CIDB MALAYSIA

MINISTRY OF WORKS

CREAM
CONSTRUCTION RESEARCH INSTITUTE OF MALAYSIA

MANUAL

FOR LANDSLIDE VULNERABILITY ASSESSMENT AND RISK ANALYSIS FOR CRITICAL INFRASTRUCTURE (CI) IN MALAYSIA

FOREWORD

A research contract on the study and development of "Guidelines for Landslide Vulnerability Assessment and Risk Analysis for Critical Infrastructure in Malaysia" was initiated and funded by Malaysian Construction Industry Development Board (CIDB) via its subsidiary Construction Research Institute of Malaysia (CREAM). The purpose is to develop the capacity and capability of construction industry players related to high land disaster risk reduction agenda by emphasis on professionalism, innovation and knowledge in the endeavour to improve the quality of life.

This cross-disciplinary research was assigned to a team of professionals from geosciences, land surveyors, geotechnical engineers, industry players and academicians. Through more than one-year duration, the product of the study has successfully produced four documents, i.e two interim reports, a manual and a guideline.

The manual explains and elaborate with case study on the methodology of assessing and developing the parameters-indicators of landslide vulnerability assessment and risk classification of critical infrastructures. The semi-quantitative approach is divided into 4 main stages namely data acquisition and pre-processing of geospatial data, improvements of landslide vulnerability cluster, indicators, sub-indicators and weight values, landslide vulnerability and risk mapping case study and finally the evaluation of the landslide vulnerability and risk assessment method. The key approach towards development of a reliable and practical landslide vulnerability assessment is to use the easily identified, measurable and most significant indicators. These were proven scientifically from the analysis of sensitivity of indicators and sub-indicators for the particular critical infrastructure.

To assess and develop the parameters-indicators of landslide vulnerability assessment and risk index of critical infrastructures and assigning level for each parameter begins with the proposed landslide vulnerability and risk assessment methods, initial landslide vulnerability clusters, indicators, sub-indicators, weight values, vulnerability class and risk class as per literature. This information is improved based on series of focus group discussion (FGD) with different stakeholders and internal experts of the consultant team members. The final landslide vulnerability clusters, indicators, sub-indicators, weight values, vulnerability class and risk class were produced based on the improvements made by the internal experts based on the initial weights assigned by the stakeholders and literature review. Furthermore, the landslide vulnerability method was tested in the specific area at Ringlet and Lembah Bertam in Cameron Highlands. The landslide validation process involves several major activities including intensive field work for field data acquisition, generation of element-at-risk maps for each critical infrastructure (CI) i.e. buildings, road, dam and utility; Tenaga Nasional Berhad (TNB) powerline, generation of landslide vulnerability and risk maps. The generation of CI maps include intensive tasks in development of several maps on the susceptibility of critical infrastructure (C), effect of surrounding or mitigation measures (E), susceptibility of people (P) and intensity of landslide hazard (I). The entire maps were produced from processing and analysis of remotely sensed data and other ancillary geospatial data collected during the field work. In addition, the landslide vulnerability assessment was evaluated based on the previous landslide disaster at Taman Bukit Mewah, Bukit Antarabangsa, Hulu Kelang on 6 December 2008.

ACKNOWLEDGEMENT

Construction Research Institute of Malaysia (CREAM), through the cooperation and support of various government department and agencies, and private sector in Malaysia, produced a series of documents on interim reports, a guideline and a manual which are related to vulnerability assessment and risk analysis for critical infrastructure in Malaysia. The aim of such publication is to develop the capacity and capability of construction industry players related to high land disaster risk reduction agenda by emphasis on professionalism, innovation and knowledge in the endeavour to improve the quality of life. This cross-disciplinary research was assigned to a team of professionals from geosciences, land surveyors, geotechnical engineers, industry players and academicians.

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1.0 PURPOSE OF ASSESSMENT

1.1 Landslide Vulnerability Assessment

The Landslide Vulnerability Assessment (LVA) is certainly useful for Disaster Risk Reduction (DRR) program in promoting the exchange of information, or for improving disaster preparedness and preventing losses, as required for the Hotspots Project by creating indicators regarding the frequency of the hazards and the foreseeable economic or human impacts at a global scale (Cardona, 2005, Birkmann, 2007). Ideally, LVA should also assist policy makers in identifying investments priorities (e.g. prevention and mitigation measures) for reducing risk, to identify national risk-management capacities, to evaluate the effects of policies and investments on risk management, and to gauge a country's relative position and follow its evolution over time (Birkmann, 2007).

Several global approaches are aim to compare disaster risk between countries exposed to selected natural hazards, as it is the case of the Disaster Risk Index (DRI), which measures the mortality by assessing the relative vulnerability, which is the ratio of the number of persons killed by the number of exposed persons (UNDP/BCPR, 2004, Birkmann, 2007). The DRI was used to identify the countries which needed prevention and development of LVA (Peduzzi et al., 2009). Another index of structural vulnerability to climate change was developed to assess the environmental vulnerability of the least developed countries which are facing environmental shocks resulting from climate change, in order to allocate adaptation funds (Guillaumont and Simonet, 2011).

Vulnerability can be measured either on a metric scale or a non-numerical scale (Glade, 2003) and is represented by different ways. One of them is the elaboration of an index which combine various indicators. The index elaboration is usually used to assess social vulnerability (e.g. Social Vulnerability Index (SoVI) which was established by Cutter et al. (2003)), economic vulnerability (e.g. Economic Vulnerability Index (EVI), established by Guillaumont (2009), human vulnerability (e.g. Disaster Risk Index (DRI), established by UNDP/BCPR (2004)) or environmental vulnerability (e.g. Index of Structural Vulnerability to Climate Change, established by Guillaumont and Simonet (2011)).

Physical vulnerability is more often expressed through vulnerability functions (e.g. Fuchs et al. (2007)) which represent the interactions between the damaging event and the element-at-risk through curves for expressing the possible resistance of the elements to an impact (Li et al., 2010, Puissant et al., 2013). In the case of landslide vulnerability, the vulnerability functions are usually used for detailed assessments (1:5000-1:10000) (Puissant et al., 2013). An example of this application is the study of Papathoma-Köhle et al. (2012), who measured the degree of loss of buildings in function of the debris flow intensity, represented by the height of the debris deposit.

1.2 Development of Risk Index for Critical Infrastructure (CI) in Malaysia

Disaster risk is considered to be a function of hazard, exposure and vulnerability, expressed as the probability of loss of life, injury, and destroyed or damaged capital stock in a given period of time (De Bono and Mora, 2014). A comprehensive risk assessment and analysis is required for a better risk management. It must be evaluated with reference to a particular return period. Maps showing the areas that may be affected by landslides are a common tool used by authorities and decision makers to interact with the public and local community. Given the importance of addressing slope hazard and associated risks in the tropics, this project consortium has taken a significant move and looks forward for the best methodological framework and operational need to holistically manage the disaster risk in a changing environment.

One of the most critical steps towards landslide risk analysis is the determination of landslides vulnerability. Vulnerability identifies the element at risk as well as the evaluation of their relationships with the hazard. The relationships relate the landslide potential damages over a specific element at risk. Vulnerability can be defined as the degree of loss to a given element at risk or set of elements at risk resulting from the occurrence of a natural phenomenon of a given magnitude and expressed on a scale from 0 (no damage) to 1 (total damage).

2.0 BACKGROUND OF ASSESSMENT

2.1 Landslide Hazard and Risk Assessment

Landslide hazard is the probability of occurrence of potentially damaging phenomenon (landslide) within a given area and in given period of time (Varnes, 1984). It uses all available information to estimate the zones where landslide of a particular type, volume, velocity and runout may occur within a given period of time (Corominas et al., 2015). Landslide hazard information are essential to conduct risk assessment for future land use planning. The level of landslide hazard relatively presents the expectation of future landslide occurrences based on the conditions and factors that caused landslide in any particular area.

Detailed landslide hazard requires spatial and temporal data of landslide, theferore, remote sensing data is an essential tool to obtain several layers of data (Metternicht et al., 2005). Minerals and Geoscience Department of Malaysia (JMG) have established project of Penghasilan Peta Bahaya dan Risiko Cerun (PBRC) at various locations as shown in Figure 2.1 to Figure 2.5 shows the area of PBRC project which are in Selangor, Cameron Highlands, Ipoh, Kota Kinabalu and Kundasang. A landslide inventory mapping is by far the most important method for assessing landslide susceptibility, hazard and associated risk.

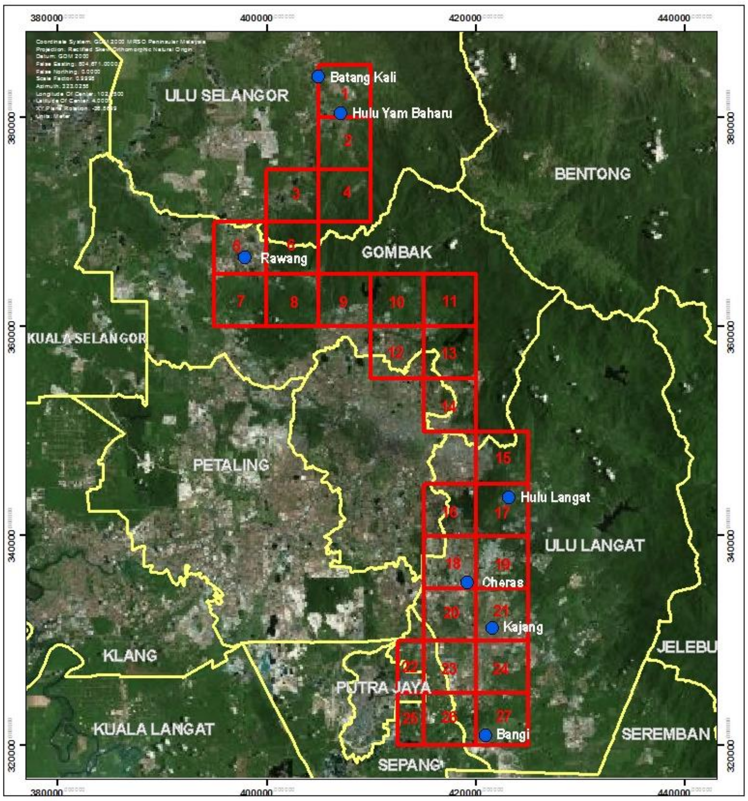


Figure 2.1: PBRC project area in Selangor (650 km^2) (NaTSIS, 2016).

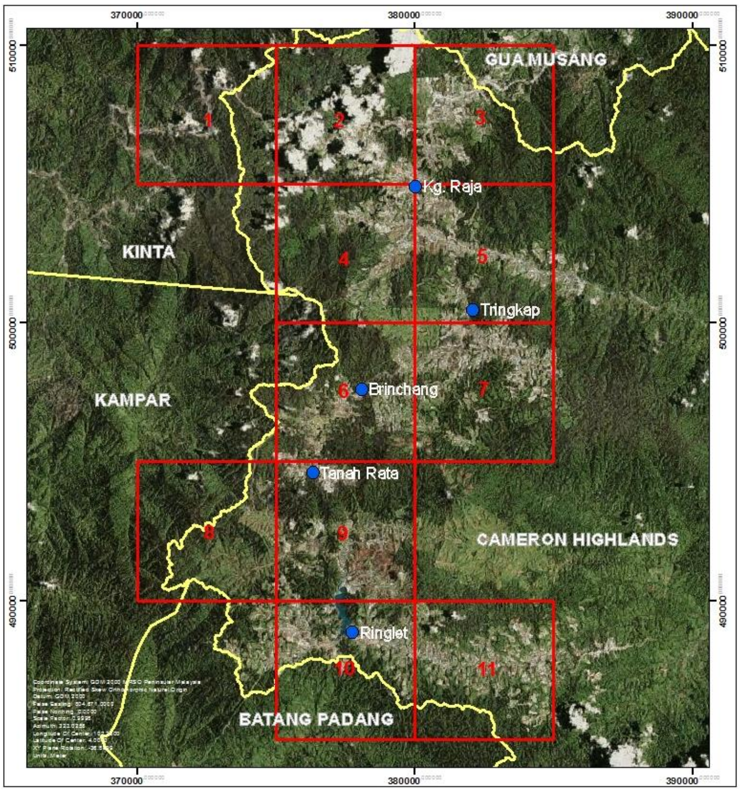


Figure 2.2: PBRC project area in Cameron Highlands (275 km^2) (NaTSIS, 2016).

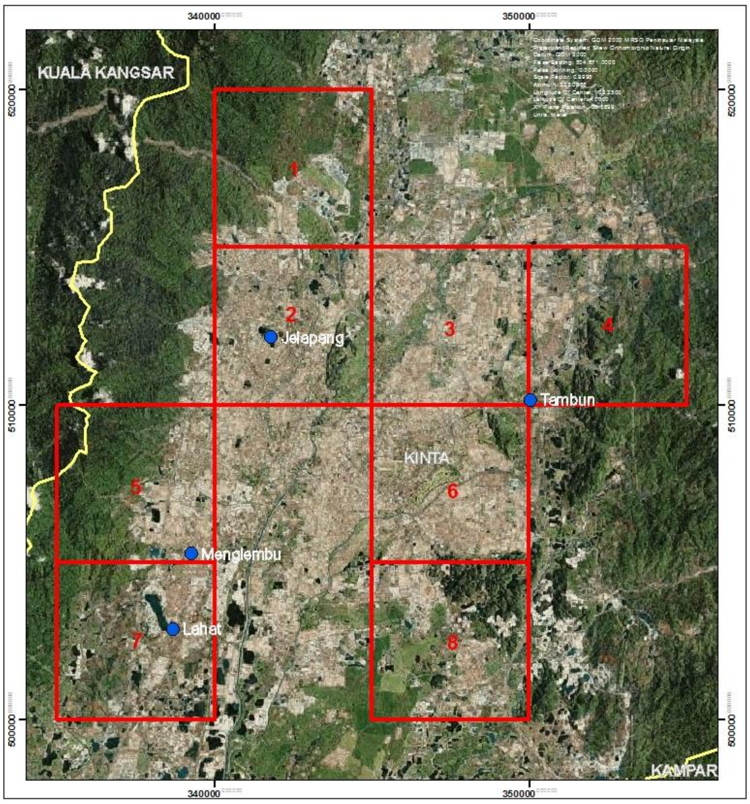


Figure 2.3: PBRC project area in Ipoh (200 km^2) (NaTSIS, 2016).

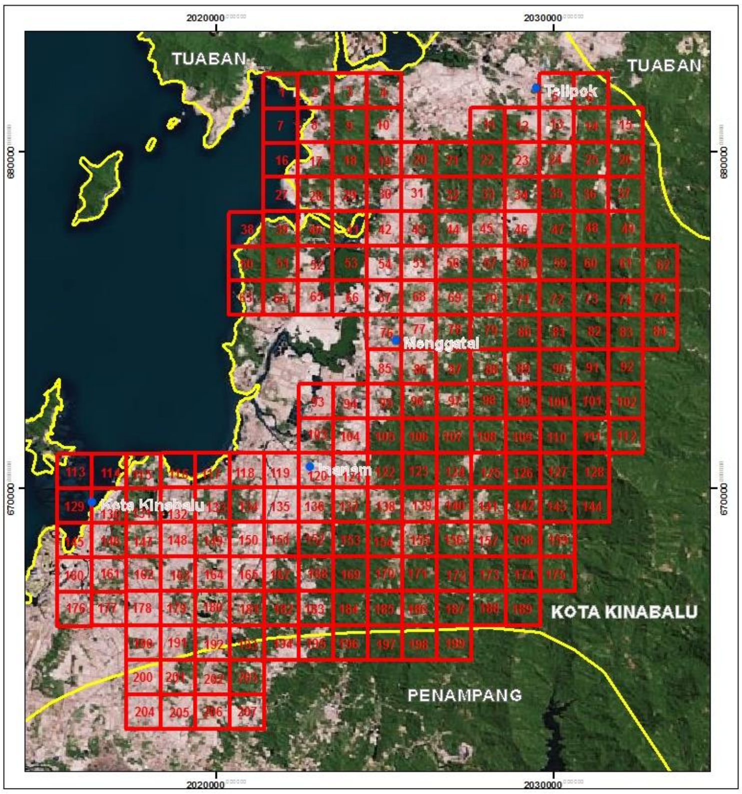


Figure 2.4: PBRC project area in Kota Kinabalu (155 km^2) (NaTSIS, 2016).

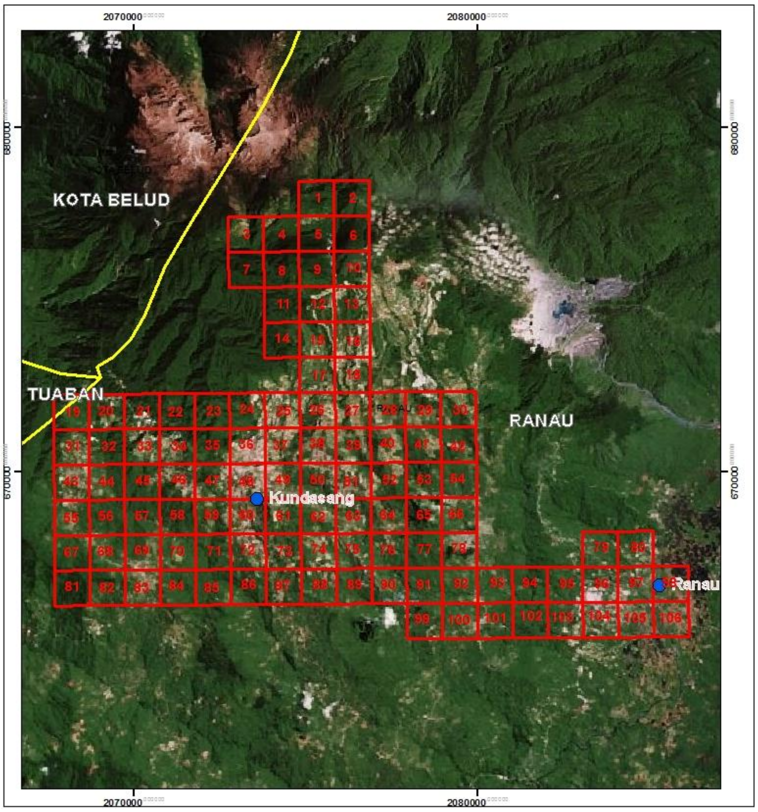


Figure 2.5: PBRC project area in Kundasang ($70km^2$) (NaTSIS, 2016).

In PBRC project, airborne laser scanning (ALS) and terrestrial laser scanning (TLS) systems were used to capture LiDAR data at all project area. A detailed description of each working step, particularly landslide inventory, susceptibility, vulnerability and risk mapping are given in Figure 2.6 and Figure 2.7. Five stages are involved, namely data collection, verification, processing, analysis and presentation (Mineral and Geoscience Department Malaysia (JMG), 2015).

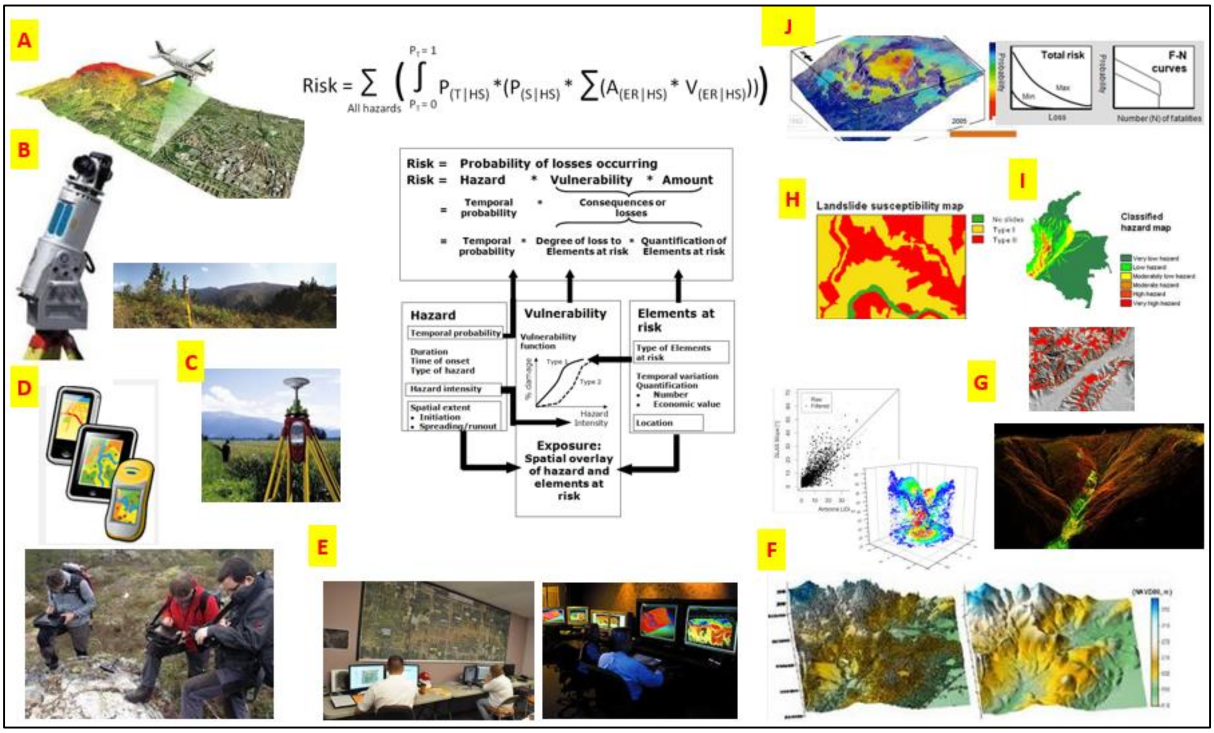


Figure 2.6: An operational framework of landslide hazard and risk analysis: (A) ALS data collection. (B) TLS field campaign. (C, D) GNSS-GIS field assisted system. (E, F) Data processing and parameterisation. (G) Making a landslide inventory from LiDAR data. (H, I) Landslide susceptibility and hazard analysis and modelling respectively. (J) Landslide risk analysis and assessment (Mineral and Geoscience Department Malaysia (JMG), 2015).

The characterisation of landslide hazard should include the location, volume (or area), classification and velocity of the potential landslides and any resultant detached materials, and the probability of their occurrence within a given period of time (Corominas et al., 2014, Pardeshi et al., 2013). Another form of expressing hazard is hazard zoning, which is defined as the subdivision of the terrain into zones that are characterised by the temporal probability of occurrence of landslides of a particular intensity within a given period of time. As a result, a landslide hazard map must indicate the zones where landslides may occur as well as the runout zones.

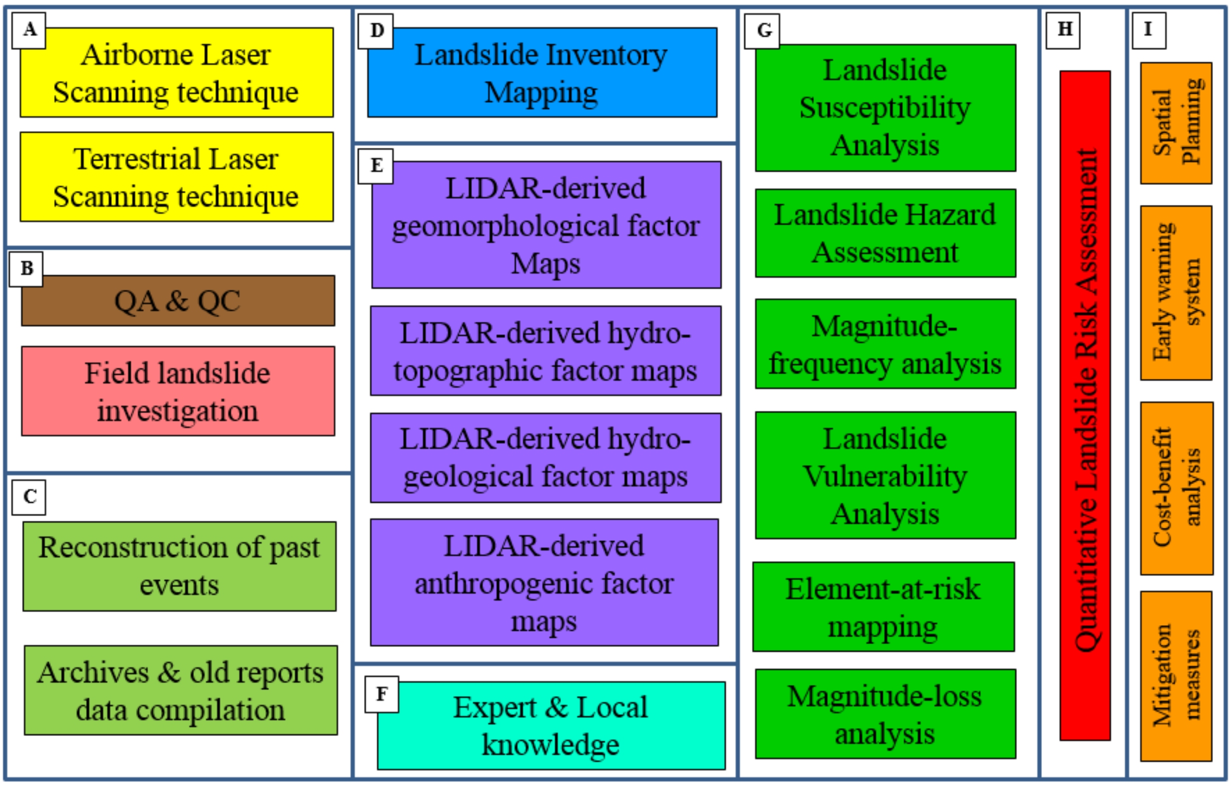


Figure 2.7: An operational requirement for landslide hazard and risk (Mineral and Geoscience Department Malaysia (JMG), 2015).

Vulnerability assessment is conducted to extract element at risk and its relation with hazard surrounding it. Landslide Vulnerability Assessment provides the degree of loss of a given element or set of elements exposed to the occurrence of a landslide of a given magnitude or intensity and expressed on a scale of 0 (no loss) to 1 (total loss). In this stage, exposure analysis will be carried out based on elements-at-risk for landslides and hazard information. The element at risk include the people, property, systems or any other elements potentially affected by landsliding on, below and up-slope of the potential landslides. They may include indirect impacts such as reduced economic activity resulting from landslide (Corominas et al., 2015, Fell et al., 2008). Suitable vulnerability methods will be developed, either based on vulnerability matrix, vulnerability matrix or expert judgment depending on the availability of data especially past records.

Risk is a function of hazard, exposure and vulnerability. Landslide risk takes the outcomes of hazard mapping, and assesses the potential damage to persons (annual probability of loss of life), to property (annual value of property loss), and environmental features (annual value of loss) for the elements at risk, accounting for temporal and spatial probability and vulnerability (Fell et al., 2005). Geohazards can be defined as condition that expresses the probability of a particular threat occurring within a defined time period and area caused by geological conditions or processes which represent serious threats to human lives, property and the natural and built environment. Figure 2.8 shows the simple graphical presentation of landslide risk map generation by combination of hazard and vulnerability. Maps showing the areas that may be affected by landslides are a common tool used by authorities and decision makers to interact with public and local community.

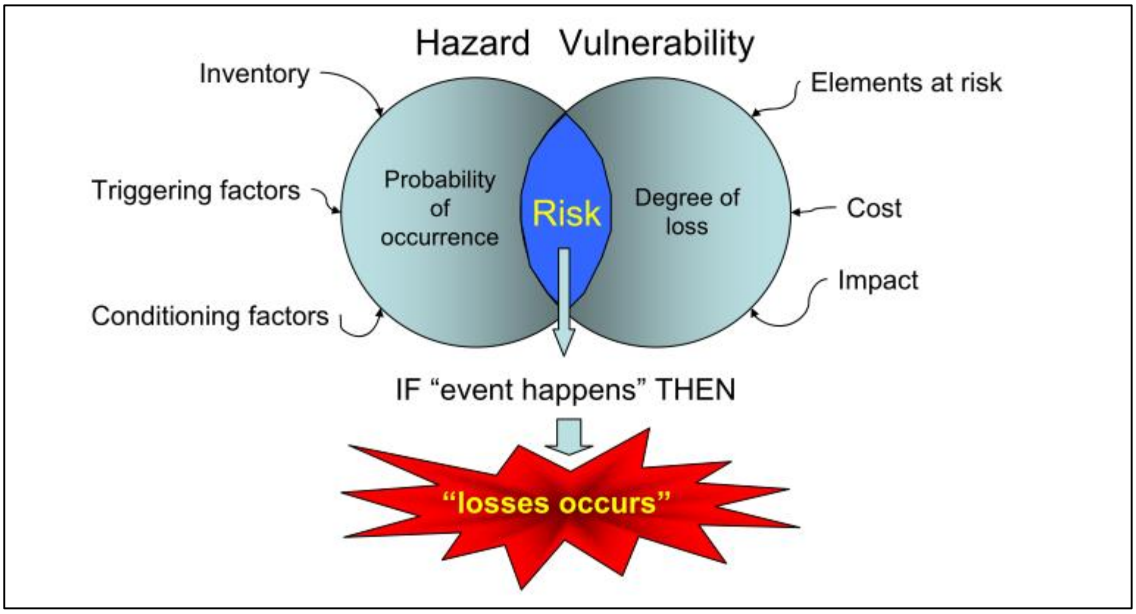


Figure 2.8: Graphical representation of landslide risk map generation (Alexander, 2002).

2.2 Landslide Classification

Classification of landslide is important to correctly understand the behavior of landslide. Consistent terminology throughout the landslide mapping and assessment shall be established. Classifications of Cruden and Varnes (1996), Varnes (1978) or Hutchinson (1988) and terminology described in International Association for Engineering Geology (1990) shall be used. Landslide can be classified by word describing the material and a second word describing the type of movement. Landslide material normally either rock, soil or both. It is described as earth if the material mainly composed of sand-sized or finer particles or debris if composed of coarser fragment (usually mixture of soil, water, rock, boulders and timber). Type of landslide movement typically explained the actual internal mechanics of how landslide mass behaves and displaced either fall, slide, topple or flow. Therefore, landslide can be described using two terms refer to type of materials and movement respectively. Example: rockfall, debris flow, earthflow earth. Table 2.1 shows landslide classification based on Cruden and Varnes (1996) and Varnes (1978).

