GUIDELINES FOR LANDSLIDE VULNERABILITY ASSESSMENT AND DEVELOPMENT OF RISK INDEX FOR CRITICAL INFRASTRUCTURE (CI) IN MALAYSIA

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1.0 INTRODUCTION

The Landslide Vulnerability Assessment (LVA) is certainly useful for Disaster Risk Reduction (DRR) program in the promoting an exchange of information, or for improving disaster preparedness and preventing losses, as aims by 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; Léone, 2007). Ideally, it should also assist policy makers in identifying investments priorities (e.g. prevention and mitigation measures) to reduce risk, to identify national risk-management capacities and 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).

Some global approaches 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 most need prevention and development (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 & 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 & 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 elements at risk through curves expressing the possible resistance of the elements to an impact (Li et al., 2010; Puissant et al., 2013). In the case of the landslide vulnerability, the vulnerability functions are usually used for detailed assessments (1:5000-1:10000) (Puissant et al., 2013). An example of 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.

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 (Bono & 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).

In this project, we propose an appropriate methodology and strategy for assessing landslide vulnerability and determination of risk index for critical infrastructures to assist the Construction Research Institute of Malaysia (CREAM). Combination of remotely sensed data, field data and expert input is capable of providing crucial input for development of method assess and estimate vulnerability index for the critical infrastructure. In addition, the risk index can be defined by the product of landslide hazard, vulnerability and value for a specific infrastructure. The project promotes pre-disaster action rather than post-disaster reaction and aims at integrating efforts for assessing landslide vulnerability and possible risk assessment in a quantitative manner at site-specific, municipality and regional scales in Malaysia.

1.1 Objectives

I. To identify issues related to vulnerability assessments and risk index for critical infrastructures.
II. To review the best practices of vulnerability assessments in other countries (Japan, Hong Kong, Taiwan, etc.) and provide benchmarking/ comparative analysis to Malaysia.
III. To assess and develop the parameters/indicators of landslide vulnerability assessment and risk index of critical infrastructures and assigning level for each parameter.
IV. To produce manual and guidelines for landslide vulnerability assessment and development of risk index.

1.2 Scope of Work

I. Review issues regarding landslide vulnerability assessments and risk index on critical infrastructures for urban, urban highlands, sub-urban and rural areas including active tectonic zone in Malaysia.

I. Data collection focusing on the landslide vulnerability assessment method and development of landslide risk index for critical infrastructures in Malaysia (urban, urban highlands, sub-urban, rural and active tectonic zone).

II. The output to this data collection will be used as indicators/ parameters for landslide vulnerability assessment and development of landslide risk index for critical infrastructures.

III. Document analysis for vulnerability assessment and development of landslide risk index for critical infrastructures.

IV. Final draft guidelines for Landslide Vulnerability Assessment and Development of Risk Index for Critical Infrastructure in Malaysia

1.3 Limitations

The implementation of the project is limited to the following scopes and limitations:

I. The guideline will only cover physical (critical infrastructures) landslide vulnerability and risk assessment that excludes social welfare, economics and ecology aspect of assessments. The guideline can be used by local authorities for landuse plan, mitigation purposes, and risk assessment for any development of the critical infrastructures.

II. Social vulnerability indicator with respect to landslide based on literature review will be identified for future study.

III. The urban, urban highlands, sub-urban, rural and active tectonic zone in Malaysia will cover Klang Valley, Cameron Highland, Kota Kinabalu and Kundasang and limited to literature review study.

IV. The field-based validation for vulnerability and risk assessment will only take into account typical landslide and critical infrastructures in the proposed study area.

V. The landslide vulnerability and risk assessment will only focuses on five critical infrastructures (residential areas, dam, building, road and utility; powerline, water supply and telecommunication) as stated in term of reference given by Construction Research Institute of Malaysia (CREAM).

VI. Generation of landslide vulnerability and risk maps require landslide hazard map as one of the main input. However, the landslide hazard map should follow certain criteria as required by the vulnerability and risk assessment for example level of details in both spatial and attribute data. Therefore, the capability to generate landslide vulnerability and risk maps will depend on the quality of the landslide hazard map of the study area.

VII. This project aims at producing a guideline for landslide vulnerability and risk assessment at large scale i.e. 1:5000 to 1:25000 (Table 1.0), which is proposed for local authorities as a basic information or supporting information for landuse plan, mitigation purposes, and risk assessment for any development of the critical infrastructure (Fell et al. 2008).

Table 1.0 Recommended types and levels of zoning and zoning map scales related to landslide zoning purpose (Fell et al. 2008).

Purpose	Type of zoning				Zoning level			Applicable zoning map scales
	Inventory	Susceptibility	Hazard	Risk	Preliminary	Intermediate	Advanced	
Regional zoning								
Information	X	X			X			1:25,000 to 1:250,000
Advisory	X	X	(X)		X	(X)		
Statutory	Not recommended							
Local zoning								
Information	X	X	X	(X)	X	(X)		1:5000 to 1:25,000
Advisory	(X)	X	X	X	X	X	X	
Statutory		(X)	X	(X)		X	X	
Site-specific zoning								
Information	Not recommended							1:1000 to 1:5000
Advisory	Not commonly used							
Statutory		(X)	X	X		X	X	
Design		(X)	(X)	X		(X)	X	

Notes: X = applicable; (X) = may be applicable.

2.0 LITERATURE REVIEW

2.1 Landslide Scenario in Malaysia

2.1.1 History of Landslide

A landslide is the movement of a mass of rock, debris, or earth down a slope. Landslides are a type of "mass wasting," which denotes any down-slope movement of soil, rock and debris under the direct influence of gravity. The term "landslide" encompasses five modes of slope movement: falls, topples, slides, spreads, and flows. These are further subdivided by the type of geologic material (bedrock, debris, or earth) (see Table 2.0). 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 2.1).

Table 2.0 Types of landslides. Abbreviated version of Varne's classification of slope movement (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
SLIDES	ROTATIONAL	Rock slide	Debris slide	Earth slide
	TRANSLATIONAL			
LATERAL SPREADS		Rock spread	Debris spread	Earth spread
FLOWS		Rock flow (deep creep)	Debris flow (soil creep)	Earth flow
COMPLEX		Combination of two or more principal types of movement		

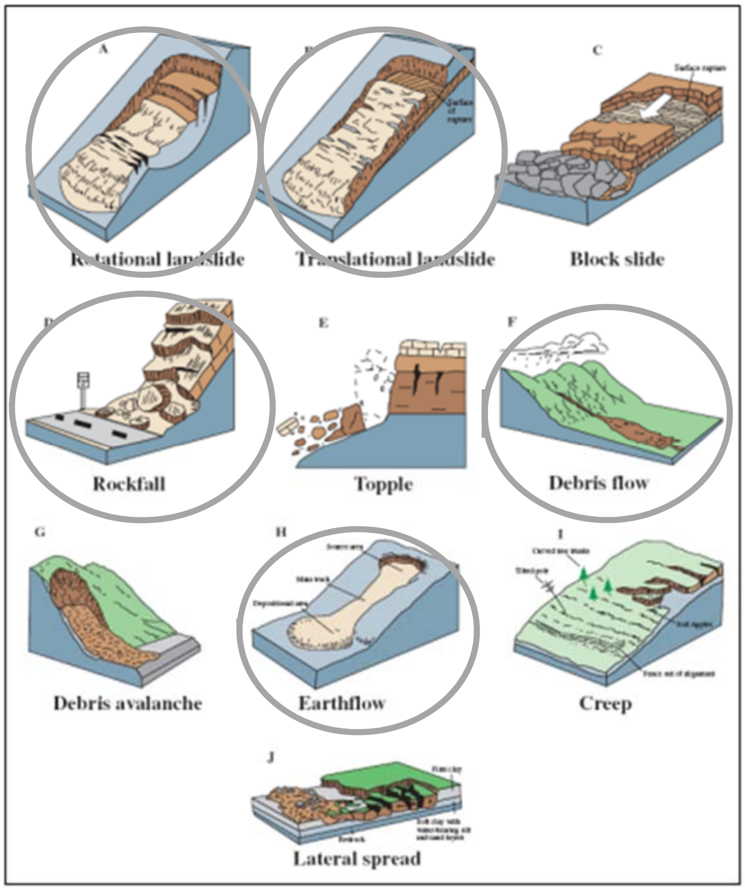


Figure 2. 1 These schematics illustrate the major types of landslide movement that are described in above. Circled are common types of landslides in Malaysia.

Almost every landslide has multiple causes. Slope movement occurs when forces acting down-slope (mainly due to gravity) exceed the strength of the earth materials that compose the slope. Causes include factors that increase the effects of down-slope forces and factors that contribute to low or reduced strength. Landslides can be initiated in slopes already on the verge of movement by rainfall, changes in water level, stream erosion, changes in ground water, earthquakes, disturbance by human activities, or any combination of these factors.

Many human-caused landslides can be avoided or mitigated. They are commonly a result of building roads and structures without adequate grading of slopes, of poorly planned alteration of drainage patterns, and of disturbing old landslides. Detailed on-site investigation is required to determine the importance of human factors in causing any particular landslide.

Despite of frequent floods and flash floods, landslide is the most significant geohazard in Malaysia that have claimed most lives, property damages and economic losses. Historical records of landslide geohazards in Malaysia are generally very poor. Some of the compiled landslide events are listed down in Table 3.0. Information on past landslides were mainly derived from newspapers, unpublished consultation/private reports, students' theses, limited journals publications and conference proceedings. The oldest record found was the rock fall incident in limestone hill in Perak 1919, followed by another rock falls at Gunung Cheroh and Kampong Sengat, both in Perak, in 1973 and 1976, respectively.

Table 3.0 List of landslide geohazards in Malaysia which caused injuries, fatalities, losses and disruption to human activities.

NO.	DATE	LOCATION	FATALITIES/ LOSES
1.	17 Dec 1919	Bukit Tunggal, Perak	12 dead
2.	1971	Kampus Universiti Malaya	
3.	18 Oct 1973	Gunung Cheroh, Perak	40 dead
4	1976	Lombong Hong Fatt & Lombong 3/5 Fasa B	
5.	21 Oct 1976	Kg Sengat, Ipoh, Perak	
6.	1977	Bt 4 – 23 KL – Karak	
7.	1980	Batu Caves	13 dead
8.	1981	Capitol Mining	
9.	1988	Jalan Bt Iedang Off Jalan Duta	
10.	10 Dec 1991	Lebuhraya KL – Karak	
11.	10 April1992	Jalan Sultan Ismail, KL	Some of the roads were closed
12.	27 Dec 1992	Kuari di Pulak Salak Batu, Sandakan	1 dead
13.	5 Feb 1993	Sekolah Menengah Maxwell, KL	Old collection of newspapers was destroyed
14.	13 May 1993	Kampung Sri Serendah, Serendah	10 families were moved
15.	15 May 1993	Pancor, Seremban	4 cars were destroyed
16.	8 Jun 1993	Bandar Baru Selayang	
17.	8 Sept 1993	Landasan keretapi Sungai Buloh	Train service was down
18.	25 Oct 1993	Jalan Kuala Lipis-Gua Musang	1 dead 1 injured
19.	13 Nov 1993	Lebuhraya Karak – Bentong	
20.	14 Nov 1993	Km 20 Jalan lama Kuala Lumpur-Bentong	
21.	16 Nov 1993	Taman Lipis II	Vehicles buried
22.	22 Nov 1993	Hong Seng Estate, Pulau Pinang	Destroyed 1 house
23.	23 Nov 1993	Km 25 Lebuhraya Karak	

24.	26 Nov 1993	Kg Setia Jaya, off Jalan Tumbuhan, Setapak	
25.	28 Nov 1993	Km 63 Lebuhraya KL – Karak	
26.	30 Nov 1993	Jalan Bandar Baru Salak – Nilai	2 dead
27.	30 Nov 1993	Taman Golden Dragon, Kampar	1 van nearly buried
28.	11 Dec 1993	Blok 1 Highland Towers, Ampang	48 dead
29.	13 Dec 1993	Bukit Berapit (Jalan Taiping-Kuala Kangsar)	
30.	22 Mac 1994	Pine Resort, Bukit Fraser	Apartment damaged
31.	2 May 1994	Perumahan Puchong Perdana(bekas lombong)	3 dead
32.	30 May 1994	Lombong Bijih timah di Kampar	2 dead
33.	10 Jun 1994	Papar (kawasan kampung)	
34.	17 Nov 1994	Km 81 Jalan Gerik-Jeli	2 dead
35.	8 Dec 1994	Cameron Highland	7 dead, 3 houses destroyed
36.	30 Jun 1995	Genting Sempah, jalan ke Genting Highlands	20 dead, 22 injured
37.	Aug 1995	Jalan KL – K. Lipis (Bukit Fraser)	
38.	9 Oct 1995	Masjid Tanah, Melaka	Damaged some part of shophouse
39.	16 Oct 1995	Changkat Tunku	Damaged part of house
40.	18 Oct 1995	Kuarters JBA Persekutuan, Jln S. Salahuddin, KL	
41.	1 Nov 1995	Jalan Tapah-Cameron Highlands	Road closure
42.	21 Nov 1995	Km27 Jalan Bahau-Tampin	
43.	24 Dec 1995	Km10 Jalan Hulu Yam Baru-Sungai Tua	
44.	6 Jan 1996	Gua Gempurung, Lebuhraya Utara-Selatan	1 dead, 1 buried lorry
45.	30 Aug 1996	Aliran debris Pos Dipang, Kampar, Perak.	44 dead, village destroyed
46.	10 Oct 1996	Km 49 Jln Ipoh, Kuala Terla, Cameron Highland	4 dead, 2 injured
47.	11 Oct 1996	Km 96 Jln KL – Raub ke Bukit Fraser	
48.	12 Oct 1996	Km 96 Jln KL – Raub ke Bukit Fraser	
49.	15 Oct 1996	Kg Chekau Hilir, Rembau, NS	
50.	18 Oct 1996	Tanah Rata Cameron Highland Pahang	16 families moved
51.	18 Oct 1996	Gelang Patah Johor	1 dead, 6 families moved
52.	10 Jan 1997	Jalan Batu Kurau Taiping, Perak	
53.	13 Feb 1997	Km 4.5 Jln Tuaran, Sabah	Part of road buried

54.	12 Mac 1997	Rumah Panjang KTM, Kg Kerinchi	1 injured
55.	11 May 1997	Jalan Pantai Dalam, KL	1 dead 4 injured, 19 families moved
56.	9 Oct 1997	Jalan Tok Ungku, Seremban	1 dead
57.	Oct 1997	Jalan Rasah, off Jalan Loop, Seremban	
58.	17 Nov 1997	Jalan Terasek Bangsar	
59.	25 Dis 1997	Km14 Lebuhraya Hulu Langat-Ampang	3 dead
60.	27 Ogos 1998	Puchong Jaya	1 car buried
61.	Okt 1998	Jalan Bukit Ledang off Jalan Duta	
62.	28 Nov 1998	Bukit Awana, Pulau Pinang	15 vehicles buried
63.	24 Dis 1998	Taman Kejora 1, Kulim	20 people moved
64.	8 Feb 1999	Kg Gelam, Sandakan, Sabah	
65.	12 Mac 1999	Taman Ceupacs	
66.	3 April 1999	Bukit Fraser	
67.	15 Mei 1999	Bukit Antarabangsa	10,000 people stranded
68.	24 Nov 1999	Km 25 Lebuhraya Karak	
69.	7 Jan 2000	Kampung Raja, Batu 48 and Batu 49,Tringkap	Interference
70.	9 Jan 2000	Tanah Rata – Brinchang, Cameron Highland	5 dead
71.	7 Feb 2000	Sandakan, Sabah	17 injured
72.	25 Feb 2000	Kampung Sri Damai, Taman Kencana, Ampang	1 dead
73.	6 Mei 2000	Bukit Berapit	
74.	28 Aug 2000	Subang Jaya	Commuter services was down
75.	6 Oct 2000	Bukit Antarabangsa, KL	
76.	Oct 2000	Rumah Rakyat Mambau, Seremban	
77.	16 Nov 2000	Taman Kobena, Cheras	
78.	Dec 2000	Jln Mulia Jaya 2/2, Taman Mulia Jaya, Ampang	
79.	22 Dis 2000	Jalan Jiran 2, Happy Gardens	
80.	28 Dis 2000	Taman Rasa Jaya	5 houses destroyed
81.	3 Jan 2001	Jalan Ulu Yam dekat Empangan Batu	
82.	*21 Sept 2001	Kg. Sungai Chinchin, Bt. 8, Jln Gombak, Selangor	1 dead and damaged few cars and houses
83.	7 Jan 2001	Sepanggar Bay, Sabah	3 dead
84.	13 April 2001	Tmn Rawang Perdana, Rawang	Houses damaged

85.	22 Sept 2001	Sg Chinchin, Km 13, Jln Gombak	1 dead
86.	28 Dis 2001	Gunung Pulai, Johor	4 dead
87.	28 Jan 2002	Simunjan, Kuching, Sarawak	16 dead, some houses were destroyed
88.	20 Nov 2002	Taman Hillview, Ampang Jaya	8 dead, 5 injured
89.	26 Nov 2003	Runtuhan batuan di Bukit Lanjan (North Klang Valley Expressway)	The highway has to be closed for a period more than 6 months.
90.	12 Oct 2004	Debris flow at Gua Tempurung (PLUS Highway)	Damage to the bridge
91.	5 Nov 2004	Taman Harmonis, Gombak	1 death, 1 house damaged
92.	31 May 2006	Kg Pasir, Hulu Kelang, Selngor	4 dead, 3 blocks long house damaged
93.	26 Jun 2006	Jalan Persekutuan 606 Sepanggar, Sabah	1 death, and some houses destroyed
94.	9 Oct 2006	Section 10, Wangsa Maju, Kuala Lumpur	Residents of 3 block long houses were forced to move
95.	Oct 2006	Jln Tg. Tualang-Sg. Durian, Perak	The road is closed periodically for repair work.
96.	22 Mac 2007	Kuarters Kerajaan, Presinct 9, Putrajaya	25 vehicles damaged
97.	Sept. 2007	Kolej Ibrahim Yaakub, UKM Bangi	1 block of the hostel is emptied
98.	26 December 2007	Lorong 1, Kampung Baru Cina, Kapit, Sarawak	Two villagers were buried alive in a major landslide, which destroyed nine wooden houses
99	2 February 2009	Bukit Ceylon, Kuala Lumpur.	One contract worker was killed in a landslide at the construction site for a 43-storey condominium.
100	21 May 2011	Children's Hidayah Madrasah Al-Taqwa orphanage in FELCRA Semungkis, Hulu Langat, Selangor.	16 people mostly 15 children and a caretaker of an orphanage were killed in a landslide caused by heavy rains a few days before incident.
101	29 Dec 2012	Puncak Setiawangsa, Kuala Lumpur	88 residents of bungalows, shophouses and double-storey terrace houses were ordered to move out because of soil movement.

102	4 Jan 2013	Putra Heights	Construction at the Kingsley Hill housing project has been halted temporarily following a landslide at the site that caused several vehicles to be submerged in mud
103	11 November 2015	km 52.4 of the Kuala Lumpur-Karak Expressway between Lentang and Bukit Tinggi, Pahang	A landslide/debris flows. The Lentang-Bukit Tinggi stretch of the expressway was closed to traffic.
104	January 2016	Karak Highway	A landslide has blocked all lanes in both directions on the Karak Highway, Four vehicles that were trapped in the landslide, but all passengers managed to escape unhurt.

Coloured rows indicate deadly landslides
Sources: Shu et al. 1981, Chow 1981, Chow 1984, Chan, 1998; Tajul Anuar Jamaluddin et al. 2003, Haliza & Jabil 2017. Arkib akbar digital di tapak web www.emedia.com.my_, News Straits Times 2007, Institut Penyelidikan Tanah Runtuh Negara (NASREC) UiTM (2007); dan tapak web Cawangan Kejuruteraan Cerun JKR, (2007)

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/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 landslide 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 (**Figure 2.2**). 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 & Tan, 2002).

Figure 2. 2 Typical example of hill site development in Malaysia. Paya Terubong, Penang.

Amongst the major landslide geohazards incidents related to mountainous and hilly terrain recorded in Malaysia history are summarised as follows and their locations are shown in (**Figure 2.3**):

I. Limestone Rock Falls, Kinta Valley, Perak
II. Collapsed of the Highland Tower, Hulu Klang, Selangor, Dec. 1993
III. Genting Sempah Debris Flow, in 1996
IV. Pos Dipang Debris Flow, in 1996
V. Gunung Pulai Landslide, Dec. 2001.
VI. Frequent landslides along the mountainous roads and highways (e.g. East-West Gerik-Jeli Highway, KL-Karak Highway and the Pos-Selim-Cameron Highland Highway).
VII. Taman Hill View, Hulu Klang, Selangor, Nov 2002

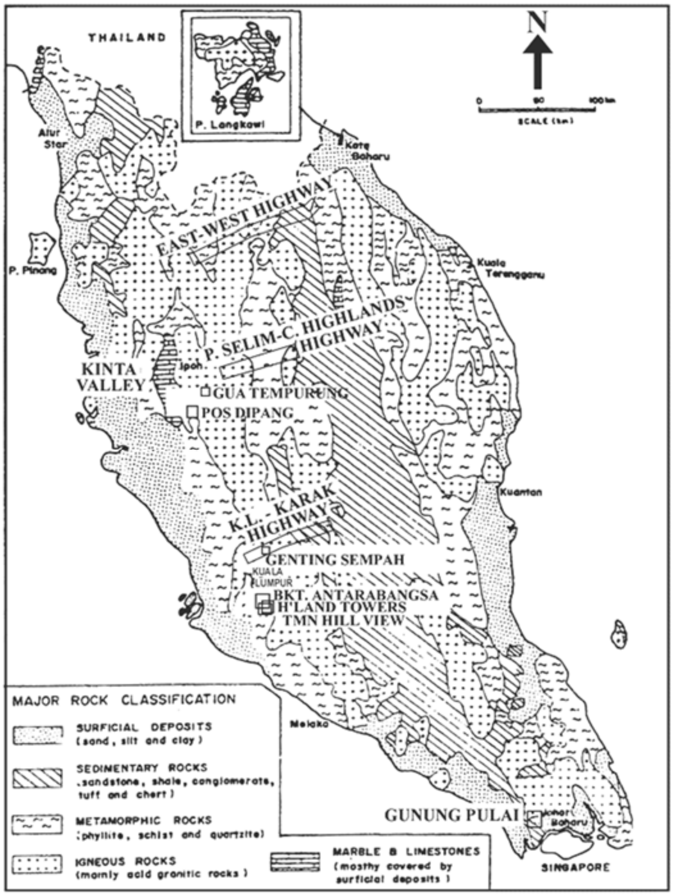


Figure 2. 3 Map showing the locations of the landslide geohazard incidents described in text.

a) Limestone Rock Falls, Kinta Valley, Perak**.**

Karstic limestone hills can be considered a unique hilly terrain in this country. The limestone hills form special landform, widely known as “mogote karst”, are characterised by spectacular, steep-sided, cliff-lined hills, which may rise to an elevation of about 700m above the surrounding plain and often standing like towers. The rocks forming the hills are generally made up of a white to pale grey crystalline limestone or marble. These mogote karstic landforms are notably well developed in Kinta Valley Perak and several parts of the country, e.g. northwest Kedah and Perlis. Natural geological processes, such as erosion, dissolution along open joints/fractures by percolating waters, in these steep-sided cliffs and rock slopes lead to rockfalls, rock slides and/or rock topples.

The earliest record of geohazard incident associated with the limestone hills is on the rockfall at Bukit Tunggal on 17th December 1919 (Shu *et al.,* 1981). In this incident, a massive rockfall, estimated weight at about 50,800 tonnes, occurred at Bukit Tunggal, which is a small limestone hill located at the 16th milestone off the Ipoh-Kuala Lumpur trunk road. This incident claimed 12 lives and destroyed some properties. The fatality was not directly due to the impact of the fallen block, but due to the powerful air blast triggered by the fallen block. The blast of air had completely demolished some brick houses about 120m away and a shop about 200m away from the hill, and killed the residents. The height of the overhanging cliff is about 70m. This suggest that the effect of the air blast which demolished the shop houses was felt at a distance equal to 3.3 times the height of the cliff.

Another similar geohazard was also reported from a small limestone hill at Gunung Cheroh, within the city of Ipoh, Perak. This incident happened on 18th October 1973. A massive piece of overhanging rock slab detached itself from the hill and fell as a single slab, which broke into 3 major pieces upon impact. The rock slabs crushed a long houses resulting in death toll of about 40 people and a large number of cattle, which penned in a small cave at the base of the cliff (Shu *et al.*, 1981, Shu & Lai, 1980).

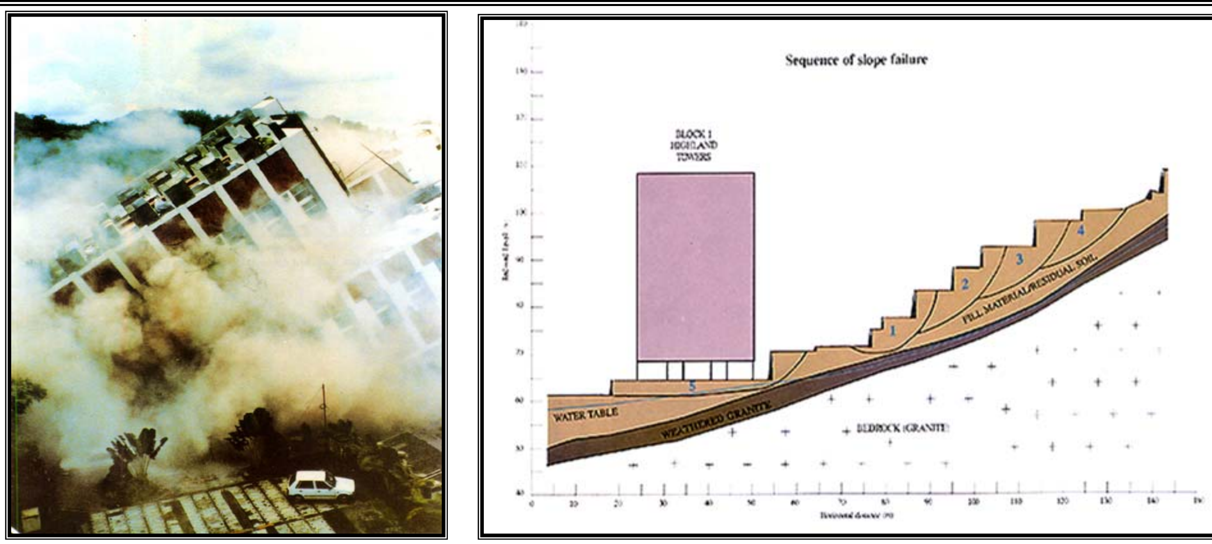
On October 21st October 1976, another rockfall occurred at a limestone quarry near Kampong Sengat, about 9km south of Ipoh, Perak. As there were no inhabitants near the quarry, no fatal casualties were recorded from this geohazard incident. However, a tourist bus travelling at that time along the nearby highway, which is about 100m away, was damaged by the flying rock chips. A bulldozer at the foot of the quarry was also damaged.

