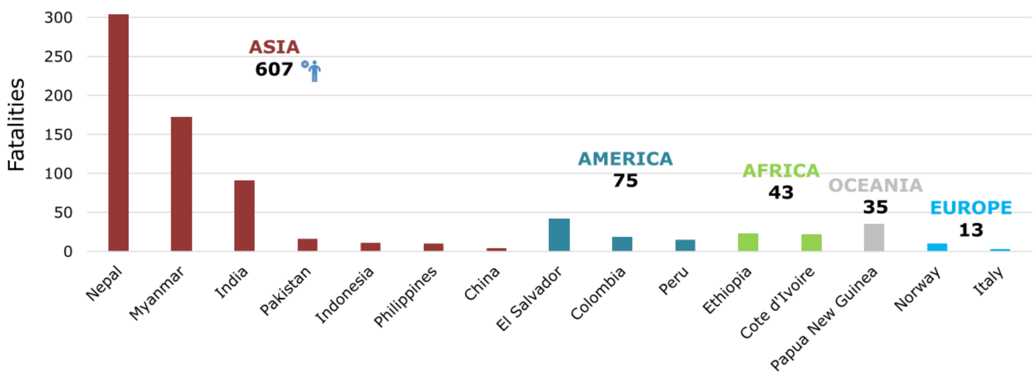


Figure 2-8 The cumulative casualties due to landslides in the most impacted nations in the year 2020 (European Commission 2021)

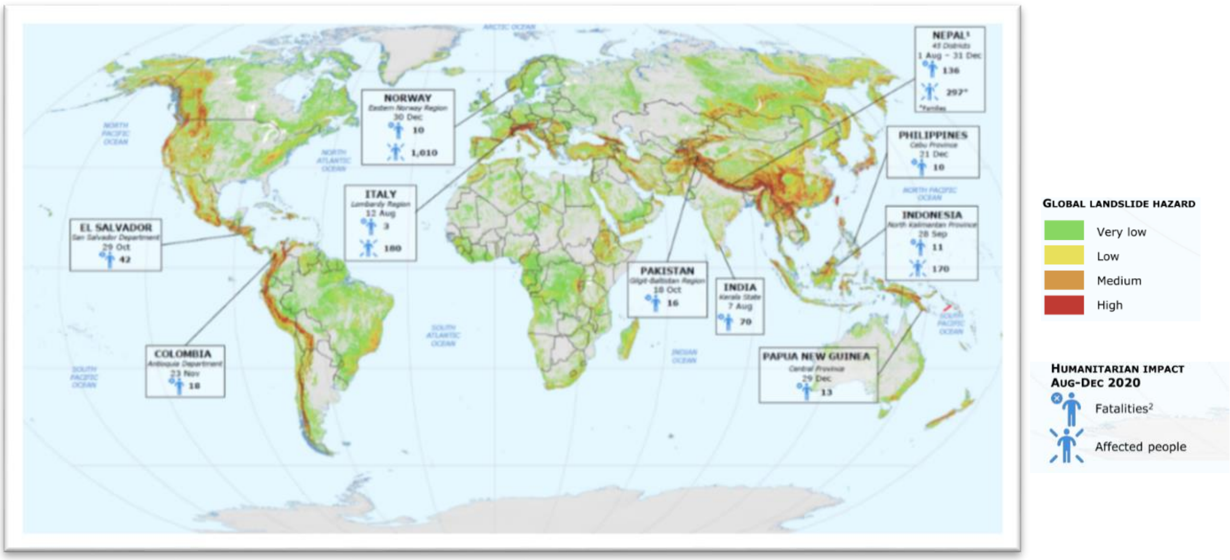


Figure 2-9 Global overview of landslides with fatalities (1 August – 31 December 2020) (European Commission 2021)

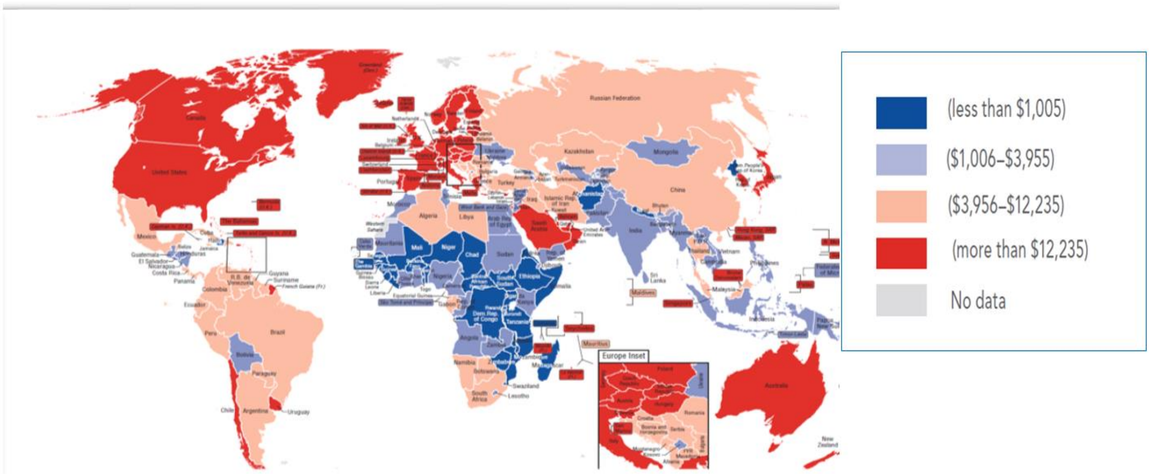


Figure 2-10 The gross national income (GNI) per capita (USD) by nations (World Bank 2020)

2.2.4 Average annual deaths caused by landslides

Figure 2-11 shows the average annual landslide deaths for various countries based on 600 years of historical data obtained from Sidle and Ochiai (2006). Data from a documented study by Froude and Petley (2018) covering period between 2004 to 2016 indicate that an average of more than 4,000 people died due to landslides every year. Apparently, the countries most affected by landslides are those from the developing countries with low value of life and GNI of Asia continent with the exception of Japan. Japan while being a highly industrialized country with high GNI and value of life, is a special case due to its lithiology, topography, climatee and tectonic activity (frequent earthquakes). Sidle and Ochiai (2006) state that most businesses and facilities in Japan are built around regions with high landslide susceptibility. Italy followed by Norway so far have the most landslide casulaties in the european nation albeit lower than its Asian and North American counterpart. Similar trend is found in (European Commission 2021). While Hong Kong have relatively low deaths compared to Nepal, China and Japan it’s the highest when it comes to deaths per unit area, due to it being a small size country with majority of its population residing on steep hillsides (Sidle and Ochiai

2006). The high casualties reported in China and Nepal signifies the susceptibility of population residing on hazardous mountaneous areas with very little structural countermeasures and little attention given to potential landslide hazards. In addition, this is also the indication of the landslide susceptibility of countries with low GNI and value of life.

As the years passed, the casualties owing to landslides reported in the African continent remains very low, (13 in 2007 (Kjekstad and Highland 2009) and 43 in 2020 (European Commission 2021)) making it not sufficient enough to form an average. This serves as strong indication that, there is severe underreporting as the number of people exposed to landslide hazards there is tremendously high as mentioned in (Kjekstad and Highland 2009). The severe underreporting is mainly caused by the remoteness of the regions and the scarcity of systematic records (Monsieurs et al. 2017). As such, the actual total losses caused by landslides worldwide could be far exceeding the reported statistics.

One can also look back at Figure 2-13 and Figure 2-10, that more than half of the Africa continent is of very low GNI and value of life, and that there are not much landslide grey dots on the African continent unlike in other high susceptibility nation like Nepal which further signifying underreporting in the African Continent. This serves as conclusion that countries with low GNI and value of life will have much more deaths owing to landslides.

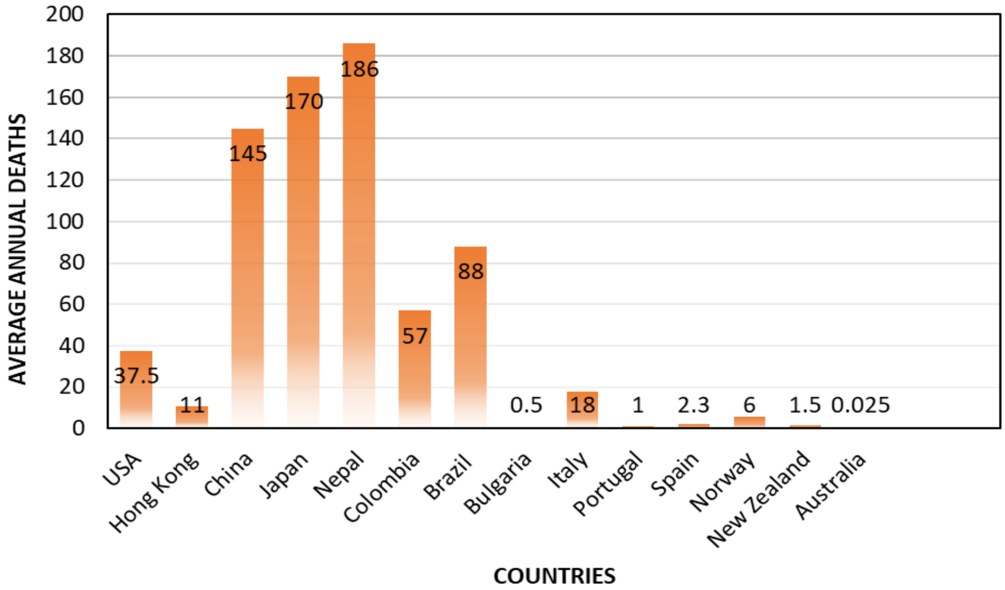


Figure 2-11 Average annual fatalities in various countries within an approximately 600 years period: data extracted from (Ojeda and Donnelly 2006; Sidle and Ochiai 2006)**.**

Nevertheless, average annual fatalities are meager indicators of cost of lives within any given year as seen in the trend of distribution of landslide occurence and fatalities of China, Portugal, Nepal, and Columbia plotted in Figure 2-12. The fluctuating patterns of annual occurrence of fatal lanslides and deaths are apparent in all four countries, with highly occupied regions like Nepal and China showing an obvious increasing trend while events in Portugal only fluctuate at relatively low numbers. China has the highest number of deaths followed by Colombia and Nepal.

Interestingly, Nepal despite being the country with the highest annual landslide occurrence, the deaths is much lower than China while China report highest fatalities among the 3 countries despite having lower disastrous landslide events. This is an indicator that high number of events does not signify a high number of fatalities, and vice versa. As stated by Chaudhary et al. (2017), the mountaneous region of the

Nepalese east development zone have a high number of reported landslide events but the cost of life is considerably low due to the small population density at that particular region where as for the western zone, the death toll is high despite lower landslide occurrence. Overall landslides are highly related to geographical condition where mountaneous regions being the zones of highest susceptibility.

An increasing trend in disastrous events is observed in Figure 2-12 for both China and Nepal which is due to the fact that both countries having high amount of susceptible mountaneous regions. There is also an increasing trend of fatalities in Nepal climaxing sharply at more than 400 deaths in 1993 and then declining therafter until the recent years despite the increasing number of landslide events. An explanation for this could be changes in development and population (Chaudhary et al. 2017). The death toll caused by fatal landslides in China show a rising trend with the average annual death toll of 331, 589, and 530 for the time stamp of 1950–1989, 1990–1999, and 2000–2016, respectively. The decrease in death toll for China in the 2010s could be due to the result of improvement of landslide disaster mitigation, prevention, and control by the Chinese authorities. As stated by Lin and Wang (2018), China’s investment for control and prevention of geological disaster increase year by year from RMB 330 million to 17.6 billion from year 2000 to 2015. In addition, a rise in geological disaster prevention and control projects is also mentioned from 429 in 2000 to 26,289 in 2015.

From Figure 2-12, one can note that there is a significant rise in the number of landslide deaths in Colombia along as the years passed with the 1980s being the most catastrophic decade. This could be due to advancement in Colombian data collection as well as the rise in urban population. According to (Aristizábal and Sánchez 2020), Colombian population transformed from a primarily rural to urban during the 1960s. In addition, Colombian population has increased from approximately 8.7 million (52% living in urban areas) million to 45.5 million (77.7% living in urban areas) in 2018. As for the trend of landslide occurrence, it is very clear that the landslide disasters increase significantly over the years and then skyrocketed during the first decade of the new millenium. A significant drop occurs after 2012 and the annual cases have been relatively low since then.

From all the data gathered it can be concluded that landslides pose a much grander risk to life in the developing world than they do in industrialized nations. The developing nations are not able to devote the essential resources to protect their population from landslides to the same extent as developed nations which in a way reflects on the value of life of the people. Nations with weaker socioeconomic standing (GNI and GDP) consistently had more dreadful landslides fatalities. As stated by Dowling and Santi (2014) landslides are indeed catastrophies resulting from social vulnerability.

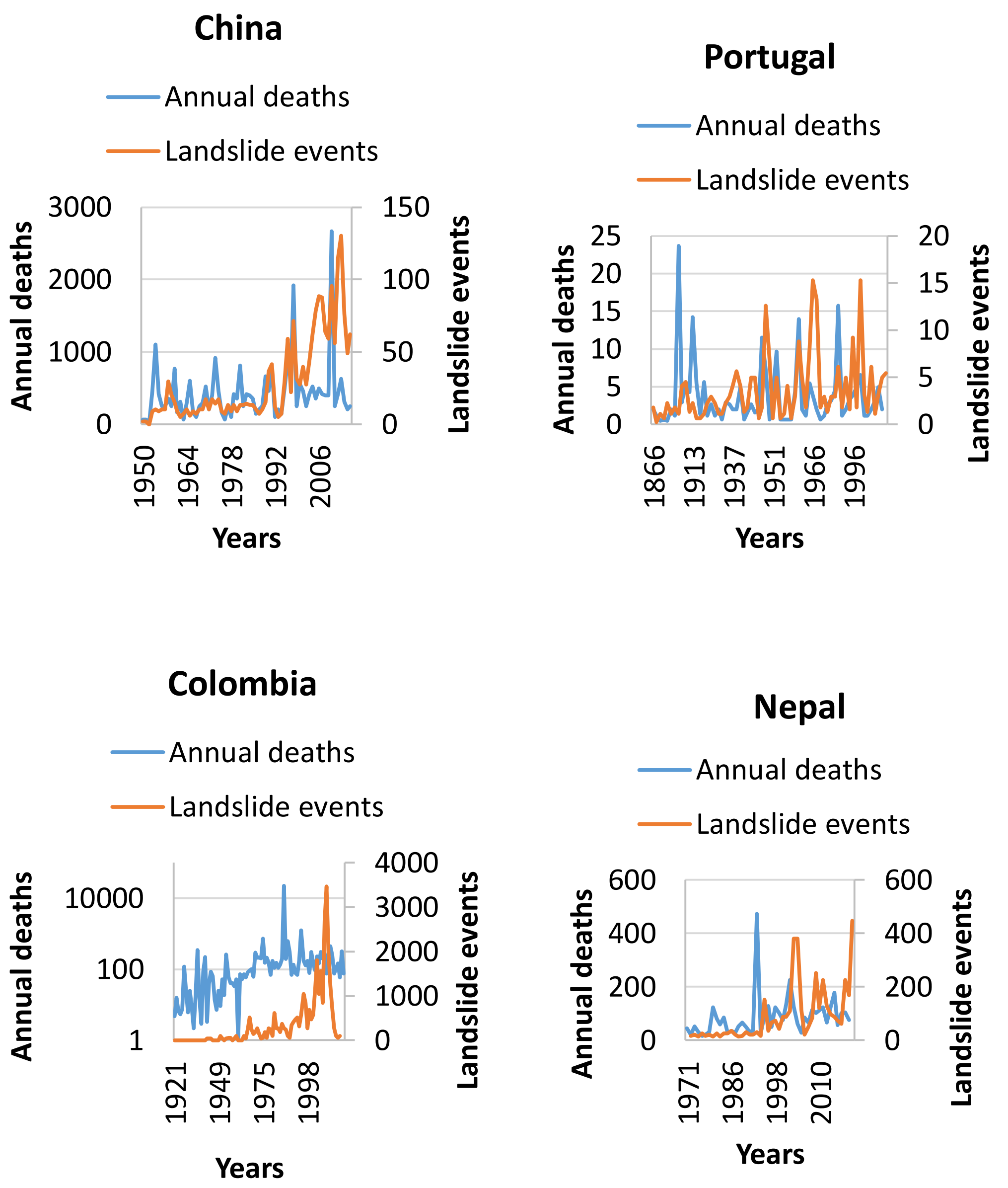


Figure 2-12 trends in landslide occurrence and deaths: comparison amongst China, Portugal, Nepal and Colombia Sources used: (Pereira et al. 2017; Lin and Wang 2018; Aristizábal and Sánchez 2020; Rakhal et al. 2021)

2.3 Economic losses caused by landslides

2.3.1 Value of life

It is very rare to take into account the economic value of loss of life due to landslides in calculating the costs of landslides due to the difficulties in placing a specific value on the life of a human. Nevertheless, towards the 21th century, federal agencies in USA have recently start to allocate a value for human life with a median of approximately $2 million for every individual in cost benefit analyses. Should these values prove to be realistic, the economic deaths from 25 to 50 landslides events per year will amount to the range of between 50 million to 100 million per annum (Schuster 1996).

The data from a documented study by Daniell et al. (2015) shows the disbribution for the value of human life between various nations from $35,000 USD in Central African Republic to $11.7 million USD in Monaco Figure 2-13. The value of life for USA as of 2014 as seen in Figure 2-13 is in the range of 2.8 million USD to 3.4 million USD which is higher than than the median value allocated in the late 20th century which is 2 million USD. This is an indication the the value of life in USA and possibly other developed nations has increased over the years. Referring to Figure 2-13 one can see the value of life of Malaysia falls in the same range as that of Japan (USD 1.75 million to 2.18 million) which is an interesting observation (Daniell et al. 2015).

It is very clearly shown that developed nations such as USA, Australia and Canada have a value of life higher than those of developing countries i.e. India, China, Latin America and South America and the African continent. Global fatal landslide clusters by Perkins (2012) which is similar to Figure 2-7 is superimposed into Figure 2-13 as shown in Figure 2-14 to give an indication about the value of human lives in countries with high susceptibility to landslides. From Figure 2-14, one can easily draw a conclusion that landslides hotspots region in the developing countries have very low value of life especially at Nepal, India, South East China while developed nations such as Italy and Norway have a very high value of life close to that of the USA (Sim et al. 2023c).

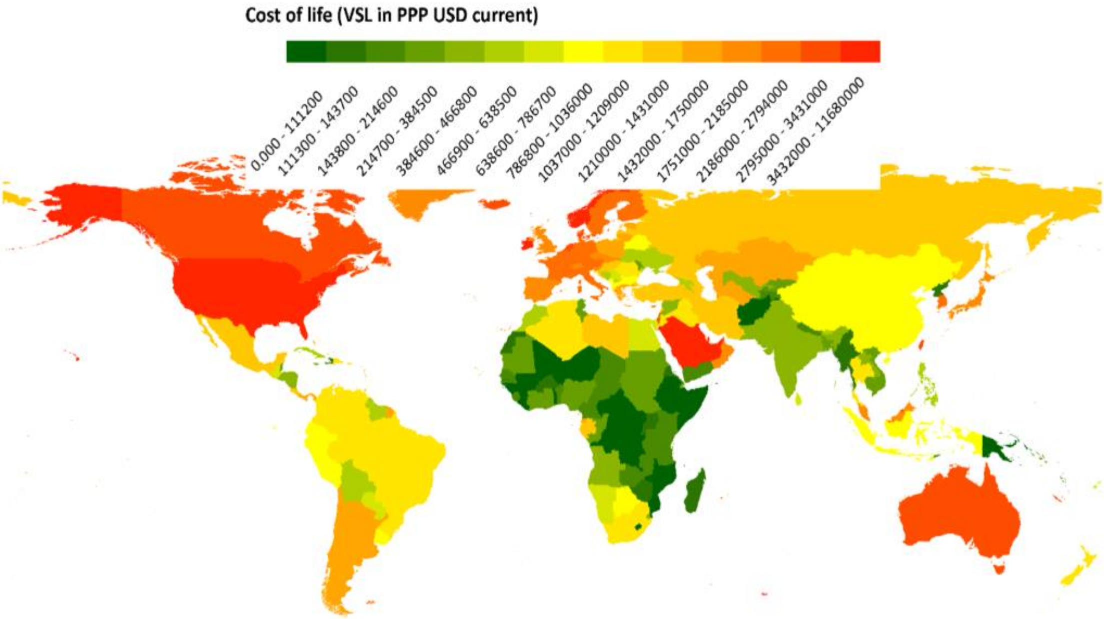


Figure 2-13 Global estimate of the average of value of a statistical life (VSL) in USD for the year 2014 (Daniell et al. 2015)

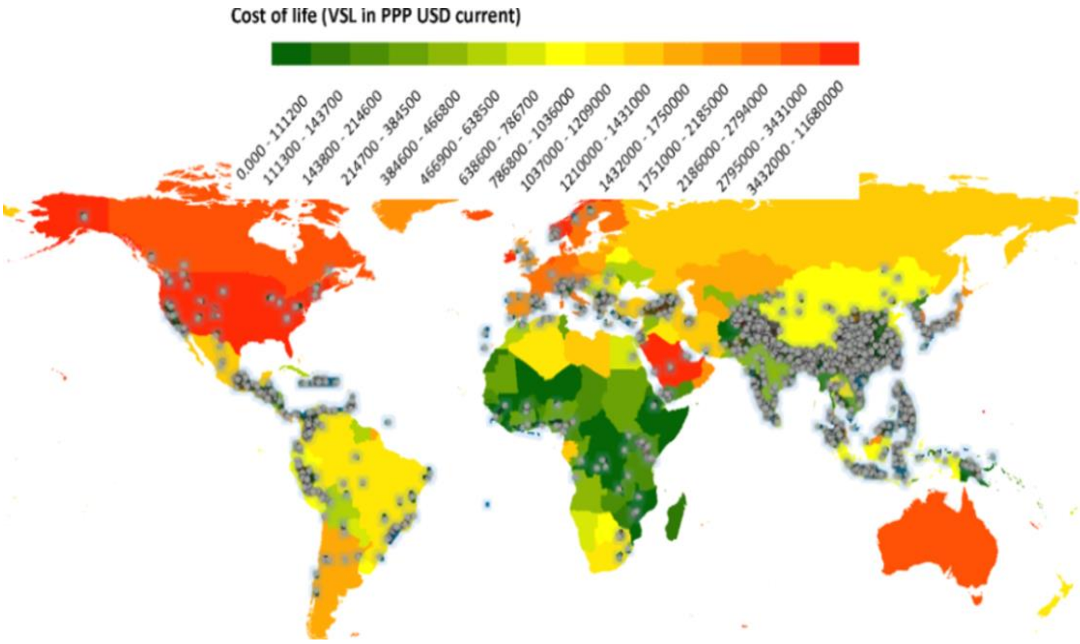


Figure 2-14 Fatal landslides (grey dots) from (Perkins 2012; Petley 2012) **and the value of human life by** (Daniell et al. 2015) **as seen in** (Sim et al. 2023c)

2.3.2 Average annual economic losses due to landslides

To determine the economic cost, government authorities, land use planners and others distinguished between direct and indirect costs. Direct costs comprise of damages directly related to the destruction resulting from the landslide as well as costs for investigation, monitoring, and remedial works to lower the risk.

In a case study by Klose et al. (2015a), the direct economic losses due to landslides affecting the federal road network in the Lower Saxon Uplands of North-West Germany were modelled. The method utilizes the locally obtained data for the purpose of extrapolating direct costs for the study area. A susceptibility assessment and infrastructure exposure model was also used. The study estimated that the average cost per kilometre of highway at risk of landslides in the study area to be US$52,000 per km. It was also mentioned that obtaining landslide restoration costs proved very challenging and, where available, their accuracy and reliability was to be questioned.

Another similar case study by Donnini et al. (2017) dealt with the direct economic impacts of rainfall induced landslides on the road network of two regions in Italy, i.e. Marche and Sicily. Road maps and landslide data were exploited using the GIS method to determine the different metrics which quantify the impact of the landslide events on the natural landscape and on the road networks, by road type. The maps were utilized with cost data obtained from various sources, i.e. local authorities, as well as special legislature, so as to assess the unit cost per metre of damaged road and unit costs per square metre. The result varied in the two study areas. The cost per metre and the cost per square metre in the secondary road of Marche region were computed to be approximately US$ 2215/m and US$55/$m^2$; whereas for the main road of Sicily, costs were estimated at US$18,431/m and US$124/m^2.

A related study by Hearn et al. (2008) collected and utilized information on the national road network of the People's Democratic Republic (PDR) of Laos, as well as road maintenance costs to assess the yearly average landslide losses per kilometre. It was reported to be between US$1000–1500 per km.

The direct landslide losses on the road networks as extracted from the studies by Hearn et al. (2008); Klose et al. (2015a); Donnini et al. (2017) are tabulated in Table 2-1. It is seen that there is a huge variation between the landslide costs incurred per metres for the regions. This could be due to a number of reasons such as; (i) both Marche and Sicily computed estimates based on a single huge landslide event where as NW Germany and Laos were based on a longer period of time where numerous landslide events have occurred; (ii) engineering features, as well as maintenance levels for different types of road will surely vary; (iii) different countries will possess different socioeconomic condition, resulting in the variation of remediation and maintenance policies and costs. The studies by Klose et al. (2015a); Donnini et al. (2017) however, only focused on direct economic impacts and the degree of extrapolation used by Klose et al. (2015a) across the road network was deemed inappropriate in regions where landslides occurred rather rarely such as in Scotland.

In August 2004, a series of rainfall-induced landslides occurred in Scotland notably at the A83 between Glen Kinglas and to the north of Cairndow (9 August), the A9 to the north of Dunkeld (11 August), and the A85 at Glen Ogle (18 August) (Winter et al. 2016). Although there were no casualties, 57 people have to be evacuated by air from the A85 Glen Ogle road when they were trapped between two huge landslides. The A83 Rest and be Thankful road, while not involved in the series of landslides of August 2004, has been subjected to numerous landslides resulting in road closures notably in 2007, 2008,2009, 2011, 2012, 2014, 2015, 2017 and 2018. The direct costs for 5 Scottish landslides between 2004 and 2014 were assessed by Winter et al. (2019) and they fall in between US$ 0.34 million and US$ 2.32 million.

Table 2-1 Direct economic impact of landslides on road networks of various regions

Region	Direct economic cost (US$ per metre)
North-West Germany	52
Sicily	18,431
Marche	2,215
Laos	1 -1.5

Nevertheless, landslides always brought about indirect costs resulting from travel diversions as well as economic constraints, environmental impacts associated to the landslide, soil sterilization for the development objectives and loss of human and animal productivity owing to injuries or death (Kjekstad and Highland 2009; Sim et al. 2022a). Indirect costs, often times, are either equal or greater than the direct costs. For example, after the 1983–84 Thistle landslide in Utah which is the costliest single landslide of the United States until present (total lost of $688 million), indirect losses amounted to approximately half of the total costs owing to the "far-reaching" closure of railway and highway links.

Following the 1993 Highland Tower incident case study by Sim et al. (2023c) (mentioned in chapter 2.2), six residents filed a lawsuit against the developers of Highland Tower and other related parties, including AmBank and Ampang Jaya Municipal Council (MPAJ), for alleged negligence on the 15th October 1994. The lawsuit pursued more than RM1.5million (USD 0.337 million) for property losses, damage, rental fees, and funeral expenses. The landowner, AmBank decides to compensate the 139 residents of the Highland Towers with a total sum of RM52 million (USD 11.7 million).

From the case study in Laos by Hearn et al. (2008), indirect losses with regards to road closures (predominantly cost of lost time and vehicle operating costs) were assessed by taking into account parameters such as GDP per head, percentage of population within working age, unemployment rates and estimated working hours per year. Their estimate was around US$50,000 per day for an average annual daily traffic (AADT) of 100 and

US$150,000 for AADT of 300. Most of the landslides affecting their national road network seemed to be shallow and localised slope failures in cut slopes. Environmental costs associated with average landslide events were estimated to be at US$8,150. Overall, the impacts of landslides on national road networks of Laos was deemed to be less than some other landslide prone Asian countries such as Nepal (Petley et al. 2007).

Indirect losses for 5 landslides in Scotland between 2004 and 2014 (which were heavily governed by the traffic volume usage of the road and disruption duration) were estimated to be between US$ 0.25 million and US$ 1.91 million using the QUADRO program (Winter et al. 2019). A similar case study by Postance et al. (2017) generated a database of possible landslide-prone road segments in Scotland by utilizing landslide susceptibility data with the aids of GeoSure program. It was shown that 34% of Scotland's strategic road networks i.e. 1,500km out of 4,300km were prone to landslides, which would bring about indirect economic losses greater than US$ 43,000 per day of closure (as computed in their SUMO road transport models).

In many other scenarios, indirect costs have exceeeded direct costs. Unfortunately, at most times, indirect costs proved to be very difficult to obtain, thus are often overlooked or when projected, are too conservative (Kjekstad and Highland 2009). Some figures from several sources are as follows (all values are converted to USD):

- Annual landslide costs in USA, Italy, Japan and India are esimated to be at least $1 billion each (Schuster and Fleming 1986) at that time. Landslides, tidal surge and mudflows in the Swiss Alps from September 2000 to March 2001, brought about an economic loss of approximately $8.5 billion.
- A more recent statement by (Turner 2018) states that the yearly losses for the United States have been estimated to be at $3.5 billion together with 25 to 50 deaths. Most of the increment is due to inflation.
- For Italy, Switzerland, Austria and France the economic losts amounted to approximately $1 to 5 billion.

- The total yearly landslide costs for Canada Canada falls in a range of $70 million to $1.4 billion (Cruden et al. 1989; Schuster and Highland 2001)
- A earthquake triggered landslide in 1987 in Andes of north-eastern Ecuador results in 1000 fatalities and the destruction of kilometers of oil pipelines and highways, totaling to $1 billion loss at that time (Lee and Jones 2004; Chiu 2015).
- In an interval of around 6 years, the 2008 Wenchuan Earthquake in China has caused 7 landslides bringing about a total of 119 deaths and economic loss of an exceess USD 0.94 billion (Huang et al. 2016).
- The landslide disaster that struck Rio de Janeiro, Brazil destroying 7 cities of around 3664.90km^2, the total cost is estimated to be around $1.25 billion with an average loss of $0.34/$m^2$ (Batista et al. 2019).
- On an annual average, total landslide damage cost in Germany is forecasted to be at $300 million (Klose et al. 2015b)
- Average annual direct landslide damage costs in Belgium amounted to $0.85 million ($0.67 million for damage to residential areas) while indirect damage rise to $3.6 million ($2.4 millionfor damage to real estate) (Vranken et al. 2013).
- In Georgia, annual losses vary from $7.57 million to $107.86 million (Haque et al. 2016).

Table 2-2 Estimated average annual cost of landslide of different countries

Country	Average Annual Direct Costs (billion USD)	Total annual loss (billion USD)	Loss as percentage of GDP	Loss Per Capita (USD)
United States	-	2.1-4.3	0.01-0.03	7-14
Canada[1]	-	0.07 to 1.4	-	-
Japan	1.5	>3.0	>0.06	23
Korea	0.06	-	-	-
Italy	-	2.6 - 5	0.19	68
Spain	0.2	-	-	-
Former USSR	0.5	-	-	-
Georgia	-	0.0076-0.11	-	-
Belgium[2]	0.00085	0.00448	-	-
Germany[3]	-	0.3	0.01	3.7
Norway	-	~0.009	-	1.03
Sweden	-	0.015- 0.03	-	-
New Zealand	0.0196	0.053	-	-
South Africa	-	0.015	-	0.42
Brazil[4]	0.045	0.35 – 1.25	-	-
Colombia	-	1.0		
Caribbean	-	0.022	-	1.13
Himalayas	-	1.4	-	34.7
Nepal	1.3	-	-	-
India	>1.3	2	0.11	1.7
China	0.5	>1.0	0.01	0.7

Worldwide[5]	**~ 20**	**-**	**-**

[1]Cruden et al. (1989); Schuster and Highland (2001); Sidle and Ochiai (2006)

[2] Vranken et al. (2013)

[3] Klose et al. (2015b)

[4] Batista et al. (2019)

[5]Klose et al. (2015b); Sim et al. (2022b, 2023c)

The rest of the data were extracted from (Glade 1998; Sidle and Ochiai 2006; Sim et al. 2022b, 2023c)

According to Klose et al. (2015b) and (Sim et al. 2022b) , worldwide annual landslide costs is estimated to be around $20 billion. The cost amounted to around 17% of the total ($121 billion) yearly mean global disaster losses from 1980–2013 and that shall offer an insight to the worldwide economic significane of landslides. The overall material damage due to natural disasters in the developing countries is generally lower than industrialized nations (Schuster and Fleming 1986; Kjekstad and Highland 2009).

Among the developed countries, the greatest economic loss due to landslides are seen in Japan and Italy. Considering the lower property values in the developing countries of China, India and the Himalayas, the economic costs in these mountainous regions are signifcantly higher. Majority of landslides in nations such as Nepal, New Zealand and Canada have their landslide damage occuring in rural areas; hence, costs are comparably lower. Landslide costs in the Scandinavian regions are trivial compared to mountainous topography in the rest of European continent; the cummulative landslide costs in Europe is less than the United States. Similar scenarios are seen in (Glade 1998; Sidle and Ochiai 2006).

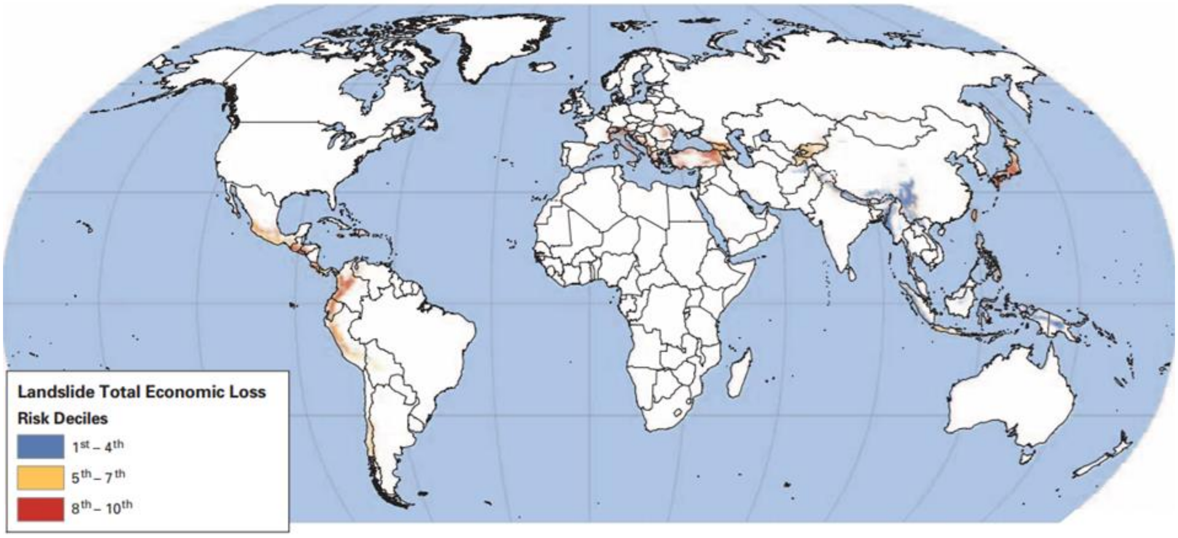


Figure 2-15 Global distribution of landslide risk in terms of total economic loss (Dilley et al. 2005)

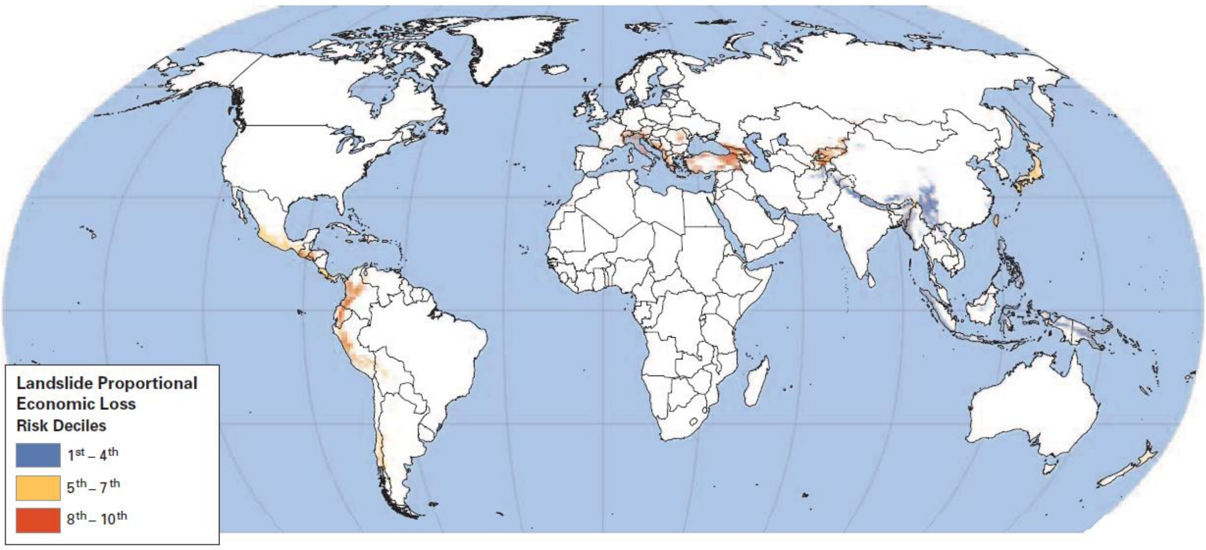


Figure 2-16 Global distribution of landslide risk in terms of total economic loss as a proportion of GDP density (Dilley et al. 2005)

From Figure 2-15, it is clear that landslide risks in terms of economic loss are significant in Central America, north-western South America, the Caucasus region, Southern Europe, Japan and Taiwan. Nepal, Southern China, Malaysia, Indonesia and Papua New Guinea are shaded in blue which shows that they have comparatively lower economic risks despite their high landslide occurrence. This is true to the statements made by (Petley et al. 2007; Lacasse et al. 2010; Lacasse and Nadim 2014) that developing countries despite the high death rate due to disasters, their economic losses are far less than developed nations. In terms of GDP, Kyrgyzstan reach the top three deciles in (8^{th} to 10^{th} percentile) but Japan drop out as seen in Figure 2-16. Other countries remain at the same risk deciles for total economic losses and economic losses in terms of GDP. By comparing Figure 2-15 and Figure 2-16 with Figure 2-7, it is very clear that landslide hotspots countries will incur higher economic and GDP losses. In addition, it is also clear that hotspot nations at risk are mostly nations with tropical climate which usually have very high amount of rainfall. Moreover, as mention earlier, rainfall is the biggest triggering factor of landslides worldwide which explains the reason why tropical regions are where landslide disasters and its losses clustered at. Countries with high population density and GDP in landslide hotspots are most likely going to suffer repeated landslide costs and losses unless vulnerability and risks are reduced (Dilley et al. 2005)

2.4 Concept of landslide risk assessment

In recent decades, QRA has been studied extensively and numerous guidelines have been published (Geotechnical Engineering Office 1999; AGS 2000, 2007; Wong et al. 2006; Lee and Jones 2014). The flow chart for QRA from Hungr (2016) is shown in Figure 2-17. The QRA consists of two stages: Stage 1, Hazard assessment, and Stage 2, Risk assessment. Hazard assessment comprises geo-scientific works such as investigation and analysis to determine and quantitatively define the probable landslide hazards. Hazard is defined as the potential occurrence of a natural or human-induced physical event that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources (Bobrowsky and Couture 2014). A hazard should be identified and characterized in the first place before its features i.e. magnitude, probability, regional extent, and intensity can be determined. The estimated intensity and its probability of occurrence can then be quantified and mapped into the region of study.

Risk assessment starts with determination of elements at risk which could be humans, infrastructures, buildings or environmental values. They could be existing ones or those in planning for future construction in the area of study. Estimation of risk comes from an intersection of hazard intensity map with the map of elements at risk, in space and time considering vulnerabilities. The Stage 2 is completed with the determination of acceptable risk and designation of mitigation measures. However, the determination of acceptable risks proves to be one of the most challenging aspects of QRA. To mitigate this challenge, it is recommended to use the F-N curve for the region of interest which is a plot showing the number of fatalities (N) plotted against the cumulative frequency (F) of N on a log-log scale (Dai et al. 2002; Song et al. 2007; Hungr et al. 2016b). To be made simpler, the F-N Curve compares the number of fatalities (N) of a landslide event with the probability (or frequency) of that event (F).

Numerous review studies on quantitative risk assessment of landslides can be found from the currently available literature. However, review studies on landslide acceptable risk and tolerable risk as well as F-N Curves are scarce despite substantial works having been reported by researchers from different parts of the world. This following section aims to review the F-N curves reported from various countries. The F-N curves collected deal exclusively with risks to life which is normally the governing factor of landslide disasters (Hungr et al. 2016b). Landslide risk acceptance criteria from various nations will also be discussed and reviewed. The findings reported herein can serve as a useful reference for developing the landslide acceptable risk and tolerable risk for a nation.