Table 2.1: Types of landslides.version of Varnes' classification of slope movements (Varnes, 1978).

TYPE OF MOVEMENT		TYPE OF MATERIAL		
		BEDROCK	ENGINEERING SOILS	
			Predominantly Coarse	**Predominantly Fine**
Falls		Rock fall	Debris fall	Earth fall
Topples		Rock topple	Debris topple	Earth topple
Slid es	Rotational	Rock slide	Debris slide	Earth slide
	Translational			
Lateral Spreads		Rock spread	Debris spread	Earth spread
Flows		Rock flow	Debris flow	Earth flow
Complex		Combination of two or more principle type of landslide		

2.3 Slope Morphology Related to Landslides

Slope morphology shows the topographical features or landforms which generally change slowly over time either by natural process (erosion, weathering or landslide) or by human activities. The understanding of slope morphology is important especially for development planning. JMG have established the guideline of Geological Terrain Mapping (GP 06) (2010) which focus on the assessment of morphology and terrain of highland areas for development purposes.

Generally, slope form can be described in three (3) types of slope morphology which are straight, concave and convex slope from crest to toe (Figure 2.9). Some examples of actual slope morphology detected from terrain data shown in Figure 2.10. These slope form reflects the balance between the imposed stresses (gravity, seismic loads, raindrop impacts, surface water flows and wind), the surface protection provided by vegetation and the strength of geological materials. A slope can be subdivided into segments where each segment has its own inputs, outputs and storage of water and sediments as shown in Figure 2.11. The output from one segment forms the input to the next.

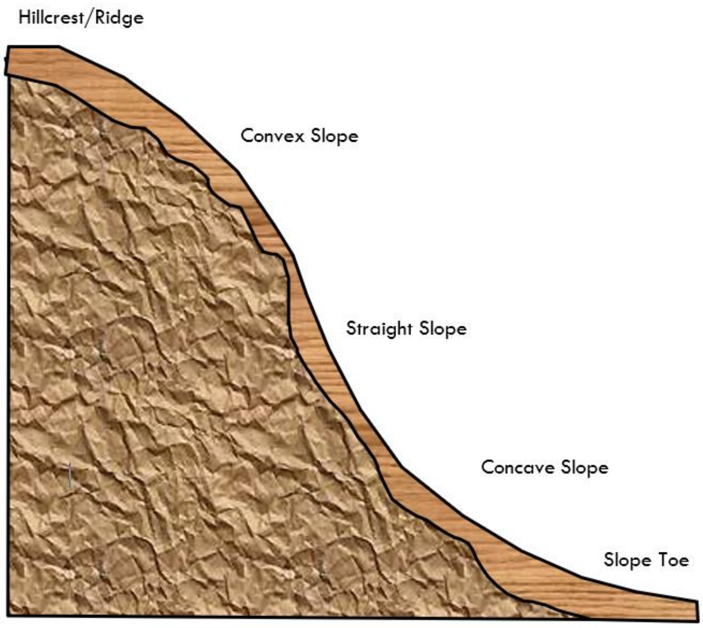


Figure 2.9: Slopes with convex, straight, and concave slope segments.

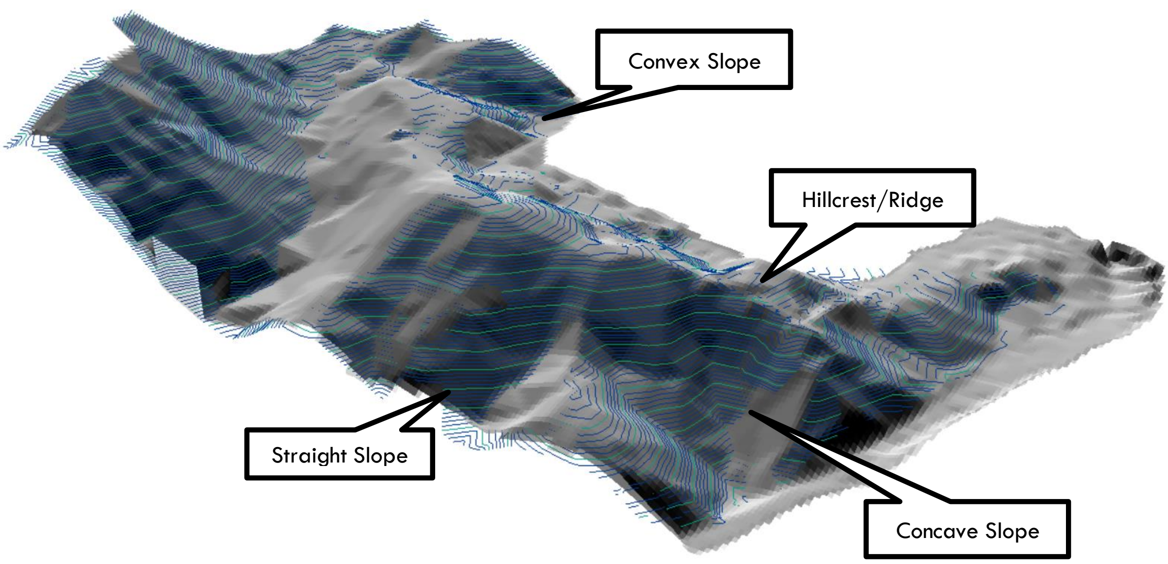


Figure 2.10: Example of actual slope morphology detected from terrain data analysis.

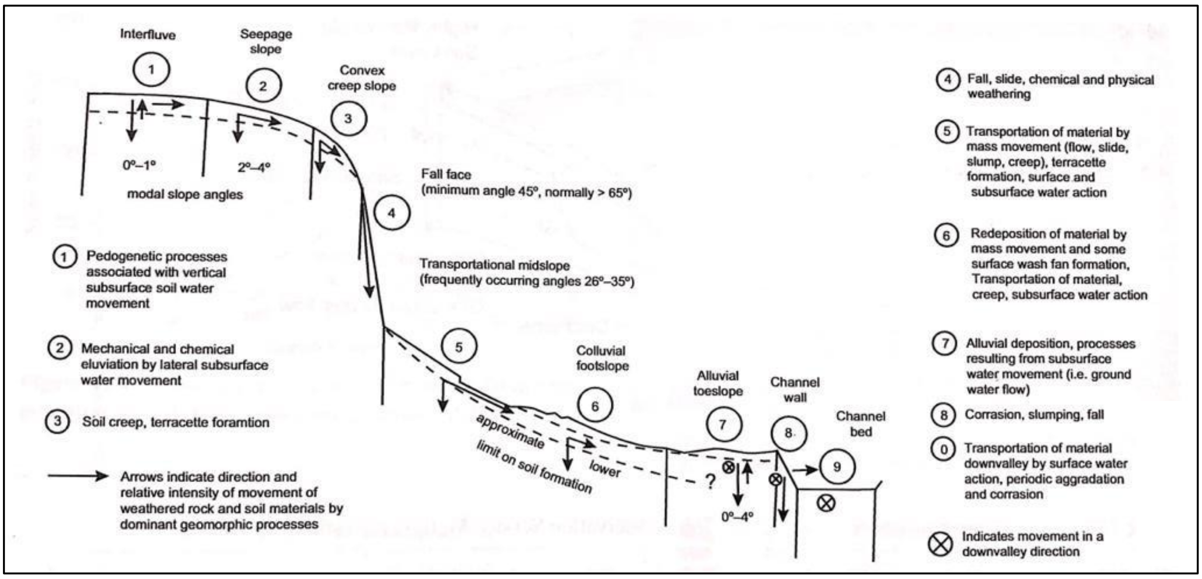


Figure 2.11: The hypothetical nine-unit slope model and associated geomorphological processes (Fookes et al., 2007).

Slope morphology also markedly influenced slope failures apart from weathering processes and erosion (Fernandes et al., 2004). Topographic parameters normally considered in estimating soil erosion losses and calculating short-term mass stability include inclination and length of slope. Most engineered or man-made slopes are planar in form with an unvarying, down-slope gradient and little, if any, plan-form curvature. Natural slopes do not typically exhibit planar slope faces with uniform, un-varying gradients. Instead natural slopes manifest a variety of complex slope forms and profiles. Slopes that start out with planar topography also tend to evolve over time into equilibrium shapes that seldom are entirely planar.

A study in Cameron Highlands, Malaysia showed that 20° to 34° slopes are highly prone to slope failures (Syed Omar et al., 2004). Steeper slopes have been found to contain shallower soil profile as it depends on the slope's resistance to downslope movement (Crozier, 1986, Selby, 1982) and are subjected to rapid slope failures since they are weakly bounded. Changes on slope gradients due to slope alteration such as in urban areas and heavy materials on top of undercutting slopes with weak materials have significant impact on slope failure occurrences in Penang, Malaysia (Chan, 1998). Frequent slope failures were noted on cut-slopes with heights more than 5 to 10 m (Chau et al., 2002).

Apart from that, water is an important parameter for the instabilities of slopes. Slopes are part of systems that transfer water and sediment towards river channels. Hillslope geomorphology and hydrologic factors (surface water and ground water) are important considerations in the stability of slope. Surface water will affect the erosion of terrain surfaces. Slope morphology (straight, convex, concave) shown in Figure 2.12 gives an indication of surface and subsurface water concentration or dispersion. Convex slopes (e.g., wide ridges) will tend to disperse water as it moves downhill. Straight slopes concentrate water on the lower slopes and contribute to the build-up of hydrostatic pressure. Concave slopes typically exhibit swales and draws. Water in these areas is concentrated at the lowest point on the slope and therefore represent the least desirable location for a road.

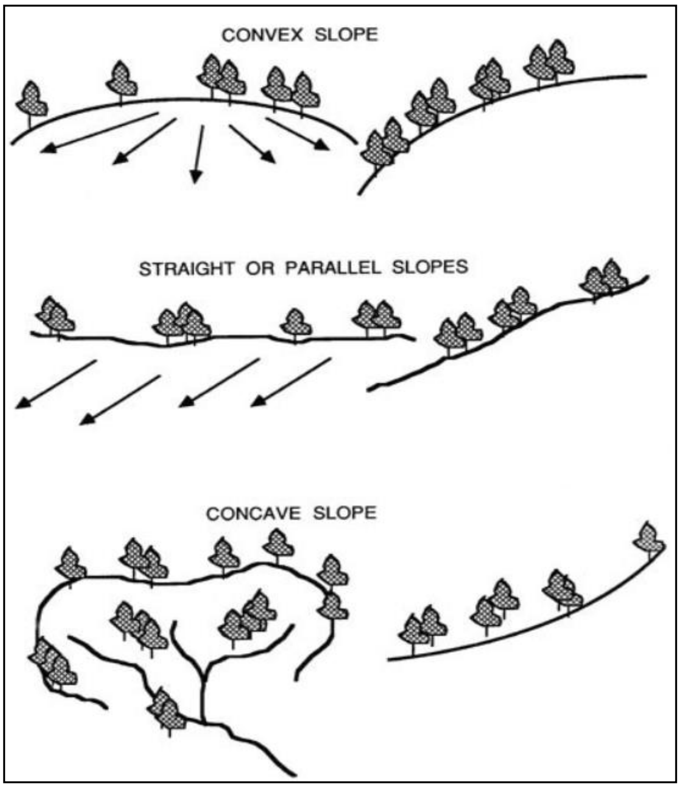


Figure 2.12: Slope shape and its impact on slope hydrology. Slope shape determines whether water is dispersed or concentrated (U.S. Forest Service, 1979).

The potential environment impact predicted is mechanical and chemical evolution process, which may result in soil erosion (sheet and rill) caused by surface run-off water if proper drainage system is not constructed. This is due to the fine particles such as clayey silt layer at the upper most surface. The scale of erosion varies with different gradient and occurrence of vegetation covered. The geomorphologic process is more active at slope gradient more than 35° where the mass movement (e.g. localized circular failure, slump, etc). At gentle slope (gradient <35°) the process of transportation and deposition took place where the material of the top surface usually contains lots of clay and silt, which might cause siltation and sedimentation problem.

2.4 History of Landslides in Malaysia

Landslides in Malaysia have been recorded from both man-made and natural slopes. Historical records indicate that most of the landslides occurred in man-made (cut and embankment) slopes found along the road or highways, in residential and industrial areas. Landslides in natural slope is comparatively rare. However, natural slopes which have been affected by human activities, such as logging and deforestation, usually would induced large scale landslides with devastating effects to the environment and built up infrastructures.

Malaysia has experienced a number of landslides geohazards throughout her history. Most of the geohazard incidents are associated to failure of the natural hill slopes (landslides, debris flows, rock falls, etc.). An increasing number of geohazard incidents in this country lately, is somehow closely related to rapid development which encroaching to hilly and mountainous terrain due to depleting of flat and low-lying ground. Other influencing factors like beautiful scenery, fresh air, exclusiveness, etc. also contribute towards development in hilly terrains. People’s perception is that the higher their residents on the hill site, the better their living status in the eyes of the public. However, due to increasing numbers of geohazard incidents in hilly terrains lately, this perception has now become a serious public issues and concerns. Appropriate policies and procedures to check the problems are imperative (Gue et al., 2002).

Shallow slide surfaces which usually less than 4m deep are the most common types of landslide in Malaysia. It occurs during or immediately after the intense rainfall (Ting, 1984). Other types of landslides found are deep-seated slides, debris flow and geologically controlled failures such as wedge failure and rock fall. Rotational landslides, translational landslides, rock falls, debris flows (commonly referred to as mudflows or mudslides) and earth flows are examples of common landslide types to be found in Malaysia (Figure 2.13).

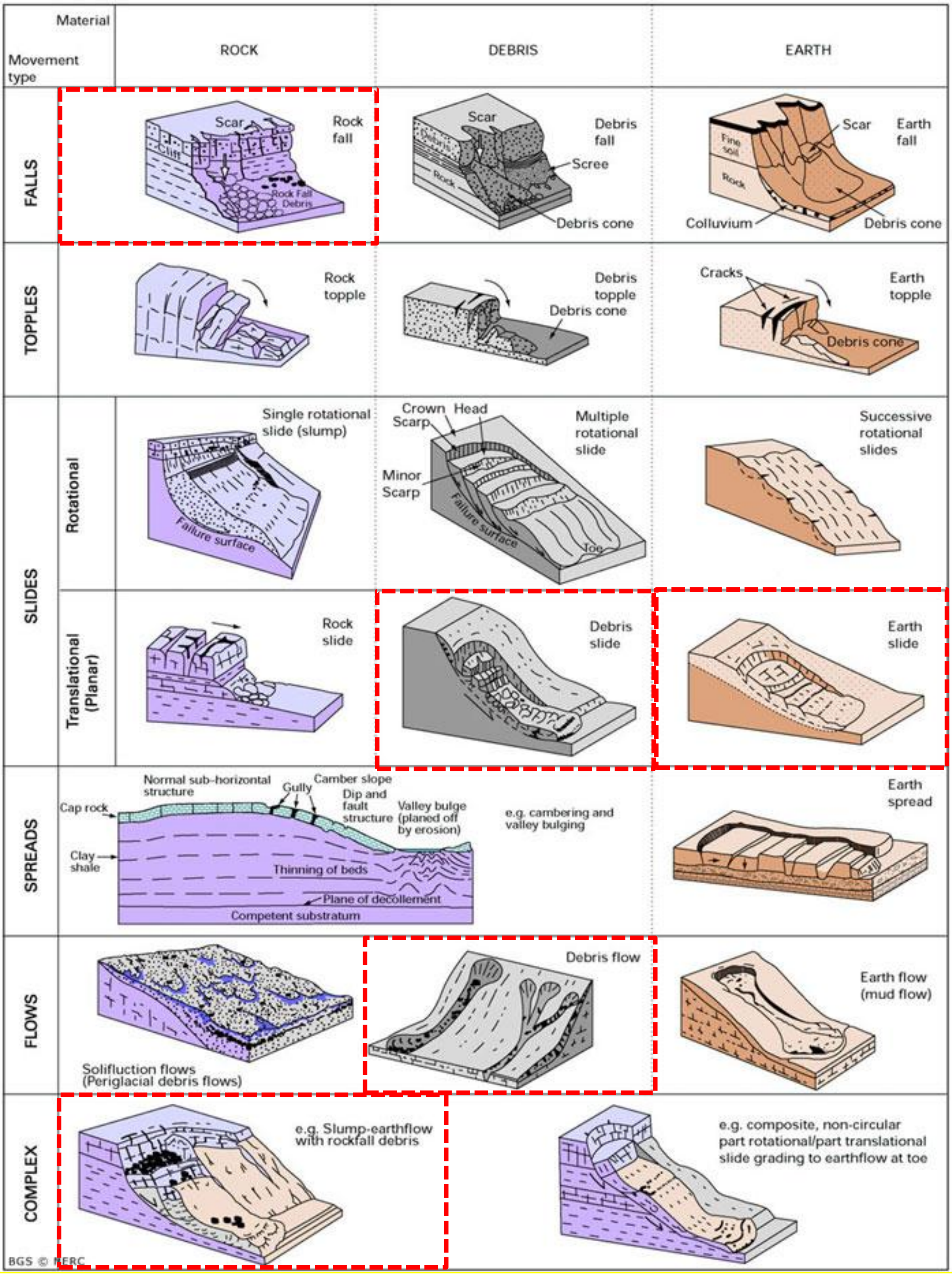


Figure 2.13: These schematics illustrate the major types of landslide movement that are based on Varne's classification of slope movement (Varnes, 1978). Circled are common types of landslides in Malaysia.

The combination of high annual rainfall (can reach up to 4500mm) and high temperatures throughout the year causes rapid weathering which form thick residual soil profile (Abdul Rahman and Mapjabil, 2017). Some locations can reach as high as 100m in depth of residual soil. These conditions with other causal factors (rain, geology) trigger landslide incident to be one of the most destructive natural disaster in Malaysia (Bujang et al., 2008).

Information gathered from National Slope Master Plan (2009-2023) shows that the first reported landslide in Malaysia was occurred in December 1919 that claimed 12 lives. Apart from that, there are series of major landslide in Malaysia recorded in history as tabulated in Table 2.2.

Table 2.2: Series of major landslide in Malaysia, compiled by Abdul Rahman and Mapjabil (2017).

Date	Location
1 May 1961	A landslide occurred in Ringlet, Cameron Highlands, Pahang
21 October 1993	The man-made Pantai Remis landslide caused a new cove to be formed in the coastline
11 December 1993	48 people were killed when a block of the Highland Towers collapsed at Taman Hillview, Ulu Klang, Selangor
30 June 1995	22 people were killed in the landslide at Genting Highlands slip road near Karak Highway
6 January 1996	A landslide in the North-South Expressway (NSE) near Gua Tempurung, Perak. One death.
29 August 1996	A mudflow near Pos Dipang Orang Asli settlement in Kampar, Perak, 44 people were killed in this tragedy
November 1998	Massive rockslide at Bukit Saujana, Paya Terubung, Penang
January 1999	Shallow rotational slide. Heavy rain triggered landslide – buried a number of house/huts in squatter’s settlement, Sandakan, Sabah. 13 deaths
15 May 1999	A massive landslide near Bukit Antarabangsa, Ulu Klang, Selangor. Most of the Bukit Antarabangsa civilians were trapped under the rubble. Only two victims survived - an Indonesian maid and a child
January 2000	Debris flow from upstream landslide and erosion washed away worker squatters in vegetable farm, Cameron Highlands, Pahang. 6 deaths.
January 2001	Shallow rotational slide in Simunjan, Sarawak. Landslide occurred on vegetable farm – buried a number of houses at the toe of slope. 16 deaths.

December 2001	Debris flow in Gunung Pulai, Johor. Heavy rain triggered debris flow resulting from a number of small landslides along upstream of Sungai Pulai – washed away settlements along the river bank. 5 deaths
20 November 2002	The bungalow of the Affin Bank Chairman General (RtD) Tan Sri Ismail Omar collapsed due to an early morning landslide in Taman Hillview, Ulu Klang, Selangor, with a fatality in his family
November 2003	A rock fall/rock debris in the New Klang Valley Expressway (NKVE) near the Bukit Lanjan interchange caused the expressway to be closed for more than six months
November 2004	Debris flow in Taman Harmonis, Gombak, Selangor. Sliding/flowing of debris soil from uphill bungalow project-toppled the back-portion of neighbouring down slope bungalow after weeklong continuous rain. 1 death.
December 2004	Rock fall – buried back portion of illegal factory at the foot of limestone hill in Bercham, Ipoh, Perak. 2 deaths
31 May 2006	Four persons were killed in the landslides at Kampung Pasir, Ulu Klang, Selangor. Buried 3 blocks 0f longhouses
March 2007	Landslide at Precint 9, Putrajaya. Some 23 cars were buried under the debris
26 December 2007	Two villagers were buried alive in a major landslide, which destroyed nine wooden houses in Lorong 1, Kampung Baru Cina, Kapit, Sarawak.
2 February 2009	One contract worker was killed in a landslide at the construction site for a 43-storey condominium in Bukit Ceylon, Kuala Lumpur
21 May 2011	16 people mostly 15 children and a caretaker of an orphanage were killed in a landslide caused by heavy rains at the Children's Hidayah Madrasah Al-Taqwa orphanage in FELCRA Semungkis, Hulu Langat, Selangor.
29 December 2012	88 residents of bungalows, shophouses and double-storey terrace houses in the Puncak Setiawangsa, Kuala Lumpur were ordered to move out because of soil movement.
4 January 2013	Construction at the Kingsley Hill housing project at Putra Heights has been halted temporarily following a landslide at the site that caused several vehicles to be submerged in mud
11 November 2015	A landslide occurred at km 52.4 of the Kuala Lumpur-Karak Expressway between Lentang and Bukit Tinggi, Pahang and GombakBentong old roads. The Lentang-Bukit Tinggi stretch of the expressway was closed to traffic
January 2016	A landslide has blocked all lanes in both directions on the Karak Highway, the main highway that connects the capital Kuala Lumpur to Genting Highlands and other parts of Pahang state. Four vehicles that were trapped in the landslide, but all passengers managed to escape unhurt.
February 2016	194 minor landslides and embankment failures. Puncak Borneo area, comprising mainly Bidayuh settlements and Padawan Ring Road, were most “critical”

The causes of these landslides can be due to the abuse prescriptive methods, inadequate study of past failures, design errors including insufficient site-specific ground investigation. However, lack of appreciation of water such as 14 underestimating existing groundwater tables and inadequate capacity of surface drainage is also one of the factors causing the landslides (Slope Engineering Branch (JKR), 2009). Figure 2.14 shows the landslide prone area map in Malaysia while Figure 2.15 shows the landslides hazard map in Peninsular Malaysia as a guide to locate high potential areas of landslide accumulation.

Figure 2.14: Landslide Prone Area in Malaysia (Slope Engineering Branch (JKR), 2009).

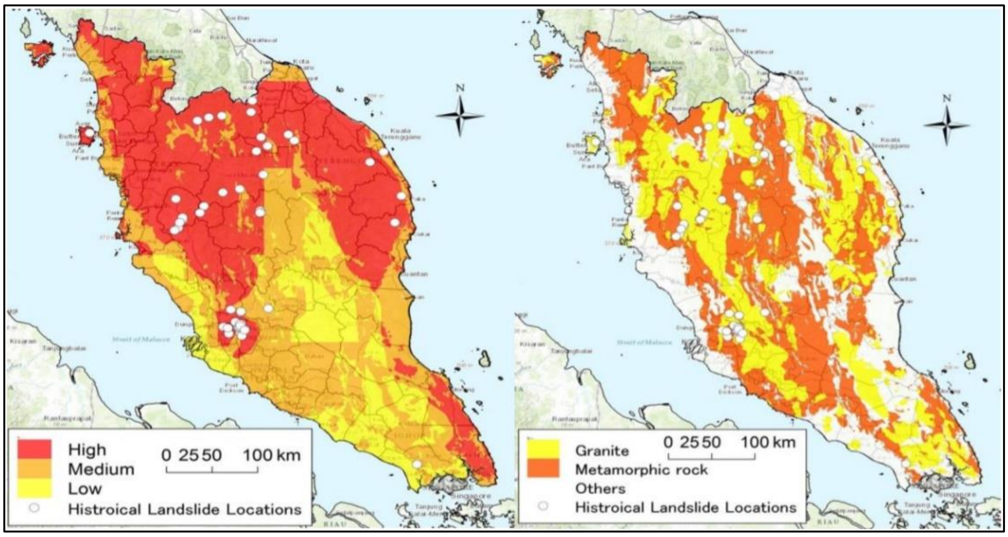


Figure 2.15: Landslide Hazard Map in Peninsular Malaysia (Slope Engineering Branch (JKR), 2009).

3.0 ISSUE AND IMPACT ON SOCIETY, ECONOMY AND NATION

3.1 Impact of Climate Change on Hill Land

The world mountains are home to about 800 million people and provide crucial ecosystem services for the entire globe, including freshwater for half of humankind (Dessens et al., 2014). They are centers of biological diversity, important tourist destinations and key sources of raw materials. However, mountain regions are especially sensitive to the impacts of a changing climate, putting at risk many of the goods and services provided by mountains.

The world mountain regions have warmed considerably over the last century, and while temperatures are expected to continue rising, projections of precipitation reveal a more differentiated pattern – some regions are expected to receive more rainfall, others less. The consequences for water availability reach far beyond mountain regions, with major development implications for irrigation, urbanization, industrialization and hydropower. Climate change is also likely to increase exposure to hazards, with extreme events such as avalanches and landslides becoming more common.

The many climatic zones along gradients and varying topography found in mountains mean that they are home to a high degree of biodiversity, including many endemic species – species that occur nowhere else. Mountains' varying topography also provides microhabitats that may enable plant species that are adapted to the cold to find nearby 'climatic refugia' in a warming world. Managing mountain biodiversity is increasingly recognized as a global priority, but robust conservation efforts are needed to achieve the target of reducing biodiversity loss. Climate change may create added pressure to achieve conservation goals, but it could also increase demand for intensive resource use in mountains if nearby lowland areas are subject to flooding and hotter temperatures. There is need for different strategies of land use and management in different mountain regions, and states that empowering mountain communities by encouraging leadership and use of local knowledge and by promoting platforms that enable learning and collective action can ensure more sustainable use of common resources and increase resilience to climate change.

Half of the global biodiversity hot spots are in mountain regions. They are an important global heritage that is being threatened by climate change and human action. Impressive achievements have been made in safeguarding this heritage; protected areas have been the fastest growing land use category in recent decades, especially in mountains. While mountain biodiversity is thus increasingly seen as a global common good by many, local communities that directly depend on its services must be included in stewardship of this valuable resource. Mountain communities should see more tangible benefits from conservation efforts than has been the case in the past.

Mountains are home to about 10% of the global population. Most mountain people live in developing countries. One third of them are food-insecure, a high proportion in global comparison. Mountains are often limited-choice environments due to harsh living conditions and a marginal position in terms of economic integration and political decision-making. External support is needed to reduce poverty levels. As temperatures rise, however, climate change might hold prospects for mountain agriculture - for crops previously not grown or limited to lower altitudes - if water, land, labor and capital through credit schemes or remittances from migrants are available to exploit such opportunities and that access to markets is assured.

Mountain areas are typically exposed to multiple hazards. Climate change is likely to increase this exposure, as extreme events such as storms, landslides, avalanches, and rockfalls are expected to become more common and more intense in mountain areas, threatening both livelihoods and infrastructure. Hazards cannot be prevented, but mountain regions can be supported in managing the risks emanating from these hazards. This support begins with preparedness and ends with recovery; key ideas include effective early warning systems, land use zoning, and strategies for intervention.

Forests cover 31% of our planet and home to hundreds of thousands of species of plants and animals (Bennett, 2017). The role of forests as the ecological roles is undeniable. Forests help to mitigate climate change by providing homes to many species of plants and animals, providing food, medicine and livelihoods for people around the globe. However, due to massive anthropogenic activities, most of the forests are now at risk.

Deforestation, clearance or clearing is the removal of a forest or stand of trees where the land is thereafter converted to a non-forest use (Sharma and Ram, 2014). Deforestation includes conversion of forestland to farms, ranches, or urban use. Since the industrial age, about half of world's original forests have been destroyed and millions of animals and living things have been endangered. Despite the improvements in education, information and general awareness of the importance of forests, deforestation has not reduced much, and there are still many more communities and individuals who still destroy forest lands for personal gains. Deforestation also provides stability to slope through which mass movement of rocks, debris could not occur. As the plant or tree roots provides some reinforcement and remove groundwater. On hilly areas vegetation can stabilize steep slopes and if the cutting of trees continues it would result in a drastic change in the atmosphere or in the environment.

Deforestation comes in many forms, including fires, clear-cutting for agriculture, ranching and development, unsustainable logging for timber, and degradation due to climate change. Over the year, many case studies have proven that clear cutting of large trees and other vegetation has had a drastic impact on the stability of the land. The frequency of landslides is increasing and the probability of them occurring in logged areas is high. Landslides occur more frequently in areas with steep slopes and highly erodible soils, clayey sub-soils or weathered and jointed bedrock, usually following intense and prolonged precipitation or earthquakes. Landslides threaten soil function in two ways:

i. Removal of soil from its in-situ position.
ii. Covering the soil down-slope from the area where the slope has failed.

Landslides are a major hazard in most mountainous and hilly regions as well as in steep river banks and coastlines. Their impact depends mainly on their size and speed, the elements at risk in their path and the vulnerability of these elements. Although landslides usually occur at steep slopes, they may also occur in areas with low relief or slope gradient. Landslides occur because of various triggering factors. Rainfall is one such factor. But the human intervention like deforestation may cause the soil to lose its capacity and ultimately lead to landslides during heavy rainfall. Hill slopes in the Himalaya or known for instability due to ongoing tectonic activity. However, increasing anthropogenic intervention in the recent time appear to be contributing to terrain instability in addition to natural factors, has observed by increasing frequency and magnitude of landside since 1970. Slope movements increase due to deforestation, as the roots provide some reinforcement and remove groundwater. On the other hand, addition of vegetation to slopes can cause slope movement, because the vegetative mass increases the weight of the slope in terms of moisture content.

