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(CONSTRUCTION INDUSTRY STANDARD)

CIS # :

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

Descriptor: Landslide risk assessment, critical infrastructure, risk classification

Construction Industry Development Board Malaysia

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LANDSLIDE VULNERABILITY ASSESSMENT AND DEVELOPMENT OF RISK INDEX FOR CRITICAL INFRASTRUCTURE IN MALAYSIA

CIDB MALAYSIA

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COMMITTEE REPRESENTATION

This Construction Industry Standard Industry (CIS) was managed and developed by the Construction Industry Development Board Malaysia with the assistance of the Technical Committee of CIS for Landslide Vulnerability Assessment and Development of Risk Index for Critical Infrastructure in Malaysia which comprises representative from the following organizations;-

Agensi Pengurusan Bencana Negara (NADMA)
Board of Engineers Malaysia (BEM)
Board of Geologists Malaysia (BoG)
Jabatan Kerja Raya Malaysia (JKR)
Jabatan Mineral & Geosains Malaysia (JPS)
Jabatan Perancangan Bandar & Desa (PLANMalaysia)
Kementerian Pembangunan & Kerajaan Tempatan (KPKT)
Kumpulan IKRAM
Majlis Perbandaran Ampang Jaya (MPAJ)
Master Builders Association Malaysia (MBAM)
Slopewatch
The Association of Consulting Engineers Malaysia (ACEM)
UEM Sunrise Berhad
Universiti Sains Malaysia (USM)
Universiti Teknologi Malaysia (UTM)
Veritas Planning Sdn Bhd

PREFACE

This Construction Industry Standard (CIS) hereby referred as CIS ##: #### was developed as Construction Industry Standard for Landslide Vulnerability Assessment and Development of Risk Index for Critical Infrastructure in Malaysia by the Construction Industry Development Board (CIDB) Malaysia which acted as a moderator and facilitator for the technical committee throughout the development process of this standard.

Compliance with this Construction Industry Standard does not of itself confer immunity from legal obligations.

In the event of a dispute in the computation methods/formulas/parameters/assumptions, criteria published and used by the Department of Irrigation and Drainage will have an upper hand or superceed this document.

Any feedback or questions on this document should be directed to CIDB at www.cidb.gov.my.

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

SECTION 1: GENERAL

1.1 Purpose

The Construction Industry Standard (CIS) for Landslide Vulnerability Assessment and Development of Risk Index for Critical Infrastructure (CI) In Malaysia is developed to establish the minimum requirements and duties for implementing landslide risk assessment in Malaysia and provide guidance on its implementation.

This CIS aims to provide a systematic and objective approach to identifying risk and vulnerability and analyzing their associated landslide risks. This CIS must be read with the Guidelines for Landslide Vulnerability Assessment and Development of Risk Index for Critical Infrastructure in Malaysia and the Manual for Landslide Vulnerability Index and Risk Classification for Critical Infrastructure (CI) in Malaysia.

This CIS is intended to provide a systematic vulnerability and risk classification method. As this CIS is based on a semi-quantitative approach, the developed sub-indicator weightage can be used to calculate a vulnerability index, which can then be used to determine a vulnerability class and produce a vulnerability map. A CI risk classification can be determined using the procedure outlined in this CIS.

The purpose of vulnerability analysis is to assist construction industry stakeholders in evaluating the CI vulnerability, which represents the interactions between the disastrous event and the element-at-risk. The risk classification is based on vulnerability and hazard class. For new development, the risk class would indicate whether the project areas affected by the project require further planning and design judgements. For existing CI, the risk class should be able to assist with the maintenance, monitoring and mitigation plan, where higher risk class areas should be given priority.

This CIS employs a semi-quantitative vulnerability and risk classification method, incorporating a heuristic approach based on on-site data and expert judgment. The risk of a landslide can be calculated using the hazard multiplied by the vulnerability.

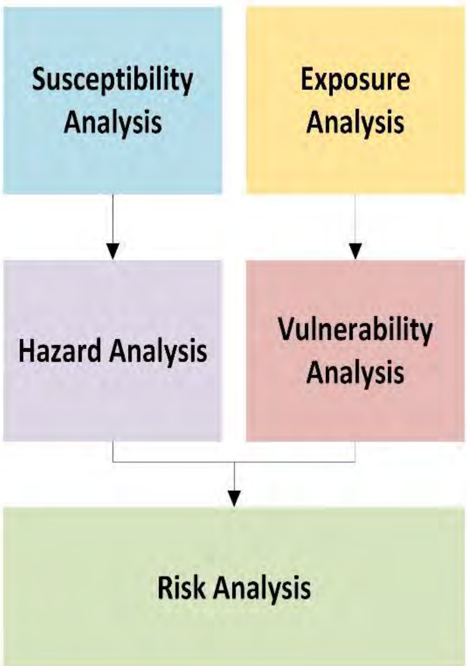

Figure 1-1: Simplified Framework for Landslide Risk Analysis

The coverage of this CIS framework extends to the level of analysis, with explicit emphasis on vulnerability analysis and then risk analysis. The hazard analysis part of this CIS focuses only on the fundamental concept and principle.