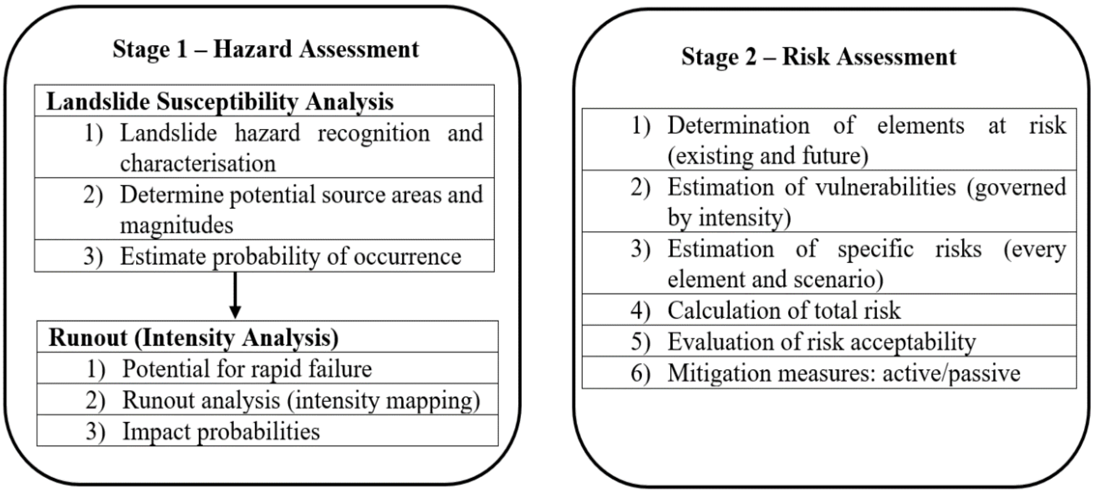


Figure 2-17 Flow chart of landslide risk assessment (Modified from Hungr 2016)

2.4.1 F-N curves of landslide

An F-N curve consists of a series of data points that denote each scenario analyzed. It is a combination of scenarios into a single curve that defines the probability (or frequency) of "N or more" fatalities of the complete dataset (Strouth and McDougall 2021). It should be noted that the label (N) can also be represented by other quantities of a consequence such as monetary loss. Such curves could be utilized to demonstrate societal risk (Vrijling and van Gelder 1997; Saw et al. 2009; Strouth and McDougall 2021) and to define the safety levels of the region of interest. It is crucial to be clear that the F-N curves only provide statistical readings and not the threshold of risk acceptance and tolerance. Figure 2-18 shows the typical F-N-curves for various hazards. It can be seen that man-made hazards have a tendency to demonstrate a steeper curve than natural hazards (Westen et al. 2011)

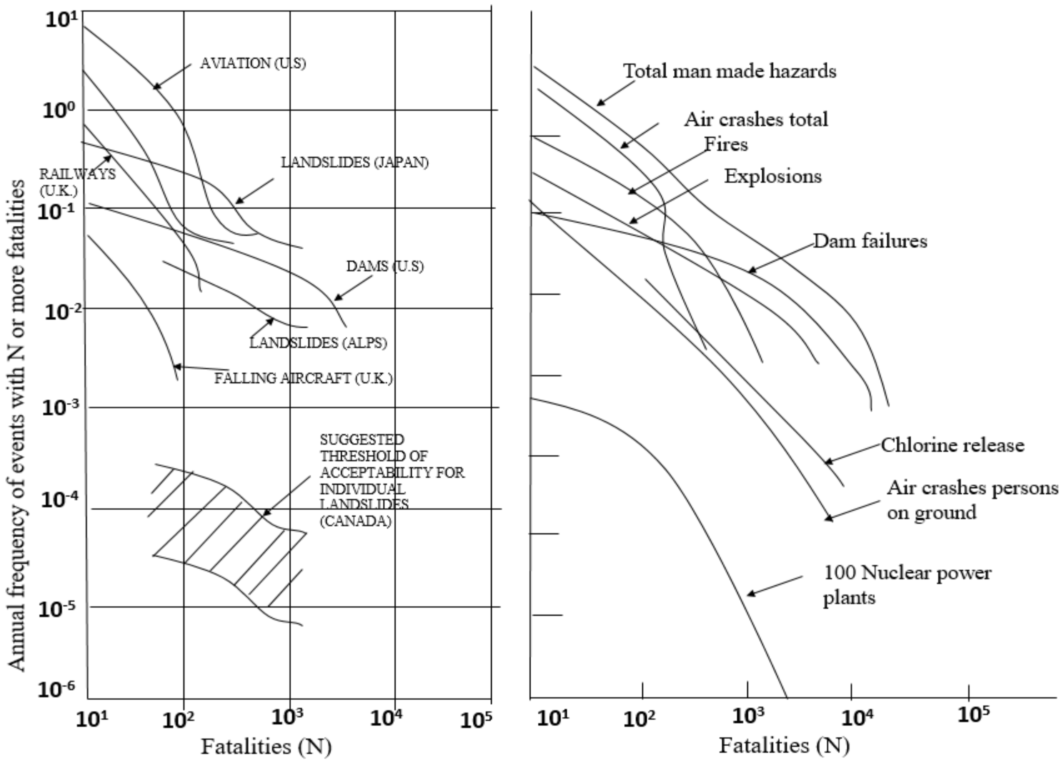


Figure 2-18 F-N curves demonstrating the number of fatalities against the annual frequency of occurrence for natural and man-made hazards (Modified from Westen et al. 2011)

2.4.2 Landslide F-N curves for various countries

Figure 2-19 presents the family of F-N curves for landslides compiled from various geographical locations. It should be clarified that some of the F-N curves do not represent an entire country because of the unavailability of data. There are mixtures of F-N curves extracted from different countries and local municipalities. It is apparent that the F-N curve is unique to a country / location.

From Figure 2-19, the frequency, F for N=1 death for Guatemala is significantly lower than those of other nations. However, this highlights a bias in the Guatemala catalogue, which lacks comparable coverage. Another thing to note about Guatemala is that the F-

N curve only covers probabilities of single deaths and no more than that which reflects on the severe lack of data. It can be seen that the F-N curve for China only begins for landslides that result in a minimum of 100 deaths while the Japanese F-N curve only starts from 10 which signifies the incompleteness of the landslide catalogue of the former countries for low intensity scenarios (Guzzetti et al. 2002). As stated by Song et al. (2007), many organizations still do not possess sufficient database to progress very far in this direction with few exceptions such as Hong Kong. Nevertheless, the Japanese and Chinese F-N curves stand higher than the curves computed for other countries, even for the shortest time intervals which denotes that the aforementioned nations faced a high landslide risk, with a great number of cataclysmic events that caused severe fatalities.

It can be seen that the F-N curves of both Hong Kong and Canada share a very similar slope and trend and they converge at N = 20. From there, the trend becomes different with Canada showing higher probabilities of casualties until they converge again at N = 70. Interestingly, the maximum N value of Hong Kong is lower than 100 even though it has a high population density living in steep hillsides. According to Duzgun and Lacasse (2005), the Hong Kong curve represents the performance of engineered slopes (risk imposed upon the community by designed slopes). At N = 10, the city of Rio de Janeiro has almost the same F-value as China which is not surprising considering both Rio and China are heavily populated region and country, respectively. Canada, Nilgiri Hills, India, and Hong Kong were observed to share approximately similar curves. The curves for Nepal and Rio de Janeiro both converged at N = 141. However, for events associated with lower casualties (i.e. N < 100), the probability of landslide fatality in Rio de Janeiro is significantly higher than that in Nepal. This is clearly related to the much higher population density in the city of Rio de Janeiro than Nepal as a country.

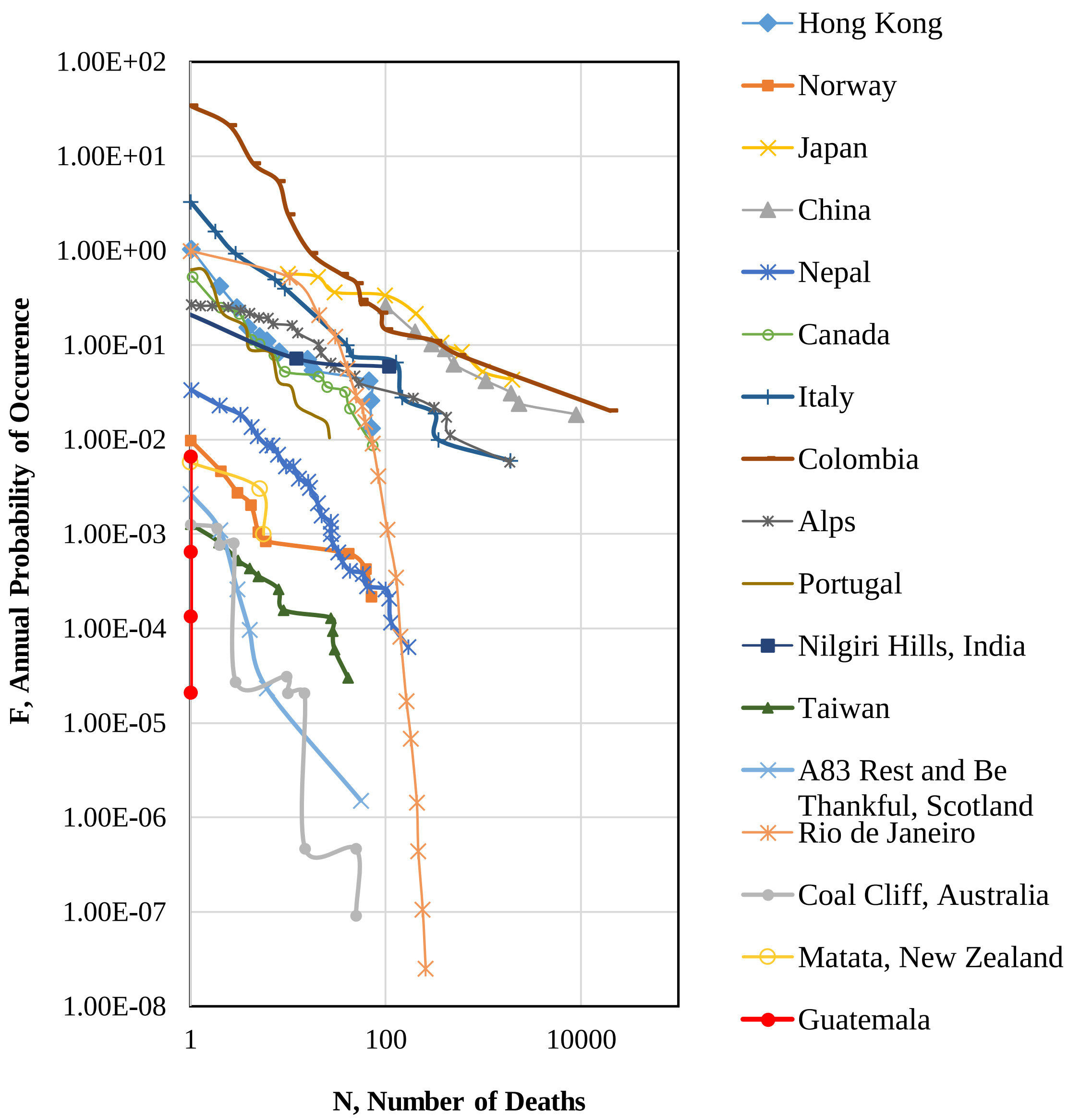


Figure 2-19 Global comparison of frequency (F) vs. number of deaths (N) curves (Guzzetti 2000; Pacheco et al. 2002; Duzgun and Lacasse 2005; Hsi and Fell 2005; Jaiswal et al. 2011; Tsao et al. 2011; Tonkin & Taylor Ltd 2015; Pereira et al. 2017; LaPorte 2018; Aristizábal and Sánchez 2020; Winter and Wong 2020)

The population density as well as the hazard spatial distribution should be included to compare the F-N curves of various nations (Duzgun and Lacasse 2005). Population density, F-values, and slope of the best-fit curve are tabulated in Table 2-3. The probability of occurrence, F for a specific N is governed by the slope of the curve. A steeper slope signifies a higher risk aversion or in other words, a lower probability of occurrence for a specific number of fatality or lower risk. For example, the slope of Japan's curve is -0.53 while Portugal's curve has a slope of -2.35. The probabilities of occurrence, F for N= 10 fatalities for Japan and Portugal are 0.8 and 0.04, respectively which show that a higher risk level is associated with the slopes in Japan than in Portugal. Comparisons of F-N curves between developed and developing worlds and between different continents are shown in Figure 2-20. It should be made clear that the curves of more discrete regions such as Nilgiri Hills, India and Matata, New Zealand were included in Figure 2-20 as well. Overall, despite the curves being inconsistent, a general observation indicated that the F-N curves of developing countries are mostly plotted higher than those of developed countries. In terms of continents, the Asian and Latin American continents generally have higher frequency of deaths followed by Europe. This is because countries in Asia such as Japan are situated in a geographical location where natural disasters are frequent. Furthermore, countries like China and Nepal have many of their population living on hazardous slopes which have further increased the risk of landslide fatalities. Colombia, situated at the northwest region of Latin America, is a mountainous tropical climate country with strong hydroclimatic variability and tectonically active and complex geology have its F-N curve stands at the highest than the rest. Other than its natural circumstances, extreme population growth, as well as an exponential rise in development in recent decades in landslide-prone regions have further amplified hazard and risk conditions. Furthermore, it was reported that the population in 2016 was around 49 million and the urban population had escalated to 75% (Aristizábal and Sánchez 2020).

Table 2-3 Population density (World Bank 2018)**, F-values, and slope of F-N curves for various geographical locations**

Locations	Population density/km^2	Slope of F-N curve	F-values		
			N=1	*N*=10	*N*=100
Japan	347	-0.53	-	0.8	0.07
China	148	-0.61	-	-	0.06
Rio de Janeiro, Brazil	-	-3.3	1	0.52	0.0011
Italy	203	-0.86	2.623	0.362	0.05
Portugal	112	-2.35	0.63	0.04	-
Hong Kong	7096	-0.79	0.6	0.01	-
Canada	4	-0.92	0.4	0.07	-
Alps	215	-0.538	0.29	0.16	0.003
Nilgiri Hills, India	-	-0.275	0.21	0.05	0.006
Nepal	196	-1.31	0.08	0.004	-
Colombia	45	-0.834	34	2.42	0.355
Norway	15	-0.72	0.006	0.001	-
Matata, New Zealand	19	-0.73	0.0057	-	-
A83 Rest and be Thankful site, Scotland	-	-1.924	0.002	0.00005	-
Taiwan	637	-0.89	0.00128	0.000157	-
Coal Cliff Australia	-	-2.375	0.00125	0.0000206	-
Guatemala	153	-	0.000134	-	-

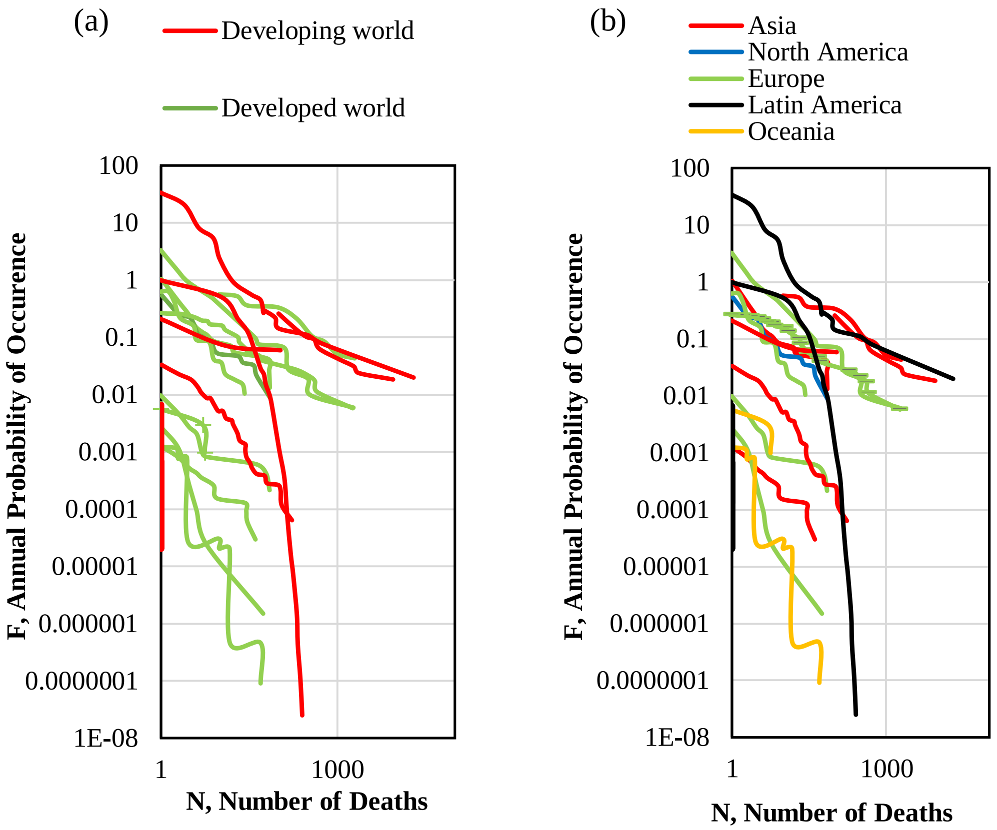


Figure 2-20 F-N curves grouped based on (a) Developed and developing worlds, (b) Geographical continents

It was stated by Holcombe et al. (2016) that rapid unplanned development is causing a rise in precipitation-triggered landslide risk in low-income areas in tropical developing nations. The number of people inhabiting overcrowded impoverished houses lacking infrastructure almost reaches the 1 billion mark exposing them to the dangers of both small and large scales catastrophes. In Latin America, Gross National Income (GNI) and value of life are generally low (Daniell et al. 2015; World Bank 2020) with many of their populations living in slums constructed on hazardous slopes with no compliance to safety standards. The majority of these slums are constructed on lands on which significant landslide hazards persist, i.e. unstable slopes (see Figure 2-21) without any design or assessment for the factor of safety. This had further propagated the landslide hazard due to localised changes in drainage, vegetation, loadings, and topography, and hence increased the associated risk to the population. Disasters of these types serve as a warning sign of a bigger issue stemming from poverty as well as a poorly-organized development (Hungr et al. 2016b). Unfortunately, there are no known F-N curves available for countries in the African continent.

(a) (b)

Figure 2-21 (a) Archetypal unplanned housing on unstable slopes in Castries, Saint Lucia, Eastern Caribbean; (b) Landslide on unplanned development (Holcombe et al. 2016)

It is crucial to note that the F-N curves only provide statistical readings and not the threshold of risk acceptance and tolerance. Nevertheless, the F-N curves are useful for evaluating the current risk level of a region / country. This information is useful for developing the risk acceptance and tolerance levels for a country.

As can be seen from Figure 2-19 and Figure 2-20 the landslide risk level varies considerably from a country to another, and hence different standards of acceptance and tolerance should be adopted with considerations of various factors (Duzgun and Lacasse 2005), which will be reviewed in further details in the following section.

2.4.3 Concept of acceptable risk & tolerable risk

According to (Strouth and McDougall 2022), upon the acknowledgement of a potentially hazardous landslide, it is imperative that decision-makers determine adequate safety for the affected population. If safety measures are insufficient, the amount of protection measures to lower the risk to tolerable levels will have to be determined. This decision-making process, which involves comparing the landslide risk of deaths with available funds and resources and the tolerable risk perception, is also known as risk evaluation. The benefits of inclusive risk consultations have been discussed by Canadian Standards Association (Association 1997). Generally, both individual risk and societal risk are evaluated within a quantitative risk management framework (Fell 1994; Macciotta and Lefsrud 2018). Individual risk refers to the probability of death due to a landslide event for a single individual (Fell et al. 2005), while societal risks encompass broader consequences from the landslide event, such as potential deaths, economic and environmental losses, as well as service interruptions.

It is crucial to differentiate between acceptable risks which the public aims to determine, mainly for new developments, and tolerable risks which they will live with, albeit lower risks still prevail as their main preference (AGS 2007). This applies to both property and loss of life. People in a society whose lives might be impacted by landslides, and authorities in charge of development approval must determine the acceptable and tolerable risks for property loss and damage (Song et al. 2007; Leventhal and Withycombe 2009). Practically, the authorities will be the ones obligated to ascertain the risk levels given its obligation to control hazards at the local municipal level. In most cases, that is the National or State authority or Local Government Area Council. Following are the brief definitions of acceptable risk and tolerable risk:

I. **Acceptable Risk** – A risk that the public is inclined to accept without regard to its management for life and work purposes. Further expenditure in lowering such risks is normally not taken under consideration by the public.

II. **Tolerable Risk** – A risk that the general public is inclined to live with in order to safeguard certain net benefits having faith that the particular risk is being properly contained. The risk level is periodically reviewed and lowered further whenever feasible. Also, the criteria where the ALARP principle, which stands for "As Low As Reasonably Practicable", may be applied so that the risk is mitigated to a marginally and practically tolerable level since the reduction to further acceptable levels is not feasible with regards to the cost to the individual or public. Figure 2-22 shows the significance of ALARP (Campbell et al. 2016).

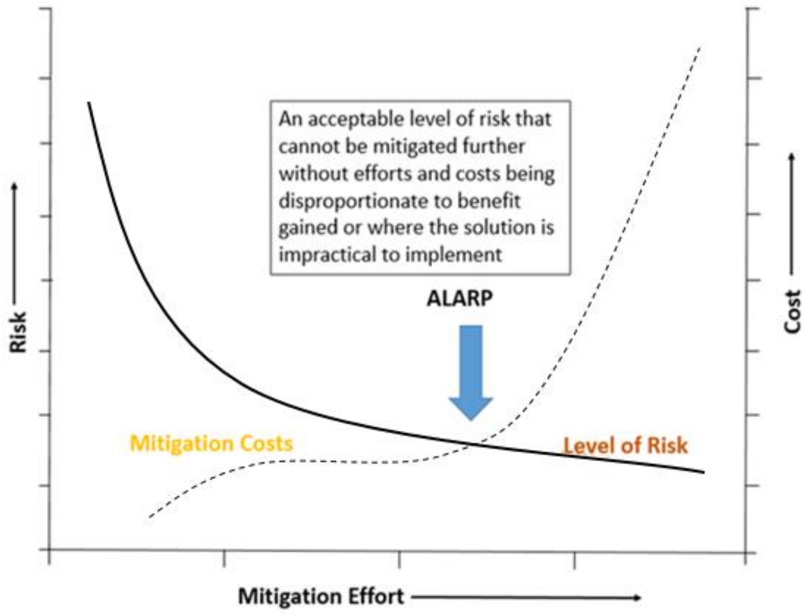


Figure 2-22 Illustration of "As Low As Reasonably Practicable" ALARP principle for risk evaluation (Campbell et al. 2016)**.**

In Figure 2-25, three elements need to be considered in an integrative manner to develop risk criteria. Firstly, the features of the system under study, such as the environment and characteristics of the system, need to be considered. Hazard characteristics, including the extent of consequences, probability of occurrence, and related uncertainties, are taken into account. The second element is the socio-political, economic, and cultural aspects. Society's perception of risks is influenced by factors such as whether the risk is natural or man-made, voluntary or involuntary, and this affects the response to risk. The third and last element is the principles for developing risk evaluation criteria, which have a philosophical nature and they are governed by technical and social aspects and principles of regulation. These principles were used to establish risk criteria (Vanem 2012; Morrison 2014). According to (Macciotta and Lefsrud 2018), the following principles should be taken into account to establish a clear framework for risk criteria development: (i) the requirement to control risks posed by nature and development, and (ii) risk thresholds to help assess the urgency for mitigation procedures. Mitigation measures will be needed for intolerable risks to ensure a minimum quality of life.

According to (Winter and Bromhead 2012), society will be more tolerant towards landslides that occur for natural slopes than for engineered slopes, although the effects of climate change may cause recurring natural slope failures in a small area defeating this greater tolerance. Tolerable risks differ between nations subjected to historic exposure to landslides, control and ownership of slopes, and natural landslide hazards. Relevant regulators may choose to apply “acceptable risk” criteria for high-risk cases, i.e. hospitals, schools, as well as emergency services taking into account their significance, and also as a means of mitigating societal risk concerns. For involuntary individual risk, generally, the acceptable risk values will be in the frequency range of 1E-5 to 1E-6 per year while for voluntary risk, it will be typically between 1E-3 to 1E-4 per annum (Fell 1994).

Figure 2-23 shows a provisional risk criterion proposed for natural slopes in Hong Kong (Geotechnical Engineering Office 1999; Lacasse et al. 2010; Lacasse 2016). The degree of aversion is represented by the slope of the F-N lines. Lines with a slope gradient of 1 are indicated as equi-risk, in which the points along the line have the same risk level. The F-N curves may be conveyed by the equation:

$$\mathbf{F \cdot N^{\alpha} = k \qquad or \qquad F = k \; x \; N^{-a}} \qquad \mathbf{(2\text{-}1)}$$

where k-value is 0.001, α equals unity. α represents the degree of aversion typically between 1 and 2. The greater the F-N slope, the higher the risk aversion (Anand 2015; Roy and Kshirsagar 2020). For example, for a slope of 2, the risk criteria is such that the frequency of events that cause 100 deaths or greater must be 100 times lower than the frequency of events that cause 10 or more deaths (Roy and Kshirsagar 2020). The tolerable / ALARP region reflects the risk to be "As Low As Reasonably Practicable" which is illustrated in Figure 2-22 (Campbell et al. 2016).

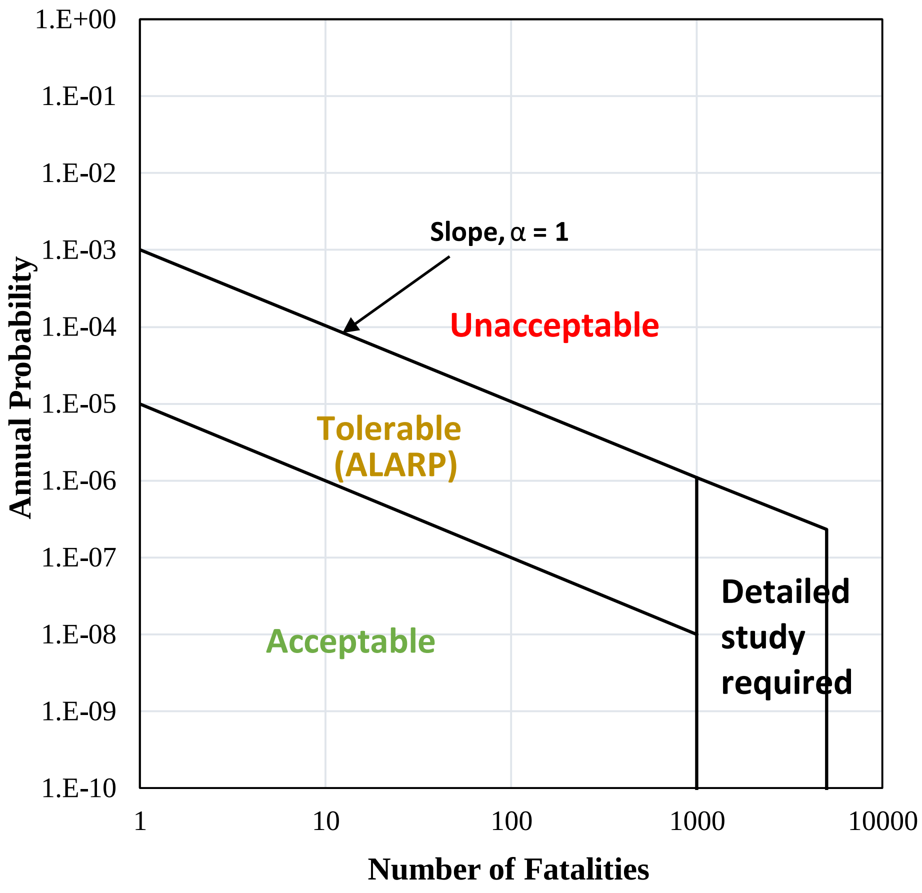


Figure 2-23 Risk criterion proposed for natural slopes in Hong Kong, modified from (Geothechnical Engineering Office 1999; Lacasse et al. 2010; Lacasse 2016; Strouth and McDougall 2020)

A study by Winter and Bromhead (2012) summarized issues that govern landslide risk acceptance such as planning and regulations, event footprint against vulnerability shadow, budgetary issue, vulnerability of vehicles all fit into the influences of social and economic factors on the risk acceptance. Figure 2-24 shows a conceptual ternary willingness diagram of various landslide incidents in different countries. The approaches of various nations in handling landslides are qualitatively compared to provide a better understanding of the factors involved in landslide risk mitigation.

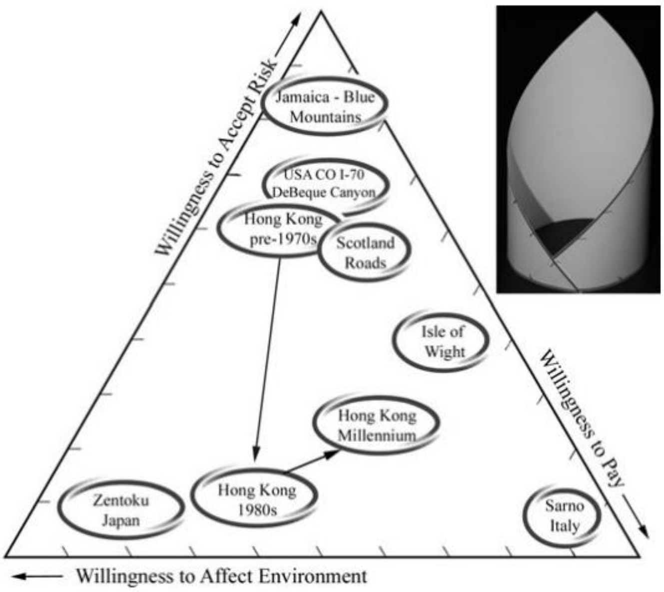


Figure 2-24 Willingness diagram by (Winter and Bromhead 2012) **demonstrating various approaches to landslide risk in different countries.**

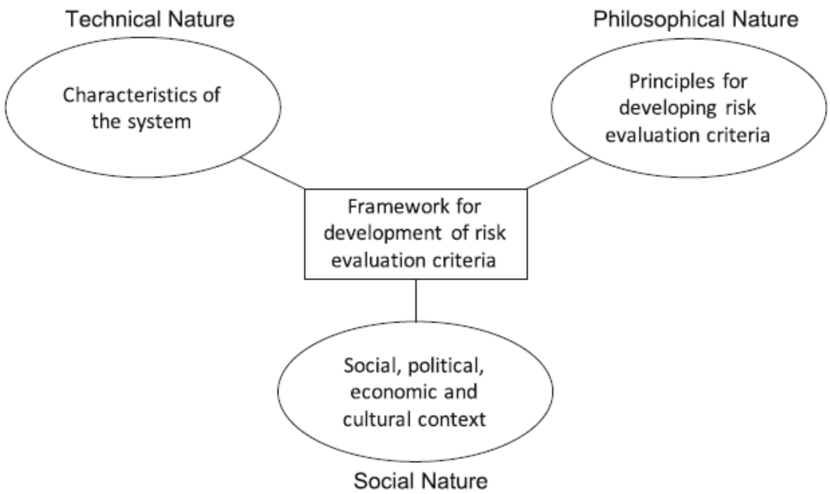


Figure 2-25 Elements (ellipses) to be considered within a framework for establishing proposed risk criterion. Source: (Macciotta and Lefsrud 2018)

It is clear that the risk level that exists in a particular area and the willingness to pay or financial power will, have a significant impact on the risk acceptance. Nevertheless, risk acceptance and financial power/willingness to pay are factors that are considered as forcing agents in the discourse on worldwide landslide risk mitigation. As stated by Turner (2018), industrialized nations have procedures for landslide mitigation planning and implementation that call for accurate knowledge of landslide hazards and risks. The landslide risk assessments are gradually becoming quantitative. Mitigation measures include structural and geotechnical procedures, in addition to political, legal, as well as administrative procedures that impact the lifestyle and behaviour of the endangered society. For example, Zentoku, Japan leans to the bottom left region of the Willingness diagram in Figure 2-24 signifying a very high willingness to pay and alter the environment to mitigate landslide risk in the region. This implies that Japan has a tremendously low tolerance of landslide risk as well as the financial ability to pay to mitigate the risk.

In contrast, Jamaica's landslide mitigation approach in the Blue Mountains puts them at the top of the triangle, showing that there is a very high willingness to accept risk and a very low willingness to pay. Jamaica is a country with limited economic resources and that limited budget forces them to accept the risk (Winter and Bromhead 2012). Similar scenarios were reported by Yifru et al. (2015), where there was no mitigation carried out on the landslides that occurred along the road corridors of two Caribbean islands, i.e. Saint Lucia and Dominica (both known to be deprived islands). Focuses given to the two Caribbean islands were only for road repairs and debris removal. This observation further supported the willingness diagram of Winter and Bromhead (2012) which demonstrates that a limited economic resource leads to a low willingness to pay, and hence leads to a high acceptance of landslide risk. Most developing nations do not possess adequate resources, capacity, and technical skills to carry out landslide risk reduction measures to the required speed and level. Rather than lowering vulnerability, their central emphasis on handling landslides has been to respond actively to emergencies and catastrophes which again results in higher risk acceptance. Support and collaboration from developed nations are needed (Kjekstad and Highland 2009; Turner 2018).

From the foregoing, it can be concluded that if acceptable and tolerable societal risk levels are to be established, each country should select different levels governed by factors such as socioeconomic standing, Gross Domestic Product (GDP), statistical value of lives, as well as financial prowess of the country (Leroi et al. 2005; Roy and Kshirsagar 2020).

2.5 A review of risk tolerance criteria for various nations

2.5.1 Hong Kong

In the late 90s, the Hong Kong Government provisional criterion for “potentially hazardous installations” for “landslides and boulder falls from natural terrain” was implemented by the Hong Kong Geotechnical Engineering Office (GEO) (Geotechnical Engineering Office 1999) (see Figure 2-23). According to Wong (2005), the criterion was occasionally adopted in the country to determine landslide risk tolerance related to developments of structures and infrastructures, etc. in near proximity to modified or natural slopes. Hungr and Wong (2007) described that in order to scale the F-N chart in proportion to its original reference frame (the perimeter of the industrial plant), it is used on a consultation area of around 500 m long section of a boundary between hazardous slopes and buildings.

The saga of the founding of the Hong Kong landslide risk management system was explained by Malone (2012). It was decided by the Hong Kong GEO that the methodology of the United Kingdom Health and Safety Executive (HSE) to create the risk tolerance criterion with a few adjustments could help in decision making procedures in Hong Kong in regards to landslides. The Hong Kong GEO conducted QRA on the basis of available records, which restricts the timeline to around 50 to 100 years. This also means that high magnitude infrequent landslides do not appear in the inventory and, the probabilities and levels of the infrequent landslides were then determined through extrapolation. This limited period over which landslide inventories exist, and the associated lack of data on high magnitude/low frequency landslides is a challenge with which all regions of the world must grapple.

Other than the F-N diagram for societal risk, it is also recommended by GEO that individual risk tolerance of 1 in 10,000 be applied for current residential areas and 1 in 100,000 for new developments. The ALARP method was employed quantitatively to Hong Kong scenarios to establish the feasibility of landslide remedial works, i.e. the Pat Heung landslide, North Lantau Expressway, Lei Yue Mun, and Shanti Heights, etc (Wong 2005).

2.5.2 China

Following a landslide that results in 79 casualties at Wulong, China on labour day of 2001, new legislation on landslide hazard and risk assessments were incited. However, no landslide individual and societal risk criteria have been recognized by the Chinese government (Song et al. 2007) though numerous criteria have been developed and employed for other projects such as dams. Nevertheless, the verdict on acceptable and tolerable risks lies in the decision of the client, owner, regulator, and persons at risk and not the risk analysts (Fell 1994).

The Chinese landslide societal risk criteria proposed by Song et al. (2007) is comparable to the Hong Kong acceptable and tolerable landslide risk criterion found in Fell (1994), Geotechnical Engineering Office (1999), and Dai et al. (2002). The proposed landslide risk criteria are about 3 times higher than the projected risk criterion for manmade structures such as buildings. More recently, landslide risk assessment has been implemented extensively in China, with real-life landslide case studies employed in various regions i.e. Western Hubei (Fu et al. 2020), eastern Jiangxi (Zhang et al. 2020), and Mayang county (Sui et al. 2020). It is further stated by Wu et al. (2020) that the Chinese government invented a system called 'Public Participation Monitoring and Warning' (PPMW) which aims to bring down mortality rate with the least cost by grouping residents to evacuate ahead of a disaster. It works by captivating the public in the disaster risk management operation.

2.5.3 Australia

In 1997, 18 deaths occurred as a result of the Thredbo landslide in Australia. This resulted in the development of a framework for risk-based landslide management by the Australian Geomechanics Society (AGS) (AGS 2007). It is stated in the framework that "risk evaluation is to be conducted by comparing estimated risks to levels of tolerable or acceptable risk, in order to assess priorities and options" and the risk tolerance criteria are to be determined by the "client/owner/regulator with advice from a technical specialist".

For individual risk, it is recommended by AGS (2000) that the tolerable individual risk criteria employed for Potentially Hazardous Industries, Australian National Committee on Large Dams (ANCOLD), as tabulated in Table 2-4, could be reasonably applied to engineered slopes as well (Lacasse 2016). Moreover, it is also being proposed that acceptable risks may be taken as one order of magnitude lower than tolerable risks.

Table 2-4 Proposed tolerable risks by AGS (2000) as seen in Lacasse (2016)

Slope types	Tolerable risk for loss of life
Engineered Slopes	1E-4 for person most at risk 1E-5 for average person at risk
New Engineered Slopes	1E-5 for person most at risk 1E-6 for average person at risk

It is then further stated by AGS (2007) that no risk tolerance criteria of Australia are legally binding lest the owner or regulator acknowledge it. Nevertheless, the landslide tolerance criteria developed in Hong Kong for Societal and Individual risk are endorsed in documented studies regarding landslide risk management practices in Australia (Fell et al. 2005).

2.5.4 Canada

A review by Evans et al. (2005) concluded that Canada has adequate comprehension of landslide hazards that it could deliver a regional quantitative risk assessment (QRA) as well as the design of tough risk-reduction procedures for majority areas that are heavily predisposed to landslides. North Vancouver was the first municipality in Canada to employ the Hong Kong individual risk acceptance criteria after the landslide in North Vancouver that occurred in 2005 due to heavy downpour which resulted in the destruction of two homes, one seriously injured resident, and one fatality (Hungr et al. 2016b; Porter et al. 2017). Restrictions were enforced by the legislation on the development of residential areas, as well as redevelopment and rezoning in regions where the Personal Individual Risk (PIR) exceeds 1 to 10,000 for existing houses or 1 to 100,000 for new development. Extensive public engagement is of paramount importance in the legislative operation (District of North Vancouver 2009; Tappenden 2014).

During an extreme rainstorm between June 19 and 21 in 2013 that brought about flood, debris flow, and debris flood in Canmore, Alberta, numerous buildings and infrastructure suffered severe damage (Town of Canmore 2015). As a result, the municipality engaged consultants conducted thorough quantitative risk assessments (QRA) on debris flow and debris flood risk on the Cougar Creek fan, on which a part of Canmore is built. Return periods between 30 and 3,000 years were adopted for the hazard circumstances (Hungr et al. 2016b). The main focus of the QRA was on direct building damage, grievances, and casualties by utilizing the Hong Kong risk tolerance criterion. A total of 190 areas in Canmore were found to have unacceptable individual and societal risks. It was not feasible to relocate the public residing there, hence four proposed options for mitigation were studied extensively, resulting in the construction of a debris flood containment structure (approximately height 30 m and width 100m storage capacity 650,000 m^3) to reduce the unacceptable risk as much as possible to the ALARP / tolerable zone (Town of Canmore 2015). Problems regarding practicability, impartiality as well as affordability were taken into account. Since then, QRA has also been conducted by other local and provincial government regulators in British Columbia and Alberta (Porter et al. 2017), which is a crucial move to obtain supports of stakeholders.

Since 2005, following a certain amount of public consultation, it is widely recognized that Canadian's insights and values in regards to landslide risk are similar to those of Hong Kong (Strouth and McDougall 2020). While there is no universal acceptance, F-N curves have influenced land-use decision making processes exceeding 50 landslides and steep-creek flood hazard regions. Since 2020, the tolerable and acceptable risk criteria have been heavily referenced with discussions of integrating them into municipal and provincial guidelines, regulations, as well as design codes (Strouth and McDougall 2020).

2.5.5 New Zealand

In New Zealand, local governments were delegated with risk tolerance criteria by the New Zealand Resource Management Act. According to Enright (2015), the Hong Kong risk tolerance criteria were employed by the City of Christchurch following the 2010 and 2011 earthquakes. GNS science proposed a tolerable risk threshold for natural hazards of 1 in 10,000 (1E-4) which was deemed to be too high and not acceptable as it doubles the number of "annual" casualties of the 2011 Christchurch earthquake. The study proposed that the annual tolerable risks threshold for existing risks to be 10^{-5} and 10^{-6} for new risks. However, the application of these criteria is still undergoing tests in the local courts and there is a possibility that they will be used by other local authorities. As of present, there are no restrictions placed on land use development for debris flow deposits adjoining the borders of active volcanoes which could only be a century old.