3.2 Climate Resilient Towards Building and Other Critical Infrastructure

Climate change is a global phenomenon and is particularly evident in the past three decades (Tang, 2019). The Intergovernmental Panel on Climate Change (IPCC), in its Fifth Assessment Report (2014), reveals an increase of average global land and ocean temperature by 0.85 °C from 1880 to 2012. The IPCC is highly confident that the period between 1983 and 2012 was the warmest in the past 800 years.

Extreme weather events constitute a potential threat to human and natural systems, as they are expected to increase in terms of both of frequency and intensity, due to the warming of the climate system. Extreme weather is among the most prominent global risks and they can induce hazards such as flooding, drought, ice formation and wild fires, which present a range of complex challenges to the operational resilience of Critical Infrastructures (CIs) (Tsavdaroglou et al., 2018).

CI are defined as “those infrastructures whose services are so vital that their disruption would result in a serious, long-lasting impact on the economy and the society”. Physical CIs include energy supply, transportation, information and telecommunication, water and solid waste systems (World Economic Forum, 2017). Those systems are vulnerable to extreme climate changes, since most of them have been designed under the assumption that climate is stationary (Klein Tank et al., 2009). Moreover, they are highly interconnected and heavily dependent upon each other and therefore a disruption in any of these systems can cascade across and affect the functioning of the entire system of CIs (Rinaldi et al., 2001).

In Europe, ‘critical infrastructures’ refers to the array of physical assets, functions, and systems that are vital to ensuring the health, wealth, and security (Council of The European Union, 2008). According to this definition, they include existing transport systems, renewable and non-renewable energy generation plants, industry, water supply networks, and education and health infrastructures. The main threats presented by climate to infrastructure assets include damage or destruction from extreme events (Handmer et al., 2012), which climate change is expected to increase (Fischer and Knutti, 2015, Pall et al., 2011). Different types of infrastructures have different levels of vulnerability to climate change. Moreover, as climate change impacts are established locally, individual assets have different hazard exposures depending on their geographical location. Understanding and quantifying these risks is crucial for planning suitable adaptation measures to safeguard and secure the functioning of society.

Quantifying the effects of climate hazards on infrastructures is a complex task because of incomplete scientific methodologies and limited understanding of vulnerabilities of infrastructures (Mechler et al., 2014, Neumann et al., 2014).

In general, critical infrastructure is exposed to various kinds of threats. There are man-made or technical (terrorism, sabotage, software failures etc.) and natural threats. The latter differ from geological (mass movements, earthquakes etc.) to hydro-meteorological hazards (climate change impacts). The effect generates a sequence of events in human subsystems that result in physical, social and/or economic disruption. Thus, an initial impact can trigger other incidents that lead to consequences with significant magnitude.

For example, the relations and interactions between the water supply and energy sector shows how a malfunction within the energy supply chain – starting from power production over distribution and transformation stations to power lines – can affect water supply. Pumps, control elements, water treatment and digital communication do not work without electricity. Finally, this leads to a breakdown of the water works. The outage of the water supply has significant impacts on other further public facilities such as health care. With respect to wastewater treatment, the lack of water supply initiates a second cascading step, because the malfunction of sewerage system elements – like sewerage treatment plants – has further impacts on other public facilities too.

Critical infrastructure is typically designed to withstand the impact of weather-related events common in a locality but changes in climate patterns increased the range and type of potential risks now facing infrastructure. Most infrastructures being built today are expected to last for 50 years or longer. Investing in infrastructure that was not designed to consider potential changes to an area’s future climate can result in significant increases in cost later on, and it can increase the potential for unplanned outages and failures. Therefore, it is important to understand how future climates might affect life-cycle costs of these investments in the coming decades and to ensure that investments are spent to anticipate these changes. This requires forward planning that considers risks and uncertainties associated with climate change, rather than reliance on models solely based on past events. It also requires an understanding that promoting adaptation in building infrastructure may be a better strategic investment than relying on rebuilding or redesigning infrastructure after an incident has occurred. That understanding should include evaluation of how depletion or alteration of natural resources may impact infrastructure operations.

The significant increase in disasters of a natural and/or technological origin seen today has serious consequences for CI, the population, the environment, and the economy (Kadri et al., 2014). These consequences have been worsened by the development of sociotechnical systems such as transport networks and industrial plants, their interdependencies, and their sensitivity to major hazardous events.

Several specific characteristics of Nat-Tech (natural hazard triggering a technological disaster) events call for greater attention to be given to the study of hazard sequences involving CI – namely, the mode of infrastructure degradation and/or propagation, the nature of infrastructure dependencies and/or interdependencies, and the resilience of infrastructure to the natural events. The scenarios generated by Nat-Tech accidents are very important in the context of quantitative risk assessment.

According to United Nations Office for the Coordination of Humanitarian Affairs (OCHA) (2011), the economic cost of natural disasters in the Asia Pacific region in the first quarter of 2011 is the highest on record. In January, floods devastated large parts of the Australian eastern seaboard, including the third-largest city, Brisbane (with an estimated US$9.8 billion in damages). On February 22, a 6.3-magnitude earthquake struck New Zealand's second-largest city, Christchurch, leaving 172 people dead and parts of the city in ruins; it is estimated that reconstruction will cost US$12 billion. On March 11 at 2:46 p.m., an earthquake caused a tsunami that devastated Tōhoku, Japan, about 240 miles from Tokyo; with estimated damages of up to $309 billion (Carafano, 2011, United Nations Office for the Coordination of Humanitarian Affairs (OCHA), 2011), this is considered the costliest disaster in the world to date.

The 9.0-magnitude earthquake that devastated northeast Japan in 2011 was followed by powerful aftershocks and gave rise to a huge tsunami, which reached several miles inland, flooding hundreds of square miles of land. Both the earthquake and the tsunami damaged or destroyed roads, bridges, ports, railways, buildings, and so forth, as well as leaving more than 28,000 people dead or missing. The havoc wreaked by the earthquake and the tsunami affected more than two dozen prefectures with an estimated population of over 15 million. In addition to material damage, and the destruction of buildings, structures and infrastructures, a nuclear disaster took place.

4.0 DEFINITIONS

4.1 Landslide

Landslide is a general term used to describe the movement of mass of rock, earth or debris down a slope (Cruden, 1991).

4.2 Critical Infrastructure

Critical Infrastructure include a range of engineered systems, assets and facilities which are essential for day-to-day societal functions, as well as continued economic and societal functioning in the aftermath of a disaster event (Bach et al., 2014).

4.3 Element-at-Risk

The population, buildings and engineering works, economic activities, public services utilities, other infrastructures and environmental values in the area potentially affected by the landslide hazard (Fell et al., 2008).

4.4 Hazard

A condition that expresses the probability of a particular threat occurring within a defined time period and area (Corominas et al., 2015).

4.5 Exposure

People, property, systems, or other elements present in hazard zones that are thereby exposed to potential losses (Corominas et al., 2015).

4.6 Vulnerability

The degree of loss of a given element or set of elements exposed to the occurrence of a landslide of a given magnitude/intensity. It is often expressed on a scale of 0 (no loss) to 1 (total loss) (Corominas et al., 2015).

4.7 Vulnerability Index

The conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards. It is given magnitude and expressed on a scale from 0 (no damage) to 1 (total damage) (UN Office for Disaster Risk Reduction, 2017).

4.8 Risk

Measure of the probability and severity of an adverse effect to life, health, property, or the environment. Quantitatively, Risk = Hazard × Potential Worth of Loss. This can be also expressed as “Probability of an adverse event times the consequences if the event occurs” (Corominas et al., 2015).

4.9 Remote Sensing

Remote sensing is the practice of deriving information about the Earth’s land and water surfaces using images acquired from an overhead perspective, using electromagnetic radiation in one or more regions of the electromagnetic spectrum, reflected or emitted from the Earth’s surface (Campbell and Wynne, 2011).

4.10 Geospatial

Usually denoted in the term of geospatial data. Geospatial Data or geographic information is data or information that identifies the geographic location of features and boundaries on Earth, such as natural or man-made features, oceans, and more. Spatial data is usually stored as coordinates and topology and can be mapped. Spatial data is often accessed, manipulated or analysed the Geographic Information Systems (GIS) (MacCGDI, 2019).

5.0 DEVELOPMENT OF LANDSLIDE VULNERABILITY ASSESSMENT AND RISK INDEX

5.1 Development of Landslide Vulnerability Assessment

5.1.1 Existing Methods on Landslide Vulnerability Assessment

One of the most critical steps towards risk analysis is the determination of landslides vulnerability (Uzielli et al., 2008). Vulnerability identifies the element at risk as well as the evaluation of their relationships with the hazard. The relationships relate the landslide potential damages over a specific element at risk. Vulnerability can be defined as the degree of loss to a given element at risk or set of elements at risk resulting from the occurrence of a natural phenomenon of a given magnitude and expressed on a scale from 0 (no damage) to 1 (total damage). Ideally vulnerability assessment accounts various factors including physical, economic, environmental, institutional and human factors. However, from the technical science perspective, vulnerability focuses primarily on the physical aspect which emphasizes on the hazard intensity and its impact on the element-at-risk (Mazzorana et al., 2014, Uzielli et al., 2008). However, this data is rarely available from the past records, and in this case the data is simulated through detailed laboratory experiments and numerical modelling (Gems et al., 2016).

Landslide vulnerability assessment can be divided into qualitative, semi-quantitative and quantitative approaches. In qualitative method of vulnerability assessment suitable vulnerability values are given to a specific element-at-risk based on the landslide type (Cardinali et al., 2002, Kappes et al., 2012). The values were assigned by experts based on their experience and historical records of damages based on a specific landslide type. These methods are flexible, for example indicator-based method is easy to use and understand by decision makers. However, this method relies on the expert judgments and there is no direct (quantified) relation between hazard intensities and degree of damage (Uzielli et al., 2008). Quantitative approaches based on statistical analysis may be more suitable for measuring attributes in larger scale studies, but qualitative approaches will be appropriate for understanding processes and relationships e.g. in community level and bottom-up studies. The semi-quantitative approach reduces level of generalization in the qualitative method (Dai and Lee, 2002). The methods are flexible to reduce subjectivity, compared with the qualitative method. One of the examples of the semi-quantitative vulnerability assessment methods is damage matrices, that are composed by classified intensities and stepwise damage levels. The applicability of this method requires statistical analysis of detailed records on landslides and their consequences (Dai and Lee, 2002). However, this certainly required detailed information on the impact of a specific landslide hazard towards specific element-at-risk.

Due to complexity and highly detailed information required by the quantitative approach, most of time this method was applied at local scale or individual infrastructures (Fuchs et al., 2007, Kaynia et al., 2008, Li et al., 2010, Uzielli et al., 2008). The method usually employed by engineers that involved in the technical decision making where more explicit objective output is required. The results can be directly used in a quantitative risk assessment with detailed analysis on the uncertainty analysis of the vulnerability assessment. The procedures for physical vulnerability assessment can be made based on the expert judgement (heuristics), damage records (empirical) or statistical analysis (probabilistics).

In the technical perspective, a number of vulnerability assessment methods have been made available for quantitative landslide risk estimation. Previous studies have shown that there is no general or universal approach in vulnerability assessment (Fuchs et al., 2011). However, (Papathoma-Köhle et al., 2015) has defined three dominant approaches to express the vulnerability of element-at-risk i.e. vulnerability matrices, vulnerability indicators (Birkmann et al., 2013) and vulnerability curves (Totschnig et al., 2010). Vulnerability matrices are the instruments being used in the qualitative vulnerability assessment which either being developed alone or most of the time based on the real events and more detailed vulnerability assessment approaches. The method presents the possible damages on element-at-risk and its corresponding intensity of the process in a matrix form (Papathoma-Köhle et al., 2017). The input for vulnerability matrices is often obtained either based on empirical data or expert judgment. Intact structural element-at-risk will be assigned with 0.0 and 1.0 for totally damage building or element-at-risk. All other conditions will be given between these values (Papathoma-Köhle et al., 2017). Vulnerability matrices method is popular due to its clear and simple method that relates process and consequences. In addition, it doesn’t require information on the monetary value of the element-at-risk, cost of damage and exact intensity of the landslide. However, it prone to high subjectivity of the vulnerability value and level as it may differ among experts. This obviously limits the transferability and applicability of this method in another area.

For example, (Guillard-Gonçalves et al., 2016) used a qualitative vulnerability matrix assessment of the physical vulnerability of buildings to landslides. The physical vulnerability assessment was based on an inquiry of a pool of European landslide experts and a sub-pool of landslide experts who know the st udy area. The variability of the answers was assessed using standard deviation of each vulnerability value. In their study structural building types was divided into 4 groups namely, 1) wood or metal (SBT1), 2) adobe,rammed earth or loose stone walls (SBT2), 3) brick or stone masonry walls (SBT3), and 4) masonry walls confined with reinforced concrete (SBT4). These building structural types were crossed with the landslide intensity in matrix (i.e. depth or slip surface and height of accumulated materials) as shown in Table 5.1.

Table 5.1: Vulnerability matrices for building structural types crossed with the landslide intensity (i.e. depth or slip surface and height of accumulated materials) (Guillard-Gonçalves et al., 2016).

		Landslide body: depth of slip surface									
		1 m		3 m		5 m		10 m		20 m	
		Avg. vuln.	SD	Avg. vuln.	SD	Avg. vuln.	SD	Avg. vuln.	SD	Avg. vuln.	SD
Pool of European experts (52)	SBT1	0.60	0.24	0.73	0.21	0.84	0.18	0.90	0.19	0.90	0.20
	SBT2	0.57	0.23	0.72	0.20	0.85	0.17	0.92	0.14	0.91	0.17
	SBT3	0.46	0.22	0.60	0.22	0.76	0.18	0.88	0.18	0.91	0.18
	SBT4	0.35	0.20	0.48	0.18	0.66	0.19	0.80	0.18	0.86	0.19
Sub-pool of study area experts (14)	SBT1	0.64	0.19	0.84	0.14	0.96	0.09	1.00	0.00	1.00	0.00
	SBT2	0.59	0.15	0.77	0.15	0.96	0.09	1.00	0.00	1.00	0.00
	SBT3	0.43	0.15	0.66	0.15	0.86	0.12	0.99	0.05	1.00	0.00
	SBT4	0.30	0.10	0.50	0.13	0.71	0.15	0.91	0.13	0.99	0.05

		Landslide foot: height of accumulated material							
		0.5 m		1 m		3 m		5 m	
		Avg. vuln.	SD	Avg. vuln.	SD	Avg. vuln.	SD	Avg. vuln.	SD
Pool of European experts (52)	SBT1	0.45	0.22	0.61	0.20	0.85	0.17	0.94	0.12
	SBT2	0.38	0.23	0.53	0.21	0.78	0.18	0.93	0.12
	SBT3	0.30	0.18	0.40	0.22	0.66	0.17	0.83	0.17

Vulnerability function or also known as vulnerability curves are commonly used to express physical vulnerability in a quantitative way (Papathoma-Köhle et al., 2017). Vulnerability curves can be defined as "a continuous curve associating the intensity of the hazard (X-axis) to the damage response of a building (Y-axis)" (Tarbotton et al., 2015). The function defines the degree of loss generally between 0 and 1 and it requires significant amount of empirical data to be reliable. In this case, the information on magnitude of loss and intensity of landslide hazard is required for different categories of element-at-risk, for example in the large scale vulnerability assessment the hazard intensity information is required for every building. The intensity of the hazard required detailed information of hazard characteristics that could potentially cause damages to the element-at-risk for example for debris flow, intensity can be represented by debris height, velocity or viscosity. The damage records for element-at-risk can be obtained directly either from the actual damage cost or compensation cost or indirectly from photographic documentation or earth observation data that may be translated later into monetary costs (Papathoma-Köhle et al., 2012).

Based on the study of social vulnerability by Birkmann (2006) vulnerability indicators can be defined as "variables which are operational representations of a characteristic or quality of the system able to provide information regarding the susceptibility, coping capacity and resilience of a system to an impact of an albeit ill-defined event linked to a hazard of a natural origin". Vulnerability indicator for landslide hazard includes the selection of relevant indicators, the identification of variables, their weighting and, finally, their aggregation in a vulnerability index (Papathoma-Köhle et al., 2017). The IBM method promotes development of inventory for the element-at-risk for example a database for building characteristics. This allows the development strategies for reduction of vulnerability at individual building scale and development of local structural protection measures. The IBM employed relative vulnerability and not the empirical data of loss and landslide intensity. This enables the method to be applied in the area with no recorded history of events which is useful in the absence of damage data. Although the IBM is not capable in predicting expected loss as the vulnerability curve, but it has a predictive power in indicating the specific buildings that will experience loss. The weighting process is flexible and can be adjusted based on the needs of the users. No expert required to collect the data which means that the determination of scores of the indicators can be based on the owner of the buildings. This will save money and time for data collection.

The use of geospatial technology in updating the information makes the landslide vulnerability assessment easier for example changing the scores of the indicator can answer the "what if" question when any protection measures taken to reduce the vulnerability. The weight and scores can be fine-tuned based on the past records. The comprehensive and flexible geospatial database may allow inclusion of spatial changes in built environment, socio-economic and land use in future scenarios. Spatial visualization in geographic information system (GIS) allows vulnerability map to be produced for individual buildings. The map can be specifically use for emergency and response activity, spatial planning and etc. The IBM method encourage involvement from the community and individual building owner in data collection and vulnerability reduction.

For example, Papathoma-Köhle (2016) highlighted that it is important to account information on intensity of the process in the indicator-based method (IBM) and indicators that reflect the physical resilience of the buildings (Figure 5.1). In this study, the relative vulnerability index (RVI) is calculated using Equation 1. The same vulnerability index was also used by Kappes et al. (2012) in their works for vulnerability analysis.

$$RVI = \sum_{1}^{m} w_m \times I_m \times S_n \tag{1}$$

where w represents the m different weights, I the m indicators and s the n scores of the indicators.

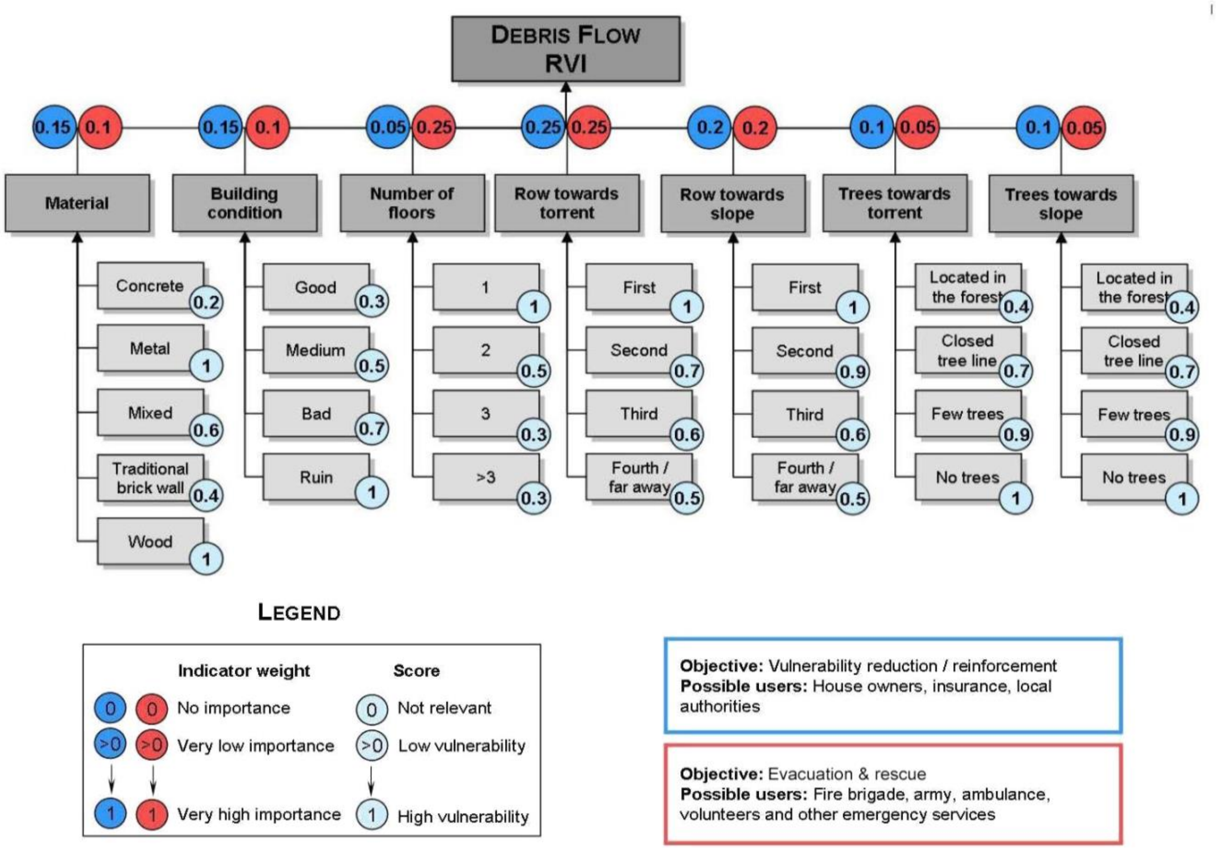


Figure 5.1: The vulnerability indicators are demonstrated together with the weight index, which varies according to the objective of the vulnerability assessment and the end users (Papathoma-Köhle, 2016).

5.1.2 Landslide Vulnerability Assessment for Malaysia

The landslide vulnerability assessment for Malaysia is based on the semi-quantitative approach of indicator-based vulnerability assessment (IBM). In the method the landslide vulnerability indicators are grouped into four (4) clusters i.e. susceptibility of critical infrastructure or CI (*C*), effect of surrounding environment or mitigation measures (*E*), susceptibility of people affected by the damaged CI (*P*) and intensity of landslide hazard (*I*) (Equation 2).

$$V = f(C, E, P, I) \tag{2}$$

Therefore, the vulnerability index for CI (*V*) is defined as in Equation 3.

$$V = \sum_{i=1}^{m} w_i \times s_i \tag{3}$$

where w_i is the i-th weight of m indicators under different clusters and S_i is i-th weight for a specific sub-indicator. The weight for each indicator ranges from 0.1 (low influence to increase vulnerability) to 1.0 (high influence to increase vulnerability). The total weight value must be equal to 1.0. The weight value for each sub-indicator also ranges from 0.1 (low influence to increase vulnerability) to 1.0 (high influence to increase vulnerability). Figure 5.2 shows the overall concept of the landslide vulnerability estimation method.

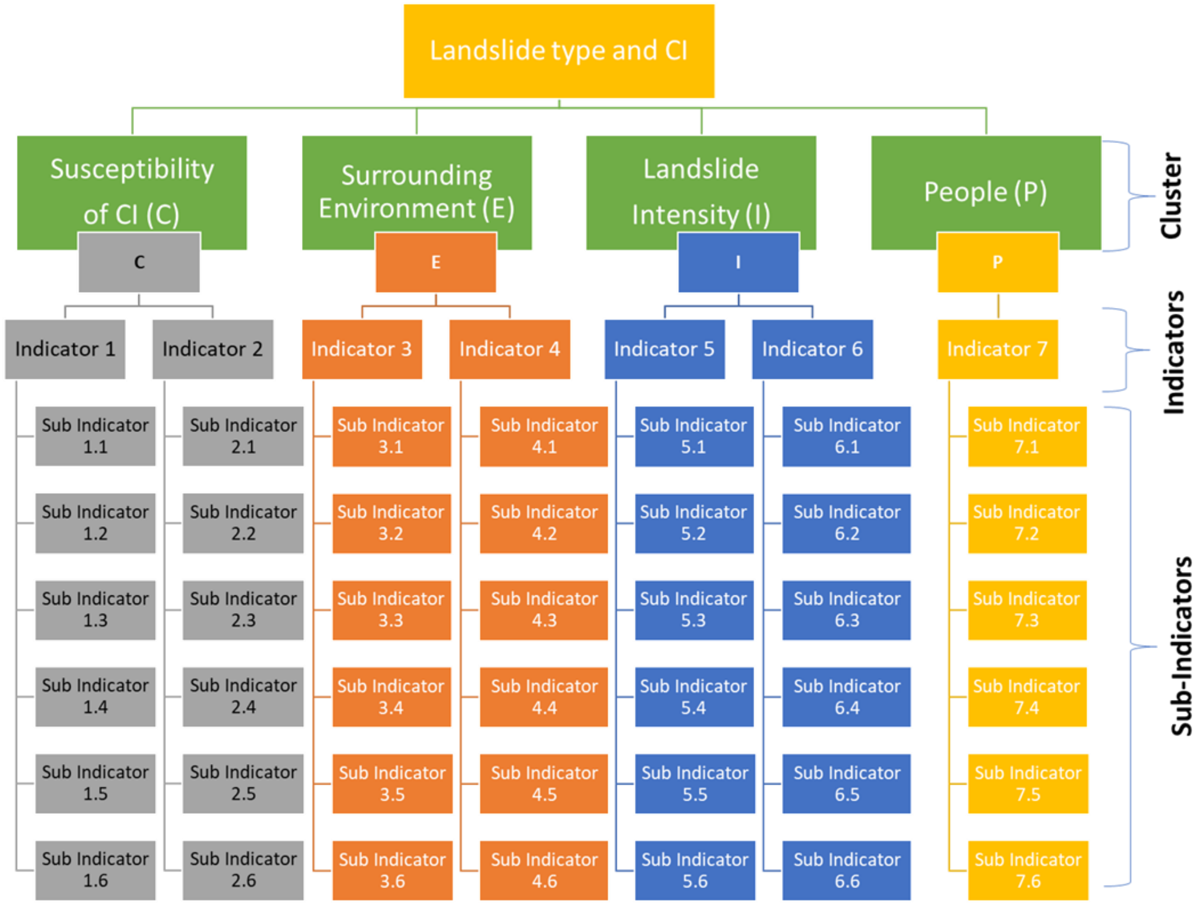


Figure 5.2: The concept of the landslide vulnerability assessment method that integrates different clusters, indicators and sub-indicators.

The CI susceptibility (C) cluster indicates the susceptibility of the CI towards specific landslide hazard intensity that accounts the physical characteristics. The surrounding environment or mitigation measures (E) cluster will take into account the role of existing mitigation measures and surrounding elements in reducing or increasing the impact of landslide on the CI. The intensity of landslide hazard (I) indicates the impact of specific intensity of landslide hazard on a specific CI. People affected by the damaged CI (P) will take into account the impact on the people inside the building-residential, road user, people living downstream area in relation with the location of the dam and people affected by the disrupted functions of utility services.

Each landslide vulnerability index for a specific CI is classified into five (5) classes i.e. very low, low, medium, high and very high landslide vulnerability. The class is given together with a detailed description on the damages and the process that causes the damage (see Table 5.2). Different sets of indicators and sub-indicators are defined for different combination of CI and landslide types. In this manual, the CI is divided into building and residential, road, dam and Tenaga Nasional Berhad (TNB) powerline. On the other hand, the landslide type takes into account rotational and translational landslides and debris flow.

Table 5.2: Landslide vulnerability for each CI.

Critical Infrastructure	Vulnerability Class	Type of Damage	Vulnerability (0-1)
Building and residential	Very low	Slight non-structural damage, stability not affected, furnishing or fitting damaged and no human casualty expected	0.01-0.19
	Low	Cracks in the wall, stability not affected, reparation not urgent and slight injuries of people in the building	0.20-0.39
	Moderate	Strong deformations, huge holes in wall, cracks in supporting structures,	0.40-0.69

		stability affected, doors and windows unusable, severe injuries and evacuation necessary	
	High	Structural breaks, partly destructed, reconstruction of destructed parts, death is highly likely (severe injury) and evacuation necessary	0.70-0.89
	Very High	Severely damaged structure or totally destructed, evacuation necessary, complete reconstruction and death is almost certain	0.90-1.00
Road	Very low	Slight damage of road and does not affect any traffic problem	0.01-0.19
	Low	No structural damage with minor repairable damage and slightly affect traffic	0.20-0.39
	Moderate	No structural damage, major damage requiring major repair work and severe effect on road traffic	0.40-0.69

	High	Structural damage that can affect the stability and functionality of the road, partly unusable road and requires road diversion	0.70-0.89
	Very high	Heavy damage seriously compromising the structural integrity: partial or total collapse of the road, totally unusable road and immediate road diversion is required	0.90-1.00
Dam	Very low	Slight damage of dam and does not affect any problem to the community	0.01-0.19
	Low	No structural damage – minor repairable damage and slightly affect the dam operation	0.20-0.39
	Moderate	No structural damage – major damage requiring major repair work and severe effect on the dam operation	0.40-0.69
	High	Structural damage that can affect the stability and functionality of the dam and partly disrupted dam operation	0.70-0.89

	Very high	Heavy damage seriously compromising the structural integrity: partial or total collapse of the dam, totally disrupted dam operation and immediate evacuation is required for the community living downstream	0.90-1.00
Utility Tenaga Nasional Berhad (TNB) powerline	Very low	Slight damage of utility and does not affect its operation	0.01-0.19
	Low	No structural damage – minor repairable damage and slightly affect the operation	0.20-0.39
	Moderate	No structural damage – major damage requiring major repair work and severely affect the operations of such utility	0.40-0.69
	High	Structural damage that can affect the stability and functionality of the utility. The operation of the utility infrastructure is highly interrupted and requires backup or alternative	0.70-0.89
	Very high	Heavy damage seriously compromising the	0.90-1.00

		structural integrity: partial or total collapse of the road, total collapse of utility operation and immediate backup operation is highly required	

The weight value for each indicator and sub-indicator was obtained based on the expert opinions through series of focus group discussions (FGD). Table 5.3 to Table 5.10 show the weight values for indicators and sub-indicators of each CI and landslide types.