The primary cause for the rockfalls is attributed to the dissolution by rainwater along open fractures, joints, faults etc. In many cases, the existing undercuts, overhangs, unfavourably oriented structural discontinuities contribute to the inherent instability of the standing rock masses. Highly soluble nature of the limestone tends to heal all discontinuities by deposition of secondary calcite, thus concealing the joints and other major discontinuities. Overgrowth of shrubs and creepers also help to cover up the irregularities and solution channels found behind the cliffs. Secondary factors such as loss of cohesion due to prolonged rainfalls and vibrations from the passing by heavy vehicles, blasting works in the nearby quarry, and rarely, vibration effect from the earthquake epicentre in Sumatra Indonesia, were also recognised to trigger rockfalls in the Kinta Valley limestone hills (Chow & Abdul Majid, 1999).

Rockfall geohazards could be difficult to prevent because of continuous natural mass-wasting processes. Understanding the structural weakness and the natural/geological processes present in the cliffs is very important before planning and undertaking steps of necessary preventive and mitigation measures; and also to know when to avoid development in the vicinity of the limestone hills.

b) Collapse of the Highland Tower, Hulu Klang, Selangor

The collapse of 12-storey, Block 1 of the Highland Tower condominium in Hulu Klang, Selangor Malaysia occurred on 11th December 1993. This was the most severe geohazard case in Malaysia history, where 48 lives were perished and a number of vehicles were crushed under the collapsed building. This tragedy is attributed to the massive retrogressive landslide behind the building. The hill behind the tower was a terraced cut slope in highly to completely weathered granite (**Figure 2.4**). The cut slope was stabilised by rubble walls. However, detailed investigation after the failure revealed that the main factor contributing to the landslide was the highly weathered granitic material, which was a weak zone within the profile that is usually prone to landslide. Poor drainage exacerbated the porous and friable nature of this weathered material, causing it to fail after a prolonged period of rain (MPAJ, 1994).



(a) (b)

Figure 2.4 a) Photograph of the tumbling Block 1 of the Highland Tower Condominium, fortuitously taken by the witness living in the next block. b) Schematic diagram showing the sequence of retrogressive failure on the slope, which caused the block to topple (MPAJ,1994)

c) Genting Sempah Debris Flow, Selangor

On the afternoon of 30th June 1995, after a spell of heavy rain throughout the Peninsular, a massive debris flow originating from the Genting Sempah catchment area swept over the Genting Highland slip road, killing 21, injuring 23 and damaging a number of vehicles (**Figure 2.5**). The slip road, which normally carries not so many vehicles, was seeing an unusual traffic jam because the road tunnel on the Kuala Lumpur- Karak Highway was flooded and some road users had decided to use the slip road to bypass the tunnel. However, some minor landslips on the slip road had caused the vehicles to stop, making a long que without knowing of the incoming danger from the hill above them a few minutes later.

On the upper slope, intense and heavy rain had saturated the residual soils, triggering at least two major landslides upstream of one of the tributary of River Gombak. The landslide material entered the stream forming a debris flow, which subsequently uprooted trees and scoured the topsoil as well as boulders in its path downstream. Gravity increased the momentum of the debris flow thereby increasing the power of the scouring. The debris flowed from 800m elevation to 570m, over the length of approximately 1 km. The estimated amount of debris moved was 3,000 cubic metres and swept away the stranded vehicles and passengers downslope in an unimaginable power of the nature.

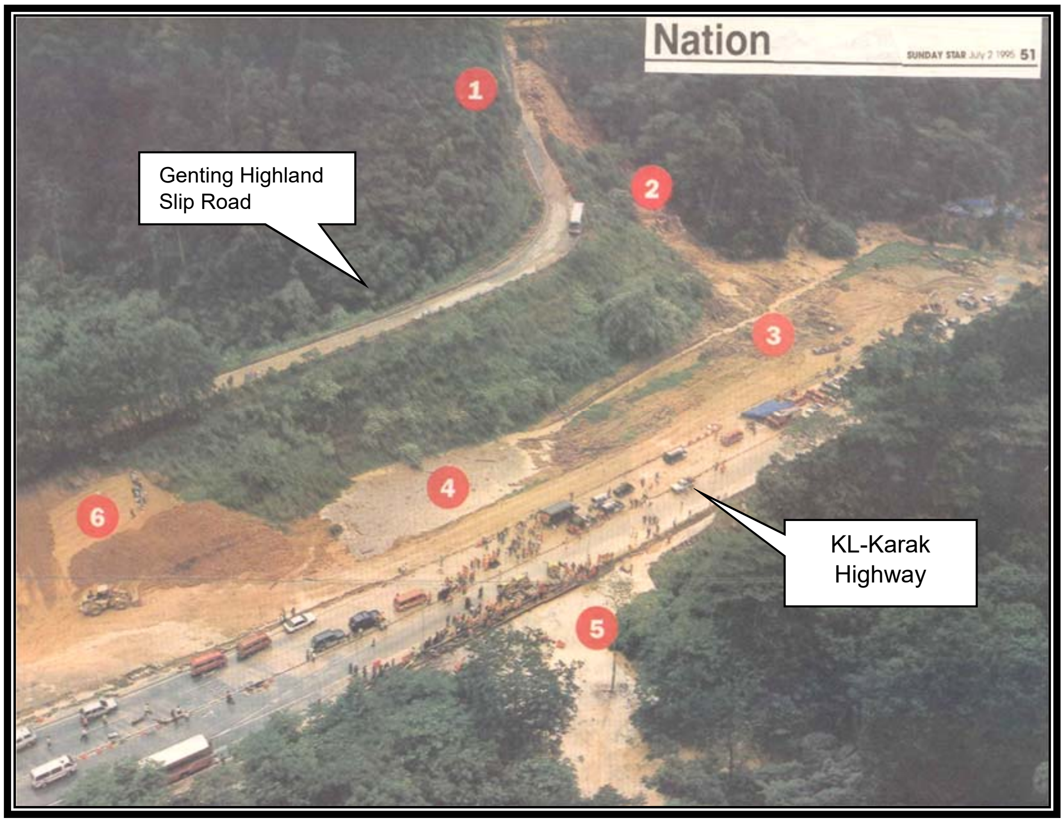


Figure 2. 5 Aerial view of the Genting Sempah Debris flow. (Photo by the Sunday Star, July 2nd, 1995).

d) Pos Dipang Debris Flood, Perak

This incident happened in the dusk of 30th August 1996. The fury of nature had devastated almost the whole village at Pos Dipang and had scoured tress, soils, boulders and everything that stood in its way for more than 5km (**Figure 2.6**). The same power that hurled mature tropical tress like matchsticks also demolished houses and swept 44 people into its roaring flows.

The geohazard was initiated by excessive rain on the night before that fateful day. A total of 461mm of rain fell on that area in the month of August 1996, as compared to 137mm in 1993 and 281mm in 1995. The copious amount of rain in the predominantly hilly area softened the ground, which subsequently triggered several landslides on the steep slopes upstream of river Dipang. The debris and mud resulting from the landslides entered the river channel, creating a huge mudflow. The force and momentum of the mudflow excavated boulders, soils and weathered rocks in the river channel as well as along the banks, thus uprooting huge trees. The stupendous amount of debris caused extreme riverbanks erosion. At several constrictions and turns in the river the tree trunks and branches formed temporary dams, which held back the torrent of water momentarily. Field evidences (Ibrahim Komoo, 1997) indicated that one of these temporary dam was formed about 200m upstream of Pos Dipang. This dam broke when it could no longer withstand the ever-increasing force of swelling waters, suddenly releasing a tremendous amount of water and debris, thus creating a huge debris flood, which deluged the village.

The geology of the area is predominantly hilly terrain consisting of coarse-grained porphyritic granitic rocks. The weathering product of this rock is mainly coarse material: sand, gravels, cobbles and core boulders. Therefore, the river terraces along the both side of the banks consist of rounded boulders and cobbles embedded in loose sand making it extremely prone to erosions.

Figure 2. 6 View part of the remaining village of Pos Dipang, Perak, as captured two days after the furious debris floods.

e) Gunung Pulai Landslide, Johor

On the night of 27th December 2001, debris flood swept away 4 houses on the riverbank of Sungai Seri Gunung Pulai at the foot of Gunung Pulai, in the district of Pontian Johor (**Figure 2.7**). This incident, which has much in common with those of the Pos Dipang tragedy in 1996, also claimed 5 lives, completely swept away 4 houses as well as 2 cars and a lorry into the river. Fourteen other victims managed to save themselves by clinging to the trees and logs. The debris flood also destroyed a bridge and causing substantial damage to the frequently visited Gunung Pulai Nature Recreational Park, resulting in the closure of the park for two years for redevelopment.

The furious debris flood was triggered by an exceptionally heavy rain in that area for the past 48 hours before the tragedy, coupled with strong wind brought over by the Vamei Typhoon (UTM, 2002). The strong winds had uprooted trees at the foothills of Gunung Pulai, which in turn loosened the underlying soils and exposing them to direct impact and infiltration of heavy rainfall. These in turn triggered several landslides on the foothill slopes. The failed masses, including the fallen trees, muds and boulders entered into river course of the Seri Gunung Pulai river, which later stuck against the Seri Gunung Pulai Bridge. The ever-growing force of swelling waters, releasing a tremendous amount of water and debris, thus creating a huge flash debris flood, which swept away the bridge and the four out of six houses on the riverbank.

Figure 2.7 The rescue team searching for the missing victims within the pile of debris and logs washed by the debris flood at Kg. Seri Gunung Pulai, Pontian, Johor

Field evidences indicated that the uphill landslides only involved natural hill slopes, suggesting that the original slopes were intact and undisturbed by human activities. The failures purely represent natural geomorphologic processes acting on hill slopes. The failed slopes consist predominantly of thick (up to 13m) sandy to silty overburden soils resting on heavily fractured/jointed weathered granite bedrock (RQD mostly less than 50%), with localised loose colluvial deposits (JMG, 2002; Kumpulan Ikram Sdn. Bhd, 2002). The colluvium consists of variable mixture of weathered soils, cobbles and boulder derived from older landslides, suggesting that the area is naturally prone to landslides. Study on the landslide scars also revealed that the failures are also attributed to unfavourably oriented relict joints.

f) Landslides along the mountainous highways

Landslide-related geohazards are commonly reported from the highways in mountainous terrain of Malaysia; namely the East-West Highway (Abd. Ghani Rafek *et al.,* 1989; Ibrahim Komoo & Abd. Ghani Rafek, 1988; Tajul Anuar, 1990), Kuala Lumpur-Karak Highway and the Pos Selim – Cameron Highland Highway (Tajul Anuar, 2002) and along some stretches of the North-South PLUS Highway.

The East-West Highway, which connects the town of Gerik in Perak to Jeli in Kelantan, is the only road in northern Peninsular Malaysia that links the east and west coasts. This 117km length highway, transverses rugged mountainous terrain, much of which is covered with dense tropical rain forest. Since it’s opening, the highway seen so many dlope failures or landslide-related geohazards, causing substantial damage to the structure of the highway itself. Landslide-related geohazards frequently resulting in temporary closure of the highway operation, notably during monsoon seasons between November and January. The cost of slope and highway rehabilitations up to now has exceeded far beyond the actual construction cost of the highway.

The Pos Selim-Cameron Highland Highway is the 3rd east-west highway, which transverses across the Peninsula Malaysia Main Range. The construction of the highway began in 1997 and was earlier expected to be completed in 2002. However, having been facing with serious problems of slope failures, the opening of the highway to public was delayed for several years later. One of the biggest landslide was the one that occurred at Gunung Pas (**Figure 2.8**). This landslide has been widely discussed and debated in literature (e.g. Malone et al. 2008; Malone, 2017; Mohd Asbi & Associates Sdn Bhd. 2005; Tajul Anuar Jamaluddin, 2003; Tajul Anuar Jamaluddin & Ibrahim Komoo, 2007; Tajul Anuar Jamaluddin et al., 2006) and it was clearly incdicated the deep-seated landslide was structurally-controlled.

Figure 2. 8 An example of major landslide encountered at Gunung Pass of the Pos Selim-Cameron Highland Highway, which cause an extensive delay to the completion of the highway construction.

Several stretches of the North-South Highway, was also experiencing geohazard. In January 1996, part of the highway slopes close to Gua Tempurung Perak, collapsed and buried the bypassing trailer and killed the driver. The slope failure resulted in total closure of the section of the highway for several days. Due to the danger of landslide recurrence, a new permanent diversion was constructed some 100m away from the tragedy site. The steep cut slope, even though was extensively supported by ground anchors and concrete wall, underwent deep sliding, dislodging more than 10,000 m^3 of earth material.

Research carried out by several workers (*op. cit*.) indicated that the slope failures were mainly found in the forms of shallow slides, rotational slumps, debris flows, rock falls and rock (wedges) slides. The study showed that most of the failures occurred on weathered materials and the plane of failures is usually associated with the boundary between the weathered rocks and soils, often controlled by relict structures inherited in this material. Three major factors unique to wet tropical terrain were the main causes for slope failure: intense and prolonged rainfall, geological nature of weathering profile with profound influences of relict structures (Tajul Anuar Jamaluddin & Ibrahim Komoo, 2007) and aggressive erosion by running water (Ibrahim Komoo, 1995).

g) Collapse of Taman Hill View Bungalow, Hulu Klang, Selangor

This is another major landslide-induced geohazard in Malaysian history, which shocked the country mainly because it brings back sad memories of the Highland Tower collapse nearly eight years ago. The pre-dawn landslide, on 20th November 2002, has completely destroyed a double-storey bungalow of a former Defence Forces Chief, Jen. (Retired) Tan Sri Ismail Omar. The tragedy claimed 8 lives, and injuring 4 others of his family members, while the General himself managed to escaped with helps of the rescue team. The bungalow is located just 300m away from the collapse Block A of the Highland Tower Condominium (**Figure 2.9**).

Figure 2. 9 The collapsed bungalow in Taman Hill View, Hulu Klang, Selangor. The tall buildings in the background are the other two blocks of the Highland Tower Condominium.

About 2 years before that, on May 15, 1999, there was also a major landslide covering 2.5 hectares at Bukit Antarabangsa not far from the Taman Hill View and the Highland Towers, but there was no loss of life (**Figure 2.10**). However, the only road connecting the people on the hill and the outside world was cut off by the landslide for a day.

In all cases, the`landslides in Hulu Klang area shared a similar geologic condition, i.e. landslide in the granitic hill slopes which have been axcessively disturbed by improper hill site development activiries. In the case of the collapse bungalow, investigation carried out on site found that the hill slope above the bungalow has been cut for development purposes. But, for unknown reasons, the modified slope has been left abandoned without proper protection and drainage systems for several years. Heavy spells on the night before the tragedy has triggered the landslide which consequently destroyed the bungalow and claim 8 lives.

Figure 2. 10 Landslide below the Athenaeum on the Peak Condominium, Bukit Antarabangsa, on May 5, 1999, which forced the tenants to evacuate the building for several days.

2.1.2 Discussion

Landslide geohazards in mountainous and hilly terrain of Malaysia are often associated with mass wasting processes; mainly landslides, due to prolonged heavy down pours. With the copious amount of water, the failed masses transformed into liquefied debris and/or mudflow of tremendous velocity and momentum, capable of sweeping away everything found along its pathway. These natural geomorphological processes are common phenomena in tropical mountainous terrain, especially during monsoon seasons.

It is a common feature in the mountainous terrain panorama, where scars of fresh and landslips or landslides are scattered throughout the hill slopes especially during and after prolonged wet seasons. The landslide scars are characterised by clear and bright spots within the green, dense tropical rainforest background (**Figure 2.11**). Their occurrences, regardless of scale, in the remote hilly terrain are always ignored and neglected except that when the impacts of these natural processes affected the human lives, properties and activities.

Experiences from the geohazard incidents at Pos Dipang, Genting Sempah, and Gunung Pulai; are very much in common. The geohazards were induced by landslides in natural hill slopes. Even though the terrains are generally covered with dense and thick tropical rain forest, the vegetation cover does not capable to retain the direct impact of the copious amount of rainwater. Landslide geohazards in developed area, e.g. the Hulu Klang area (Bukit

Antarabangsa, Highland Tower and Taman Hill View incidents) and the mountainous highways/roads are usually accelerated by human activities, such as slope cuttings, deforestation, and excessive modification of the natural ground topography. Human activities inadvertently, have disturbed the equilibrium achieved by the natural geological/geomorphological processes, some of which took thousands or even millions of years to be accomplished.

Figure 2. 11 Examples of scars of recent natural landslides in the remote mountainous tropical terrain of Malaysia, often characterized by barren spots in a green, thick-forested background.

Studies have shown that the major factors underlying landslide-associated geohazards in wet tropics are the engineering properties of the weathered materials and the nature of the weathering and structure. Hence to tackle these problems, an understanding of the climate, geological processes acting on slopes, and the characteristics of the weathering profile is vitally important. Without proper understanding of the geology, the natural processes and their behavioural response of the nature to human disturbances, we are actually alluring for unsuspected geohazards.

2.1.3 Concluding Remarks

Landslide is one of the principal geomorphic processes through which the mountainous terrains evolve. Every location on a hill slope can be considered as part of a continuous “tug-of-war” between the driving force of gravity and resisting forces due to materials that constitute slopes. Both natural processes and human modifications of slopes can impair this balance in favour of gravity. The strength of slope materials is reduced due to internal changes (weathering, seepages, erosions, ground water changes, etc), while stress on slope can be increased as a result of external factors (steepening of slopes through excavations, loading of slopes, deforestation, etc.). The major triggering mechanism is heavy and prolonged rainfalls associated with tropical storms.

Understanding the natural geomorphic and geological processes acting on tropical mountainous terrain is the key to understand the nature and extend of the associated geohazards. It is very important to create awareness amongst the people on the appropriate geohazard mitigation and prevention measures, or avoidance. While it is true that tropical mountainous terrains are heavens for its breath-taking greenery and tranquillity as well as excellent bio- and geo-diversities, but when come to prolonged wet and monsoon seasons we are advised to be more conscious about the landslide-related geohazards.

2.2 Landslide Vulnerability Assessments

2.2.1 Types of Vulnerability Assessment

Vulnerability can be generally divided into 5 main categories namely:

I. Physical vulnerability
II. Vulnerability of person
III. Socio-economic vulnerability
IV. Environmental vulnerability
V. Cultural heritage vulnerability

Generally, the physical vulnerability is the most straightforward vulnerability assessment. Depending on the availability of data, the monetary impact of damage to a building or to infrastructure can be readily assessed and is easily understood. Furthermore, the vulnerability of physical elements can be expressed in terms of the extent of damage as a result of a specific given landslide event. This information provides useful input for quantitative physical vulnerability assessment. Vulnerability of person relates to whether or not a landslide event will result in injury or fatalities. In several cases, the level of vulnerability is closely related to the physical vulnerability of the structure. Monetary values can be assigned in cases of injury or loss of life or reduced quality of life. Specific vulnerability model can be developed to assign such monetary values that take into account the cost of rescue, hospitalisation, and treatment, loss of earning potential (in both the short term in the case of injury and in the long term. Quantitative method of vulnerability assessment has an advantage over the numeric scale of the monetary value. However, other impacts of the loss of life or injury due to a landslide, including trauma and loss of family, are wider-reaching and have social implications that do not readily lend themselves to quantification.

Socio-economic vulnerability assessment covers wider aspect of group or community affected by landslide catastrophes. For example, where a landslide event results in the isolation of a community due to disrupted lifelines (e.g. road and rail), the vulnerability can be quantified on the losses as a result of this isolation. This may include loss of trade in tourist areas where the community is reliant on passing trade, or the need to use alternative, longer routes i.e. for travel to work and the additional expense of the commute. Vulnerability assessment of a particular environment due to landslide can be quantified for example the clean-up costs of pollution or the loss of an economic resource i.e. forestry. The monetary worth of a site of cultural heritage can, in some cases, be assessed which again provides a means of estimating vulnerability using quantitative approach. More often than not a site of cultural heritage has no real monetary expression as it is irreplaceable.

2.2.2 Physical 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).

In the technical perspective, a number of 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. 2011). The development of this indicator can easily be described in Figure 2.12. In another hand, physical vulnerability is generally defined as a scale ranging from 0 (no loss/damage) to 1 (total loss/damage), representing the degree of loss/potential damage of the element at risk. Table 4.0 presents various sub-definitions of physical vulnerability pertaining to the general definition described above.

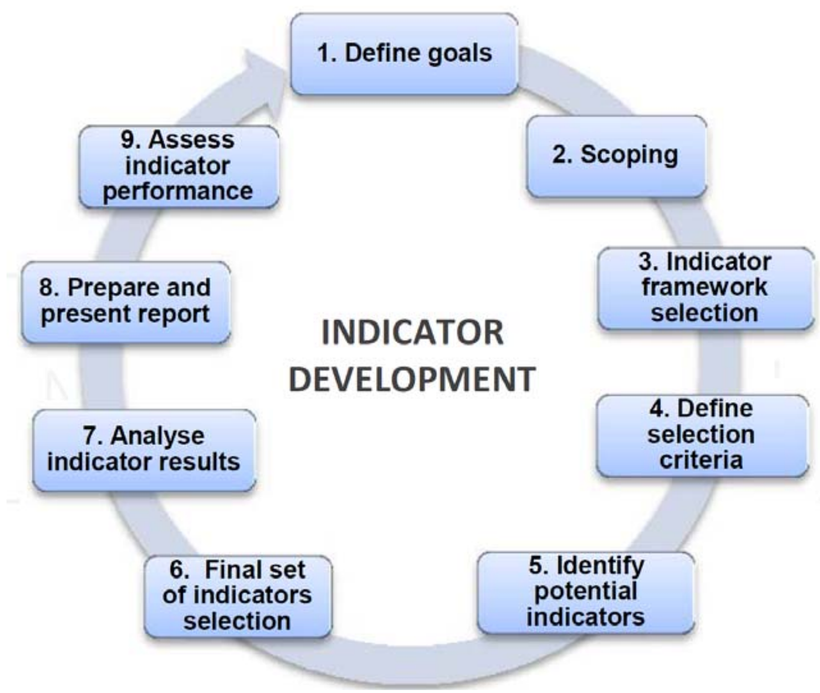


Figure 2. 12 Development process of Vulnerability Indicators.

Table 4.0 General definitions of vulnerability used in risk assessment due to natural hazards and climate change.

Working definitions(s): Vulnerability is…
The degree of loss to a given element at risk or a set of elements at risk resulting from the occurrence of a natural phenomenon of a given magnitude and expressed on a scale from) (no damage) to 1 (total damage)
The conditions determined by physical, social, economic, and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards.
The characteristics of a person or group in terms of their capacity to anticipate, cope with, resist and recover from impacts of a hazard.
The intrinsic and dynamic feature of an element-at-risk determines the expected damage/harm resulting from a given hazardous event and is often even affected by the harmful event itself. Vulnerability changes continuously over time and is driven by physical, social economic and environmental factors.
The degree to which geophysical, biological and socio-economic systems are susceptible to, and unable to cope with, adverse impacts of climate change.

Uzielli et al. (2008) stated that landslide vulnerability assessment is more difficult compared to other types of hazard i.e. flooding and earthquake due to several reasons:

1. The complexity and the wide range of landslide process (landslides are determined by different predisposing and triggering factors which results in various mechanisms of failure and mobility, size, shape, etc.)
2. The lack systematic approaches to express landslide intensity. There is no general indicator of landslide intensity (e.g. for rock falls, impact pressure or volume can be used whereas for debris flow deposit height is common; other indicators such as flow velocity are rarely considered) and in practice data scarcity reduces their number significantly
3. The quantitative heterogeneity of vulnerability of different elements at risk for qualitatively similar landslide mechanisms due to their intrinsic characteristics (here, human life constitutes a special case)
4. The variability in spatial and temporal vulnerability
5. The lack of historical damage databases – usually only events which cause extensive damage are recorded and data about the type and extent of damage is often missing
6. Non-physical factors influence the vulnerability of people (e.g. early warning, hazard and risk perception, etc.)

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). Cardinali et al. (2002) estimated qualitatively the vulnerability of rockfall-exposed buildings in Umbria, for the different rockfall intensities and structural typologies of the area, based on the damage that landslides had caused to the buildings. Mavrouli and Corominas (2010) investigated the vulnerability of reinforced concrete buildings to rockfall impact. 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 et al. 2002). The methods are flexible to reduce subjectivity, compared with the qualitative method. Based on this method, damage matrices, for example, are composed by classified intensities and stepwise damage levels. Previous study by Frédéric et al. (1996) damage matrices were suggested based on damaging factors and the resistance of the elements at risk to the impact of landslides. Based on the First-Order Second-Moment (FOSM) approach introduced by Kaynia et al. (2008), which allows for the quantification of uncertainty from the input parameters up to the vulnerability estimates. Results on the application of the method show vulnerability estimates for susceptible categories on structures and people for prescribed study areas. Research made by Guillard-Gonçalves et al. (2016) shows the representation of the buildings' vulnerability at the municipal scale is a satisfactory. Other physical vulnerability studies of semi-quantitative, assigning empirical weighting of a set of building resistance parameters to buildings exposed to landslides (Silva and Pereira 2014) The applicability of this method requires statistical analysis of detailed records on landslides and their consequences (Dai et al. 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 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 (probabilistic).

2.2.2.1 Vulnerability Matrices

Vulnerability matrices are qualitative method 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 (Papathoma-Köhle et al. 2017). The input for vulnerability matrices is often either based on empirical data or expert judgment. Intact structural element-at-risk will be assigned with 0 and 1 for totally damage building. 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.

Guillard-Gonçalves et al. (2016) used a qualitative 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 study 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/loose stone walls (SBT2), 3) brick/stone masonry walls (SBT3), and 4) masonry walls confined with reinforced concrete (SBT4). These building structural types were crossed with the landslide intensity (i.e. depth or slip surface and height of accumulated materials) as shown in Table 5.0.

Zêzere et al. (2008) defined the physical vulnerability of buildings and road not only on structural properties of exposed elements, but also on the type of process, and its magnitude (see Table 6.0). The vulnerability values were defined based on the past records of landslides occurrences in the study area. Landslides affect the physical element-at-risk at various impact mechanisms for example burial, collision impact, earth pressures, differential shearing in tension, compression or torque, plastic deformation (flow), by object displacement and by removal or deformation of valued ground, such as productive soil and foundation substrate. The degree to which these mechanisms are manifest is generally reflected by the type of landslide (Glade 2004). However, many landslides exhibit complex behaviour and a variety of different impact mechanisms may be represented in the one landslide type. Despite this problem, a classification scheme has been suggested by (Flageolett 1999) as shown in Figure 2.13.