2.5.6 Norway

Throughout history, the Norwegian Fjords have been impacted by large rock slope failures triggering tsunamis that cause many deaths (Hermanns et al. 2013). A trio of the most epic of natural disasters transpired in the twentieth century where tsunamis caused by massive rockslides into fjords or lakes (Loen in 1905 and 1936 and Tafjord in 1934), claiming an excess of 170 lives (Eidsvig et al. 2011). Over the past few years, the Geological Survey of Norway has employed a systematic mapping method to distinguish unstable rock slopes disposed to calamitous failures, so that future events could be predicted and the population at risk could become accustomed to the hazard. The vulnerable regions are continuously monitored and an early warning system together with an evacuation plan is at hand (Hermanns et al. 2013). In 2015, procedures were established by the Direktoratet for Byggequalitet to specify development restrictions in regions vulnerable to landslides or landslide-generated waves (Clague et al. 2015). The restrictions take into account single and multi-family structures of fewer than 10 households, and construction is only allowed if the probability of landslide impact falls below the 1,000-year return period event. Facilities and tall buildings housing numerous occupants i.e. schools, hospitals must be situated in zones with a probability of land sliding impact under the 5,000-year return period event. There are exceptions such as when "the consequences of building restrictions are serious, and the construction has a significant impact on the society." In addition, exceptions are also allowed for scenarios where a warning could be given out three days prior to the incident. As of the present, 523 unstable rock slopes were detected, of which 110 were categorized as hazardous and risky. Out of the 110 hazardous and risky slopes, hazard zones were found in 48 slopes resulting in impediments on building projects. 7 sites were labelled as high risk and they are under constant monitoring (Hermanns et al. 2020).

2.5.7 Switzerland

Bründl et al. (2009) briefly explained that the Swiss National Platform for Natural Hazards (PLANAT) recommended an individual landslide risk “goal” of 1 in 100,000 per year for residential areas in the year 2005. However, the government of Switzerland apparently has not approved the usage of risk tolerance criteria for natural disasters. The present practice in avalanche warning demonstrates that educational courses are one of the crucial components in introducing new ways and skills to natural hazard experts. It is one of the means of communicating risk and there is a high possibility that educational courses will serve as the main part of integral risk management in Switzerland (Bründl et al. 2009). Furthermore, frequent training and educational courses will result in an increased public awareness towards potential consequences, as well as improvement to the compliance rate of the warning systems. Although showing promising results during the Preonzo rockfall event (zero injury and everybody evacuated successfully), further studies are still required to evaluate the effectiveness of the system on the basis of an integrated risk management approach (Sättele et al. 2016a, b, c).

It was stated by the Swiss Ministry of the Environment that “while industrial risks can be governed by legislations using risk tolerance criteria, the same does not apply to natural hazard risks” (Hungr et al. 2016b). This is an arguable statement that was refuted by Hungr *et al.* (2016a). The risk tolerance criteria have been well applied to natural hazards in different parts of the world such as Hong Kong (Wong 2005; Wong and Ko 2005; Chiu 2015), the UK (Winter and Wong 2020), the Netherlands (Hungr et al. 2016b), Australia (Leventhal and Withycombe 2009), Italy (Rossi et al. 2019) and Canada (Town of Canmore 2015; Strouth and McDougall 2020).

A documented discourse by PLANAT (National Platform for Natural Hazards) (2014) regarding tolerable landslide risk criteria stated that “The average risk of death for human beings is not significantly augmented by natural hazards. The yearly risk of death resulting from natural hazards is significantly lower than the average probability of death for the age group with the lowest mortality rate in Switzerland." It can be concluded that their local regulators would prefer to use the landslide hazard probability assessments described in Lateltin et al. (2005). According to Lateltin et al. (2005), it was made mandatory by the new Federal Ordinances on Flood and Forest Protection for the cantons to develop hazard maps for incorporation into the regional and local development plans. This program was subsidized by the federal authorities up to 70%. The three steps of constructing the hazard maps were outlined by Raetzo et al. (2002) as follows:

(i) Hazard identification step which comprises making an inventory of past slope failures.
(ii) Hazard assessment of the magnitude or intensity of landslides with time. Hazards are mapped into one of four hazard classes based on the probability of the land sliding hazard: high danger (probability: 82% - 100%; red zone), moderate danger (probability: 40% - 82%; blue zone), low danger (probability: 15% - 40%; yellow zone) and no danger (probability: <15%; white zone);
(iii) Risk management and land-use planning

It was made mandatory by the federal government that the maps must follow a standard colour coding: red where construction is prohibited, blue where construction is permitted provided certain safety requirements are fulfilled, and yellow where construction can be carried out without any restriction. Hazard maps are deemed invaluable for planning protective measures such as warning systems and emergency plans (Raetzo et al. 2002; Lateltin et al. 2005).

2.5.8 Malaysia

Based on data obtained from the Global Landslide Catalog (GLC) of the United States National Aeronautical Space Administration (NASA), Malaysia is the 10th highest ranked country for the highest number of slope failures, with 171 major slope failures between 2007 and March 2016 (Abd Majid and Rainis 2019). The majority of the landslides occurred on cut slopes or embankments alongside roads and highways in mountainous regions with a few occurring close to high-rise apartments and residential areas, resulting in numerous causalities.

Over the years, there have been numerous studies conducted on Malaysian landslide hazards using various methods such as GIS (Mukhlisin et al. 2010; Althuwaynee and Pradhan 2017; Abd Majid and Rainis 2019), statistical logistic regression method (Lee and Pradhan 2007; Pradhan and Lee 2010) and deterministic safety factor method (Ng 2012; Ismail and Yaacob 2018a). However, research on acceptable and tolerable risk is still scarce in Malaysia, with a few researchers (Ahmad et al. 2017; Roslee 2019) having a more thorough understanding of it. It was proposed by Ahmad et al. (2017) that the interim risk criteria for Malaysia should be higher (higher acceptance of risk, one fatal landslide in every 50 years) than Hong Kong (one fatal landslide every 1000 years) while Roslee (2019) proposed a risk tolerance criterion similar to that found in Hong Kong (Song et al. 2007; Lacasse et al. 2010). It can be concluded that QRA and landslide risk assessments are still a developing art in Malaysia and much surveys and studies are still required.

2.5.9 Comparison of risk tolerance criteria

Figure 2-26 presents comparisons between societal risk criteria adopted by different countries. and institutions. The guidelines shown for comparison are by no means exhaustive and are focused not just on landslides but other hazards as well, i.e. flood, transportation, and Occupational Health and Safety (OHS). While there are variations, the risk levels of Denmark, New South Wales, China, and ANCOLD /AGS generally converge at the anchor point of F = 1E-4/year (1 in 10,000) for N = 10 casualties. Most countries adopt F between 1E-2/year to 1E-3/year for N =1 in their societal risk criteria. The Netherlands, the Czech Republic, and European Commission (EC) have the most risk-averse slope; the steepest compared to those of other nations and entities. The risk criterion of Malaysia proposed by Ahmad et al. (2017) is liberal and has the highest risk tolerance (N= 1000 occurring at a frequency of 1E-4/year). The Chinese risk criterion proposed by Song et al. (2007) is exactly the same as the one of the Australian National Committee on Large Dams (ANCOLD) / Australian Geomechanics Society (AGS). It can be seen that the French criterion is not governed by the number of fatalities, *N*. This will lead to a lower level of safety at high *N* values and at the same time result in extremely stringent and uneconomical safety procedures at low *N* values. Remarkably, lowland nations such as Belgium, the Czech Republic, and the Netherlands employ stricter, more risk-averse criteria than mountainous nations such as Hong Kong and the UK as seen in the steeper slope and a lower *F* value for *N*=1. As events and fatalities are rare in any case in lowland nations, it is relatively straightforward to establish and work successfully with stricter risk-averse criteria.

As seen in Figure 2-26, the risk tolerance criteria for most countries fall below the Hong Kong criteria with the exception of Malaysia, Vietnam, U.S. Bureau of Reclamation (USBR) and the UK. Vietnam, a developing country, advocated a highly liberal risk criterion for floods, whereas Malaysia proposed for a more liberal risk threshold for landslides. One can see in Figure 2-26 that transportation risk was given a slightly more liberal threshold than other hazards in the constitution of Netherlands (Hartford 2009). In addition, a more liberal threshold was employed for risks involving pipelines in the UK. The risk criteria of Denmark and New South Wales (NSW) are higher than Hong Kong's at lower fatalities until they converge at N=10. At higher *N* levels, the *F*s of NSW and Denmark fall below Hong Kong's as evident in its steeper slope, which signifies a more stringent risk aversion and lower tolerance of risk for higher fatalities (N>10). Generally, most countries adopted F between 1E-2/year to 1E-3/year for N =1 (Figure 2-26). The risk criteria of many countries lie below Hong Kong's suggesting a more stringent approach should be employed when it comes to risk assessments. However, the Hong Kong criterion is still widely adopted and referred to in other societies (Fell et al. 2005; Strouth and McDougall 2020)

The criterion proposed by Malaysia, a developing country, is above the criteria of other nations. It has the highest risk tolerance compared to other countries which is unduly liberal and calls for improvements to be made. In addition, it has a risk aversion gradient of 1, similar to Hong Kong's criteria. Other developing countries such as China and Sri Lanka employ risk criteria similar to that of developed countries (China's being exact same criterion as that of Australia's, while Sri Lanka uses the same slope and F =1E-3 for N=1 as that of Hong Kong's). It can be assumed that risk assessment is still new in many developing countries. Many of them employ the criteria of developed countries rather than making their own. As stated by Duzgun and Lacasse (2005), every nation should develop its own risk criterion as they all possess different F-N curves. More works should be devoted to developing risk tolerance criteria particularly for less developed and mountainous countries. The landslide risk tolerance level threshold depends on the capability of a social system to preserve its functionality and to replace lost functionalities, the recovery time and the recovery degree impact by landslides (Tian and Lan 2023).

The risk threshold for 1 death for Malaysia and some other nations and organizations are extracted from Figure 2-26 and simplified into Figure 2-27 for easier comparison. It is not surprising that the risk thresholds are consistent across different organizations, as they generally adopt the frameworks and methodologies established by the UK (Macciotta and Lefsrud 2018), as well as those utilized by Hong Kong and the AGS (Fell et al. 2005; Strouth and McDougall 2020; Sim et al. 2022b, 2023a). As noted earlier, a threshold of F between 1E-2/year to 1E-3/year is commonly adopted for N =1. A risk aversion gradient of 1 is the most commonly employed gradient by most countries. Malaysia, classified as an upper-middle-income country by World Bank (2020), is shown in Figure 2-27 to be the most liberal, which, once again, calls for improvements to be implemented. Both Denmark and the Netherlands are high-income nations, with a Gross National Income (GNI) exceeding USD 12,235 (World Bank 2020) and a value of statistical life (VSL) that could reach as high as USD 11.8 million as seen in Figure 2-13, which enables them to adopt such a risk aversion gradient of two times greater than that of most nations. As noted by Winter and Bromhead (2012), nations with significant economic power are both willing and capable of allocating substantially greater resources to risk prevention measures, leading to a reduction in casualties over time. Interestingly, Czech Republic being a country with lower VSL compared to both Netherlands and Denmark is willing to adopt a tolerable threshold of 1E-4/year for 1 death (one magnitude lower than Hong Kong, ANCOLD/AGS, Netherlands, Taiwan, China and European Commision) with a risk aversion gradient of 2 making it one of the most risk averse nation in Figure 2-27. Another interesting observation is that Rio de Janeiro and Rio Grande do Sul adopts a criteria with a risk averse gradient of greater than 1 (Figure 2-26) with threshold of 1E-2 for 1 death similar to that of the UK despite its country's VSL being much lower (USD 1.03 – 1.2 milion as seen in Figure 2-13). Furthermore it has a risk aversion gradient greater than 1. Indeed, it is evident that each nation has its distinct priorities and approaches in dealing with risk management. The risk criteria of every nation is unique to one another and should take into account the socio-political, economic, and cultural aspects of the nation (Macciotta and Lefsrud 2018).

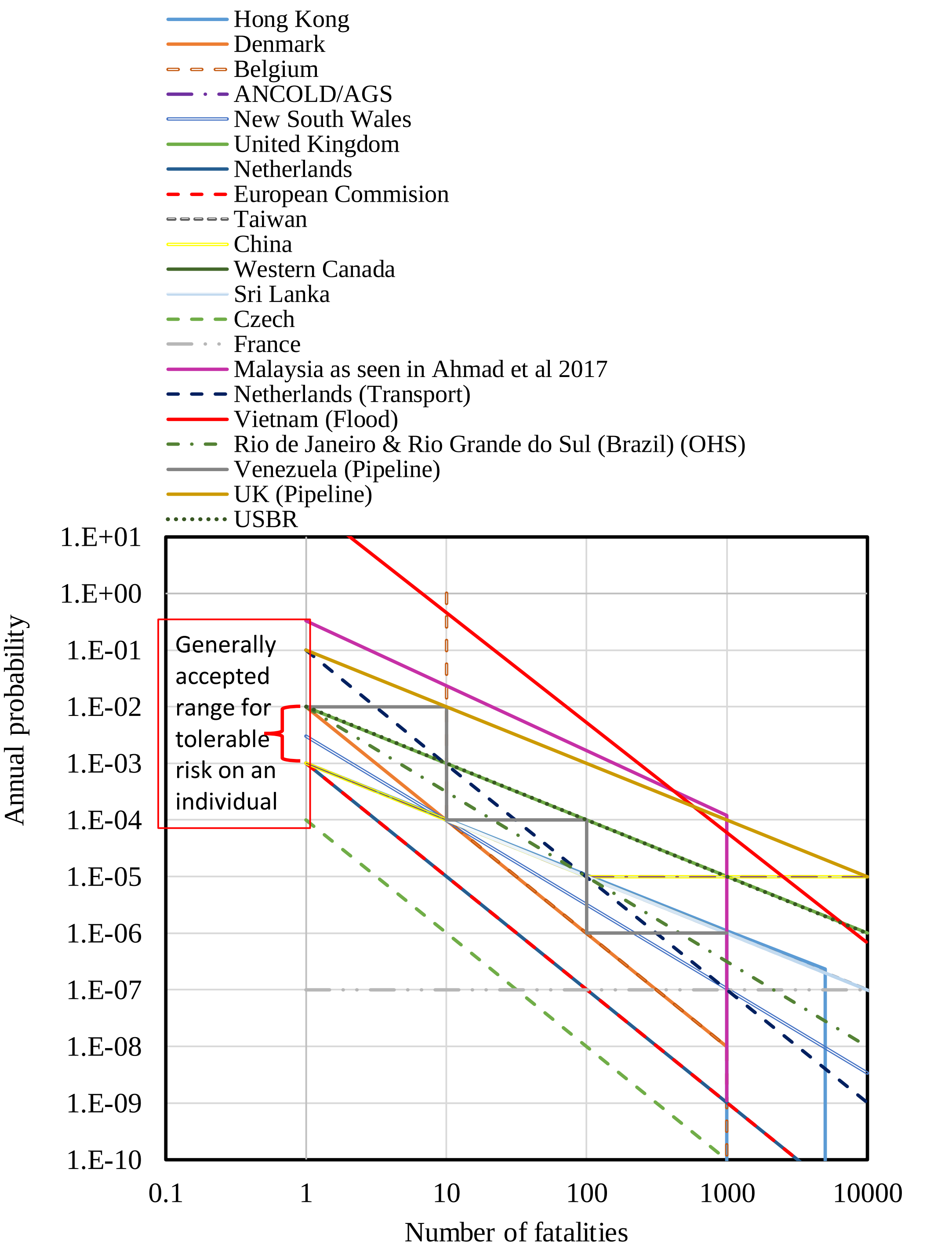


Figure 2-26 Risk criteria of different nations. Extracted from (U.S. Bureau of Reclamation 2003; Kirchhoff and Doberstein 2006; Hartford 2009; Cong 2014; Marhavilas and Koulouriotis 2021; Sim et al. 2022b)

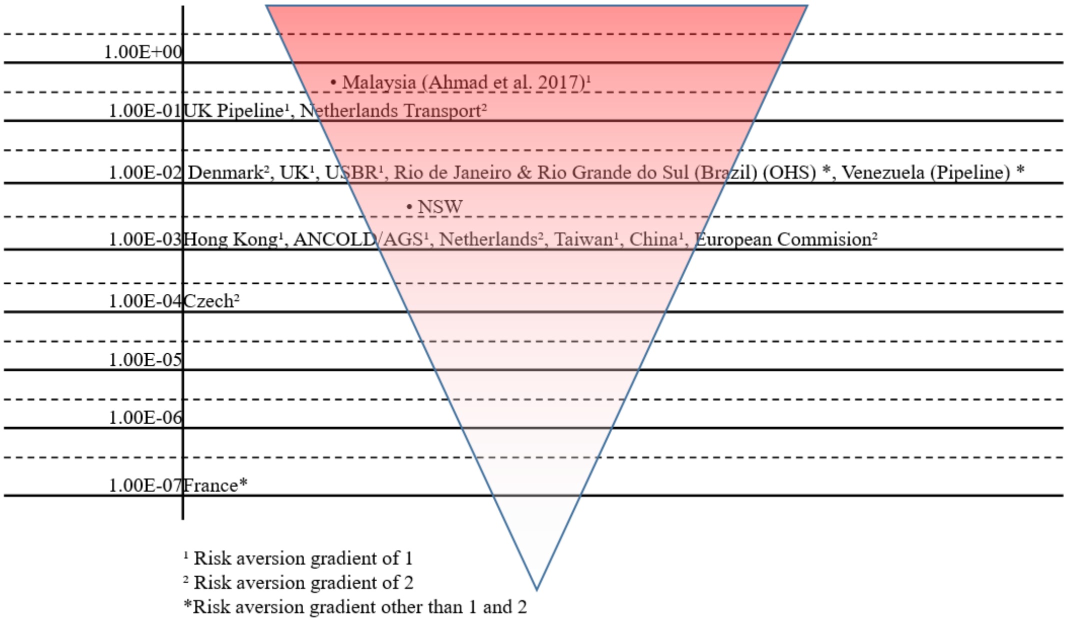


Figure 2-27 Annual probability of occurrence (F) for N=1 death, as adopted in the tolerable risk criteria of various nations, commonly cited in the literature on landslides and other hazards.

2.6 Discussions

While data shows that losses are incurring everywhere throughout the world, the impact is much greater in the developing world. This is true especially at countries with tropical climate such as Nepal, India and China which are acutely affected by landslides due to extreme precipitation as a consequence of climate change. On the basis of worldwide data, landslide incur losses of around $20 billion per annum with total death toll exceeding 110,000 cumulative from the beginning of the 20th century till present. The hazard will almost certainly increase as population grows, weather and climate become more severe and anthropogenic triggers increase. The frequency of fatal landslides is still on the rise in the developing world with a large portion of the casualties and economic losses in terms of GDP occurring in less developed regions especially the tectonically-active monsoonal and tropical tornado prone regions of Asia and the America (Petley et al. 2007). Vulnerability is shifting resulting in the exceedance of threshold values for casualties, property loss and destruction in those developing nations. Actions have to be taken to mitigate these adverse scenarios.

The combination of human and economic losses make landslide worldwide an economic and humanitarian issue. There is a crucial requirement for governmental agencies and other policy-making bodies worldwide to develop a better understanding of the socioeconomic impacts of landslides. Such comprehension will permit rational allocation of funds necessary for landslide research, prevention, avoidance, control, and warning systems, as well as post-disaster repair and reconstruction. Until vulnerability and risks are lowered, nations with high population density and GDP and landslide hotspots particularly developing nations in the tropical region are most likely to suffer repeated acute landslide related losses and costs if not even more. Landslide risks hence merit serious attention as an issue for sustainable development in high risk regions (Dilley et al. 2005). Unfortunately, risk mitigation and prevention have not attracted sufficient attention and public support in cities during the past decades. It is crucial for geotechnical researchers and engineers to develop methods suitable for dealing with global climate change, policies and demographics (Lacasse et al. 2010). Contribution to an improved comprehension of risk assessment, mitigation and management is of utmost importance.

A practical method to risk management is crucial to significantly bring down the fatalities and material damage associated with geohazards. Over the past 5 to 10 years, widespread media attention has been provided regarding major geohazards which as a result have altered the minds of society in acknowledging risk management as an alternative to emergency response. A worldwide positive trend can be seen where preventive measures is increasingly accepted, both on the government scale and among international donors. For example, following the establishment of “risk-informed justification” also known as quantitative risk assessment (QRA) by The Geotechnical Engineering Office (GEO) of Hong Kong, the overall landslide risk related to the man-made slopes in the country was lowered significantly by 75% (Chiu 2015). Since then, the approach had been adopted by several developed western countries such as the UK

(Winter and Wong 2020), the Netherlands (Hungr et al. 2016b), Australia (Leventhal and Withycombe 2009), and Canada (Hungr 2016; Porter et al. 2017; Strouth and McDougall 2020). Lin and Wang (2018) reported that China has invested heavily in geological disaster control and prevention in recent years, i.e. an increase in allocation from Chinese RMB 330 million in 2000 to 17.6 billion in 2015. As the result, a lower death toll (by about 10%) by landslides was reported in the 2010s.

It is apparent that every nation has its own priorities and approaches towards landslide risk management. While it is interesting to compare the broad range of policies and discussions among various nations worldwide, this review by far does not feature coverage on the countries of the African continent. There is practically no or very limited data available on the QRA of landslides in the African continent. It is also clear from the comparison of F-N curves that the Asian world has the highest frequency of landslide deaths followed by Latin America.

Generally, most countries adopted F between 1E-2/year to 1E-3/year for N =1 (Figure 2-26). Although it is easy to state that the landslide risk criterion should have a minimum level of tolerance for landslides, i.e. F =1E-3 for N =1, the acceptance of tolerance for landslides in every country will be governed by its financial standing. While a developing nation might face similar matters in risk governance and decision-making as the developed nations, the trade-off between economy and safety might differ (Roy and Kshirsagar 2020). Developments that occur in developing nations will amass bigger benefits than their developed counterpart. For example, the construction of railways, roads may contribute to job opportunities, easier access to certain areas, and goods transportation which will help to increase turnover and create wealth to boost the economy (European Maritime Safety Agency 2015). However, against these potential advantages, the development of roads may inflict higher risk to the users i.e. landslides that occur along roads in Scotland, Jamaica, and Colorado as well as many others mentioned by Winter and Bromhead (2012). Nevertheless, under an agreed level of risk, there are potentially higher net benefits from the developments of a developing nation than for a developed one. Thus, should a variety of risk acceptance and tolerance criteria be employed in the developing nations in regards to their developed counterparts? An unduly liberal risk acceptance criterion will bring about more development but at the expense of higher societal risk. On the contrary, an extremely conservative acceptance criterion will hamper development and economics. Under these circumstances, cost-benefit considerations will be required to formulate a suitable acceptance criterion. Technically, risk acceptance criteria need to be established in a way that the cost spent must not be in gross disproportion to the potential benefits –"the risk being insignificant in relation to the sacrifice", as quoted from Lee and Jones (2014). Regardless, the rationalization of acceptance of hazardous developments in developing nations at a risk level which is deemed unacceptable in the developed nations remains a challenge. Criterion should be developed locally with historical landslide inventory, public perception, and engineering aspects being considered.

2.7 Concluding remarks

From the past centuries, highest number of landslide focus in America and Europe, then into new millennium, shifted to Asia (Froude and Petley 2018). This implies that development / construction is a major contributing factor. Landslide events concentrate mainly in tropical region (Figure 2-7) signifying the importance of rainfall as main triggering factor. Malaysia being both a developing country and located in tropical region would be the focus of the present study.

From the present review, it was found that many countries already have their landslide risk tolerance criteria in place (some were self-developed while others were adapted from the models of developed countries). However, the actual enforcement and implementation of the criteria in real life landslide risk control are still not encouraging, particularly for less developed countries. For example, the currently available landslide risk criteria for Malaysia have a very high-risk tolerance (N=1000 occurring at a frequency of 1E-4/year) as compared to other countries, which is unduly liberal and calls for improvements to be carried out. It should be noted that the survey questionnaires conducted by Ahmad et al. (2017) to determine the landslide risk perception for the development of the Malaysian risk criterion were limited to an unknown number of residents in Ulu Klang and Ulu Langat, which are a municipality and district area of the state of Selangor. The risk criterion was proposed on the assumption that the societal landslide risk of Malaysia was exactly the same as that of Hong Kong's. However, both Ulu Langat and Ulu Klang have experienced several landslides in the past (Gue and Liong 2007; Mukhlisin et al. 2010; Manap et al. 2018). The high threshold of landslide risk in the criterion proposed by Ahmad et al. (2017) reflected the residents' familiarity with living with landslide risk and their higher acceptance of it. When establishing the risk criteria for the entire country of Malaysia, it should not be based solely on the risk perception of the populations in the selected landslide prone areas. It should also consider the perception of people from diverse geographical locations, as residents in different regions may exhibit varying tolerance and acceptance towards landslide risk (Finlay and Fell 1997; Salvati et al. 2014; Liu et al. 2019). In other words, the criteria should encompass the entire nation of Malaysia. Every country worldwide has its own unique societal landslide risk. (Sim et al. 2022b) Therefore, the proposed risk criterion for a specific nation should consider the actual landslide societal risk of that nation instead of assuming it is equal to that of another nation (Vrijling and van Gelder 1997; Roy and Kshirsagar 2020; Strouth and McDougall 2020; Sui et al. 2020). One of the objective of this study is to further improve the previous excellent works by Ahmad et al. (2017) through collection of opinions from populations of more diverse backgrounds and experts from different sectors to establish a more inclusive landslide risk criterion.

Furthermore, the currently available landslide data in Malaysia is rather scattered with some of them are stored in archive of certain database, while some in other authorities such as the Public Works Department. One can say that the landslide database for Malaysia is rather incomplete. Moreover, the concept of landslide risk management is still at its infant stage in Malaysia. Often, engineers still favour to employ the deterministic safety factor method when carrying out designs for new development. There is still limited proper landslide risk management in place in Malaysia.

3. Methodology

3.1 Introduction

The methodology employed in this study is shown in this chapter. Figure 3-1 presents the framework that details the workflow of this study from the commencement until its completion.

Firstly, literature review was performed on the various aspects of this study such as factors affecting landslides, socioeconomic impacts of landslides worldwide, comparison of landslide risk levels of various nations in the form of F-N curves, as well as the risk criterions adopted by different countries around the world.

This is followed by defining the objectives of this study before working on the main tasks of this study. Historical landslides data were collected and analysed to form a F-N curve to determine the overall societal risk of landslides of Malaysia.

Subsequently, questionnaires were distributed to obtain the public opinion on the landslide problem of Malaysia. Interviews were also conducted with authorities and landslide experts to obtain professional opinion on the landslide risk problem of Malaysia.

The results from the quantitative study through the F-N curve and the qualitative study from the surveys and interviews enabled a proper landslide risk criterion for Malaysia to be established. The risk criteria were compared with those of other nations i.e. Hong Kong's to ensure its rigor level.

The last phase involves the verification of the risk criterion by conducting Quantitative Risk Assessment (QRA) on a selected case study. For the first part of this phase, empirical model was developed to predict landslide runout distance in Malaysia. This included establishing empirical correlations between travel distance, runout, retrogression distance, slope height, slope angle, and landslide volume. Probabilistic slope stability analysis was conducted to establish probability of slope failures using the "Groundwater" and "Slope Stability" modules in PLAXIS LE software. Subsequently, runout of the landslide of the case study was predicted using the developed empirical model. The risk levels for elements at located along the run-out path of the landslide were estimated. The overall risk to society was expressed using an F-N diagram, showcasing the practical implementation of the novel Malaysian risk criterion proposed in the present study.

Phase 1 - Desk Study

1) Literature review,
2) Collection of reported F-N curve and risk criteria

↓

Phase 2 Data collection

Quantitative data

1) Historical landslide inventory data collection
2) Synthesize F-N curve

Qualitative data

1) Questionnaire survey among public
2) Interview with experts

↓

Phase 3 Establishment of landslide tolerable and acceptable risk criteria

1) Synthesize risk criteria using data from both quantitative and qualitative analyses
2) Compare established risk criteria with other nations' i.e. Hong Kong’s

↓

Phase 4 Verification through Case Study

1) Development of empirical model for predicting landslide travel distance
2) Probabilistic slope stability analyses on a case study using PLAXIS LE
3) Landslide runoff prediction using the developed empirical model
4) Risk estimation of the case study

Figure 3-1 Flowchart of research work

3.2 Data analysis

3.2.1 Data collection

The existence of reliable databases on geohazards is vital to analyse mortality due to landslides in regards to temporal trends, spatial distribution and epidemiological topics (Pereira et al. 2017). One limitation to study the fatalities caused by landslides faced by many researchers is the relatively short time span of the existing databases and the lack of field validation (Petley 2012).

One way to obtain data regarding fatalities will be through newspaper reports. However, the total number of deaths caused by landslide disasters is most likely underreported as the fatalities that occur sometime after the landslide would normally not reported, and thus it is not possible to analyse the landslide deaths using newspapers as the single data source. Data collection in Malaysia, as noted by Sim et al. (2022a) and Gue et al. (2009), is a labor-intensive process involving mining information from various sources. Much information is scattered among different parties, and some of the documents are classified, either because they contain sensitive information or due to the trade secrets used by certain parties (Gue et al. 2009). For this study, social impacts caused by landslides in Malaysia were obtained from the National Slope Master Plan and relevant reports, as well as published studies. The data contain information such as the landslide location, date, and social consequences such as fatalities. Sufficient landslide inventory of Malaysia spanning years 1961 to 2022 were successfully obtained for this study.

From the whole dataset of landslide incidents occurring in Malaysia, only the events associated with cost of human lives were included in this study. In the present study, the mortality patterns resulting from fatal landslides occurred in Malaysia from the earliest date of data availability were explored.

3.2.2 Development of F-N curve

Societal risk was determined through the plotting of annual frequency F of events causing N or more fatalities against the number N of fatalities (i.e. an F-N curve).

Societal risk could be well represented by a F-N curve as long as the circumstances which globally results in slope failures in the past and affected the associated consequences stays the same over time. To obtain data points for the curve in regards to historical landslide records, the available data of previous landslides were chosen in accordance with associated deaths (N) and ranked in descending order. These data were used to calculate the F-N curve for the Malaysian lanslides. The frequency of an event (f) was computed by dividing the total number of events contributing to a specific number of death (N) by the period of which they were based on (i.e. 62 years). The cumulative frequency (F) was then computed by summing up the frequency of each landslide event with the number of fatality in descending order.

3.3 Questionnaire Survey and expert interviews

A questionnaire survey method has proven to be very useful in determining the public's psychological responses and mental anticipations related to disasters (Fell 1994; Bird 2009; Liu et al. 2019). Finlay and Fell (Finlay and Fell 1997) successfully conducted a questionnaire survey regarding landslide risk acceptance and proposed landslide risk guidance for Australia and Hong Kong. They concluded that the acceptable frequency of landslide occurrence for the community is 1E-4 per annum. Most respondents expressed relatively low acceptable frequencies of landslide events, i.e. around 1E-6 per annum. Approximately 80% of the responses, spread widely over the range of frequencies from 1E-3 to 1E-6 per annum, corresponded to the tolerable risk region, also known as the "as low as reasonably practicable" (ALARP) region, reflecting a wide diversity of risk attitudes. It was suggested that voluntary risks, such as traffic accidents, have a higher acceptance level than involuntary risks, such as natural hazards (Fell 1994). A similar study suggested that in Russia, the acceptable frequency of fatal injury due to industrial activities was lower than 1E-5 per annum (Yelokhin et al. 2004). A typical acceptable frequency of events related to involuntary risk, especially due to man-made structures such as dams and chemical plants, would be 1E-6 per year, and no higher than 1E-5 per year (Fell 1994). In a documented study by Liu et al. (Liu et al. 2019), regarding an on-site questionnaire survey and interviews with participants in Zhouqu (Northwestern China) and Dongchuan (southwestern China), it was found that gender and salary were common influencing factors for landslide-disaster acceptability in the two landslide-prone regions. In another similar study by Calvello et al. (Calvello et al. 2016), surveys were conducted using face-to-face interviews with 100 residents of Sarno in Southern Italy for three months between March and May 2013. The questionnaire included questions relating to perceived risk exposure, trust in authorities responsible for risk management, evaluations of risk mitigation measures, and the early-warning strategy. Results from the survey showed, among other issues, that it was vital for organizations responsible for risk management in Sarno to establish a more effective communication strategy to deliver knowledge about the implemented actions, in order to reduce landslide risk in the area.

Over the past 20 years, decision-making processes in disaster risk management have been developed, attributing to the rise of a people-centered approach rather than the conventional top-down approach (Anderson et al. 2014; Scolobig et al. 2015). In order to establish a people-centered approach, authorities need to have a better understanding of public perspectives and expectations and improve communications and long-term dialogues with the public. The top-down approach often fails to effectively communicate with the most vulnerable communities, resulting in a lack of motivation for the public to utilize new mitigation measures (Anderson et al. 2014). As a result, questionnaire surveys on people's attitudes regarding disaster risk acceptance have become dominant in aiding authorities as a reference for decision-making on risk guidelines for sustainable development in landslide-prone regions (Scolobig et al. 2015). Questionnaire survey studies have been widely used to investigate landslide risk perception among populations in various parts of the world, including Hong Kong (Finlay and Fell 1997), Australia (Finlay and Fell 1997), China (Liu et al. 2019; Gao et al. 2020), Mexico (Hernández-Moreno and Alcántara-Ayala 2017), Italy (Salvati et al. 2014; Calvello et al. 2016; Antronico et al. 2020), Austria (Damm et al. 2013), and Germany (Blöchl and Braun 2005). Additionally, numerous landslide acceptability criteria have been developed in different parts of the world, such as Canada (Strouth and McDougall 2020), China (Song et al. 2007), Sri Lanka (De Silva et al. 2017), Hong Kong (Geothechnical Engineering Office 1999) etc. However, the study on public perception in Malaysia is still very limited, and a proper landslide risk criterion has yet been established for the country.

3.3.1 Questionnaires development

Questionnaires was developed for a landslide risk acceptance survey to suit the objectives and scopes of the current study. To the best of authors' knowledge, there were no similar questionnaires that has been done in Malaysia so far. The survey was conducted to determine the perception of the communities towards landslide risk while landslide experts from various sectors were interviewed to obtain their valuable knowledge and expertise gained from the extensive experience they have acquired while working on landslides in Malaysia. The survey comprised 19 questions that offer various response formats. These formats included closed questions with options for yes/no responses, multiple-choice questions, and a 5-level scale where participants can indicate their level of concern, with (1) representing the least concerned and (5) representing the most concerned. Furthermore, there was a 7-level probability of acceptance scale that ranged from once a month to once in 10,000 years or more. The questionnaire consisted of two sections: (i) Socio-demographics of participants (Q1-11); and (ii) Views on landslide disasters (Q12-19). The section of views on landslide disasters investigated the following research questions: a) respondents' sources of information regarding landslide; (b) ranking of landslides and other hazards and natural hazards; (c) acceptable distance between respondents' living or working place and the location with history of landslides; (d) frequency of maximum acceptable probabilities of landslides in various scenarios of fatalities; (e) annual insurance premium level that respondents are willing to pay if their house is at risk of landslides. Full questionnaire is available at appendix 3.

Survey questionnaires were developed and distributed to the public in order to get their perception on the current landslide problems. The main goal of the survey of landslide risk perception is to obtain the qualitative and quantitative data conveying views of landslide risk. While it is not wrong that the opinion of an individual may not align with their actions, their preferences are, however, a key factor in the evaluation of the landslide risk criteria (Finlay and Fell 1997; Calvello et al. 2016). Without any input from the public on their opinions and sentiments, decision makers who make assumptions in the name of the public without any prior consultation does not seem right.

3.3.2 Interviews

Landslide experts in from various sectors i.e. government, NGO, practitioner, IEM chairman of Geotechnical division, academic etc. were interviewed. The expert interviews are intended to enhance the collection of background information, as well as the verification of collective interests. In addition, their opinions and comments provided an idea of what the landslide tolerance and acceptance level should be.

The questions used for the expert interviews comprised the following: (i) The current landslide situation in Malaysia; (ii) Views on the top-down approach or community-based approach for setting landslide risk guidelines; (iii) Comments on questionnaire survey results, including the public's knowledge sources of landslides, public's ranking of landslides and other hazards, as well as natural hazards, and public's perception of factors causing landslides; (iv) The public's choice of the level of insurance premium to safeguard against landslides; (v) Additionally, the experts were asked to provide their frequency of maximum acceptable probabilities of landslides in various death scenarios. (vi) Lastly, the experts were asked to comment on the suitability of applying the well-established Hong Kong's landslide risk criteria to Malaysia.

3.3.3 Sampling methods

The sample size for the present study was calculated using the Raosoft sample size calculator (Raosoft Inc., Seattle, WA, USA). According to the latest data from the Department of Statistics Malaysia, the population of the Malaysia is approximately 33 million. It was reported in Statista that around 23 million of the Malaysian population are adults. Taking into account a confidence level of 90%, a margin of error of 5%, and a response distribution of 50%, the recommended sample size was 271 for a population of 23 million adults living in Malaysia. Similar parameters were utilized in a study conducted by Liu et al. (2019) concerning the acceptability of landslides in China, as well as in other studies (Salama and Soltan 2017; Rosdi et al. 2019; Mohta et al. 2021). Questionnaires were distributed to communities residing in various sites that have experienced landslides including both urban and rural areas. It should be noted that questionnaires were also distributed to residents living in regions that are less vulnerable. The study aims to encompass Malaysia as a whole and not just the communities that are most at risk. There have been previous studies on landslide risk perception conducted, which included both communities at risk and those not at risk (Finlay and Fell 1997; Salvati et al. 2014).

A combination of sampling techniques was used to select participants, comprising both random selection and snowball sampling lead with the goal of maximising the heterogeneity. Some of the respondents were target people because a rough balance in gender ratio among respondents was sought after and it was required to establish a fair representation of people living near to slopes and people who have encountered landslides before. All the participants fully and willingly volunteered to participate in the study. The participants (with the exception of the interviewed landslide experts) were kept anonymous and they were not demanded to sign or to give out personal information i.e. identity card number. A total of 392 completed questionnaire samples were collected. Five landslide experts that were interviewed in person in their respective office in the present study. Each of the five experts represented the top specialist in their respective sector in Malaysia, namely government, non-governmental organizations (NGO)s, practitioners, professional institutions, and academics. Their opinions are based on their extensive knowledge and practical experience in addressing landslide issues in Malaysia. These opinions held significant relevance in establishing an interim landslide risk criterion for Malaysia, which was the main objective of this study. The expert interviews lasted an average of 1 hour and 30 minutes each, and all five experts willingly participated and provided their informed consensus prior to the interviews.

The author acknowledged that the sample may not be assembled in a rigorous fashion—which was impossible owing to the available time and resources. While the snowball sampling technique utilized can facilitate the acquisition of a larger number of respondents more quickly, it was not without its limitations such as the potential for bias in participant recruitment. Since participants were obtained through referrals, there was a risk of self-selection bias, wherein individuals who were well-connected, sociable, or more inclined to participate may be disproportionately represented in the sample.

3.3.4 Data treatment

The collection of participants’ personal data was carried out in accordance with the terms stated within (i) The University of Nottingham's Royal Charter, (ii) the UK's General Data Protection Regulation (GDPR), (iii) The Malaysian Personal Data Protection Act 2010 and (iv) the University's Code of Research Conduct and Research Ethics. These collectively spell out the legal basis for processing participants’ personal data, rights as a data subject as well as data sharing/management arrangements. The full Privacy Notice that spells out participants’ rights as a data subject is available upon request

The raw questionnaire data was keyed into a spreadsheet format in SPSS (Statistical Package for Social Science) software for analysis. The method employed of data treatment included summary statistics i.e. distribution plots, calculations of means, medians, and modes, frequency analyses, and cross-tabulation of correlations. Statistical tests were also carried out to determine the factor significance of demographics.

To study the significance of various demographics, independent sample t-test and one-way analysis of variance (i.e., F- test) were employed. The t-test was used to verify the factor significance of two subgroups (i.e., the gender of respondents: male and female) while the F-test was utilized to authenticate the factor significance of more than two subgroups (age, educational level, occupation, and income). The factors that neither satisfied the t-test nor F- test were applied by Brown–Forsythe test (BF-test) (Roth 1983; Karagöz and Saraçbasi 2016; Liu et al. 2019). Finally, the statistical results of the t-test and F-test, the significant factors affecting landslide risk acceptability, insurance premium etc. were obtained.

3.4 Risk criteria development

The risk criteria for landslides in Malaysia were established through the analysis of questionnaire and expert interview results, encompassing participants' perceptions of acceptable risk levels and willingness to invest in mitigation measures such as insurance premiums. This financial instrument aimed to mitigate potential losses or damages from landslide events (Klose et al. 2015b). By considering these factors, valuable insights into the attitudes and preferences of the surveyed population regarding landslide risk management in Malaysia were gained. While tailored to Malaysia, this criterion may also serve as a valuable preliminary action for other cultures.