5.1.3 CI with Landslide Type (Translational and Rotational)

Rotational landslide: Landslide that move along a surface rupture that is curved upward (spoon-shaped) and concave (Cruden and Varnes, 1996). Rotational landslide occurs mostly in homogeneous material. Figure 5.3 shows the type of slides graphically which are (A) rotational landslide, (B) translational landslide and (C) block slide.

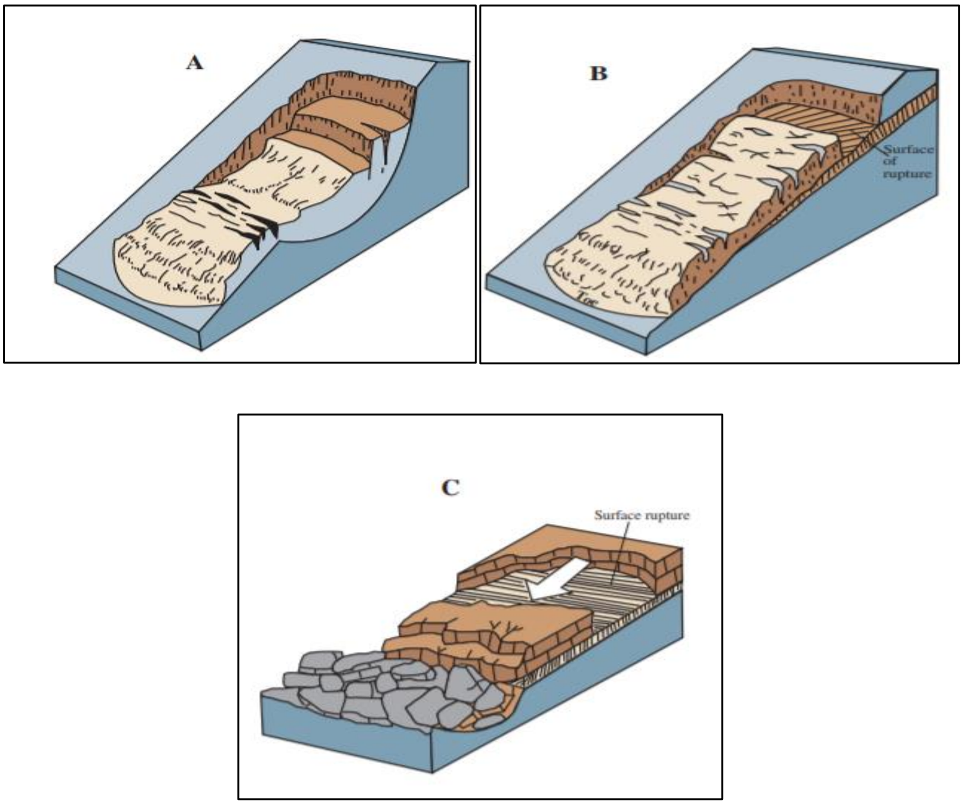


Figure 5.3: (A) Rotational landslide, (B) Translational landslide, (C) Block side (Highland and Bobrowsky, 2008).

The landslide mass moves along a roughly planar surface with little rotation or backward tilting. A block slide is a translational slide in which the moving mass consists of a single unit or a few closely related units that move downslope as a relatively coherent mass.

Table 5.3: Indicators, sub-indicators and weight values of CI (building) with landslide type (translational/rotational).

CLUSTER	COMPONENT (WEIGHT)	INDICATOR	INDICATOR (WEIGHT)	SUB-INDICATOR	SUB-INDICATOR (WEIGHT)
SUSCEPTIBILITY OF CRITICAL INFRASTRUCTURE [C]	0.36	STRUCTURAL TYPOLOGY / STRUCTURE CONSTRUCTION MATERIALS	0.14	Steel structure	0.30
				IBS structures	0.40
				Reinforced concrete structure	0.40
				Masonry structure	0.50
				Timber structure	0.70
				Semi light weight	0.80
				Light weight	1.00
		BUILDING FOUNDATION DEPTH (LANDSLIDE TYPE VS DEEP FOUNDATION BUILDING)	0.12	Accumulation height/landslide depth <1.5 meter, deep foundation (pile)	0.10
				Accumulation height/landslide depth 1.5 - 5 meter, deep foundation (pile)	0.20
				Accumulation height/landslide depth > 5 meter, deep foundation (pile)	0.40
		BUILDING FOUNDATION DEPTH (LANDSLIDE TYPE VS SHALLOW FOUNDATION BUILDING)		Accumulation height/landslide depth < 1.5 meter, shallow foundation (pad footing)	0.60
				Accumulation height/landslide depth 1.5 - 5 meter, shallow foundation (pad footing)	0.80
				Accumulation height/landslide depth > 5 meter, shallow foundation (pad footing)	1.00
		NUMBER OF FLOOR	0.10	High rise (> 5 storey)	0.20
				Medium rise (2 - 5 storey)	0.50
				Low rise (Single storey)	0.80
	0.18		0.07	Engineered protection system	0.10

SURROUNDING ENVIRONMENT [E]		PRESENCE OF PROTECTION		Non-engineered protection system	0.40
				Natural / Vegetation protection	0.70
				No protection	1.00
		DISTANCE BETWEEN BUILDING	0.05	> 5 meter	0.10
				3 - 5 meter	0.50
				< 3 meter	0.90
		BUILDING LOCATION	0.07	Building is located at a distance more than height of slope	0.10
				Building is located at a distance within height of slope	0.20
				Building is located at the toe of slope	0.60
				Building is located at the crest of slope	0.80
				Building is located at the mid-height of slope	1.00
LANDSLIDE INTENSITY [I]	0.33	ACCUMULATION HEIGHTS	0.15	< 0.2 meter	0.10
				0.2 meter - 0.5 meter	0.40
				0.5 meter - 2.0 meter	0.70
				> 2.0 meter	1.00
		LANDSLIDE VOLUME	0.18	< 500 meter3	0.30
				500 - 10,000 meter3	0.50
				10,000 - 50,000 meter3	0.70
				50,000 - 250,000 meter3	0.90
				> 250,000 meter3	1.00
PEOPLE INSIDE BUILDING [P]	0.13	POPULATION DENSITY	0.04	Low	0.30
				Medium	0.60
				High	0.90
		EVACUATION OF ALARM SYSTEM	0.03	Yes	0.10
				No	1.00

		AGE OF PEOPLE	0.03	Adults	0.20
				Teenagers	0.30
				Children	0.50
				Senior citizen (65 - 74 years old)	0.80
				Senior citizen (75 - 84 years old)	0.90
				Senior citizen (> 85 years old)	1.00
		HEALTH CONDITION	0.03	Health (Good)	0.10
				Health (Poor)	0.50
				Disabled person	1.00

Table 5.4: Indicators, sub-indicators and weight values of CI (road) with landslide type (translational/rotational).

CLUSTER	COMPONENT (WEIGHT)	INDICATOR	INDICATOR (WEIGHT)	SUB-INDICATOR	SUB-INDICATOR (WEIGHT)
SUSCEPTIBILITY OF CRITICAL INFRASTRUCTURE [C]	0.38	ROAD CATEGORY (JKR STANDARD DESIGN)	0.09	R6 (expressway)	0.10
				U6 (urban expressway)	0.10
				R5 (highway)	0.40
				U4 / U5 (urban arterial road)	0.40
				R4 / R5 (primary rural road)	0.60
				U3 / U4 (urban collector road)	0.70
				R3 / R4 (secondary rural road)	0.80
				R1 / R1a / R2 (minor rural road)	0.90
				U1 / U1a / U2 / U3 (urban local street)	0.90
		LOCATION OF ROAD	0.10	Road is located at a distance more than height of slope	0.10
				Road is located at a distance within height of slope	0.30
				Road is located at the toe of slope	0.50
				Road is located at the crest of slope	0.70
				Road is located at the mid-height of slope	0.90
		ROAD MATERIAL	0.09	Rigid pavement / Concrete road	0.10
				Flexible pavement / Bituminous road	0.50
				Unpaved road	0.90
		ROAD MAINTENANCE	0.10	Good maintenance	0.10
				Poor maintenance	0.50
				No	1.00
	0.17		0.06	Engineered protection system	0.10

SURROUNDING ENVIRONMENT [E]		PRESENCE OF PROTECTION		Non-engineered protection system	0.40
				Natural / Vegetation protection	0.70
				No protection	1.00
		PRESENCE OF WARNING SYSTEM	0.06	Yes	0.10
				No	1.00
		ROAD DRAINAGE SYSTEM	0.05	Yes	0.20
				No	0.90
LANDSLIDE INTENSITY [I]	0.32	ACCUMULATION HEIGHTS	0.10	< 0.2 meter	0.10
				0.2 - 0.5 meter	0.50
				0.5 - 2.0 meter	0.70
				> 2.0 meter	0.90
		LANDSLIDE THICKNESS	0.10	< 1.5 meter	0.30
				1.5 - 5 meter	0.50
				5 - 20 meter	0.70
				> 20 meter	0.90
		LANDSLIDE VOLUME	0.12	< 500 meter3	0.30
				500 - 10,000 meter3	0.50
				10,000 - 50,000 meter3	0.70
				50,000 - 250,000 meter3	0.90
				> 250,000 meter3	1.00
ROAD USER [P]	0.13	TRAFFIC VOLUME	0.13	(R2 / R1 / R1a / U2 / U1/ U1a (less than 1000 ADT)) - Low traffic volume	0.30
				(R3 / U3 - 3000 to 1000 ADT)	0.50
				(R4 / U4 - 10,000 to 3000 ADT)	0.60
				(R5 / U5 - more than 10,000 ADT)	0.80
				(R6 / R5/ U6 - all traffic volume) - High traffic volume	0.90

Table 5.5: Indicators, sub-indicators and weight values of CI (dam) with landslide type (translational/rotational).

CLUSTER	COMPONENT (WEIGHT)	INDICATOR	INDICATOR (WEIGHT)	SUB-INDICATOR	SUB-INDICATOR (WEIGHT)
SUSCEPTIBILITY OF CRITICAL INFRASTRUCTURE [C]	0.38	BASIN / CATCHMENT)	0.06	Very large (> 100 kilometer2)	0.20
				Large (50 - 100 kilometer2)	0.40
				Medium (25 - 50 kilometer2)	0.50
				Small (5 - 25 kilometer2)	0.60
				Very small (< 5 kilometer2)	1.00
		RESERVOIR	0.07	Very high (> 30 kilometer2)	0.20
				High (11 - 30 kilometer2)	0.30
				Medium (6 - 10 kilometer2)	0.50
				Low (1 - 5 kilometer2)	0.60
				Very low (< 1 kilometer2)	1.00
		DAM DIMENSION (MAIN STRUCTURE - HEIGHT)	0.06	< 5 meter	0.20
				6 - 15 meter	0.30
				16 - 50 meter	0.50
				51 - 99 meter	0.60
				> 100 meter	0.80
		DAM DIMENSION (MAIN STRUCTURE - LENGTH)	0.06	> 300 meter	0.20
				201 - 300 meter	0.30
				101 - 200 meter	0.40
				51 - 100 meter	0.60
				< 50 meter	0.70
			0.06	Sedimentation / Recreational	0.20

		DAM TYPOLOGY/CATEGORIES		Flood mitigation	0.40
				Irrigation	0.50
				Power generation	0.60
				Water supply	0.80
		DAM CONSTRUCTION MATERIALS	0.06	Reinforced concrete	0.30
				Composite	0.50
				Rockfill	0.60
				Earthfill	0.80
SURROUNDING ENVIRONMENT [E]	0.17	PRESENCE OF PROTECTION	0.09	Fully engineered protection system	0.10
				Partially man-made protection system	0.40
				Natural protection (e.g vegetation)	0.60
				No protection	1.00
		PRESENCE OF WARNING SYSTEM	0.08	Yes	0.10
				No	1.00
LANDSLIDE INTENSITY [I]	0.32	LANDSLIDE VOLUME	0.32	< 500 meter3	0.20
				500 - 10,000 meter3	0.40
				10,000 - 50,000 meter3	0.60
				50,000 - 250,000 meter3	0.80
				> 250,000 meter3	1.00
PEOPLE AFFECTED BY DAM OPERATION [P]	0.13	POPULATION DENSITY	0.13	Low (< 25 people per km2)	0.10
				Medium (25 - 50 people per km2)	0.50
				High (> 50 people per km2)	0.70

Table 5.6: Indicators, sub-indicators and weight values of CI (TNB powerline) with landslide type (translational/rotational).

CLUSTER	COMPONENT (WEIGHT)	INDICATOR	INDICATOR (WEIGHT)	SUB-INDICATOR	SUB-INDICATOR (WEIGHT)
SUSCEPTIBILITY OF CRITICAL INFRASTRUCTURE [C]	0.30	TYPOLOGY OF UTILITIES	0.07	Telco tower	0.20
				Substation 33KV	0.30
				PMU	0.50
				GRID 132KV (Height 29 meter) (Width 5.7 meter)	0.70
				Hybrid tower (Combination of KV)	0.80
				GRID 500KV (Height 46 - 67 meter) (Width 10.5 - 19 meter)	0.80
				GRID 275KV (Height 34 meter) (Width 7.5 meter)	0.90
		TOWER AND TOWER COMPONENT MATERIAL	0.06	Composite	0.30
				Steel	0.50
				Wood	0.80
		BUILDING STRUCTURE FOUNDATION (TELCO, PMU, SUBSTATION 33KV)	0.04	For surficial landslide, < 1.5 meter	0.20
				For shallow landslide, 1.5 - 5 meter	0.30
				For deep seated landslide, 5 - 20 meter	0.60
				For very deep seated landslide, > 20 meter	0.90
		TOWER STRUCTURE FOUNDATION (132KV, 275KV, 500KV, HYBRID)	0.07	For surficial landslide, < 1.5 meter	0.10
				For shallow landslide, 1.5 - 5 meter	0.30
				For deep seated landslide, 5 - 20 meter	0.60
				For very deep seated landslide, > 20 meter	0.90
		LOCATION OF TOWER	0.06	Toe of slope	0.30
				Top of slope	0.50

				Face of slope	0.90
SURROUNDING ENVIRONMENT [E]	0.15	PRESENCE OF PROTECTION	0.03	Engineered protection system	0.10
				Non-engineered protection system	0.40
				Natural / Vegetation protection	0.70
				No protection (Including Encroachment & ROW)	1.00
		SLOPE MORPHOLOGY (SHAPE)	0.03	Straight	0.30
				Convex	0.50
				Concave	0.90
		PRESENCE OF WARNING SYSTEM	0.02	Yes	0.10
				No	1.00
		DISTANCE OF TOWER FROM THE RIVER	0.03	> 50 meter	0.10
				25 - 50 meter	0.40
				10 - 25 meter	0.70
				< 10 meter	0.90
		PRESENCE OF EROSION	0.04	No erosion	0.10
				Sheet	0.30
				Rill	0.70
				Gully	0.90
LANDSLIDE INTENSITY [I]	0.45	ACCUMULATION HEIGHTS	0.14	< 0.2 meter	0.10
				0.2 - 0.5 meter	0.50
				0.5 - 2.0 meter	0.70
				> 2.0 meter	0.90
		LANDSLIDE THICKNESS	0.16	Surficial deposit, < 1.5 meter	0.10
				Shallow landslide, 1.5 - 5 meter	0.30
				Deep seated landslide, 5 - 20 meter	0.60
				Very deep seated landslide, > 20 meter	0.90

		LANDSLIDE VOLUME	0.14	< 50 meter3	0.10
				50 - 500 meter3	0.20
				500 - 10,000 meter3	0.50
				10,000 - 50,000 meter3	0.80
				50,000 - 250,000 meter3	0.90
				> 250,000 meter3	1.00
PEOPLE AFFECTED BY TNB POWERLINE OPERATION [P]	0.10	POPULATION DENSITY	0.10	Low (< 25 people per km2)	0.10
				Medium (25 - 50 people per km2)	0.50
				High (> 50 people per km2)	0.70

5.1.4 CI with Landslide Type (Flows)

There are five basic categories of flows that differ from one another in fundamental ways. A debris flow is a form of rapid mass movement in which a combination of loose soil, rock, organic matter, air, and water mobilize as a slurry that flows downslope (Figure 5.4). Debris flows include <50% fines. Debris flows are commonly caused by intense surface-water flow, due to heavy precipitation or rapid snowmelt, that erodes and mobilizes loose soil or rock on steep slopes. Debris flows also commonly mobilize from other types of landslides that occur on steep slopes, are nearly saturated, and consist of a large proportion of silt- and sand-sized material. Debris-flow source areas are often associated with steep gullies, and debris-flow deposits are usually indicated by the presence of debris fans at the mouths of gullies. Fires that denude slopes of vegetation intensify the susceptibility of slopes to debris flows.

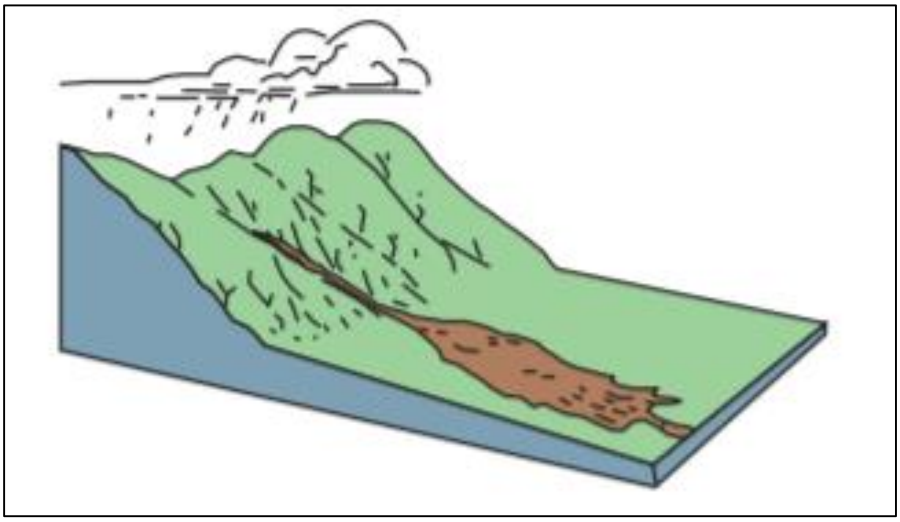


Figure 5.4: Debris flow (Highland and Bobrowsky, 2008).

Earthflows have a characteristic "hourglass" shape (Figure 5.5). The slope material liquefies and runs out, forming a bowl or depression at the head. The flow itself is elongate and usually occurs in fine-grained materials or clay-bearing rocks on moderate slopes and under saturated conditions. However, dry flows of granular material are also possible.

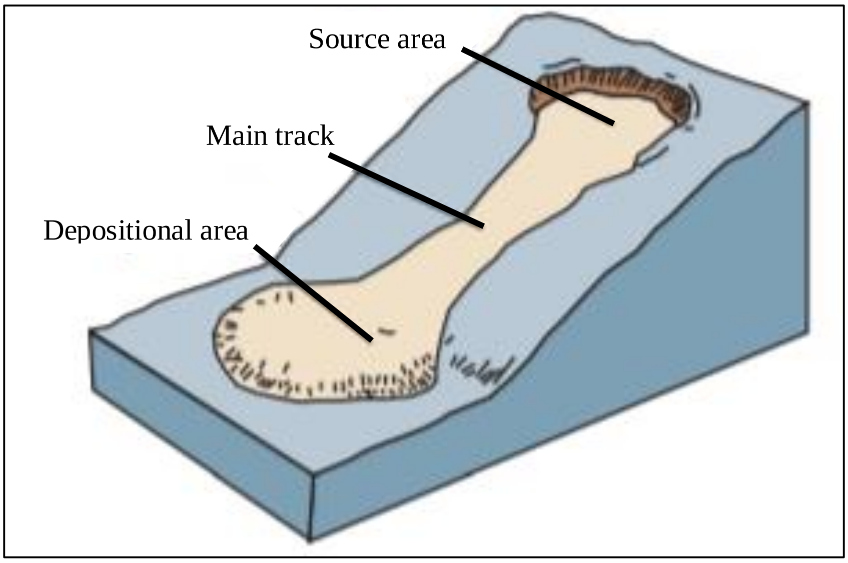


Figure 5.5: Earthflow (Highland and Bobrowsky, 2008).

Creep is the imperceptibly slow, steady, downward movement of slope-forming soil or rock. Movement is caused by shear stress sufficient to produce permanent deformation, but too small to produce shear failure. There are generally three types of creep: (1) seasonal, where movement is within the depth of soil affected by seasonal changes in soil moisture and soil temperature; (2) continuous, where shear stress continuously exceeds the strength of the material; and (3) progressive, where slopes are reaching the point of failure as other types of mass movements. Creep is indicated by curved tree trunks, bent fences or retaining walls, tilted poles or fences, and small soil ripples or ridges (Figure 5.6).

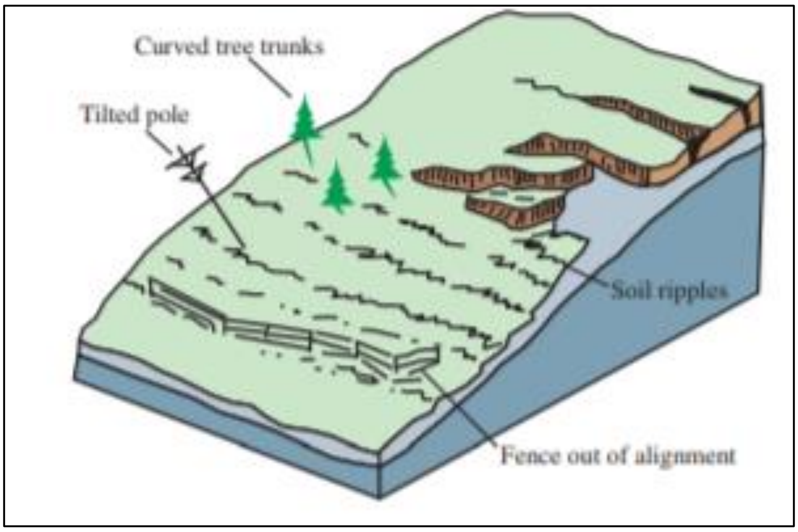


Figure 5.6: Creep landslide (Highland and Bobrowsky, 2008).

Table 5.7: Indicators, sub-indicators and weight values of CI (building) with landslide type (debris flow).

CLUSTER	COMPONENT (WEIGHT)	INDICATOR	INDICATOR (WEIGHT)	SUB-INDICATOR	SUB-INDICATOR (WEIGHT)
SUSCEPTIBILITY OF CRITICAL INFRASTRUCTURE [C]	0.36	STRUCTURAL TYPOLOGY / STRUCTURE CONSTRUCTION MATERIALS	0.14	Steel structure	0.30
				IBS structures	0.40
				Reinforced concrete structure	0.40
				Masonry structure	0.50
				Timber structure	0.70
				Semi light weight	0.80
				Light weight	1.00
		BUILDING FOUNDATION DEPTH (LANDSLIDE TYPE VS DEEP FOUNDATION BUILDING)	0.12	Accumulation height/landslide depth <1.5 meter, deep foundation (pile)	0.10
				Accumulation height/landslide depth 1.5 - 5 meter, deep foundation (pile)	0.20
				Accumulation height/landslide depth > 5 meter, deep foundation (pile)	0.40
		BUILDING FOUNDATION DEPTH (LANDSLIDE TYPE VS SHALLOW FOUNDATION BUILDING)		Accumulation height/landslide depth < 1.5 meter, shallow foundation (pad footing)	0.60
				Accumulation height/landslide depth 1.5 - 5 meter, shallow foundation (pad footing)	0.80
				Accumulation height/landslide depth > 5 meter, shallow foundation (pad footing)	1.00
		NUMBER OF FLOOR	0.10	High rise (> 5 storey)	0.20
				Medium rise (2 - 5 storey)	0.50
				Low rise (Single storey)	0.80
	0.18		0.07	Engineered protection system	0.10

SURROUNDING ENVIRONMENT [E]		PRESENCE OF PROTECTION		Non-engineered protection system	0.40
				Natural / Vegetation protection	0.70
				No protection	1.00
		DISTANCE BETWEEN BUILDING	0.05	> 5 meter	0.10
				3 - 5 meter	0.50
				< 3 meter	0.90
		BUILDING LOCATION	0.07	Building is located at a distance more than height of slope	0.10
				Building is located at a distance within height of slope	0.20
				Building is located at the toe of slope	0.60
				Building is located at the crest of slope	0.80
				Building is located at the mid-height of slope	1.00
LANDSLIDE INTENSITY [I]	0.33	LANDSLIDE VELOCITY	0.10	Extremely slow (16 millimeter/year)	0.10
				Very slow (16 millimeter/year)	0.20
				Slow (1.6 meter/year)	0.40
				Moderate (13 meter/month)	0.50
				Rapid (1.8 meter/hour)	0.70
				Very rapid (3 meter/minute)	0.90
				Extremely rapid (5 meter/second)	1.00
		ACCUMULATION HEIGHTS	0.08	< 0.2 meter	0.10
				0.2 - 0.5 meter	0.40
				0.5 - 2.0 meter	0.70
				> 2.0 meter	1.00
		LANDSLIDE THICKNESS	0.06	Surficial landslide, < 1.5 meter	0.20
				Shallow landslide, 1.5 - 5 meter	0.40
				Deep seated landslide, 5 - 20 meter	0.60

				Very deep seated landslide, > 20 meter	0.80
		LANDSLIDE VOLUME	0.09	< 500 meter3	0.30
				500 - 10,000 meter3	0.50
				10,000 - 50,000 meter3	0.70
				50,000 - 250,000 meter3	0.90
				> 250,000 meter3	1.00
PEOPLE INSIDE BUILDING [P]	0.13	POPULATION DENSITY	0.04	Low	0.30
				Medium	0.60
				High	0.90
		EVACUATION OF ALARM SYSTEM	0.03	Yes	0.10
				No	1.00
		AGE OF PEOPLE	0.03	Adults	0.20
				Teenagers	0.30
				Children	0.50
				Senior citizen (65 - 74 years old)	0.80
				Senior citizen (75 - 84 years old)	0.90
				Senior citizen (> 85 years old)	1.00
		HEALTH CONDITION	0.03	Health (Good)	0.10
				Health (Poor)	0.50
				Disabled person	1.00

Table 5.8: Indicators, sub-indicators and weight values of CI (road) with landslide type (debris flow).

CLUSTER	COMPONENT (WEIGHT)	INDICATOR	INDICATOR (WEIGHT)	SUB-INDICATOR	SUB-INDICATOR (WEIGHT)
SUSCEPTIBILITY OF CRITICAL INFRASTRUCTURE [C]	0.38	ROAD CATEGORY (JKR STANDARD DESIGN)	0.09	R6 (expressway)	0.10
				U6 (urban expressway)	0.10
				R5 (highway)	0.40
				U4 / U5 (urban arterial road)	0.40
				R4 / R5 (primary rural road)	0.60
				U3 / U4 (urban collector road)	0.70
				R3 / R4 (secondary rural road)	0.80
				R1 / R1a / R2 (minor rural road)	0.90
				U1 / U1a / U2 / U3 (urban local street)	0.90
		LOCATION OF ROAD	0.10	Road is located at a distance more than height of slope	0.10
				Road is located at a distance within height of slope	0.30
				Road is located at the toe of slope	0.50
				Road is located at the crest of slope	0.70
				Road is located at the mid-height of slope	0.90
		ROAD MATERIAL	0.09	Rigid pavement / Concrete road	0.10
				Flexible pavement / Bituminous road	0.50
				Unpaved road	0.90
		ROAD MAINTENANCE	0.10	Good maintenance	0.10
				Poor maintenance	0.50
				No	1.00
	0.17		0.06	Engineered protection system	0.10

SURROUNDING ENVIRONMENT [E]		PRESENCE OF PROTECTION		Non-engineered protection system	0.40
				Natural / Vegetation protection	0.70
				No protection	1.00
		PRESENCE OF WARNING SYSTEM	0.06	Yes	0.10
				No	1.00
		ROAD DRAINAGE SYSTEM	0.05	Yes	0.20
				No	0.90
LANDSLIDE INTENSITY [I]	0.32	LANDSLIDE VELOCITY	0.08	Extremely slow (16 millimeter/year)	0.10
				Very slow (16 millimeter/year)	0.20
				Slow (1.6 meter/year)	0.40
				Moderate (13 meter/month)	0.50
				Rapid (1.8 meter/hour)	0.70
				Very rapid (3 meter/minute)	0.90
				Extremely rapid (5 meter/second)	1.00
		ACCUMULATION HEIGHT	0.08	< 0.2 meter	0.10
				0.2 - 0.5 meter	0.50
				0.5 - 2.0 meter	0.70
				> 2.0 meter	0.90
		LANDSLIDE THICKNESS	0.08	< 1.5 meter	0.30
				1.5 - 5 meter	0.50
				5 - 20 meter	0.70
				> 20 meter	0.90
		LANDSLIDE VOLUME	0.08	< 500 meter3	0.30
				500 - 10,000 meter3	0.50
				10,000 - 50,000 meter3	0.70
				50,000 - 250,000 meter3	0.90

				> 250,000 meter3	1.00
ROAD USER [P]	0.13	TRAFFIC VOLUME	0.13	(R2 / R1 / R1a / U2 / U1/ U1a (less than 1000 ADT)) - Low traffic volume	0.30
				(R3 / U3 - 3000 to 1000 ADT)	0.50
				(R4 / U4 - 10,000 to 3000 ADT)	0.60
				(R5 / U5 - more than 10,000 ADT)	0.80
				(R6 / R5/ U6 - all traffic volume) - High traffic volume	0.90

Table 5.9: Indicators, sub-indicators and weight values of CI (dam) with landslide type (debris flow).