Table 5.0 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

Table 6.0 Vulnerability matrices for building and road types crossed with the landslide types namely, shallow translational slides and rotational slides (Zêzere et al. 2008)

Elements at risk value and vulnerability considering exposure to different landslide types within the Fanhões-Trancão test site

Vulnerable elements		Value €		Vulnerability		
		m^2	Pixel	Shallow translational slides	Translational slides	Rotational slides
Buildings	Poor traditional masonry buildings	600	15,000	0.5	1	1
	Poor adobe stone or taipa buildings	600	15,000	0.5	1	1
	Poor other resistant elements (wood, metallic) buildings	600	15,000	0.4	1	1
	Usual traditional masonry buildings	1197	29,925	0.5	1	1
	Usual reinforced concrete buildings	1197	29,925	0.3	1	1
	Luxurious reinforced concrete buildings	2186	54,650	0.3	1	1
	Heritage traditional masonry	2217	55,425	0.5	1	1
Roads	Motorway, bridges, viaducts	933	23,325	0.6	1	1
	National road	933	23,325	0.6	1	1
	County road	8	200	0.6	1	1
	Rural road	2.5	62.5	0.6	1	1

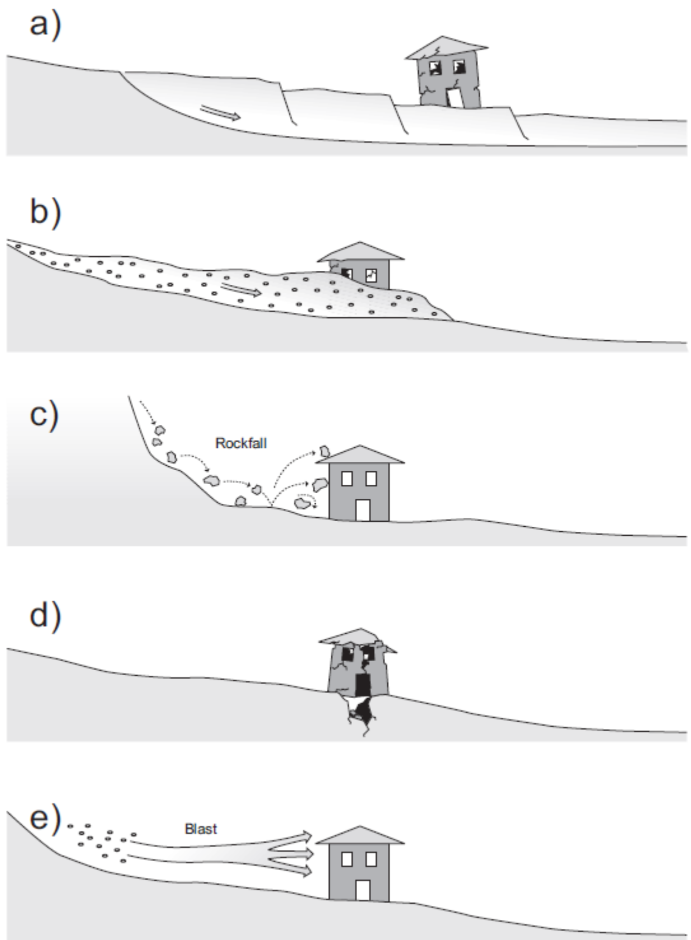


Figure 2. 13 Schematic representation of structural damage to buildings for different landslide types (according to Flageollet (1999)). Damage is assigned to slide and flow processes (a), to flows (b), to falls and topples (c), to subsidence (d), and to rock avalanches or large rock failures.

Frédéric et al. (1996) proposed a vulnerability matric that relates different types of element-a-risk with different intensities of landslides. Figure 2.14 shows a sample of the structural damage matric for different categories of buildings, which damages were explained in Table 7.0.

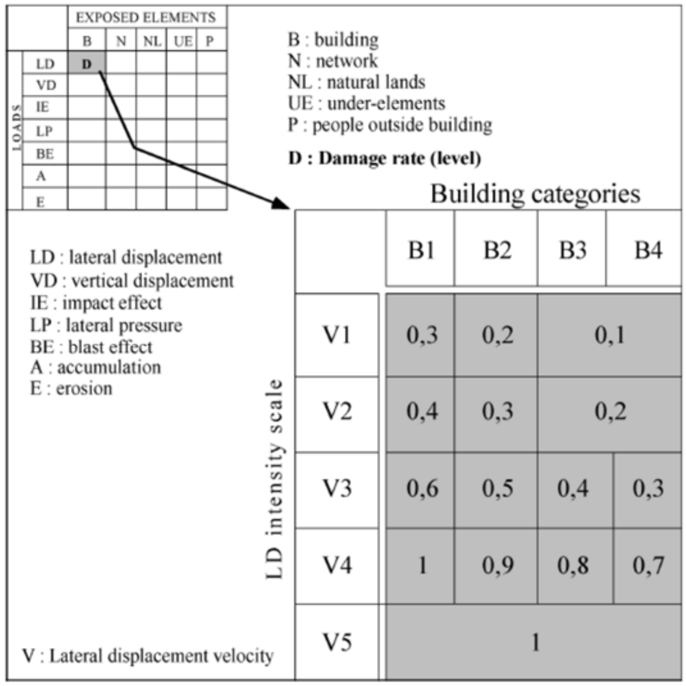


Figure 2. 14 Sample of vulnerability matric for different building categories (Frédéric et al. 1996).

Table 7.0 Sample of the typology of the types and levels of damage of the main elements exposed (Frédéric et al. 1996)

I	Light damage (on furniture only). Stability not affected.	0.01-0.1
II	Cracks on walls, but stability not affected. Repairs not urgent.	0.2-0.3
III	Important deformations, cracks widely open. Cracks on structures. Stability affected. Doors and windows unusable. Necessity of evacuation.	0.4-0.6
IV	Breaks on structures. Separation of parts. Partial collapse of floor and breaks on walls. Necessity of evacuation. Rehabilitation compromised.	0.7-0.8
V	Total collapse. Area must be evacuated. No possibility of rehabilitation.	0.9-1.0

2.2.2.2 Vulnerability Curves

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. 2012a).The degree of loss for a specific element-at-risk can be estimated by combining for example building construction value with the value of the damage.

Inevitably development of vulnerability curve for a specific element-at-risk required detailed information about for example age, material, condition, size and etc. for each building, which maybe expensive and labor intensive (Papathoma-Köhle et al. 2017).

Papathoma-Köhle et al. (2015) developed a toolbox to support landslide vulnerability assessment mainly in field damage assessment standard method, method for future hazard assessment and database to update vulnerability curve for different element-at-risk. Structural vulnerability per building was defined as the ratio between the values of the building (in terms of reconstruction costs) to the monetary damage caused by the event. The vulnerability curve for a specific type of building was developed based on empirical damage data of buildings and the height of deposits caused by debris flow.

Remondo et al. (2008) developed a landslide vulnerability from a detailed analysis of past damage over 50 years from mass movements. The inventory of landside damages was based on field surveys and consultations with both local inhabitants and public and private. The vulnerability values were determined from a detailed analysis of past damage from mass movements, which has been recorded over nearly 50 years. The inventory is based on field surveys and consultations with both local inhabitants and public and private. However, the data is still not complete and extrapolations and theoretical assumptions were needed for the assessment. The vulnerability of infrastructure was defined as the ratio between Loss of the element due to a landslide of a given type and magnitude and value of the element. In general, the vulnerability values could theoretically be greater than 1, since repair could cost more than construction of a new structure. However, the maximum value considered in this analysis is 1 (total loss). In this study, the values of past losses were corrected for inflation, an assumption which can also be used for predicted future losses. They have only considered shallow slide for the risk estimation. The risk was estimated using Equation 1.

$$R = H \times E \times V \quad (1)$$

Where *R* is the risk, *E* is the value for each element-at-risk and *V* is the vulnerability. They have pointed that a complete view of the risk for a given element-at-risk should combine multiple scenarios of hazards and vulnerability values for the different types of mass movements and their magnitude.

In Quan Luna et al. (2011) approach, the vulnerability functions were calculated using damage data obtained from the official documents of damage assessment coupled with the information from the modelling outputs. This approach allows calculation of vulnerability functions using the height of debris accumulation and also the impact pressure. The impact pressure information is widely used in snow avalanche risk assessment but it is not widely applied for debris flows risk calculations. The obtained results were consequently coupled with the modelling results (height of accumulation, impact pressures). This allows developing vulnerability curves that relate the building vulnerability values with the process intensity. The generated physical vulnerability curves can be used as an approach for the estimation of the structural resistance of buildings affected by a debris flow event. The height of accumulation values was extracted for each affected building. However, for every building the maximum and minimum heights of accumulation varied a lot. As a consequence, an average height near building walls oriented towards the flow direction was considered in the calculation. Impact pressure values were extracted in the same way as accumulation heights considering the values near building walls oriented towards the flow direction. The aim in presenting different types of vulnerability curves in this analysis is to help the decision makers to decide which type of intensity description best fits their needs and affected area.

However, shortcomings in their analysis still exist and further research needs to be done regarding them. One of the major shortcomings is the insufficient data points regarding the affected element-at-risk and the variation in values due to the differences in building quality, state, and structural characteristics. This should also be complimented by collecting more data of damaged buildings affected by debris flows, organizing them according to the type and use. This kind of description plays a very important role for the analysis, as in the case where damage to buildings contents will be higher than to the building structure itself (i.e. shops and warehouses). Hence, a better estimation of the reported damage should be assessed based on structural and non-structural damage. Nevertheless, the presented approach attempts to propose a quantitative method to estimate the vulnerability of an exposed element to a debris flow that can be independent on the temporal occurrence of the hazard event.

Kang and Kim (2016) stated that the range of damage to the buildings makes it possible to assess the vulnerability using a vulnerability curve that relates the intensity of debris flow with the degree of damage. In their work, vulnerability curves were estimated using the degree of damage to the buildings that was combined with the intensities of the debris flow events. An average value of vulnerability index corresponding to degree of damage to the building was used in vulnerability curves. Three different empirical vulnerability curves were obtained, which were as function of debris flow depth, flow velocity, and impact pressure. The suggested vulnerability functions have many limitations because the damaged building in this study was simply divided into two groups i.e. RC building and non-RC building. The degree of damage to the buildings depends not only on structural types of building but also on shape, direction, position, etc. However, in a practical application, there is a need for a more detailed classification of damaged buildings with establishment of database regarding debris flow events. Nevertheless, the presented approach attempts to propose a quantitative method to estimate the vulnerability of an exposed element to a debris flow. The resulting physical vulnerability curves can be used to estimate the structural resistance of buildings to debris flow events.

Pereira et al. (2017) assessed the physical vulnerability of building using semi-quantitative vulnerability curves. The assessment was based on a very detailed field inventory of the buildings characteristics, in contrast to the more usual situation, where information about the buildings is aggregated into statistical units of the census. Physical vulnerability of buildings was assessed for two landslide magnitudes based on expert knowledge. The vulnerability curves represent an estimation of average level of damages that was derived from an empirical relation between the landslide area and the landslide thickness. However, the number of cases with known landslide thickness is not enough to improve the uncertainty due to the rough evaluation carried out. Another uncertainty was on the average level of damage that a landslide of a certain thickness can cause to different types of buildings. The proposed vulnerability curves are site specific and should only be applied in areas with similar building characteristics and landslide typology. In addition, the vulnerability values that correspond to the expected average level of damages in buildings was estimated in the rupture zone of a shallow translational slide where buildings are dominantly affected by horizontal displacement. The estimated buildings vulnerability and risk could not be independently validated in this study. Unfortunately, the samples of landslide damages on buildings are very few in the study area which did not allowed generation of statistical correlation with the degree of damage necessary to derive a validated vulnerability curve.

Within the framework of the presented study by Totschnig et al. (2011), an empirical vulnerability function was developed for buildings located on alpine torrent fans and which are prone to torrent processes, i.e., fluvial sediment transport. The vulnerability function presented refers to the physical susceptibility of buildings and was based on an economic approach linking object based loss data to reconstruction values. Thus, the proposed vulnerability function can be used in operational risk analyses for torrent hazards, particularly since the approach is suitable for a spatially explicit valuation within a GIS environment. Physical susceptibility of elements at risk and thus vulnerability is strongly dependent on the construction material used. The developed vulnerability functions are applicable to buildings, which are constructed by using brick masonry and concrete, a typical design in post-1950s building craft in Alpine countries. Consequently, the adjusted functions may be applicable to this mixed construction type if residential buildings are assessed during risk analyses. However, a wider application of the presented approach to additional building categories such as hotels or business establishments is still required.

2.2.2.3 Vulnerability Indicators

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).

Isaza-Restrepo et al. (2016) estimated physical vulnerability of building as in Equation 2.

$$VE = V_E \times A_E \times D_\$ \qquad (2)$$

where *VE* is the structural vulnerability (given in likely total economic losses), V_E is the structural vulnerability index, A_E is the area of the structure or of the built area and $D_\$$ is the commercial cost of the structure per square meter. The structural vulnerability was defined based on the type of structure, state of maintenance and age (Equation 3).

$$V_E = BSF \times W_{BSF} \qquad (3)$$

where *BSF* is the building susceptibility factor and W_{BSF} is the weight of each factor. The value for BSF factor was obtained from decision trees that correspond to different building structure types.

Uzielli et al. (2008) and Kaynia et al. (2008) proposed a vulnerability assessment framework quantitative estimation of physical vulnerability of element-at-risk for a specific landslide hazard. In their study, vulnerability was defined as the product of landslide intensity and susceptibility of element-at-risk (Equation 4). Both intensity and susceptibility (Equation 5) are expressed in dimensionless terms with values between 0 and 1.

$$V = I \times S \qquad (4)$$

$$S = 1 - \coprod_{i=1}^{n_s}(1 - \varepsilon_i) \qquad (5)$$

Where ε_i is the i-th of n_s susceptibility factors (each defined in the range [0, 1]) contributing to the category susceptibility. The susceptibility of the element-at-risk refers to the lack of inherent capacity of the elements in the spatial extension under investigation to preserve their physical integrity and functionality in the course of the physical interaction with a generic sliding mass. They have stressed that susceptibility as defined in the study is independent of the characteristics of the acting agent, i.e. the landslide. The susceptibility value accounts its physical resilience to landslide occurrence, which mainly depends on the technological and its state of maintenance. The susceptibility classes for structural typology (ξ_{STY}) were divided into 6 classes as listed in Table 8.0.

Table 8.0 Proposed values of susceptibility factor for structural typology.

Structural Typology	Resistance	Susceptibility
Lightest, simple structures	None	1.00
Light structures	Very low	0.90
Rock masonry, concrete and timber	Low	0.70
Brick masonry, concrete structures	Medium	0.50
Reinforced concrete structures	High	0.30
Reinforced structures	Very high	0.10

The state of maintenance (ξ_{SMN}) expresses the reduced capacity of structures in comparison with the "very good" category in which maximum capacity is expected. Table 9.0 shows the proposed values for the state of maintenance.

Table 9.0 Proposed values for the state of maintenance.

State of maintenance	ξ_{SMN}
Very poor	0.50
Poor	0.40
Medium	0.25
Good	0.10
Very good	0.00

The landslide intensity parameter can be defined quantitatively using various approaches. Landslide intensity has been addressed and defined quantitatively using a variety of parameters i.e. maximum velocity, total displacement, differential displacement (relative to points adjacent to the point under consideration), depth of the moving mass, depth of deposits after the movement ceases, depth of erosion, unit discharge, kinetic energy per unit area, maximum thrust, impact pressure, maximum normal or shear strain at or below ground surface (Hungr 1997). Uzielli et al. (2008) and Isaza-Restrepo et al. (2016) in their study used a composite landslide intensity parameter that accounts kinetic and kinematic characteristics of the interaction between the sliding mass and the reference area (Equation 6).

$$I = k_S + I_K + r_M + I_M \tag{6}$$

Where

$$k_S = {}^{A_i}/_{A_t} \tag{7}$$

k_s is the spatial impact ratio, A_i is the area pertaining to the element-at-risk that is affected by the landslide, A_t is the total area pertaining to the element-at-risk, r_K is the kinetic relevance factor of the category, r_M is the kinematic relevance factor of the category, I_K is the kinetic intensity parameter of the element-at-risk and I_M is the kinematic intensity parameter of the element-at-risk.

Li et al. (2010) proposed a new quantitative model for vulnerability of structures and persons based on landslide intensity and resistance of exposed elements. In their study, vulnerability (*V*) was defined as a function of the hazard intensity (*I*), the exposed elements at risk and the resistance ability (*R*) of the elements to withstand the hazard.

$$V = f(I,R) = 2\frac{I^2}{R^2}\ for\ \frac{I}{R} \leq 0.5 \quad (8)$$

$$V = f(I,R) = 1.0 - 2\frac{(R-I^2)}{R^2}\ for\ \frac{I}{R} \leq 1.0 \quad (9)$$

$$V = f(I,R) = 1.0\ for\ \frac{I}{R} > 1.0 \quad (10)$$

In their study, the landslide intensity is defined as a function of dynamic and geometric intensity factors.

$$I = I_{dyn} + I_{dpt} \text{ for structure outside landslide area} \quad (11)$$

$$I = I_{dyn} + I_{dfm} \text{ for structure inside landslide area} \quad (12)$$

where I_{dyn} is the dynamic intensity factor that accounts stationary and non-stationary element-at-risk, I_{dpt} is the debris-depth factor, which was used to evaluate the element-at-risk outside rapid landslide area, and I_{dfm} is the deformation factor, which is mainly used to evaluate the structures within the sliding mass of a slow landslide. The resistance reflects the physical resilience of vulnerable element-at-risk to withstand specific landslide hazard intensity. The resistance of structure was defined as follows:

$$R_{str} = \left(\varepsilon_{sfd} \times \varepsilon_{sty} \times \varepsilon_{smn} \times \varepsilon_{sht}\right)^{1/4} \quad (13)$$

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 2.15 and Figure 2.16). In this study, the relative vulnerability index (RVI) is calculated using Equation 14. The same vulnerability index was also used by Kappes et al. (2012) in their works for vulnerability analysis.

$$RVI = \sum_{1}^{m} w_m \times I_m \times S_n \quad (14)$$

where *w* represents the m different weights, *I* the *m* indicators and *s* the *n* scores of the indicators. Figure 2.15 shows that empirical data between landslide intensity and level of damage recorded after the landslide events can be used to update the vulnerability curve, indicator and its weight value for IBM. Papathoma-Köhle (2016) highlighted several benefits of IBM compared to vulnerability curve as follows:

a) 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.
b) 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.
c) The weighting process is flexible and can be adjusted based on the needs of the users.
d) 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.
e) The use of GIS in updating the information makes the 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 GIS database may allow inclusion of spatial changes in built environment, socio-economic and land use in future scenarios.
f) Spatial visualization in 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.
g) Transferability of the method is good since the method is intensity dependent.
h) The IBM method encourage involvement from the community and individual building owner in data collection and vulnerability reduction.

However, there are still several disadvantageous of this IBM method highlighted by Papathoma-Köhle (2016) as follows:

a) The major drawback of IBM is the intensity relevance where the IBM assigns a relevant vulnerability index to each building which more or less shows which building is more vulnerable than another in a worse-case scenario without indicating a specific intensity of the event.
b) Inconsistencies between two methods (i.e. vulnerability curve and indicator) for specific buildings are may due to incompleteness of the set of indicators like the existence of openings on the slope side, their size and quality, as well as the existence of a basement are not considered as one of characteristics for vulnerability assessment.
c) Completeness of datasets and costs of data collection: Detailed datasets at local level are required for the implementation of the methodology.
d) Description of scores for building condition such as “good” or “medium” leads to large dependence on data collector’s judgment in deciding score that will be assigned to a building.

e) Classification of results as well as the weighting should also be decided by the user as this way the users may set priorities.
f) A disadvantage for practitioners because of the vulnerability map was translated without proper capacity to translate the building vulnerability into a quantitative value.
g) Decision makers are in need of vulnerability assessment methods that they can use for risk analysis but they also need to know the uncertainties that are associated with the vulnerability values. The uncertainties are intensity of event, damage pattern, degree of loss, and credibility of existing data.

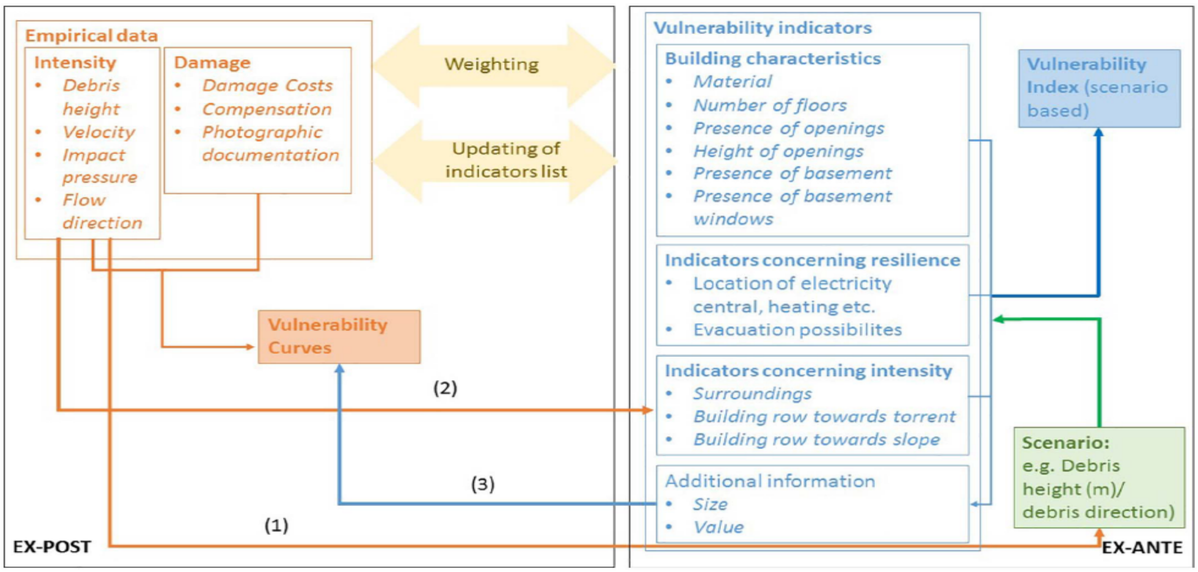


Figure 2.15 A framework indicating how different approaches of physical vulnerability assessment may interact with each other (Papathoma-Köhle 2016).

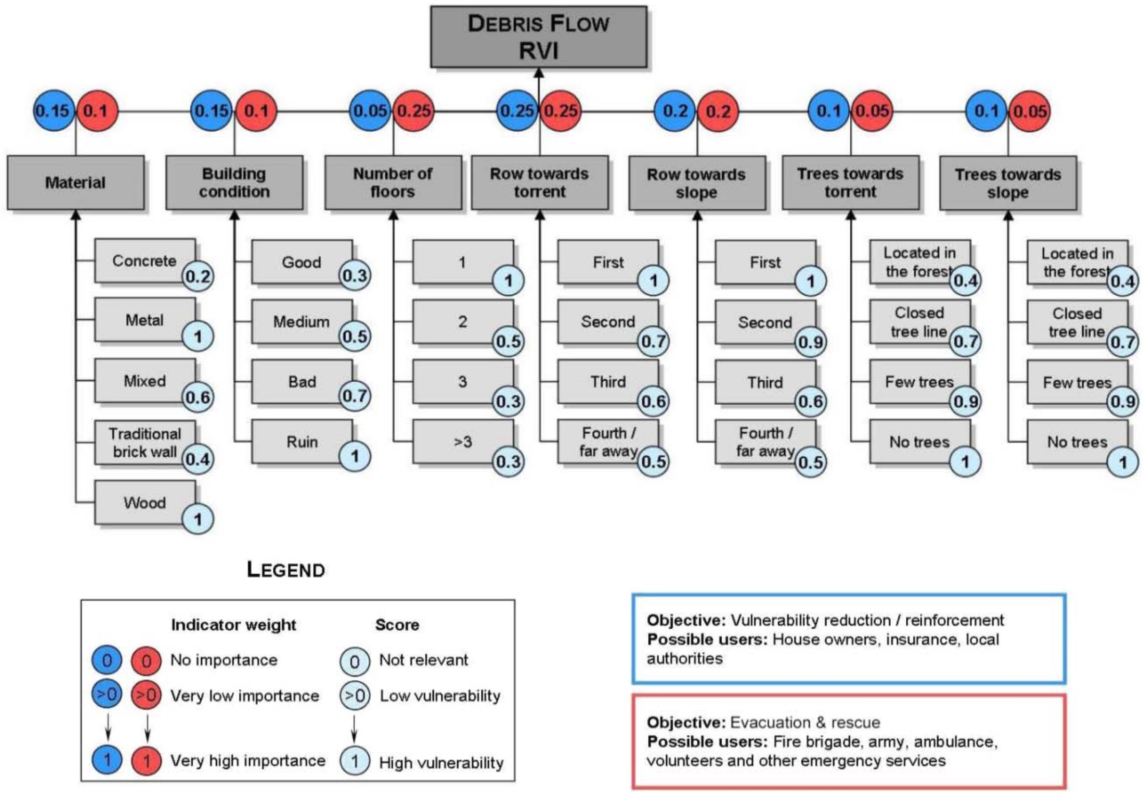


Figure 2.16 The vulnerability indicators are demonstrated together with the weight index, which varies according to the objective of the vulnerability assessment and the end users (Papathoma-Köhle 2016).

The underlying concept applied in Fuchs et al. (2007) work is relied on the concept of risk, which with respect to natural hazards is defined as a quantifying function of the probability of occurrence of a process and the related extent of damage, the latter specified by the damage potential and the vulnerability (Equation 15).

$$R_{i,j} = f(p_{Si}, A_{Oj}, v_{Oj,Si}, P_{Oj,Si}) \tag{15}$$

Hence, specifications for the probability of the defined scenario (p_{Si}), the value at risk affected by this scenario (A_{Oj}), the vulnerability of object *j* in dependence on scenario *I* ($v_{Oj,Si}$), and the probability of exposure of object *j* to scenario *i* ($p_{Oj,\ Si}$) are required for the quantification of risk ($R_{i,j}$).

Table 10.0 concludes detailed advantageous and disadvantageous of vulnerability matrices, curves and indicators.

Table 10.0 Advantageous and disadvantageous of vulnerability matrices, curves and indicators (Papathoma-Köhle et al. 2017).

Method of vulnerability expression	Advantage	Disadvantage
Vulnerability matrices	• Qualitative results with the input from expert judgement to evaluate empirical data. • Clear relationship between process and consequence and easy to understand by non-experts. • Information on financial value, costs of damage and exact intensity is not required.	• The results are highly subjective. • Description of damage levels e.g. high, medium or insignificant may differ among experts. • Transferability and comparison possibilities are limited.
Vulnerability curves	• Require less detailed data and popular among practitioners. • Provide a quantitative representation of physical vulnerability.	• Do not provide information about the building characteristics e.g. building type, structural features, location orientation, etc. since all data is combined into a single function. • The results can't be connected to the consequences in order to explore ways of reducing vulnerability based on building information. • The intensity of the process is expressed in a single way (e.g. debris height) that ignores other characteristics of the process. • Data availability problem - in order to develop vulnerability curves information on the intensity of the process on each building should be available. • Reliability depends on the quality and the quantity of the available empirical data, survey

		method for the data collection, method for the calculation of the monetary damage and the statistical method used for the analysis of the data. • Uncertainty in curve fitting. • Each vulnerability curve is based on a different set of empirical data - issues regarding the possibilities for transferability to other area.
Vulnerability indicators	• The method is not based on empirical data and therefore they can be implemented in absence of this type of data and also in locations with no event record. • Do not require expert for data collection. • The assignment of a vulnerability index to buildings makes the prioritisation of resources easier for the decision makers especially if the resources are limited. • Characteristics of buildings are taken into consideration and for the case that also empirical data on damages are available, the interaction of the process with different building characteristics can be investigated and empirical weighting may be possible.	• Uncertainty in terms of selection of parameters, standardisation, weighting and aggregation, as well as the availability of required data. • Neglects the intensity of the process. • The data required are too detailed (per building) and may be collected only after field work.

2.2.3 Indicators and Hazard Intensity Parameter for Physical Vulnerability Assessment

Determination of indicators for the element-at-risk susceptibility and hazard intensity has been made by previous researches regardless of vulnerability assessment methods. Papathoma-Köhle (2016) listed the quality criteria in selecting vulnerability indicators (Table 11.0).