Figure 1-1 shows the simplified framework for landslide risk analysis. It comprises five main categories of analysis: susceptibility analysis, hazard analysis, exposure analysis, vulnerability analysis, and risk analysis. Hazard and vulnerability analyses are essential prerequisites for the subsequent risk analysis.

Table 1-1 outlines the topic, analysis and output of the sections in this CIS. The sequence of producing the risk classification and the risk map includes the calculation of vulnerability index, identification of vulnerability class, development of vulnerability map, and identification of risk class and development of risk map.

Table 1-1: Outlines of the topic covered, the analysis, and the outcomes in this CIS

Section	Topic	Analysis	Output
2.2	Landslide Hazard Analysis Framework	Susceptibility and hazard	Hazard Class
2.3	Landslide Vulnerability Analysis Framework	Semi-quantitative approach consists of four clusters	Vulnerability Class
2.4	Landslide Risk Classification Matrix	Hazard class and vulnerability class	Risk Class
3.2	Development of Inventory, Critical Infrastructure, Exposure Analysis and Hazard Maps	Digital Elevation Model (DEM) of Hillshade	Landslide Inventory Map
		High spatial resolution remote sensing data	Critical Infrastructure Map
		Critical Infrastructure map and Landslide Inventory Map	Landslide exposure map
		Landslide inventory, causal factors and triggering factors	Landslide Hazard Map
3.3	Landslide Vulnerability Cluster Maps	The weightage of each indicator and sub-indicator of CI polygons is determined, and map created by Geographic Information System (GIS)	CI Susceptibility (C) Map
			Surrounding Environment (E) Map
			Intensity of Landslide Hazard (I) Map
			People Affected (P) by Damaged CI Map
3.4	Landslide Vulnerability Map for Critical Infrastructure	Combination of all maps: (C) Map, (E) Map, (I) Map and (P) Map	Landslide vulnerability map
4.1	Landslide Vulnerability Index	Determination of indicator and weightage of C, E, I and P	Landslide Vulnerability Index
4.4	Landslide Vulnerability Classes for CI	Landslide Vulnerability Index	Landslide Vulnerability Class

1.2 Scope

The CIS is subjected to the following:

i. Must be read together with the Guidelines for Landslide Vulnerability Assessment and Development of Risk Index for Critical Infrastructure (CI) in Malaysia and the Manual for Landslide Vulnerability Index and Risk Classification for Critical Infrastructure (CI) in Malaysia.
ii. The standard only covers landslide vulnerability assessment and risk classification.
iii. The standard only covers ground surface CI and does not apply to sub-surface structures such as tunnels, tunnel roads, underground utilities or any other underground structure.
iv. The landslide vulnerability and risk analysis **ONLY FOCUS** on Critical Infrastructures: residential houses, buildings, roads, dams, and utility towers.
v. The landslide types include only rotational slides, translational slides and debris flow.
vi. The generation of landslide vulnerability and risk maps requires a landslide hazard map. Landslide hazard maps should follow specific criteria, such as the level of detail in spatial and temporal. Therefore, generating these maps will depend on the quality of the study area's landslide hazard map.
vii. The field-based vulnerability and risk analysis validation will consider the area's typical landslides and Critical Infrastructures.
viii. The social vulnerability indicator concerning landslides is based on a literature review and shall be identified for future studies.

1.3 Normative references

The following normative reference is indispensable for applying this construction industry standard. For dated reference, only the edition cited applies. The latest editions of the normative reference (including any amendments) apply for undated references.