CLUSTER	COMPONENT (WEIGHT)	INDICATOR	INDICATOR (WEIGHT)	SUB-INDICATOR	SUB-INDICATOR (WEIGHT)
SUSCEPTIBILITY OF CRITICAL INFRASTRUCTURE [C]	0.38	BASIN / CATCHMENT)	0.06	Very large (> 100 kilometer2)	0.20
				Large (50 - 100 kilometer2)	0.40
				Medium (25 - 50 kilometer2)	0.50
				Small (5 - 25 kilometer2)	0.60
				Very small (< 5 kilometer2)	1.00
		RESERVOIR	0.07	Very high (> 30 kilometer2)	0.20
				High (11 - 30 kilometer2)	0.30
				Medium (6 - 10 kilometer2)	0.50
				Low (1 - 5 kilometer2)	0.60
				Very low (< 1 kilometer2)	1.00
		DAM DIMENSION (MAIN STRUCTURE - HEIGHT)	0.06	< 5 meter	0.20
				6 - 15 meter	0.30
				16 - 50 meter	0.50
				51 - 99 meter	0.60
				> 100 meter	0.80
		DAM DIMENSION (MAIN STRUCTURE - LENGTH)	0.06	> 300 meter	0.20
				201 - 300 meter	0.30
				101 - 200 meter	0.40
				51 - 100 meter	0.60
				< 50 meter	0.70
			0.06	Sedimentation / Recreational	0.20

		DAM TYPOLOGY/CATEGORIES		Flood mitigation	0.40
				Irrigation	0.50
				Power generation	0.60
				Water supply	0.80
		DAM CONSTRUCTION MATERIALS	0.06	Reinforced concrete	0.30
				Composite	0.50
				Rockfill	0.60
				Earthfill	0.80
SURROUNDING ENVIRONMENT [E]	0.17	PRESENCE OF PROTECTION	0.09	Fully engineered protection system	0.10
				Partially man-made protection system	0.40
				Natural protection (e.g vegetation)	0.60
				No protection	1.00
		PRESENCE OF WARNING SYSTEM	0.08	Yes	0.10
				No	1.00
LANDSLIDE INTENSITY [I]	0.32	LANDSLIDE VELOCITY	0.18	Extremely slow (16 millimeter/year)	0.10
				Very slow (16 millimeter/year)	0.20
				Slow (1.6 meter/year)	0.40
				Moderate (13 meter/month)	0.50
				Rapid (1.8 meter/hour)	0.70
				Very rapid (3 meter/minute)	0.90
				Extremely rapid (5 meter/second)	1.00
		LANDSLIDE VOLUME	0.14	< 500 meter3	0.20
				500 - 10,000 meter3	0.40
				10,000 - 50,000 meter3	0.60
				50,000 - 250,000 meter3	0.80
				> 250,000 meter3	1.00

PEOPLE AFFECTED BY DAM OPERATION [P]	0.13	POPULATION DENSITY	0.13	Low (< 25 people per km2)	0.10
				Medium (25 - 50 people per km2)	0.50
				High (> 50 people per km2)	0.70

Table 5.10: Indicators, sub-indicators and weight values of CI (TNB powerline) with landslide type (debris flow).

CLUSTER	COMPONENT (WEIGHT)	INDICATOR	INDICATOR (WEIGHT)	SUB-INDICATOR	SUB-INDICATOR (WEIGHT)
SUSCEPTIBILITY OF CRITICAL INFRASTRUCTURE [C]	0.30	TYPOLOGY OF UTILITIES	0.07	Telco tower	0.20
				Substation 33KV	0.30
				PMU	0.50
				GRID 132KV (Height 29 meter) (Width 5.7 meter)	0.70
				Hybrid tower (Combination of KV)	0.80
				GRID 500KV (Height 46 - 67 meter) (Width 10.5 - 19 meter)	0.80
				GRID 275KV (Height 34 meter) (Width 7.5 meter)	0.90
		TOWER AND TOWER COMPONENT MATERIAL	0.06	Composite	0.30
				Steel	0.50
				Wood	0.80
		BUILDING STRUCTURE FOUNDATION (TELCO, PMU, SUBSTATION 33KV)	0.04	For surficial landslide, < 1.5 meter	0.20
				For shallow landslide, 1.5 - 5 meter	0.30
				For deep seated landslide, 5 - 20 meter	0.60
				For very deep seated landslide, > 20 meter	0.90
		TOWER STRUCTURE FOUNDATION (132KV, 275KV, 500KV, HYBRID)	0.07	For surficial landslide, < 1.5 meter	0.10
				For shallow landslide, 1.5 - 5 meter	0.30
				For deep seated landslide, 5 - 20 meter	0.60
				For very deep seated landslide, > 20 meter	0.90
		LOCATION OF TOWER	0.06	Toe of slope	0.30
				Top of slope	0.50

				Face of slope	0.90
SURROUNDING ENVIRONMENT [E]	0.15	PRESENCE OF PROTECTION	0.04	Engineered protection system	0.10
				Non-engineered protection system	0.40
				Natural / Vegetation protection	0.70
				No protection (Including Encroachment & ROW)	1.00
		SLOPE MORPHOLOGY (SHAPE)	0.04	Straight	0.30
				Convex	0.50
				Concave	0.90
		PRESENCE OF WARNING SYSTEM	0.03	Yes	0.10
				No	1.00
		DISTANCE OF TOWER FROM THE RIVER	0.04	> 50 meter	0.10
				25 - 50 meter	0.40
				10 - 25 meter	0.70
				< 10 meter	0.90
		PRESENCE OF EROSION	0.05	No erosion	0.10
				Sheet	0.30
				Rill	0.70
				Gully	0.90
LANDSLIDE INTENSITY [I]	0.45	LANDSLIDE VELOCITY	0.13	Extremely slow (16 millimeter/year)	0.10
				Very slow (16 millimeter/year)	0.20
				Slow (1.6 meter/year)	0.40
				Moderate (13 meter/month)	0.50
				Rapid (1.8 meter/hour)	0.70
				Very rapid (3 meter/minute)	0.90
				Extremely rapid (5 meter/second)	1.00
			0.10	< 0.2 meter	0.10

		ACCUMULATION HEIGHTS		0.2 - 0.5 meter	0.50
				0.5 - 2.0 meter	0.70
				> 2.0 meter	0.90
		LANDSLIDE THICKNESS	0.13	Surficial deposit, < 1.5 meter	0.10
				Shallow landslide, 1.5 - 5 meter	0.30
				Deep seated landslide, 5 - 20 meter	0.60
				Very deep seated landslide, > 20 meter	0.90
		LANDSLIDE VOLUME	0.10	< 50 meter3	0.10
				50 - 500 meter3	0.20
				500 - 10,000 meter3	0.50
				10,000 - 50,000 meter3	0.80
				50,000 - 250,000 meter3	0.90
				> 250,000 meter3	1.00
PEOPLE AFFECTED BY TNB POWERLINE OPERATION [P]	0.10	POPULATION DENSITY	0.10	Low (< 25 people per km2)	0.10
				Medium (25 - 50 people per km2)	0.50
				High (> 50 people per km2)	0.70

Table 5.11 shows the example of landslide vulnerability assessment based on the IBM approach. The landslide vulnerability scenario depicts detailed information on indicators and sub-indicators for building and residential developed over rotational and translational landslide. Each indicator and sub-indicator is given specific weight value from which the total vulnerability index is calculated. In this scenario the calculated vulnerability index is 0.20 and classified as low vulnerability class.

Table 5.11: Example of landslide vulnerability assessment for building and residential.

Landslide type: Translational/Rotational

CI: Building

Susceptibility of CI (C):

- *Structural Typology* ***(0.14)***: *Steel structure* ***(0.30)***
- *Foundation Depth* ***(0.12)***: *Landslide Type Vs Deep Foundation Building: Accumulation height/landslide depth <1.5 meter, deep foundation (pile)* ***(0.10)***
- *Number of floor* ***(0.10)***: *High rise (> 5 storey)* ***(0.20)***

Surrounding Environment (E):

- *Presence of protection* ***(0.07)***: *Engineered protection system* ***(0.10)***
- *Distance between building* ***(0.05)***: *> 5 meter* ***(0.10)***
- *Building location* ***(0.07)***: *Building is located at a distance more than height of slope* ***(0.10)***

Landslide intensity (I):

- *Accumulation height* ***(0.15)***: *Height < 0.2 meter* ***(0.10)***
- *Landslide volume* ***(0.18)***: *< 500 meter^3* ***(0.30)***

People inside the building (P):

- *Population density* ***(0.04)***: *Low* ***(0.30)***
- *Evacuation of alarm system* ***(0.03)***: *Yes* ***(0.10)***
- *Age of people* ***(0.03)***: *Adults* ***(0.20)***
- *Health condition* ***(0.03)***: *Health (Good)* ***(0.10)***

Vulnerability index = (0.14 x 0.30) + (0.12 x 0.10) + (0.10 x 0.20) + **(0.07 x 0.10)** + **(0.05 x 0.10)** + **(0.07 x 0.10)** + **(0.15 x 0.10)** + **(0.18 x 0.30)** + **(0.04 x 0.30)** + **(0.03 x 0.10)** + **(0.03 x 0.20)** + **(0.03 X 0.10)** = **0.20**

Vulnerability index: 0.20

Class of vulnerability: **Low**

Vulnerability description: Cracks in the wall, stability not affected, reparation not urgent and slight injuries of people in the building

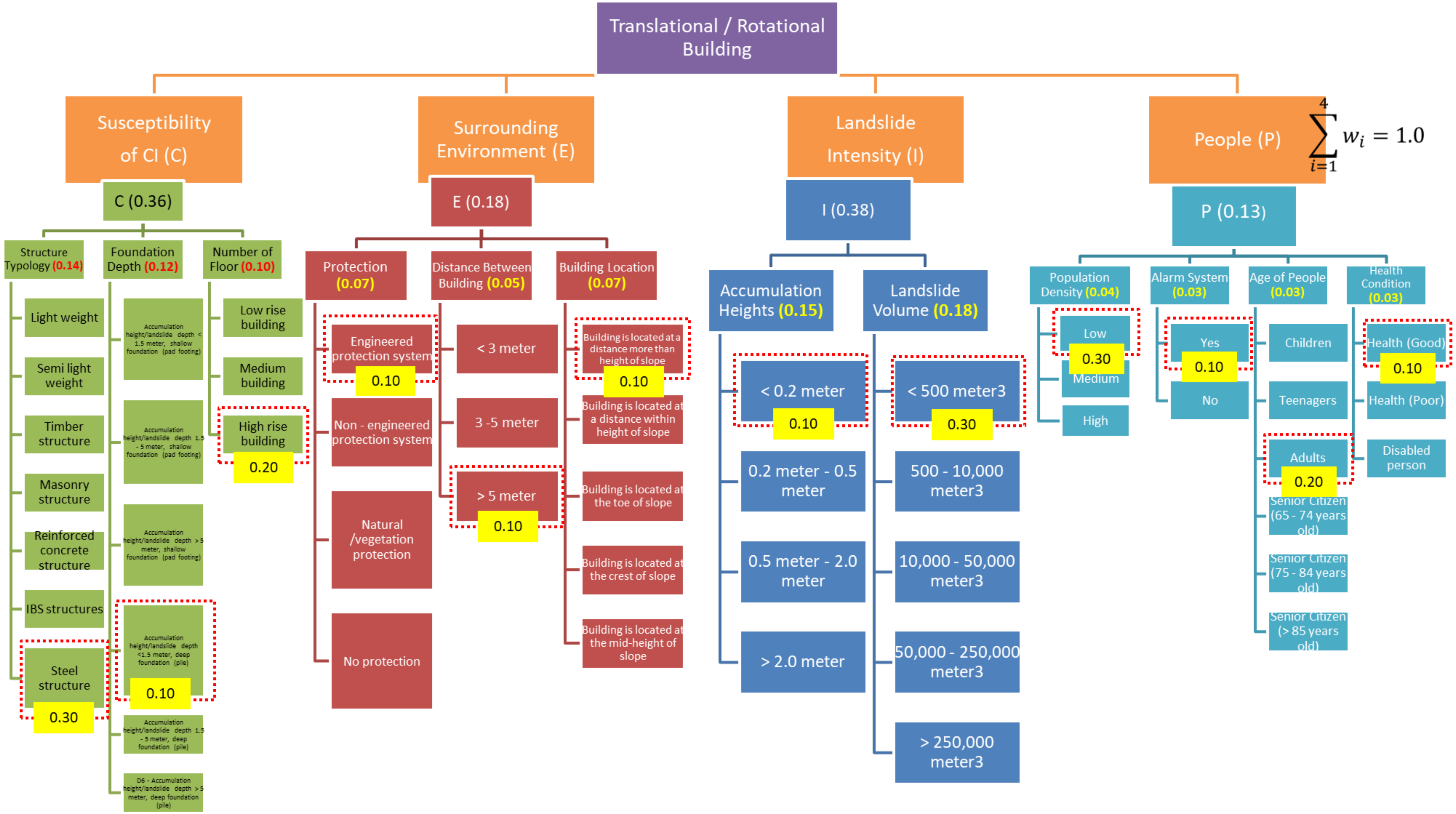


Figure 5.7: Conceptual division of indicators, sub-indocators and weight value for landslide vulnerability assessment scenario in Table 5.11.

5.2 Development of Landslide Risk Assessment

5.2.1 Existing Methods on Landslide Risk Assessment

Traditionally, landslide risk is defined as "the expected number of life lost, persons injured, damage to property and disruption of economic activity due to a particular damaging phenomenon for a given area and reference period" (Varnes, 1984). On a simpler note, International Union of Geological Sciences similarly defines landslide risk as a measure of the probability and severity of an adverse effect to health, property and the environment (Cruden, 1997). Both definitions highlight three different elements at risk associated with landslide which are critical physical infrastructure, socio-economic and environment.

Therefore, a final map of landslide risk shall technically present the subdivision of the terrain into zones that are characterized by different probabilities of losses that might occur due to landslides of a given type within a given period of time. Two common methods are available, either in the form of qualitative or quantitative manner. Qualitative risk analysis refers to an analysis that uses word form, descriptive or numerical scales to describe the magnitude of potential consequences and the likelihood that those consequences will occur, whereas quantitative risk analysis is based on numerical values of the probability, vulnerability and consequences, resulting in a numerical value of risk (Cruden, 1997, UN/ISDR, 2004, Fell et al., 2008). Depending on the completeness of data, a semi-quantitative approach can be devised which provides indicative probability via qualitative terms given a team of expert is established for heuristic assessment (van Westen et al., 2006).

In specific, loss can be grouped into direct and indirect losses which both can be further separated into human, physical, economic and cultural environment (Table 5.12) (Winter et al., 2016). The loss assessments required different level of information depending on the level of information obtained for element-at-risk (Table 5.13).

Table 5.12: Classification of landslide risk assessments (Winter et al., 2016).

	Human - Social	Physical	Economic	Cultural Environmental
Direct Losses	Fatalities Injuries Loss of income or employment Homelessness	Structural damage or collapse to buildings Non-structural damage and damage to contents Structural damage infrastructure	Interruption of business due to damage to buildings and infrastructure Loss of productive workforce through fatalities, injuries and relief efforts Capital costs of response and relief	Sedimentation Pollution Endangered species Destruction of ecological zones Destruction of cultural heritage
Indirect losses	Diseases Permanent disability Psychological impact Loss of social cohesion due to disruption of community Political unrest	Progressive deterioration of damaged buildings and infrastructure which are not repaired	Economic losses due to short term disruption of activities Long term economic losses Insurance losses weakening the insurance market Less investments Capital costs of repair Reduction in tourism	Loss of biodiversity Loss of cultural diversity

Table 5.13: Level of information required for different type of element-at-risk (Winter et al., 2016).

Physical elements Buildings: Urban land use, construction types, building height, building age, total floor space, replacement costs. Monument and cultural heritage	**Population** Density of population, distribution in space, distribution in time, age distribution, gender distribution, handicapped, income distribution
Essential facilities Emergency shelters, schools, hospitals, fire brigades, police	**Socio-economic aspects** Organizations of population, governance, community organization, government support, socio-economic levels. Cultural heritage and traditions.
Transpotation facilities Roads, railway, metro, public transportation systems, harbor facilities, airport facilities.	**Economic activities** Spatial distribution of economic activities, input-output table, dependency, redundancy, unemployment, economic production in various sectors
Life lines Water supply, electricity supply, gas supply, telecommunications, mobile telephone network, sewage system	**Environmental elements** Ecosystems, protected areas, natural parks, environmentally sensitive areas, forests, wetlands, acuifers, flora, fauna, biodiversity.

As a form of realization from landslide risk definitions, previous studies have shown that quantitative risk (R) can be defined conceptually based on Equation 4 (Vega and Hidalgo, 2016). Hence the risk map can be generated by combining three contributing factors i.e.: 1) the probability of occurrence of a landslide of a given magnitude (Hazard); 2) the valued attributes at risk (Value); and 3) the expected degree of loss resulting from the specified landslide magnitude (Vulnerability).

$$R = H \times E \times V \tag{4}$$

where H is the specific landslide hazard, E is the value for a specific element-at-risk and V is the vulnerability value for element-at-risk. The value of E could be more specific according to different type of landslide risk assessment, i.e. quantitative and semi-quantitative. For quantitative assessment of critical physical infrastructure, the dollar value relative to the value of the critical infrastructure is used (Fell et al., 2008). On the other hand, the value of E for semi-quantitative landslide risk assessment is closely related to the total amount of the exposed critical infrastructure when landslide happens (Abella and van Westen, 2007). According to van Westen et al. (2006), the simplicity of the formula will be more complex once particular situation of landslide is considered such as for the specific risk of people inside buildings. Furthermore, a general scenario-based risk formulation can be explained by Equation 5 (Roberds, 2005).

$$E[loss] = \sum_{all\ S} \sum_{all\ C} C \times P[C|S]P[S] \tag{5}$$

where $E[loss]$ is the expected value of loss, C is a particular set of losses (of a collectively exhaustive and mutually exclusive set of possible losses), $P[S]$ is the probability of occurrence of scenario S and $P\ [C \mid S]$ is the conditional probability of loss set C given that scenario S has occurred. This scenario-based risk assessment approach involves the following steps:

i. Define scenarios for landslide triggering
ii. Compute the run-out distance, volume and extent of landslide for each scenario
iii. Identify the elements at risk and their vulnerabilities
iv. Estimate the loss for the different landslide scenarios
v. Estimate the risk and compare it with tolerable or acceptable risk levels

The qualitative risk assessment does not involve the usage of any equation, instead it is based on the classes of relative risk for example the risk matrix that can be generated by combining the relative probability of landslide occurrence and relative classes of loss (Figure 5.8) (Dai and Lee, 2002).

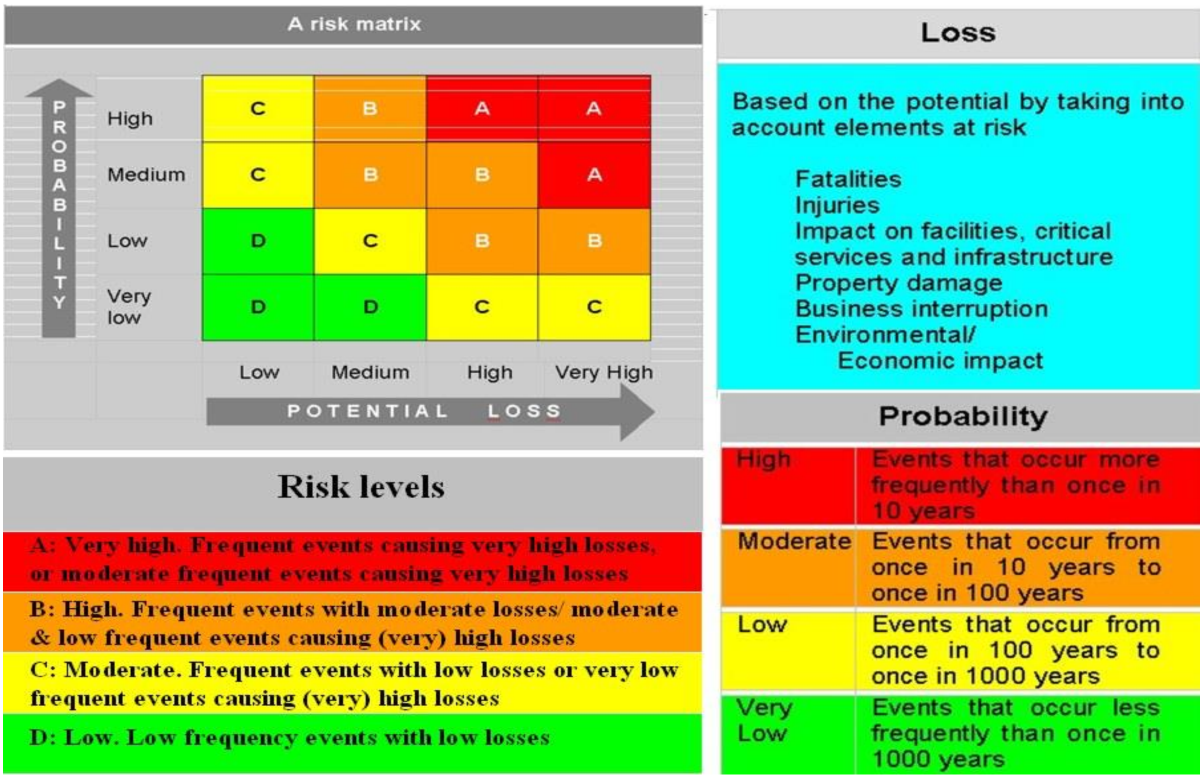


Figure 5.8: Level of information required for different type of element-at-risk (Winter et al., 2016).

Table 5.14 shows an example of how the risk index is determined using qualitative approach of risk assessment. Once determined, the selection of mitigation method is conducted by referring to Table 5.15. Examples of options for mitigation of risks for a slope or group of slopes would include: 1) Reduce the frequency of landsliding – by stabilization measures such as groundwater drainage, slope modification, anchors; or by scaling loose rocks & 2) Reduce the probability of the landslide reaching the element at risk – e.g. for rockfalls, construct rock catch fences; for debris flows construct catch dams.

Table 5.14: Examples of matrix selection for landslide mitigation categories (based on Roslee et al. (2017), Roslee and Tongkul (2018)).

Degree of Hazard	Degree of Vulnerability					Categories
		Very Low	Low	Moderate	High	Very High
	Very Low	I	I	II	III	III
	Low	I	II	II	III	III
	Moderate	II	II	III	III	IV
	High	III	III	III	IV	IV
	Very High	III	III	IV	IV	V

Table 5.15: Examples of landslide mitigation method (based on Roslee et al. (2017), Roslee and Tongkul (2018)).

Categories	Mitigation Method	Structural Cost	Non-Structural Cost
I	Accept and modify the risk	High	Moderate
II	Modify and reduce the risk	Very High	High
III	Reduce the risk, risk monitor and postpone the results	Very High	Very High
IV	Risk monitor, postpone the results and ignore the risk	High	Moderate
V	Postpone the results, ignore the risk and risk transfer	Moderate	Moderate

Figure 5.9 highlighted the information or input data for landslide risk assessment. Notice that the top part of the figure specifies this input data which are environmental factors, landslide inventory (or occurrences), triggering factors and elements at risk (Hazarika, 2016). Each input data corresponds to the identical component of Equation (3) where the environmental and triggering factors, plus landslide inventory subsequently will produce hazard maps or H, the elements at risk is used for vulnerability assessment or V and also the value of E. On top of listing corresponding data for landslide risk assessment, the bottom of Figure 5.9 also shows the specific type of quantitative and qualitative risk assessment which are risk curve, event-tree, risk matrix and indicator approach.

Suitable approach for landslide risk method will be determined based on requirement by the authorities for example scale of mapping and essential information that should be considered by the risk index. Practically, the remaining time scale of the project will also greatly influence the selection of landslide risk methodology. In addition, the risk index is proposed for each element-at-risk and detailed explanation on the losses is explained clearly. As for quantitative approach, the availability of complete set of data ranks high as a criteria selection.

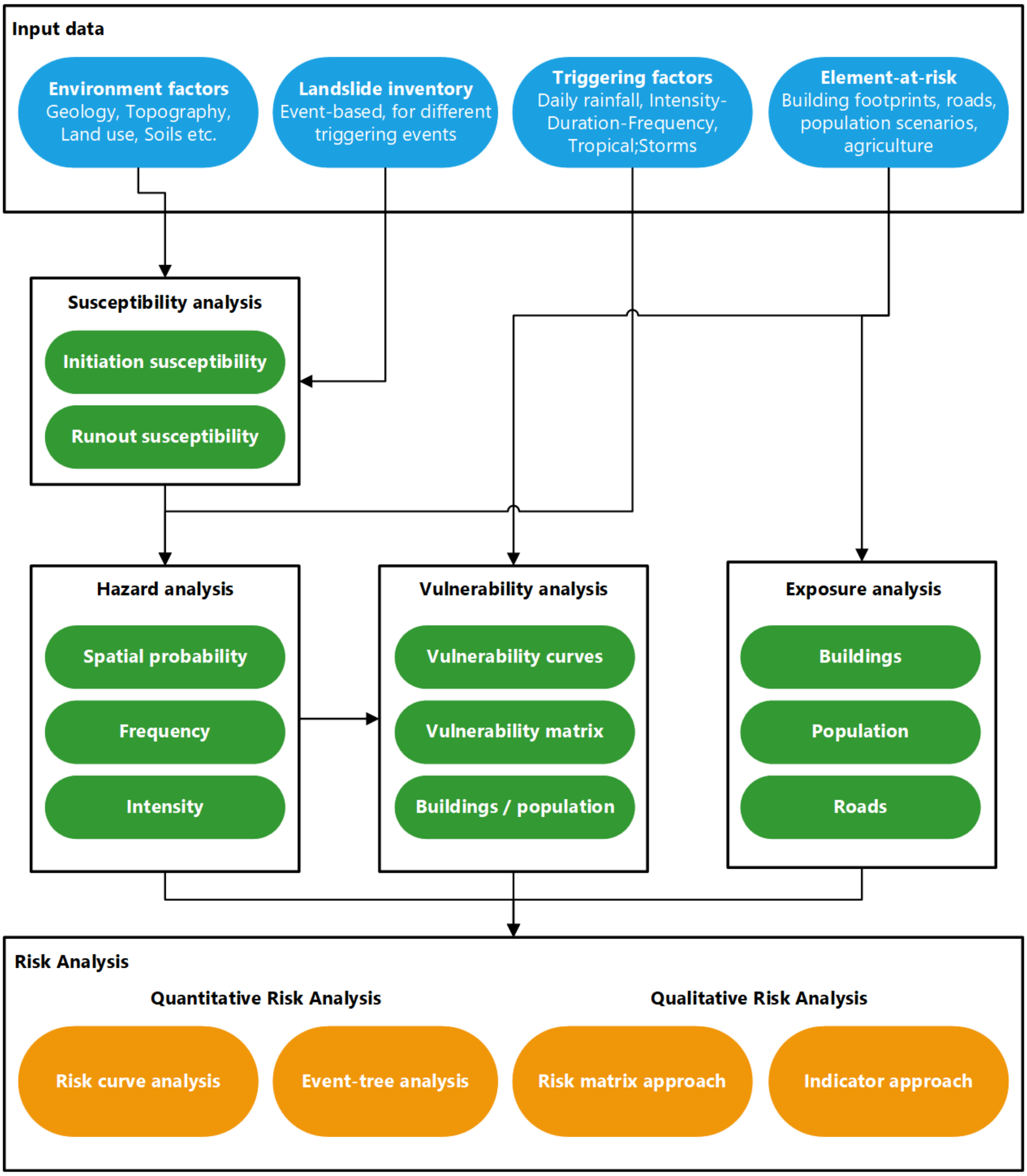


Figure 5.9: Schematic representation of landslide risk assessment methodology (van Westen et al., 2006, Hazarika, 2016).

Another important consideration when choosing specific method of landslide risk is the comparison against the type of landslide hazard method. As proposed by van Westen et al. (2006), there exists a level of suitability for landslide risk method depending on the specific methodology of landslide hazard assessment which is carried out much earlier. Table 5.16 specifies this suitability, ideal for scales of 1:10,000 to 1:50,000. The numbers in Table 5.16 have the following explanation, in a reverse statement from what is mentioned in the original text:

i. 0: The risk method is not suitable for the matching hazard method.
ii. 1: The risk method is less suitable for the matching hazard method.
iii. 2: The risk method could be suitable for the matching hazard method, which depends on the availability of data (e.g. historical landslide records).
iv. 3: The risk method is the most suitable for the matching hazard method given the availability of data.

Table 5.16: Suitability of risk approach compared against hazard approach (van Westen et al., 2006).

Hazard Approach	Risk Approach		
	Qualitative	Semi-quantitative	Quantitative
Inventory-based probabilistic	2	2	2
Heuristic/geomorphological/direct mapping/expert-based	3	3	0
Statistical (bivariate or multivariate)	3	2	2
Deterministic and dynamic modelling	0	1	3

Recent advancement provides better technique for landslide risk assessment. In their paper, Martha et al. (2013), employs quantitative risk assessment for the purpose of loss assessment. A non-concave shape risk curve as shown in Figure 5.10 is an outcome of the risk assessment where it highlighted the total loss of critical infrastructure, which are buildings and roads as y-axis against annual probability of landslide as x-axis. The non-concave nature of the curve reflects uncertainty in vulnerability calculation plus non-consideration of few elements at risk.