The determination of social acceptance and tolerance levels towards landslide risk within vulnerable communities can be achieved through the utilization of questionnaires and analysis of socio-economic data. Additionally, input from experts and professionals plays a crucial role in establishing the threshold for risk acceptance and tolerance. While public opinion is acknowledged as a vital aspect in formulating risk criteria, the perspectives of professionals are essential in assessing the feasibility of the public's tolerance and acceptance thresholds. As stated by Macciotta and Lefsrud (2018), the development of risk criteria should take into account the socio-political, economic, and cultural aspects of the country, as society's perception of risks, influenced by factors such as their nature and voluntariness, shapes their response to risk. By integrating the viewpoints of both the general population and experts, alongside quantitative analysis of historical landslide data, a viable and robust landslide risk criterion can be successfully developed. Furthermore, a comparative analysis was conducted with criteria adopted by other nations, such as Hong Kong, to evaluate whether the present proposed criteria were excessively strict or overly lenient.

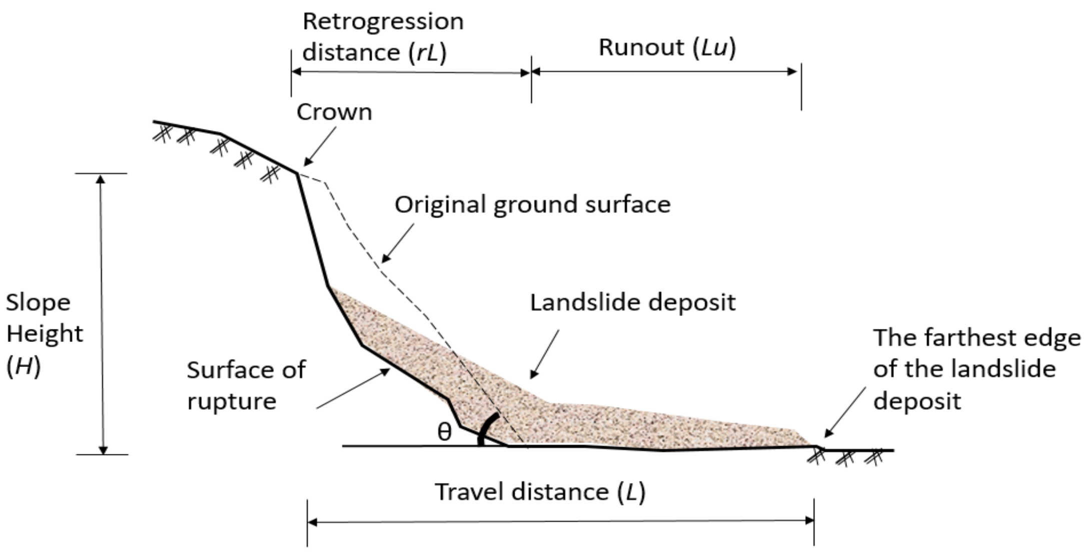
3.5 Empirical-statistical model for landslide runout distance prediction

One of the critical components in landslide hazard and risk assessment is the reliable estimate of the runout distance of the sliding mass. Replicating and investigating landslide runout, which results from various causes and factors, is extremely challenging in laboratory models (Ward and Day 2006; Falconi et al. 2022). There are two common approaches for landslide runout prediction: empirical-statistical models, based on geometric parameter correlations, and numerical modeling, which simulates physical processes (McDougall 2014; Peruzzetto et al. 2020). The distinction between the two methods is often insignificant due to the complexity of collecting universal guidelines for runout modeling (Scheidl and Rickenmann 2010; Huang and Cheng 2017). Additionally, applying numerical models for landslide propagation is still too complex (Li et al. 2019; Falconi et al. 2022).

Empirical-statistical methods are useful for predicting landslide runout and the coverage impact area (Rickenmann 1999). They rely on simple correlations between landslide parameters and runout (Jakob et al. 2005) (Figure 3-2). Despite the simplified dynamics, these methods can provide reliable predictions of landslide propagation (Berti and Simoni 2007; Falconi et al. 2022), aiding decision-making and complying with guidelines for landslide risk assessment (Corominas et al. 2014; Falconi et al. 2022). In developing countries, with limited data, experts, and funding, these simple, low-cost procedures are imperative (Guinau et al. 2007; Falconi et al. 2022; Sim et al. 2024).

Table 3-1 summarizes the empirical models for predicting the runout distance of landslides. There are more than 10 empirical equations proposed by 10 researchers. It can be seen that height of slope *(H)* is the most used parameter by researchers, as it is the most widely available worldwide, followed by landslide volume (*V)*. Prediction models based on Runout (*Lu*) and retrogression distance (*rL*) are still relatively scarce.

Figure 3-2 Geometrical variables: height of slope *(H)*, run out distance *(L)*, slope angle *(*θ*)*, retrogression distance *(rL)*, runout *(Lu)*



Modified from: Hungr et al. 2005; Strand et al. 2017

Table 3-1 Summary of empirical models for predicting landslide runout distance

No.	Researcher(s)	Equations		Parameters used
1	(Corominas 1996)	$L = 1.03V^{-0.105}\, H$	*(3-1)*	*V, H*
2	(Rickenmann 1999)	$L=1.9V^{0.16}\, H^{0.8}$	*(3-2)*	*V, H*
3	(Legros 2002)	$L=8V^{0.25}$	*(3-3)*	*V*
4	(Locat 2008)	$Lu = 8.8rL^{0.8}$	*(3-4)*	*rL*
		$Lu= 4.4rL^{0.8}$	*(3-5)*	*rL*
5	(Guo et al. 2014)	$L = 2.672\, H - 208.31$	*(3-6)*	*H*
6	(Qarinur 2015)	$L=1.267H^{1.027}$	*(3-7)*	*H*
		$L= 1.066H^{1.093}$	*(3-8)*	*H*
		$L = 1.448\, H^{1.062}\, tan\, \theta^{-0,482}$	*(3-9)*	*H*, θ
7	(Strand et al. 2017)	$Lu = 3.0\, rL$	*(3-10)*	*rL*
		$Lu = 1.5rL$	*(3-11)*	*rL*
		$Lu = 0.5rL$	*(3-12)*	*rL*
8	(Samodra et al. 2018)	$L=1.65H+1.09$	*(3-13)*	*H*
9	(Zhou et al. 2019)	$L = 0.04\, V^{1/3}$	*(3-14)*	*V*
		$L= 0.05\, H^{0.43}\, V^{0.28}$	*(3-15)*	*V H*
10	(Apriani et al. 2022)	$L = 6.918\, H^{0.84}$	*(3-16)*	*H*

Source: Corominas 1996; Rickenmann 1999; Legros 2002; Locat 2008; Guo et al. 2014; Qarinur 2015; Strand et al. 2017; Samodra et al. 2018; Zhou et al. 2019; Apriani, Credidi, and Khala 2022

The physical characteristics of landslides in Malaysia were studied. Subsequently, empirical correlations between these physical characteristics such as travel distance, runout, retrogression distance, slope height, slope angle, and landslide volume were established. Empirical procedures to determine runout distance were proposed, along with key findings and recommendations.

3.5.1 Data selection of landslide events and their parameters

The selection criteria for landslides in this study concern the ability to measure their extent and the availability of reliable geotechnical and geometric information. For this study, landslide data from 1993 to 2022 were collected based on satellite imagery interpretation, investigation reports, and descriptions from published papers and newspapers. Data collection encompassed mostly quantitative information of past landslide events in Malaysia (i.e. the runout distance, landslide volume etc.) allowing comprehensive analyses of the landslide parameters needed for developing the empirical models. The landslides in the dataset are those induced by rainfall.

Table 3-2 displays the distribution of landslides and their parameters, which were used to develop a statistical model for landslide runout distance. Among these parameters, data on slope height is the most widely available. However, obtaining data on other parameters, such as retrogression distance and landslide volume, proved to be challenging, as they are often absent from reports. This is similar to Indonesia, where parameter such as landslide volume *(V)* is frequently neglected in reports (Apriani et al. 2022). Despite this limitation, past studies have established empirical models using less than 20 cases (Edgers and Karlsrud 1983; Costa 1988; Qarinur 2015; Shan et al. 2022). Using IBM software SPSS, statistical analyses were employed to derive empirical equations for landslide runout distance, considering height of slope *(H)*, travel distance *(L)*, slope angle (θ), retrogression distance *(rL)*, runout *(Lu)*, and landslide volume (*V)*.

3.5.2 Relationship between landslide runout distance and landslide parameters

Given the multitude of factors influencing landslide movement, it is imperative that the predictive model for landslide travel distance take into account the various influential parameters. To accomplish this, regression analyses were employed, supported by the application of significance tests (i.e. F-tests and t-tests), to derive an optimized model for predicting landslide travel distance (Guo et al. 2014; Apriani et al. 2022; Shan et al. 2022). R-squared (R^2) values were used to determine the fitting performance between the variables in the model. R^2 denotes the coefficient of determination, indicating the degree of correlation between the dependent variable and its independent counterparts (Zhan et al. 2017; Yang et al. 2022). The computation of R^2 takes into account the variable count and serves as a means to assess the goodness of fit and accuracy across diverse regression models (Guo et al. 2014; Zhan et al. 2017; Shan et al. 2022; Yang et al. 2022) . An R^2 value of 0.6 or higher signifies a strong correlation and suggests that the constructed regression models are reliable (Zhou et al. 2019; Apriani et al. 2022, 2023). Moreover, the *p*-value served as a tool to examine statistical significance. Relationships with a *p*-value less than 0.05 will be deemed statistically significant (Zhou et al. 2019; Shan et al. 2022).

Table 3-2 The parameters of rainfall triggered landslides in Malaysia

No.	Name	slope angle,(θ), degrees	slope height *(H)*, m	landslide volume *(V)*, m^3	Retrogression distance *(rL)*, m	Runout, *(Lu)*, m	Travel distance *(L)* , m	Source
1	Highland tower 1993	20 °-30 °	48	40,000	-	-	120	(Qasim and Osman 2013; Sim et al. 2023c)
2	Bukit Antarabangsa 2008	45° - 50 °	65	101,500	120	210	330	(Huat et al. 2012; Qasim and Osman 2013)
3	Batang kali 2022	45 °	70	450,000	330	270	600	(New Straits Times 2022; Halim et al. 2023)
4	Taman Zooview, Ulu Kelang, 2006	-	60		-	-	100	(Ooi 2009)

5	Puncak Setiawangsa 2012	35°-66 °	42	-	-	-	71	(Najib 2016; Ismail and Yaacob 2018b)
6	Failure investigation of a fill slope in Putrajaya, Malaysia, 6th of January 2001	22° to 25 °	25	-	-	-	50	(Hussein and Mustapha 2004)
7	Cut slope in kedah	45 °	27	-	-	-	250	(Shong et al. 1982)
8	Filled Slope in Selangor	22-45 °	21	-	-	-	120	(Shong et al. 1982)
9	Kem Terendak, Melaka 2019	30 °	21	-	-	-	44	(Lias et al. 2022)
10	Bukit Nanas 7th May 2013	30°-45 °	30	-	50	100	150	(Osman et al. 2014)
11	laluan Seksyen 6, Jalan Sungai Ikan, Kampung Raja, Cameron Highland, Pahang , April 2019	-	38	-	-	-	108	(Khairul Anuar 2022)

12	Ruan Changkul, Simunjan on the 28th January 2002.	25°-40 °	76	20,000 to 22,000	130	92	222	(Hashim and Among 2003)
13	Slope Failure at Putrajaya 2007	45 °	50	-	23	25	58	(Ahmed et al. 2012; Alsubal et al. 2019)
14	Bukit Lanjan 2003	70 °	70	35,000	-	-	160	(Gue and Cheah 2008; Sapari, Nasiman and Tipol, Farah Hanan and Rahamat Noor, Nurul Farah and Mohamed Zaid 2011)
15	Taman Hillview 20 November 2002	20-30 °	60	25,000	110	90	200	(Komoo and Lim 2003)

Source: Shong et al. 1982; Hashim and Among 2003; Komoo and Lim 2003; Hussein and Mustapha 2004; Gue and Cheah 2008; Ooi 2009; Sapari, Nasiman and Tipol, Farah Hanan and Rahamat Noor, Nurul Farah and Mohamed Zaid 2011; Ahmed et al. 2012; Huat et al. 2012b; Qasim and Osman 2013; Osman et al. 2014; NAJIB 2016; Ismail and Yaacob 2018b; Alsubal et al. 2019; Khairul Anuar 2022; Lias et al. 2022; Sim et al. 2023; Halim et al. 2023

3.6 Verification through case study

QRA was applied to a specific case study with the aim of providing an understanding of the risks associated with rainfall-triggered landslides. These simulations functioned as an initial warning system, particularly in areas prone to severe landslides that can result in extensive devastation and potential loss of lives. To mitigate these risks to both lives and property, it becomes imperative to conduct thorough stability analyses and risk assessments of slopes within specific regions.

The probabilistic slope stability analysis was performed using a 2-D numerical software, PLAXIS LE allowing the determination of the most critical slip surface as well as the probability of land sliding of the case study area. First of all, the "Groundwater" module of PLAXIS LE was used to establish the pore pressures of the study area under extreme rainfall event. Precipitation was added to the model as a boundary condition so that one will be able to determine the changes in pore water pressure due to rainfall on the slope.

Subsequently, the "Slope Stability" module of PLAXIS LE was utilized. For probabilistic slope stability analyses, PLAXIS LE have three methods namely the Monte-Carlo, Latin hypercube and APEM method. The APEM method provides the most precise probability as well as the shortest computing time among the rest, and hence it was employed for the probabilistic slope stability analyses. With the critical slip circle and probability of land sliding established, one will need to determine the runout distance of impact of the landslide event. It should be noted that Limit equilibrium method (LEM) is not able to demonstrate the post-failure behaviour of a sliding mass due to the inability of LEM cannot capture strain and displacement. Runout distance for the case study was then estimated (using the developed empirical model) together with the number of houses or occupants affected by the landslide. The severity of the landslide was shown in the form of F-N curve and its position in the established risk criterion was determined. Comments were made regarding the risk level of the case study area and the applicability of the area for future developments etc.

3.6.1 Extreme rainfall analysis

Rainfall records spanning the past 48 years were acquired from the Department of Irrigation and Drainage. Employing the Gumbel extrapolation technique (Gofar and Lee 2008; Shrestha et al. 2021), the maximum rainfall anticipated within those specific days was computed for a return period of 10 years. The choice of a 10-year return period aligns with recommendations stipulated in the Geotechnical Manual for Slope in Hong Kong (Geotechnical Engineering Office 2011) and stands as a prevailing design standard for Malaysian slopes, as cited in various studies (Liew and Shong 2005; Gofar and Lee 2008).

3.6.2 Seepage analysis

In this study, an unsaturated/saturated transient seepage analysis was conducted using the Groundwater component within the PLAXIS LE computer program. The simulation spanned a 30-day period, simulating of extreme rainfall condition. The analysis commenced by defining the initial state as the position of the initial groundwater table, accompanied by a designated maximum negative pore water pressure head. This approach enabled a more realistic execution of the analysis.

Preceding the seepage analysis, the definition of material or soil properties and the establishment of boundary conditions were necessary prerequisites. The characterization of soil properties relied on volumetric water content (VWC) functions, soil water characteristic curves (SWCC), and Hydraulic Conductivity Functions (HCF), considering both unsaturated and saturated material models. Among the numerous available functions integrated into PLAXIS LE i.e. VWC data point function, Van Genuchten function Gardner Fit, and Fredlund-Xing function etc., this study employed the data point function for defining volumetric water content. A general SWCC specific to silty residual soil from Malaysia, as outlined by Lee et al. (2014), was implemented in the simulation. Figure 3-3 (a) & (b) illustrate the SWCC and hydraulic conductivity function utilized in the simulation, respectively. The impermeable underlying rock layer was replicated within the simulation by allocating an extremely low hydraulic conductivity value, specifically set at 1E−17 m/s.

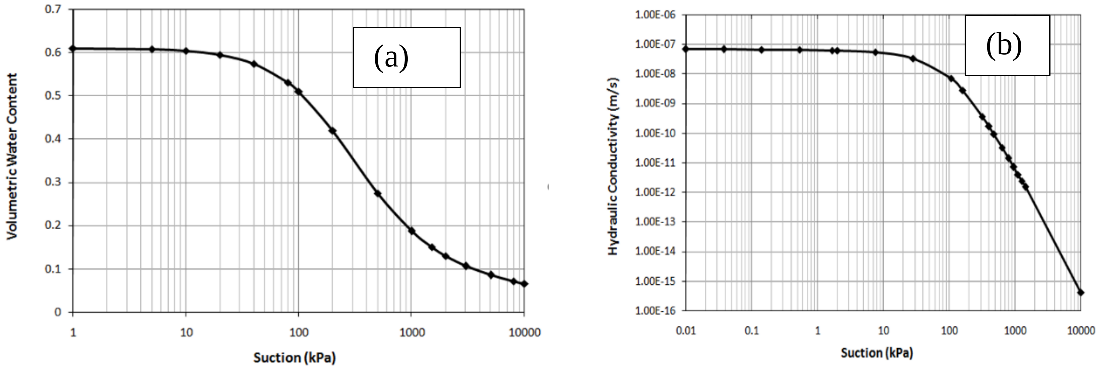


Figure 3-3 (a) Soil–water characteristic curve (SWCC), (b) hydraulic conductivity function

Figure 3-4 shows the slope model simulated in PLAXIS LE. The geometric configuration of the slope was subject to the following boundary conditions:

- Rainfall intensity was modeled as a flux boundary condition on the slope's surface.
- Below the groundwater table, total head boundary conditions were applied along the sides of the slope.
- Above the groundwater table, a nodal flux of Q = 0 m^3/s was enforced along the slope's sides, symbolizing a no-flow boundary condition.

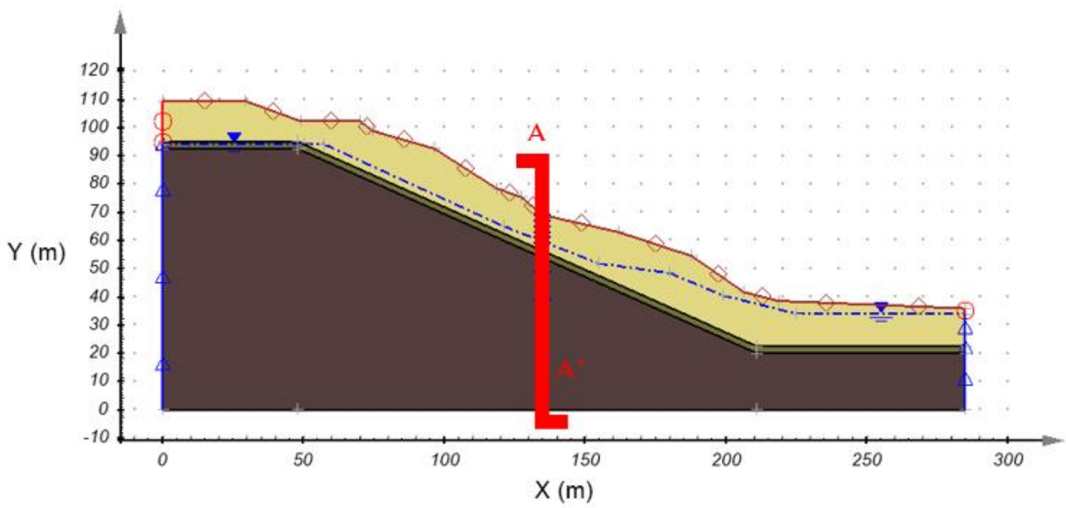


Figure 3-4 General profile of the slope at the case study area

3.6.3 Probabilistic slope stability analysis

The results derived from the seepage analysis, which portray the distribution of Pore Water Pressure (PWP), serve as input data within the Slope Stability module of the

PLAXIS LE computer program. The determination of unsaturated shear strength was conducted within the PLAXIS LE program, employing the Mohr–Coulomb failure model. Details regarding soil properties can be found in Table 3-3.

Table 3-3 Soil properties of the slope of study

Soil Layer	Soil Type	Depth (m)	Effective Cohesion, c' (kPa)	Effective Friction Angle, ϕ (°)	Soil Unit Weight γ'(kPa)
Layer 1	Silt	0–13.5	3	26	17.5
Layer 2	Sandy gravel	13.5–17	8	32	18
Layer 3	Granite	17 onwards	10	38	18.5

The Alternative Point Estimated Method (APEM), was employed for probabilistic analysis (Fredlund and Gitirana 2011; The Bentley Systems Team 2021; Gitirana et al. 2022) , as it reduces the necessary number of analyses when employing the Monte Carlo method. APEM significantly cuts down the computational time essential for statistical analysis (Petrovic et al. 2016; Gitirana et al. 2022). With 2N + 1 model runs, where N represents the quantity of model input variables, this method can compute probabilities efficiently. It particularly appeals in scenarios with numerous input variables exhibiting variance. The parameter Cohesion was assigned as a log-normal probability density function (Petrovic et al. 2016) while friction angle and unit weight are assigned to follow a normal distribution (Petrovic et al. 2016; Shrestha et al. 2021). The outcomes will be presented in terms of the probability of failure, *pf*. Moreover, APEM allows the depiction of results via a tornado diagram, indicating the relative impact of each input variable (Fredlund and Gitirana 2011). Consequently, it becomes feasible to ascertain both the overall probability of failure and the input variable exerting the most substantial influence on the factor of safety.

3.6.4 Risk estimation

The risk analysis approach was primarily built upon the framework outlined (Lee and Jones 2014) and was adjusted and broadened according to the specific scenarios being examined. Consequently, a definition for risk analysis was formulated as follows:

$$Risk = \mathrm{P}(Event)\ x\ \mathrm{P}(Hit|Event)\ \ x\ \mathrm{P}(Damage|Hit)\ x\ C \qquad (3\text{-}17)$$

Here, P*(Event)* represents the anticipated likelihood of a landslide event occurring annually, P(*Hit*|*Event*) signifies the yearly probability of an element being impacted given a landslide event, considering both spatial and temporal probabilities of affecting elements at risk, P(*Damage*|*Hit*) denotes the yearly probability of damage occurring given that an element is impacted, measured on a scale between 0 and 1, and C signifies the consequences stemming from the landslide event.

In the context of this study, 'Damage' was interpreted to denote the occurrence of one or more deaths among the residents, effectively encapsulating the combined notions of 'Damage' and 'Consequences.' As a result, the equation is transformed into:

$$Risk = \mathrm{P}(Event)\ x\ \mathrm{P}(Hit|Event)\ \ x\ \mathrm{P}(Death|Hit)\ x\ C \qquad (3\text{-}18)$$

3.6.4.1 P(*Event*)

According to Winter (2018), landslide hazard, referred to as P(*Event*), is defined as the yearly probability of occurrence derived from historical data. This explicitly adopts a uniformitarian perspective, assuming that the past serves as a reference for future events. There remains a debate on the suitability of relying solely on historical natural process patterns as a predictor of future occurrences. For example, uncertainties arise regarding the projected qualitative rise in landslide frequency due to climate change (Kristo et al. 2017; Dhanai et al. 2022). Furthermore, this method requires a complete landslide inventory which unfortunately is not ideal hence it will lead to complications in directly evaluating landslide hazard (Gue et al. 2009; Jaiswal et al. 2011; Sim et al. 2022a). On the other hand, P(*Event*) can also be determined through the computation of the probability of failure of a slope (Corominas and Moya 2008; Jaiswal et al. 2011). In the present study, P(*Event*) is denoted by the likelihood of an annual occurrence (or frequency) of a landslide covering a certain travel distance. This likelihood was determined through Probabilistic Slope Stability Analysis (section 3.6.3) and the developed empirical model (section 3.5**)**. The P(Event) would fall in between 0 (no chance of landslide event) to 1.

3.6.4.2 P(*Hit*|*Event*)

When a landslide occurs on the slopes adjacent to the residential area within the study zone, the individuals residing in the houses are considered the potential vulnerable elements. This risk factor comprises two contributing aspects, specifically denoted as P(*Wrong Place*) and P(*Wrong Time*) (Lee and Jones 2014). The duration for which an asset or an individual remains susceptible to the hazard—being in the 'wrong place' at the 'wrong time'—can vary significantly. For instance, there exists a disparity in exposure between a person walking underneath an overhanging rock and someone occupying a stationary beach hut (Lee and Jones 2014). The probability of being in the wrong place at the wrong time contributes to P(*Hit*|*Event*), which quantifies the probability of an occurrence described as a 'hit' connected with a landslide event.

In the context of individuals residing in the buildings, the determination of ‘wrong place, wrong time’ relied on the assessment of the amount of time these individuals spend inside the building throughout a year (Jaiswal et al. 2011). The frequency of occupancy by individuals is contingent upon the building's purpose. For individuals who occupy a residence almost constantly (such as elderly individuals or homemakers), probability for ‘wrong place, wrong time’ was considered as 1. However, for individuals in workplaces like offices, and students in schools, it was computed based on an average of 8 hours per day and 5 days per week, resulting in a value of 0.23. Regarding individuals present in the building during the night for 12 hours, the value will be taken as 0.5.

For the present study, the ‘wrong place, wrong time’ will be taken as the probability where the residents are in the house when the landslide occurs. For simplification purposes, residents within this study were assumed to be at their residences from 7 pm to 7 am on weekdays, totalling 12 hours. On weekends, it is presumed that they are absent from home for 8 hours, considering weekend activities like shopping, recreation, dining out, etc. Consequently, this assumption leads to a P(*Hit*|*Event*) of around 0.55. Accordingly, the probability where the house will be hit by the landslide when the resident is residing in the house was computed in accordance with the referencing documented workflows (Lee and Jones 2014; Winter 2018):

$$P(Individual\ House\ Hit) = P(Event)\ x\ P(Hit|Event) \quad (3\text{-}19)$$

3.6.4.3 P(*Death|Hit*)

P(*Death|Hit*), denoting human vulnerability (i.e., the likelihood of death upon the convergence of a house and landslide), was established as a quantitative representation of the probability of death resulting from an encounter with a landslide event affecting the house. It signifies the probability of fatality within the hazardous zones of the landslide (i.e., the 'Wrong Place' in either scenario).

Several determining factors influencing human vulnerability in the context of landslides were as follows (AGS 2000, 2007):

- Whether the landslide covers the individual(s).
- Whether the individual(s) are outdoors or sheltered inside a vehicle or building.
- Whether the building collapses upon impact by debris.
- The nature of collapse in case of building collapse

A vulnerability rating of 1 signifies certain death, while a rating below 0.5 suggests a significantly higher chance of survival. Jaiswal et al. (2011) recommends a value of 0.2 to 1.0 for people in reinforced concrete buildings where as the value of 1 (certain death) is recommended for residents residing in tin-shed buildings and 0.6 to 1.0 for residents of houses made of brick in mud without column structures (Jaiswal et al. 2011). The likelihood of survival increases comparatively when an individual is inside a reinforced conrete building due to its greater structural strength. Several other documented studies also recommend the value of 0.2 for people inside a building indundated by landslides (Dai et al. 2002; Wong et al. 2018). According to previous reports, there was a landslide event that struck the same area in 1999 that results in 0 death (Rahman 2014). In addition, there have been several other landslide that results in the destruction of bungalows with zero fatalities i.e. 2014 and 2022 Ampang landslide which is not far from the site of case study; 2016 Cameron Highlands landslide (Bloomberg 2014; Bernama 2016; Qarina 2022). Harahap & Hazirah (2012) proposes a vulnerability rate of 0.48 for the residents affected by landslides in the studied area; however, considering the preceding information, this latter figure appears notably high and somewhat conservative.The evidence provided above strongly indicates a notably reduced figure, and a value of 0.2 for P(*Death*|*Hit*) appears fitting within the context of the case study.

3.6.4.4 Societal Risk

The societal risk posed by landslide along the case study area was addressed using the F-N diagram. The calculation for the societal risk associated with fatalities of inhabitants of the case study area was derived using the following equation (Lee and Jones 2014):

$$\textit{Societal Risk} = \textit{Individual Risk x Exposed Population} \qquad (3\text{-}20)$$

The specific group exposed to the landslide hazards were all the inhabitants of the houses in the study area, and their population size was determined based on reasonable assumption in accordance to the past reports (Huat et al. 2012; Azmi et al. 2013; Lee et al. 2014). In this study, house occupancies ranging from 1 to 8 per home has been taken as an estimate of for the at the site. Assuming equal exposure to landslide risks within the study area, the research categorized eight consequence classes based on house occupancy. This classification involved grouping houses into these classes, and subsequently, determining the quantity of houses within each class. The calculation of the probable fatalities (N) for each consequence class involved multiplying the house occupancy by the probability of fatality given a hit (P(*Death*|*Hit*)). As mentioned earlier in section 3.6.4.3, the value of 0.2 was used for P(*Death*|*Hit*). Various methods exist for generating data for the F-N diagram, outlined by (Wong et al. 2006, 2018), and (Lee and Jones 2014), none holding a superior claim to the other. In this study, Wong et al.(1992) and Wong et al. (2006)'s approach was used as it has been proven to yield data better suited for plotting on the F-N diagram, resulting in a clearer representation (Winter 2018; Winter and Wong 2020). The societal risk of landslide of the case study area was benchmarked against the improved Malaysian risk criterion proposed in the present study to demonstrate its applicability.

4 Societal Risk of landslides in Malaysia (1961-2022)

4.1 Introduction

Societal risk is defined as the risk of multiple fatalities or injuries in society as a whole: one where society would have to carry the burden of a landslide causing a number of deaths, injuries, financial, environmental and other losses(AGS 2007). In Quantitative Risk Assessment (QRA), societal risk can be measured in terms of a cumulative probability (*F*) per year that *N* or more lives will be lost in accordance to fatal event scenarios (Cascini et al. 2008). The estimation of the societal risk could be determined by correlating, in a log-log scale, the annual frequency *F* of landslides causing *N* or more fatalities versus the number *N* of fatalities provided that events of past fatal landslide records are available (Strouth and McDougall 2021). Such curve reveals the rate of fatal landslides, the risk that the society is currently living with (Vrijling and van Gelder 1997; Saw et al. 2009; Strouth and McDougall 2021), and the overall safety level of the particular region.

In this chapter, landslide inventories and number of deaths caused by each landslide event in Malaysia between 1961 and 2022 were compiled. Based on the data, the trends of landslide occurrences and fatalities were analysed. Subsequently, the F-N curve of landslide hazard in Malaysia was produced, and it was compared with those of other nations. Understanding the societal risk level is useful for the public authorities to roll out appropriate QRA measures for the country.

4.2 Available data of fatal landslides (1961-2022)

This section derives and presents empirical FN-curves for landslides of Malaysia. The data for landslides cover the 62 years from 1961 to 2022. The year 1961 is the starting year that landslide information was recorded after the indepence of Malaya in 1957. The primary source of data is from the National Slope Master Plan as seen in (Izumi et al. 2019). Data were also gathered from other sources such as newspapers and reports. Table 4-1 gives the distributions of numbers of fatalities in all fatal landslides for the 62 years period.

Major landslides in Malaysia are mainly related to urban development on hillsides and road construction in hilly terrain. Landslides can be contributed by natural, geological as well as anthropogenic factors i.e. land use, poor design, and unscrupulous construction practices.

Nevertheless, landslides in Malaysia are regularly triggered by extreme or prolonged precipitation. It is of no surpise that with the nation's ongoing development, together with the augmentation of the volume of rainfall induced by global warming, the number of landslides and its consequences will intensify.

Table 4-1 Distributions of numbers of fatalities of landslides in Malaysia: 1961-2022

Number of fatalities	No of events (1961-2022)	Frequency (f)	Cumulative frequency (F)
302	1	0.0161	0.0161
48	1	0.0161	0.0323
42	1	0.0161	0.0484
38	1	0.0161	0.0645
31	1	0.0161	0.0806
24	1	0.0161	0.0968
21	1	0.0161	0.1129
18	1	0.0161	0.1290
17	1	0.0161	0.1452
16	3	0.0484	0.1935
15	1	0.0161	0.2097
11	1	0.0161	0.2258
10	1	0.0161	0.2419
8	1	0.0161	0.2581
7	3	0.0484	0.3065
5	2	0.0323	0.3387
4	7	0.1129	0.4516
3	8	0.1290	0.5806
2	16	0.2581	0.8387
1	30	0.4839	1.3226
Total	**82**		

Table 4-2 gives a summary of the main results for landslide disasters of Malaysia for the 62 year periods. Table 4-3 gives the proportions of landslides and fatalities occurring in each of four broad fatality ranges. Table 4-2 shows that over the long term there were an average of 1 fatal landslide and an average of 10 fatalities per year. The details of the landslides is shown in Table 4-4. It can be seen that there have been 14 landslides with 10 or more fatalities. The worst landslide occur on 26 December 1996 where a debris flow caused by Tropical Storm Gregg wiped out a few villages in Keningau, Sabah that claims 302 lives. Table 4-3 shows the distribution of the largest number of fatalities occurred in landslides in the 2-9 fatality range and 50+ death range. It should be noted that over the recent years there has been no landslide events that results in more than 30 deaths per event. It should also worth noting that throughout the years there was only one event that cause more than 50 deaths which was the landslide caused by Tropical Storm Gregg as mentioned earlier. The event with the second highest fatalities was the 1993 collapse of highland tower that resulted in 48 deaths. This shows that the occurrences of very high fatality events were scarce in Malaysia.

Table 4-2 Summary of Malaysian Fatal Landslides: 1961-2022

	Landslide 1961-2022
Years of data	62
Fatal incidents	82
Fatalities	778
Fatal incidents per year	1.32
Fatalities per year	12.55
Fatalities per fatal incident	9.49
Accidents with =>10 fatalities	15
Fatalities in worst accident	302

Table 4-3 Proportions of landslide and fatalities by landslide size band

	Landslide 1961-2022
Proportion of landslides with fatalities in given range	
1 fatality	37%
2-9 fatalities	45%
10-49 fatalities	17%
=>50 fatalities	1%
Proportion of fatalities in accidents of given size	
1 fatality	4%
2-9 fatalities	16%
10-49 fatalities	42%
=>50 fatalities	39%

Table 4-4 Landslides in Malaysia with 10 or more fatalities

Deaths	year	location	Date
16	1961	Ringlet, Cameron Highlands	11-May-61
42	1973	Kampung Kachang Puteh, Gunung Cheroh, Ipoh	18-Oct-73
24	1981	Kampung Kandan, Puchong, Selangor	4-Mar-81
48	1993	Highland towers, ulu klang	11-Dec-93
21	1995	KM 39, Genting Sempah, KL - Karak Highway	30-Jun-95
15	1996	KM 1.5, KL-Karak Highway, Selangor	15-Jul-96
38	1996	Perkampungan Orang Asli Pos Dipang, Perak	29-Aug-96
302	1996	Taufan Gregg, Keningau, Sabah	26-Dec-96
17	1999	Jalan Leila, Kg Gelam, Sandakan, Sabah	8-Feb-99
16	2002	Kg. Ruan Changkul, Simunjan, Sarawak	28-Jan-02
16	2011	Rumah Anak Yatim At-Taqwa Hulu Langat, Selangor	21-May-11
18	2015	Gunung Kinabalu, Sabah	5-Jun-15
11	2017	Housing Project at Lengkok Lembah Permai, Tanjung Bunga (857am)	21-Oct-17
10	2017	Bukit Bendera area	5-Oct-17
31	2022	Batang Kali, Selangor, Malaysia	16-Dec-22

Source: (Izumi et al. 2019; Bernama 2021; Bunyan 2021; Razali 2022)

4.2.2 Trend of fatalities caused by landslides

The first event for which the number of related fatalities was quantified corresponds to a rainfall induced landslide at Ringlet, Cameron Highlands which occurred on 11 May 1961 (3 years after gaining independence in 1957). As a result, the cumulative curve of fatalities caused by landslides Malaysia was generated starting from 1961.

Looking at the fatalities caused by all the events over the years (Figure 4-1) it is worth mentioning that the trend of the cumulative deaths curve takes on a ‘stepped’ shape, with pertinent differences in the ordinate values, in correspondence to the most intensive events in terms of recorded fatalities. Furthermore, the gradient of the curve is almost flat for the period spanning from 1961 to the beginning of the 1990s.

The steeper slope starting from the 1990s was contributed by active developments on hilly terrains as low lying terrains have become gradually scarce (Jamaludin and Hussein 2006). It is worth noting that the slope gradient rise greatly in 1993 onwards. This was brought about by the Highland Towers Tragedy on 11 December 1993 that claimed 48 lives. Notably, more fatal landslide events occurred since then that results in a steeper slope. The most catastrophic event documented for a single landslide, was on 26 December 1996 where a debris flow caused by Tropical Storm Gregg wiped out a few villages in Keningau, Sabah that results in 302 lives lost (highest fatality recorded event). This cause the cumulative death curve to rise sharply in the ordinate value. Since then, the average slope of the curve increases, thanks to the availability of data regarding events that resulted in casualties.

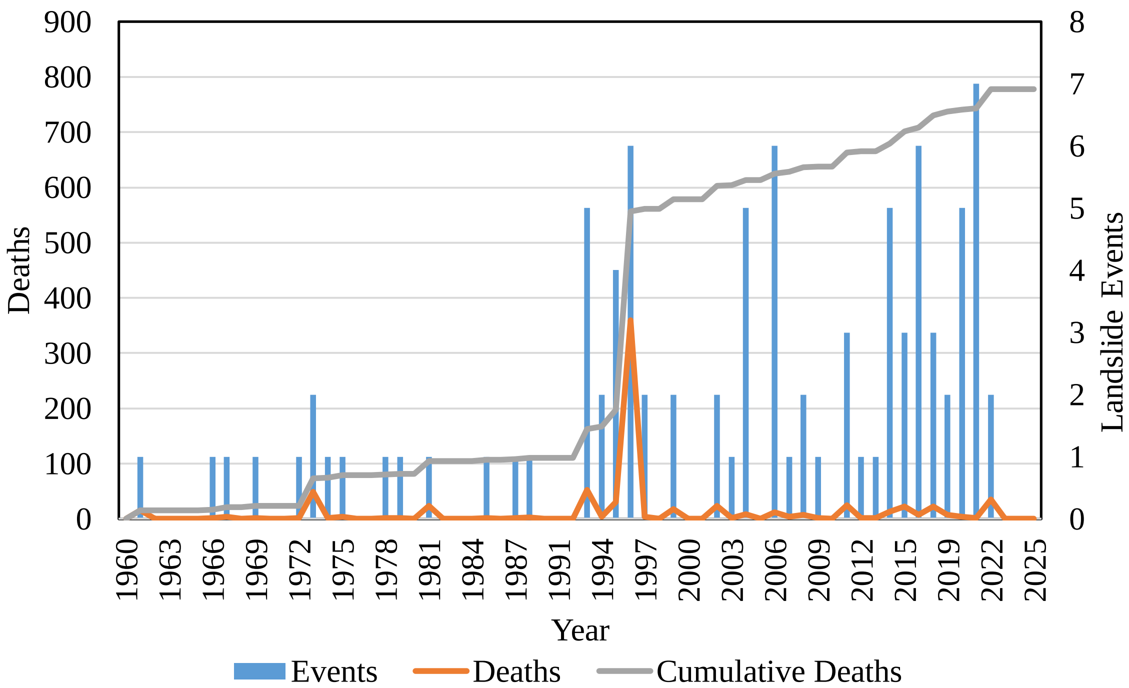


Figure 4-1 Fatal landslides and death trends of Malaysia.

4.3 F-N curve for Malaysia

Landslide inventory of Malaysia spanning years 1961 to 2022 was obtained from (Izumi et al. 2019). The risk curve for Malaysia was obtained by using the method described in (Westen et al. 2011). Given the data in Table 4-1, it was straightforward to calculate the FN-curve for Malaysian lanslides for the 62-year period. The total number of events contributing to a specific number of death (N) were first be divided by the period on which they are based to convert them to frequencies which are the (lower case) f(N)'s. The (upper case) F(N)'s are subsequently computed from f(N)'s.

Figure 4-2 plots the Malaysian fatal landslide cumulative annual frequency (F) against the number (N) of fatalities associated with landslides in 1961-2022 (log–log scale). This 'FN curve' has been used to analyse the occurrence of historical landslides (Guzzetti 2000; Cascini et al. 2008; Aristizábal and Sánchez 2020), as well as, in some cases, to express societal risk and tolerability levels (Lacasse 2016; Ahmad et al. 2017; Roy and Kshirsagar 2020; Sui et al. 2020). Here, it was employed to assess the frequency of fatal landslides and their consequences in Malaysia and to compare the data with that for several other countries that have been majorly impacted.

The FN curve for Malaysia for 1961-2022 can be divided into three segments. The first segment corresponds to low casualty and high frequency landslides with between 1 and 1.5 casualties; the annual frequency is slightly above one—that is, there is at least one landslide resulting in 1 to 1.5 deaths every year in Malaysia. The second segment corresponds to landslides with between 10 and 100 casualties; the annual frequency varies between 0.2 and 0.03. The third segment corresponds to very high casualty and low frequency events with above 100 casualties; the annual frequency ranges from 0.03 to 0.01.

It can be seen that the FN curve of Malaysia crosses the curve of Hong Kong, Nilgiri Hills, India and Alps at least once. Among those that it intersects with, Malaysia's death is more frequent but less severe; deaths in the Alps is less frequent but more severe It is clear from Figure 4-3 that the frequency for 1 death for Malaysia is very similar to Hong Kong's (slightly above F=1) and that they intersect each other at around (N=42, F=0.05). The overall F-N curve of Malaysia shows similarity of slope with those of Italy, Colombia and Hong Kong. Colombia, being a tropical country with annual rainfall exceeding 2500mm per year have similar trend too as Malaysia albeit the frequencies of deaths much higher than one magnitude. This could also be due to the GNI and VSL of Colombia which is very low (see Table 4-5). Although the population density of Hong Kong is higher than Malaysia's (2096 and 99 respectively), the landslide risk of Malaysia is slightly higher than Hong Kong's. This could be due to the VSL and GNI of Hong Kong which is much higher than Malaysia's. As stated by Winter and Bromhead (2012), countries with high economic power will be willing and able to spend much more on preventive measures against landslides which will result in lower casualties as the years passed.