Table 11.0 Quality criteria for vulnerability indicators (adapted from Birkmann, 2006).

Criteria	Vulnerability Indicators
Measurable	The indicators used are not always easily measurable. The difference between a building of "good" and "medium" condition is not clear and not measurable in quantitative terms. The scores for each building may be dependent on the judgment of the data collector and may not always objective. Moreover, this information is process specific. The scoring of the same indicators would be different for a study focusing e.g. on earthquakes. Improved data collection techniques (e.g. detailed standardized questionnaires) may improve the measurability of the indicators.
Relevant	The indicators have been based on reports and documentation of past events and for this reason are relevant to the assessment. They have been also chosen according to the needs of the end users although the latter could be more involved in the selection process in the future. The weighting, however, is done directly by the end users, offering flexibility to the method as well as subjectivity.
Policy-relevant	Although not demonstrated in the specific article, the indicators may be policy relevant. The vulnerability indicators may give decision makers an overview of damage potential for future events. Moreover, they may be used for emergency planning and they may guide local structural protection measures as shown by Holub and Fuchs (2009) for case studies in the Austrian Alps. However, intensity should also be included in the assessment.
Measure important	The indicators are connected to key elements (e.g. vulnerability to other hazard types); however, they do not consider the intensity of the process.
Analytically and statistically sound	Although the indicators may give an overview of the actual situation, the link between natural process and degree of loss, as well as the reaction of a structure to the natural process according to its characteristics, are not fully understood and, therefore, further research is required (Mazzorana et al., 2014).
Understandable/easy to interpret	The indicators used in this study are easy to interpret. No experts are required for their collection. Although this is an advantage of the method, the judgment of the collector may influence the result significantly and increase uncertainties.
Sensitivity	Although the indicators are specific to the phenomenon of debris flow, they are not sensitive to changes related to this phenomenon (e.g. intensity).

	However, they are sensitive to changes in the structure of the building, which means that they are able to express changes in the physical vulnerability should a building be reinforced.
Validity/Accuracy	The indicators have the capacity to express the physical vulnerability of buildings in most of the cases and this may also be confirmed by the results of the vulnerability curve. However, this is not always the case. The cases where high vulnerability has been assigned for buildings that have experienced low degree of loss have to be investigated, and based on the conclusions of this investigation the methodology may be improved.
Reproducible	Theoretically, the set of indicators could be reproducible for another area facing a threat of debris flows. However, significant differences in the architecture and building standards of buildings should be considered.
Based on available data	The indicators are not always based on available data. Some information could be available from the municipality. However, the majority of the required information may be collected through field work or interpretation of ortho-photos.
Data comparability	The indicators may be compared to similar ones in other areas but also to past or future conditions of the same area.
Cost effective	The indicators are cost effective. The assessment of the vulnerability for debris flow usually involves a limited amount of buildings. Although fieldwork is necessary there are ways to avoid it by sending questionnaires to the building owners or interpreting ortho-photos for rapid data collection.

In addition, there are several common weighting methods for IBM as follows (CIMNE 2009):

a) **Equal weighting**: all indicators are assigned equal weighting, which assumed that the indicators are equally significance.
b) **Expert judgment weighting**: according to expert opinions (e.g. literature review) weights are assigned to each indicator in relation to their degree of relevance within the model framework.
c) **Analytic hierarchy process**: a technique where a complex problem is broken down to a hierarchy of simpler sub-problems more easily analysed using expert judgment. A numerical procedure is applied to translate the sub-problem expert judgment into an assessment of the initial complex problem
d) **Principal component analysis (PCA)**: a statistical technique transforming a multi-parameter data set into a set of independent parameters ranked by how important each parameter is in representing the variation in the data.
e) **Factor analysis**: a statistical technique applied on a multi-parameter data set, finding a potentially lower number of unobserved/underlying parameters called factors
f) **Multiple regression models**: if data for calibration are available, a regression analysis can be performed to determine how the value of the dependent variable (e.g. vulnerability) changes when any of the independent variables (e.g. indicators) are varied. The weights are selected based on the results of the regression analysis.

Based on the previous studies, various indicators have been selected based on the characteristics of the element-at-risk and type of landslides (Table 12.0). The index value for each indicator was determined either quantitatively using specific model or qualitatively based on expert judgments. Table 13.0 summarizes the list of indicators found from the literature review, which have been grouped into physical characteristics of the element-at-risk, surrounding elements and hazard intensity. Figure 2.17 and Table 14.0 suggested landslide intensity indicators for different type of landslides.

Table 12.0 Overview of the Vulnerability Assessment Studies.

Type of vulnerability assessment	**Indicators for physical vulnerability**	**Indicators for landslide intensity**	**Type of landslides**	**Authors**	**Area (urban/urban highland/sub-urban/rural)**
Quantitative (indicator based)	1.Structural typology 2.State of maintenance	1.Kinetic factors (Velocity of landslide) 2.Kinematic factors (displacement of landslide)	Debris flow	(Uzielli et al. 2008)	
Quantitative (indicator based)	1.Foundation depth 2.Structure type 3.Maintenance state 4.Height	1.Dynamic intensity (landslide velocity) 2.Geometric intensity (size-linked features of elements or landslides)	Debris flow	(Li et al. 2010)	
Qualitative (Indicator based)	1.Structure material 2.Building condition 3.Number of floor	1.Row towards torrent 2.Row towards slope 3.Trees toward torrent 4.Trees toward slopes	Debris flow and shallow landslide	(Kappes et al. 2012)	
Quantitative (indicator based)	1. Size of buildings 2. Function of buildings 3. Number & kind of storeys	1.Accumulation heights 2.Flow depths	Debris flow	(Fuchs et al. 2007)	Austrian Alps, Austria (suburban highland)
Semi-quantitative (indicator based)	1. Structure’s technological features 2. State of maintenance	1. Kinetic characteristics (kinetic energy) 2. Kinematic Intensity (size-linked features of a reference landslide)	General	(Kaynia et al. 2008)	Lichtenstein, Baden-Württemberg, Germany (rural)
Quantitative (indicator based)	1. Building categories 2. Construction materials and techniques	1. Flow depths 2. Accumulation heights 3. Flow velocities and pressures	Debris flow	(Totschnig et al. 2011)	Austrian Alps, Austria

	3. State of maintenance 4. Presence of protection structures 5. Presence of warning systems				(suburban highland)
Quantitative (vulnerability curves)	1.Building height 2.Impact pressure	1.Kinematic viscosity	Debris flow	(Quan Luna et al. 2011)	Selvetta, Italy (suburban)
Qualitative (vulnerability matrix)	1. Frontal impact 2. Dominant in the proximal portion of debris flows 3. Accumulation and abrasion, 4. Dominant in the distal portion of debris flows 5. The boundary decreasing effect 6. The back shielding effect	1. Flow velocity – kinetic-potential energy transformation formula	Debris flow	(Hu et al. 2012)	Zhouqu, Western China (suburban)
Quantitative (vulnerability curves)	1. Structure type 2. Structure material 3. Building height	1.Impact pressure 2.Flow velocity 3.Flow depth	Debris flow	(Kang and Kim 2016)	South Korea (urban)
Quantitative (indicator based)	1. Building material 2. Number of floors 3. Presence of openings 4. Height of openings 5. Presence of basement 6. Basement windows	1. Surroundings 2. Building row towards river 3. Building row towards slope	Debris flow	(Papathoma-Köhle 2016)	Martell, Italy (urban)
Semi-quantitative (vulnerability curve)	1. Construction techniques 2. Construction materials 3. Number of floors	1.Landslide thickness 2.Landslide area	General	(Pereira et al. 2017)	Santa Marta de Penaguião, Portugal (suburban)

Quantitative (vulnerability curve)	Specifically for double storey concrete reinforced building Distance to the crest	1. Peak ground acceleration (PGA) of horizontal and vertical components 2. Intensity of horizontal and vertical components	Earthquake induced landslide	(Fotopoulou and Pitilakis 2017)	
Quantitative (indicator based)	1.Type of structure 2.Age 3.Type of maintenance	1. Kinetic factors (velocity of landslide) 2. Kinematic factors (displacement of landslide)	Earthquake induced landslide	(Isaza-Restrepo et al. 2016)	Urban
Indicator based	1. Material of building 2. Height 3. Number of floors 4. Size of building 5. Use of building 6. Age of building 7. Maintenance state 8. Surrounding wall 9. Surrounding vegetation 10. Existence of mitigation measures 11. Roof type 12. Roof condition 13. Roof slope 14. Location of opening 15. Height of opening 16. Material of opening 17. Type of foundation 18. Present of basement 19. Present of basement opening 20. Row of building from the river		Debris flow	(Papathoma-Köhle et al. 2017)	

	21. Distance between building 22. Existence of protruding parts 23. Building orientation 24. Existence of adjacent auxiliary building 25. Use of first floor 26. Floor material 27. Existence of local mitigation measures 28. Location of the electricity central appliance 29. Maintenance and condition of electricity network 30. Location of heating central appliance 31. Maintenance and condition of heating system 32. Maintenance and condition of sewage system 33. Condition/location of water supply network				
Quantitative (indicator based)	1. Damage pattern by analysing the process impact on the building	1. Height of the deposits	Debris flow	(Papathoma-Köhle et al. 2012b)	South Tyrol (Highland area)

Semi-quantitative	1. Building categories or types 2. Construction materials and techniques 3. State of maintenance 4. Presence of protection structures 5. Presence of warning systems	1. Height of the deposits	Fluvial sediment	(Reinhold et al. 2011)	Austrian Alps (suburban)
Review Paper	**Buildings** 1. Structural system 2. Geometry 3. Material properties 4. State of maintenance 5. Levels of design codes 6. Foundation 7. Superstructure details 8. Number of floors 6. Impact location on the structure 7. Importance of the impacted members to the stability of the building 9. Age 10. Geographic location of the exposed elements within the landslide body (crest, transport zone, toe, runout zone, etc.)	1. Landslide volume 2. Volume/ kinetic energy 3. Block volume 4. Debris volume 5. Velocity	All type of landslides	(Corominas et al. 2014)	

	11. Impact location on the structure 12. Impacted members to the stability of the building **Roads** 1. Partial or complete blockage of the road 2. Structural damage 3. Level of serviceability 4. Type of road (e.g. highway, main road, or unpaved road) 5. Width 6. Traffic volume				
Qualitative	1. Structural condition of the building 2. Type 3. Nature of building 4. Age	1. Runout distance 2. Volume 3. Velocity of landslide	All type of landslides	(Erener and Sebnem Düzgün 2012)	Kumluca, Turkey (rural)

Table 13.0 List of building and road physical characteristics, surrounding element of critical infrastructure and the intensity of hazards.

Type of landslide	Critical Infrastructure	Physical of building	Mitigation measures	Hazard Intensity Indication
Debris flow	Building	1. Material of building 2. Height 3. Number of floors 4. Size of building 5. Use of building 6. Age of building 7. Maintenance state 8. measures 9. Roof type 10. Roof condition 11. Roof slope 12. Location of opening 13. Height of opening 14. Material of opening 15. Type of foundation 16. Present of basement 17. Present of basement opening 18. Existence of protruding parts 19. Building orientation 20. Use of first floor 21. Floor material 22. Location of the electricity central appliance 23. Maintenance and condition of electricity network	1. Building row towards river 2. Building row towards slope 3. Frontal impact 4. Dominant in the proximal portion of debris flows 5. Accumulation and abrasion 6. Dominant in the distal portion of debris flows 7. The boundary decreasing effect 8. The back shielding effect 6. Presence of warning systems 7. Presence of protection structures 9. 9. Surrounding vegetation 10. Existence of mitigation 11. Surrounding wall 12. Distance between building 13. Row of building from the river 14. Existence of adjacent auxiliary building 15. Existence of local mitigation measures	1. Kinetic factors - velocity of landslide 2. Kinematic factors - displacement of landslide 3. Impact pressure 4. Flow depth 5. Flow velocity – kinetic-potential energy transformation formula 6. Kinematic viscosity 7. Accumulation heights 8. Geometric intensity - size-linked features of elements or landslides

		24. Location of heating central appliance 25. Maintenance and condition of heating system 26. Maintenance and condition of sewage system 27. Condition/location of water supply network 28. Impact pressure 29. Building categories 30. Foundation depth		
Shallow landslide	Building	1. Structure material 2. Building condition 3. Number of floor	1. Row towards torrent 2. Row towards slope 3. Trees toward torrent 4. Trees toward slopes	
Earthquake induced landslide	Building	1. Type of structure 2. Age 3. Type of maintenance 4. Specifically for double storey concrete reinforced building 5. Distance to the crest		1. Kinetic factors (velocity of landslide) 2. Kinematic factors (displacement of landslide) 3. Peak ground acceleration (PGA) of horizontal and vertical components 4. Intensity of horizontal and vertical components
All type of landslides	Building	1. Structural condition of the building 2. Type or categories of building 3. Nature of building 4. Age 5. Geometry 6. Material properties	1. Impact location on the structure 2. Importance of the impacted members to the stability of the building 3. Geographic location of the exposed elements within the landslide body (crest,	1. Runout distance 2. Block/debris volume 3. Velocity of landslide 4. Kinetic energy 5. Height of the deposits 5. Landslide thickness 6. Landslide area

		7. Construction techniques 8. State of maintenance 9. Levels of design codes 10. Foundation 11. Superstructure details 12. Number of floors 13. Structure's technological features	transport zone, toe, runout zone, etc.) 4. Presence of protection structures 5. Presence of warning systems	7. Kinetic characteristics (kinetic energy) 8. Kinematic intensity (size-linked features of a reference landslide)
	Road	1. Partial or complete blockage of the road 2. Structural damage 3. Level of serviceability 4. Type of road (e.g. highway, main road, or unpaved road) 5. Width 6. Traffic volume		

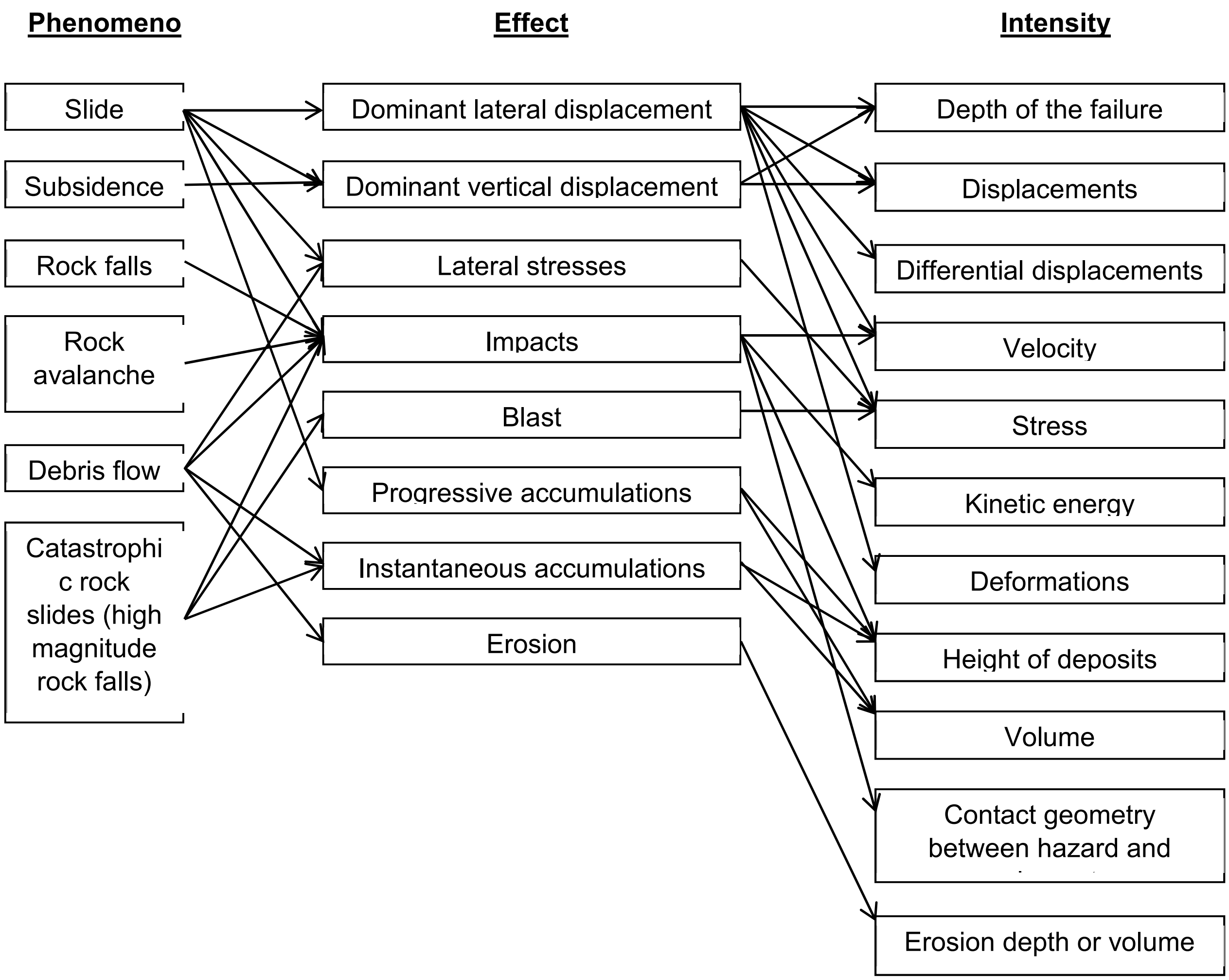


Figure 2. 17 Proposed intensity criteria (Safeland 2012).

Table 14.0 Landslide damage types, related to different landslide types, elements at risk and the location of the exposed element in relation to the landslide (van Westen et al. 2006).

Type	Likely damage to elements at risk	Factors determining risk
Impact by large rockmass	**Buildings:** Total collapse likely **Persons in buildings:** Loss of life/major injury likely **Infrastructure:** Coverage and obstruction/destruction of surface **Persons in traffic:** Loss of life/major injury possible	• Volume of rockfall mass • Location of source zone • Distance to elements at risk • Triggering factors • Local topography along track • Intermediate obstacles • Precursory events
Impact by single blocks	**Buildings:** Total collapse not likely. Localized damage **Persons in buildings:** Minor to major injury likely **Infrastructure:** Coverage and obstruction of traffic **Persons in traffic:** Loss of life/major injury possible	• Volume of rockfall blocks • Number of rockfall blocks • Location of source zone • Distance to elements at risk • Triggering factors • Local topography along track • Intermediate obstacles
Impact by landslide mass	**Buildings:** Collapse/major damage depending on volume **Persons in buildings:** None, persons are normally able to escape **Infrastructure:** Coverage and obstruction of traffic **Persons in traffic:** None, persons are normally able to escape	• Volume of landslide mass • Water content • Landslide material type • Triggering factors • Distance to elements at risk • Local topography along track • Speed of landslide movement
Loss of support due to undercutting	**Buildings:** Collapse/major damage likely **Persons in buildings:** None, persons are normally able to escape **Infrastructure:** Complete destruction of road surface	• Volume of landslide mass • Water content • Landslide material type • Triggering factors

	Persons in traffic: None, persons are normally able to escape	• Retrogressive landslide • Cliff erosion • Speed of landslide movement
Differential settlement/tilting due to slow movement	**Buildings:** Tilted buildings with cracks. Normally no collapse **Persons in buildings:** None, slow movement. People not in danger **Infrastructure:** Tilting and cracks, traffic slowed down **Persons in traffic:** None, slow movement	• Volume of landslide mass • Water content • Landslide material type • Triggering factors • Speed of landslide movement • Amount of displacement
Impact by debris flow on slope	**Buildings:** Filled by mud, damage to contents **Persons in buildings:** Minor-major injuries. Depends on speed **Infrastructure:** Coverage of road surface. Obstruction of traffic. **Persons in traffic:** Minor-major injuries. Depends on speed.	• Volume of landslide mass • Water content • Slope steepness • Local topography • Landslide material type • Triggering factors • Speed of movement • Size of blocks transported
Flooding by debris flow on alluvial fan	**Buildings:** Filled by mud, damage to contents **Persons in buildings:** None, persons are normally able to escape **Infrastructure:** Coverage **Persons in traffic:** None, persons are normally able to escape	• Volume of debris flow • Water and sediment content • Local topography of fan • Triggering factors • Distance from source • Distance from lahar channel • Speed
Impact by Sturzstrom	**Buildings:** Total collapse **Persons in buildings:** Loss of life **Infrastructure:** Total destruction **Persons in traffic:** Loss of life	• Volume of rockfall mass • Location of source zone • Distance to Elements at risk • Triggering factors • Local topography along track

		• Distance from source zone • Precursory events
Liquefaction	**Buildings:** Differential settlement, cracks **Persons in buildings:** Minor injuries or no-injuries **Infrastructure:** Differential settlement, cracks **Persons in traffic:** No-injuries	• Soil types • Soil strength • Grainsize distribution • Foundation types • Earthquake intensity • Water table
Deep seated creep movement	**Buildings:** Differential settlement, tilting, cracks **Persons in buildings:** Minor injuries or no-injuries **Infrastructure:** Differential settlement, cracks, broken pipes **Persons in traffic:** No-injuries	• Speed of movement • Local geological situation • Age of landslide • Seasonality of movement

2.3 Landslide Risk Assessments

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 phenomena 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 and Fell, 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 and Fell, 1997, Technical Committee on Risk Assessment and Management, 2004, UN-ISDR, 2004, Fell et al., 2008). Depending on the completeness of data, a semi-quantitative approach can be devise 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 (Figure 2.18) (Winter et al., 2016). The loss assessments required different level of information depending on the level of information obtained for element-at-risk (Figure 2.19).

	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 weaken-ing the insurance market • Less investments • Capital costs of repair • Reduction in tourism	• Loss of biodiversity • Loss of cultural diversity

Figure 2. 18 Classification of landslide risk assessments (Winter et al., 2016).

Physical elements Buildings: Urban land use, construction types, building height, building age, total floor space, replacement costs. Monuments 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** Organization of population, governance, community organization, government support, socio-economic levels. Cultural heritage and traditions.
Transportation 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.

Figure 2. 19 Level of information required for different type of element-at-risk (Winter et al., 2016).

As a form of realization from landslide risk definitions, previous studies have shown that quantitative risk (*R*) can be defined conceptually based on Equation 15 (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).

$$R = H \times E \times V \tag{15}$$

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 16 (Roberds, 2005).

$$E[loss] = \sum_{all\ S} \sum_{all\ C} C \times P[C|S]P[S] \tag{16}$$

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* | *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:

a. Define scenarios for landslide triggering
b. Compute the run-out distance, volume and extent of landslide for each scenario
c. Identify the elements at risk and their vulnerabilities
d. Estimate the loss for the different landslide scenarios
e. 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 2.20) (Dai et al., 2002).

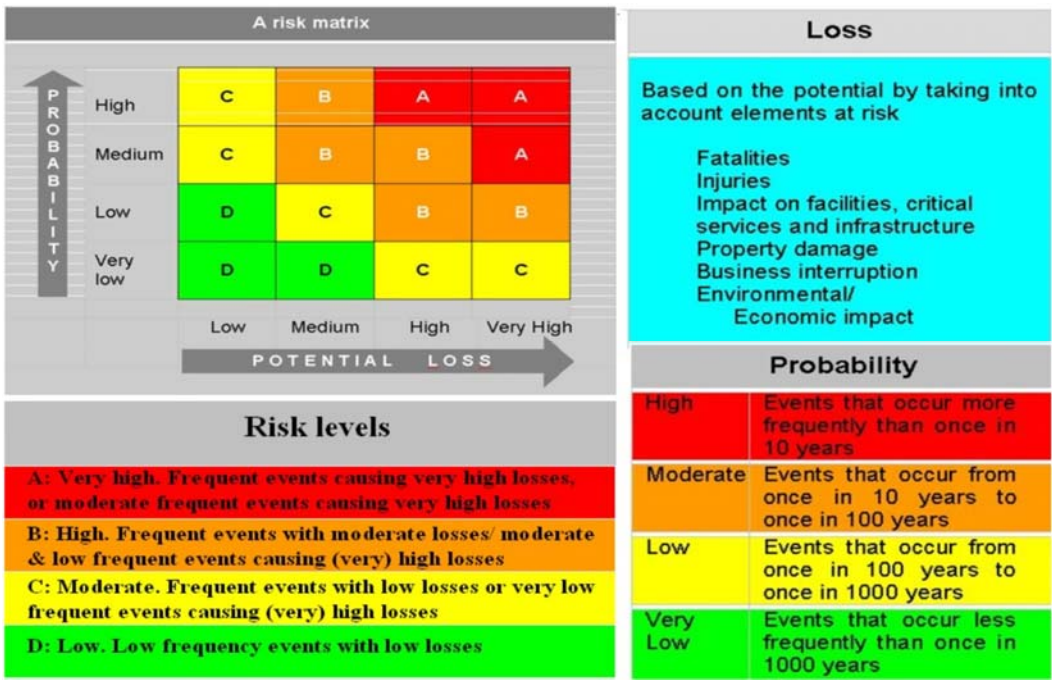


Figure 2. 20 Risk matrix for qualitative landslide risk assessment (Dai et al., 2002).

Table 15.0 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 16.0. 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 15.0 Examples of matrix selection for Landslide mitigation categories (Based on Rodeano, 2015; 2018).

Degree of Hazard	Degree of Vulnerability →	Very Low	Low	Moderate	High	Very High	Categories
	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 16.0 Examples of Landslide mitigation method (Based on Rodeano, 2015; 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 2.21 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 (Carribean Handbook on Risk Information Management, n.d.). Each input data corresponds to the identical component of Equation (15) 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 2.21 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.

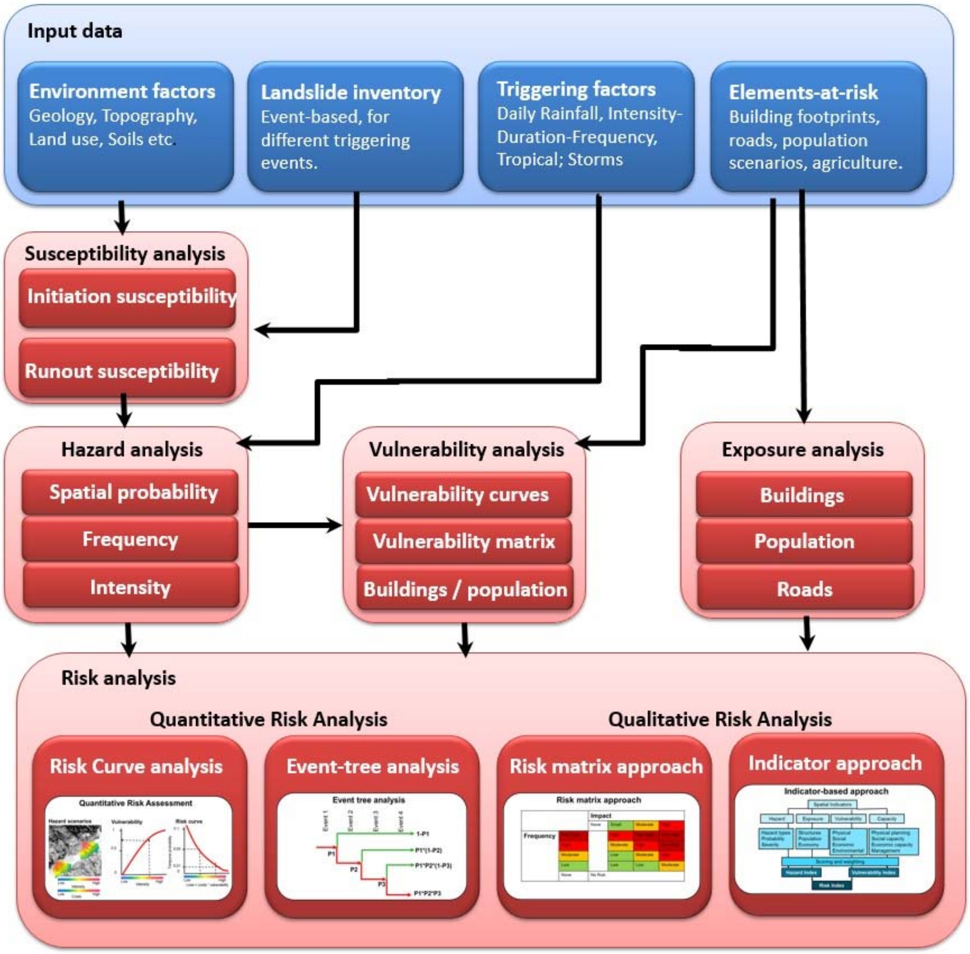


Figure 2. 21 Schematic representation of landslide risk assessment methodology (Van Westen et al., 2006, Carribean Handbook on Risk Information Management, n.d.)