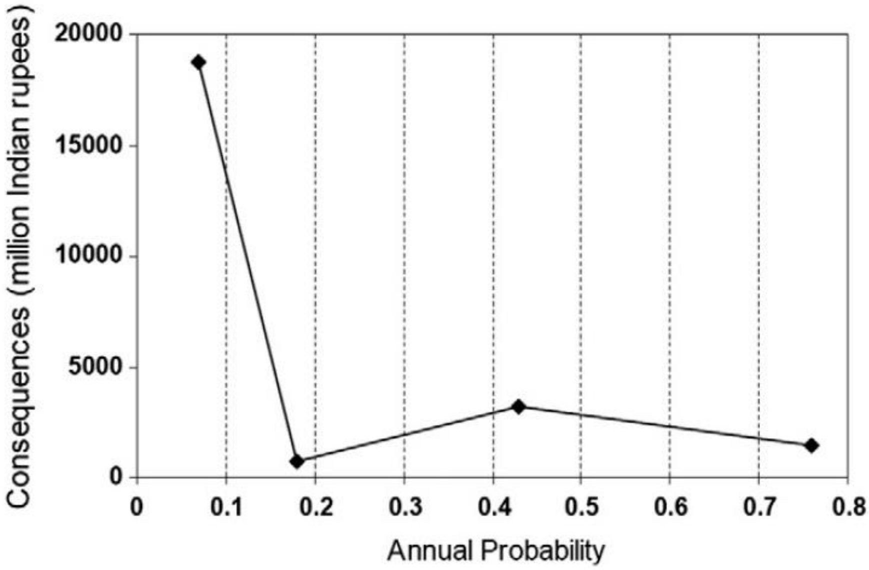


Figure 5.10: Risk curve for the combined critical infrastructure of buildings and roads (Martha et al., 2013).

The usage of quantitative risk using curve highlights the completeness of data and total control over the overall methodology of landslide hazard and risk assessment. As can be seen from Figure 5.11, the overall methodology commencing from landslide inventory is self-conducted therefore the quality of data and process prior to generation of landslide risk is able to be control by the researcher. This fulfil the integral criteria for using quantitative risk assessment of data completeness.

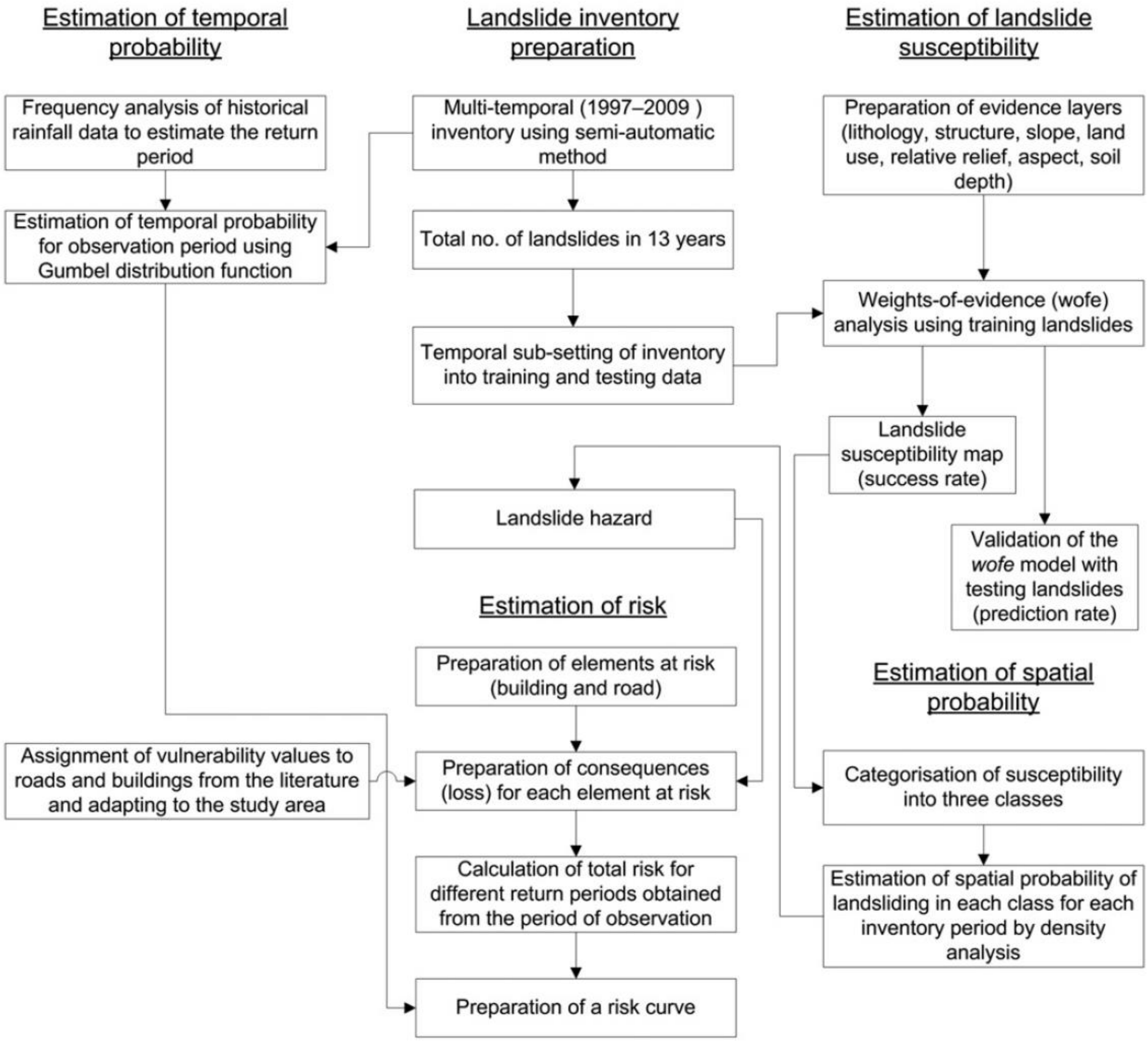


Figure 5.11: The overall procedure of landslide hazard and risk (Martha et al., 2013).

In their paper, Guillard-Gonçalves (2016) make use of semi-quantitative approach for landslide risk assessment. The exact process of obtaining landslide risk only commences by establishing vulnerability and by using Portuguese Tax Services formula, the relative economic value of buildings is derived. Figure 5.12 highlights the risk map of Loures municipality for building elements at risk on a landslide body. The risk index is relative to the pixel or the number of buildings which makes it a semi-quantitative approach. Although the actual process starts at the vulnerability stage, the fact that the anatomy of building data is extensively obtained makes this semi-quantitative approach quite robust.

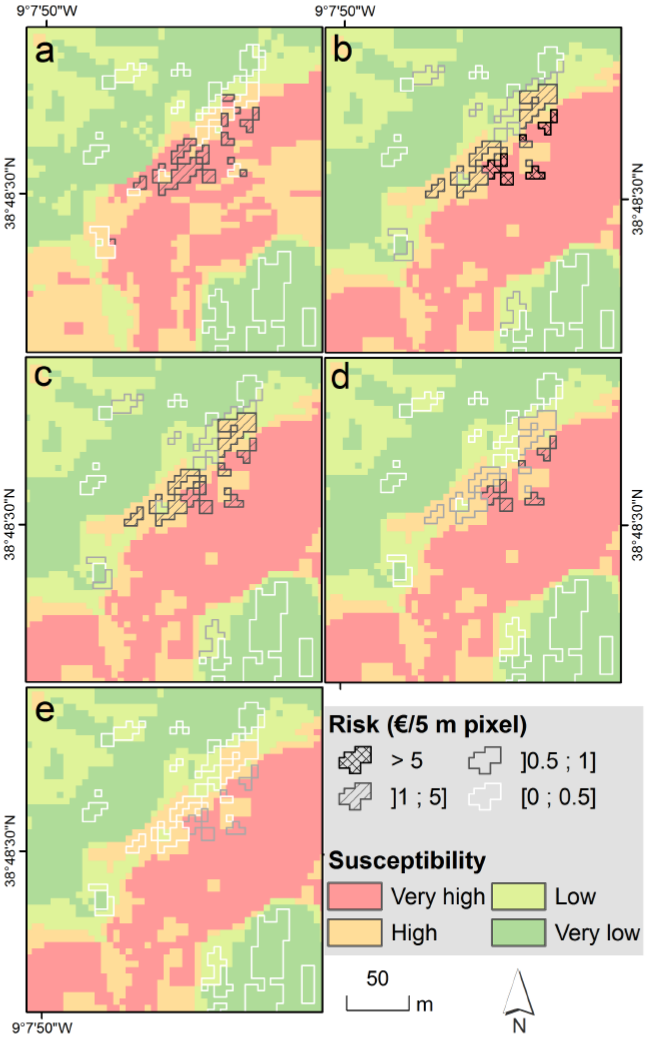


Figure 5.12: Landslide risk map for buildings at landslide body (Guillard-Gonçalves, 2016).

The concept of qualitative landslide risk assessment, although much earlier introduced is still useful due to its simplicity and straightforwardness. Anbalagan and Singh (1996) uses risk assessment matrix as shown in Table 5.17 for highlighting relative risk level for land categories in regards to damage potential (vulnerability) and hazard probability. From Table 5.17, notice that the specific intersection of damage potential and hazard probability will produce corresponding index of landslide risk. Five categories of risk index ranging from very low risk (VLR) until very high risk (VHR). This category is straightforward in a way that, generally, if both hazard probability and damage potential are very high, the resultant category of risk index will be very high as well. In contrast, generally, a very low category of risk index is a resultant of very low hazard probability and damage potential. Other corresponding risk assessment matrices need to be established for each critical socio-economic and environmental aspects plus physical infrastructure.

Table 5.17: Risk assessment matrix for land categories (Anbalagan and Singh, 1996).

	Hazard Probability				
Damage potential (DP)	VLHP (Very Low Hazard Probability)	LHP (Low Hazard Probability)	MHP (Medium Hazard Probability)	HHP (High Hazard Probability)	VHHP (Very High Hazard Probability)
VLDP (Very Low Damage Potential)	VLR	VLR	LR	LR	LR
LDP (Low Damage Potential)	VLR	VLR	LR	MR	MR
MDP	LR	LR	MR	HR	HR
HDP	LR	LR	HR	HR	VHR
VHDP	LR	LR	HR	VHR	VHR

Using Table 5.17, a risk assessment map of Sukhidang area is generated where specific categories of landslide risk as stated in Table 5.17 are used. This map is shown as Figure 5.13. This map combines both environmental aspect which is land categories and socio-economic aspect which is human dwellings.

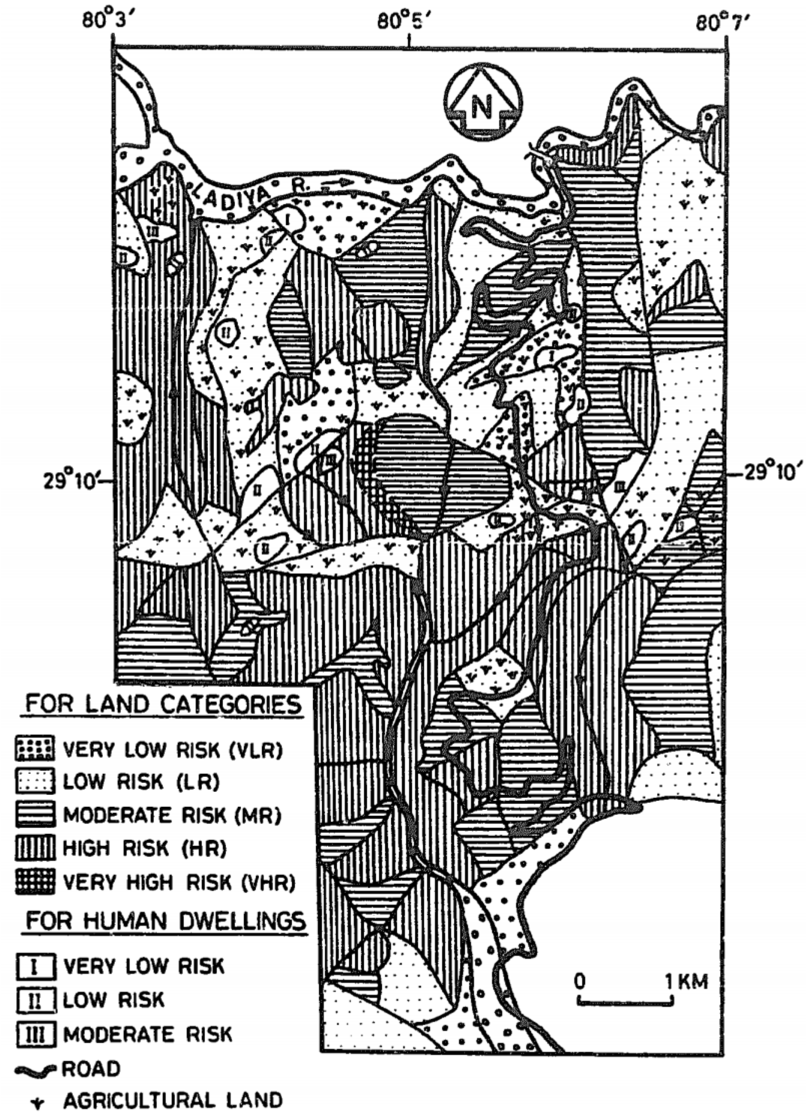


Figure 5.13: Risk assessment map of Sukhidang area (Anbalagan and Singh, 1996).

Another concept of qualitative risk estimation through the implementation of indicator based approach is carried out by Papathoma-Köhle et al. (2015) where they invented a toolbox where non-expert can assess landslide risk for building element-at-risk. The tool which is able to assess the monetary loss of building is intended for end users such as local council or decision-makers personnel. Figure 5.14 highlights the Graphical User Interface (GUI) for the intended tool where several parameters such as functionality of building, ground plan area, floors, ground plan area of garage, water depth and deposition depth are needed for the calculation of building loss. Though the toolbox looks convenient to end users, the fact that non-expert is able to use this can create conflict against expert opinion, as in qualitative landslide risk assessment, expert opinion is integral for the reliability of results (Kloos et al., 2015).

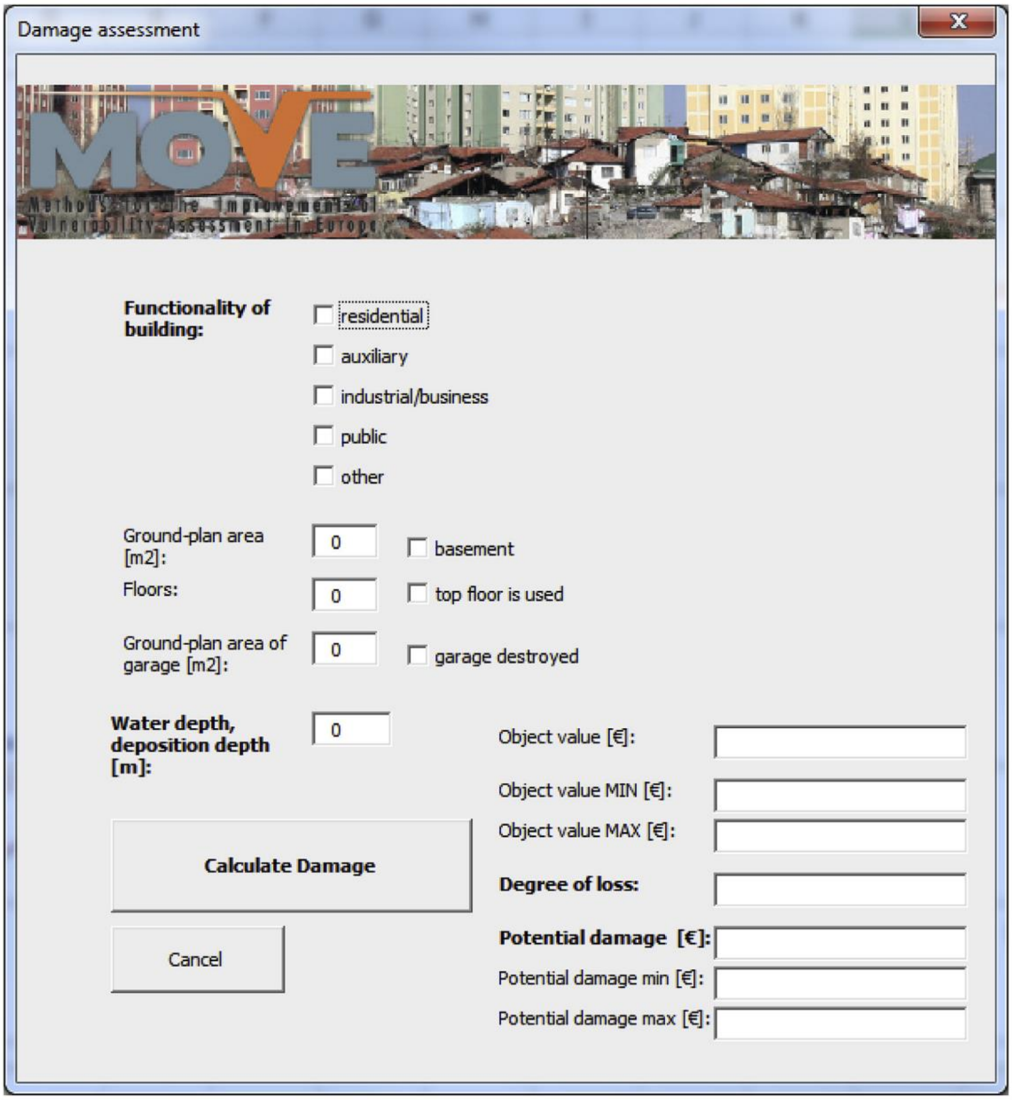


Figure 5.14: Graphical User Interface (GUI) for the Loss Estimation Tool (Papathoma-Köhle et al., 2015).

5.2.2 Landslide Risk Assessment for Malaysia

5.2.2.1 Implementation of Landslide Risk Assessment

Unlike the suggested semi-quantitative method for landslide vulnerability assessment, it is proposed that a qualitative method for landslide risk assessment via risk assessment matrix is used in this project (Anbalagan and Singh, 1996). Primarily, this suggestion is made given that the majority of literatures and practice for landslide risk assessment is based on a qualitative method, therefore the method is proven to be effective and convenient (Glade, 2003). For this to happen, Equation (6) is adjusted to only accommodate two elements of qualitative risk assessment matrix which are hazard and vulnerability, as below.

$$R = H \times V \tag{6}$$

In Equation (6), R = risk, H = hazard and V = vulnerability. To execute this, the challenge is to define the scale of the risk index, however, much earlier, the qualitative measurement of hazard and vulnerability needs to be established. That said, either to straightaway use the already existing qualitative hazard and vulnerability measurement or to modify the quantitative measurement to qualitative. It is proposed that the measurement used is adopted from the Australian Geomechanic Society's *Qualitative Measures of Likelihood of Landsliding* (Hazard Measurement) and *Qualitative Measures of Consequences to Property* (Vulnerability Measurement) as shown in Table 5.18 and Table 5.19 (Fell et al., 2005).

Table 5.18: Qualitative measures of likelihood of landsliding (hazard measurement) (Fell et al., 2005).

Level	Descriptor	Description
A	Almost certain	The event is expected to occur
B	Likely	The event will probably occur under adverse condition
C	Possible	The event could occur under adverse condition
D	Unlikely	The event could occur under very adverse condition
E	Rare	The event is conceivable but only under exceptional circumstances
F	Not credible	The event is inconceivable or fanciful

Table 5.19: Qualitative measures of consequences to property (vulnerability measurement) (Fell et al., 2005).

Level	Descriptor	Description
1	Catastrophic	Structure completely destroyed or large-scale damage requiring major engineering works for stabilisation
2	Major	Extensive damage to most of structure, or extending beyond site boundaries requiring significant stabilisation works
3	Medium	Moderate damage to some of structure, or significant part of site requiring large stabilisation works
4	Minor	Limited damage to part of structure, or part of site requiring some reinstatement/stabilisation works
5	Insignificant	Little damage

The combination of Table 5.18 and 5.19 translates into Table 5.20 which is an international standard risk assessment matrix (Ko Ko et al., 1999). Combining likelihood with consequence results in a risk assessment matrix divided into 5 classes of risk index from very low risk (VL) to very high risk (VH). Although the risk index seems straightforward, the measurement of hazard and vulnerability is ideally done by experts to avoid spurious outcomes and for it to be value-adding (Fell et al., 2005).

Table 5.20: International improvised standard risk assessment matrix after (Ko Ko et al., 1999).

Likelihood (hazard)	Consequences to property (Vulnerability)				
	Catastrophic	Major	Medium	Minor	Insignificant
Almost certain	VH	VH	H	H	M
Likely	VH	H	H	M	M
Possible	H	H	M	M	L
Unlikely	H	M	M	L	VL
Rare	M	M	L	VL	VL
Not credible	VL	VL	VL	VL	VL

Legend:

VH	=	Very high risk
H	=	High risk
M	=	Moderate risk
L	=	Low risk
VL	=	Very low risk

The other reasons for using a qualitative risk assessment via risk assessment matrix are:

i. Serve as a useful role in landslide risk management in providing a relative comparison of risks of different sites and prioritisation of follow-up actions in addressing the risk portfolio posed by a large number of sites (Fell et al., 2005).
ii. Risk index is relatively simple and straightforward therefore is ideal for non-expert to judge based on landslide cases (Corangamite Catchment Management Authority, 2013).
iii. Ideally used when information related to quantitative landslide risk assessment is absence (Pellicani et al., 2017).
iv. In reference to Table 5.21 against the semi-quantitative method of indicator approach suggested for vulnerability assessment executed via direct mapping, the ideal landslide risk assessment technique is qualitative risk.

Table 5.21: Suitability of risk approach compared against hazard approach (van Westen et al., 2006).

Hazard Approach	Risk Approach		
	Qualitative	Semi-quantitative	Quantitative
Inventory-based probabilistic	2	2	2
Heuristic/geomorphological/direct mapping/expert-based	3	3	0
Statistical (bivariate or multivariate)	3	2	2
Deterministic and dynamic modelling	0	1	3

5.2.2.2 Landslide Risk Mapping using Geospatial Approach

For coming up with a landslide risk map, Equation (6) is solved using geospatial approach. A landslide hazard map is derived using three inputs which are: (a) landslide inventory, (b) landslide causal factors, and (c) landslide triggering factors. Most of the triggering factors are related to climate change factors such as rainfall and seismicity. Figure 5.15 shows an example of a landslide hazard map. Notice that the landslide hazard map has five different classifications from very low until very high. Geospatial data for producing landslide hazard map came from various sources such as LiDAR and high-resolution satellite images. For verification, a field data collection mission can be arranged.

Subsequently, a landslide vulnerability map is produced from the approach of Section 5.2.2.1. Similar as landslide hazard map, the landslide vulnerability map comprises several classifications, however this time only from very low until high. Figure 5.16 highlighted a landslide vulnerability map for the same area.

Finally, Equation (5) is solved by using a geospatial raster processing method of combining both landslide hazard and risk maps. The specific tool is called 'raster calculator' which has the specific ability of merging two or more raster layers to come out with a single output raster layer. Figure 5.17 shows the final landslide risk map of the same area. Exactly similar like the vulnerability map, the landslide risk map has only four classifications from very low until high.

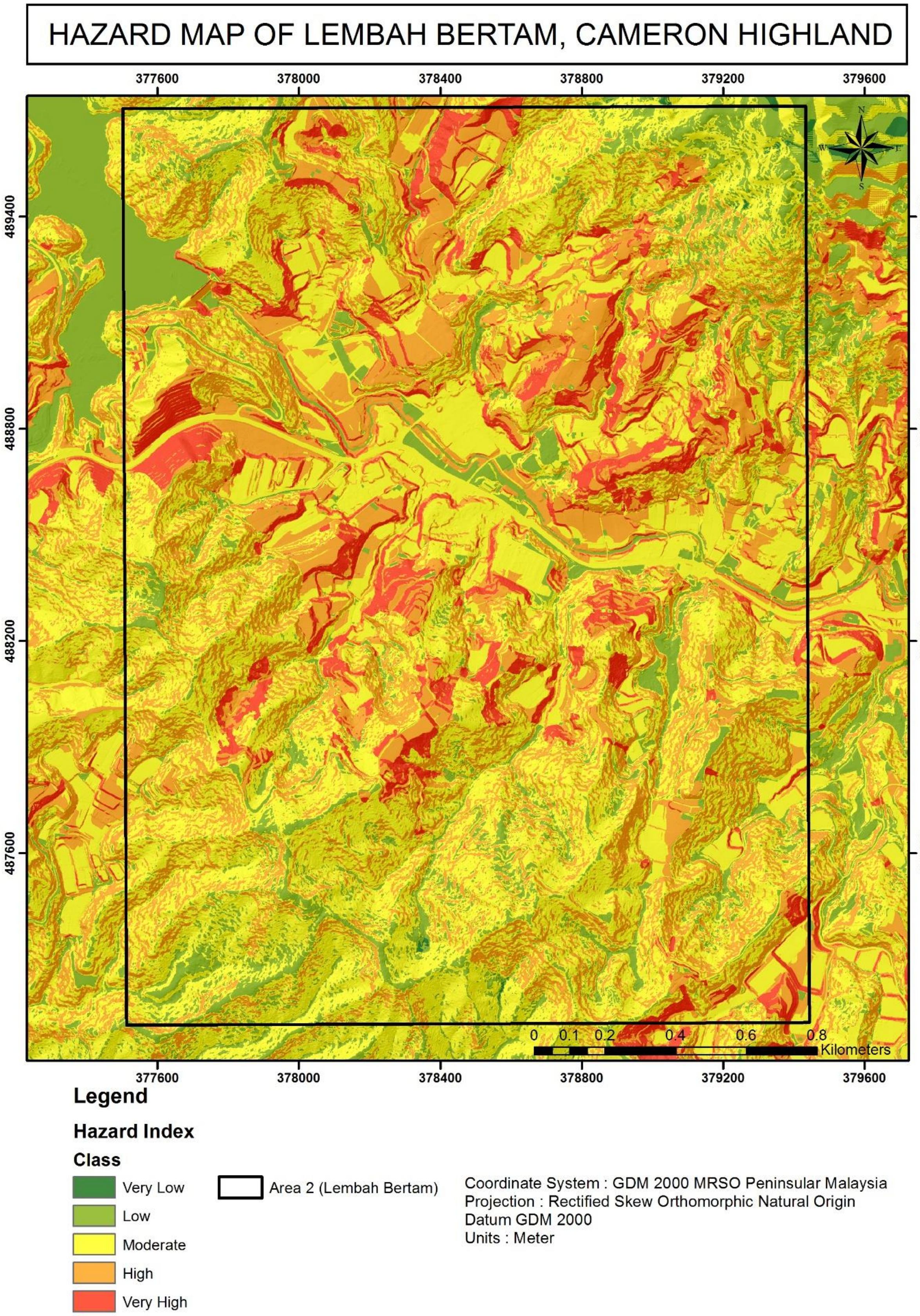


Figure 5.15: Example of landslide hazard map.

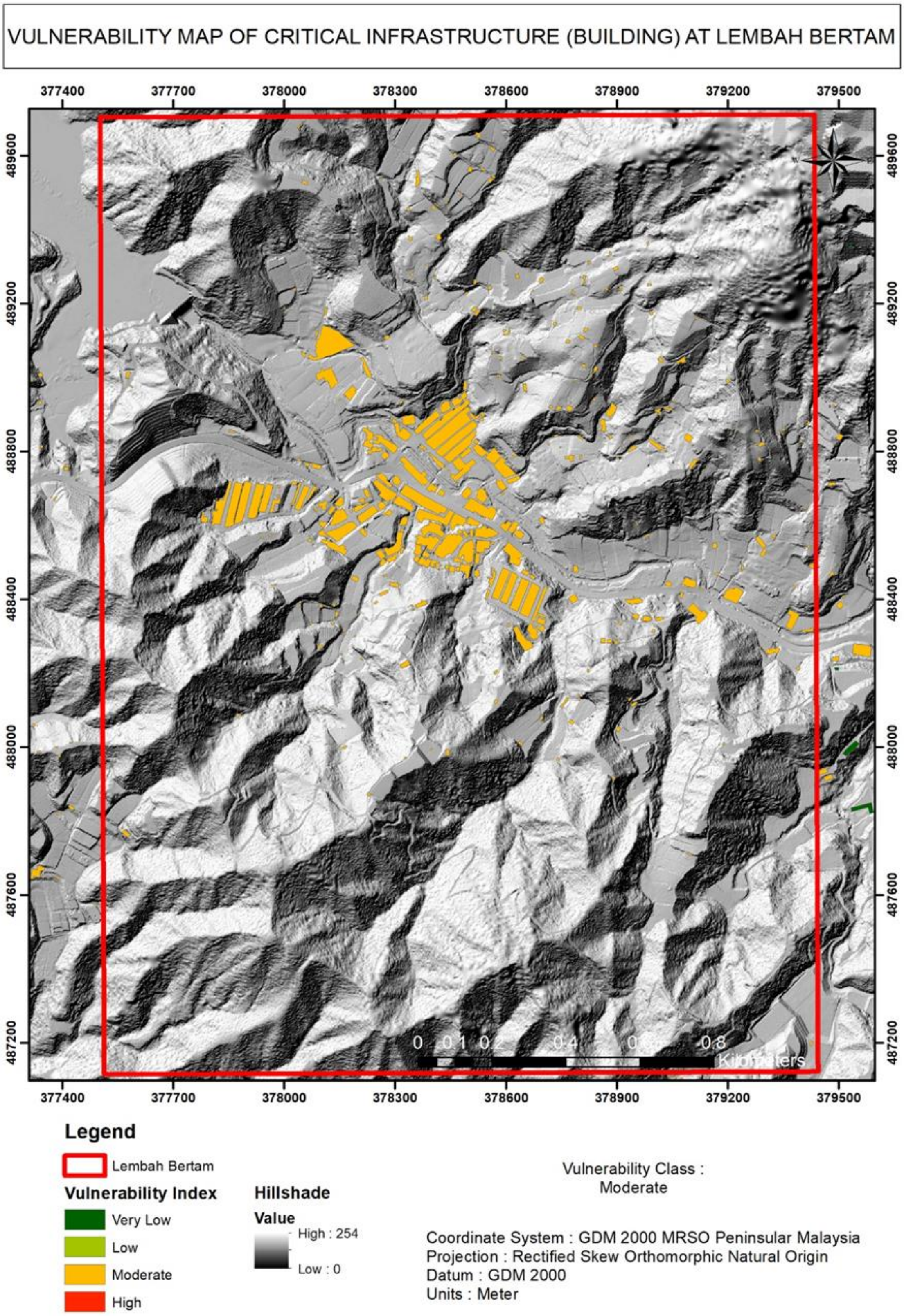


Figure 5.16: Example of landslide vulnerability map.