Malaysia's terrain generally consists of coastal plains with hills and mountains in the interior (Library of Congress 2006). It is rather similar to Hong Kong's which is also hilly and mountaneous. Owing to rapid development in Malaysia since the 1980s, appropriate low-lying areas for development have become gradually scarce (Jamaludin and Hussein 2006). Consequently, development on highlands or hilly terrain has increased, especially in areas with close proximity to densely populated cities which has increased the risk of landslides. The landslide experts that we interviewed stated that Malaysia especially the Penang island region is broadly similar to Hong Kong in the 1980s to 1990s. As seen in Figure 4-1, the landslide events of Malaysia have been increasing after the 1980s. The annual landslide deaths of Malaysia are generally not very high (less than 60) except for the year where the landslide deaths are 360 (mostly from the anomaly of Tropical Storm Greg that results in landslides and mud-flows in Keningau, Sabah). The notorious fall of the Highland tower in year 1993 has resulted in 48 deaths couple with deaths from other landslide disasters bringing the total to 51 for that year. Subsequently, there have been other few major debris flow events within this area i.e. the May 1999 landslide in Bukit Antarabangsa, the Taman Hillview landslide (November 2002) that resulted in 8 deaths in the collapsed bungalow (Gue and Liong 2007). Almost all the landslides of Malaysia that occurred in the hilly areas are a result of slope cutting involving construction activities. Consequently a combination of inferior design and construction errors, geological features or inadequate maintenance also play a significant role to the regular landslide events of the country (Majid 2020). Italy's terrain is mostly rugged and mountainous; some plains, coastal lowlands which could explain the F-N curve standing higher than Malaysia and Hong Kong. The landslides of Hong Kong, Malaysia, Colombia and Italy are frequently triggered by extreme precipitation (Giannecchini 2006; Peruccacci et al. 2017; Aristizábal and Sánchez 2020; Majid 2020). As seen in Table 4-5, the mean annual precipitation for the four nations are quite similar and that Froude and Petley (2018) has proven that rainfall is the biggest triggering factors of landslides worldwide. According to Aristizábal and Sánchez (2020), the Andean mountaneous region is the most populated region of Colombia with population density of 110/m^2 and annual rainfall of up to 11,000mm. It is no surprise that the F-N curve of Colombia stands at the top due to these facts . Thus it is a sound observation that Malaysia's F-N curve stood below Italy and Colombia due to the terrain of Malaysia which is less hilly than Italy and Colombia.

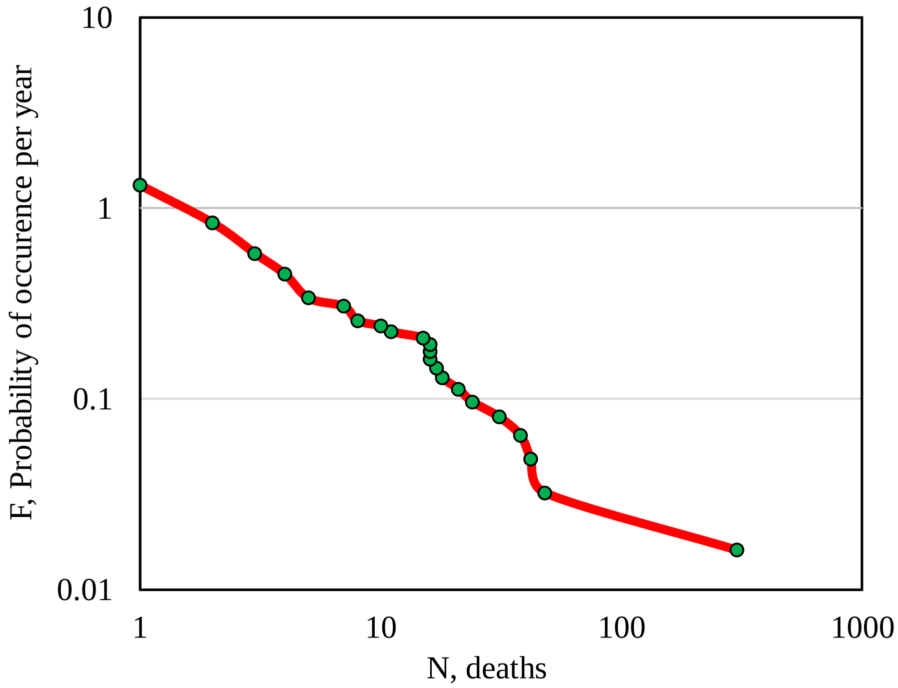


Figure 4-2 F-N curve for Malaysia

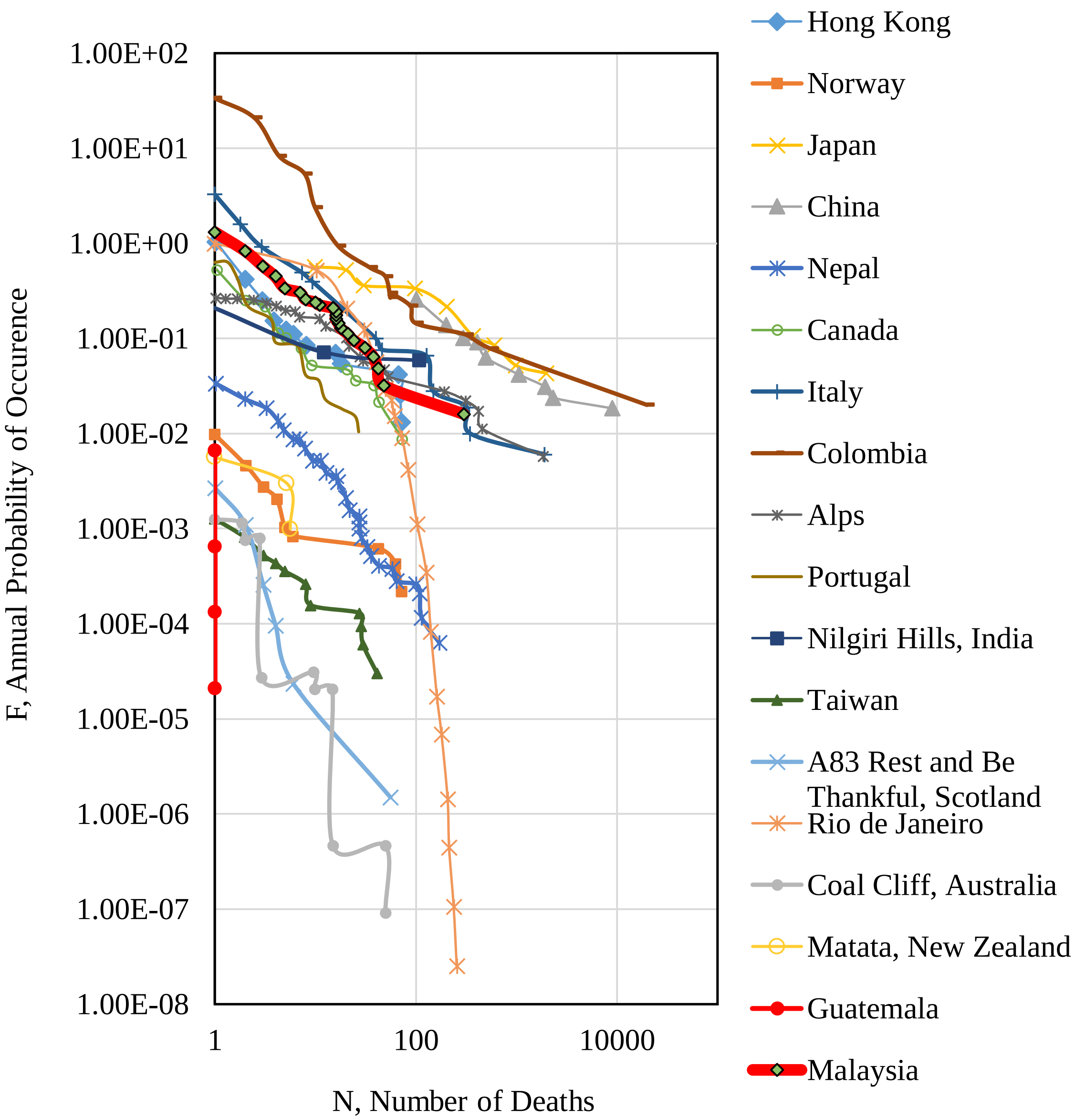


Figure 4-3 Comparison of F-N curve for Malaysia with other countries (Guzzetti 2000; Aristizábal and Sánchez 2020; Sim et al. 2022b)

Table 4-5 Population density, average annual rainfall, F-N curve slope, GNI and VSl of Malaysia and other nations

Locations	Population density/km^2	Average Annual rainfall/mm per year	Slope of F-N curve	Gross National Income (USD)	Value of Statistical Life (VSL) (USD millions)
Colombia	45-110	3240-13,000	-0.834	3,956-12,235	1.04-1.21
Italy	203	800->3000	-0.86	>12,235	2.18-2.79
Malaysia	99	2875-3085	-0.824	3,956-12,235	1.75-2.18
Hong Kong	7096	1400-3000	-0.79	>12,235	3.43-11.6
Canada	4	508-2032	-0.92	>12,235	3.43-11.6
Nilgiri Hills, India	421.97	1665	-0.275	1,006-3,995	0.38-0.47
Portugal	112	854	-2.35	>12,235	1.75-2.18
Alps	215	564	-0.538	>12,235	2.18-2.79

Source: (Giannecchini 2006; Daniell et al. 2015; World Bank 2020, 2021; Peruccacci et al. 2017; Sujatha and Suribabu 2017; World Bank 2017, 2018; Aristizábal and Sánchez 2020; Hong Kong Observatory 2020; Sim et al. 2022b; Weather-Atlas 2022)

4.4 Concluding remarks

This chapter investigates the trends, distributions, and societal risk level of landslides in Malaysia between 1961 and 2022. Following conclusions can be drawn from the present study:

i. Between 1961 and 2022, a total of 82 fatal landslide events were recorded in Malaysia, resulting in 778 losses of lives, i.e. averaging 12.5 lives annually.

ii. Landslides with high number of fatalities were frequent in the early-mid of the 1990s. With proper measures and risk management plan implemented by the government and authorities, the frequency of catastrophic landslide events (those that caused more than 10 casualties) were successfully reduced since late of 1990s, despite the frequency of small-scaled fatal landslides still stood high.

iii. From the landslide F-N curve, Malaysia shares similar risk characteristics with Hong Kong, Italy, and Colombia. These countries are characterized by mountainous terrains coupled with intense rainfall throughout the year.

iv. The occurrence of landslide in the mountainous tropical countries like Malaysia is inevitable. However, with a proper landslide risk management plan in place and adequate investment, the societal risk of landslide in the country can be minimized as demonstrated by those developed countries.

It should be noted that the F-N curve simply illustrates the frequency and consequences of fatal landslide occurrences. However, to ascertain whether these occurrences are deemed acceptable by the general populace or specific communities, they must be compared against predefined risk criteria. These criteria, represented as curves on the F-N chart, delineate thresholds for acceptable, tolerable, and unacceptable risks. Establishing these risk thresholds, however, is a complex endeavour. In order to identify a suitable social research approach, the subsequent chapter, which incorporates results gleaned from interviews with landslide experts across different sectors and survey questionnaires administered to various communities in Malaysia, was adopted to develop the landslide risk criteria for the country.

5 Perception on landslide risk in Malaysia: A comparison between communities and experts' surveys)

5.1 Introduction

A critical component of landslide risk assessment is the establishment of risk tolerance criteria (Fell 1994; Porter and Morgenstern 2013; Strouth and McDougall 2022; Tian and Lan 2023). The results in the previous Chapter 4 provided a quantitative estimate of the annual losses in terms of deaths and the overall societal risk of landslides in Malaysia, expressed using an F-N curve. These results hold significant societal value and will serve as valuable input for developing risk criteria for the country. Without a risk criterion, any estimated risk cannot be adequately evaluated, as there will be no proper risk tolerance criterion available to determine whether the risks are sufficiently low to be considered tolerable or not. Questionnaire surveys on people's attitudes regarding disaster risk acceptance have become dominant in aiding authorities as a reference for decision-making on risk guidelines for sustainable development in landslide-prone regions (Scolobig et al. 2015). Questionnaire survey studies have been widely used to investigate landslide risk perception among populations in various parts of the world, including Hong Kong and Australia (Finlay and Fell 1997), China (Liu et al. 2019; Gao et al. 2020), Mexico (Hernández-Moreno and Alcántara-Ayala 2017), Italy(Salvati et al. 2014; Calvello et al. 2016; Antronico et al. 2020), Austria (Damm et al. 2013), and Germany (Blöchl and Braun 2005). Additionally, numerous landslide acceptability criteria have been developed in different parts of the world, such as Canada (Strouth and McDougall 2020), China (Song et al. 2007), Sri Lanka (De Silva et al. 2017), Hong Kong (Geothechnical Engineering Office 1999) etc. However, the study on public perception in Malaysia is still very limited, and a proper landslide risk criterion has yet been established for the country.

Landslides are recurring and significant phenomena in Malaysia, resulting in property damage and threatening the lives of the population (Chan 1996; Rahman and Mapjabil 2017; Lim et al. 2019). In recent years, increased awareness of landslide issues has led to substantial changes in the control of hillside development. The Malaysian government and highway authorities have been emphasizing the requirements for local planning authorities to consider landslides at all stages of the landslide hazard mapping process (Pradhan and Lee 2010; Althuwaynee and Pradhan 2017; Sharir et al. 2017). Despite these efforts, not much is known about the perception of the Malaysian population regarding the risk posed by landslides. A proper perception of the risk by the country's population is crucial for the successful execution of risk management or adaptation strategies (Salvati et al. 2014). These perceptions influence decisions regarding risk acceptability and serve as the main influence on attitudes prior to, during, and after a disaster (Rohrmann 2008). As quoted in Renn (Ortwin 1990), "*Risk perception studies offer valuable insights for designing and implementing risk communication programs*."

This chapter details the study of the landslide risk perception among Malaysians. The similarities and differences of the responses from the public towards landslide disasters in Malaysia were evaluated. In addition, landslide experts from various sectors including government, non-governmental organizations, practitioners, professional institutions, and academics were interviewed. The expert interviews were intended to enhance the collection of additional background information, as well as the verification of the collective interests.

A brief overview of the methodologies employed in this study has been provided including the development of the questionnaires in Chapter 3.3. The analyses of the results obtained from the questionnaires and experts' interviews were provided in Sect. 5.2 to 5.7. Subsequently, statistical tests were applied to determine the significance of demographic influences on landslide risk perception (Sect 5.8). The current scenario of landslide risk management in Malaysia was discussed in Sect. 5.9, and this provide the basis on how an interim landslide risk criterion for Malaysia (Sect 5.10) is established based on the questionnaire and interview results collected from the present study. Lastly, the study and lessons learned were concluded in Sect. 5.11 and 5.12. The shortcomings of the currently proposed risk criterion for Malaysia were also discussed. Modifications that are deemed more suitable for Malaysia are proposed, taking into consideration the findings from questionnaire surveys and expert interviews. The combination of questionnaire surveys and expert interviews allows for cross-validation of data and findings. The survey responses were compared and corroborated with the expert opinions and insights obtained through interviews. This validation process enhances the credibility and robustness of the established risk criteria. The suitability of existing criteria proposed previously, as well as the effectiveness of the newly proposed criteria were discussed. It is believed that the findings of this study will provide critical insights for landslide risk mitigation and reduction in Malaysia. Furthermore, this endeavour will result in more logical and uniform decision-making processes, ultimately leading to the preservation of lives and resources in regions prone to landslides worldwide.

5.2 Analysis of respondents' socio-demographics

Table 5-1 shows that the sample of 392 respondents comprising an almost equal number of male (50.26%) and female (49.74 %), with an age range of 18 to above 60 years. More than 80% of the respondents live in the city. Around 60.97% of the respondents are single. Most of the respondents live in their own landed unit in the city. More than 80% of the sample has at least a college diploma, and the sample has the following distribution in terms of employment status: at professionals (64.8 %), non-professional (10.46 %), self-employed (10.71 %), student (9.44 %) and unemployed (4.59 %). 21.68% of the respondents lived near to a slope and 7.91% have experience a landslide near their residence. This distribution is not surprising as no more than 35% of regions in Malaysia are hilly (Gue and Wong 2009).

Table 5-1 Socio-demographic characteristics of the respondents

Factor	Group	Number of persons	Proportion/%
Age	18–30 years old	234	59.7
	31–45 years old	72	18.4
	46–60 years old	42	10.7
	61 years old and above	44	11.2
Gender	Male	197	50.3
	Female	195	49.7
Highest level of education	Secondary school	27	6.9
	College/ University – diploma / undergraduate	225	57.4
	University - Postgraduate	140	35.7

Occupation	Student	37	9.4
	Non-professional	41	10.5
	Professional	254	64.8
	Self-employed	42	10.7
	Unemployed	18	4.6
Income	< RM 1500 /month	54	13.8
	RM 1501–3000 /month	81	20.7
	RM 3001–5000 /month	111	28.3
	RM 5001–10,000 /month	96	24.5
	> RM 10,000 /month	50	12.8
Marital Status	Single	239	61.0
	Married with kids	114	29.1
	Married without kids	39	9.9
Geographical location of residence	City	351	89.5
	Rural	41	10.5
Type of residence	Low rise apartment/flat/condominium (< 5 storeys)	32	8.2
	High rise apartment/flat/condominium (> 5 storeys)	63	16.1
	Landed house	297	75.8
ownership of residence	Own unit	308	78.6
	Rented unit	84	21.4
whether their residence is near to slope or far from slope	Near to slope (within 1 km radius)	85	21.7
	Far from slope (beyond 1 km radius)	307	78.3
whether there has	Yes	31	7.9

been a landslide occurrence near their residence or within 1 km radius in their area	No	361	92.1

5.3 Sources of landslide information

From Figure 5-1, it is clear that the vast majority of respondents obtained sources on landsliding from the media (85.46%), followed by official and published reports from geotechnical authorities and personal experience. 6.38% of the total respondents are the least informed, as they selected the option “I don’t know anything about landslides”. It is not surprising that Malaysians obtain information of landslides through media than geotechnical reports as the majority of the population would not have an access to landslide reports or technical papers. The respondents who acquired information from these reports were mostly professionals. General publics will just likely obtain information from news and media.

It was evident from the interview conducted with the landslide expert from the government sector that the Public Works Department (JKR) utilized various media channels to disseminate awareness about landslides, including social media and mass media. For instance, Malaysian television channels TVI and TV3 provided comprehensive and timely coverage of the 'Bukit Antarabangsa' landslide tragedy when it occurred in 2008. Additionally, the local newspaper consistently highlighted the government's initiatives in addressing landslide issues (Jamilah and Lateh 2016). From this survey result, it can be concluded that their effort paid off well in disseminating landslide awareness to the public through the media as shown in Figure 5-1. It was also mentioned by the expert that geotechnical reports are rarely published partly due to private and confidential reasons which also in line with the results of the survey.

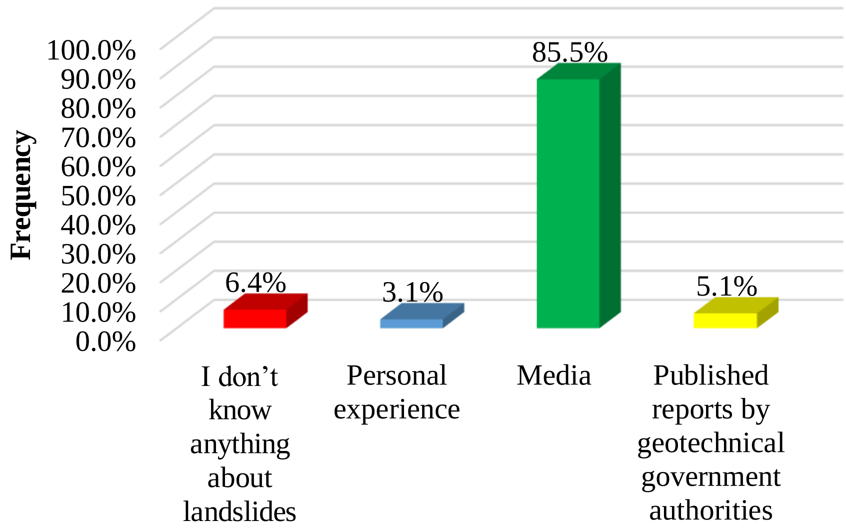


Figure 5-1 Response to Question 12 (Where do you normally obtain information regarding landslides?)

5.4 Ranking of landslide relative to other hazards

One method of examining the perception of landslide hazards involves comparing it to the perception of other hazards (Slovic 1987) and (Fell 1994). Comparison of landslides hazards with other hazards have been done in various studies i.e. (Finlay and Fell 1997) for Hong Kong and Australia, (LaPorte 2018) in Guatamela and (Salvati et al. 2014) in Italy. These perceptions will aid in establishing a proper landslide risk criterion for Malaysia.

5.4.1 Comparison with travel, health and occupational hazards

Q13 of the questionnaire survey was formulated to rank the perception of the risks posed by landslides against the perception of the risks posed by travel hazard (road accidents), health hazard (smoking, pollution), and two human induced (occupational and industrial) risks. Results were summarized in Figure 5-2. From the results it can be seen that people in Malaysia felt more exposed to technological than to natural risks, and specifically to health hazard (52%, including 22.96% of participants that felt “most concerned” and 29.08% that felt “somewhat concerned”), followed by travel hazard (51.3%, 25.51% “most concerned” and 25.77% “somewhat concerned”). 25% to 30% of Malaysians felt indifferent towards both travel and health hazard.

Compared to other hazards landslide are ranked 4th (being at 45.19% after industrial hazard which is 50.3%) which is not surprising as the annual deaths from landslides in Malaysia are always kept far below 4 digits as seen in the data published in Figure 4-1. It can be seen from Figure 4-1 that there is a significant increase in the number of deaths caused by landslides between 1995 and 1998. This major increase was caused by a landslide triggered by tropical storm Gregg on Dec 26, 1996 that claim 302 lives (Rahman 2014). Several villages in Keningau, Sabah were destroyed and it remains as the deadliest geological disaster throughout the history of Malaysia (Rahman 2014; Rosli et al. 2021). In addition, there were also several fatal landslides that occurred during that period i.e. the 1995 Genting Sempah landslide at Karak Highway, Selangor that killed 21 and the 1996 landslide at the Pos Dipang Indigenous Village, Perak that claimed 38 lives (Izumi et al. 2019).

Travel hazard is the biggest concern among Malaysians which is no surprise as the rate of car and motorcycle accidents are very high in Malaysia. It was reported that there were a total of 265,175 road accidents in Malaysia in the year 2001 that claimed 5230 lives, serious injuries of 6942 and moderate injuries of 30,684 (Kareem 2003). Studies have shown that fatal road accidents in Malaysia are still rising every year (Azhari et al. 2022). Another report by the Ministry of Transport of Malaysia states that an average of 18 deaths occur daily due to road accidents in Malaysia (Ministry of Transport Malaysia 2018).

In general, the interviewed experts stated that it is understandable that landslides are not of significant concern among the public respondents. They explained that the impacts of landslides are very localized, and there are not many people who live in hillside zones. Hillside regions in Malaysia comprise not more than 35% of total land area Gue et al. (2009). Furthermore, hillside developments in Malaysia are catered more towards prestigious luxury homes for the elites (Farisham 2007; Ahmad et al. 2014). Experts also stated that health hazards such as Covid-19 pandemic are reported worldwide, and travel accidents occur daily. It was also further stated that there were numerous occurrences of small-medium scaled landslides, but those landslides did not cause any loss of life and properties. For examples, the documented study by (Izumi et al. 2019) showed that there was only 1 fatal event out of 4 major landslide occurrences in 2019, 2 out of 5 major landslide occurrences in 2020, and 1 out of 7 major landslides events in 2021. Those landslides that were reported in the media by the government were those that involved loss of lives and those that covered a very large residential area.

5.4.2 Comparison with other natural hazards

Among natural hazards (Figure 5-3), the participants felt most concerned to flood (65.8%, 33.67% “most concerned” and 32.14% “somewhat concerned”), followed by landslides (50.5%, 23.47 “most concerned” and 27.04% “somewhat concerned”), earthquake (48.3%, 30.08% “most concerned” and 18.21% “somewhat concerned”), Tsunami (46.9%, 31.63% “most concerned” and 15.31% “somewhat concerned”). Again, similar results were observed in (Salvati et al. 2014; Bustillos Ardaya et al. 2017) where overall ranking of flooding being a higher concern for Italians and brazillians followed by landslide hazards. However, Italians overall felt most exposed to earthquake than the former two natural hazards which is a contrast to Malaysia’s response. Earthquake and Tsunamis are very rare in Malaysia, which explains the reversal of the positions of the natural hazards. Interestingly, Malaysians showed the lowest level of concern for the haze hazard (38%, 17.35% “most concerned” and 20.66% “somewhat concerned”) despite it occurring almost every year. However, haze is not lethal as compared to other hazards like landslides, and hence it is understandable that it is ranked the lowest.

As mentioned by the expert from academic sector, tsunamis and earthquakes were extremely rare in Malaysia as they occur more in Japan and Indonesia (Marfai et al. 2008; Parwanto and Oyama 2014; Binti Harith and Adnan 2017; Nazaruddin and Duerrast 2021). The only natural hazards that were taken seriously by the public are floods as the impact covers a very large area, they occur frequently (almost annually) and that the number of people affected by floods is far greater than those affected by landslides, as mentioned by the expert from academic sector. The result of the survey was noted to be absolutely spot-on by the landslide expert from landslide NGO as the “Unit Pengurusan Bencana Negeri” (UPBN), disaster management unit have put in a great effort to compile all disaster information and disseminate it to governmental agencies. From their statistics it is clear that storm surges and floods occurred most often in Malaysia followed by landslides which is similar to Brazil (Bustillos Ardaya et al. 2017). Therefore, these observations were reasonably consistent with the publics' perception.

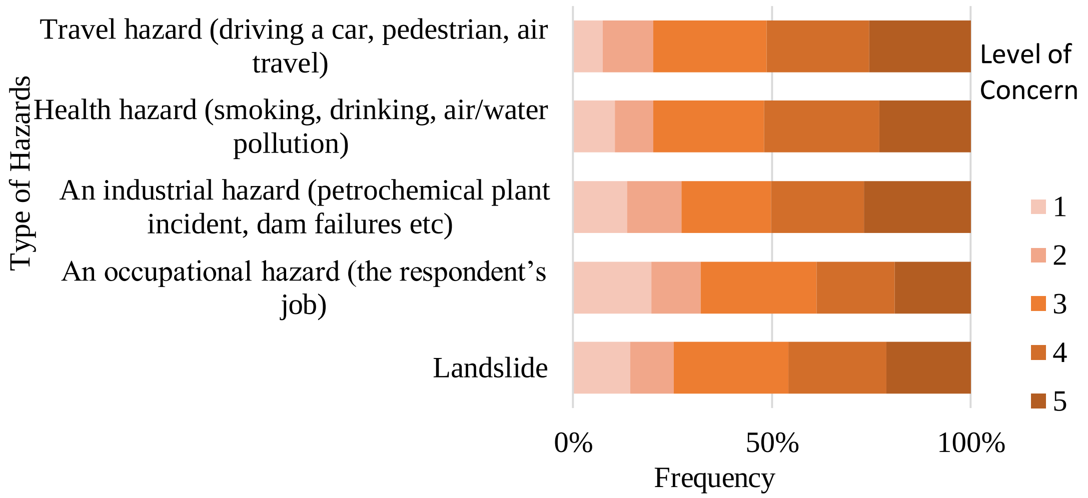


Figure 5-2 Answers to Question 13 (Q13 Ranking of land sliding relative to other hazards, with (1) being least concerned – (5) most concerned)

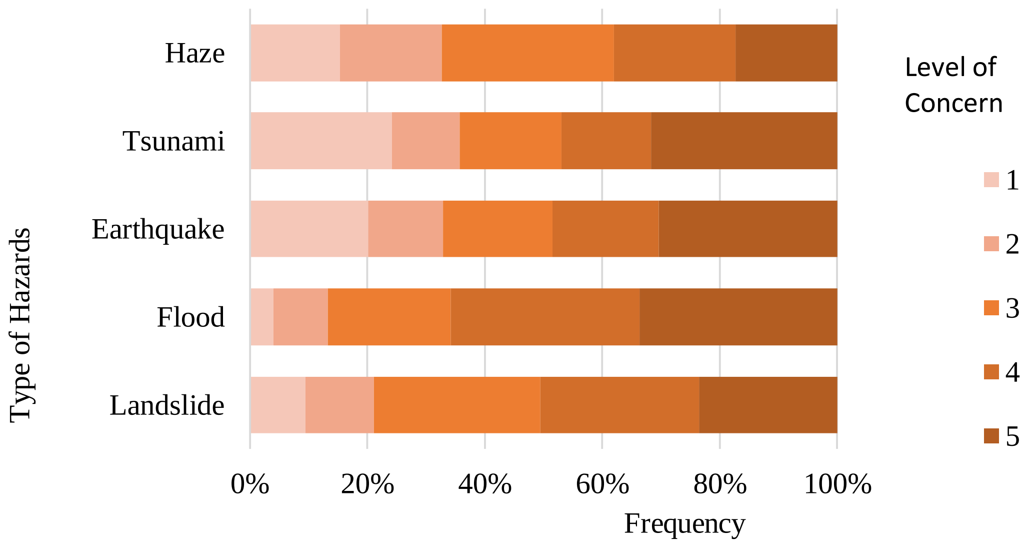


Figure 5-3 Answers to Question 14 (Q14 Ranking of land sliding relative to other natural events, with (1) being least concerned – (5) most concerned)

5.5 Factors causing Landslides

From the questionnaire survey, Q15 (refer to Appendix 3) was formulated to rank the Malaysians' perception of the factors causing landslides. The authors were fully aware that landslides may occur due to a combination of contributing and triggering factors.

According to (Griffiths 1999), a slope may undergo failure due to many contributing factors, i.e. geological, morphological, human and physical, but there is only one factor that triggers the landslide at the moment of failure. By definitions, triggering factors are those extrinsic factors that cause a sudden failure to the slope, while contributing factors are defined as the intrinsic factors that gradually reduce the safety margin of slope over a long period (Sim et al. 2022a). In some situations, landslides may occur without any clear identifiable trigger, as they can result from a combination of various factors (Wieczorek 1996). These factors may include the gradual chemical or physical weathering of materials, which progressively weaken the slope until failure occurs. (Wieczorek 1996). However, this differentiation is arguable as both contributing and triggering factors are inter-related. For instance, the infiltration of rainfall can trigger slope failure. As rainwater seeps into the soil, it weakens the soil strength, which is considered a contributing factor. A documented study by (Dille et al. 2022) stated that urbanization (a contributing factor) brings about significant alterations to the groundwater conditions within slopes, which subsequently has a direct impact on the stress state of the hillslope (Price 2011). While at the same time, movement of landslides is primarily triggered by the variations in soil pore-water pressure caused by rainfall (Iverson and Major 1987; Hilley et al. 2004; Dille et al. 2021). Elevated pore water pressure decreases the effective stress of the soil, which then lowers the shear strength of the soil. The reduction in shear strength increases the susceptibility of the soil to failure, and hence triggers a landslide event. Furthermore, the presence of excess water can also lead to a loss of cohesion and an increase in soil erosion, further compromising the stability of slopes. (Lacroix et al. 2020) studied slow-moving landslides and pointed out that the landslides worldwide were influenced by intricate interactions between contributing factors, i.e. the condition of the landslide material and pore fluids, and triggering factors such as seismic activity, river incision, or human activities. Consequently, landslides exhibit diverse kinematic behaviours that have significant implications for both hazard and landscape evolution. The kinematics of slow-moving landslides unveil a spectrum of intricate physical parameters, encompassing the mechanical properties of the material (i.e. cohesion, friction, and bulk damage), sliding history, pore-water pressure, as well as dynamic loading. Hence, it is evident that slope failure involves a complex mechanism whereby it is often not caused by a single factor but rather a combination result of a coupled combination of tectonics, geomorphology, climate, hydrology and human activities.

However, in Q15, the options presented to the respondents comprise both triggering factor and contributing factors. This was to make it easier for respondents to participate in the question. The authors believed that the respondents will be confused and not be able to fully understand the question and answer properly if the question is divided into one for triggering factors and another for contributing factors. Understanding the causes of landslides with respect to triggering and contributing factors requires substantial knowledge and as mentioned earlier, the respondents for this study consists of Malaysian communities from various backgrounds.

50% of the respondents felt very strongly (option (5) - most influential) about deforestation (logging) being the main cause of landslides (Figure 5-4). This is not surprising as there have been many illegal loggings carried out in Malaysia. The second ranked influencing factor causing landslide is voted to be failure of retaining structures, with 42.35% voting it as most influential. Although studies have reported that rainfall are the biggest triggering factor in causing landslides (Highland and Bobrowsky 2008; Ng 2012; Froude and Petley 2018), less than 40% of Malaysians felt strongly about it.

It was suggested that Malaysians tended to associate rainfall with flooding incidents rather than landslides. There were several reasons that led to this observation: (i) Malaysia received intense rainfall throughout the year, but not every rainfall event resulted in landslides; (ii) Over a couple of recent decades, publics have been educated about forestry, which contributed to an increased understanding of global warming and natural disasters; (iii) There was a lack of technical knowledge among some individuals to understand the mechanisms of landslides, making it challenging to distinguish between contributing factors and triggering factors of landslides.

According to an interview with a landslide expert at the Institution of Engineers Malaysia (IEM), rainfall is the main triggering factor of landslides including management of surface water runoff. Deforestation will only contribute landslides if it is not conducted in a proper way. The expert further stated that landslides could occur even without deforestation, as proven by the landslides that occurred in natural undisturbed slopes. For example, as mentioned by the expert from the academic sector, the landslide in the forests of Gunung Jerai was triggered by rainfall. They further stated that the strength of soil is governed by moisture content (Gerard 1965; Mulqueen et al. 1977), and the respondents' viewed that deforestation and failure of retaining structures were the top causes of landslides are due to their lack of understanding of the landslide mechanism. The expert from consultant sector/practitioner stated that the rainfall is indeed a crucial factor in triggering landslides.

Deforestation being a contributing factor will cause tree roots to decay, alter the hydromechanical effects provided by root (Murgia et al. 2022) and eventually results in a higher ground water seepage. However, they stated that the microbe action is significantly more effective in minimizing occurrence of landslides than the hydromechanical effects of root (Marcacci et al. 2022), as certain fungi will feed on the trees through photosynthesis while providing water to support the tree which ultimately improves the stability of slopes (Meadows et al. 1994; Yildiz et al. 2015). Deforestation will eliminate this relationship and consequently it will result in a landslide. Failure of a retaining wall can be easily observed by public and hence there is no surprise that the respondents give this as a more crucial factor than rainfall. The landslide expert from an NGO stated that in December 2021 numerous small-scaled localized landslides occurred in the Ulu Langat region, and they were all triggered by rainfall. In their opinion, the significant influence of landslides for natural slopes included geomorphology and subsurface profile, for example, clay profile is more susceptible to landslides than sandy slopes in Malaysia. On the other hand, the significant factors for landslides of man-made slopes, especially those that are decades' old, were due to a lack of geotechnical knowledge and guidelines in the past decades which resulted in a poor design of the slope. They further stated that the risk of landslide in man-made slopes for recent developments is significantly lower due to new stringent guidelines, enforced by the authorities such as Public Works Department (JKR), Mineral and Geoscience Department (JMG), etc. As for the landslide expert from the federal government agency, Public Works Department (JKR), the main contributing factors for landslides were topography and type of soil involved. They stated that the hills and mountainous regions of Malaysia were generally made of granite and residual soil of 3 to 4 meters which often causes shallow slides to occur. In addition, soil modification due to erosion and stormwater runoff were also factors causing landslides in Malaysia (Karamage et al. 2017; Nseka et al. 2022). In summary, it is clear that all the landslide experts agreed that rainfall plays a significant part in causing landslides in Malaysia.

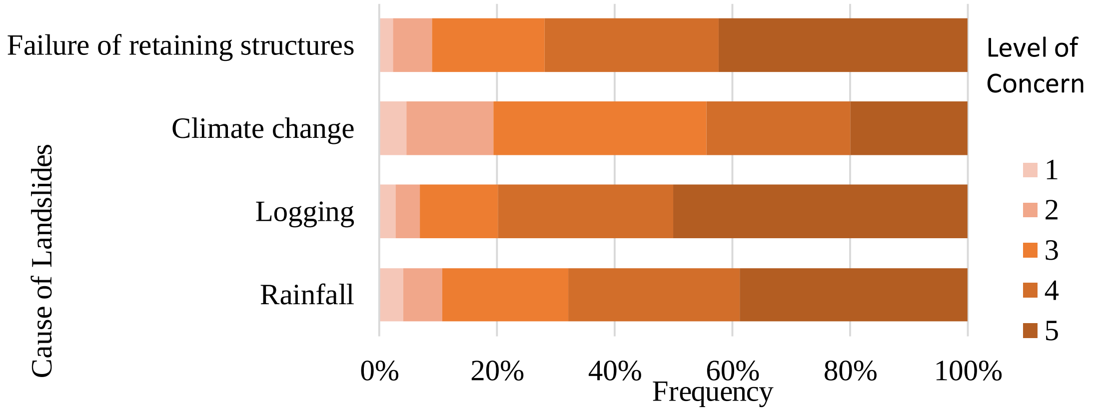


Figure 5-4 Response to question 15 (Q15 In your opinion, which of the following factors have the most influence in the occurrence of landslides? Rank them with (1) being least influential – (5) most influential)

5.6 Top down approach or community based approach for landslide risk reduction in Malaysia

The interviewed experts generally shared the same consensus that the top-down approach is still the best in Malaysia. The setting of landslide risk guidelines cannot be relied solely on the public because no matter how stringent the demands are from the public, it will be for naught if the government turn a blind eye against it. Moreover, the funding from the public are always capped at a certain limit. The expert from practitioner sector stated that the people who have faced landslide situations will get used to it and therefore developed a higher acceptance while those who have very little experience with it will have a very low tolerance and will demand tons of mitigations or completely against hillside development and all these factors will result in conflict of interests. As quoted by Scolobig et al. (2015), “people-centred approaches may not be appropriate in all situations, may generate tensions or even foster conflicts. One model of disaster risk management, whether people-centred or top down, may not be appropriate for all hazard circumstances, cultural contexts, or institutional settings.”

In this scenario it is imperative to have a body at the top to regulate landslides rather than just the community. Landslide awareness needs to be formed among all stakeholders. At the moment, the local government have the PBRC so they are in rather good position to monitor any incoming landslides. The expert from NGO further mentioned that in dialogue with GEO Hong Kong, their landslide risk guidelines were set by the government itself instead of the public. In Malaysia, JKR, JMG together with local authorities are the suitable body to set landslide risk guidelines taking into account consultation with the stakeholders, i.e. the public.

Despite all these, one cannot say that the people-centred approach is totally impractical. Rather one should strive for a better integration of the two approaches. The landslide experts stated strongly during the interviews the importance for the local community be given training to monitor and watch for signs of incoming landslides as the local authorities are always having their hands full with other duties. These awareness programs have been conducted by the landslide NGO in which they had provided trainings to watch and monitor slopes for any incoming landslides to residents in certain areas such as Bukit Antarabangsa and Penang Island. When a sign of landslide is being observed, the residents will then report to NGO which will then push the government agencies to take action. Besides NGO, the government is also in the midst of implementing awareness to the community through their National Slope Master Plan 2019-2023 program. It was also further mentioned that Japan have developed a very good landslide awareness among the community.

5.7 Acceptable probabilities of fatal landslide

Table 5-2 summarizes the ranges of acceptable frequency responses for each fatal landslide scenarios. Ranges were given for both the mode (the most frequent response) and for 80% of the responses. The ranges of acceptable frequency for events with lower deaths are higher than the events of high deaths, which is to be expected (Figure 5-5). It should be noted also, the modal frequency is mostly low, often around 1E-4 or higher, and that for 80% of respondents the range was relatively wide, about four orders of magnitude. This reflected a wide diversity of risk attitudes. Interestingly, the acceptable frequency for landslide deaths of 1 ranged from once a year to once in a 10,000 years or more (6 orders of magnitude). It was clear that the acceptable landslide risks expressed by the respondents were rather liberal especially for events of lower deaths. One reason for the underestimation of landslide risk could be due to a lack of personal experience with landslide events.