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 17.0 specifies this suitability, ideal for scales of 1: 10,000 to 1: 50,000. The numbers in Table 17.0 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 17.0 Suitability of Risk Approach Compared Against Hazard Approach

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 2.22 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.

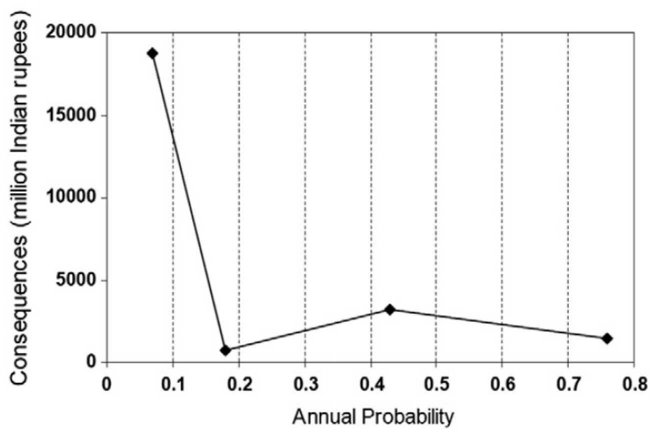


Figure 2. 22 Risk Curve for the Combined Critical Infrastructure of Buildings and Roads

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 2.23, 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.

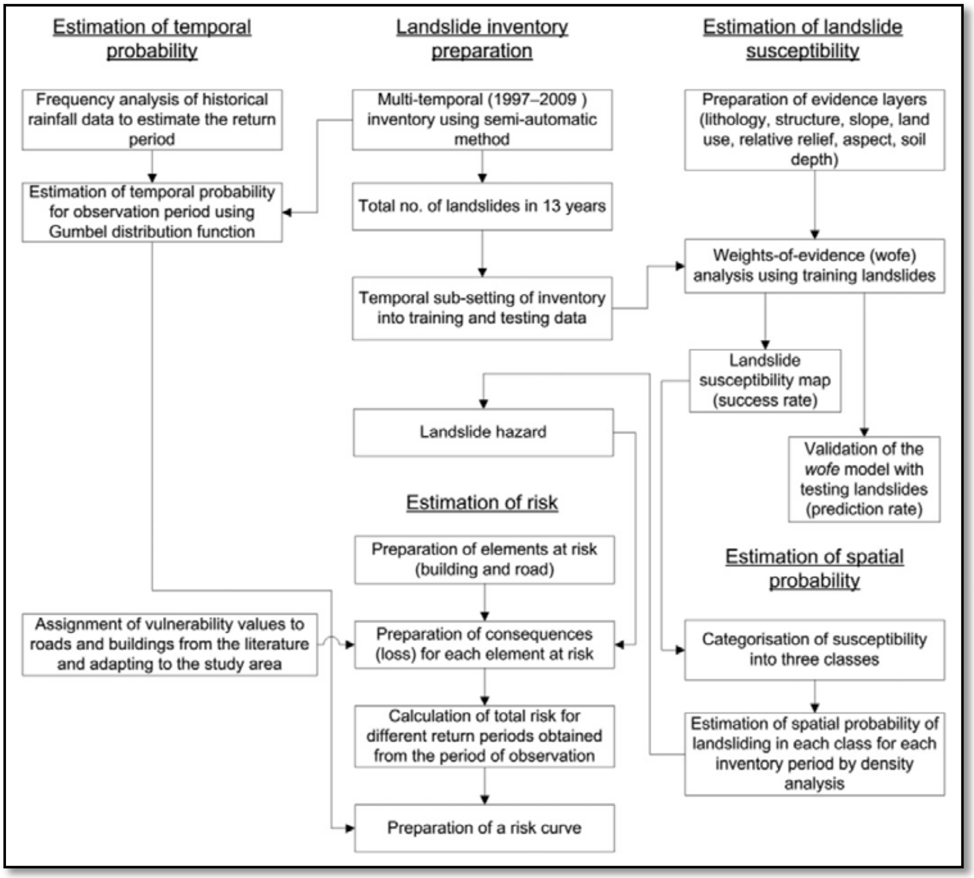


Figure 2. 23 The Overall Procedure of Landslide Hazard and Risk (Martha et al., 2013)

In their paper, Guillard-Gonçalves et al. (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 2.24 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.

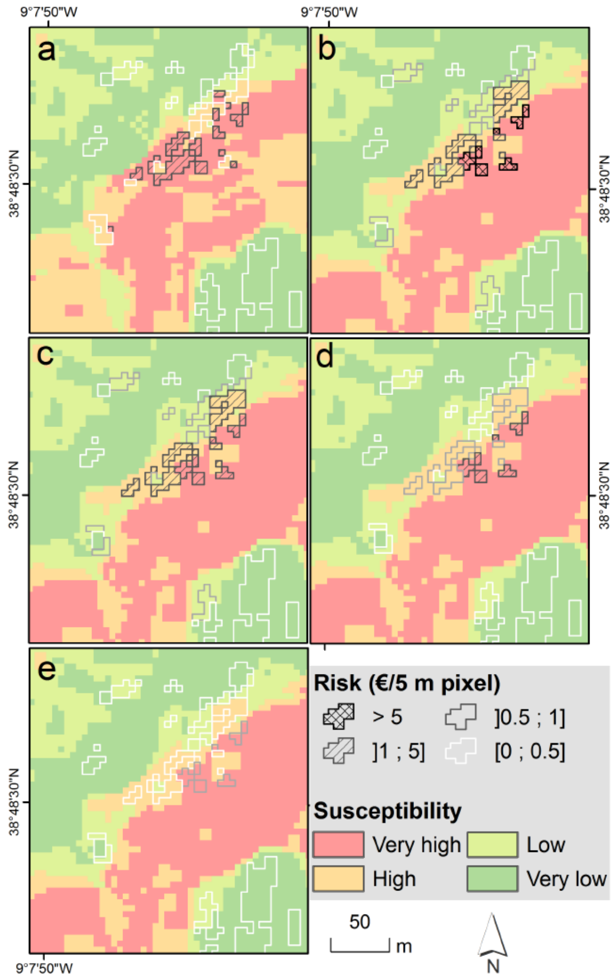


Figure 2. 24 Landslide Risk Map for Buildings at Landslide Body

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 18.0 for highlighting relative risk level for land categories in regards to damage potential (vulnerability) and hazard probability. From Table 18.0, 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 18.0 Risk Assessment Matrix for Land Categories

Damage potential (DP)	**Hazard Probability**				
	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 18.0, a risk assessment map of Sukhidang area is generated where specific categories of landslide risk as stated in Table 18.0 are used. This map is shown as Figure 2.25. This map combines both environmental aspect which is land categories and socio-economic aspect which is human dwellings.

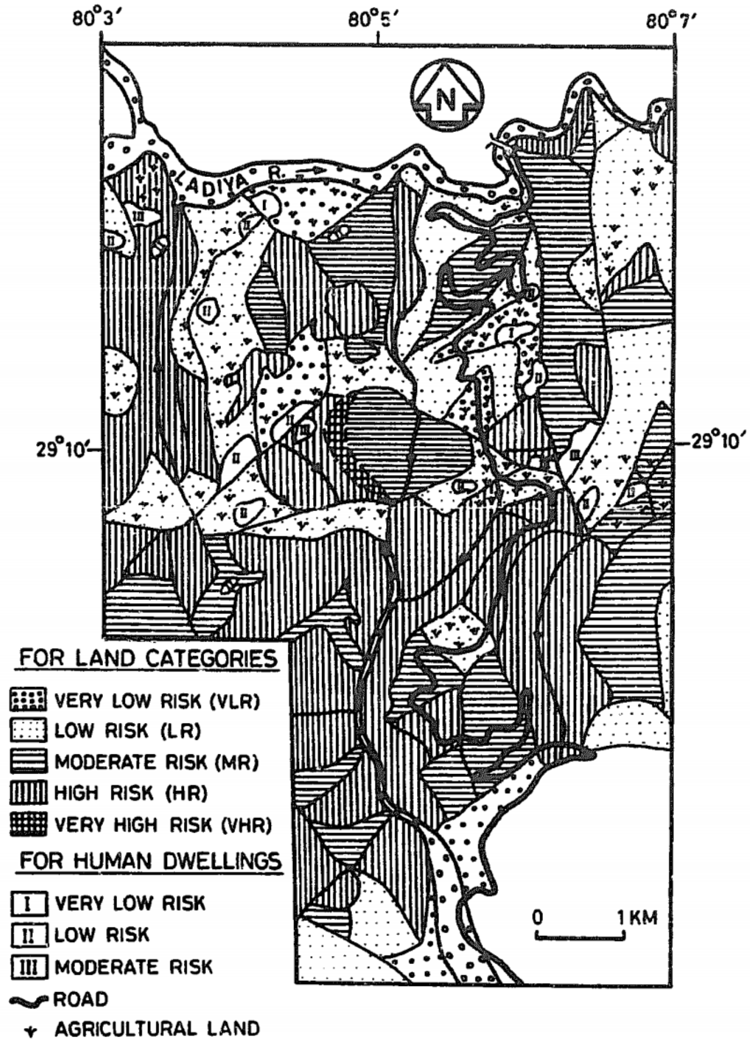


Figure 2. 25 Risk Assessment Map of Sukhidang Area

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-maker's personnel. Figure 2.26 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).

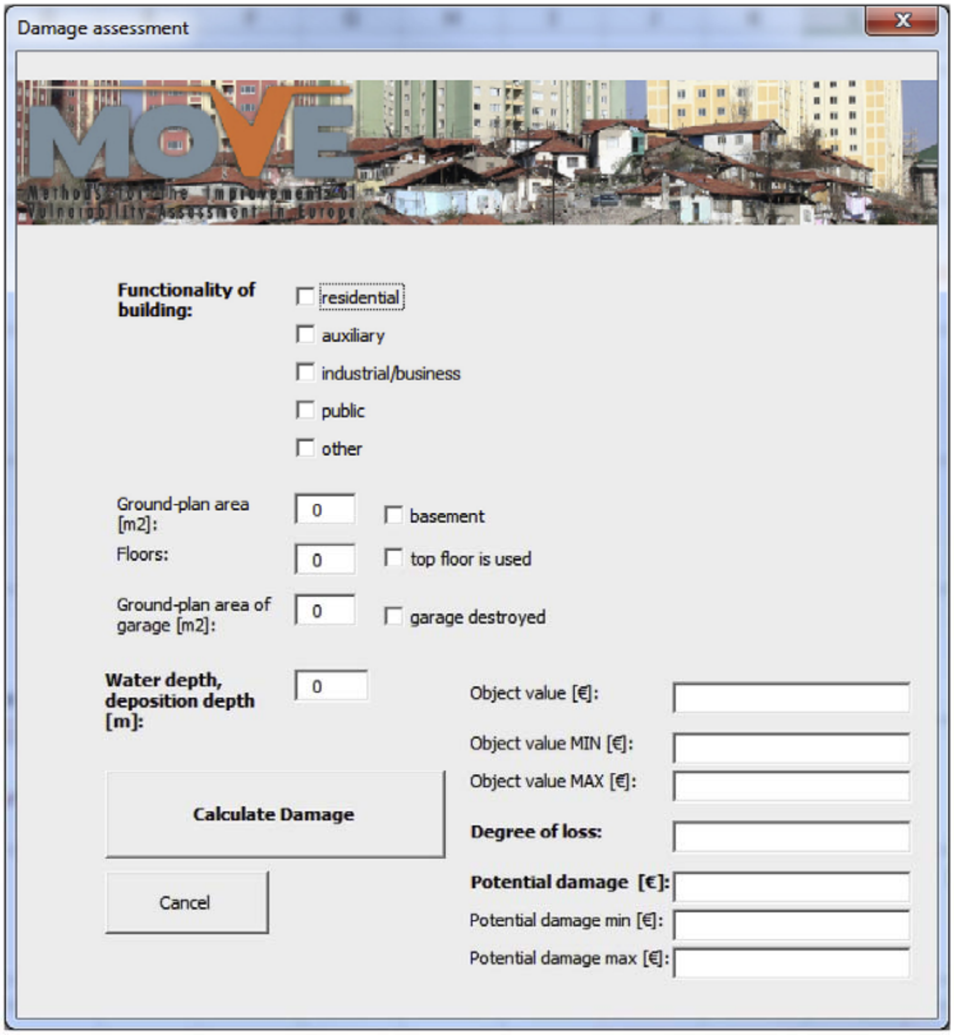


Figure 2. 26 Graphical User Interface (GUI) for the Loss Estimation Tool

2.4 Landslide Social Vulnerability Indicators

The previous methods are focusing on the physical vulnerability assessment of the critical infrastructure. However, for other types of vulnerability assessment e.g. social welfare, economics and ecology aspect require different methods and indicators. For example, vulnerability to natural hazards from the perspective of social science has been defined by several researchers e.g. Blaikie et al., (1994) provided the following definition: "… the characteristics of a person or group in terms of their capacity to anticipate, cope with, resist and recover from the impacts of natural or man-made hazards". The importance of indicators for social vulnerability was also stressed as one of the key activities proposed in the Hyogo Framework. The framework suggested that the development of "systems of indicators of disaster risk and vulnerability at national and sub-national scales that will enable decision makers to assess the impact of disasters on social, economic and environmental conditions and disseminate the results to decision-makers, the public and populations at risk".

Cutter et al., (2003) highlighted factors that influenced social vulnerability which includes lack of access to resources (including information, knowledge, and technology), limited access to political power and representation, social capital, belief and customs, building stock and age, frail and physically limited individuals, type and density of infrastructure and lifelines. Table 19.0 shows complete indicators that influence the social vulnerability that usually used in previous researches.

Table 19.0 Social vulnerability concepts and metrics

Concept	Description	Increases (+) or Decreases (-) Social Vulnerability	Cause
Socioeconomic status (income, political power, prestige)	The ability to absorb losses and enhance resilience to hazard impacts. Wealth enables communities to absorb and recover from losses more quickly due to insurance, social safety nets, and entitlement programs. ***Source***: Cutter, Mitchell, and Scott (2000), Burton, Kates, and White (1993), Blaikie et al. (1994), Peacock, Morrow, and Gladwin (1997), Hewitt (1997), Puente (1999), and Platt (1999), Eidsvig (2014), Yadav and Barve (2017), Park et al., (2016), Samodra et al., (2012), Nisha and Punia (2014), Ratemo and Bamutaze (2017), Guillard-Gonçalves and Zêzere (2016)	High status (+/-) Low income or status (+)	Landslide, flood, hurricane, cyclone and natural hazards
Gender	Women can have a more difficult time during recovery than men, often due to sector-specific employment, lower wages, and family care responsibilities. ***Source***: Blaikie et al. (1994), Enarson and Morrow (1998), Enarson and Scanion (1999), Morrow and Phillips (1999), Fothergill (1996), Peacock, Morrow, and Galdwin (1997), Hewitt (1997), and Cutter (1996), Tapsell et al. (2005), Aliabadi et al. (2015), Eidsvig (2014), Yadav and Barve (2017), Park et al., (2016), Samodra et al., (2012), Nisha and Punia (2014), Ratemo and Bamutaze (2017), Guillard-Gonçalves and Zêzere (2016)	Gender (+)	Landslide, Flood, earthquake, cyclone, natural hazards
Race and ethnicity	Imposes language and cultural barriers that affect access to post-disaster funding and residential locations in high hazard areas. ***Source***: Pulido (2000), Peacock, Morrow, and Gladwin (1997), Bolin	Nonwhite (+) Non-Anglo (+)	Landslide, natural hazards

	and Stanford (1998), and Bolin (1993), Eidsvig et al.(2014)		
Age	Extremes of the age spectrum affect the movement out of harm's way. Parents lose time and money caring for children when daycare facilities are affected; elderly may have mobility constraints or mobility concerns increasing the burden of care and lack of resilience. ***Source***: Cutter, Mitchell, and Scott (2000), O'Brien and Mileti (1992), Hewitt (1997), and Ngo (2001), Tapsell et al. (2005), Eidsvig et al. (2014), Aliabadi et al. (2015), Yadav and Barve (2017), Park et al. (2016)	Elderly (+) Children (+)	Flood, landslide, earthquake. Cyclone, natural hazards
Commercial and industrial development	The value, quality and density of commercial and industrial buildings provides an indicator of the state of economic health of a community, and potential losses in the business community, and longer-term issues with recovery after an event. ***Source***: Heinz Center for Science, Economics, and the Environment (2000) and Webb, Tierney and Dahlhamer (2000), Aliabadi et al. (2015), Park et al. (2016)	High density (+) High value (+/-)	Earthquake, Landslide, natural hazards
Employment loss	The potential loss of employment following a disaster exacerbates the number of unemployed workers in a community, contributing to a slower recovery from the disaster. ***Source***: Mileti (1999).	Employment loss (+)	Natural hazards
Rural/urban	Rural residents may be more vulnerable due to lower incomes and more dependent on locally based resource extraction economies (e.g.,farming, fishing). High-density areas (urban) complicate evacuation out of harm's way. ***Source***: Cutter, Mitchell, and Scott (2000), Cova and Church (1997), and Mitchell (1999), Tapsell et al. (2005), Yadav and Barve (2017), Eidsvig et al. (2014)	Rural (+) Urban (+)	Flood, cyclone, landslide, natural hazards

Residential property	The value, quality, and density of residential construction affects potential losses and recovery. Expensive homes on the coast are costly to replace; mobile homes are easily destroyed and less resilient to hazards. ***Source***: Heinz Center for Science , Economics, and the Environment (2000), Cutter, Mitchell, and Scott (2000), and Bolin and Stanford (1991), Tapsell et al. (2005), Steinführer et al. (2009)	Mobile homes (+)	Flood, natural hazards
Infrastructure and lifelines	Loss of sewers, bridges, water, communications and transportation infrastructure may place an insurmountable financial burden on smaller communities that lack the financial resources to rebuild. ***Source***: Heinz Center for Science , Economics, and the Environment (2000) and Platt (1991), Park et al. (2016), Nisha and Punia (2014)	Extensive infrastructure (+)	Landslide, natural hazards
Renters	People that rent do so because they are either transient or do not have the financial resources for home ownership. They often lack access to information about financial aid during recovery. In the most extreme cases, renters lack sufficient shelter options when lodging becomes uninhabitable or too costly to afford. ***Source***: Heinz Center for Science, Economics, and the Environment (2000) and Morrow (1999), Guillard-Gonçalves and Zêzere (2018)	Renters (+)	Landslide, natural hazards
Occupation	Some occupations, especially those involving resource extraction, may be severely impacted by a hazard event. Self-employed fisherman suffers when their means of production is lost and may not have the requisite capital to resume work in a timely fashion and thus will seek alternative employment. Those migrant workers engaged in agriculture and low-skilled service jobs (housekeeping, childcare and	Professional or managerial (-) Clerical or labourer (+) Service sector (+)	Flood, natural hazards

	gardening) may similarly suffer, as disposable income fades and the need for service declines. Immigration status also affects occupational recovery. ***Source***: Heinz Center for Science, Economics, and the Environment (2000), Hewitt (1997), and Puente (1999), Tapsell et al. (2005)		
Family structure	Families with large numbers of dependents or single-parent households often have limited finances to outsource care for dependents, and thus must juggle work responsibilities and care for family members. All affect the resilience to and recovery from hazards. ***Source***: Blaikie et al. (1994), Morrow (1999), Heinz Center for Science, Economics, and the Environment (2000), and Puente (1999) Tapsell et al. (2005),	High birth rate (+) Large families (+) Single-parent households (+)	Flood, natural hazard
Education	Education is linked to socioeconomic status, withhigher educational attainment resulting in greater lifetime earnings. Lower education constraints the ability to understand warning information and access to recovery information. ***Source***: Heinz Center for Science, Economics, and the Environment (2000), Tapsell et al. (2005), Park et al. (2016), Ratemo and Bamutaze (2017), Park et al. (2016)	Little education (+) Highly educated (-)	Flood, landslide, natural hazards
Population growth	Countries experiencing rapid growth lack available quality housing, and the social services network may not have had time to adjust to increased populations. New migrants may not speak the language and may not be familiar with bureaucracies for obtaining relief or recovery information, all of which increase vulnerability. ***Source***: Heinz Center for Science, Economics, and the Environment	Rapid growth (+)	Landslide, cyclone, natural hazards

	(2000), Cutter, Mitchell, and Scott (2000), Morrow (1999), and Puente (1999), Eidsvig et al. (2014), Yadav and Barve (2017), Park et al. (2016), Ratemo and Bamutaze (2017), Guillard-Gonçalves and Zêzere (2018)		
Medical services	Health care providers, including physicians, nursing homes, and hospitals are important post-event sources or relief. The lack of proximate medical services will lengthen immediate relied and longer-term recovery from disasters. ***Source***: Heinz Center for Science, Economics, and the Environment (2000), Morrow (1999), and Hewitt (1997), Park et al. (2016), Nisha and Punia (2014)	Higher density of medical (-)	Landslide, flood, Natural hazards
Social dependence	Those people who are totally dependent on social services for survival are already economically and socially marginalized and require additional support in the post-disaster period. ***Source***: Morrow (1999), Heinz Center for Science, Economics, and the Environment (2000), Drabek (1996), and Hewitt (2000).	High dependence (+) Low dependence (-)	Natural hazards
Special needs populations	Special needs populations (infirm, institutionalized, transient, homeless), while difficult to identify and measure, are disproportionately affected during disasters and, because of their invisibility in communities, mostly ignored during recovery. ***Source***: Morrow (1999), and Tobin and Ollengurger (1992).	Large special needs population (+)	Natural hazards

Source: Modified from Cutter, Boruff, and Shirley (2001); Heinz Center for Science, Economics, and the Environment (2002).

For social vulnerability specifically related to landslide hazard, most of the studies used indicators as developed by Safeland (2012). Some studies grouped the indicators according to the three main subindexes (Table 20.0); Demographic and Social Index (DSI), Secondary-Damage-Triggering Index (STI), and Preparation and Response Index (PRI) (Park, et al., 2016). DSI is evaluated by six population-related and social variables that may be affected by natural disasters. For example, 'age distribution' is classified into vulnerable people group. The children or elderly people are more vulnerable than young people. 'Population density' influences vulnerability. If landslide event happens in high population density area, it will cause heavy casualties. STI is an index to evaluate the indirect damage caused by natural disasters. For example, when roads are malfunctioning, damage such as traffic jam and destruction of many life lines is caused. Public office causes secondary damage due to absence of control systems in emergency such as landslide event. PRI assesses the ability to prevent and respond to natural disasters. Their findings suggested that the higher population density areas under a weaker fiscal condition that are located at the downstream of mountainous areas are more vulnerable than the areas in the opposite conditions.

Table 20.0 List of indicators used to study social vulnerability of landslide in urban area in Korea (Park et al. 2016)

Social-economic vulnerability index
DSI (demographic and social index) - Age distribution - Number of workers who may be exposed to disasters - Population density - Foreigner ratio - Education level - Housing type
STI (secondary-damage-triggering index) - Number of public offices - Road area ratio - Number of electronic supply facilities - School area ratio - Commercial and industrial area ratio
PRI (preparation and response index) - Disasters frequency - Internet penetration rate - Number of disaster prevention facilities - Perceived safety - Number of medical doctors - Financial independence of the borough

For landslide in rural areas, Samodra et al. (2012) has conducted a detail study to investigate the spatial pattern of socio-economic landslide vulnerability in Kayangan Catchment, Indonesia. The indicators used their study were separated into three main groups; exposure, coping capacity and resilience. The exposure indicators are mostly relating to physical vulnerability whilst coping capacity and resilience are more to socio-economic indicators. The list of these two groups of indicators can be summarized in Table 21.0. The findings concluded that the spatial distribution of socio economic vulnerability level coincided with the economic, social and ecological dimensions of livelihood in Kayangan Cactchment.

Table 21.0 Two groups of indicators used for social vulnerability for landslide in Kayangan Catchment, Indonesia (Samodra et al., 2012)

Coping Capacity Indicators	Resilience Indicators
1. Age 2. Gender 3. Preparedness 4. Knowledge of landslide:	1. Income 2. Saving 3. Building material

For landslide hazard in the Sagarejo Municipality, Georgia (Sagarejo Municipality, 2010), the following indicators in Table 22.0 were used for the social-economic vulnerability assessment. Another study was also done for the social vulnerability at the municipal level for landslide in Loures, Portugal (Guillard-Gonçalves and Zêzere, 2018). The social vulnerability was defined as the average of the sensitivity of the population and its lack of resilience. The identification of all the indicators were also taking into the consideration of the availability of the data and the context of the place (Table 23.0). The findings suggested that social vulnerability is important and should be also combined with physical vulnerability to assess the landslide risk.

For mountainous and basin catchment area, Nisha and Punia (2014) have studied flood and landslides affected the socio-economic vulnerability of the communities in Bhagirathi Basin, Uttarakhand, India. This study used a combination of three main indicators; social development index, economic development index and infrastructure development index, which consist of total 19 indicators. The list of all the indicators are listed in Table 24.0. The results concluded that socio economic vulnerability depends upon a balance between the developmental aspiration of people and a concern for conservation of resources in the mountain region simultaneously.

Another study for landslide hazard at mountainous area was conducted by Ratemo and Bamutaze (2017) to quantity household vulnerability in Mt. Elgon, Uganda. In their study, the social vulnerability to landslide was determined by considering the existing socio-economic characteristics of the study area. The indicators used in this study was grouped into five main categories; demography, social, economic indicators, recovery indicators and administrative indicators. Detail of these indicators are listed in Table 25.0. The results shown that that agricultural land, houses and human population are most vulnerable elements at risk compared to livestock and other social infrastructures. The study further revealed that 95% of community in one of the districts are vulnerable to landslide hazards. The main reason was the majority of the societal and physical indicators were neither not available at all as this area was characteristically rural area with high number of less educated people (97%), no early warning systems, no emergency response procedures, no coverage of insurance, no regulatory enforcement, no hazard evaluation and poor housing materials due to low income in the area.