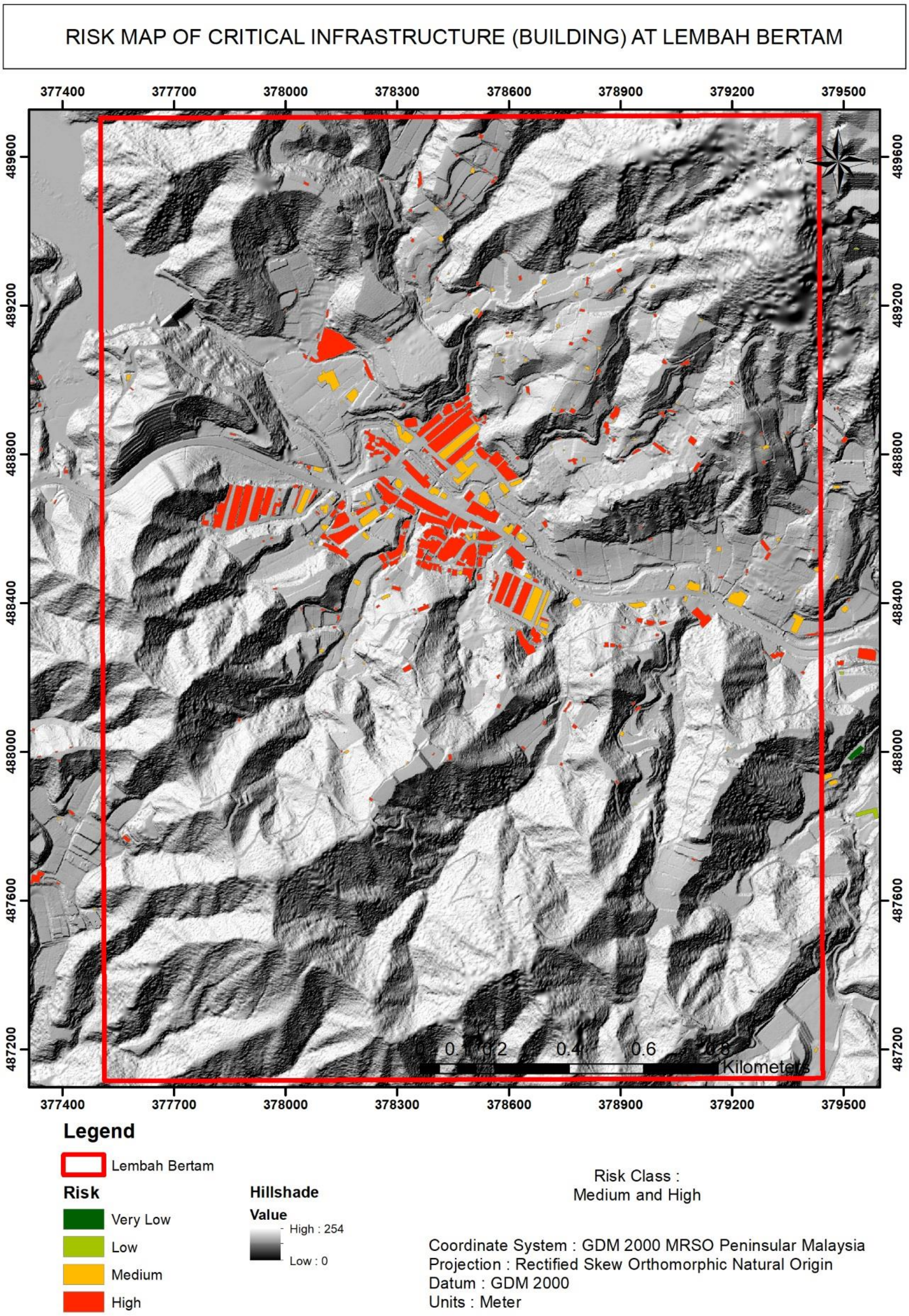


Figure 5.17: Example of landslide risk map.

6.0 METHODOLOGY (Landslide Vulnerability Assessment & Risk Analysis)

Geospatial based landslide vulnerability and risk analysis is divided into 7 stages namely 1) generation of landslide inventory map, 2) generation of CI maps, 3) landslide exposure analysis, 4) generation of landslide vulnerability cluster (C, E, I and P) maps for each CI, 5) generation of landslide vulnerability map for each CI, 6) acquisition of landslide hazard map, and 7) generation of landslide risk map for each CI (Figure 6.1).

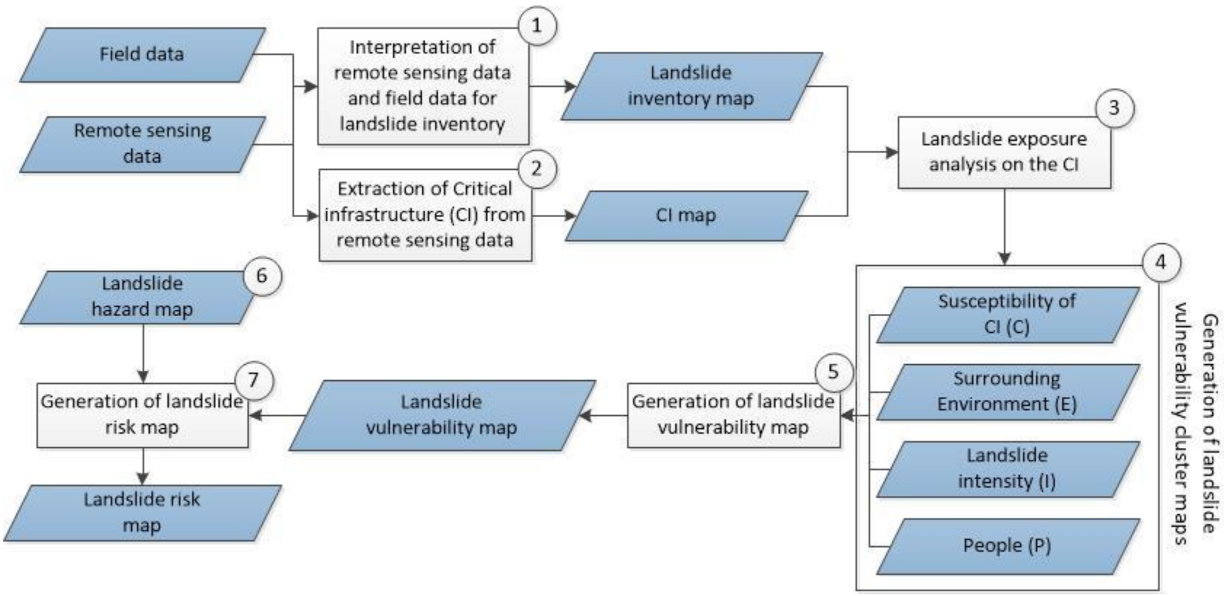


Figure 6.1: Geospatial based landslide vulnerability and risk assessment.

6.1 Data Requirement

The advancement of technology in geospatial data acquisition can be used to extract and characterize the critical infrastructures automatically in the study area. In this case, remote sensing data acquisition such as airborne LiDAR data and aerial photograph are utilized to visualize CI and landslide onto maps. Mapping of landslide requires another type of data which is field data verification in order to inspect the delineated landslide polygon on map and characterize the landslide type and its activity. Table 6.1 shows the summary of data type, source of data and the information that can be obtained from the acquired data.

Table 6.1: Type of data.

Type of Data	Source of Data	Data Information
Critical infrastructure	Remotely sensed data, LiDAR	Geometric features, footprint, height, size and length of CI
	Fieldwork inspection	Classification of slope, geology, condition of slope face, drainage system, slope distress, slope stabilization, facilities, scale of failure, slope geometry, vulnerability
Slope information	In-situ drone survey remotely sensed data; LiDAR	Slope gradient, slope aspect, plan curvature, stream network, watershed
Topography map	Survey and Mapping Department Malaysia (JUPEM)	Slope angle, road, river, contour, DEM
Aerial photo	Survey and Mapping Department Malaysia (JUPEM), private sector	Detail visualization of study area

6.2 Generation of Landslide Inventory Map

Landslide inventory is a record of recognized landslides in a particular area. The landslides can be distinguished by typology, geometry and activity. Landslide inventory map should be generated using high resolution remote sensing data to delineate area of landslide, possible area of landslide runout and detailed characteristics of each landslide as required by the landslide intensity cluster (I) indicators of the landslide vulnerability assessment i.e. landslide volume, landslide velocity and accumulation height.

Understanding some basic geologic and geomorphologic features associated with a landslide is the key to reliable landslide detections, either in the field or from remotely sensed images. Figure 6.2 illustrates the common geomorphic features that are associated in a landslide.

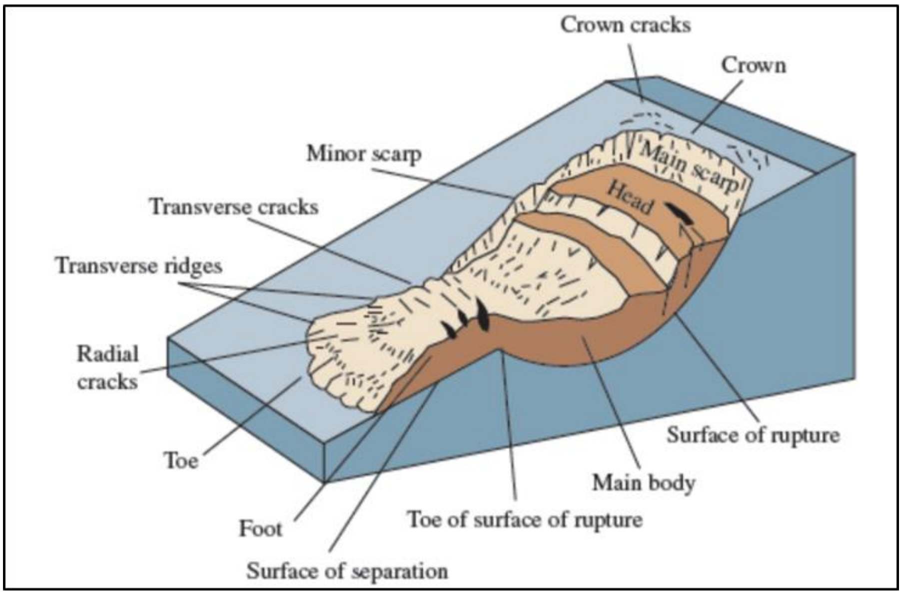


Figure 6.2: An idealised sketch of a landslide (rotational slides or slump) and the associated geomorphological features (Varnes, 1978).

Some basic examples of landslide detection based on pattern of contour lines are shown in Figure 6.3. In this exercise, drainage and topographic keys, such as divergent contours, opposing contours, crenulated contours, arcuate headscarp evacuation areas, and isolated topographic benches, are used to recognise anomalous site characteristics typical of landslides.

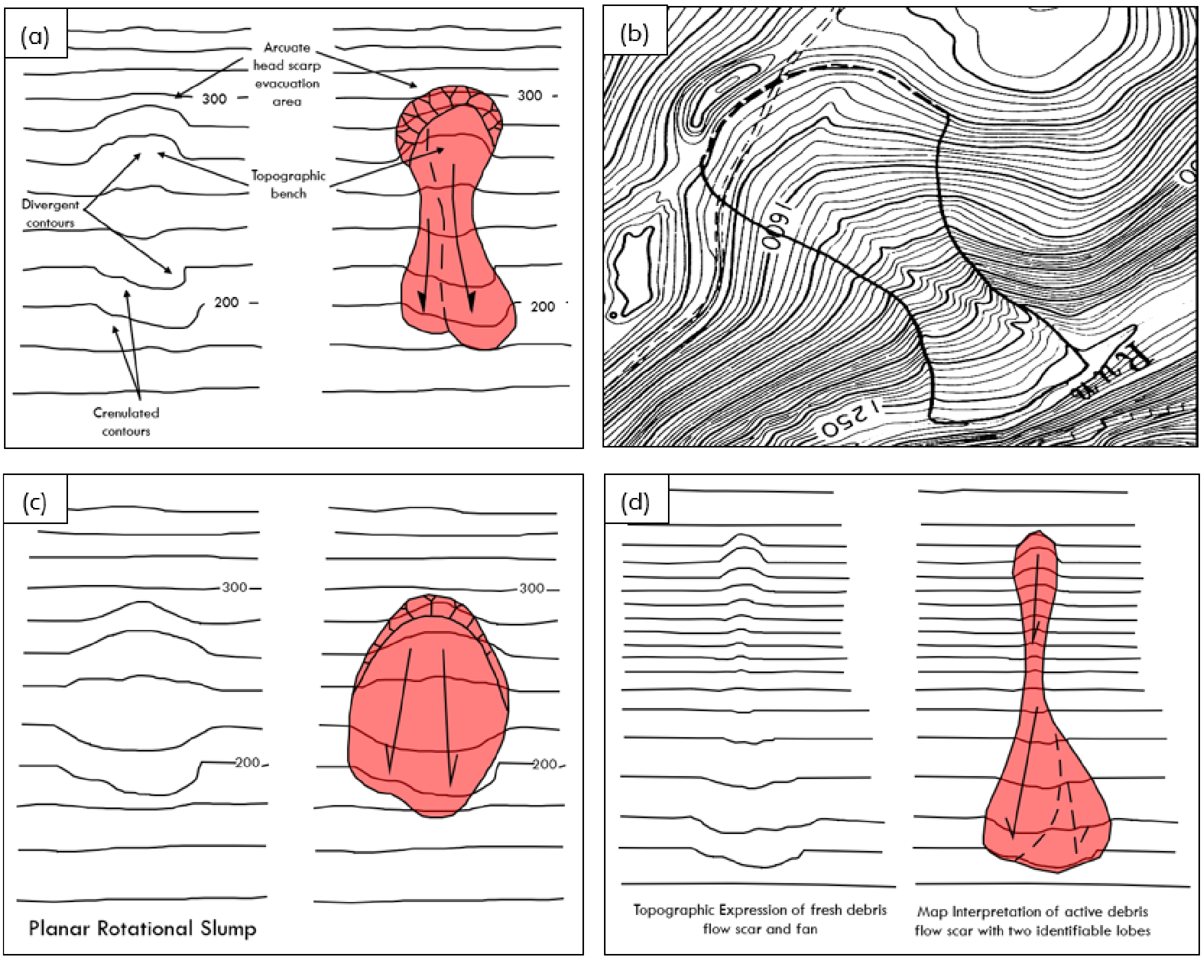


Figure 6.3: Landslide detection based on topographic expressions and pattern of contour lines (a) Earthflows, (b) Actual example of earthflow in the Appalachian highlands mapped by USGS, (c) Topographic expression of a rotational slump, such as commonly occur in the soil regolith overlying resistant bedrock, (d) Topographic expression of debris flow scar and fan. (Rogers, 1998).

Features on the ground surface provide the key to understanding the details of landslide types, processes and causes. Landslide deposits can be classified by age and type of movement according to the features observed on the ground surface. Therefore, particular attention must be paid to these features in landslide detection and mapping from the remotely sensed images and/or topographic map. The boundaries of landslide deposits may appear gradational, but a boundary may actually be a zone of subparallel cracks and bulges that mark a shear zone.

An active landslide may affect existing structures, utilities, and other man-made features in ways that provide insight into the processes and cause of the feature. Cracks in pavement, buildings, and other brittle materials can support inferences about the stress produced by movement of the landslide. The timing of breakage of water lines, electrical cables, and similar utilities can suggest the sequence of deformation before field observations or supplement observations of continuing movement. Measuring the tilt of structures assumed to be vertical or horizontal before movement can give an idea of the amount of displacement on certain parts of the landslide.

The geometry and nature of the sliding surface are among the most important of the subsurface conditions in landslide evaluations. Surface measurements can be employed to estimate the shape of the slip surface. A series of lines is projected through stations used to construct a topographic cross section from the main scarp to the toe of the landslide. By graphical representation, the lines define the probable slip surface can thus be projected to estimate landslide's thickness and volume. Hutchinson (1988) noted several other techniques using surface observations to infer the slip surface and related subsurface movement. Seismic-refraction and electrical-resistivity techniques (Carroll et al., 1968, Miller et al., 1980, Cummings and Clark, 1988, Palmer and Weisgarber, 1988) and electromagnetic methods (McCann and Forster, 1990) can also be used in landslide investigations. It probably will be necessary to interpret the results obtained along a number of geophysical lines and to incorporate surface observations of ground cracks- and bedrock exposures.

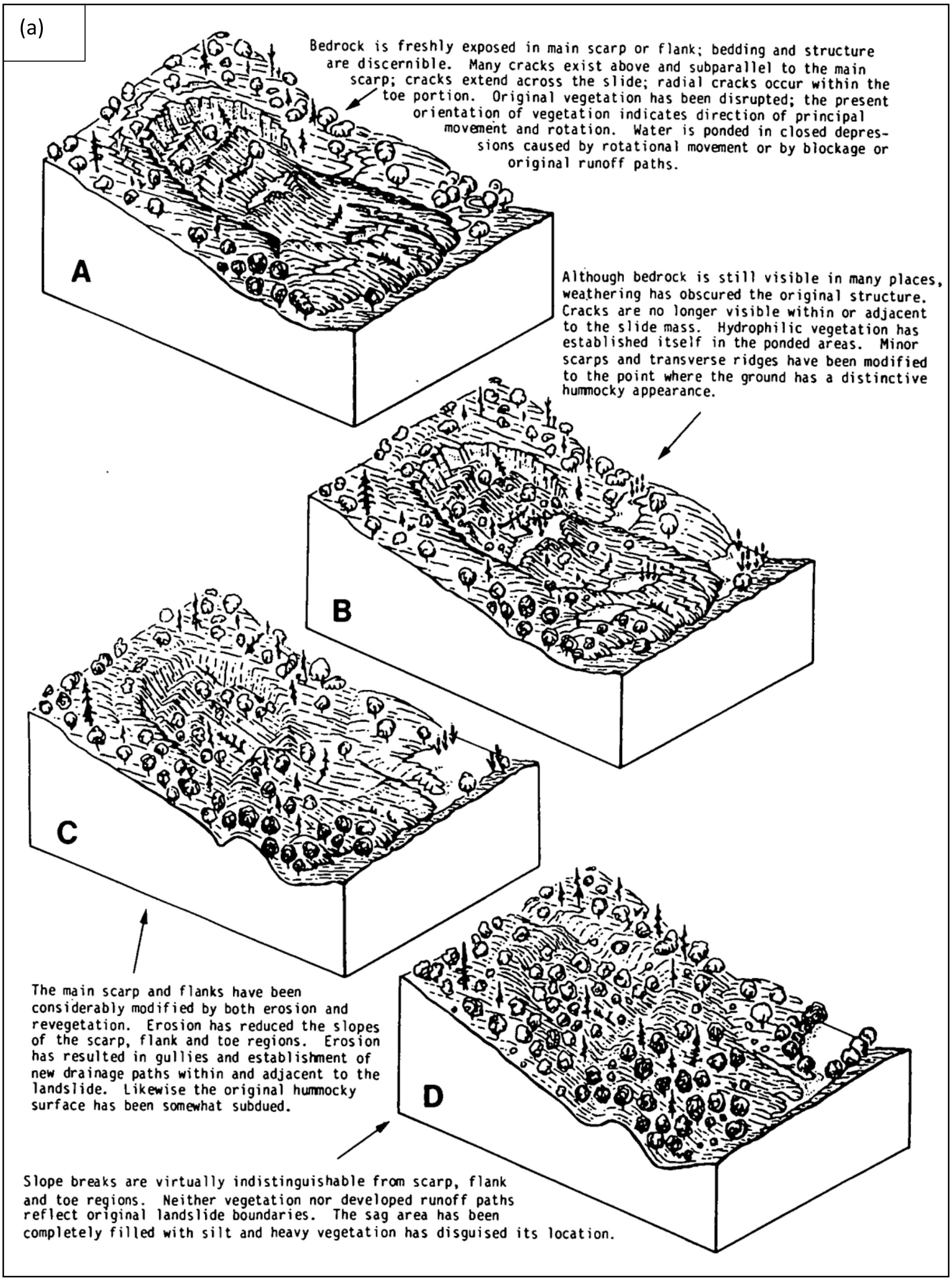
For an old and dormant landslide, their existence can be detected through careful observation and by understanding the geological processes involved in modifying and altering the original slope morphology. Landslide features become modified with age and mollified by geological processes acting on slopes (e.g. weathering, erosions, deposition of sediments and washed down materials). Active landslides have sharp, well-defined surface features, whereas landslides that have been stable for hundreds or thousands of years have features that are subdued and poorly defined. The changes of landslide features from sharp and well-defined to subdued and poorly defined were incorporated into an age classification by McCalpin (1984), as shown in Table 6.2, for the Rocky Mountains of western North America. In wet tropical country such as Malaysia, the challenges in landslide detection is even greater by rapid growth and dense vegetation covers, intense weathering and erosions due to prolonged and heavy rainfalls. Mollification of landslide features and bodies are often relatively faster. The key features are the main scarp, lateral flanks, internal morphology, contrast in vegetation cover and density, and toe relationships. In the hilly terrain such as Cameron Highlands, hanging valley morphology or isolated sub-catchment areas are favourable sites for landslides to occur naturally. In this exercise, systematic panning of the LiDAR derived DEM/hillshaded topographic map were done manually looking for key features like: a) Hummocky surface, b) Steep and arcuate scarps and flanks, c) Thick and bulging toe and d) Concavity of valley walls or hanging valley morphology.

Table 6.2: Age classification of most recent activity for landslides in Rocky Mountain-Type climate (McCalpin, 1984).

ACTIVE STATE	MAIN SCARP	LATERAL FLANKS	INTERNAL MORPHOLOGY	VEGETATION	TOE RELATIONSHIPS	ESTIMATED AGE (YEARS)
Active, reactivated, or suspended; dormant-historic	Sharp, unvegetated	Sharp, unvegetated; streams at edge	Undrained depression; hummocky topography; angular blocks separated by scarps	Absent or sparse on lateral and internal scarps; trees tilted and or/bent	Main valley stream pushed by landslide; floodplain covered by debris; lake may be present	< 100 (historic)
Dormant-young	Sharp, partly vegetated	Sharp, partly vegetated; small tributaries to lateral streams	Undrained and drained depressions; hummocky topography; internal cracks vegetated	Younger or different type or density than adjacent terrain; older tree trunks may be absent	Same as for active class but toe may be modified by modern stream	100 to 5,000 (Late Holocene)
Dormant-mature	Smooth, vegetated	Smooth, vegetated; tributaries extend onto body of slide	Smooth, rolling topography; disturbed internal drainage network	Different type or density than adjacent terrain but same age	Terraces covered by slide debris; modern stream not constricted but wider upstream floodplain	5,000 to 10,000 (Early Holocene)
Dormant-old or relict	Dissected, vegetated	Vague lateral margins; no lateral drainage	Smooth, undulating topography; normal stream pattern	Same age, type, and density as adjacent terrain	Terraces cut into slide debris; uniform modern floodplain	>10,000 (Late Pleistocene)

The rate of change of landslide features summarised in Table 6.2 might be useful as a guide to guestimate the relative age of landslides activity. By intuition, the general sequence of changes must occur in all climates and terrains.

Figure 6.4 can serve as a useful guide in the identification, detection and mapping of landslide geohazards in the study area. Figure 6.4 A - shows an example of a new and active landslide that is still clear, sharp and well-defined geomorphic features. An inactive and relatively young-dormant landslide is shown in Figure 6.4 B, where the bedrock might still be visible in places, but weathering has obscured the original structure. Cracks may no longer visible within or adjacent to the slide mass. Minor scarps and transverse ridges have been modified to the point where the ground has a distinctive hummocky appearance. For a dormant-mature landslide (Figure 6.4 C) the main scarp and flanks have been considerably modified by both erosion and revegetation. Erosion has reduced the slopes of the scarp, flank and toe regions. Erosion has resulted in gullies and establishment of new drainage paths within and adjacent to the landslide. Likewise, the original hummocky surface has been somewhat subdued. For an old-dormant landslide (Figure 6.4 D), slope breaks are virtually indistinguishable from scarp, flank and toe regions. Neither vegetation nor developed runoff paths reflect original landslide boundaries. The sag area almost completely filled up with sediments and heavy vegetation might obscured its location. Each of these landslides catageries can be classified as landslide geohazards. Malaysia’s experiences (e.g. Tajul Anuar Jamaluddin, 2006, 2011, 2015) indicate that old landslides bodies and scars are areas prone to landslide recurrence and reactivation, notably under extreme climatic conditions and disturbance by human activities.


(a)
Bedrock is freshly exposed in main scarp or flank; bedding and structure are discernible. Many cracks exist above and subparallel to the main scarp; cracks extend across the slide; radial cracks occur within the toe portion. Original vegetation has been disrupted; the present orientation of vegetation indicates direction of principal movement and rotation. Water is ponded in closed depressions caused by rotational movement or by blockage or original runoff paths.
A
Although bedrock is still visible in many places, weathering has obscured the original structure. Cracks are no longer visible within or adjacent to the slide mass. Hydrophilic vegetation has established itself in the ponded areas. Minor scarps and transverse ridges have been modified to the point where the ground has a distinctive hummocky appearance.
B
C
The main scarp and flanks have been considerably modified by both erosion and revegetation. Erosion has reduced the slopes of the scarp, flank and toe regions. Erosion has resulted in gullies and establishment of new drainage paths within and adjacent to the landslide. Likewise the original hummocky surface has been somewhat subdued.
D
Slope breaks are virtually indistinguishable from scarp, flank and toe regions. Neither vegetation nor developed runoff paths reflect original landslide boundaries. The sag area has been completely filled with silt and heavy vegetation has disguised its location.

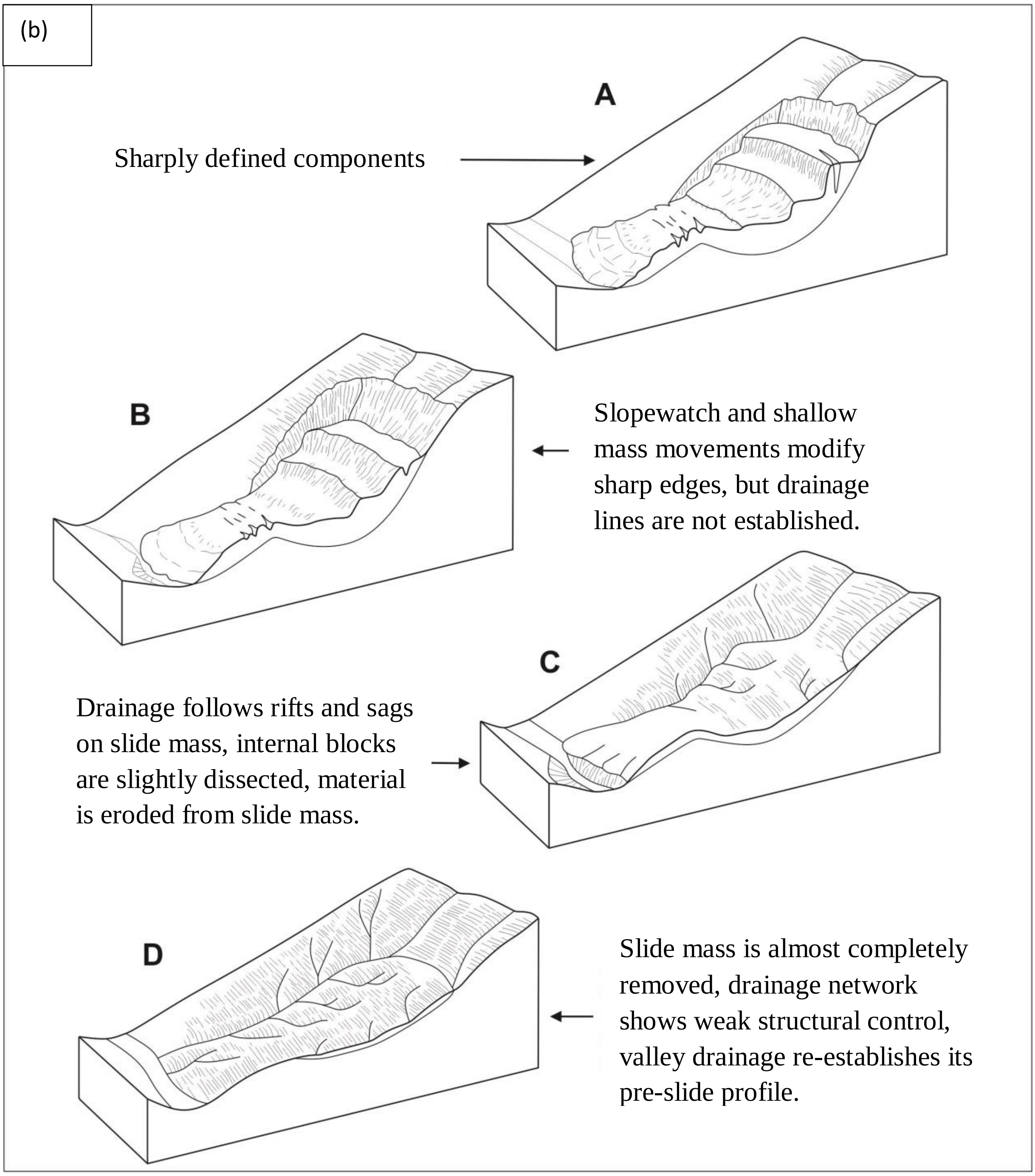


Figure 6.4: Block diagrams of morphologic changes with time of idealized landslide (a) in humid climate (Wieczorek, 1984) and (b) in and or semiarid climate modified from McCalpin (1984).

Note regarding illustrative in Figure 6.4:

A - active or recently active (dormant-historic) landslide features are sharply defined and distinct;

B - dormant-young landslide features remain clear but are not sharply defined owing to slope wash and shallow mass movements on steep scarps;

C - dormant-mature landslide features are modified by surface drainage, internal erosion and deposition, and vegetation;

D - dormant-old landslide features are weak and often subtle.