5.7.1 Acceptable probabilities of fatal landslide between those who live near slopes and others

The perception of landslide risk will vary between individuals living near slopes and those who do not. Residents in proximity to slopes tended to have direct exposure and first-hand experience with landslides, which potentially enhances their awareness of the associated risks. In the present study, 25% of respondents living near slopes have experienced landslides occurring at least near their residence. Their close proximity to areas prone to landslides can shape their perception of the potential hazards and the importance of implementing measures to mitigate them. Mode frequency of acceptance for various landslide death scenarios were compared in Table 5-3. The most risk averse group by far is the group of people living far from slopes. Regardless of the death scenario the modal response was always a frequency of ≥1E-4 (the lowest possible in the survey). The residents living near to slopes exhibited a higher propensity for risk-taking in terms loss of life compared to those who live far from slopes. Their risk preferences were notably higher, with a mode of frequency occurrence of 1 death per event in every 10 years. One explanation for this could be that these respondents were aware that they had intentionally constructed or purchased their homes near slopes, which indirectly exposes them to an inherently riskier area.

The respondents who have experienced landslides are the most risk taking. Their risk preferences were notably higher, with a mode at least ten times greater than the other groups for scenarios involving 1 to 100 deaths per event. This attitude can be attributed to either a pragmatic approach within the community towards a known hazard or a belief that the hazard is manageable. This observation aligned with the statement made by the landslide experts who stated that residents who have experienced landslide situations tended to adapt to such occurrences, leading to the development of a higher acceptance level. In addition, most of the participants who have experienced landslides were those with an income bracket of (Ringgit Malaysia) RM 1501-3000. The modal income for the other group of participants were RM 3001 to 5000 which was higher than those who have experienced landslides. As stated by Winter and Bromhead (2012), lower financial power means a higher tolerance level towards landslide risks, and vice versa.

A clear inclination towards lower acceptable probabilities, especially concerning higher deaths in hazardous landslide scenarios, was evident. All three groups showed similar risk aversion to scenarios involving 1,000 deaths per landslide event (lowest possible option chosen). The question to consider further would be which frequency is acceptable for decision making purposes. Is the lowest of the conveyed frequency, i.e., ≥ 1E–4, too stringent for Malaysia's context? Would the modal responses be the utmost feasible? All these queries, as well as judgements in response to them, will definitely have financial repercussions in a landslide risk management system. A simple straightforward answer unfortunately does not exist. In the light of reality, these queries and judgements are part of a political procedure, and they will have to be dealt with accordingly.

5.7.2 Experts' opinion on the acceptable probabilities of fatal landslide

In addition to the questionnaire surveys, interviews with local experts in landslides in various sectors (i.e. federal government, NGO, practitioner, IEM government body) were conducted to determine the risk acceptance criterion that is suited for Malaysia. It was stated by the experts that, individuals who have experienced landslides tended to acclimate to these situations, leading to a greater acceptance of the risks involved. In contrast, those with limited exposure to landslides exhibited lower tolerance and may demand stronger mitigation measures or express opposition to hillside development. In general, all the experts who were interviewed acknowledged the competency of Hong Kong in managing and turning around their landslide hazards. Except for the expert of the NGO sector, all other experts stated that Malaysia is currently not at the position to adopt the same level of risk criterion as Hong Kong's. The criterion of 1 death in 1,000 years used by Hong Kong (Figure 2-23) were deemed to be too stringent for Malaysia given its current economic and mindset of the people. The landslide expert from federal Government stressed that Malaysia is not ready to strictly follow the Hong Kong criterion. One reason being the work ethics of the local contractors. The compliance of local contractors’ works to stringent rules and guidelines could be an issue and need improvement. The expert further stated that with the current mentality of the people, it was doubtful to even establish a criterion of ‘1 death in 10 years’ in the next decade. Expert from academic sector stated that the public are not so well equipped in terms of slope safety and that rules and regulations written on papers are not being well enforced by authorities. These factors of the public and authorities make rather impossible for Malaysia to be able to adopt exactly the Hong Kong criterion. As seen in Table 5-2, all experts have shown a higher acceptance to landslide risk with four out of five accepting a frequency of 1 landslide death per year. However, the views of the experts might be too pessimistic as according to the expert from landslide NGO, currently, there are some ex-GEO Hong Kong members on board in the Penang Technical Action Committee (PTAC). With ex-GEO members on board, she is optimistic that Malaysia would and have to follow the Hong Kong criterion. The landslide practitioner expert however stated that Malaysia would have to establish their own level of acceptance instead of following exactly like Hong Kong’s. On a positive note, the expert stated that the established criterion for Malaysia should not greatly differ from Hong Kong’s.

Table 5-2 acceptable frequency of landsliding between lay persons and landslide experts

Death scenario	Acceptable frequency						
		Laypersons	Landslide experts of various sectors				
	Mode	80% of responses	IEM chairman of Geotechnical Division	Consultant/practitioner	NGO	Government/ JKR Cerun	Academic
1 death	≥1E-04	1 to ≥1E-4	1	1	1E-01	1	1
10 deaths	≥1E-04	1E-1 to ≥1E-4	≥1E-4	1E-1 or 2.5E-1	1E-02	1E-02	1E-01
100 deaths	≥1E-04	1E-2 to ≥1E-4	≥1E-4	1E-02	1E-03	1E-03	1E-02
1,000 deaths	≥1E-04	1E-2 to ≥1E-4	≥1E-4	≥1E-4	≥1E-4	≥1E-4	≥1E-4

Table 5-3 Acceptable probabilities of landslide between residents living near slopes and those who do not

	Mode Acceptable Frequency between respondents		
Deaths per landslide event	**Respondents living near to slopes**	**Respondents living far from slopes**	**Respondents who have experienced landslides occurring near their residence**
1 death	1E-1	≥1E-4	1.E-1
10 deaths	≥1E-4	≥1E-4	1E-2
100 deaths	≥1E-4	≥1E-4	1E-3
1,000 deaths	≥1E-4	≥1E-4	≥1E-4

Note: 1E-2 means a frequency of occurrence of once every 100 years; ≥1E-4 means frequency of occurrence of once every 1,000 years or more

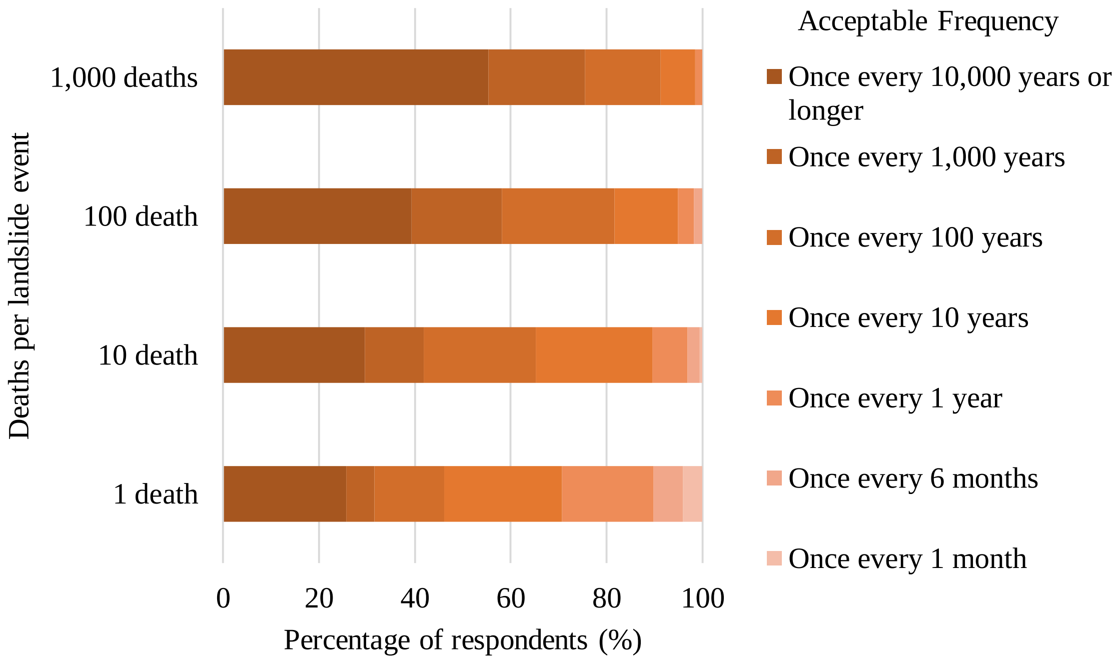


Figure 5-5 Answers to question 18 (Q18 What frequency of occurrence of landslides that kill X number of people can you accept in your community?)

5.8 Significance of demographic influences on landslide perception

To study the significance of among the demographics, independent sample t-test and one-way analysis of variance (i.e., F- test) were employed. The t- test was used to verify the factor significance of two subgroups (i.e., the gender of respondents: male and female) while the F-test was utilized to authenticate the factor significance of more than two subgroups (age, educational level, occupation, and income). The factors that did not satisfy neither t-test nor F- test were applied by Brown–Forsythe test (BF-test) (Roth 1983; Karagöz and Saraçbasi 2016; Liu et al. 2019). Finally, the statistical results of the t-test and F-test, the significant factors affecting landslide risk acceptability, insurance premium etc. were obtained. Table 5-4 presents the tabulated results of the t-test and F-test, indicating the statistically significant demographics that influenced the acceptability of landslide distance, frequency, and insurance premiums.

5.8.1 Factors affecting distance acceptability between living/working place and location with history of landslides

As displayed in Table 5-4, gender is the sole significant factor influencing distance acceptability. Generally, women are more sensitive to disasters than men. The psychological differences between men and women could also be one of the factors that explains this observation (Liu et al. 2019). According to (Grossman and Wood 1993) women have a stronger reaction to disasters and having lower self-confidence than men when it comes to dealing with the disasters.

5.8.2 Factors affecting frequency acceptability

As seen in Table 5-4, gender, educational level and occupation are the significant factors affecting landslide frequency of acceptance. Women are more risk averse specially for the landslide event with 1,000 deaths. Similar observation was observed in (Liu et al. 2019), where males can accept higher frequency of landslide disasters compared to women. It can be seen in Figure 5-6 that the influence of educational level showed a lower acceptance among those who have at least a diploma to a higher frequency acceptance of landslide disaster among those who have lower education level, i.e. secondary school level which again correlates to the findings by (Liu et al. 2019).

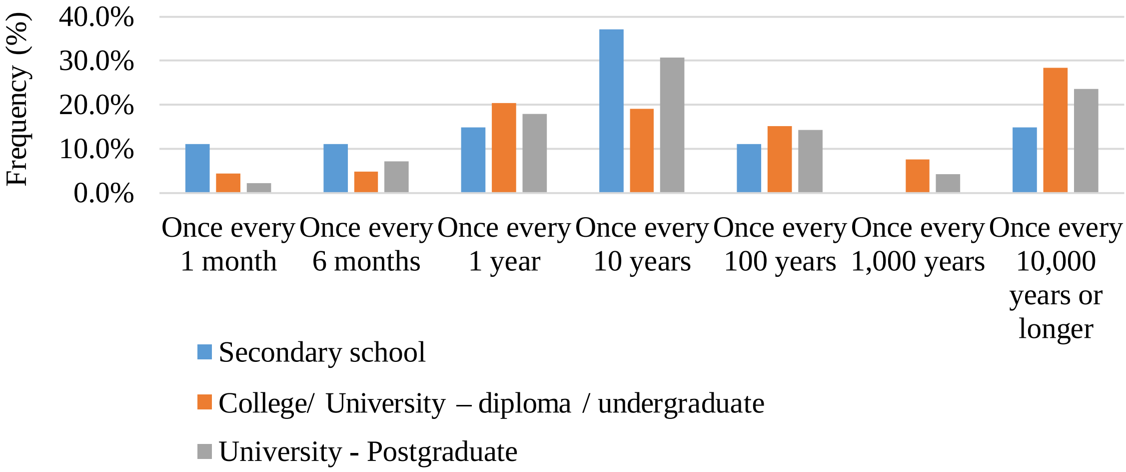


Figure 5-6 Graph of education level against landslide acceptable frequency for 1 death per event

In terms of occupation groups, the more risk-taking groups were the non-professionals, self-employed. These groups were more risk taking (frequency mode of 1E-1) mainly in the scenario of "a landslide that kills 1 person" (see Figure 5-7 (A)) . One can see in Figure 5-7 (B), that for the event of 100 deaths, less than 35% of the self-employed and non-professionals choose the highest possible option (once every 10,000 years or longer or frequency of ≥1E-4). The risk taking attitude of the self-employed was even more notable for the event of 1,000 deaths (Figure 5-7 (C)) in which the highest possible option was chosen by less than 45% of the self-employed respondents. This behaviour could be owing to a belief that the hazard is controllable. In addition, the group of non-professionals and self-employed have a similar income bracket (mode of RM 1500-3000 a month) which is rather low which then explains the higher tolerance and acceptance towards landslide risks. Similar survey results can be seen in (Finlay and Fell 1997) where the non-professionals expressed a more risk taking attitude.

The most risk averse group by occupation as far are the professionals and students. The mode monthly income of the professionals is in the range of RM 3001 - 5000 with 18.7% of professionals surveyed having income of higher than RM 10,000 per month which explains the strong risk averse behaviour. As seen in the study by (Winter and Bromhead 2012), more financial power means a lower tolerance towards landslide risks and vice versa.

Student group showed a strong risk averse behaviour (mode of ≥1E-4). The unemployed respondents showed both high risk aversion as well as risk accepting (mode of 1E-1 and ≥1E-4). Most of the student respondents are aged 30 and below and have at least a college education. From the statistics in Figure 5-8, a mode acceptable frequency of 1E-2 i.e once every 100 years was found among respondents aged 31 and beyond (with 40.5% of respondents aged 41-60 accepting a 1 death per event in a frequency of once in every 100 years). It is also found in separate studies (Finlay and Fell 1997; Liu et al. 2019), that the more risk taking group are also found to be the group that consists of older participants. From this observation, it can thus be surmised that older people are more risk taking while the younger ones are more risk averse, when considering their attitudes towards acceptance of landslide risk. Both students and unemployed groups have mode income bracket of less than MYR 1500 (lowest possible in the survey). The unemployed group have a larger percentage of elderly and married with kids. However the data from Table 5-4 have shown that age and marital status are not one of the significant factors affecting the frequency of acceptance of landslide risk.

Figure 5-7 Correlation between Occupation against landslide acceptable frequency for the following scenarios: (A)1 death per event; (B)100 deaths per event; (C) 1,000 deaths per event

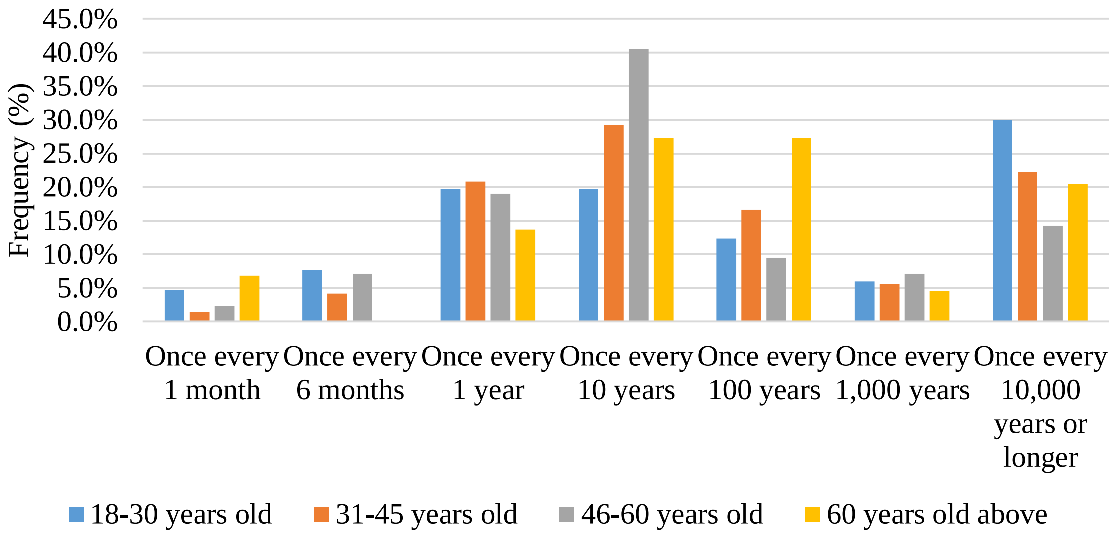


Figure 5-8 Correlation between age and landslide acceptable frequency for 1 death per event

5.8.3 Factors affecting insurance premium acceptability

As presented in Table 5-4, age and marital status are the significant factors for insurance premium acceptability in Malaysia. Malaysians who are married with kids are seen be more willing to pay for a higher insurance premium. This is not surprising as couples who are married with kids generally would have protective parental instincts towards their children. Interestingly, the younger generation, showed less interest to purchase insurance premium (mode answer was the cheapest option (<RM200)) and rather tolerate landslide disasters. Middle-aged people (those 46 to 60 years of age) are more risk averse as they are in the age group that have the highest percentage of respondents choosing the most expensive insurance premium i.e. greater than MYR 2,000. In addition, middle-aged Malaysians generally have higher incomes (54.8% of middle aged respondents having monthly income bracket of RM5001 to 10,000 and 33.3% having income exceeding RM10,000 per month). They were willing to pay more money to purchase insurance premium against landslide disasters. Surprisingly, the elderly (aged 61 and above) are not willing to pay high insurance premium although more than 50% of elderly have income bracket of greater than MYR 5,000 with mode income bracket of greater than RM10,000. This observation is similar to the survey result by (Liu et al. 2019) which reported that with the increase of age, the respondents in Dong

Chuan and Zhoqu demonstrate less interest to purchase insurance premium and would rather tolerate debris flow disasters. The interviewed landslide experts however, strongly agreed that residents should pay high premium for landslide insurance. One of the experts further quoted one incident where the tenants of a residential area were able to claim landslide damages when a landslide struck their dwellings. It was also further stated that the importance of having landslide insurance among Malaysians were brought up following the landslide event at Bukit Antarabangsa. Insurance premiums can be regarded as a mitigation strategy within the realm of risk management pertaining to landslides (Klose et al. 2015b; Kalfin et al. 2021). It serves as a financial instrument aimed at mitigating potential losses or damages that may arise from such events. (Klose et al. 2015b).

Table 5-4 Statistical results of t-test, F-test for the demographics

Factor	**Indicator**	**Homogeneity of variance**	**T-test/ F-test**	**BF test**
Age	Distance between living/working place and location with history of landslides	0.121*	0.361	
	Frequency for 1 death per event	0.001		0.566
	Frequency for 10 death per event	0.019		0.413
	Frequency for 100 death per event	0.354*	0.513	
	Frequency for 1,000 death per event	0.446*	0.572	
	Insurance Premium	0.013		0.008*
Sex	Distance between living/working place and location with history of landslides	<0.001		<0.001*
	Frequency for 1 death per event	0.286*	0.11	
	Frequency for 10 death per event	0.609*	0.131	
	Frequency for 100 death per event	0.390*	0.133	
	Frequency for 1,000 death per event	0.715*	0.087*	
	Insurance Premium	0.043		0.616
Education level	Distance between living/working place and location with history of landslides	0.652*	0.091*	
	Frequency for 1 death per event	0.126*	0.051*	
	Frequency for 10 death per event	0.307*	0.196	
	Frequency for 100 death per event	0.078		0.08*

	Frequency for 1,000 death per event	0.061		0.2
	Insurance Premium	0.903*	0.559	
Occupation	Distance between living/working place and location with history of landslides	0.189*	0.127	
	Frequency for 1 death per event	0.209*	0.261	
	Frequency for 10 death per event	0.672*	0.267	
	Frequency for 100 death per event	0.186*	0.083*	
	Frequency for 1,000 death per event	0.007		0.047*
	Insurance Premium	0.062		0.175
Marital status	Distance between living/working place and location with history of landslides	0.086		0.524
	Frequency for 1 death per event	0.003		0.149
	Frequency for 10 death per event	0.005		0.182
	Frequency for 100 death per event	0.614*	0.33	
	Frequency for 1,000 death per event	0.793*	0.583	
	Insurance Premium	0.007		0.098*
Income	Distance between living/working place and location with history of landslides	0.173*	0.656	
	Frequency for 1 death per event	0.01		0.486
	Frequency for 10 death per event	0.219*	0.483	
	Frequency for 100 death per event	0.324*	0.377	
	Frequency for 1,000 death per event	0.152*	0.495	
	Insurance Premium	0.236*	0.108	

Note: * means the factor is significant for the indicator under $p < 0.10$. i.e., the confidence interval was 90%, which was practically fit the sample data.

5.9 Landslide Risk Management (LRM) in Malaysia

Generally, the interviewed experts stated that landslide risk management (LRM) are not being well adopted yet in Malaysia. The expert from the professional institution that risk management is probably employed for certain construction projects but not in slopes. This scenario is similar to Germany in the 2000s where there is no risk management in regards to landslide (Blöchl and Braun 2005). However, the experts from consultant and academic sector believed that risk management is being adopted albeit in a slow manner. For example, the expert from consultant side mentioned that automated rain gauge for early warning purposes were installed by private entities in

Genting Highlands. He further mentioned that any approval for new developments would now require submission of documents such as terrain maps, constructability reports to JMG which would endorse them and then pass it to local authorities. In the experts' opinion, landslide risk management is not well employed yet in Malaysia for the following reasons:

- Lack of knowledge and more effort required for LRM.
- Most geotechnical practitioners are still using the deterministic factor of the safety method instead of LRM.
- Lack of funds from client, especially those for private developments, to bear the additional cost of carrying out LRM.
- Lack of manpower in agencies which results in difficulties to carry out regular inspections.

The general consensus from the expert interviews is that risk management of landslides is being slowly implemented. However, it is still below par or in other words, 'fragmented' as in risk is being managed in certain parts of the country by agencies such as Ampang Jaya Municipal Council (MPAJ), DBKL, Penang Island City Council (MPPP) while in other parts it is not being well managed. Certain areas such as Ulu Klang and Bukit Antarabangsa were given great attention as they are landslide hotspots. Owing to climate change, landslides hazards are rising in Malaysia. However, risk of deaths and slope failures for new developments is diminishing due to the implementation of stringent guidelines i.e. appointment of auditors and checkers. More authorities are now looking into development of hazard maps as mentioned by the expert from academic sector. Landslide hazards for existing slopes and old developments from the 1980s and 1990s still remain high due to the lack of control guidelines during that time.

An ongoing study by JMG to develop hazard and risk maps started in 2010, entitled Peta Bahaya Risiko Cerun (PBRC). In addition, the national slope master plan was carried out by the public works department (JKR) from 2007 to 2009 but unfortunately the main focus was towards highways. JMG have improved the maps and handover to local authorities but alas, the PBRC only captures large scale landslide hazards. As a consequence, a landslide occurred in Bukit Permai which results in 5 fatalities caused a shock within JMG as that affected region was not recorded in the hazards maps itself. The current measures could have been better implemented, as they were not prevention-based measures but more to event-based measures which are akin to "putting out the fire" instead of "avoiding the fire". More attentions should be given to monitoring and responding to slope issues preventatively.

5.10 Development of Societal Risk Criterion for Malaysia

Societal death risk assessment and FN criteria (defined as the criteria relating the probability per year (F) of causing (N) or more deaths) can be valuable decision-making tools (Strouth and McDougall 2020). However, as stated plainly by the landslide experts, risk evaluation tools that are highly effective in Hong Kong may not be as effective (or potentially unfeasible) elsewhere due to the conflicting attitudes towards risk, perceptions towards landslide hazards, financial limitations, funding mechanisms and mentality of the public. Each and every nation has limited resources in managing a wide range of hazards, i.e. road accidents, violence, environmental pollution, disease outbreaks, food and water shortage, and fires, etc. One of the aims of the present study is to take a preliminary step at improving resource allocation by encouraging towards fair, feasible and efficient distribution of resources to landslide hazards. With that goal in mind, this section defines prospects to improve the societal risk criteria for Malaysia.

The risk criteria for landslides in Malaysia was established based on the analyzed questionnaire results. This process encompassed the examination of participants' perceptions of landslide risks particularly the acceptable levels of risk and their willingness to invest in mitigation measures i.e. insurance premium which serves as a financial instrument aimed at mitigating potential losses or damages that may arise from landslide event (Klose et al. 2015b). By considering these factors, the risk criteria was established, providing valuable insights into the attitudes and preferences of the surveyed population regarding landslide risk management in Malaysia. The criterion is tailored to fit the scenario in Malaysia but may also be a valuable preliminary action for other cultures.

5.10.1 Analysis of suggested landslide acceptable Risk Criteria by various stakeholders

Figure 5-9 presents the possible landslide risk criteria that can be formed based on the mode frequency of acceptance for different death scenarios by different stakeholders obtained from the questionnaire surveys and expert interviews. The stakeholder comprised of landslide experts, communities as a whole, communities living near to slopes, and communities who have experienced landslides occurring near their premises. The thresholds were compared with the societal risk of landslides in Malaysia, criterion of Hong Kong and the Malaysian criterion proposed by Ahmad et al. (2017). The following principles can be derived from the survey and interview results, which was subsequently used to establish an improved risk criterion for Malaysia:

1) It has been verified that the perception of landslide hazards among the participants are broadly correct. Landslide hazard has ranked 4th out of five hazards by Malaysians. Comparing landslide hazards with other natural hazards, landslide was ranked 2^{nd} after flood. This shows that the general public has a reasonable ability to accurately perceive the relative severity of each hazard. In this case, the public will be able to assess the frequency of acceptance for various landslide death scenarios satisfactorily.

2) It is apparent from Figure 5-9 that Malaysia's current societal landslide risk predominantly lies above all the possible threshold lines. Therefore, the societal risk of landslides in Malaysia is unacceptable by the standards of the country.

3) All the possible risk criterions from the modes of frequency of acceptance of various stakeholders differs greatly from that proposed by Ahmad et al. (2017) with the exception of the criterion from the mode of landslide experts which is a little more similar to that of Ahmad et al. (2017). In fact, there are two important data points: one is the probability of 1 death, and the other is the probability of 1000 deaths which are very important. The probability of 1 death for the experts is once every year or 1 which is very close to that of the societal landslide risk level of Malaysia, while the probability of 1 death for the criterion

of Ahmad et al. (2017) is once every 5 years. The Experts stressed that Malaysia at its current state is not ready to adopt a stricter risk criterion, because of the mentality of the people and the economic status of the nation.

4) The public mostly chose the maximum option available which was a modal frequency of once in 10,000 years or more. The criterion that can be formed (option 1) based on the perception of the public and by utilizing the gradient of 1 like in Hong Kong's criterion will result in the risk threshold of 1E-4 or once every 10,000 for 1 deaths and 1E-7 for 1,000 deaths respectively. It should be noted that this criterion is ten times stricter than that of Hong Kong (1 death at 1E-3 and 1,000 deaths at 1E-6). Another possibility is to establish the criterion with zero gradient like the criterion used by France as seen in Figure 2-26 The option 2 (Figure 5-9*)* criterion appeared to be independent to the number of fatalities, N. This will lead to a lower level of safety at high N values and at the same time result in extremely stringent and uneconomical safety procedures at low N values. While the majority of the people expressed very high-risk aversion, they also expressed the desire to pay as little as possible when it comes to insurance cover against landslides which is less than RM200 (the lowest possible choice in this survey). This attitude is reflected even for floods, which are a natural disaster of utmost concern among Malaysians. A study conducted by Kamaludin et al. (2018) found that over 60% of Malaysians are unwilling to contribute to flood mitigation programs, and more than 75% do not pay for insurance cover. Overall, the respondents in the present study have expressed a desire for a low risk of fatal landslides, but they are less willing to pay to ensure protection from such landslides.

5) It is not possible to establish a risk criterion following exactly the one expressed by the overall public. Let alone it is already not feasible to adopt the risk criterion of Hong Kong which is 10 times lower than the one expressed by the public due to Malaysia's current economic situation and mindset of the people. According to data from (World Bank 2020), Hong Kong, being a high-income nation, has a Gross National Income (GNI) that exceeds USD 12,235, which

dwarfs Malaysia, an upper-middle-income nation with a GNI ranging from USD 3,956 to USD 12,235. Furthermore, data from (Daniell et al. 2015) shows that the value of statistical life (VSL) of Malaysia falls in the range of 1.75-2.18 million USD while Hong Kong’s VSL could reach as high as 11.8 million USD which is similar to that of the USA and Canada (Strouth and McDougall 2020). VSL, according to (Andersson and Treich 2011) also refers to the sum that individuals within a particular society are willing to contribute in exchange for enhanced safety, such as slight reductions in their risk of mortality. (Kamaludin et al. 2018) reported that the willingness to pay of Malaysian for flood prevention program was merely about 5 USD per month. This demonstrated the attitude of general Malaysians towards contributing for a safety environment.

6) The risk criterion that can be established based on the mode frequency of acceptance by the people living near slopes and those who have experienced landslides near their residence is more feasible to be established for Malaysia. It has a frequency of acceptance for 1 death at 1E-1 or one death every 10 years. Additionally, the same frequency for 1 death is also chosen by the expert in the NGO sector (Table 5-2). It should also be noted that the frequency of one death every 10 years is the second most chosen answer among all the respondents. Interestingly, the unduly liberal criterion proposed by Ahmad et al. (2017) (1 death every 5 years) was based on the survey conducted at two very vulnerable districts of Selangor. The criterion based on the mode frequency of acceptance of people who have experienced landslides occurring near their dwelling is more liberal, as seen in the fact that it does not deviate significantly from the experts' criterion and converges with the experts' criterion at (N=1000, F=1E-5). This relatively liberal attitude could be also due to the risk being tolerated rather than accepted which is a crucial distinction (Finlay and Fell 1997). People who have experienced landslides occurring near their dwelling are likely to be the most vulnerable and have a better understanding of the risks involved. Their experience of living through a landslide event near their house gives them a unique perspective and insights into the dangers associated with such occurrences. This understanding may align more closely with the expertise of experts who have accumulated vast experience and knowledge through their

work on landslides. Therefore, considering the acceptance criteria based on the experiences of these individuals can provide valuable insights into risk assessment and mitigation strategies.

7) One might say that the criterion should only consider the most vulnerable group of people which in this case are those who live on slopes and have experienced landslides occurring near their place. However, this study was conducted to establish a feasible criterion for the majority of the people of Malaysia. Based on the earlier mentioned expert interviews, a firm assertion can be made that regions perceived as having lower vulnerability levels may unexpectedly become highly vulnerable. This was evidenced by the experts' statement that the landslide incident in Bukit Permai in 2022, resulting in five fatalities, caused significant concern within the JMG. It was noteworthy that the affected region was not initially considered in the PBRC hazard maps, highlighting the potential for previously overlooked areas to pose significant risks. The landslide risk criterion which is more feasible for Malaysia will be established by taking into account the frequency of acceptance expressed by all stakeholders above.

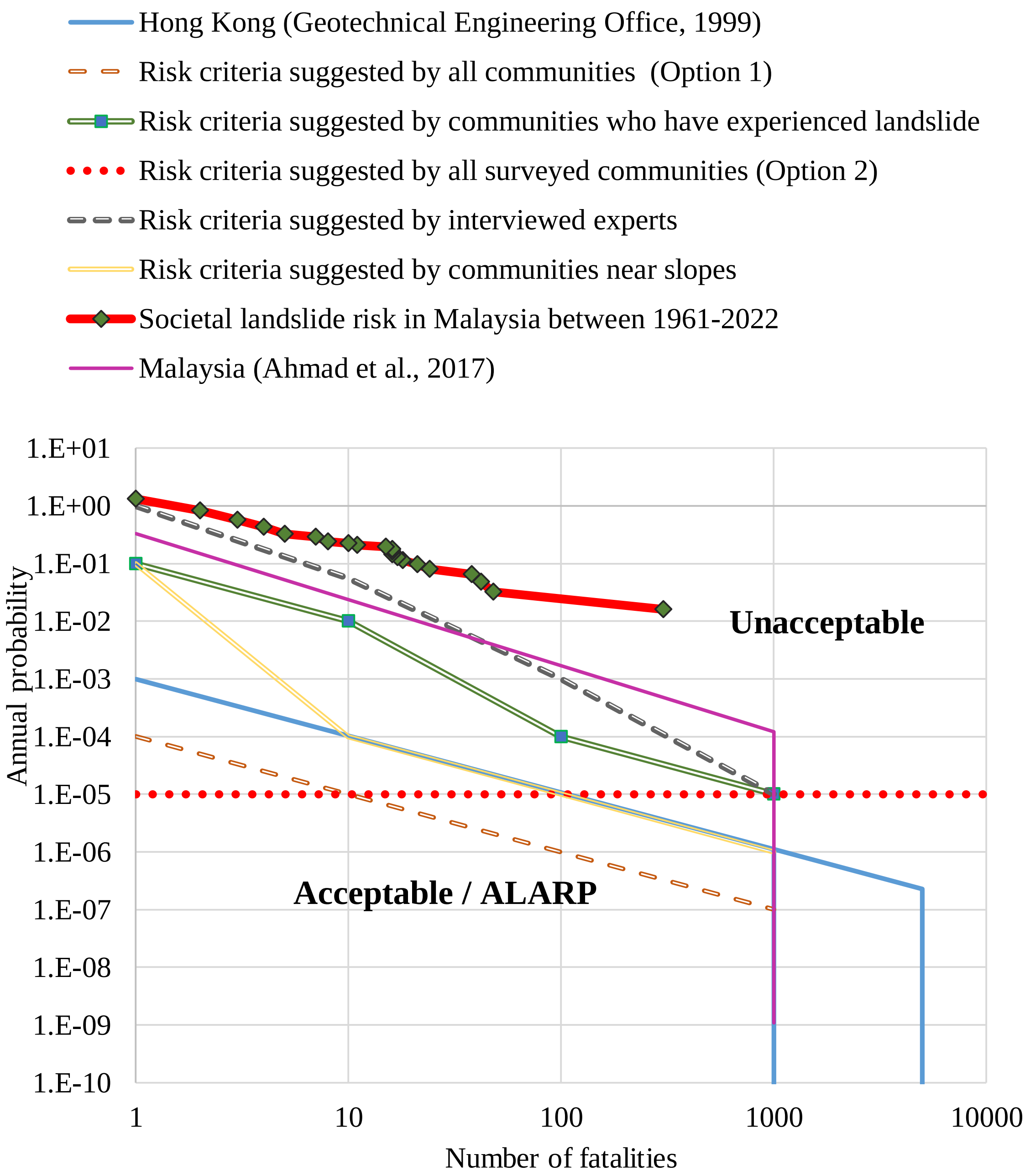


Figure 5-9 Comparison of mode of frequency of acceptance for different stakeholders with the societal risk of Malaysia's landslide with the proposed Malaysian criteria by Ahmad et al. (2017) **with Hong Kong's landslide risk criteria.**

5.10.2 Proposed new Landslide Risk Criterion for Malaysia

The criterion shown in Figure 5-10 was proposed for societal landslide risk evaluation in Malaysia and could be feasible in other similar nations. The authors acknowledge that, similar to the study by (Strouth and McDougall 2020), further studies are still needed to determine its effectiveness. The criterion is in accordance with the expectations of the public as well as suggestions of landslide experts who deal with landslide hazards. The criterion is proposed based on the following proposals to analysts and decision-makers dealing with landslide hazards:

1) As stated by (Strouth and McDougall 2020) the inclusion of broadly acceptable and intense scrutiny zones can be deemed unnecessary as a limited number of hazard sites fall within these zones when represented on an FN diagram. Furthermore, their presence often leads to confusion when these diagrams are communicated to the general public. However, it is essential to establish a higher standard for new development projects situated in recognized hazard zones. Such projects should adhere to a more stringent set of criteria, considering that undertaking new development without implementing adequate mitigation measures increases the level of risk. There exists a responsibility to proactively manage this risk.

2) The criterion for assessing landslide risk should consider the well-being of the majority of the population, including those living near slopes (frequency of 1 death every 10 years), as well as the landslide experts (frequency of 1 death every year). Applying the risk criterion used in Hong Kong (1E-3) or following the modal choice of the communities to establish the risk criterion would yield a significantly high target safety level (≥1E-4), which is not realistic in the current perspective of Malaysian society as discussed earlier. Based on the statistical survey results data presented in Figure 5-5, by establishing a threshold of one death per every 100 years, it would be addressing the perceptions of up to 70% of the communities, constituting a significant majority. This falls within the generally accepted range of 1 death is between 1E-2 and 1E-3 (Figure 2-26).

In addition, a guideline of 1E-5, representing the threshold for 1,000 deaths, would align with the modal acceptance level of landslide probabilities, which is ≥1E-4.

3) Instead of using strict criteria, it is advised to employ guidelines when interpreting the lines displayed on FN diagrams. These lines should serve as references to guide decision-making and justify actions or inactions (Strouth and McDougall 2020). This recommendation, emphasized by the founders of societal risk evaluation tools is occasionally overlooked by practitioners (Strouth and McDougall 2020). The inclusion of the reference line depicted in Figure 5-10, representing an annual probable life loss of 1E-2, aligns with the risk tolerance threshold reference line established in the United Kingdom. Data from (Daniell et al. 2015) showed that the VSL of Malaysia falls in the range of 1.75-2.18 million USD which happens to be the same as the UK's. Other organizations that employ 1E-2 for 1 death includes the USBR (U.S. Bureau of Reclamation 2003; Macciotta and Lefsrud 2018), as well as Venezuela and Brazil (Kirchhoff and Doberstein 2006; Marhavilas and Koulouriotis 2021).

4) The interim risk criterion in Malaysia is one magnitude higher than that of Hong Kong, and both criteria exhibit the same gradient of risk aversion. This criterion aligns with the assertions made by landslide experts, who suggest that while Malaysia may not adopt an identical criterion to that of Hong Kong, the criterion established for Malaysia should bear substantial similarities and not deviate significantly from the Hong Kong standard. The new interim risk criteria proposed for Malaysia reflect a higher degree of risk aversion compared to the previous criteria. Under the new criteria, the tolerable frequency of landslides resulting in fatalities is reduced to once every 100 years, whereas the previous Malaysian criterion allowed for such occurrences once every 5 years. This difference is not surprising, as the previous criterion solely considered the perception of the vulnerable communities of just two districts in the state of Selangor. As stated by the experts, residents who have experienced landslide situations tend to acclimate to such occurrences, leading to the development of a heightened level of acceptance. In contrast, the newly devised criterion was

formulated by considering the perceptions of communities from various regions, states, and levels of vulnerability. As such, it exhibits a greater degree of representativeness for Malaysia as a whole.

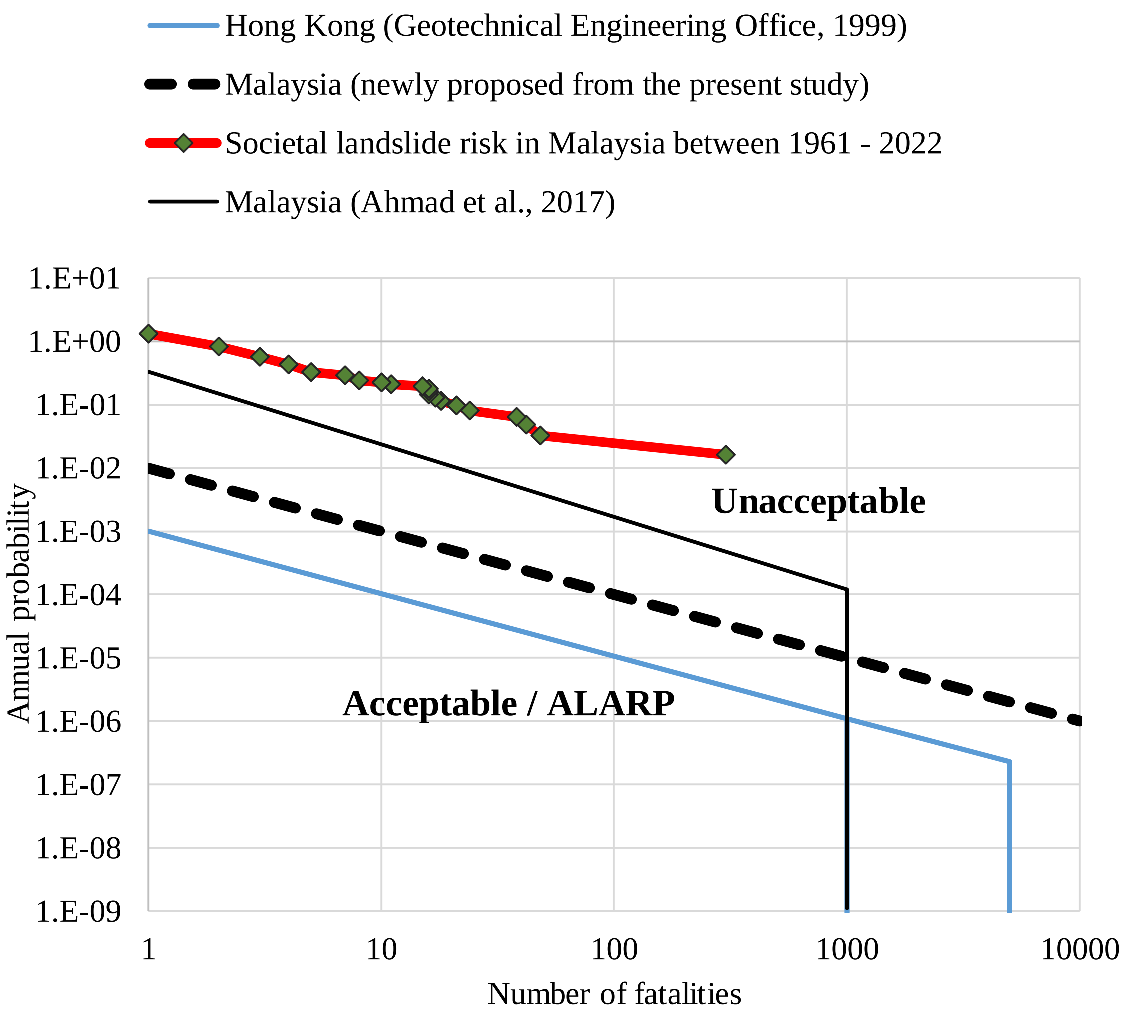


Figure 5-10 Proposed FN diagram for societal landslide risk evaluation in Malaysia compared with other nations, intended for further studies and discussion.