In Malaysia, recent study has been carried out by Indan et al. (2018) to quantify the social vulnerability from earthquake hazards in mountainous area in Ranau, Sabah. The aim of their study was to investigate the social vulnerability and environmental vulnerability at this area. For social vulnerability, the indicators used are injury, fatalities, safety, loss of accommodation and public awareness while for the environmental vulnerability; affected period, daily operation and diversity were used in their study. Both social and environmental vulnerabilities were tested to five different villages in Ranau. The results suggested that the social vulnerability in this area has a moderate level of social vulnerability but high for environmental vulnerability.

Table 22.0 List of indicators used for social vulnerability study in Sagarejo Municipality, Georgia

No.	Indicators
1	percentage of women in the community
2	Percentage of people under 16 and above in the community
3	Percentage of people engaged in the budgetary sector
4	Percentage of socially vulnerable families
5.	Distance from the municipal center
6.	Average density of the population in the community
7.	Area of agricultural lands per capita

Table 23.0 List of indicators used for social vulnerability study of landslide risk in Loures, Portugal (Guillard-Gonçalves and Zêzere, 2018).

No.	Indicators
1	Population density: number of residents per square kilometre
2	Young population: Population younger than 13 years old
3	Old population: Population older than 64 years old
4	Female population: Number of female residents
5.	Illiterate population: Number of residents who do not read neither write
6.	Without activity: Number of residents living without economic activity
7.	Unemployed population: Number of unemployed residents looking for a first job or for a new job
8.	Number of dwellings without water, toilet, sewer or bathroom
9.	Rented dwellings: Number of classical family accommodation of usual residence which are rented
10.	Reclassified location coefficient: used to characterise the property market and the accessibility of the buildings by the Portuguese Tax Services

Table 24.0 List of socio-economic vulnerability indicators to study the impact of flood and landslides in Bhagirathi, India (Nisha and Punia, 2014)

Social development index	Economic development index	Infrastructure Development Index
• Literacy rate • Female literacy rate • Child sex ratio	• Total work participation rate • Percentage of female worker to total worker • Percentage of main worker to total worker • Percentage of female main worker to total worker • Percentage of net sown are to total area	• Number of primary and middle school per 500 population • Number of secondary, senior secondary school: College and other per 1000 population • Number of medical (allopath, ayurvedic) institution per 1000 population • Number of dispensary per'000 population • Number of primary Health Sub-Centre per 3000 population • Number of Primary Health Center per 20000 population • Number of post and telecom facility per 1000 population • Number of bank facility per'000 population • Drinking water facility, communication facility • Power facility

Table 25.0 List of indicators for household vulnerability study from landslide hazards in Mt. Elgon, Uganda (Ratemo and Bamutaze, 2017)

Indicators	Variables
Demography	• Age: ≤12 years ≥60 are vulnerable • Urban: Urbanized area is likely to be greatly impacted
Social	• Education level: Higher education level better prepared and quickly recover • Level of integration: Highly integrated society is less vulnerable
Economic	• Rural population: Depend on natural resources, highly impacted • GDP per capita: High GDP quick recovery and resilient
Recovery	• Building type: permanent structures resistant to landslide • Quality of medical services: Better medical services quick recovery • Insurance and disaster funds: Availability of insurance and disaster fund quick recovery and resilient
Administrative	• Regulation control: implementation of legislation minimizes community exposure to landslide • Early warning system: Early warning system minimizes community exposure to landslide • Hazard evaluation: Designated hazard zones help people keep away from prone areas • Emergency response: Quick response saves lives and property

2.5 Best Practices of Vulnerability and Risk Assessment

Hong Kong has a land area of 1,100 km^2, about 60% of which is hilly natural hillsides (with 75% of the land steeper than 15^o and 30% steeper than 30^o). Rapid population growth and economic expansion from the 1950s to 1970s have led to intensive urbanization of the foothill areas, giving rise to a large number of substandard man-made slopes formed without geotechnical control and exposing people to landslide risk from natural hillsides. The substandard slopes and steep natural terrain, combined with deep weathering profile and high seasonal rainfall, are highly susceptible to rain-induced landslides. Following its establishment in 1977 as a central body to regulate slope safety and geotechnical engineering in Hong Kong, the Geotechnical Engineering Office (GEO) in 1991, has progressively developed an integrated slope safety system that serves to manage landslide risk in a holistic manner through an explicit risk-based approach and strategy (F.W.Y. Ko, 2015).

Previously, the Geotechnical Control Office (GCO) of Hong Kong has made a detailed study on about slope failures that occurred in the late 1980s. As a result, the Hong Kong has taken action to identify the areas that require improvement in slope design and construction using the georisk management system. It is the best approach to be used for slope investigation and supplement the conventional approach of slope stability assessment process. It was found that the system was efficient by integrated with GIS and database as the basis for georisk assessment and management. From the georisk database, the results can be used to propose a real time warning system to prevent slope failure.

Lacasse & Nadim (2006), applied georisk deterministic approach by factor of safety (FOS) is based on the numerical analysis and widely employed in civil engineering and engineering geology for slope stability analysis and slope failure mapping. The determination of FOS depends on the type of failure such as circular or non-circular failures and slope material such as soil or rock mass to be analyzed. Correct FOS results depend on the reliability of the data on the appropriateness of the model. The summary of slopes stability analysis for soil and rock were shown in Table 26.0 and Table 27.0.

Table 26.0 Method of stability of soil slope

Method	Failure Surface	Assumptions	Advantages	Limitations
Infinite slope	Straight line	Any vertical slice is representative of the whole slope.	Simple hand calculation.	Failure surface assumption always an approximation. Method may only be used for slip surface where the length to depth ratio is large and end effects can be neglected.
Sliding block	More Then Straight Line	The sliding mass can be divided into 2 or more blocks, the equilibrium of each block is considered independently using interblock forces.	Suitable for hand calculation when 2 or 3 blocks are used.	Does not consider the deformation of blocks. Result sensitive to the angle to the horizontal chosen for the interblock forces and the inclination of the surface between the blocks.
Bishop	Circular	Consider force and moment equilibrium for each slice. Rigorous method assumes values for the vertical forces on the slides of each slice until all equations are satisfied. Simplified method assumes	Simplified method compares well with finite element deformation methods (average F within 8%), Computer programs	Circular failure not always suitable for Hong Kong slope but large radius circle can sometimes be used.

		the resultant of the vertical force is zero on each slice.	readily available.	
Bishop & Mongenstrens Charts	Circular	Uses Bishop's Simplified method with an average ru value.	Simple to use. More accurate than Hoek's Chart	
Hoek's Charts	Circular	Sliding mass considered as a whole. Lower bound solution, assuming normal stresses are concentrated at one point.	Slope angle from 10˚ to 90˚ given. Very simple to use.	Limited to homogenous soils and 5 specified groundwater conditions.
Janbu	Non-circular	Generalized procedure considers force and moment equilibrium on each slice. Assumptions on line of action of inter slice forces must be made. Vertical inter slice forces no included in Routine procedure and calculated F then corrected to allow for vertical forces.	Realistic shear surfaces can be used. Routine analysis can be easily handled by a programmable calculator or by hand.	Published to factors are for homogenous materials and routine procedure can give large errors in slopes composed of more than 1 material. Factor of safety is usually underestimated in these cases. Generalized method does not have the same limitations.
Mogenstrens & Price	Non-circular	Considers force and moments on each slice similar to Janbu generalized procedure.	Considered more accurate than Janbu. Computer programs readily available.	No simplified method. Computer solution necessary, often very time consuming.
Sarma	Non-circular	A modification of Morgenstren & Price which reduces the iterations required by using earthquake forces.	Considered reduction in computing time without loss of accuracy.	Computer programs not yet readily available but can be used with a calculator.

(Source: GCO, 1991)

Table 27.0 Method of stability of rock slopes

Methods	Failure Surface	Assumptions	Advantages	Limitations
Plain failure	Simple plane with tension crack	Both sliding surface and tension crack strike parallel to the slope surface. Release surfaces are present so there is no resistance on lateral boundaries.	Water pressures in tension crack and on sliding plane can be included simple analysis method.	Moments of considered in analysis. Can give over estimate of factor of safety on steep slopes where toppling could occur.
Wedge failure	2 joint planes form 3-D wedge	Line of intersection of joints dips less steeply the rock face and daylight within the face. Both joint lanes remain in contact during sliding.	Tension crack and water pressure can be included in analysis. Charts, which consider friction only, are available.	Moments not considered.
Toppling failure	Stepped cross joints	Analysis assumes that some blocks will slide and some topple. Water pressure not included.		Limited to a few simple cases with suitable geometry.

(Source: GCO, 1991)

For FOS value less that 1.0 is considered as slope failure whereas FOS higher than 2.0, the slope was identified as extremely stable. If FOS is equal to 1.09, the slope strength was only 9% greater than the disturbing force and the slope may fail when heavy rain, slope steepness or slope undercutting occurred. The Geotechnical Control Office (GCO, 1991) has introduced the guideline called Geotechnical Manual for Slopes. GEO has classified the FOS with respect to life lost and economic loss. The recommended FOS value for a new slope is shown in Table 28.0.

Table 28.0 Recommended FOS for new slope

Economic Risk	Risk-to-Life		
	Negligible	**Low**	**High**
Negligible	>1.0	1.2	1.4
Low	1.2	1.2	1.4
High	1.4	1.4	1.4

Note:

1. The FOS above is based on Ten-Year Return Period Rainfall or Representative Groundwater Conditions.

2. A slope in the high risk-to-life category should have a FOS of 1.1 for the predicted worst groundwater conditions.
3. The FOS listed is recommended values. Higher or lower FOS must be warranted in particular situations in respect to both risk-to-life and economic risk.

(Source: GCO, 1991)

The FOS results also incorporate a ten-year return period rainfall. Besides, GCO have recommended the FOS value as 1.1 on slopes that have high risk to life and having worst water conditions. The FOS for existing slope, the analysis (i.e. studies on geology and subsoil conditions of the slope) of the slope requires determining the stability of the slope for remedial works. The FOS value for existing slope that is recommended by GCO is shown in Table 29.0.

Table 29.0 Recommended FOS for existing slope

FOS against Loss of Life for a Ten-Year Return Period Rainfall		
Negligible	Low	High
>1.0	1.1	1.2

Note:

1. These FOS are minimum values recommended only where rigorous geological and geotechnical studies have been carried out, where the slope has been standing for considerable time, and where the loading conditions, slope remain substantially the same as those of the existing slope.
2. Should the back-analysis approach be adopted for the design of remedial or preventive works, it may be assumed that the existing slope had a minimum FOS of 1.0 for the worst known loading and groundwater conditions.
3. For a failed or distressed slope, the causes of the failure or distress must be specifically identified and taken into account in the design of the remedial works.

(Source: GCO, 1991)

The comprehensive risk assessment of slopes in Hong Kong was elaborated by W.Y Kong,2002. The hazard and risk posed by the natural slopes can impact on safety and the technical and financial viability of both urban and newly developed areas. Under these circumstances, the local government Geotechnical Engineering Office (GEO) has been tasked since the 1970s with conducting a series of Geotechnical Area Studies Programmes (GASP). These provide geotechnical information for the planning and land use management of Hong Kong. GASP is based on terrain classification techniques using aerial photographs as well as field reconnaissance and interpretation of a large number of available ground investigation records. In the 1990s, GEO has put effort into the study of natural terrain landslides, including boulder fall hazards.

However, most landslides on natural terrain in Hong Kong are relatively small in size. These occasionally develop into channelized debris flows with long run out distances. These failures tend to be shallow, occurring during intense rainfall within the upper two meters of the colluvium or residual soil developed on bedrock. Failure mechanisms probably initiate due to intense rainfall leading to elevated pore pressure and/or loss of soil suction. They can develop into large, rapid, mobile failures which pose a significant potential hazard, destroy buildings or structures and cause significant casualties and damage. The conventional factor of safety approach in a slope stability analysis for natural terrain is often not appropriate when dealing with such a region where parameters cannot be uniquely defined. Here the estimation of the annual probability is developed based on a fatality occurring as a result of natural terrain failure.

The risk analysis of the probability of fatality occurrence (or probability of loss of life) resulting from natural landslide or rockfall is based on five probability parameters of rain, slope failure/ rockfall, elements at risk, impact significance (i.e. death, injury and property loss) and fatality occurrence. The probability of occurrence and other factors such as value of life, design lifetime and costs of implementing measures can be used to assess the cost-benefit of the proposed mitigation measures. The cost-benefit analysis demonstrates that from an economical point of view, risks should be reduced until the marginal cost of measures is equal to the marginal benefit to be protected.

2.5.1 Landslide frequency

Using the official aerial photograph records archived in the Lands Department (Hong Kong Government), landslide incidents have been identified throughout the 20th Century. The studies carried out proposed that about 100 years should be used as a working figure when estimating average annual natural landslide frequency. Although the average annual landslide frequency is approximately 325, 80% of Hong Kong area is rural and half the territory has vegetation protected by country parks where no development is allowed, this figure may well be too low to be used as a basis for risk analysis due to many slides not being detected or recorded.

2.5.2 Elements at risk

The elements at risk from any landslide event was generally classified into two categories:

(1) Roads and Highways
- Population in vehicles on road in lane furthest from slope
- Population in vehicles on road in lane nearest to slope
- Pedestrians

(2) Buildings / Structures
- Squatters
- Playground
- Outdoor residential
- Indoor residential ground floor; and,
- Indoor residential upper floors.

For the landslide risk assessment for Hong Kong, the derived vulnerability values based on deaths arising from landslide debris, summarized in Table 30.0. Table 30.0 considers an individual event of a person being buried by a landslide. There are a number of factors influencing the vulnerability of people to death or injury within each affected case. These are:
- The amount of warning time available,
- Proximity of person(s) / vehicle(s) / building to the slope,
- Density of person / vehicle in the elements.

- Debris run-out distance and depth,
- Magnitude of the landslide,
- Whether the person(s) is in the open or enclosed in a vehicle or building

The probability of fatality of landslide is a sequence of interrelated events, in the order of rain, slope failure/rockfall, elements at risk, impact significant (i.e. death, injury and property loss) and fatal occurrence.

Table 30.0 Summary of vulnerability values based on deaths arising from landslide debris.

Case	Vulnerability Range	Recommended Value for Vulnerability	Comments
Vulnerability of Person in Open Space 1.If struck by a rock fall 2. If buried by debris 3. If not buried	 0.1 – 0.7 0.8 – 1.0 0.1 – 0.5	 0.5 1.0 0.1	 May be injured but unlikely to cause death. Death by asphyxia. High chance of survival.
Vulnerability of Person in a Vehicle 1. If the vehicle is buried/ crushed 2. If the vehicle is only dam- aged	 0.9 – 1.0 0 – 0.3	 1.0 0.3	 Death is almost certain
Vulnerability of Person in a Building 1. If the building collapses 2. If the building is inundated with debris and the person buried 3. If the building is inundated with debris and the person is not buried 4. If the debris strikes the building only	 0.9 – 1.0 0.8 – 1.0 0 – 0.5 0 – 0.1	 1.0 1.0 0.2 0.05	 Death is almost certain Death is highly likely High chance of survival Virtually no danger

2.5.3 Probability of occurrence

Natural terrain hazards include landslides and rock and boulder falls. When undertaking risk analysis, sequential events (i.e. event tree analysis) could be compromised since two or more events may be interrelated. There are five categories of probability which could be taken into account;

(1) Extremely probable event – rain.
(2) Highly probable event – probability of natural slope failures triggered by rain.
(3) Probable event – probability of landslides which elements at risk.
(4) Moderately probable event – probability of elements impact significant that injury and death is reported.
(5) Low probability event – probability of fatality occurring due to landslide.

The sequential events model provides the basis for the probability charts presented in Figures 2.27 and 2.28. These present a number of approaches for the estimation of the annual probability of a fatality occurring as a result of natural slope failures. Past experience also show that almost all landslides occurring in Hong Kong are triggered by intense rainfall leading to elevated pore pressure and/or loss of soil suction. Rain is an extremely probable event leading to a highly probable event of a natural slope failure. Using the five probability events, the event tree model in Figures 2.27 and 2.28.has been developed. Figures 2.27 and 2.28 indicate that the annual probability of fatalities resulting from a person being hit or buried by a natural terrain failure triggered by rain are given by $8.11X10^{-5}$ and $1.62\ X10^{-4}$ respectively. Therefore, the probability of a fatality (or probability of loss of life) arising from a natural terrain hazard equals $2.43X10^{-4}$.

2.5.4 Risk acceptability criteria

The risk acceptability criteria guidelines for planning applications around a Potential Hazardous Installation (PHI), for example a power plant or cut-slope, have been established in a number of countries. In Hong Kong, the guidelines published as the Hong Kong Planning Standards & Guidelines (Chapter 11 published by the Government of Hong Kong 1994). This has the form of an F–N curve (Frequency vs. Number of fatalities). An F–N curve provides a measure of probability of fatalities obtained by plotting the frequency of incidents which affect public users. There are three regions indicated on F-N curve:

1) Unacceptable Region
2) As Low as Reasonably Practicable (ALARP) Region
3) Acceptable Region

For considering new developments which are located adjacent to a PHI, the risk guidelines must be applied. For example, if a new highway is proposed at the toe of a natural slope (i.e. a PHI), the Highways Department requires a Risk Assessment for the natural terrain hazard in order to demonstrate that the risks to the highway lie outside the 'unacceptable' region. If the risks of the F–N curve lie wholly/partly within the 'unacceptable' region, then the Highways Department has to implement risk mitigation measures to minimize the debris volume and impact force, and to stop or redirect the debris flow so as to reduce the risks to as low as reasonably practicable.

In summary, the sequential events model of the risk assessment is straight forward, easy to develop and can be expanded for other cases. The historical landslide data can be identified from aerial photograph interpretation, information archived in governmental departments and newspaper cuttings. Despite the annual natural landslide frequency in Hong Kong being as high as 325, the annual probability of fatalities occurring is relatively small, approximately $2.43X10^{-4}$. Preventive measures may not be cost effective or practical for natural slopes but mitigation measures such as boulder fences, rock ditches or debris flow traps can be considered and may be cost effective. Selection can be assisted by cost-benefit analysis criteria.

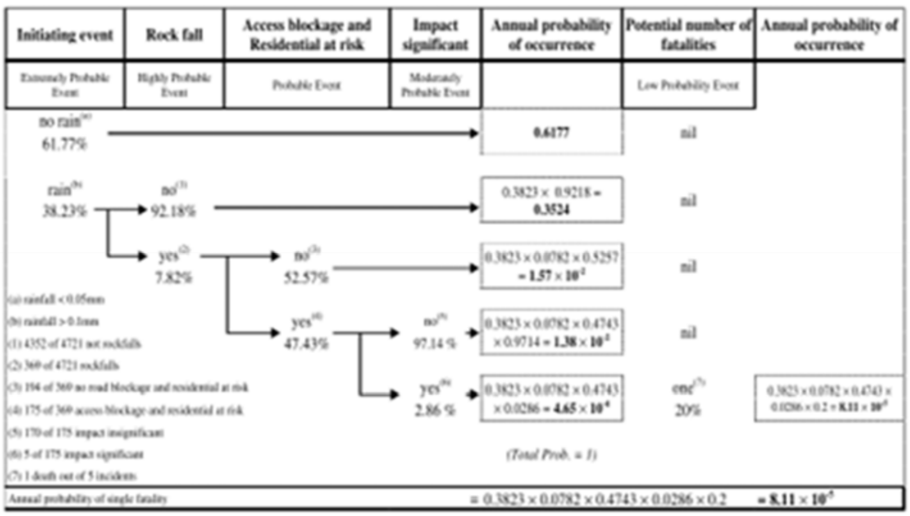


Figure 2.27 Event tree analysis of rockfall

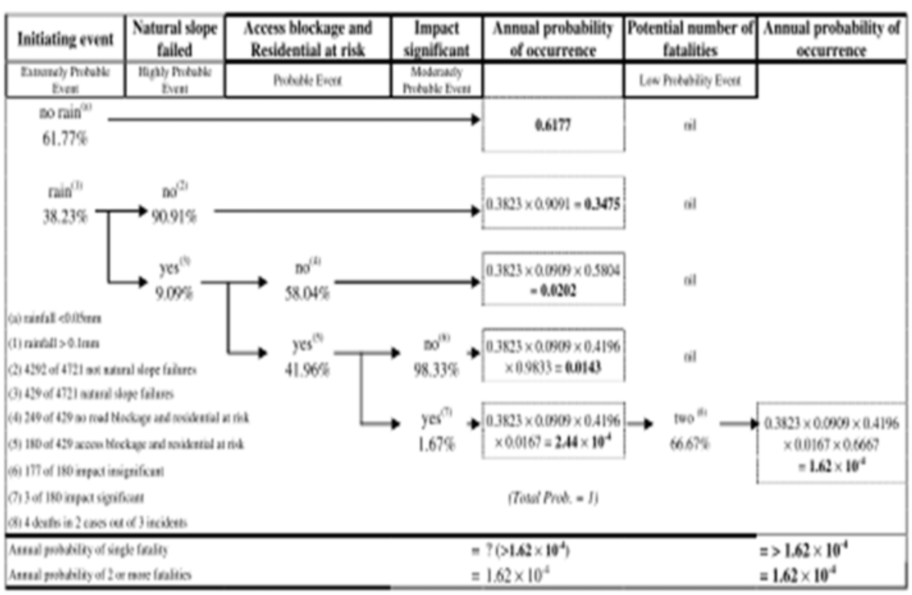


Figure 2. 28 Event tree analysis of natural slope failure

Recent advancement on the risk assessment of slope in Hong Kong was published by F.W.Y. Ko (2015). Hong Kong faces a unique long-term slope safety due to its dense urban development in a hilly terrain combined with high seasonal rainfall. Its slope engineering practice and landslide risk management have evolved in response to experience and through continuous improvement initiatives and technology advances. The application of state-of-the-art slope engineering practice and quantified landslide risk management has reduced landslide risk to an as low as reasonably practicable level that meets the needs of the public and facilitates safe and sustainable developments. He elaborates on an overview of the slope safety system and provide an update on the recent initiatives undertaken as part of the continuous efforts to enhance landslide risk management, in particular for landslide risk arising from natural terrain. These initiatives include identifying new candidates of vulnerable hillside catchments, developing a territory-wide rainfall-based landslide susceptibility model and assessing potential implications to the risk profile of natural terrain due to extreme rainfall events that are projected as becoming more frequent in terms of occurrence due to climate change effects.

The slope safety system in Hong Kong comprises a range of initiatives that serve to manage landslide risk in a holistic manner through an explicit risk-based approach and strategy. The goals are:

(a) to reduce landslide risk to the community through a policy of priority and partnership, and
(b) to address public perception and tolerability of landslide risk so as to avoid unrealistic expectations.

Apart from saving lives through averting potential fatalities, the system also adds value to the society by improving the built environment through landscaping of slopes as well as landslide preventive and mitigation measures. The continuous efforts to enhance risk management of landslides of natural terrain, Hong Kong recent initiatives were undertaken to identify further the vulnerable hill criteria:

1. Identifying New Candidates of Vulnerable Hillside Catchments

Following the ‘react-to-known-hazard’ principle, the vulnerable hillside catchments were selected based on their risk-based ranking order for action under Landslip Prevention and Mitigation Programme (LPMitP). The LPMitP marks a new chapter in Hong Kong’s landslide risk management, by incorporating systematic study and mitigation of natural terrain landslide risk as an integral part of Hong Kong’s long-term slope safety endeavour. In 2013, the GEO identified the following new candidates of vulnerable hillsides that may warrant inclusion under LPMitP for priority action.

(a) Historical Landslide Catchments (HLC) - The original inventory of vulnerable hillside catchments (i.e. HLC) was compiled in 2007, based on the proximity of the historical landslides in the Enhanced Natural Terrain Landslide Inventory (ENTLI) to existing developments. The ENTLI is an enhancement of the Natural Terrain Landslide Inventory that was compiled in the mid-1990s. A natural hillside catchment is defined as an HLC if the selection criteria in Figure 2.29 are met. The landslides considered under these criteria include both relict and recent channelized debris flows (CDF) and open hill slope landslides (OHL).

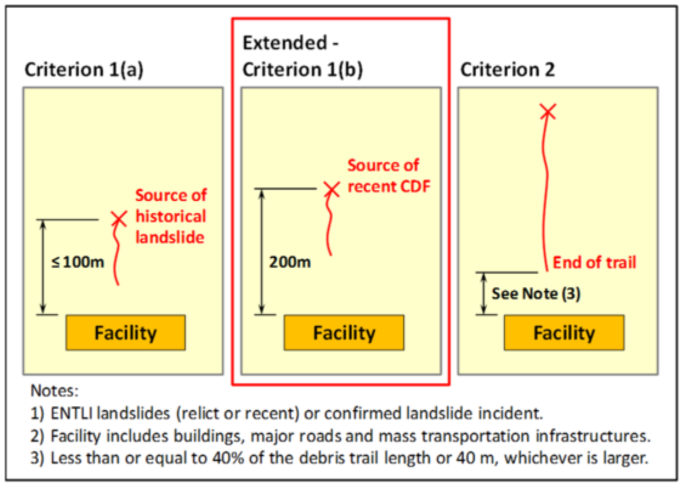


Figure 2.29 Extended HLC selection criteria.

(b) Hillside Pockets - A hillside pocket is defined as an area of hillside that is located within the predominantly developed area and satisfies all of the following three criteria: (i) maximum slope angle > 20^{o}; (ii) elevation difference > 8 m; and (iii) plan area > 400 m^2. It was reported that during the June 2008 rainstorm, landslides occurred on some hillside pockets close to existing developments. Of these 1,700 hillside pockets, about 300 hillside pockets are considered to have known hazards. These include those with relict or recent landslides, and those with known disturbance as anthrogenic disturbance is one of the key contributing factors for landslides within hillside pockets. A risk-based ranking system has been developed to prioritize the 300 hillside pockets for action under LPMitP.

(c) Sizeable Catchments with Major Drainage Lines (MDC) - MDC were delineated for all natural hillsides according to the boundary of catchment (BOC) with major drainage line, length of head of drainage line and area of water shed. The number of MDC affecting multi-storey buildings or clusters of low-rise buildings were identified within BOC. If the MDC do not satisfy the HLC selection criteria, there were no landslides in close proximity. However, these MDC can pose a potential threat in respect of a low-frequency, large-magnitude landslide, especially under extreme weather conditions, due to the presence of large catchment areas and long drainage lines. Further study is to assess the characteristics of the MDC in terms of landslide risk. Where considered appropriate, deserving MDC would be prioritized for action.

2. Developing a Territory-wide Rainfall-based Landslide Susceptibility Model.

In 2014, a new rainfall-based landslide susceptibility model was developed for assessing the susceptibility to landslides of natural terrain in Hong Kong. The purpose of the model is to make approximate territory wide predictions of the scale of landslide impacts for anticipated precipitation events, in order to provide information necessary for emergency preparedness and planning purposes. Landslides are very sensitive to rainfall and if rainfall is not considered in a susceptibility analysis, any direct application of the results of the susceptibility analysis would not be very accurate and may mislead important risk-based decision making.

3. Assessing Potential Implications to the Risk Profile due to Extreme Rainfall Events.

The effect of more frequent and severe rainfall due to climate change on the risk profile of man-made slopes and natural terrain in Hong Kong is being studied. The GEO is developing and reviewing natural terrain landslide scenarios associated with different extreme rainfall events, which include assessments of different extreme event scenarios in terms of potential landslide consequence and risk. It concluded that there are considerable uncertainties in the assessment of hillside behavior when subjected to intense rainfall and forecast of extreme rainfall. They remain some of utmost key challenges to managing natural terrain landslide risk.