6.3 Generation of CI Map

` Generation of CI maps should be done using high spatial resolution remote sensing data. The boundary of each CI should be delineated either manually or based on digital image classification process. The generation of CI maps using digital image processing approach should be based on the supervised image classification process. Various parametric and non-parametric algorithms for example maximum likelihood, artificial neural network, support vector machine can be used to produce CI map using high spatial resolution remote sensing data. The classified remote sensing data is in raster format and should be converted into vector format to be used in the next data processing stage.

6.4 Landslide Exposure Analysis

The landslide exposure analysis involves the process of identifying the exposed CI within the landslide and run-out zones. The CI map is overlaid with the landslide inventory map and each CI is marked based on its location either within the landslide and runout zones or outside both zones.

6.5 Generation of Landslide Vulnerability Cluster (C, E, I & P) Maps for Each CI

The landslide vulnerability cluster maps (C, E, I and P) should be generated depending on the type of CI obtained from CI maps and landslide types obtained from landslide inventory map. Suitable weight value for indicators and sub-indicators for each landslide cluster should be determined and stored in each polygon of CI in the CI map.

6.5.1 Generation of C Map

Generation of *C* map aims at characterizing the susceptibility of CI by taking into account all the indicators in the *C* cluster. The CI map that contains information on the location of the CI is required as the main input. The map for cluster *C* should be generated for each CI, in which detailed information as required by each indicator and sub-indicator have to be determined for each polygon of CI. Finally weight value should be assigned to each indicator and sub-indicator of each polygon of CI in the map. Table 5.2 to 5.13 shows all indicators, sub-indicators and their corresponding weight values under *C* cluster for each CI and landslide types. The map of C cluster is generated by assigning the weight values into the database for each of CI footprint and later visualized using colour coded map. Each footprint will have different set of colour representing the weight values.

6.5.2 Generation of E Map

The *E* cluster map focuses on characterizing the impact of surrounding land features towards vulnerability of CI. The impact of landslide on a specific CI either can be increased or reduced by the surrounding environment of the CI. For example, slope mitigation measures will reduce the impact of landslide or vulnerability of CI. Indicators and sub-indicators of the surrounding environment (E) cluster should be observed within a specific distance from each CI polygon. Next, the corresponding weight value for indicator and sub-indicator should be assigned for each CI polygon of the CI map. Table 5.2 to 5.13 shows all indicators, sub-indicators and their corresponding weight values under *E* cluster for each CI and landslide types. Generation of E cluster map is made by assigning the weight values into the database for each of CI footprint and later visualized using colour coded map. Each footprint will have different set of colour representing the weight values.

6.5.3 Generation of I Map

The I cluster map shows the landslide intensity that describe the characteristic of particular landslide body. Landslide intensity is very important to evaluate the vulnerability of element at risk such as buildings, roads, dam and utilities. In this case, three (3) indicators are chosen to be evaluate and identified which are; i) accumulation high of the landslides, ii) landslide thickness and iii) landslide volume. Weightage are given to these three (3) indicators and will be calculated in a sum together with the other indicators depend on the types of element at risk.

In order to analyse the landslide intensity at project area, it is important for researchers to detect and identify all potential landslide and relict landslide at study area. In this case, Digital Terrain Map (DTM) and orthophotographs derived from LiDAR data supported with Google Earth images that was supplemented was optimized to identify all potential landslide and relict landslide scar. The interpretation was conducted based on topography, contour, terrain morphology and any evidence of debris from landslides incident.

Hillshade viewing allows the user to be able to visualize the terrain such that distinct landslide characteristics can be identified. The most readily identifiable landslide features include the head scarp and flanks of a slide which have characteristic arcuate (plan) shapes and steeper slope segments near the crest. Other characteristics of landslides identifiable by hill shade viewing include irregular stepped relief or flow-like features within the slide masses, convex or concave surfaces and/or distinct toe areas. It is important to understand the morphological terrain of the study area which may have relation to slope instabilities. Table 6.3 shows the terrain features and its relation to slope instabilities according to Soeters and van Westen (1996).

Table 6.3: Morphologic features charateristics of slope instabilities (Soeters and van Westen, 1996).

Terrain Features	Relation to Slope Instabilities
Concave/Convex slope features (Figure 6.5)	Landslide niche and associated deposit
Steplike morphology	Retrogressive sliding
Semicircular backscarp and steps	Head part of slide with outcrop of failure plane
Back-tilting of slope faces	Rotational movement of slides blocks
Hummacky and irregular slope morphology	Microrelief associated with shallow movements or small retrogressive slide blocks
Infilled valleys with slight convex bottom, where V-shaped valleys are normal	Mass movement deposit of flow-typr form.

Landslide scar identified will be digitized by using GIS Software in polygon format to calculate the landslide volume based on landslide area depicted from digitized polygon.

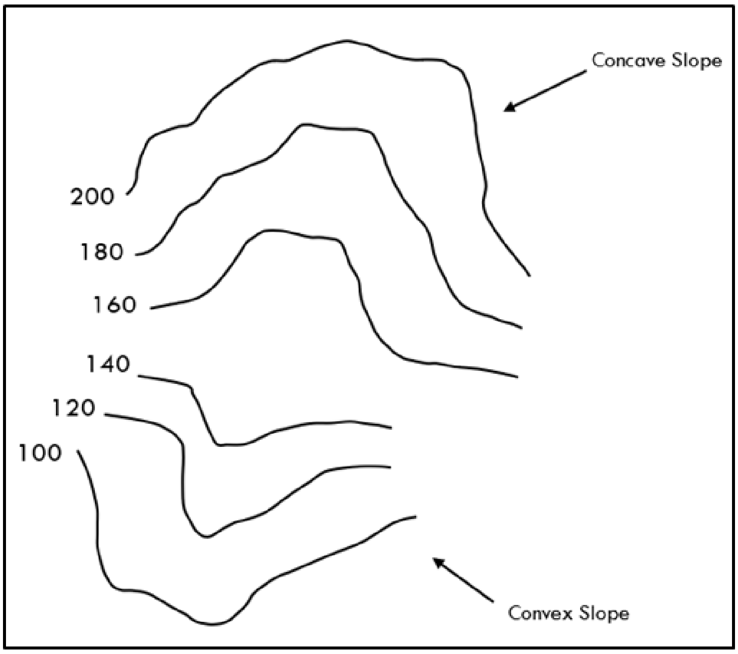


Figure 6.5: Contour pattern of concave features and convex features that give indicators on potential landslide or instabilities.

In a wet tropical region like Malaysia, deep weathering profile can have a thickness of up to 100 m. Even though the characteristics of weathering profiles differ from place to place, two most common types of profiles are with and without core-stones (Komoo, 1985, Komoo, 1989, Komoo, 1998). The thickness of landslide depends on the thickness of weathering profile or residual soil. In the case of Bukit Antarabangsa landslide that occurred in the year of 2008, the average thickness of the weathered profile is approximately 30m thick (Park et al., 2017) and the depth of landslide scarp is about 15m (Mariappan et al., 2008).

Value of landslide intensity are given to every unit of landslide based on its parameter (accumulation high of the landslides, landslide thickness and landslide volume). Considering there are no deterministic analysis or surveys (geophysics, soil investigation etc.) conducted during this study or by previous researchers at this specific location, several expert judgment and estimation need to be established. Apart from that, the study conducted to estimate the intensity of landslide which not yet occur that are very difficult.

Based on site observation and expert judgment at site location, 5 to 20m thickness of landslide was assumed and estimated for the Critical Infrastructure (CI) located in the landslide scarp. 1.5 to 5m thickness was estimated for the CI located in the runout zone and 1.5m thickness for CI located at the end of runout zone. This estimation was considered in this case study as there are lack of other properly recorded available data regarding landslide dimension and thickness.

In the case of Cameron Highlands area, landslide volume calculated by multiplying the total area of landslide (area of polygon digitized in arc gis software) with estimated thickness of landslide which is 1.5m, 1.5to 5m and 5 to 20m (based on expert judgment) depend on the location of Critical Infrastructure (CI). It is assumed that only 10%-20% of total volume calculated (based on digitized polygon) will be fail.

The value of accumulation height is calculated based on its slope inclination, location of the CI, cross section of landslide and estimated runout distance that may occur in this case study. As there is no proper record on the accumulation height of landslide, it is estimated that the location of CI is the main factor of selecting the value of accumulation height. The CI located in the landslide scarp, more than 2m accumulation height is considered. For CI near to the scarp, value of 0.5 to 2m is considered. CI located in the middle of runout distance, 0.2 to 0.5m is considered and for CI located at the end of runout distance, 0.2m is considered.

The proper site investigation (geophysics, boreholes etc) shall be conducted to confirm or to assess the true thickness of weathered soil profile that tend to fail or debris of previous landslide incident. Figure 6.6 until Figure 6.8 shows the example of investigation needed for the investigation or estimation of landslide intensity.

In the case of I cluster map, it is generated by assigning the weight values into the database for each of CI footprint and later visualized using colour coded map. Each footprint will have different set of colour representing the weight values.

Figure 6.6: Example of borehole layout plan within the failure area and the neighbouring sides at Bukit Antarabangsa landslide (Mariappan et al., 2008).

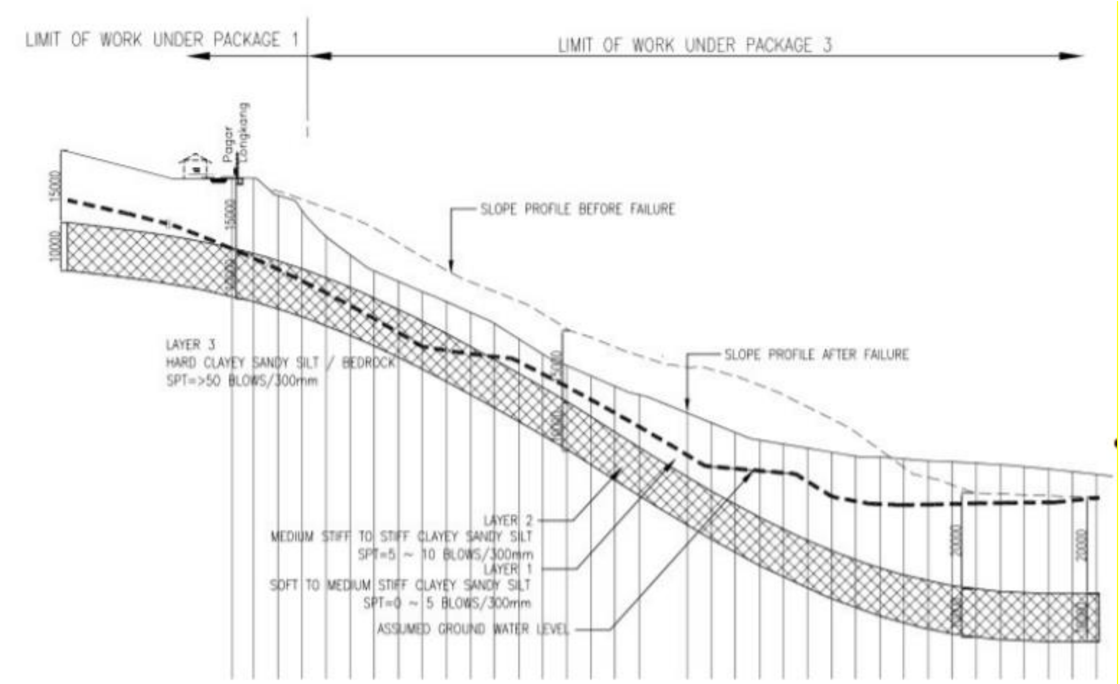


Figure 6.7: Cross section of subsoil stratum along the slope profile at main Bukit Antarabangsa failure area (Mariappan et al., 2008).

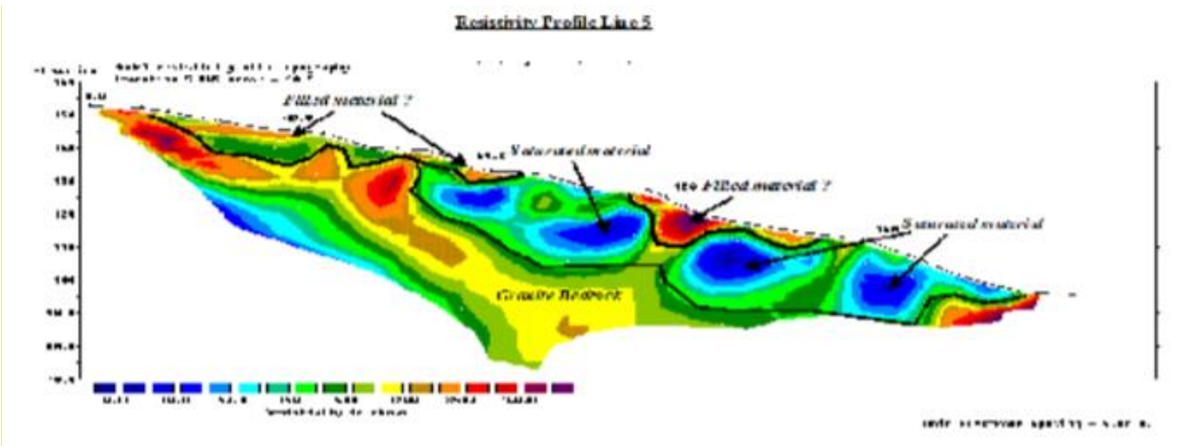


Figure 6.8: The resistivity test result conducted to investigate the subsurface profile of the fail slope and estimated the thickness of weathered soil layer of debris of the landslide (Mariappan et al., 2008).

6.5.4 Generation of P Map

Generation of *P* cluster map accounts the impact of damaged or disrupted CI services on community. Indicators and sub-indicators of *P* cluster should be selected for each CI polygon, in which suitable weight will be assigned into each CI polygon. Table 5.2 to 5.13 shows all indicators, sub-indicators and their corresponding weight values under *P* cluster for each CI and landslide types. P cluster map is generated by assigning the weight values into the database for each of CI footprint and later visualized using colour coded map. Each footprint will have different set of colour representing the weight values.

6.6 Acquisition of Landslide Hazard Map

The landslide hazard map will be used together with the landslide vulnerability map for landslide risk estimation. The landslide hazard map should contain information on the spatial and temporal probability of landslide occurrence for a specific landslide type. In this manual, the landslide vulnerability and risk assessments are carried out for rotational or translational landslides and debris flow. The landslide hazard map should be classified into five (5) level of hazards i.e. very low, low, moderate, high and very high hazards.

6.7 Generation of Landslide Vulnerability Map for Each CI

The landslide vulnerability map for each CI is generated by combining all cluster maps, C, E, I and P using Equation 2. The resulting landslide vulnerability index is classified into its specific vulnerability class for each CI as shown in Table 5.2.

6.8 Generation of Landslide Risk Map for Each CI

The landslide risk map for each CI is generated by combining the hazard map and vulnerability map by using Equation (6). The resulting landslide risk index is classified into 5 classes from very low (VL) to very high (VH) risk using risk assessment matrix as in Table 5.20.

7.0 LANDSLIDE VULNERABILITY AND RISK ASSESSMENT TOOL (MaLVRAT 1.0)

7.1 Tool Overview

A toolbox of landslide vulnerability and risk assessment was developed to ease users in calculating the vulnerability index and risk class when there is an event of landslide occurrence with the involvement of critical infrastructure for particular area. This tool was implemented into a Microsoft Excel spreadsheet by using VBA and the same windows form of the database. The spreadsheet-based tool can be used on a computer without internet connection. The Graphical User Interface (GUI) of the tool is as shown in Figure 7.1.

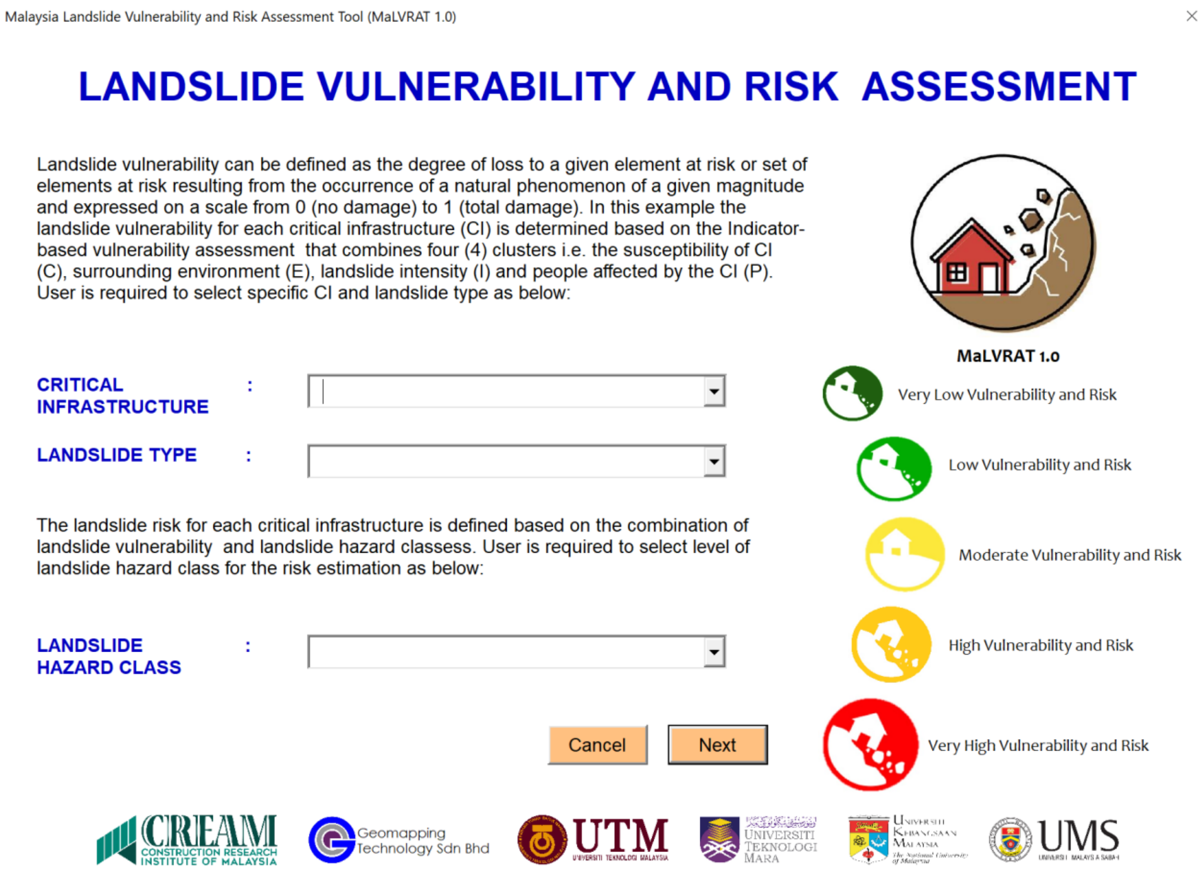


Figure 7.1: Graphical user interface of landslide vulnerability and risk assessment tool.

An important benefit of the toolbox is that it can be used by multiple users that are not necessarily experts or experienced specialists. Decision makers and stakeholders with different backgrounds, such as, scientists, technicians, and administrative personnel, may all make use of the advantages of the toolbox. The situation and damage pattern following a disastrous event may change very quickly due to the need of the authorities and the local population to bring the situation back to normal. The tool offers a quick way of expressing damage directly on site, so that the original situation of the damaged elements following an event can be directly recorded.

7.2 Guidance on Toolbox

The toolbox introduces its homepage to the users with 3 important parameters selection which are critical infrastructure type, landslide type and landslide hazard class. Figure 7.2 shows the steps for users to use the toolbox where; (1) selection of critical infrastructure type, (2) selection of landslide type, (3) selection of landslide hazard class and (4) NEXT button after completing the selection. Take note on the landslide hazard class selection where the class can be identified from the local landslide hazard map. The details of the selection are as follows:

1. Critical infrastructure : building-residential, road, dam, TNB powerline (telco, pmu, substation 33KV), and TNB powerline (132KV, 275KV, 500KV, hybrid).
2. Landslide type : translational / rotational, debris flow and rock fall.
3. Landslide hazard class : very low, low, medium, high and very high.

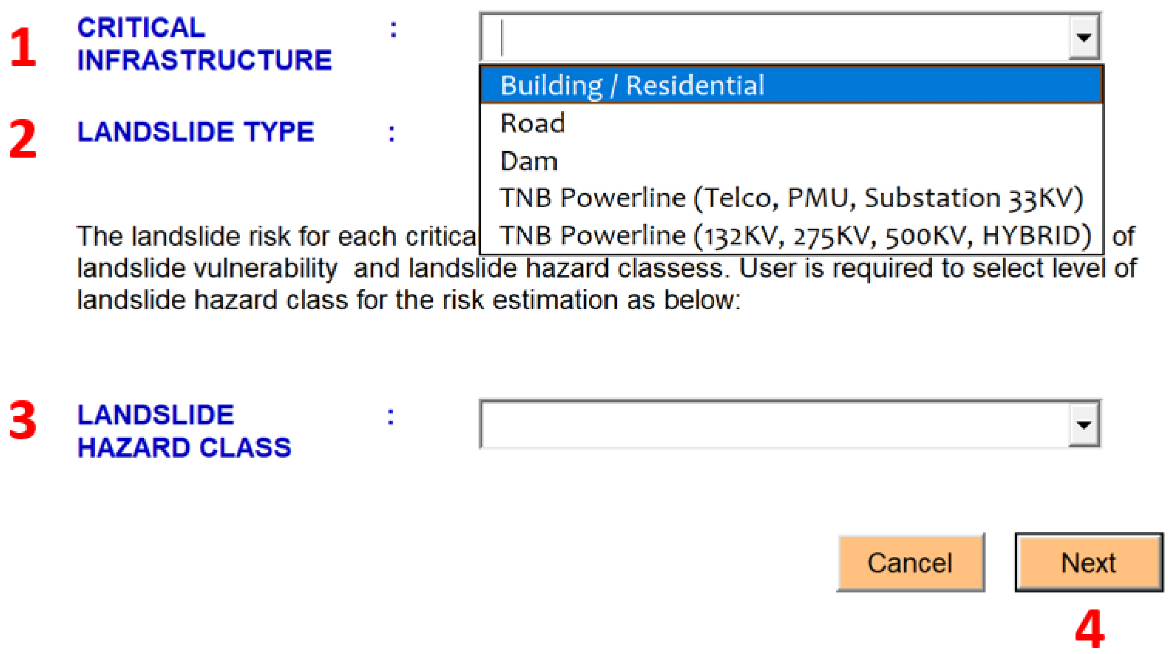


Figure 7.2: Selection of parameters.

The GUI will direct the users to the Microsoft Excel spreadsheet for selection of indicators and sub-indicators according to C, E, I and P clusters. Each of the indicators and sub-indicators are selected based on the features that represent in the hazard event. The landslide vulnerability index, vulnerability class and risk class quantification can be made after the parameters selection are completed. The steps are as shown in Figure 7.3.

COMPONENT	COMPONENT (WEIGHT)	INDICATOR	INDICATOR (WEIGHT)	SUB-INDICATOR	SUB-INDICATOR (WEIGHT)	CHECKBOX
SUSCEPTIBILITY OF CRITICAL INFRASTRUCTURE [C] C	0.36	5 STRUCTURAL TYPOLOGY / STRUCTURE CONSTRUCTION MATERIALS	0.14	Light weight	1.00	□
				Semi light weight	0.80	□
				Timber structure	0.70	□
				Masonry structure	0.50	□
				Reinforced concrete structure	0.40	□
				IBS structures	0.40	□
				Steel structure	0.30	□
		6 BUILDING FOUNDATION DEPTH (LANDSLIDE TYPE VS SHALLOW FOUNDATION BUILDING)	0.12	Accumulation height/landslide depth <1.5 meter, deep foundation (pile)	0.10	□
				Accumulation height/landslide depth 1.5 - 5 meter, deep foundation (pile)	0.20	□
				Accumulation height/landslide depth > 5 meter, deep foundation (pile)	0.40	□
		BUILDING FOUNDATION DEPTH (LANDSLIDE TYPE VS DEEP FOUNDATION BUILDING)		Accumulation height/landslide depth < 1.5 meter, shallow foundation (pad footing)	0.60	□
				Accumulation height/landslide depth 1.5 - 5 meter, shallow foundation (pad footing)	0.80	□
				Accumulation height/landslide depth > 5 meter, shallow foundation (pad footing)	1.00	□
		7 NUMBER OF FLOOR	0.10	Low rise (Single storey)	0.80	□
				Medium rise (2 - 5 storey)	0.50	□
				High rise (> 5 storey)	0.20	□
SURROUNDING ENVIRONMENT [E] E	0.18	8 PRESENCE OF PROTECTION	0.07	Engineered protection system	0.10	□
				Non-engineered protection system	0.40	□
				Natural / Vegetation protection	0.70	□
				No protection	1.00	□
		9 DISTANCE BETWEEN BUILDING	0.05	< 3 meter	0.90	□
				3 - 5 meter	0.50	□
				> 5 meter	0.10	□
		10 BUILDING LOCATION	0.07	Building is located at a distance more than height of slope	0.10	□
				Building is located at a distance within height of slope	0.20	□
				Building is located at the toe of slope	0.60	□
				Building is located at the crest of slope	0.80	□
				Building is located at the mid-height of slope	1.00	□
LANDSLIDE INTENSITY [I] I	0.33	11 ACCUMULATION HEIGHTS	0.15	< 0.2 meter	0.10	□
				0.2 meter - 0.5 meter	0.40	□
				0.5 meter - 2.0 meter	0.70	□
				> 2.0 meter	1.00	□
		12 LANDSLIDE VOLUME	0.18	< 500 meter3	0.30	□
				500 - 10,000 meter3	0.50	□
				10,000 - 50,000 meter3	0.70	□
				50,000 - 250,000 meter3	0.90	□
				> 250,000 meter3	1.00	□
PEOPLE INSIDE BUILDING [P] P	0.13	13 POPULATION DENSITY	0.04	Low	0.30	□
				Medium	0.60	□
				High	0.90	□
		14 EVACUATION OF ALARM SYSTEM	0.03	Yes	0.10	□
				No	1.00	□
		15 AGE OF PEOPLE	0.03	Children	0.50	□
				Teenagers	0.30	□
				Adults	0.20	□
				Senior citizen (65 - 74 years old)	0.80	□
				Senior citizen (75 - 84 years old)	0.90	□
				Senior citizen (> 85 years old)	1.00	□
		16 HEALTH CONDITION	0.03	Health (Good)	0.10	□
				Health (Poor)	0.50	□
				Disabled person	1.00	□

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Figure 7.3: C, E, I and P parameter selection.

Figure 7.4 shows an example of calculated relative landslide vulnerability index ranging from 0 to 1, vulnerability class and risk class for building-residential where each class of vulnerability, hazard and risk reflects the obtained vulnerability index with colour coded including with the descriptions.

RELATIVE VULNERABILITY INDEX (VI)	0.97

TYPE	CLASS	DESCRIPTIONS
VULNERABILITY	Very High Vulnerability	Severely damaged structure or totally destructed, evacuation necessary, complete reconstruction and death is almost certain
HAZARD	Moderate Hazard	Moderate frequency of landslide occurrence
RISK	High Risk	High frequency of landslide occurrence with structural breaks, partly destructed, reconstruction of destructed parts, death is highly likely (severe injury) and evacuation necessary

Figure 7.4: Example of calculated relative landslide vulnerability index, vulnerability class and risk class for building-residential.

8.0 SUMMARY

In conclusion, the study has successfully achieved the objective to assess and develop the parameters-indicators of landslide vulnerability assessment of critical infrastructures (CI) and assigning level for each parameter is addressed. The landslide vulnerability indicators, sub-indicators and its corresponding weights were tested in Ringlet and Lembah Bertam, Cameron Highland with supports from various remotely sensed data, field data and other ancillary geospatial data.

9.0 APPENDIX

9.1 Validation of Landslide Vulnerability Indicator Based Method

In this simulations the best case scenarios are expected to produce the lowest vulnerability value and classified as “very low vulnerability” class. On the other hand, the medium case scenario expects the estimated vulnerability value will be classified as “medium vulnerability” class. Finally, the worst case scenario is expected to produce the highest vulnerability value that can be classified as “very high vulnerability” class.

9.1.1 Case Study - Taman Bukit Mewah, Bukit Antarabangsa

The estimation of landslide vulnerability index and class at Taman Bukit Mewah is carried out as follows in Table 8.1. The indicators are extracted from the JKR (CKC) official report and the vulnerability index estimated is 0.75 which fall under high class of vulnerability. The description of high vulnerability class meets the expectation as described in the official report.

Table 9.1: Landslide validation at Taman Bukit Mewah, Bukit Antarabangsa.

Scenario: Taman Bukit Mewah, Bukit Antarabangsa, Hulu Kelang, Selangor (6th December 2008)
Landslide type: Translational/Rotational
CI: Building
Susceptibility of CI (C) (0.36): • *Building typology (0.14)*: Reinforced concrete structure (0.40) • *Building Foundation Depth (Landslide Type Vs Deep Foundation Building (0.12)*: Accumulation height/landslide depth > 5 meter, shallow foundation (pad footing) (1.00) • *Number of floor (0.10)*: Medium rise (2 - 5 storey) (0.50) **Surrounding Environment (E) (0.18)**: • *Presence of protection (0.07)*: No protection (1.00) • *Distance between building (0.05)*: 3-5 meter (0.50) • *Building location (0.07)*: Building is located at the toe of slope (0.60) **Landslide intensity (I) (0.33)**: • *Accumulation height (0.15)*: > 2.0 meter (1.00) • *Landslide volume (0.18)*: 50,000 - 250,000 meter3 (0.90) **People inside the building (P) (0.13)**: • *Population density (0.04)*: High (0.90) • *Evacuation of alarm system (0.03)*: No (1.00) • *Age of people (0.03)*: Adults (0.20) • *Health condition (0.03)*: Health (Good) (0.10) ***Estimated vulnerability value***: 0.75
Class of vulnerability: High
Class of vulnerability: Structural breaks, partly destructed, reconstruction of destructed parts, death is highly likely (severe injury) and evacuation necessary.

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