5.11 Discussions

In 2022, questionnaire surveys were carried out to investigate the perception of landslide risk in Malaysia. In addition, interviews were conducted with slope experts from different sectors. Differences in opinion between experts and lay-persons were noted in this study. Analysis of the results showed that respondents were more worried about technological risks (health hazards and travel accidents) than to natural risks which was not surprising as experts noted that people always fear the unknown or things that they do not have access to information. Of the natural hazards, they felt more exposed to floods, followed by landslides and then earthquake and tsunamis. This was in general agreement with the experts' as they noted that storm water surge flooding occurs most frequently and covers huge areas, whereas landslides (the second most frequently occurring disaster in Malaysia) are more localized and that there are not as many people who live on slopes as of now compared to those who live on lowlands. Analysis of the socio-demographic factors indicated that gender, educational level, and occupation were the significant factors affecting landslide frequency of acceptance.

The clearest difference of opinion between experts and public was in terms of the risk acceptance. Experts were able to accept a higher frequency of death (i.e. 1 death in 1 year to 10 years), possibly due to their experience and understanding in dealing with landslides in the country. The public, in contrast, mostly chose the maximum option available which was a modal frequency of once in 10,000 years or more. Experts recognized that Malaysia at its current state is not ready to adopt a stricter risk criterion, because of the mentality of the people and the economic status of the nation. The public, in contrast were less aware of the overall situation in Malaysia. Most of them will have very high expectations on the government to control the risks. Indeed, there are some respondents who will accept higher risk, i.e. those who live near to slopes and those with lower income bracket. The huge range of 80% of the responses over the 1E-2 to =>1E-4 per annum raw probability range for 1 death scenario signified a wide diversity of risk attitudes. Overall, participants showed a desire for a low landslide risk to life which is expected. However, in reality, some of the participants continue living with landslide risks way higher than what they expressed in the questionnaires, hence disclosing a higher "acceptance" of risk than expressed. Risk averse attitude is high among professionals and this opposed the opinions of landslide experts (also professionals) who are willing to accept a higher frequency of occurrence. This could be due to the risk being tolerated rather than accepted which is a crucial distinction (Finlay and Fell 1997).

5.12 Concluding remarks

The results of this study may provide policy-makers with useful information for improving landslide risk management system, i.e. in establishing a risk criterion for Malaysia. Crucial insights were given by the respondents' and experts' preferences on acceptable risk level, such as the frequency of acceptance for a landslide event that results in certain number of deaths. The development of societal landslide risk evaluation criteria in Hong Kong represents a significant advancement in this regard, which remains unparalleled. While it may appear straightforward to prescribe a minimum threshold for landslide risk criteria, such as F = 1E-3 for N = 1 used by Hong Kong, the acceptance of this threshold varies based on the financial capacity of each country. Although developing nations may encounter similar issues in risk governance and decision-making as developed nations, the balance between economy and safety may diverge (Roy and Kshirsagar 2020). Developments in developing nations often yield greater benefits compared to their developed counterparts. For instance, the construction of railways and roads can contribute to job opportunities, improved access to specific areas, and efficient transportation of goods, thereby boosting economic turnover and wealth creation (European Maritime Safety Agency 2015). Adopting an excessively lenient risk acceptance criterion would foster more development but elevate societal risk. Conversely, an extremely conservative acceptance criterion would impede development and hinder economic growth. It is important to recognize that each society possesses unique values, perceptions, and beliefs, and any risk evaluation tool inherently simplifies these complex attitudes.

This chapter introduces modification to the societal landslide risk criteria that aims to address the shortcomings of the existing proposed Malaysian landslide risk criteria. Specifically, the proposed modifications lower the inherent acceptance towards deaths present in the existing Malaysian landslide risk criteria through analyses of the results of the surveys and expert interviews with a greater focus being placed on serving the majority of the communities in Malaysia. One suggestion clearly emerging from the study is the need to develop strategies in order to transform the mindset of the people to be able to establish a better and more stringent risk guidelines in Malaysia. This would have the effect of promoting awareness amongst citizens and favouring the development of individual as well as collective forms of responsibility. Improved communication could also achieve the aim of improving the mindset of the people. A mindset of "cutting corners to reap the most profit" among those involved in construction can significantly reduce the quality of developments and result in the difficulty to implement a better risk criterion for the country. It is essential that the regulators understand the opinions and perceptions of all the stakeholders and work around them, as the effective management and operation of risk reduction procedures will not materialize without the active involvement of all parties. While the development of these tools specifically targets the socio-political conditions of Malaysia, it is the authors' aspiration that the discussions presented in this article will serve as an inspiration for others to adapt and tailor these tools for application in diverse societies and various types of hazards.

With the enhancement of the proposed risk criteria for landslides in Malaysia, it is clear that the societal risk of landslide in the country falls in the unacceptable zone. To illustrate the applicability of the novel risk criteria further, a case study will be undertaken on a slope in Malaysia. This case study will undergo quantitative risk assessment (QRA), determining and comparing the societal risk of that case study slope against the present proposed Malaysian landslide risk criterion. An essential aspect of the landslide hazard and risk assessment involves evaluating the runout distance. When an area is deemed potentially hazardous for landslides, accurately estimating the runout distance becomes critical for evaluating the risk posed. In most instances, runout distance is determined empirically using established landslide data, which relies on factors such as landslide height, volume, travel distance, and other related parameters (Jaiswal 2011). The subsequent chapter entails the development of empirical models for predicting landslide runout distance in Malaysia.

6 An Empirical Method for Predicting Landslide Runout Distance in Malaysia

6.1 Introduction

This chapter focuses on the physical characteristics of landslides in Malaysia, establishing empirical correlations between travel distance, runout, retrogression distance, slope height, slope angle, and landslide volume. It presents an empirical procedure to determine runout distance, along with key findings and recommendations. Applying these empirical formulas will contribute to evaluating landslide hazard in Malaysia and supporting the national slope master plan for landslide disaster risk reduction.

6.2 Relationship between landslide runout distance and landslide parameters

As stated in chapter 3, it is necessary that the various influential parameters be considered in the development of the predictive model for landslide travel distance owing to the myriad of factors influencing landslide movement. Regression analyses were conducted, supported by the application of significance tests (i.e., F-tests and t-tests), to establish an optimized model for the prediction of landslide travel distance (Guo et al. 2014; Apriani et al. 2022; Shan et al. 2022).

6.2.1 Correlation between slope height *(H)*, volume *(V)* and total travel distance *(L)*

In Figure 6-1 and Figure 6-2, the relationship between landslide travel distance *(L)* and two variables, slope height *(H)* and landslide volume *(V)*, respectively, is illustrated. Figure 6-1 shows a weak linear correlation (R^2=0.271) between slope height and landslide travel distance. Using the slope height alone to predict landslide travel distance is not sufficient due to the unknown positions of the toe of the failed mass and the crest of the sliding source before the landslide event (Guo et al. 2014). Therefore, considering other influential factors simultaneously is recommended.

Figure 6-2 reveals a relatively strong linear correlation between landslide travel distance *(L)* and landslide volume *(V)* ($R^2=0.709$). The p-value = 0.035<0.05, indicating that landslide volume significantly affects travel distance. The results suggest an exponential correlation between travel distance and landslide volume, meaning that travel distance rapidly increases with landslide volume.

This observation supports the statement by Legros (2002) that "the travel distance depends primarily on the volume and not on the fall height, which just adds scatter to the correlation." The stronger correlation between volume *(V)* and travel distance *(L)* compared to slope height *(H)* and travel distance *(L)* suggests that landslide propagation is mainly influenced by their own volume rather than slope height.

Nonetheless, the coefficient of determination (R^2) of using a combination of *H* and *V* together is higher (R^2=0.879 as seen in Figure 6-3) than those using only the parameters of height of slope, *H* alone (R^2=0.269) or volume, *V* alone (R^2=0.709). This shows that multivariate runout relationship provides higher accuracy. The correlation can be expressed into power law relationships as follows:

$$L = 0.0078 H^{1.46} V^{0.387} \qquad (6\text{-}1)$$

Other than having a coefficient of determination (R^2) of 0.879, the regression model is also statistically significant as it has a *p*-value of ($0.042 < 0.05$).

6.2.2 Correlation between slope height *(H)* and slope angle (θ) and runout distance *(Lu)*

As there are two independent variables, slope height *(H)* and slope angle (θ), multiple linear regression is employed to analyse the data. The predictive equation of multiple linear regression analysis can be seen as follows:

$$L = 4.788\, H^{0.898} \tan\theta^{\,0.048} \qquad (6\text{-}2)$$

The coefficient of determination R^2 is 0.307 which is rather weak. In the study conducted by Qarinur (2015) it is stated that an equation form from a combination of slope height *(H)* and slope angle (θ) is a better landslide runout predictor compared to relying solely on slope height *(H)* due to the change of the value of R^2. In this study, it should be noted that the rise of R^2 value obtained from using slope height *(H)* and slope angle (θ) (R^2=0.307), while the coefficient of determination R^2 of using only slope height *(H)* is only (R^2=0.271). This observation seems to concur with the results of (Qarinur 2015).

In terms of significance, the model with a combination of slope height (H) and slope angle (θ) has an *p*-value value of 0.159>0.05. The *p*-value of 0.159 > 0.05 indicates that the model does not provide strong statistical evidence to reject the null hypothesis, implying that the relationship between variables is not be statistically significant. Furthermore, the p-value for slope angle parameter (θ) is found to be higher than 0.05 which further confirms that the slope angle parameter (θ) does not have a significant effect on the travel distance. Similar observations were seen in the recent empirical statistical study by (Apriani et al. 2022).

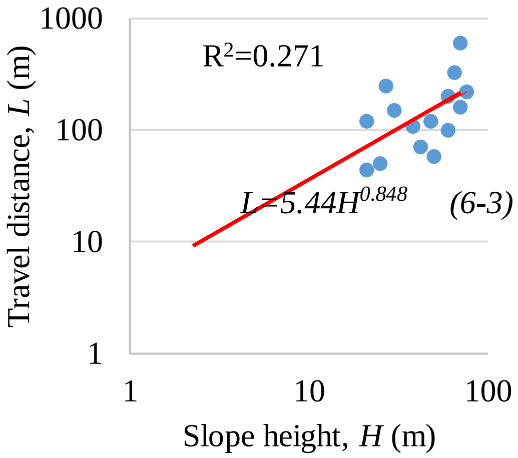


Figure 6-1 Landslide travel distance in relations with slope height

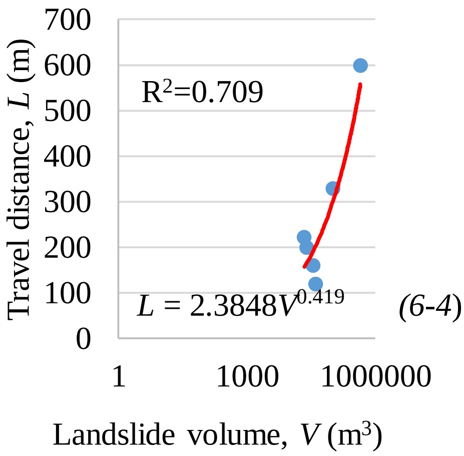


Figure 6-2 Landslide travel distance in relations with landslide volume

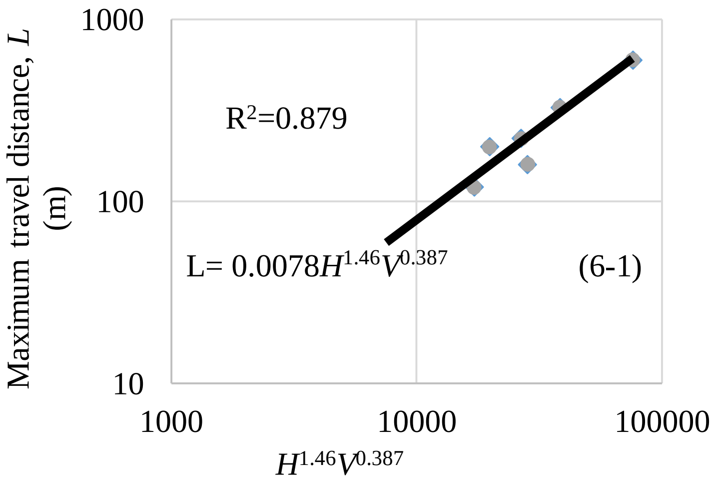


Figure 6-3 Relationship of maximum travel distance *(L)* versus slope height *(H)* and landslide volume *(V)*

6.2.3 Retrogression and runout distances, *Lu* and *rL*

There are currently no direct guidelines for determining *rL* in Malaysia. Therefore, slope stability analyses specific to Malaysia's conditions need to be conducted to investigate *rL* more thoroughly (Strand et al. 2017). Figure 6-4 demonstrates a relatively strong relationship (R^2=0.774) between *rL* (retrogression distance) and *Lu* (runout), described by the power function: (dotted line in Figure 6-4):

$$Lu = 2.6697 rL^{0.8051} \qquad (6\text{-}5)$$

The upper limit for the studied cases is defined by the power function: (solid line in Figure 6-4):

$$Lu = 3.6322rL^{0.8475} \qquad (6\text{-}6)$$

These equations align with those developed by (Locat 2008). The statistical analysis confirms the appropriateness of the model, with *p*-value of 0.02 < 0.05. Additionally, *Lu* can be estimated using the relationship from Figure 6-4 as follows:

$$Lu = 0.9125rL \qquad (6\text{-}7)$$

The upper limit/ maximum credible runout is defined by the following relationship (dash line in Figure 6-4) :

$$Lu = 1.787rL \qquad (6\text{-}8)$$

Overall, one can conclude that the variable retrogression distance significantly affects the runout.

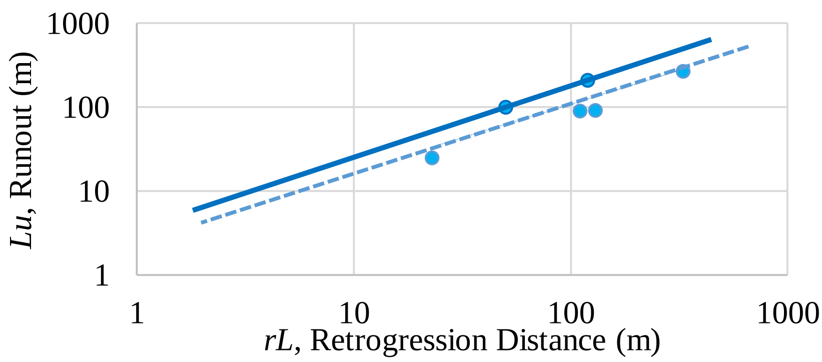


Figure 6-4 Relationship between runout, *Lu*, and retrogression distance, *rL*

6.3 Model validation

To further validate the proposed models, the runout/travel distance in each case study were back-calculated using the models developed by past researchers in Table 3-1 as well as the newly developed ones from the present study. The estimation of errors of each landslide were obtained using equation (6-9): $|Lpredicted - Lobserved| / Lobserved \times 100\%$ where *Lpredicted* is defined as the predicted runout/travel distance and *Lobserved* is the actual runout/travel distance. The average errors for the models are shown in Table 6-1. The percentage shown in the table indicates the extent to which the predicted values differ from the actual values. For example, a 90% average error of means that, on average, the predicted value using model equation (*3-1*) differs by 90% from the actual value. This is not favorable, as a large average error suggests significant discrepancies.

Table 6-1 Landslide travel distance/runout prediction models and their comparisons

Researcher(s)	Equations		Parameters used	Average error(%)
(Corominas 1996)	$L = 1.03V^{-0.105} H$	(3-1)	$V\ H$	90%
(Rickenmann 1999)	$L=1.9V^{0.16} H^{0.8}$	(3-2)	$V\ H$	45%
(Legros 2002)	$L=8V^{0.25}$	(3-3)	V	44%
(Locat 2008)	$Lu = 8.8rL^{0.8}$	(3-4)	rL	242%
	$Lu= 4.4rL^{0.8}$	(3-5)	rL	72%
(Guo et al. 2014)	$L = 2.672\ H – 208.31$	(3-6)	H	195%
(Qarinur 2015)	$L=1.267H^{1.027}$	(3-7)	H	50%
	$L= 1.066H^{1.093}$	(3-8)	H	47%
	$L = 1.448\ H^{1.062} \tan \theta^{-0,482}$	(3-9)	H, θ	44%
(Strand et al. 2017)	$Lu = 3.0\ rL$	(3-10)	rL	192%
	$Lu = 1.5rL$	(3-11)	rL	59%
	$Lu = 0.5rL$	(3-12)	rL	51%
(Samodra et al. 2018)	$L=1.65H+1.09$	(3-13)	H	43%
(Zhou et al. 2019)	$L = 0.04\ V^{1/3}$	(3-14)	V	308%
	$L= 0.05\ H^{0.43} V^{0.28}$	(3-15)	$V\ H$	97%
(Apriani et al. 2022)	$L = 6.918\ H^{0.84}$	(3-16)	H	68%
The present study	$L= 0.0078H^{1.46}V^{0.387}$	(6-1)	H, V	14.80%
	$L= 4.788\ H^{0.898} \tan \theta^{0.048}$	(6-2)	H, θ	60%
	$L= 5.44H^{0.848}$	(6-3)	H	51%
	$L = 2.3848V^{0.419}$	(6-4)	V	25.17%
	$Lu= 2.6697rL^{0.8051}$	(6-5)	rL	32%
	$Lu= 3.6322rL^{0.8475}$	(6-6)	rL	75%
	$Lu= 0.9125rL$	(6-7)	rL	29%
	$Lu = 1.787rL$	(6-8)	rL	78%

Source: Corominas 1996; Rickenmann 1999; Legros 2002; Locat 2008; Guo et al. 2014; Qarinur 2015; Strand et al. 2017; Samodra et al. 2018; Zhou et al. 2019; Apriani, Credidi, and Khala 2022

Based on the results in Table 6-1, it is not surprising that empirical expressions *Eq. (6-3*) and *Eq. (6-2*) show large errors, as they have low correlation coefficients of R^2 at 0.271 and 0.307, respectively. Notably, models *Eq. (3-8*) and *Eq. (3-9*) proposed by (Qarinur 2015), and empirical model *Eq. (3-13*) proposed by (Samodra et al. 2018), have similar accuracy with errors around ±45%. This observation is understandable as both Indonesia and Malaysia are tropical countries with high rainfall throughout the year, and they share similar coastal plains, hills, and mountainous terrains. It should be noted that while geographical and climatic similarities might contribute to similar landslide behaviors, the accuracy of any model remains fundamentally rooted in the quality and relevance of the employed datasets.

Other models, such as those proposed by Zhou et al. (2019) and Corominas (1996), do not yield satisfactory results, with average errors of 97% and 308% respectively. The model by Zhou et al. (2019) predicts longer travel distances than observed, but none smaller than the actual observations. This discrepancy might be because their dataset consists of debris flows in the earthquake-prone area of Wenchuan, China, whereas most landslides in Malaysia are rainfall-induced and involve different mechanisms. Similarly, the model by Corominas (1996) may not be applicable to Malaysia due to differences in geological and hydrogeological conditions. More popular empirical models proposed by Rickenmann (1999) and Legros (2002) show relatively more reasonable average errors within ±44%. The proposed models Eq. (*6-1*) and Eq. (*6-4*), using parameters *H* and *V*, exhibit good performance in predicting landslide travel distance, with relative errors within ±15% and ±25% respectively.

Comparative analyses reveal that models *Eq.* (*6-5*) and *Eq.* (*6-7*), which incorporate retrogression distance *(rL)*, produce reasonably good performance in predicting landslide runout, with relative errors within ±30%, consistent with studies in (Guo et al. 2014; Apriani et al. 2022; Sim et al. 2024). However, the upper limit empirical models *Eq.* (*6-6*) and *Eq.* (*6-8*) predict runout distances nearly 80% higher than actual values. These models were designed to be conservative and provide a safety margin for emergency situations, avoiding underestimation of risk and hazard. On the other hand, models proposed by Strand et al. (2017) and Locat (2008) do not yield satisfactory results, with average errors reaching overestimations as high as 242%. These models were tailored to flow slide of sensitive clays in Norway and Eastern Canada, which differ significantly from the landslides in Malaysia, possibly due to distinct geological and hydrogeological conditions.

Overall, the runout predictions in this study show the closest resemblance to observed values because they are based on local datasets, making them more applicable to specific ground conditions in Malaysia. They shall contribute to bolstering safety measures and enhancing decision-making support in landslide-prone regions. It is proposed that probabilistic slope stability analyses to be conducted to determine the potential occurrence of landslides for any particular development in a specific region in the country. Following that, the retrogression distance (*rL*) will be used to determine the runout for the aforementioned landslide study, as (*rL*) can be determined through slope stability analyses. Accurate runout predictions empower authorities and infrastructure planners to proactively implement tailored mitigation strategies. In addition, landslide runout predictions is crucial to establish safety measures when creating buffer zones, aiming to mitigate the effects of landslides (Erfen and Musta 2022; Xu and Stark 2022).

6.4 Concluding remarks

Landslide runout distance is crucial for assessing landslide hazard and risk, particularly for identifying potentially affected elements. Predicting runout typically involves either empirical/statistical methods or analytical dynamic methods. However, obtaining reliable predictions requires sophisticated rheology models and material parameters, which are often unavailable, especially in developing nations such as Malaysia. In the absence of such data, it is highly recommended to estimate runout and landslide impacts using empirical methods (Guinau et al. 2005, 2007; Guo et al. 2014; Apriani et al. 2022; Falconi et al. 2022; Shan et al. 2022).

In this study, the newly proposed empirical model was used to estimate landslide runout in Malaysia and the results were compared with the existing models proposed by other researchers. Statistical analyses were performed to assess the efficiency of various parameters, such as height of slope *(H)*, travel distance *(L)*, slope angle (θ), retrogression distance *(rL)*, runout *(Lu)*, and landslide volume *(V)* in predicting travel distance of landslide. By comparing the proposed models with other established models using coefficients of determination (R^2) and other statistical parameters like *p*-values, the accuracy of the newly developed models could be ascertained.

The analyses revealed that multivariate equations, such as those combining *V* and *H*, yielded better predictions than univariate models that only use parameter *V*. Univariate runout relationships are simpler but less accurate, while multivariate models offer improved accuracy. Notably, there was a strong relationship between retrogression distance *(rL)* and runout, as well as volume *(V)* and slope height *(H)* with runout. Determining landslide volume *(V)* can be challenging in practice. However, an equation (*6-10*): $V = 2.482\ A^{1.024}$ with determination coefficient of 0.99 was proposed by (Amirahmadi et al. 2016) to estimate volume of landslides by analyzing the landslide area. This equation is stated to be applicable globally as it utilizes data from diverse regions across different countries (Amirahmadi et al. 2016; Apriani et al. 2022) . On the other hand, accurate *rL* values can be obtained through slope stability analyses.

The limitation of this study is that the influences of more sophisticated parameters such as landslide types and soil parameters on travel distance were not studied. In addition, it would be interesting to be able to complete the missing geotechnical information for the dataset in Table 3-2 and to add more landslide cases. Data collection in Malaysia, as noted by Sim et al. (2022a) and Gue et al. (2009), is a labor-intensive process involving mining information from various sources. Much information is scattered among different parties, and some of the documents are classified, either because they contain sensitive information or due to the trade secrets used by certain parties (Gue et al. 2009). Despite all the challenges, the predicted results are in reasonable agreement with observations. Additional explorations are recommended to further refine the newly developed empirical models. It will be desirable for other researchers to utilize and add to this database continuously to enhance both the quantity and quality of the data, as statistical analyses rely on robust datasets.

The proposed empirical models presented herein demonstrated promising results, with relative errors within ±30% consistent with those reported in documented studies (Guo et al. 2014; Apriani et al. 2022). These models such as *Eq. (6-5*) and *Eq. (6-7*) incorporating *rL*, as well as *Eq. (6-1*) incorporating *H* and *V*. The models demonstrated strong correlation, evident from their high R^2 values of > 0.7 along with *p*-values below 0.05, indicating significant relationships between the parameters. Conversely, the upper limit models incorporating *rL,* i.e. *Eq. (6-6* and *6-8*) have been developed with a conservative approach, aiming to incorporate a safety margin for emergency situations and thereby preventing the underestimation of risk and hazard. As stated by Turmel et al. (2018), conservative estimations offer adequate protection to guarantee the safety of the populace, particularly in instances of prospective residential expansions. Furthermore, a conservative approach could be highly suitable for initial evaluations of landslide susceptibility and hazard (Hungr et al. 2005). By providing reasonably accurate predictions, this model equips decision-makers with a valuable idea for implementing proactive safety measures, thereby mitigating the risks associated with landslides. Hence, for runout evaluation in future landslide hazard and risk assessment, the authors recommend the implementation of model (6-5): $Lu = 2.6697rL^{0.8051}$ and its conservative upper limit model (6-6): $Lu = 3.6322rL^{0.8475}$.

In the following chapter, a method for estimating the risk along the slope of a case study is outlined. The risk levels to elements at risk situated from the crest to the toe within the runout path of the landslide were evaluated by integrating the runout distance into the risk assessment. The societal risk as a whole will then be compared against the landslide risk criterion proposed in Chapter 5.

7 Verification of the proposed landslide risk acceptability Model through case study

7.1 Introduction

In this chapter, a specific case study was selected for numerical simulations aiming at providing an understanding of the risks associated with rainfall-triggered landslides. These simulations function as an initial warning system, particularly in areas prone to severe landslides that can result in extensive devastation and potential loss of lives. To mitigate these risks to both lives and property, it becomes imperative to conduct thorough stability analyses and risk assessments of slopes within specific regions.

This chapter focuses on evaluating the direct risk to life within a residential area in Malaysia. The developed empirical landslide run-out model was employed to quantify the risk of landslide run-out for elements, situated downhill from the area where landslides initiate. From the analysis, one shall see that the slope was already within the unacceptable risk region of the Malaysian risk criterion, leading to the occurrence of slope failure resulting in high casualties. In addition, the results of this analysis will serve as a foundation for conducting a cost-benefit analysis, designing risk reduction measures aligned with the established risk acceptance criteria, and informing future land use planning.

Using PLAXIS LE, the numerical model was conducted as follows: (i) Examining the transient seepage into soil slopes during an extreme rainfall scenario with a 10-year Annual Recurrence Interval (ARI); (ii) Evaluating the probabilistic slope stability associated with transient seepage induced by extreme rainfall infiltration. Through this analysis, the probability of an event of a specific magnitude was ascertained. The consequence of an event of a particular size was assessed in relation to the vulnerability of the residents by taking into account the runout distance, enabling the estimation of the annual probability of a fatality, resulting from a landslide in the study area.

7.2 Background of case study

The selected case study was the Bukit Antarabangsa 2008 landslide, acknowledged as one of the most significant incidents in the Hulu Kelang region in the preceding decade.

The landslide occurred around 3:30 am on December 6th, 2008, resulting in four fatalities and fourteen injuries. The landslide was measured approximately 109 m in width at the crest, 120 m in length, and 15 m in depth. An estimated 101,500 cubic meters of earth moved, resulting in a maximum runoff distance of about 210 m from the base of the slope (Huat et al. 2012; Qasim and Osman 2013). The original slope had a height of approximately 65 m and a length of 145 m, with an inclination of roughly 25 degrees. Site investigation data, as documented by (Huat et al. 2012; Lee et al. 2014; Kazmi et al. 2017), indicated that the slope was composed of three soil layers: silt, sandy gravel, and granite, with detailed soil properties provided in Table 3-3. A typical SWCC particularly for silty residual soil from Malaysia, as described in Lee et al. (2014), was employed in the model. Figure 3-3 (a) & (b) depict the SWCC and the corresponding hydraulic conductivity function utilized in the simulation. The groundwater table was identified at approximately 15 m from the ground level at the crest and 1.5 m at the toe during dry conditions.

Although numerous slope stability analyses have been conducted on Bukit Antarabangsa (Lee et al. 2010, 2014; Ng 2012; Mariappan et al. 2016), to the authors' knowledge, no probabilistic analyses have been carried out yet, especially those employing extreme rainfall scenarios on the slope. Through Quantitative Risk Assessment (QRA), the societal risk posed to residents can be evaluated, along with the acceptability of this risk when benchmarked against the newly improved Malaysian risk criteria. The procedure for conducting probabilistic analyses on slopes subjected to extreme rainfall scenarios may also be applicable to future developments.

7.3 Extreme rainfall analyses

Figure 7-1 displays the computed maximum potential rainfall and rainfall intensity expected over durations of 1, 2, 3, 5, 7, 14, and 30 days for a 10-year return period, derived through Gumbel's extrapolation method (Gofar and Lee 2008; Shrestha et al. 2021). The data illustrates that the pattern of rainfall across various days does not follow a linear progression due to the non-uniform nature of precipitation over extended durations. The difference of rainfall intensity between day 1 and day 2 was seen to be drastic, while day 2 onwards the difference was seen to be more gradual. As the total volume of rainfall accumulates over a given timeframe, the intensity tends to diminish.

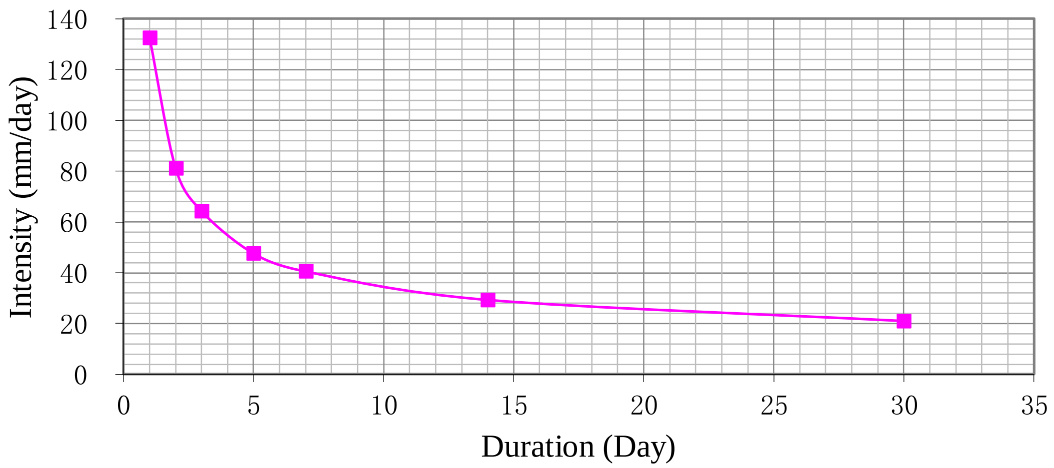


Figure 7-1 Intensity of Rainfall occurring at different days for return period of 10 years.

7.4 Pore-water pressure results

Transient Pore-Water Pressure (PWP) variations at the middle of the slope (Section A–A’) are shown in Figure 7-2. Similar PWP trend and results were seen in the documented study by Dhanai et al. (2022). It should be noted that PWP at the soil surface at the middle section became near zero after a period of 3 days of continuous rainfall for the entire period the extreme rainfall. Again, similar results were obtained by Dhanai et al. (2022) where the PWP at soil surface saturates at an early phase under extreme rainfall conditions. The early saturation occurs due to the swift decline in matric suction and reduced cohesion among soil particles (Dhanai et al. 2022). It is important to highlight that no positive pore-water pressure was observed at the surface during the entire simulation duration, which is similar to the results in the model by (Ng 2012; Lee et al. 2014). The PWP at 2 meters below the surface at section A-A’ (Figure 3-4) never reaches zero, suggesting that the water table does not rise to that extent during the entire 30 days of continuous extreme rainfall.

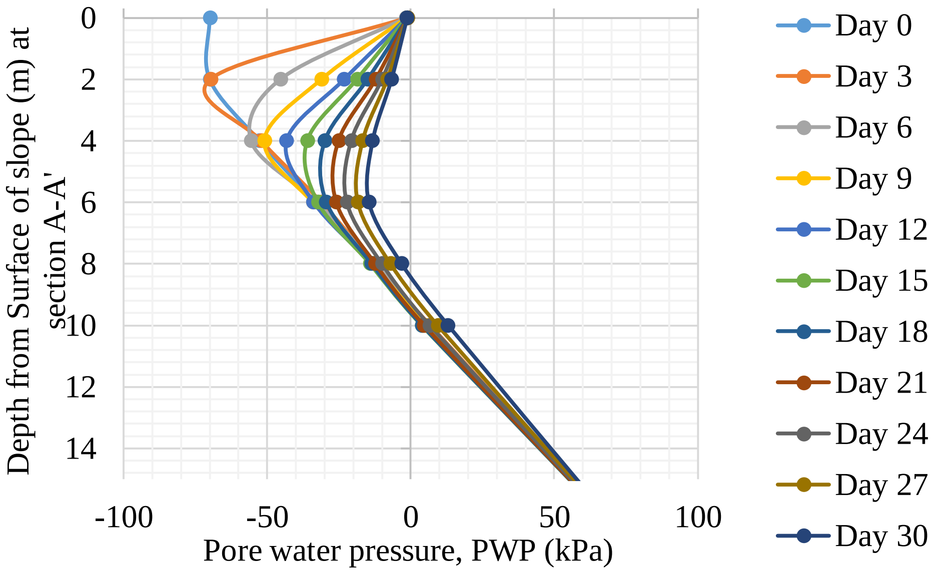


Figure 7-2 PWP profiles for the slope at section A- A' during the simulation

7.5 Probabilistic slope stability analysis results

The changes of the Factor of Safety (FOS) with time in the simulation is shown in Figure 7-3. The findings from the analysis of slope stability showed a pattern akin to PWP, demonstrating a decline in Factor of Safety (FOS) from 1.18 at the initial stage, reaching near critical value of 1.04 at the end of the 30th day of extreme rainfall. Similar results were seen in documented studies related to the same slope (Lee et al. 2010, 2014; Ng 2012). As the PWP at the slope built up, the safety factor decreased. The drastic drop in FOS at the beginning could be explained by the high rainfall intensity at the beginning of the simulation as seen in Figure 7-3. Due to the substantial increase in water load during early stages of extreme rainfall, there was a rise in pore water pressure and a simultaneous decrease in matrix suction. Consequently, this caused a decline in the slope's safety factor. The slow and marginal decrease in FOS safety after the initial drastic drop was due to the lower value of saturated hydraulic conductivity of the soil. Overall, the observed decrease in Factor of Safety (FOS) was attributed to prolonged extreme rainfall and the subsequent redistribution of the infiltrated rainwater (Lee et al. 2014).

Figure 7-5 displays the most vulnerable slip surface with the minimal FOS. Following 30 days of intense rainfall, the critical safety factor reaches 1.04 when employing the General Limit Equilibrium (GLE) (Fredlund) solution technique. Analysis using this method indicates that the calculated safety factor just after the 30-day rainfall period hovers close to the brink of failure. In real life scenario, the same slope experienced the failure resulting in deaths due to prolonged antecedent rainfall when its FOS approach and drop slightly below the critical safety factor of 1.0 (Lee et al. 2010, 2014). This indicates that this slope will be likely to fail if subjected to 30 days continuous rainfall of 10 years-ARI. It should be noted that in real life, failure occurred at the top layer of the soil which greatly aligned with the simulation results presented in Figure 7-5 (Ng 2012; Lee et al. 2014).

The tornado diagram in Figure 7-6 shows the relative influence of the material parameters to the factor of safety value. The analysis indicates that the FOS for this slope was primarily affected by the friction angle of silt, the soil at the top layer. Following this, the cohesion of top silt layer did exert some influence on the factor of safety. However, the cohesion of the second layer, comprised of sandy gravel, alongside the materials' unit weight, has a relatively uniform and minimal impact on the slope's safety factor, which is not suprising, as the critical slip circle occurs only on the top soil layer of the slope. Similar results were obtained in published studies where friction angle exert the highest influence on FOS followed by cohesion of the materials (Fredlund et al. 2011; Petrovic et al. 2016; Shrestha et al. 2021).

The probability of failure, *pf*, throughout the simulation is presented in Figure 7-4. The *pf* during the initial condition is computed at 0.0786 through the APEM analysis in PLAXIS LE. According to the expected levels of performance in terms of probability of failure by U.S. Army Corps of Engineers as seen in (Petrovic et al. 2016), the computed *pf* at initial stage is *unsatisfactory*. The unsatisfactory performance of the slope is not suprising at all, as numerous slope failure incidents have been reported in the area (Farisham 2007; Lee et al. 2010, 2014; Saadatkhah et al. 2015; Izumi et al. 2019). There is a drastic rise in *pf* at the early stages which aligns with the drastic drop in FOS due to the high extreme rainfall intensity at that time. Increased rainfall intensity elevates the likelihood of failure as it swiftly generates positive porewater pressure, thereby diminishing shear strength parameters (Shrestha et al. 2021). Conversely, lower rainfall intensity decreases the probability of failure due to the absence of these effects. It should be noted that the standards by U.S. Army Corps of Engineers considers that a slope with *pf* of 0.16 and above as *hazardous.* The slope of this case study reached the hazardous stage at day 16 of continuous rainfall and reaches a final *pf* of 0.355 after 30 days. Thus, the expected level of performance of the slope after 30 days extreme rainfall at 10 year-ARI is *hazardous.* It should be noted that the hazardous performance is in good agreement with numerous documented studies found in (Farisham 2007; Lee et al. 2010, 2014; Saadatkhah et al. 2015; Izumi et al. 2019). Furthermore, in real life scenario, fatal landslide has occurred in this slope which resulted in deaths due to prolonged antecedent rainfall (Gasim et al. 2011; Lee et al. 2014; Kazmi et al. 2017; Sim et al. 2023a). The findings derived from PLAXIS LE models indicate the potential criticality of the slope in the event of a 30-day rainfall of a 10-year return period. Previous studies have demonstrated that landslides triggered by rainfall occurred in slopes within Hulu Kelang, particularly in areas with soils of moderate permeability, primarily due to extended antecedent rainfall (Farisham 2007; Lee et al. 2010, 2014; Saadatkhah et al. 2015; Izumi et al. 2019). Hence, the outcomes of this investigation align with documented studies, further supporting their validity.