Azami (2006) conducted a comprehensive review on the landslide hazards and risk studies in Malaysia. He summarized the reported slope failure incidences in Malaysia and its consequences to loss of life and property loss as in Table 31.0. The classification of slope base on slope gradient and rating determine the vulnerability of landslide as shown in Table 32.0.

Table 31.0 Some of the reported slope failure incident in Malaysia

Date of Occurrence	**Slope Failure Location**	**Loss of Life**	**Property Loss**
17 Dec 1919	Ipoh, Perak	12	-
18 Oct 1973	Ipoh, Perak	40	-
15 Jan 1981	Puchong, Selangor	13	-
11 Dec 1993	Highland Tower, Selangor	48	One apartment, four abandon apartment
7 Dec 1994	Cameron Highlands, Pahang	7	Road closure
30 Jun 1995	Genting Sempah, Pahang	21	Vehicles and road closure
6 Jan 1996	Gua Tempurung, North-South Highway, Km 303.8, Perak	1	Several vehicles
30 Aug 1996	Pos Dipang, Perak	44	30 houses

28 Nov 1998	Paya Terubong, Penang	-	16 vehicles
7 Feb 1999	Sandakan, Sabah	17	Four squatter houses
15 May 1999	Bukit Antarabangsa, Selangor	-	Three vehicles
6 Jan 2000	Cameron Highlands, Pahang	5	-
28 Dec 2001	Gunung Pulai, Johor	5	Four houses and a few vehicles
28 Jan 2002	Simunjan, Sarawak	16	An Iban longhouse
20 Nov 2002	Taman Hillview, Selangor	8	One bungalow, four vehicles
26 Nov 2003	Bukit Lanjan, North-South Highway, Km 21.8, Selangor	-	Closure of the highway
11 Oct 2004	Gua Tempurung, North-South Highway, Km 303, Perak	-	Six vehicles
31 May 2006	Taman Zooview, Selangor	4	Three block of houses
8 Oct 2006	Section 10, Wangsa Maju, Selangor	-	Road and dumping areas
16 Nov 2006	Bukit Kinrara, Selangor	-	3 houses
22 March 2007	Precinct 9, Putrajaya, Selangor	-	-
5 May 2007	Jalan Sultan Salahuddin, Kuala Lumpur	-	-
4 June 2007	Jalan Duta, Kuala Lumpur	-	-

(Source: Azami et al., 2006)

Table 32.0 Guideline hilly terrain development areas

Slope Gradient	Description
Below 15º	**Class 1**
16º - 25º	**Class 2**
26º - 35º	**Class 3**
Above 36º	**Class 4**

(Source: MGD, 2002)

Table 33.0 summarize the slope rating system based on risk on consequences. Whereas Table 34.0 summarize the slope rating system established and used by the respective authorities.

Table 33.0 Slope rating system based on risk on consequence.

Name of Classification	Author	Year	Applications	Description of The Rating System
Missouri Rockfall Hazard Rating System (MORH RS)	Youssef et al	2003	Road	The rating system that has been developed for analysis of rockfall hazards along roads of Missouri State Highway, USA. In MORH RS, 22 parameters have been considered which are: 1. 9 factors for risk rating such as rock cut height, slope angle, rock fall history, weathering, rock strength, face irregularities, face looseness, block size and water on face 2. 10 factors for consequence rating such as ditch width, ditch volume, slope angle, shoulder width, roadway width, average daily traffic, average vertical risk, sight distance and block size 3. 3 adjustment factors such as dip angle of discontinuities, filled sinkhole size and ditch capacity exceedence
New Priority Classification Systems for Slopes (NPCS)	Geotechnical Control Office (GCO)	1998	Rock and soil slopes	The rating system has been developed by Geotechnical Control Office of Hong Kong (GCO). The system was developed based on slope instability and consequences to risk element such as building and road. The parameter that involved are divided into two categories which are: 1. Slope instability parameters which

				included slope geometry, geology, slope condition, slope distress, slope drainage, slope stabilization 2. Consequences parameters such as facilities that affected, scale of failure, topography and vulnerability.
Rockfall Hazard Rating System (RHRS)	Oregon State Highway Division		Road	The purpose of the system is to identify the slopes which are particularly high risk and required urgent remedial work for safety checks. The system has been applied along mountainous highway in Western United States and Canada. There were nine main parameters that have been adopted such slope height, ditch effectiveness, average vehicle risk, percent of decision sight distance, roadway width, geologic character, block size, climate and presence of water on slope and rockfall history.

(Source: Youssef et al., 2003; GCO, 1991**)**

Table 34.0 Slope rating system that available in Malaysia

Name of Slope Rating System	Authority	Applications	Description of the System
Slope Maintenance System (SMS)	PWD	Slope maintenance works at East-West Highway and Gerik – Jeli in Kelantan	The parameters that considered in the system are slope geometry, berm geometry, topography, logging activity, drainage system, erosion and mode of failures. In addition, helicopter integrated with digital video graphic and laser profiling have been used for acquisition data to acquire better results of slope profiling. The output of this system was risk values that obtain by multiply hazard and consequence
Malaysian Engineered Hill Slope Management System (MEHMS)	PWD	To reduce the number of slope failures along the Gunung Raya road, Langkawi	The system combined with Combined Hydrology and Stability Model (CHASM) software which can be used to calculation factor of safety and also for assessment of the slope condition.
Slope Priority Ranking System (SPRS)	PWD	To identify the cut and embankment slopes that require urgent need for maintenance along the road in Malaysia	Slope inventory form was used in the system based on experience obtained previous rating system such as SMS and MEHMS. The calculation of risk rating score has been adopted in the system which the score is defined as be multiply between hazard score and consequence score. Generally, the parameters of hazard score can be summarized as slope geometry, slope covered, surface drainage, seepage, erosion, slope failure, weathering and slope discontinuity. While the parameters of consequence score were affected to building, vehicle, road and human life.
Slope Information Management System (SIMS)	Japanese International Cooperation Agency & PWD	To monitor the slope along the road Malaysia	The system developed to enhance the existing SPRS. The system has been developed with collaboration between JICA and PWD.

Expressway Slope Maintenance Management (ESMM)	Projek Lebuhraya Utara-Selatan (PLUS)	To monitor the slopes that are close to the highway	There are six main parameters that have been considered in system such as slope geometry, geological, surface condition of the slope, drainage system, slope distress and existing stabilization of the slope
Slope Management and Risk Tracking (SMART)	PWD	To monitor slope failure that occurred along road such as Tamparuli – Sandakan	SMART is system that capable to collect, store, analyze and slope information for the slopes along the roads. There are embankment slope and cut/natural slope. The parameters that incorporate for embankment slope for SMART system are main cover type, vegetation covered, slope angle, geology, plan profile, presence of structures and topography. While for cut/natural slope the parameters that included in the system are vegetation covered condition, height, presence of core stone boulder, measure of ground saturation, slope angel, cutting topography relationship, slope shape, exposed percentage, rock condition profile, plan profile and surface drainage rating.
Landslide Assessment System (LAS)	Mineral & Geoscience Department	Use for landuse planning	The system has adopted four parameters that induced slope instability such as slope gradient, morphology, activity, erosion and instability. The assessment of the system was carried out using Qualitative Map Combination with GIS software. The equation that has been used same as risk equation in SMS but the parameters that involved were slope gradient, morphology, activity, erosion and instability.

(Source: Azami 2006)

The scale of slope failure in the form of the rating to determine the severity failure. The failure can be classified into three, complete failure, partial failure, minor failure or intact slope as shown in Table 35.0.

Table 35.0 Rating scale of failure

Categories	Rating
Minor failure	0.4
Partial failure	0.7
Complete failure	1.0

(Source: Jamaludin et al., 2004)

Azami 2006, focused his study only on the hilly terrain developments in U10, Puncak Perdana, Selangor, which is sedimentary rock formation. In his study GIS software, ArcView 3.2a has been used to process the data such as topography map, aerial photo, fieldwork inspection results and annual intensity rainfall results. The results of this study were visualized in 2D and 3D aerial view. Besides, the results were also produced in 2D mapping. The study was not proposed for engineering design but it was useful either for future planning or in early mitigation of slope failure. In addition, the study was focused on slope rating system approach that has been developed and being used for fieldwork inspection such as the physical surface of the slope, classification of slope rating, site geology, condition of slope face, drainage system and serviceability, slope distress, slope stabilization, rainfall level, risk element, slope geometry, scale of failure and vulnerability to risk element. However, rock mass properties were not included in the study. The study was expected to benefit local authorities, engineer, geologist and planner and being used to monitor hilly terrain development areas. The contributions of the research were:

1. Measuring current state, previous and future safety of the slope in the form of 2D or 3D georisk map
2. Identifying degree of slope consequence risk for the purpose of prioritizing the urgency of remedial actions.

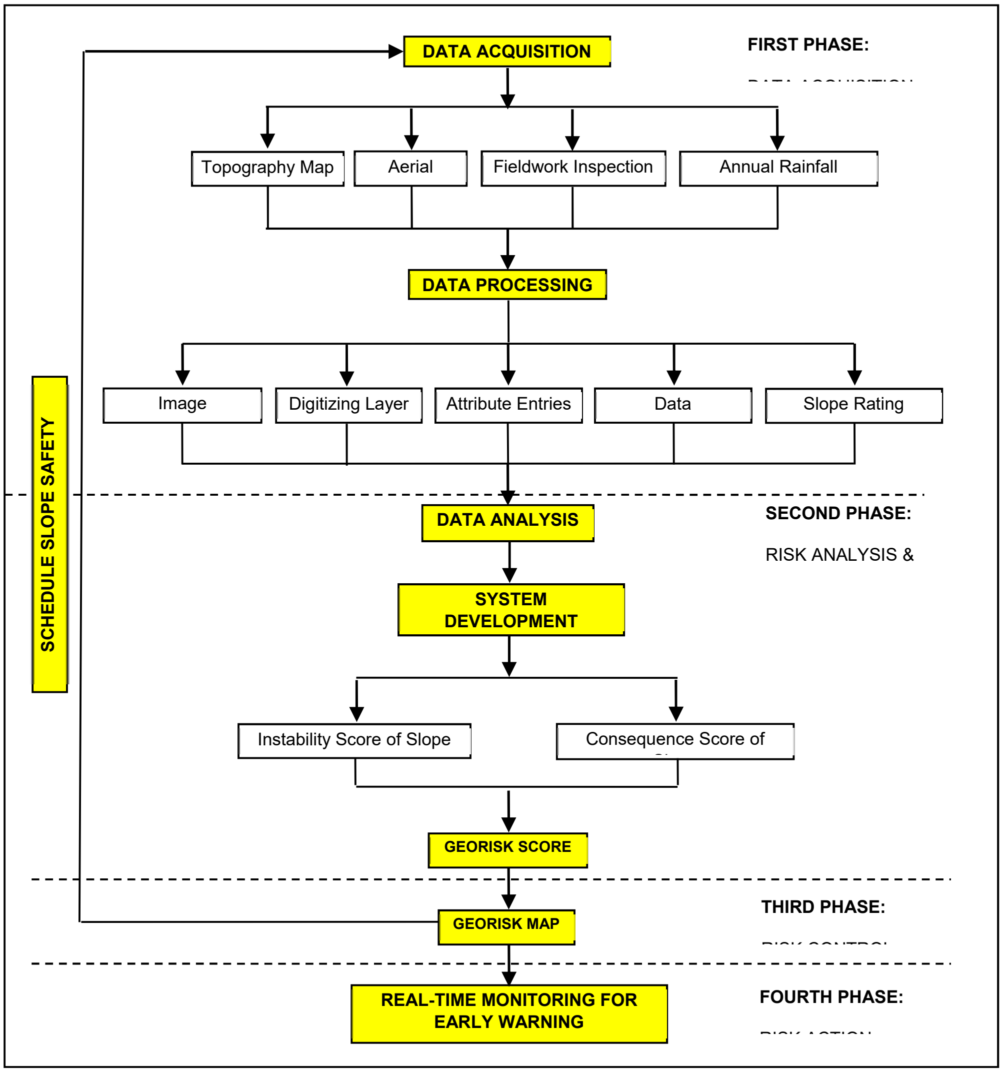


Figure 2.30 Flowchart methodology of slope georisk management system

Based on the georisk results, the integration between slopes and planning map was done. The integration process that has been carried out was the same as the integration process between slope and residential areas as discussed. The integration layer between georisk score and future development layer where the layer was named “futuredevelop.shp”. The classification followed the georisk score classification.

Table 36.0 The classification of georisk score which is modified from the SMART system

		Instability Score				
		Very Low	Low	Moderate	High	Very High
	Very Low	0 – 0.2	0.0 – 0.2 (Slopes 2,4,5,6,7,8, 11,12,13,14,18,19)	0.0 – 0.2 (Slopes 1,3,9)	0.0 – 0.2	0.0 – 0.2
	Low	0.0 – 0.2	0.0 – 0.2	0.2 – 0.4	0.2 – 0.4 (Slope 10)	0.2 – 0.4
	Moderate	0.0 – 0.2	0.0 – 0.2	0.2 - 0.4 (Slope 15)	0.4 - 0.6	0.4 - 0.6
	High	0.0 – 0.2	0.0 – 0.2	0.4 - 0.6 (Slope 16)	0.4 - 0.6 (Slope 17)	0.6 - 0.8
	Very High	0.0 - 0.2	0.0 – 0.2	0.4 - 0.6	0.6 - 0.8	0.8 – 1.0

Table 37.0 Indicator of georisk

Very low georisk	Low georisk	Moderate georisk	High georisk	Very high georisk

Instability score (IS) is to determine the stability state of the slopes. The instability score is determined by the sum of actual instability score parameters and divided by the maximum instability score. The results and the classification of the instability score using ArcView 3.2a are shown in Figure 2.31. The consequence scores of 19 slopes showed that several areas have been identified as high consequence risk due to slope failure. Each degree of consequence risk is different in terms of color code as shown in risk map and is divided into five classes as shown in Figure 2.32. Finally, the georisk score is presented in pictorial image as shown in Figure 2.33 where the typical classification of georisk score is shown.

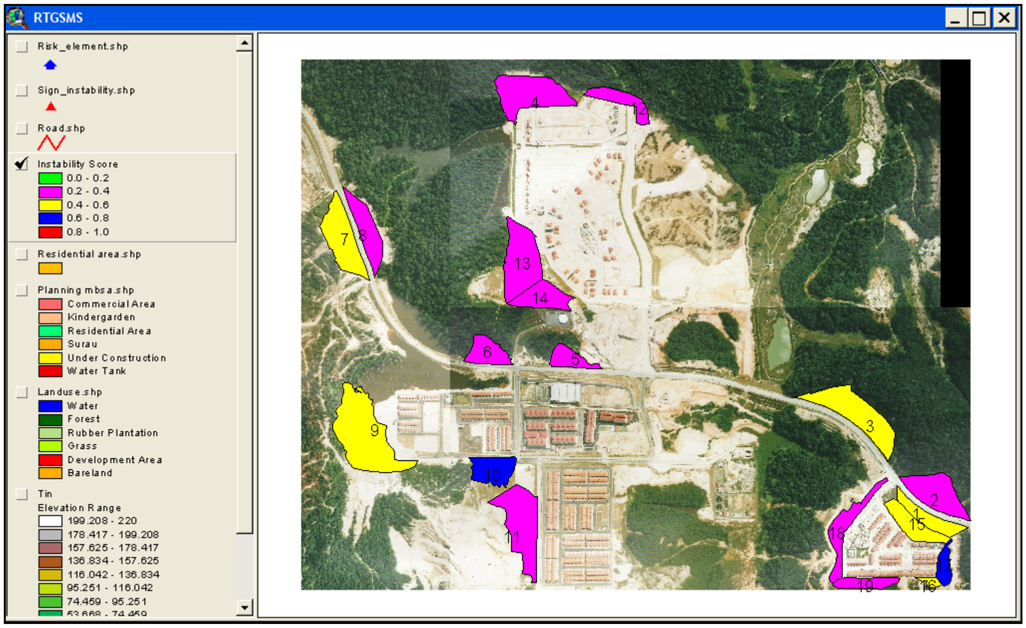


Figure 2.31 The classification of instability score

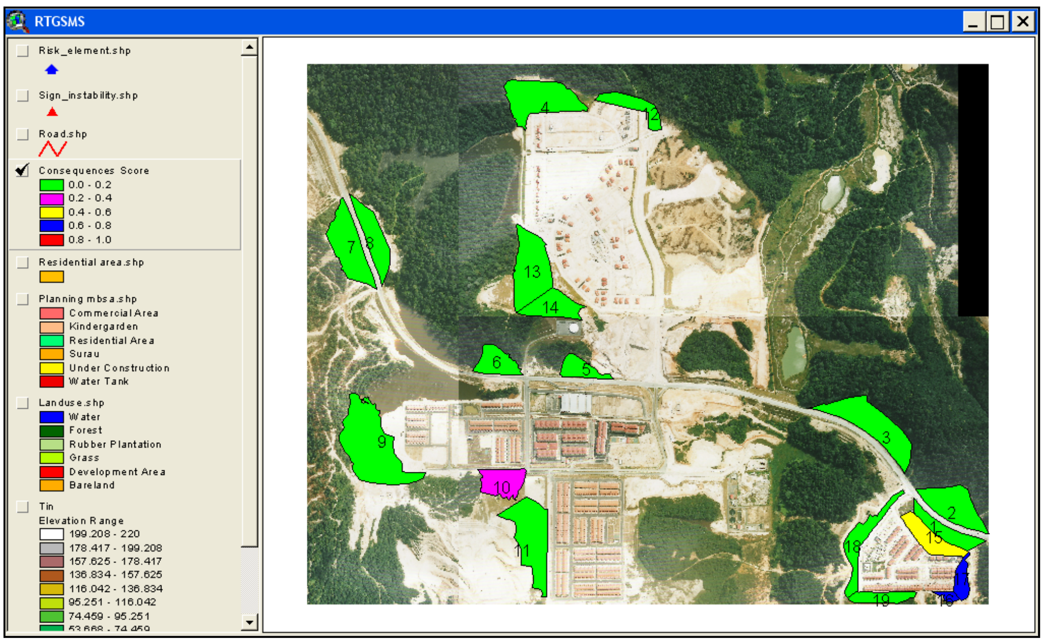


Figure 2.32 The classification of consequence score

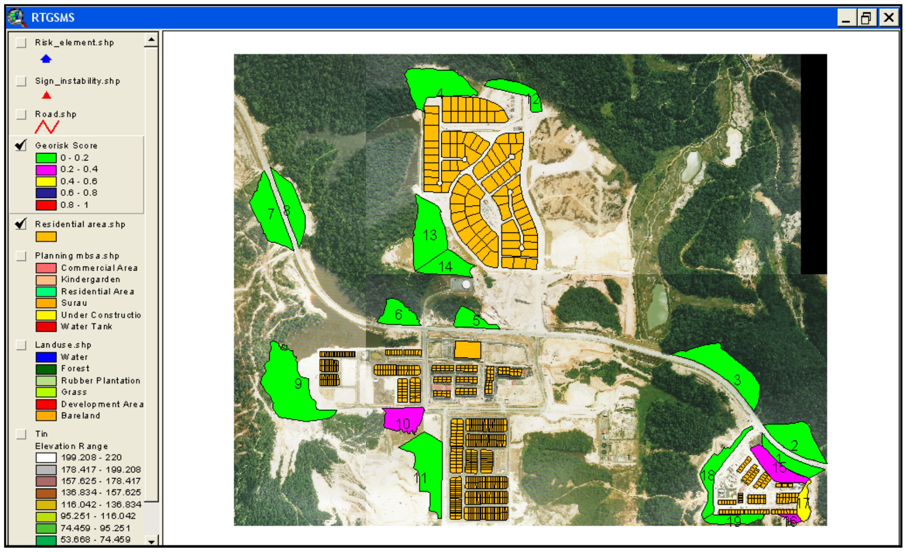


Figure 2. 33 The classification of georisk score which are very low

2.6 Suggested Methods for Landslide Assessments for Critical Infrastructure

2.6.1 Vulnerability Assessment

Based on previous study, the proposed landslide vulnerability assessment is based on the semi-quantitative approach indicator-based vulnerability assessment (IBM) introduced by Papathoma-Köhle (2016) and and Uzielli et al. (2008). The previous method however did not clearly consider the intensity of landslide hazard in the IBM method. Therefore in this project the hazard intensity will be clearly integrated as part of the indicators in the IBM as it was strongly suggested by Papathoma-Köhle (2016). Uzielli et al. (2008) on the other hand considered the susceptibility of people inside the building but did not consider surrounding environment or mitigation measure in the vulnerability estimation. In the proposed method the vulnerability indicators are grouped into 4 i.e. susceptibility of critical infrastructure (*C*), effect of surrounding environment or mitigation measures (*E*), susceptibility of people inside the residential building (*P*) and intensity of landslide hazard (*I*) (Equation 16).

$$V = f(C, E, P, I) \tag{16}$$

Therefore, the vulnerability index for CI (*V*) is defined as in Equation 17.

$$V = \sum_{i=1}^{m} \quad \sum_{j=1}^{n} w_i \times S_j \tag{17}$$

Where w_i is the *i*-th weight of *m* indicators under different indicator groups (in this case $m = 4$ for Figure 2.35) and S_i is *i*-th score for a specific class of the indicators. The weight for each group 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 score value for each indicator under specific group also ranges from 0.1 (low influence to increase vulnerability) to 1.0 (high influence to increase vulnerability). Figure 2.34 shows the overall concept of the proposed vulnerability estimation method.

The building susceptibility indicator group indicates the susceptibility of the critical infrastructure towards specific landslide hazard intensity that accounts the physical characteristics. The surrounding environment or mitigation measures group 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 is the final indicator group will indicate the intensity of landslide hazard on a specific CI.

The final vulnerability value is a weighted and aggregated value explained by Equation 17. In this method, the weighting is not static and varies depending on the needs of the users. The method allows the user to set their own priorities and change the weighting accordingly. Kappes et al. (2012) suggest that the main advantage of the model is the flexibility. In addition, they also consider that the method is not hazard-intensity specific to be an advantage, in which the method can still be used in absence of the intensity or the process characteristics.

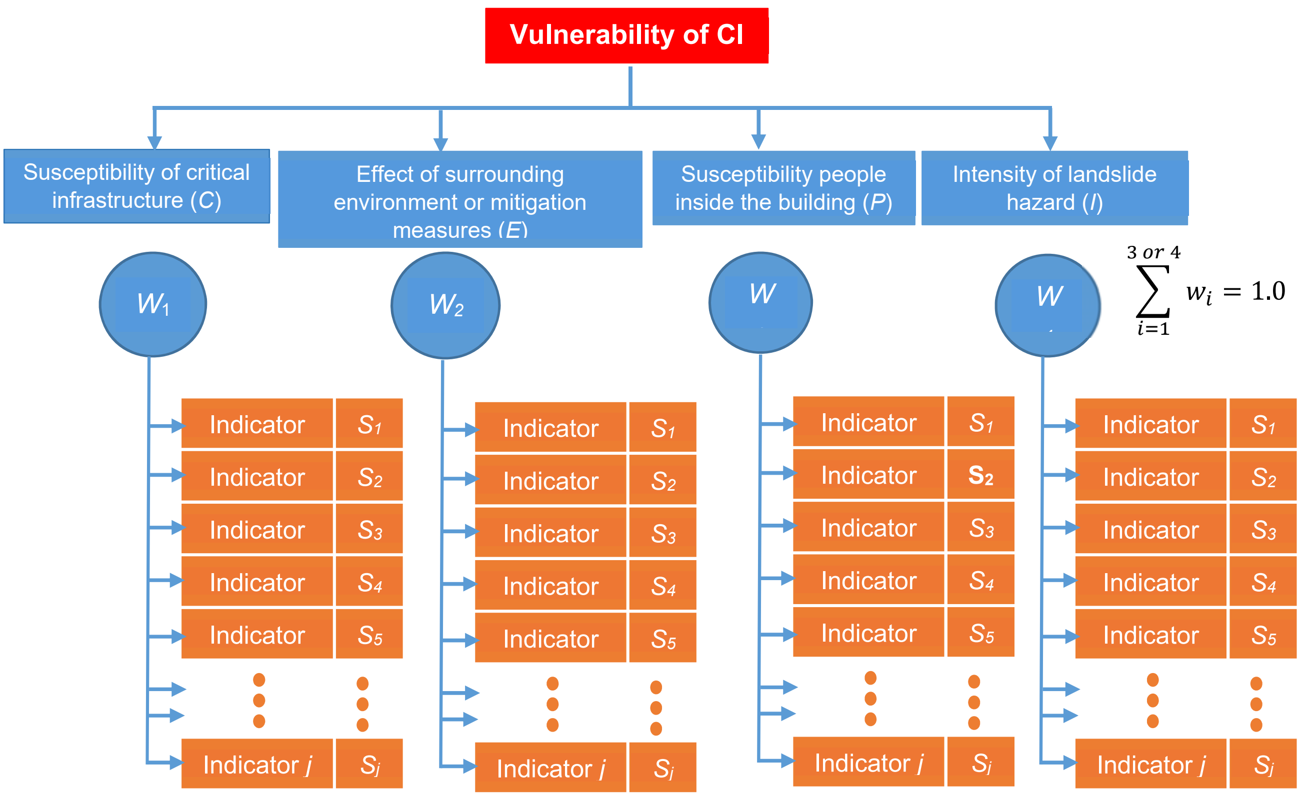


Figure 2. 34 The concept of the proposed IBM's method after Kappes et al. (2012).

The reasons for using a semi-quantitative model based on a scoring system are:

a) **Data availability**: The ranking of indicators into several vulnerability classes requires less data than assessing a quantitative value to each indicator. The quantitative approach of vulnerability assessment certainly required huge amount of past records for landslide damages. However, in this project gathering such data is very challenging and till now the recorded data of landslide damages do not fit with the requirements of the quantitative method.
b) **The possibility for combining qualitative and quantitative indicators**: Through predefined ranking criteria for indicators, both quantitative and qualitative indicators may be ranked and combined into a semi-quantitative vulnerability parameter.
c) **The results can be easily analyzed in GIS**: The vulnerability value for each CI can be easily stored flexibility in the GIS database. This allows effective analysis on the vulnerability data for example adjustment of the weight and indicators for re-evaluation of vulnerability based on updated landslide records. The GIS system allows spatial analysis for "what if" scenario on the vulnerability data for example that aims at reducing vulnerability and risk by applying specific mitigation measures.
d) **The weighting process is flexible**: The weight assigned for each indicators can be adjusted based on the needs of the users.
e) **Data collection process can be carried out by non-expert**: determination of scores of the indicators can be based on the owner of the buildings. This will save money and time for data collection.
f) **The IBM methods encourages the involvement of local community**: Local and individual building owners involves in data collection and vulnerability reduction process.

The selection of indicators and their weight values will be based on combination of qualitative (expert judgment on previous records) and quantitative approach (specific numerical modelling on the impact of landslides). However, the former approach (expert judgement) will be the main input since we have lack of previous landslide damage records and validated numerical modelling for landslide impacts in Malaysia. Determination of weight and scores will be made through detailed interviews and workshops with related agencies and experts. Determination of landslide vulnerability indicators, value and index will be made for different areas (urban, sub-urban, urban highland and rural), critical infrastructures (residential, building, road, dam, pipeline and tele-communication tower) and typical landslide type in Malaysia. Each vulnerability index for a specific CI will be given together with detailed description on the damages and the process that causes the damage. The damages will be ranked into a specific level for example low, medium, high and very high based on the requirement and vulnerability perception of the related authorities, agencies and experts. The recommended model, indicators, weight and indicators will be tested and evaluated based on a specific study area in Cameron Highlands. The applicability of the proposed method (model, indicators, weight and indicators) will be evaluated based on the accuracy of the estimated vulnerability index and class. The proposed vulnerability assessment method will be optimized by the following step-by-step approach:

a) Add or remove the indicator groups or change its corresponding weight value.
b) Add or remove the indicators and its corresponding score value.
c) Change the method of weight and score aggregation.

2.6.1.1 Suggested indicators for landslide vulnerability assessment

The proposed landslide vulnerability assessment requires determination of 4 group of indicators i.e. susceptibility of critical infrastructure (C), effect of surrounding environment or mitigation measures (E), susceptibility of people inside the residential building (P) and intensity of landslide hazard (I) (Equation 16). In this project each group indicator is treated equally, in which all the group of indicators has the same influence towards the vulnerability value. In this case each group is given with 25% (or 0.25) weight value. The weight value will be given equally among the indicators under each group or differently based on their level of importance in vulnerability estimation. The weight for each indicator will be assigned based on intensive discussion with the stakeholder. Different sets of indicators and weight values will be determined for different types of typical landslides in Malaysia i.e. rotational landslide, translational landslide, rockfall and debris flow. However, in this project we have proposed the suitable indicators for different types of landslides and CI.

Table 38 shows the proposed landslide indicators for building. The indicators that represents the susceptibility of building and residential area consists of structural typology of the building, foundation depth, number of floor, and special. Each indicators has specific classes, in which specific weight value (between 0.1 and 1.0) should be assigned to each class for example as given in Table 6. The low the weight value implies low contribution to the increase in total vulnerability value. The higher the weight value will increase the total vulnerability value of the CI. Other indicators representing surrounding environment/mitigation measures, landslide intensity and people inside the building are divided shown in Table 1. Table 2 to Table 5 show the proposed landslide vulnerability indicators for residential, road, dam and utilities. Table 7 shows justification of each proposed indicators. The final vulnerability value for each CI as calculated using Equation 16 (ranges between 0.1 and 1.0) will be classified into different classes of vulnerability index as shown in Table 8.

Table 38.0 Proposed landslide vulnerability indicators for building

No	Vulnerability Indicators	Type of Landslide			Weightage
		Rotational & Translational	Rockfall	Debris Flow	
	Building Characteristic				0.25
1	Structural typology/ Structure construction materials	x	x	x	
2	Foundation depth	x	x	x	
3	Number of floor	x	x	x	
4	Building categories	x	x	x	
	Surrounding Environment/Mitigation measures				0.25
1	Presence of protection	x	x	x	
2	Surrounding wall			x	
3	Surrounding vegetation	x	x	x	
4	Row of building from the river			x	
5	Distance between building			x	
	Landslide Intensity				0.25
1	Accumulation heights	x	x	x	
2	Flow depths			x	
3	Landslide thickness	x		x	
4	Landslide area				
5	Landslide volume	x	x	x	
6	Volume/ kinetic Energy		x	x	
7	Block volume/size		x		
8	Debris volume	x		x	
9	Runout distance	x	x	x	
10	Landslide Velocity	x	x	x	
	People Inside Building				0.25
1	Population Density	x	x	x	
2	Age of people	x	x	x	
3	Presence of warning systems	x	x	x	
Total					**1.00**

Table 39.0 Proposed landslide vulnerability indicators for residential

No	Vulnerability Indicators	Type of Landslide			Weightage
		Rotational & Translational	Rockfall	Debris Flow	
	Residential Characteristic				**0.25**
1	Structural typology / Structure construction materials	x	x	x	
2	Foundation depth	x	x	x	
3	Building height	x	x	x	
4	Number of floor	x	x	x	
	Surrounding Environment/Mitigation measures				**0.25**
1	Presence of protection	x	x	x	
2	Surrounding wall	x	x	x	
3	Surrounding vegetation			x	
4	Row of building from the river			x	
5	Distance between building			x	
	Landslide Intensity				**0.25**
1	Accumulation heights	x	x	x	
2	Flow depths			x	
3	Landslide thickness	x		x	
4	Landslide area	x	x	x	
5	Landslide volume	x	x	x	
6	Volume/ kinetic Energy		x	x	
7	Block volume		x		
8	Debris volume	x		x	
9	Runout distance	x	x	x	
10	Landslide Velocity	x	x	x	
	People Inside Building				**0.25**
1	Population Density	x	x	x	
2	Age of people	x	x	x	
3	Presence of warning systems	x	x	x	
Total					**1.00**

Table 40.0 Proposed landslide vulnerability indicators for roads

No	Vulnerability Indicators	Type of Landslide			Weightage
		Rotational & Translational	Rockfall	Debris Flow	
	Roads Characteristic				**0.25**
1	Level of serviceability	x	x	x	
2	Type of road	x	x	x	
3	Width	x	x	x	
	Surrounding Environment/Mitigation measures				**0.25**
1	Presence of protection	x	x	x	
2	Presence of warning systems	x	x	x	
3	Surrounding wall			x	
4	Surrounding vegetation			x	
5	Row of building from the river			x	
6	Distance between building	x	x	x	
	Landslide Intensity				**0.25**
1	Accumulation heights	x	x	x	
2	Flow depths			x	
3	Landslide thickness	x		x	
4	Landslide area	x	x	x	
5	Landslide volume	x	x	x	
6	Volume/ kinetic energy		x	x	
7	Block volume		x		
8	Debris volume	x		x	
9	Runout distance	x	x	x	
10	Landslide velocity	x	x	x	
	Road user				**0.25**
1	Traffic volume	x	x	x	
Total					**1.00**

Table 41.0 Proposed landslide vulnerability indicators for dam

No	Vulnerability Indicators	Type of Landslide			Weightage
		Rotational & Translational	Rockfall	Debris Flow	
	Dam Characteristic				**0.25**
1	Size of catchment	x	x	x	
2	Dam Typology	x	x	x	
3	Foundation depth	x	x	x	
4	Dam height	x	x	x	
5	Dam construction materials	x	x	x	
	Surrounding Environment				**0.25**
1	Presence of protection	x	x	x	
2	Presence of warning systems	x	x	x	
3	Surrounding wall			x	
4	Surrounding vegetation			x	
	Landslide Intensity				
1	Accumulation heights	x	x	x	
2	Flow depths				
3	Landslide thickness	x	x	x	
4	Landslide area			x	
5	Landslide volume	x		x	
6	Volume/ kinetic energy	x	x	x	
7	Block volume	x	x	x	
8	Debris volume		x	x	
9	Runout distance		x		
10	Landslide velocity	x		x	
	Population living downstream area				**0.25**
1	Population density	x	x	x	
Total					**1.00**

Table 42.0 Proposed landslide vulnerability indicators for utilities (i.e. pipeline and tele-communication tower)

No	Vulnerability Indicators	Type of Landslide			Weightage
		Rotational & Translational	Rockfall	Debris Flow	
	Utilities Characteristic				**0.25**
1	Maintenance of utilities	x	x	x	
2	Typology of utilities	x	x	x	
	Surrounding Environment				**0.25**
1	Presence of protection	x	x	x	
2	Presence of warning systems	x	x	x	
3	Surrounding wall			x	
4	Surrounding vegetation			x	
5	Row of building from the river				
6	Distance between building	x	x	x	
	Landslide Intensity				
1	Accumulation heights	x	x	x	
2	Flow depths			x	
3	Landslide thickness	x		x	
4	Landslide area	x	x	x	
5	Landslide volume	x	x	x	
6	Volume/ kinetic energy		x	x	
7	Block volume		x		
8	Debris volume	x		x	
9	Runout distance	x	x	x	
10	Landslide velocity	x	x	x	
	Users of Utilities				**0.25**
1	Population density	x	x	x	
Total					**1.00**

Table 43.0 Proposed class of indicators for building and residential

No	Vulnerability Indicators	Classifications	Reference
	Building Characteristic		
1	Structural typology / Structure construction materials	1. Lightest, simple structures 2. Light structures 3. Rock masonry, concrete and timber 4. Rock masonry, concrete structures 5. Reinforced concrete structures 6. Reinforced structures	(Li, Nadim, Huang, Uzielli, & Lacasse, 2010; Uzielli, Nadim, Lacasse, & Kaynia, 2008)
2	Foundation depth	1. For landslide depth <2 meter a. ≤2 meter b. >2 meter 2. For landslide depth 2 – 10 meter a. Less than a landslide depth b. 10 – 13 meter c. >13 meter 3. For landslide depth >10 meter a. Any depth of building foundation	(Li et al., 2010)
3	Number of floor	1. Single storey (1 storey) 2. Low rise building (2 storey) 3. Medium rise building (3,4,5 storey) 4. High rise building (+6 storey)	(Li et al., 2010)
4	Building categories (combination of number of floor, structure materials,)	1. Four storey or higher reinforced concrete building with pile foundation. 2. Three storey or lower reinforced concrete building with shallow foundation. 3. Single storey reinforced concrete building with shallow foundation. 4. Building with combination of bricks/timber/zinc materials. 5. Temporary structure and timber houses.	Ir Rozlan

		1. Poor traditional masonry buildings. 2. Poor adobe stone or taipa buildings 3. Poor other resistant elements (wood, metallic) buildings 4. Usual traditional masonry buildings 5. Usual reinforced concrete buildings 6. Luxurious reinforced concrete buildings 7. Heritage traditional mansory	(Zêzere, Garcia, Oliveira, & Reis, 2008)
	Surrounding Environment		
6	Presence of protection	1. No protection 2. Bad 3. Medium 4. Strong	(Li et al., 2010)
7	Surrounding wall	1. Wall >1.5 meter 2. Wall <1.5 meter	(Papathoma-Köhle, 2016)
		1. Concrete wall >0.7 meter 2. Concrete wall <0.7 meter 3. Concrete foundation closed 4. Concrete foundation open 5. Stoned wall 6. Earth-filled dam 7. Lattice fencing	(Fuchs, Heiss, & Hübl, 2007)
8	Surrounding vegetation	1. Vegetation (trees) 2. Vegetation (bushes)	(Papathoma-Köhle, 2016)
9	Row of building from the river	1. First 2. Second 3. >Third	(Papathoma-Köhle, 2016)
10	Distance between building	NA	NA
	Landslide Intensity		
11	Accumulation heights	1. Height <0.5 meter 2. 0.5 meter < height < 2 meter 3. Height > 2 meter	(Roxana, Dagmar, & Thomas, 2013)
12	Flow depths	NA	NA
13	Landslide thickness	NA	NA
14	Landslide area	NA	NA
16	Landslide volume	Estimated volume in (m^3) 1. <0.001 2. <0.5 3. >0.5 4. <500 5. 500 – 10,000 6. 10,000 – 50,000 7. >500,000 8. >>500,000	(Cardinali et al., 2002)
17	Volume/ kinetic Energy	NA	NA
18	Block volume/size	NA	NA
19	Debris volume	NA	NA

20	Runout distance	NA	NA
21	Landslide Velocity	1 – Extremely slow (16mm/year) 2 – Very slow (16mm/year) 3 – Slow (1.6m/year) 4 – Moderate (3m/week) 5 – Rapid (1.8m/hour) 6 – Very rapid (3m/min) 7 – Extremely rapid (5m/sec)	(Cardinali et al., 2002; Cruden & Couture, 2011)
	People Inside Building		
22	Population Density	NA	NA
23	Age	0 – 5 5 – 10 10 – 15 15 – 20 20 – 50 50 – 55 55 – 60 60 – 65 65 – 70 70 – 75 ≥ 75	(Isaza-Restrepo, Martínez Carvajal, & Hidalgo Montoya, 2016; Kaynia et al., 2008; Uzielli et al., 2008)
24	Gender	Male Female	NA
25	Presence of warning systems	NA	NA

Table 44.0 Justification of indicators in estimating landslide vulnerability

Type of Critical Infrastructure	Indicators	Description/Justification
All CIs	Structure materials	The scores may vary according to the case study and it is clear that each material type reacts in a different way to the impact of a debris flow
Building/ Residential/Dam	Height of the building or structure	The height of the building or structure directly influences the degree of loss. The higher the building the lower the degree of loss.
Building/ Residential	Number of floors	Building height is significant for its response to sliding debris. Additionally, multi-storey buildings offer opportunities for vertical evacuation. A one-floor high building does not necessarily offer this possibility.
Road	Level of serviceability	The limit state design of structures includes factors such as durability, overall stability, cracking resistance and excessive vibration.
Road	Type of road	Different types of road may have different structural designs that might reduce the impact of landslide
Road	Width of road	Different width of road may have different structural designs that might reduce the impact of landslide
All CIs	Surrounding wall	Surrounding wall has a protection effect for the building according to its height and material
All CIs	Surrounding vegetation	Surrounding vegetation reduces the intensity of the process on the building to a lesser degree than a surrounding wall does.
Building/ Residential/Dam	Depth of foundation	An appropriate foundation may prevent the collapse of buildings and other structure
All CIs	Row of building from the river	Other buildings may act as protection to other buildings.
All CIs	Distance between buildings	The back shield effect of surrounding buildings has been recognised in many studies as a factor that reduces the vulnerability of a building to debris flow
All CIs	Presence of protection or mitigation measures	Local protection measures (such as extra window protection, no windows from the slope side, basement with elevated entrance etc.), when present, may significantly reduce the vulnerability of the building.
All CIs	Accumulation heights	The height of the displaced material, which lies above the original ground surface. The height of accumulation has been used by previous studies in estimating landslide damages depending on the height of the structure.
All CIs	Flow depths	Involve the depth of fluid of materials down slope movement. The height of accumulation has been used by previous studies in estimating landslide damages.
All CIs	Landslide thickness	The most striking difference between the two types of landslides is in thickness. Thin landslides, less than 2 m thick, occupy the upper parts of hillslopes

		where the colluvium is thin. Thick landslides, more than 2 m thick, occupy the lower parts of the slopes.
All CIs	Landslide area	The area of the landslide within which the displaced material lies above the original ground surface. The impact of landslide on a specific structure was also determined by the location of the structure in relation with the landslide area for example building inside the landslide area might have different impact compared to building outside the landslide area.
All CIs	Landslide volume	Volumes of landslides are recorded in the scientific literature using cubic kilometres (km3) for the largest and millions of cubic metres. The volume of landslide has a significant impact on the structure.
All CIs	Volume/kinetic energy	Potential to kinetic energy transfer is especially important in understanding the evolution of landforms. Potential to kinetic energy transfer is the driving force behind wind and water movement leading to erosion and weathering.
All CIs	Block volume/size	The volume of overlying material moves as a single, little-deformed mass.
All CIs	Debris volume	Large fraction of the debris flow is water. As the flow comes to rest, the water and fine-grained sediments segregate, forming a hyperconcentrated flow that can continue for great distances.
All CIs	Runout distance	Used for the depositional part or terminal flow path downstream of a defined point.
All CIs	Landslide velocity	A velocity range is connected to the different type of landslides, on the basis of observation of case history or site observations.
All CIs	Population density	Population density is the number of people per unit of area, usually quoted per square kilometer or square mile. The higher the density of people in the building resulting higher risk of human casualties.
All CIs	Age of people	This would exclude specific ages, but the groupings could be of any scope from 10-20 year-olds, 30-40 year-olds, etc. Old people might have difficulties in responding towards hazard thus increase the risk of casualties.
All CIs	Gender	The range of characteristics differentiating between masculinity and femininity.
All CIs	Presence of warning systems	Any system of biological or technical nature deployed by an individual or group to inform of a future danger. This might have a positive impact towards vulnerability since it increases the chance of the resident survival during the landslide event.
Road	Traffic volume	The number of vehicles crossing a section of road per unit time at any selected period. Road with high traffic volume will have high risk of human casualties during the landslide event.

Table 45.0 Proposed landslide vulnerability classes for building and residential

Element-at-Risk	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	0.01-0.1
	Low	Cracks in the wall, stability not affected, reparation not urgent and slight injuries of people in the building	0.2-0.3
	Moderate	Strong deformations, huge holes in wall, cracks in supporting structures, stability affected, doors and windows unusable, severe injuries and evacuation necessary	0.4-0.6
	High	Structural breaks, partly destructed, reconstruction of destructed parts, death is highly likely (severe injury) and evacuation necessary	0.7-0.8
	Very High	Severely damaged stucture or totally destructed, evacuation necessary, complete reconstruction and death is almost certain	0.9-1.0
Road	Very low	Slight damage of road and does not affect any traffic problem	0.01-0.1
	Low	No structural damage with minor repairable damage and slightly affect traffic	0.2-0.3
	Moderate	No structural damage, major damage requiring major repair work and severe effect on road traffic	0.4-0.6
	High	Structural damage that can affect the stability and functionality of the road, partly unusable road and requires road diversion	0.7-0.8
	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	0.9-1.0
Dam	Very low	Slight damage of dam and does not affect any problem to the community	0.01-0.1
	Low	No structural damage – minor repairable damage and slightly affect the dam operation	0.2-0.3
	Moderate	No structural damage –major damage requiring major repair work and severe effect on the dam operation	0.4-0.6
	High	Structural damage that can affect the stability and functionality of the dam and partly disrupted dam operation	0.7-0.8
	Very high	Heavy damage seriously compromising the structural integrity: partial or total collapse of the dam, totally disrupted dam operation and immediate evacuation is	0.9-1.0

		required for the community living downstream	
Utility	Very low	Slight damage of utility and does not affect its operation	0.01-0.1
	Low	No structural damage – minor repairable damage and slightly affect the operation	0.2-0.3
	Moderate	No structural damage –major damage requiring major repair work and severely affect the operations of such utility	0.4-0.6
	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	0.7-0.8
	Very high	Heavy damage seriously compromising the structural integrity: partial or total collapse of the road, total collapse of utility operation and immediate backup operation is highly required	0.9-1.0

2.6.2 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, n.d.). For this to happen, Equation (15) is adjusted to only accommodate two elements of qualitative risk assessment matrix which are hazard and vulnerability, please refer to Equation (16) below.

$$R = H \times V \tag{16}$$

In Equation (16), 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 46.0 and Table 47.0 (Fell, 2000).

Table 46.0 Qualitative Measures of Likelihood of Landsliding (Hazard Measurement)

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 47.0 Qualitative Measures of Consequences to Property (Vulnerability Measurement) (Fell, 2000)

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 46.0 and 47.0 translates into Table 48.0 which is 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, 2000).

Table 48.0 International Standard Risk Assessment Matrix (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	L-M
Possible	H	H	M	L-M	VL-L
Unlikely	M-H	M	L-M	VL-L	VL
Rare	M-L	L-M	VL-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:

a. 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, 2000).
b. Risk index is relatively simple and straightforward therefore is ideal for non-expert to judge based on landslide cases (Corangamite Catchment Management Authority, 2012).
c. Ideally used when information related to quantitative landslide risk assessment is absence (Pellicani et al., 2017)
d. In reference to Table 17.0 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.

2.7 Conclusions

Detailed advantages and disadvantages for each vulnerability based on matrices, curves and indicators have been shown in Table 10.0 In general the issues of each method can be grouped into the following aspects:

a) Data requirement and availability
b) Subjectivity and uncertainty of the approahes
c) Applicability of the methods
d) Transferability of the methods

Generally, the quantitative approach of landslide vulnerability assessment through the application of vulnerability curves requires huge amount of record compilation for landslide damages. On the other hand, the application semi-quantitave and qualititave approaches using IBM and vulnerability matrices requires less amount and detailed information. However the subjectivity and uncertainty of these methods are higher compared to the quantitative approach. In terms of the applicability of the method, the semi-quantitative method are more popular for decision maker with its versatile approach in selection of indicators and estimation of the final vulnerability value for a specific element-at-risk. The methods allows participations of non-expert users for data collection and it can be relatively easy to be used by the owner of the element-at-risk to estimate the vulnerabiltity index for their properties. Furthermore, the use of Geographical Information System (GIS) in the vulnerability assessment allows spatial analysis for “what if” scenario on the vulnerability data for example analysis that aims at reducing vulnerability and risk by applying specific mitigation measures. However previous studies have also strongly suggested the inclusion of the landslide hazard intensity in the vulnerability assessment. In addition detailed method of vulnerability index classification (e.g. low, medium and high vulerability level) and its corresponding description of damages should be defined carefully for each element-at-risk. In general the vulnerability assessment method (model, indicators, weight and indicators) are scale and area dependent. Thus, the scales and requirement of end users should be defined before the selecting the suitable method for the vulnerability assessment. Furthermore, different area would have different physical vulnerability values that are also influenced by the special coping capability measures implemented by the community in a specific area.

Inevitably in Malaysia the compilation and recording important information of landslide damages are still at early stage. Therefore development of empirical model between landslide hazard intensity with the damage in a quantitavie manners are always hampered with the quality and the quantity of the required data. Thus, based on the literature reviews and current situation in Malaysia, the semi-quantitative IBM method is suitable for landslide vulnerability assessment. In this case, determination of indicators and its corresponding weight values will be highly based on the expert judgments. The assigment of weight will be also assissted with the existing validated quantitative landslide impact models in Malaysia.

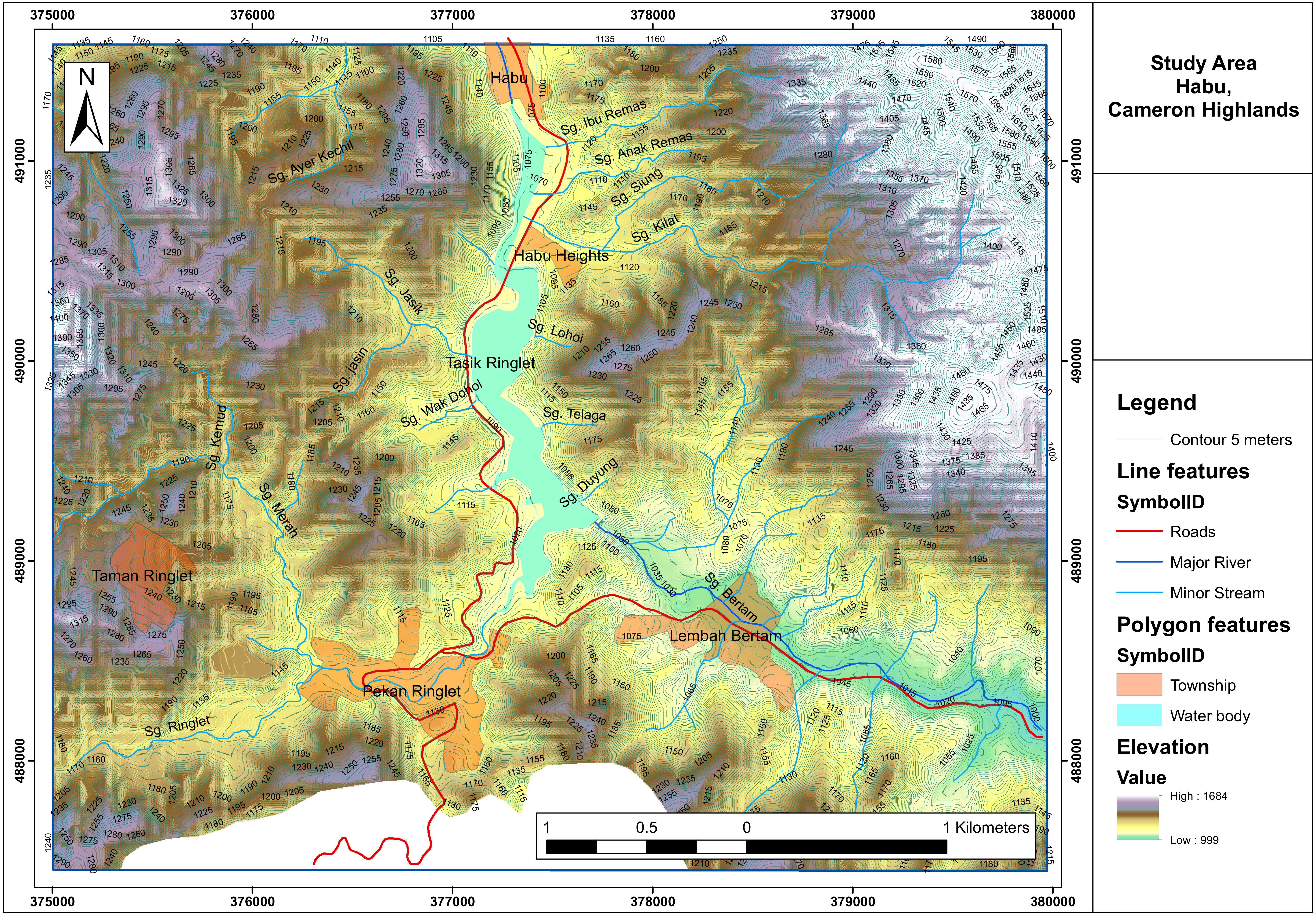
In most of the studies, there are some common indicators used to measure social vulnerability from landslide hazards. Some of these indicators are, for example age, female population, education level and population density. These indicators seem to be a primary information needed to investigate in detail the level of social vulnerability. However, the selection of other indicators is depending on the locality of the study (i.e. site specific) as well as the culture and socio-economic of the people at those areas. For example, different people at different areas might have different understanding on the levels of hazards. Therefore, people with different cultures or economic backgrounds (i.e. from different countries) will certainly need different indicators if the level of social vulnerability is to be quantified. This is not surprised as any social study at one place cannot be generalized at other places without understanding the needs and requirements of the people at the areas. In other words, the selection of detail indicators for social vulnerability study at one area can only be completed if researchers willing to go to the field and meet the related people, experts or other personnel involved through detail interviews, observations, carry out surveys and questionnaires and filling out necessary forms. Data acquired through this session is seen to be more reliable as compared to the desktop study (e.g. literature review) alone because the information obtained describes the status and the conditions of the people from direct observations.

3.0 PROJECT DELIVERABLES

Table 3.0 : Guidelines for Landslide Vulnerability Assesssment and Development of Risk Index for Critical Infrastructure (CI) in Malaysia

Task Name	Duration	Start	Finish	Progress (%)
Inception Report (Objective 1)	16 days	4/6/2018	27/6/2018	10%
Interim Report 1 (Objective 2)	42 days	27/6/2018	27/8/2018	20%
Interim Report 2 (Objective 3)	55 days	3/9/2018	23/11/2018	20%
First Draft Report (Objective 4)	34 days	15/10/2018	3/12/2018	10%
First Draft Final Report (Objective 4)	25 days	4/12/2018	10/1/2019	10%
Final Report (Objective 4)	20 days	11/1/2019	11/2/2019	30%

4.0 APPENDICES


Study Area
Habu,
Cameron Highlands
Legend
Contour 5 meters
Line features
SymbolID
Roads
Major River
Minor Stream
Polygon features
SymbolID
Township
Water body
Elevation
Value
High : 1684
Low : 999
N
1 0.5 0 1 Kilometers
375000
376000
377000
378000
379000
380000
491000
490000
489000
488000
Habu
Sg. Ibu Remas
Sg. Anak Remas
Sg. Ayer Kechil
Sg. Siung
Sg. Kilat
Habu Heights
Sg. Jasik
Sg. Lohoi
Tasik Ringlet
Sg. Jasin
Sg. Wak Dohol
Sg. Telaga
Sg. Kemud
Sg. Merah
Sg. Duyung
Taman Ringlet
Sg. Bertam
Lembah Bertam
Pekan Ringlet
Sg. Ringlet

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