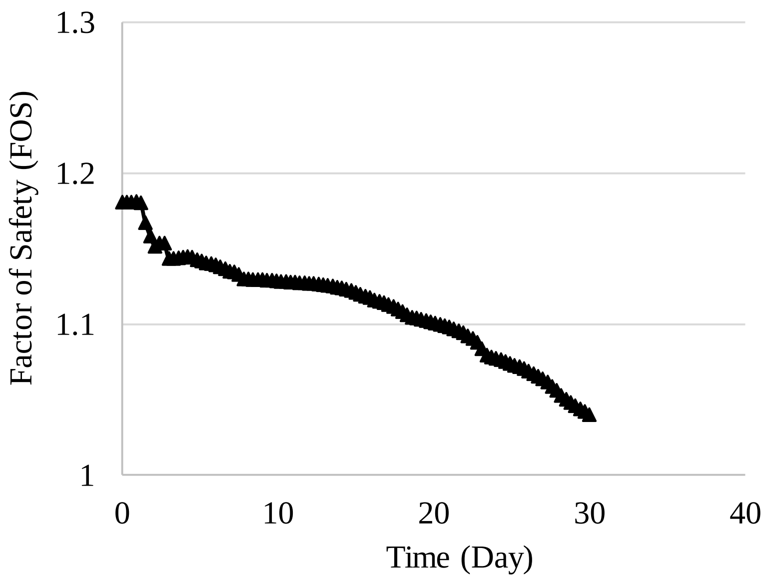


Figure 7-3 changes in FOS with time

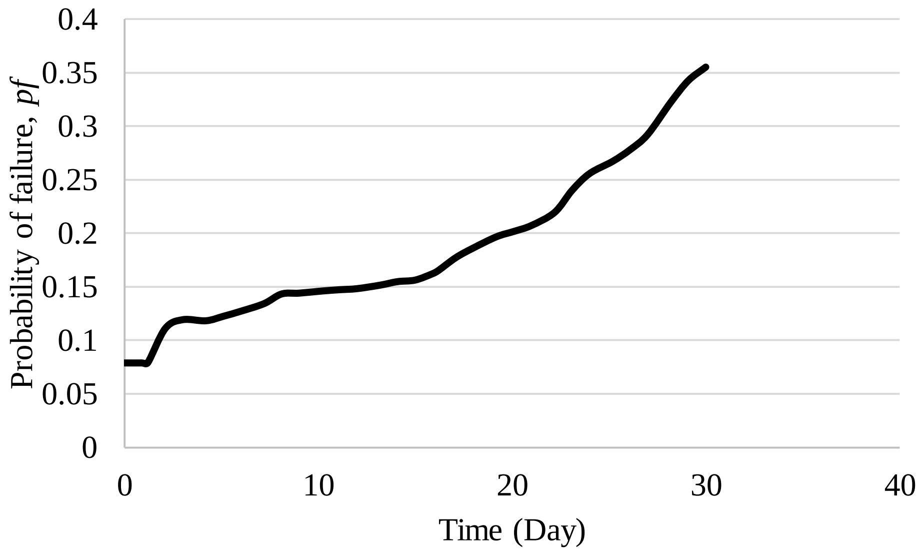


Figure 7-4 Changes in probability of failure with time

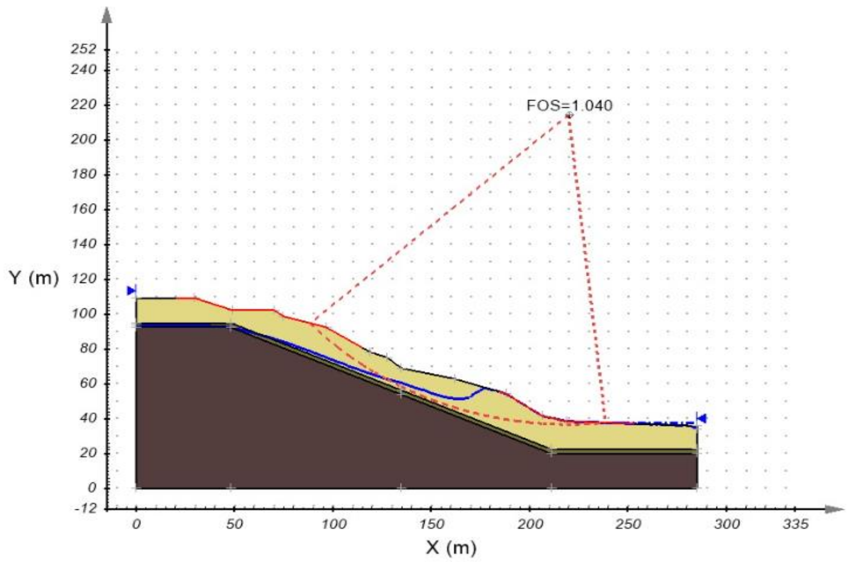


Figure 7-5 Critical slip surface with lowest factor of safety after 30 days of extreme rainfall at 10-year ARI with GLE method

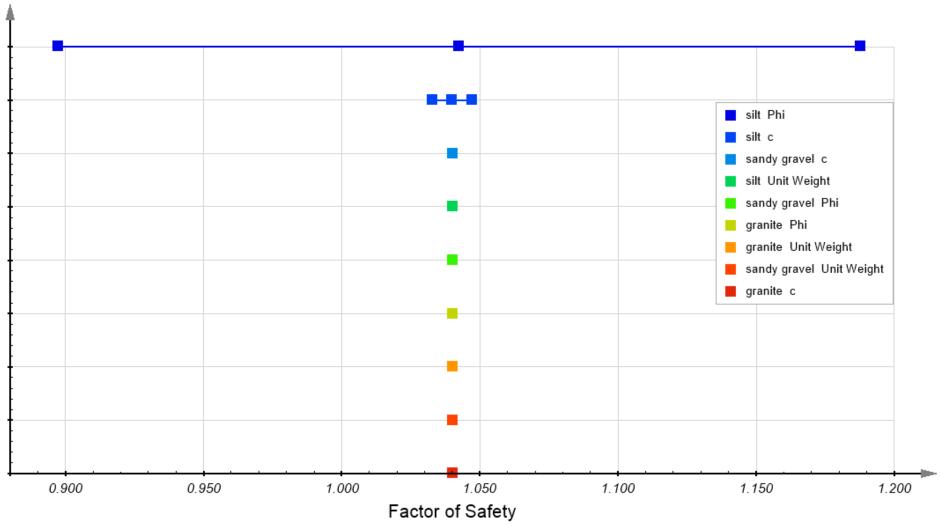


Figure 7-6 Relative influence of material parameters to FOS

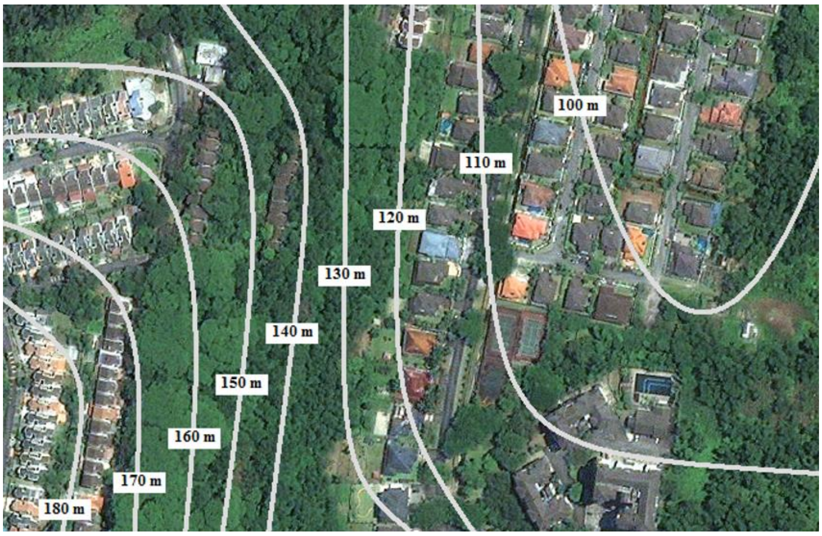


Figure 7-7 Aerial image of the case study slope. *Source:* (Lee et al. 2010)

Figure 7-8 predicted runout of the potential landslide

7.6 Risk estimation and quantification results

From Figure 7-5, the retrogression distance, *rL*, was calculated to be 150 m. Relationship between retrogression distance, *rL* of a landslide and its subsequent runout, *Lu* was formulated to be $Lu = 3.6322rL^{0.8475}$ as defined in *Eq. (6-6)* (Sim et al. 2024). Using the established empirical model, the runout was subsequently calculated at 254 m which is a little higher than the actual runout that occurred (210 m). The total travel distance from the crest to the toe of the slide will thus be approximately 404 m. These estimates are a little more on the conservative side (real life total travel distance 330m). The model was made to give runout parameters on the conservative side and to provide a safety margin for emergency situations, avoiding underestimation of risk and hazard. As stated by (Hungr et al. 2005), a conservative prediction could be highly suitable for initial evaluations of landslide susceptibility and hazard. In addition, although the prediction was conservative, it is not unrealistic as the model was developed on the basis of real life landslide cases (Hungr et al. 2005). With a ten-year return period rainfall, (probability of occurrence of 0.1 (1 in 10)) and a resulting probability of slope failure of 35.5% or 0.355, the probability where a landslide would occur and that would result in a total runout distance of 404 m is thus computed to be at 0.0355. The estimated landslide affected area is plotted in Figure 7-8 taking into account the predicted travel distance of 404 m and the satellite image interpretation of

Figure 7-7. The residential area comprises mainly of houses and its occupants were treated as elements of risk. The loss of human lives is the main focus for risk estimation. There are around 21 houses located in the affected area as seen in Figure 7-8**.**

After conducting comprehensive probabilistic slope stability analyses, the likelihood of an annual occurrence (or frequency) of a landslide covering a total travel distance of 404 meters, capable of potentially damaging 21 houses situated at the toe of the slope in the case study, has been calculated to be P(*Event*) = 0.0355. As stated in section 3.6.4.2, a value of 0.55 will be applied for P(*Hit*|*Event*), and utilizing equation (3-19), P(*Individual House Hit*) i.e. the likelihood of the landslide hitting a house while residents are inside is calculated at 1.92E-2. Furthermore, P(*Death*|*Hit*) is specified as 0.2 in section 3.6.4.3. These values were utilized in calculating the societal risk associated with the landslide event of the case study.

The calculation for the F-N curve is tabulated in Table 7-1. As mentioned in section 3.6.6.4, Wong et al.'s (2006, 2018) approach was used, as it has been proven to yield data better suited for plotting on the F-N diagram, resulting in a clearer representation (Figure 7-9) (Winter 2018; Winter and Wong 2020). From the F-N curve in Figure 7-9, it was evident that the value of F for N of 4 -5 deaths falls between 10 years to 100 years. In reality, it didn't take more than 100 years after the construction of Bukit Antarabangsa for landslides to cause fatalities. The 4-5 deaths occurred in 2008, which was over 10 years after the development of Bukit Antarabangsa began around the time of the Highland Tower incident in 1993 (Lee et al. 2014; Sim et al. 2023c). This aligns well with actual reports of the landslide tragedy at the site. Furthermore, the F-N curve falls in the "Unacceptable" region when benchmarked against the risk criterion of Malaysia (Sim et al. 2023a). This also means that the study site falls into the unacceptable category of yearly fatalities established by Hong Kong (Geothechnical Engineering Office 1999; Sim et al. 2022b). This precariousness explains the landslide tragedy that occurred in real life at the site and also it is of the utmost priority concerning slope mitigation or countermeasure strategies.

Table 7-1 Calculation for plotting F-N curves for residents at the site using. The consequence class simply refers to the different levels of house occupancy.

House Occupancy [2]/ Consequence Class	**P(Death|Hit) [3]**	**Number of Houses [4]**	**Frequency of Occurrence of N Deaths [5] = [1] x [3] x [4]**	**Cumulative Frequency of occurrence of N or more Deaths (F) [6]**
1	0.169642857	1	3.25E-03	6.83E-02
2	0.169642857	2	6.50E-03	6.50E-02
3	0.169642857	3	9.75E-03	5.85E-02
4	0.169642857	5	1.63E-02	4.88E-02
5	0.169642857	4	1.30E-02	3.25E-02
6	0.169642857	3	9.75E-03	1.95E-02
7	0.169642857	2	6.50E-03	9.75E-03
8	0.169642857	1	3.25E-03	3.25E-03
[1] P(Individual House Hit)		1.92E-02		

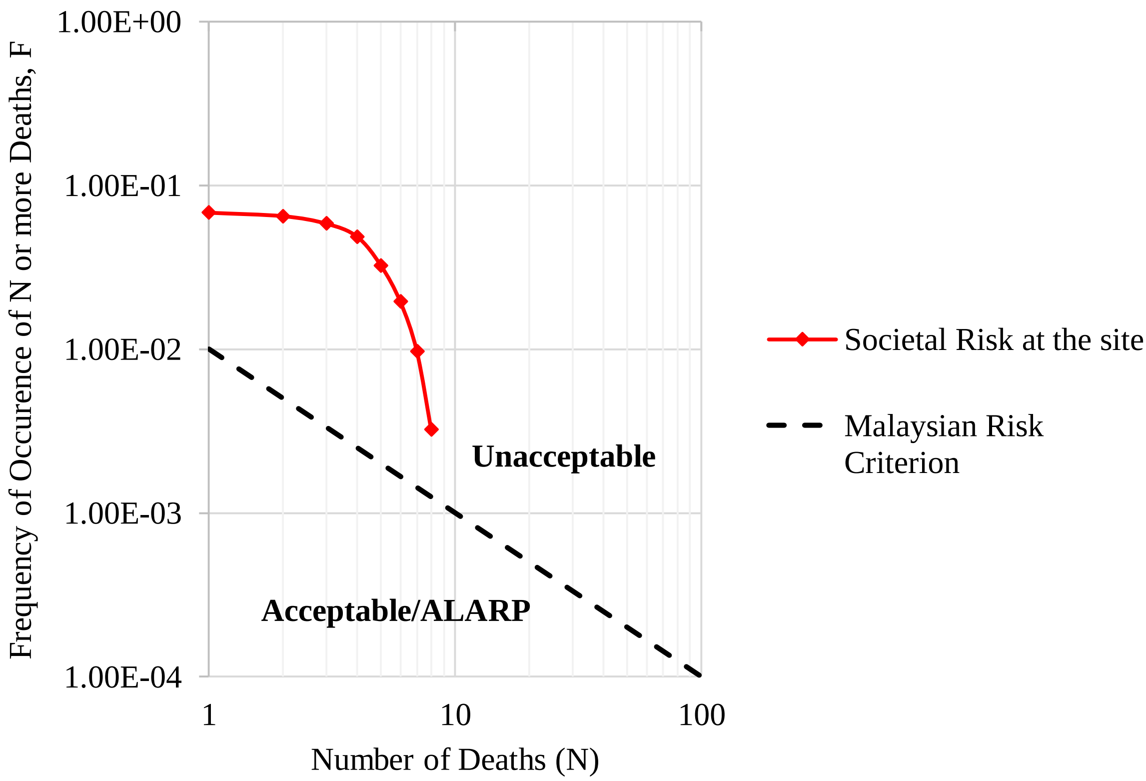


Figure 7-9 F-N curve of the site benchmarked against the interim Malaysian Risk (Sim et al. 2023a)

7.7 Concluding remarks

This section illustrates how one can apply the proposed F-N risk criterion through Quantitative Risk Assessment (QRA). QRA emerges as a proficient method for comprehending, forecasting, and expressing the levels of risk associated with landslides at a specific location. In this section, QRA for the impact of a landslide on residents (potential fatalities) was reported for a hazardous site in Malaysia through a selected case study. Subsequently, runout of the landslide of the case study was predicted using the developed empirical model. Risk levels were estimated for elements at risk located along the run-out paths of the landslide and the overall risk to society was expressed using an F-N diagram, showcasing the practical implementation of the proposed Malaysian risk criterion.

The methodology takes into account the probability of a slope experiencing a landslide event, predicting both the runout distance and the potentially affected zone. It also factors in the conditional probabilities associated with a house being affected, given an event, and the likelihood of damage or death occurring when a house is affected. The analysis encompasses scenario involving a house being struck by a landslide.

Probabilistic slope stability analysis has shown that the site considered in this study is already in the *unsatisfactory* level of performance at initial stage by the standards of U.S. Army Corps of Engineers as seen in (Petrovic et al. 2016). After 30 days of extreme rainfall, the performance further plummeted to *hazardous* level. The overall travel distance from the crest to the toe of the landslide was predicted to be around 404 m. These estimates are a little more on the conservative side as the real-life total travel distance was 330 m. The model was made to give runout parameters on the high side and to provide a safety margin for emergency situations, avoiding underestimation of risk and hazard. A conservative approach could be highly suitable for initial evaluations of landslide susceptibility and hazard (Hungr et al. 2005). The societal risk was conveyed through the F-N diagram, indicating that the annual risk falls within the unacceptable zone of the proposed Malaysian risk criterion (Sim et al. 2023a).

Furthermore, the societal risk level well described the landslide disaster that occurred in real life at that site. This also shows that the vulnerability value of $P(Death|Hit) = 0.2$ used in this study seems fitting to context of the study. This is not surprising as previous reports regarding the landslide incident on the same slope brought about the destruction of 14 bungalows resulting in 4 to 5 deaths with 14 individuals sustained injuries and 93 people escaped unharmed (Huat et al. 2012; Azmi et al. 2013; Lee et al. 2014). The analyses function as an initial warning system for areas prone to significant landslides, capable of causing extensive damage. Conducting a thorough stability analysis of the slopes in specific regions is crucial to determine the risks and vulnerability of the population and to implement mitigation measures to minimize the potential risks to both lives and property. The assessment approach demonstrated in this chapter can be applied to future hillside developments in Malaysia, especially when human lives are concerned.

8 Conclusion and Recommendations

8.1 Conclusion

This thesis sought to create a risk-informed approach for rainfall-induced slope instability assessment as an enhancement to the conventional deterministic FOS method widely employed in Malaysia. The approach involved introducing novel modifications to rectify deficiencies identified in the existing Malaysian landslide risk criteria, particularly in comparison to societal landslide risk criteria. These adjustments were designed to reduce the inherent acceptance of fatalities within the current Malaysian landslide risk criteria, based on analyses of survey outcomes and expert interviews. The emphasis was placed on catering to the needs of the majority of communities in Malaysia. The applicability of the improved criterion was successfully tested using a case study.

Four conclusions are drawn in regards to the four objectives of the present study stated in Chapter 1. The conclusions are presented as follows.

8.1.1 Landslide F-N curve in Malaysia (addressing Objective 1)

A comprehensive analysis was conducted to develop a societal landslide risk curve covering the period from 1961 to 2022 in order to establish criteria for evaluating landslide risk in Malaysia. As far as the authors are aware, no similar curve has been created for Malaysia before. The curve for Malaysia during this period was divided into three sections. The first section involves low casualty, high frequency landslides resulting in 1 to 1.5 deaths annually, occurring slightly more than once per year. The second section involves landslides with 10 to 100 casualties, occurring at a frequency ranging from 0.03 to 0.2 times annually. The third section involves very high casualty, low frequency events with over 100 casualties, occurring at a frequency ranging from 0.01 to 0.03 times annually.

It was found that the societal landslide F-N curve of Malaysia exhibits similar risk patterns to those of Hong Kong, Italy, and Colombia. The frequency of one death in Malaysia is closely aligned with that of Hong Kong, slightly exceeding F=1, intersecting at approximately (N=42, F=0.05). These countries share mountainous terrain and heavy rainfall throughout the year. Colombia, being a tropical country with annual rainfall exceeding 2500mm, shows a similar trend to Malaysia, albeit with significantly higher death frequencies, possibly due to Colombia's low Gross National Income (GNI) and Value of Statistical Life (VSL). Additionally, the Andean mountain region, with a population density of 110/m^2 and annual rainfall of up to 11,000mm, contributes to Colombia's high landslide risk. Consequently, Colombia's F-N curve ranks highest due to these factors. Therefore, it is reasonable to conclude that Malaysia's F-N curve lies below those of Italy and Colombia due to Malaysia's less rugged terrain compared to Italy and Colombia.

Most of the contents in regards to this objective have been published as (Sim et al. 2023a, b).

8.1.2 Public and experts' perception of landslide risk in Malaysia (addressing Objective 2)

Analysis of the survey questionnaire and expert interview results showed that respondents are more worried about technological than to natural risks, and specifically to health hazard (52%), followed by travel hazard (51.3%). Landslide ranked 4th (being at 45.19% after industrial hazard which is 50.3%) than to natural risks which was not surprising as experts noted that people always fear the unknown or things that they do not have access to information. Of the natural hazards, they felt more exposed to floods (65.8%), followed by landslides (50.5%) and then earthquake (48.3%), Tsunami (46.9%). This was in general agreement with the experts' as they noted that storm water surge flooding occurs most frequently and covers huge areas, whereas landslides (the second most frequently occurring disaster in Malaysia) are more localized and that there are not as many people who live on slopes as of now compared to those who live on lowlands. Analysis of the socio-demographic factors indicated that gender, educational level, and occupation were the significant factors affecting landslide frequency of acceptance.

The clearest difference of opinion between experts and public was in terms of the risk acceptance. Experts were able to accept a higher frequency of death (i.e. 1 death in 1 year to 10 years), possibly due to their experience and understanding in dealing with landslides in the country. The public, in contrast, mostly chose the maximum option available which was a modal frequency of once in 10,000 years or more (i.e. 25.8% of all respondents chose once in 10,000 years or more as acceptable frequency for landslide occurrence that results in 1 death). Indeed, there are some respondents who will accept higher risk, i.e. those who live near to slopes and those with lower income bracket. The huge range of 80% of the responses over the 1E-2 to ≥1E-4 per annum raw probability range for 1 death scenario signified a wide diversity of risk attitudes. Overall, participants showed a desire for a low landslide risk to life which is expected. However, in reality, some of the participants continue living with landslide risks way higher than what they expressed in the questionnaires, hence disclosing a higher "acceptance" of risk than expressed. Risk averse attitude is high among professionals and this opposed the opinions of landslide experts (also professionals) who are willing to accept a higher frequency of occurrence. This could be due to the risk being tolerated rather than accepted which is a crucial distinction.

The results of this study shall provide policy-makers with useful information for improving landslide risk management system, i.e. in establishing a risk criterion for Malaysia. Crucial insights were given by the respondents' and experts' preferences on acceptable risk level, such as the frequency of acceptance for a landslide event that results in certain number of deaths.

The results pertaining to this objective have been published as (Sim et al. 2023a).

8.1.3 Proposed landslide tolerable and acceptable risk criteria for Malaysia (addressing Objective 3)

One of the significant contributions of this study is the innovative enhancement made to Malaysia's societal landslide risk criteria. The newly improved criterion for societal landslide risk evaluation in Malaysia may also be applicable to similar nations. The criterion aligns with public expectations and incorporates suggestions from landslide experts dealing with landslide hazards. The proposed criterion is put forth for consideration by analysts and decision-makers involved in addressing landslide hazards. The novel Malaysian risk criterion omits the broadly acceptable and intense scrutiny zones of the Hong Kong criterion considering them unnecessary. The inclusion of such zones can often result in confusion when these diagrams are communicated to the general public. A threshold of one death per 100 years (similar to UK's risk tolerance threshold) addresses concerns for about 70% of communities, aligning with the generally accepted range of 1E-2 to 1E-3. Adopting a guideline of 1E-5 to represent the threshold for 1,000 deaths corresponds to the modal acceptance level of landslide probabilities (≥ 1E-4). While Malaysia's interim risk criterion is one magnitude higher than Hong Kong's, both share the same risk aversion gradient. The criterion, though not identical, maintains substantial similarities as suggested by landslide experts. The newly devised criterion, considering perceptions of communities across regions and vulnerability levels, offers a more representative framework for Malaysia.

The results pertaining to this objective have been published as (Sim et al. 2023a).

8.1.4 Validation of the proposed QRA through case study (addressing Objective 4).

The final stage entails validating the risk criterion through the implementation of Quantitative Risk Assessment (QRA) on a chosen case study. In the initial segment of this stage, an empirical model was devised to forecast landslide runout distance specifically tailored for Malaysia. The empirical models proposed in this study have shown promising outcomes, with relative errors falling within ±30%, consistent with findings from documented studies. These models, such as Eq. (6-5) and Eq. (6-7), which integrate *rL*, as well as Eq. (6-1), incorporating *H* and *V*, demonstrate a robust correlation, as indicated by their high R^2 values of 0.7 and above, coupled with p-values below 0.05, signifying significant associations between the variables. Conversely, upper limit models that incorporates the parameter *rL*, Eq. (6-6 and 6-8) have been developed with a conservative approach, aiming to include a safety margin for emergency scenarios, thereby averting the underestimation of risk and hazard. A conservative approach could be highly suitable for initial evaluations of landslide susceptibility and hazard (Hungr et al. 2005).

Probabilistic analysis of slope stability has indicated that Bukit Antarabangsa, the slope of case study initially falls below satisfactory performance levels, with a probability of failure (*pf*) at 0.0786, as per the criteria outlined by the U.S. Army Corps of Engineers. Subsequent to 30 days of extreme rainfall, the performance deteriorates further, reaching a hazardous level with a *pf* of 0.355. Using the runout model developed ($Lu = 3.6322rL^{0.8475}$), the total travel distance from the crest to the toe of the landslide was approximately 404 meters. The societal risk, as depicted by an F-N curve, illustrates that the occurrence of 4-5 deaths (F) corresponds to a timeframe ranging from 10 years to 100 years (N). However, in reality, it took less than a century after the construction of Bukit Antarabangsa for fatal landslides to transpire. The incidents resulting in 4-5 deaths took place in 2008, occurring more than a decade after the commencement of development in Bukit Antarabangsa, which began around the time of the Highland Tower incident in 1993. This correlation aligns closely with documented reports of the tragic landslide at the location. Additionally, when compared to Malaysia's recently established risk criterion, the F-N curve falls within the "Unacceptable" category. This vulnerability verifies the real-life landslide disaster at the site and underscores the paramount importance of prioritizing slope mitigation or countermeasure strategies.

Majority of the contents of this objective have been presented in a conference and it is now accepted for publication.

8.2 Recommendations for future work

This thesis provided valuable perspectives on assessing slope instability triggered by rainfall through a risk-informed approach. The discussion also highlighted potential avenues for future research that emerged from the findings.

- **Improvement of the landslide runout prediction model:** The present empirical models does not take into account more complicated parameters, such as the relationship between landslide types; soil parameters with travel distance. The dataset used for the empirical model development study is notably limited, predominantly featuring rainfall-triggered landslides. Therefore, it would be beneficial to address this limitation by augmenting the existing dataset with additional geotechnical information, incorporating a broader range of landslide cases, and considering more sophisticated parameters to enhance the empirical models. A more robust model would be required for the development of landslide hazard maps.

- **Comprehensive QRA on more case studies:** Uncertainties arose during the computation of population risk, primarily stemming from the challenge of estimating the likelihood of being in the 'wrong place at the wrong time'; the probability of death when a building is impacted by a landslide. Approaches for evaluating landslide risk should consistently account for these uncertainties and be applicable for implementation across extensive areas without excessive data demands. It is crucial to integrate these uncertainties into the analysis, presenting results as a spectrum of risk values, as demonstrated in this study where we assessed the range of expected losses from the affected zone owing to the landslide runout from the crest to the toe. Given the uncertainties associated with diverse input data in the risk analysis, it is advisable to conduct a comprehensive risk assessment on a large scale to inform the planning of risk reduction strategies. Furthermore, these uncertainties can be modelled through various scenarios based on value ranges, employing simulation methods such as Monte Carlo simulation—a potential avenue for exploration in subsequent studies. In other words, incorporating uncertainty quantification methodologies to assess the confidence intervals of estimations would greatly enhance the robustness and reliability of the results.

- **Studying the methods to improve the population mentality:** The analyses of the results from the questionnaire surveys and expert interviews have highlighted the necessity to devise strategies for shifting the mindset of the population which is crucial to establish more robust and stringent risk guidelines in Malaysia. It is imperative for regulators to comprehend the perspectives of all stakeholders and navigate accordingly, as effective management and operation of risk reduction procedures require active involvement from all parties.

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Appendix

Appendix 1. Photos taken during interviews with landslide experts

Left: interview with Dr Niizarr bin Abdurahman, JKR Cerun (government); Right: Interview with Ir Dr Low Tian Huat (practitioner)

Appendix 2. Proof of ethics application approval to distribute survey questionnaires and to conduct interviews with landslide experts

UNM Ethics Committee Reviewer Decision Form
(version 5, Oct 2021)

University of Nottingham
UK | CHINA | MALAYSIA

Ethics Committee Reviewer Decision

This form must be completed by each reviewer. Each application will be reviewed by at least two members of the Ethics Committee. Reviews should be completed electronically and emailed to the **Ethics Administrator** (serec@nottingham.edu.my) from a University of Nottingham email address.

Applicant full name:	SIM KWAN BEN
Application identification number:	SKB050722

REVIEWED BY:

Reviewer ID:	BN
Date:	21 July 2022
Outcome:	Approval Awarded

Major amendments required:

No comment

Minor amendments required:

No comment

Comments:

No comment

Appendix 3. Questionnaire survey on the landslide risk perception in Malaysia

Introduction

Landslide risk perception in Malaysia

Welcome! You are invited to participate in the survey to gather information about your perception on landslide disasters in Malaysia. This survey will take about 10 minutes to complete. This questionnaire is part of a research inquiry of a PhD Civil Engineering student from University of Nottingham Malaysia Campus. The objective of this survey is to study the views, perception, knowledge and opinions of the public on landslide risk in Malaysia.

The target participants of this research are individuals who are currently living in Malaysia. All participation in the survey is on voluntary basis. Please note that there is neither right nor wrong answer.

If you have any question regarding this study, please contact Mr. Sim Kwan Ben (evxks8@nottingham.edu.my). If you have any queries or complaints about this research, please contact the project supervisor of this research: Associate Professor Dr. Lee Min Lee, (MinLee.Lee@nottingham.edu.my). If this does not resolve the query to your satisfaction, please write to the Administrator to Science & Engineering Research Ethics Committee (serec@nottingham.edu.my) who will pass your query to the Chair of the Committee.

Note: The collection of your personal data is carried out in accordance with the terms stated within (i) The University of Nottingham's Royal Charter, (ii) the UK's General Data Protection Regulation (GDPR), (iii) The Malaysian Personal Data Protection Act 2010 and (iv) the University's Code of Research Conduct and Research Ethics. These collectively spell out the legal basis for processing your personal data, your rights as a data subject as well as data sharing/management arrangements. The full Privacy Notice that spells out your rights as a data subject is available upon request.

Consent form **Agreement of Participation**

The answers provided in this survey will be used as data for research purposes.

If you agree to participate in this study, please select 'Yes'. If you do not agree to participate in this study, please select 'No'.

Do you agree to participate in this study?

○ Yes

○ No

Section 1: Demographics

Q1 Age:

- ○ 18–30 years old
- ○ 31–45 years old
- ○ 46–60 years old
- ○ 61 years old and above

Q2 Gender:

- ○ Male
- ○ Female

Q3 Highest level of education:

- ○ Primary school
- ○ Secondary school
- ○ College/ University – diploma / undergraduate
- ○ University - Postgraduate

Q4 Occupation:

- ○ Student
- ○ Non-professional
- ○ Professional
- ○ Self-employed
- ○ Unemployed

Q5 Income:

- ○ < RM 1500 /month
- ○ RM 1501–3000 /month
- ○ RM 3001–5000 /month
- ○ RM 5001–10,000 /month
- ○ > RM 10,000 /month

Q6 Marital status:

- ○ Single
- ○ Married with kids
- ○ Married without kids

Q7 Geographical location of your house:

- ○ City
- ○ Rural

Q8 Type of house you live in:

- ○ Low rise apartment/flat/condominium (< 5 storeys)
- ○ High rise apartment/flat/condominium (> 5 storeys)
- ○ Landed house

Q9 Are you currently living in your own unit or rented unit?

- ○ Own unit
- ○ Rented unit

Q10 Is your current residence located on or near to a slope?

- ○ On or Near to slope (within 1 km radius)
- ○ Far from slope (beyond 1 km radius)

Q11 Have there ever been any landslide occurrences near your house or within 1 km radius in your area?

- ○ Yes
- ○ No

Section 2: Views on landsliding

Q12 Where do you normally obtain information regarding landslides?

- ○ I don't know anything about landslides
- ○ Personal experience
- ○ Media
- ○ Published reports by geotechnical government authorities

Q13 Ranking of landsliding and other hazards, with (1) being least concerned – (5) most concerned:

	1	2	3	4	5
Landslide	○	○	○	○	○
An occupational hazard (the respondent's job)	○	○	○	○	○
An industrial hazard (petrochemical plant incident, dam failures, etc.)	○	○	○	○	○
Health hazard (smoking, drinking, air/water pollution)	○	○	○	○	○
Travel hazard (driving a car, pedestrian, air travel)	○	○	○	○	○

Q14 Ranking of landsliding and other natural events, with (1) being least concerned – (5) most concerned:

	1	2	3	4	5
Landslide	○	○	○	○	○
Flood	○	○	○	○	○
Earthquake	○	○	○	○	○
Tsunami	○	○	○	○	○
Haze	○	○	○	○	○

Q15 In your opinion, which of the following factors have the most influence in the occurrence of landslides? Rank them with (1) being least influential – (5) most influential

	1	2	3	4	5
Rainfall	○	○	○	○	○
Logging	○	○	○	○	○
Climate change	○	○	○	○	○
Failure of retaining structures	○	○	○	○	○

Q16 If a landslide occurs, in addition to casualty, what are other consequences of the disaster that you are concerned about? Rank them with (1) being least concerned – (5) most concerned

	1	2	3	4	5
Property loss	○	○	○	○	○
Disease occurrence	○	○	○	○	○
Environmental destruction	○	○	○	○	○
Social chaos	○	○	○	○	○

Q17 What distance do you think may be acceptable between your living or working place and the location with history of landslides?

- ○ <1 km
- ○ 1–5 km
- ○ 5 – 10 km
- ○ 10 – 20 km
- ○ > 20km

Q18 What frequency of occurrence of landslides that kill 'X' number of people can you accept in your community?

	Once every 1 month	Once every 6 months	Once every 1 year	Once every 10 years	Once every 100 years	Once every 1,000 years	Once every 10,000 years or longer
1 death	○	○	○	○	○	○	○
10 deaths	○	○	○	○	○	○	○
100 deaths	○	○	○	○	○	○	○
1,000 deaths	○	○	○	○	○	○	○

Q19
Insurance Premium

If a landslide disaster occurs in your community or village, what level of insurance premium are you willing to pay yearly?

○ < RM 200

○ RM 200–500

○ RM 500–1000

○ RM 1000–2000

○ > RM 2000

Appendix 4. Landslide records in Malaysia: 1961-2022

Deaths	year	location	Date
16	1961	Ringlet, Cameron Highlands	11-May-61
1	1966	PDRM Headquarters, tanjong Rambutan, Ipoh, Perak	10-Oct-66
4	1967	Government Agricultural Experimental Station (MARDI), Tanah Rata, Cameron Highlands	26-Jun-67
2	1969	Jalan University, Petaling Jaya	23-Sep-69
1	1972	New Lahat Tin Mine, Ipoh, Perak	18-Nov-72
7	1973	Yew Meng Tin Mine, Gunong Rapat, Ipoh, Perak	22-Jun-73
42	1973	Kampung Kachang Pu□h, Gunung Cheroh, Ipoh	18-Oct-73
2	1974	Bharat Tea Estate, Cameron Highlands	3-May-74
4	1975	Ho Pak Yew Tin Mine, Tronoh, Perak	5-Feb-75
1	1978	Luen Seng Tin Mine, Gopeng, Perak	9-Apr-78
1	1979	Asia Mining Sdn Bhd, Perak	9-Nov-79
24	1981	Kampung Kandan, Puchong, Selangor	4-Mar-81
2	1985	Jalan Pending, Kuching, Sarawak	1-Jul-85
1	1987	Taman Yoon Seng, Seremban, Negeri Sembilan	22-May-87
3	1989	Bukit Permai, Ampang, Selangor	14-Nov-89
1	1993	KM 58, Kuala Lipis - Gua Musang	24-Oct-93
2	1993	KM 25.5, Kuala Lumpur - Karak Highway	23-Nov-93
0	1993	KM 63, Kuala Lumpur - Karak Highway	28-Nov-93
48	1993	Highland towers, ulu klang	11-Dec-93

1	1993	km 59.5, Timur-Barat Highway	31-Dec-93
3	1994	Puchong Perdana, Puchong, Selangor	2-May-94
1	1994	Cameron Highlands, Pahang	9-Dec-94
21	1995	KM 39, Genting Sempah, KL - Karak Highway	30-Jun-95
1	1995	Kea Farm, Tringkap, Cameron Highlands	24-Oct-95
7	1995	Cameron Highlands, Pahang	1-Dec-95
1	1995	Taman Chiap Aik, Seremban, Negeri Sembilan	20-Dec-95
1	1996	Km 308.8, PLUS highway, gua tempurung, Ipoh	6-Jan-96
15	1996	KM 1.5, KL-Karak Highway, Selangor	15-Jul-96
38	1996	Perkampungan Orang Asli Pos Dipang, Perak	29-Aug-96
3	1996	Kuala Terla, Cameron Highlands	10-Oct-96
1	1996	Kampung Baru, Gelang Patah, Johor	17-Oct-96
302	1996	Taufan Gregg, Keningau, Sabah	26-Dec-96
1	1997	Jalan Pantai, Kuala Lumpur	11-May-97
3	1997	KM 17 Lebuhraya Ampang - Ulu Klang, Selangor	25-Dec-97
17	1999	Jalan Leila, Kg Gelam, Sandakan, Sabah	8-Feb-99
1	1999	Jalan Wangsa 1, Bukit Antarabangsa, Selangor	15-May-99
16	2002	Kg. Ruan Changkul, Simunjan, Sarawak	28-Jan-02
8	2002	Taman Hillview, Ulu Klang, Selangor	20-Nov-02
1	2003	Kg. Lanchang Sijo, Serian, Sarawak	5-Feb-03
1	2004	Kg. Podam, Bau, Sarawak	24-Jan-04
1	2004	Taman Sri Harmonis, Gombak, Selangor	5-Nov-04

4	2004	KM 59, Kuala Lipis - Merapoh, Pahang	29-Nov-04
1	2004	Damansara Century Heights, Tol Sg Penchala, Selangor	1-Dec-04
2	2004	Taman Bercham Utama, Ipoh, Perak	2-Dec-04
1	2006	Sungai Menson, Cameron Highlands (Agriculture, date and month not	1-Jan-06
3	2006	Kg. Sundang Darat, Batu Sapi, Sandakan, Sabah	8-Feb-06
4	2006	Kg. Pasir, Ulu Klang, Selangor	31-May-06
1	2006	KM 8.5, FT606, Pelabuhan Sepanggar, Kota Kinabalu, Sabah	26-Jun-06
2	2006	Kuari Gunung Jerai, Gurun, Kedah (Mining)	7-Nov-06
1	2006	Kg. Bukit Sungai Seputeh, Lembah Jaya, Ampang, Selangor	11-Nov-06
4	2007	Lorong 1, Kampung Baru Cina, Kapit, Sarawak	26-Dec-07
2	2008	Ulu Yam Perdana, Kuala Selangor, Selangor	30-Nov-08
5	2008	Taman Bukit Mewah, Bukit Antarabangsa, Ulu Klang, Selangor	6-Dec-08
2	2009	Bukit Kanada, Miri, Sarawak	16-Jan-09
0	2009	Bukit Ceylon, Kuala Lumpur	12-Feb-09
2	2011	Residential areas in Sandakan, Sabah	29-Jan-11
16	2011	Rumah Anak Ya□m At-Taqwa Hulu Langat, Selangor	21-May-11
7	2011	Perkampungan Orang Asli Sg. Ruil, Cameron Highlands	7-Aug-11
0	2012	Puncak Se□awangsa, Kuala Lumpur	29-Dec-12
2	2012	Kampung Terusan, Lahad Datu	18-Feb-12
0	2013	Kingsley Hill housing project at Putra Height	4-Jan-13
1	2013	Kampung Masilou, Kundasang	15-Jul-13

1	2014	Kampung Melayu Subang, Subang, Selangor	18-May-14
2	2014	Ulu Temani, Tenom, Sabah	4-Jun-14
3	2014	Quarry at Bukit Sagu 4, Kuantan, Pahang	8-Sep-14
5	2014	Kg. Raja, Pekan Ringlet, Lembah Bertam, Cameron Highlands	5-Nov-14
2	2014	KM 46, Jalan Brinchang-Tringkap, Cameron Highlands	30-Dec-14
3	2015	Tapak Bintong, Tringkap, Cameron Highlands	1-Jan-15
1	2015	Desan Corina, Cameron Highlands	1-Jan-15
18	2015	Gunung Kinabalu, Sabah	5-Jun-15
0	2015	Kuala Lumpur-Karak Expressway (between Lentang and Bukit Tinggi and Gombak Bentong Old Road	11-Nov-15
1	2016	Terisu, Cameron Highlands	14-Jan-16
1	2016	Ara Damansara Selangor	23-Feb-16
1	2016	Kuala Pilah, Negeri Sembilan	28-Feb-16
1	2016	Lombong pAsir Linggiu, Bandar Tenggara, Kota Tinggi	9-Apr-16
1	2016	Bukit Manggak, Padang Terap, Kedah	6-Oct-16
0	2016	Serendah, Rawang, Selangor	26-Nov-16
2	2016	Hutan matau, Jerantut, Pahang	11-Dec-16
1	2017	Flower Orchard, Batu 49, Kuala Terla, Kampung Raja, Cameron Highlands	25-Jan-17
0	2017	Jalan Tun Sardon-Bukit Baru Road, Paya Terubong (causing the main roads leading to Balik Pulau and George town to be blocked)	21-Sep-17
11	2017	Housing Project at Lengkok Lembah Permai, Tanjung Bunga (857am)	21-Oct-17
10	2017	Bukit Bendera area	5-Oct-17

0	2017	Bukit kukus project site for constructing twin road connecting paya terubong to relau	19-Oct-17
0	2018	Landslide of 0.4 hectare land at telipok Residential scheme, Kota kinabalu which destoryed 12 houses	20-Oct-17
0	2018	Ladang lada, Tanjung Bungah	5-Jan-18
0	2018	heavy rains with strong winds caused 14 concrete beams measuring 25m fell on the slopes at Bukit Kukus project	11-Oct-18
3	2019	Batu 49, Kampung Tiga, Kuala Terla, Cameron Highlands	14-Oct-18
0	2019	Jalan Ringlet-Blue Valley	25-May-19
0	2019	Jalan Ulu Merah	25-May-19
0	2019	Jalan 19 / 144A, Taman Bukit Cheras (wall failure caused by earthworks)	12-Jun-19
4	2019	Resort near the site of the landslide at Jalan Batu Ferringhi, Tanjung Bungah	26-Jun-19
2	2020	Mount Jerai, near Gurun, Kedah,	23-Mar-20
0	2020	Taman Kelab Ukay, Bukit Antarabangsa, Ulu Klang, Selangor due to continuous rain, resulting in soil movement.	29-May-20
2	2020	Banjaran Hotsprings Retreat, Tambun, Ipoh, Perak.	10-Nov-20
0	2020	Raub-Bukit Fraser Road	21-Dec-20
0	2020	Damansara Utama, Selangor	29-Dec-21
0	2021	Segamat-Kuantan Highway, near Pekan, Pahang.	1-Jan-21
0	2021	Old Bentong-Raub trunk road	3-Jan-21
0	2021	Kenyir-Felda Aring road was closed due to landslide caused by heavy rains.	6-Jan-21
0	2021	Padawan, Sarawak.	12-Jan-21

0	2021	Kemensah Heights, Ampang, Selangor due to underground water flow.	17-Jan-21
2	2021	A landslide, caused by continuous rainfall. Simpang Pulai-Blue Valley road near Cameron Highlands	2-Dec-21
0	2021	Simpang Pulai-Blue Valley road near Cameron Highlands	20-Dec-21
4	2022	Taman Bukit Permai.	10-Mar-22
31	2022	Batang Kali, Selangor, Malaysia	16-Dec-22