The existing acts, regulations and guidelines on development planning and development in the hilly area are referred to as follows:

i. Akta 171: Akta Kerajaan Tempatan, 1976
ii. Akta 172: Akta Perancangan Bandar dan Desa, 1976
iii. National Slope Master Plan, 2009
iv. Garis Panduan Perancangan Pembangunan Di Kawasan Bukit dan Tanah Tinggi, KPKT, 2009
v. Guideline for Development Planning on Hills and Slopes in the Federal Territory – KWP GPWPKL, 2010
vi. Garis Panduan Pengelasan Zon Bahaya di Sekitar Batu Kapur, JMG.GP.15, 2013
vii. Garis Panduan Perancangan Pembangunan Di Kawasan Bukit dan Tanah Tinggi Negeri Selangor, 2015
viii. Environmental Quality (Prescribed Activities) (Environmental Impact Assessment) Order 2015. Federal Government Gazette. PU (A) 195, 2015
ix. Akta 133: Akta Jalan, Parit Dan Bangunan (Pindaan), 2019
x. Garis Panduan Perancangan Bandar Berdaya Tahan Bencana di Malaysia, KPKT, 2019
xi. Manual OSC 3.0 PLUS, Proses dan Prosedur Cadangan Pemajuan Serta Pelaksanaan Pusat Setempat (OSC), Edisi Pertama, 2019
xii. Guideline for Agriculture Activity on Steep Hill Slopes – Agriculture Department, 2020
xiii. Penang Safety Guideline For Hill Site Development, 2020
xiv. Garis Panduan Ulasan Cadangan Pemajuan Untuk Pusat Setempat Pihak Berkuasa Tempatan (OSC), JMG.GP.08, Edisi kedua, 2021
xv. Garis Panduan Pemetaan Geologi Terain, JMG.GP.06, Edisi kedua, 2021

Under Act 172, all development must obtain planning approval before work starts. The development includes any ground modification, including removing the earth or changing the building or any part thereof. All states require detailed information, analyses and designs upon submission for approval. This CIS shall be used as complementary to existing rules and guidelines. This application is suitable for assisting in decision-making and early assessment as part of the approval process.

Several states require additional information and specific designs for approval submission for hillside development. In Selangor, based on Garis Panduan Pembangunan Di Kawasan Bukit dan Tanah Tinggi Negeri Selangor (2015), all slopes exceeding 25 degrees must submit planning approval. In Penang, the submission of the geotechnical report is required for Classes 2, 3 and 4 hillsides (above 15 degrees). All geotechnical reports must be submitted to the Committee for Development on Land with Risk, Penang (*Jawatankuasa Tanah Berisiko Negeri Pulau Pinang*) for approval.

1.4 Terms and definitions

For this document, the following terms and definitions apply.

i. **Critical Infrastructure** – a range of engineered systems, assets, and facilities essential for day-to-day societal functions and continued economic and societal functioning in the aftermath of a disaster (Bach et al., 2014).
ii. **Development of Risk Index** – referring to developing a risk index for critical infrastructure based on this CIS.

iii. **Element-at-risk** – includes the population, buildings and engineering works, economic activities, public services utilities, other infrastructures, and environmental values in the area potentially affected by the landslide hazard (Fell et al., 2008).

iv. **Geospatial** – Geospatial data or geographic information is data or information that identifies the geographic location of features and boundaries on earth, natural or human-made.

v. **Landslide** – Several processes that result in the downward and outward movement of slope-forming materials, such as rock, soil, man-made filling, or a combination of these (UNISDR, 2017)

vi. **Landslide Hazard** – the likelihood of a landslide in an area. It is a function of susceptibility (spatial propensity to landslide activity) and temporal frequency of landslide triggers (UNISDR, 2017).

vii. **Landslide Susceptibility** – the possibility of potential landslides based only on the site's physical assets. It is the relative spatial likelihood for the occurrence of landslides of a particular type and volume (Van Westen, 2016).

viii. **Landslide Vulnerability** – the degree of loss of a given element or set of elements exposed to the occurrence of a landslide of a given magnitude or intensity. It is often expressed on a scale of 0 (no loss) to 1 (total loss) (Corominas et al., 2014).

ix. **Remote sensing** – Deriving information about the earth's land and water surfaces using images acquired from an overhead perspective, using electromagnetic radiation in one or more electromagnetic spectrum regions, reflected or emitted from the earth's surface (Campbell and Wynne, 2011).

x. **Risk** – The combination of the probability of an event and its negative consequences. Risk measures the probability and severity of an adverse effect on life, health, property, or the environment. Risk = Hazard × Vulnerability.

xi. **Vulnerability Assessment** – The characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard (UNISDR, 2008).

xii. **Vulnerability Index** – the conditions determined by physical, social, economic, and environmental factors or processes that increase an individual's susceptibility, a community, assets, or systems to the impacts of hazards (U.N. Office for Disaster Risk Reduction, 2017).

1.4.1 Landslide Types

Landslides are classified according to the type of material involved and the mode of movement. Table 1-2 shows the abbreviated version of Varnes's classification of slope movements (Varnes, 1978). Figure 1-2 depicts the major types of landslide movement. Typically, landslide movement explains the actual internal dynamics of how landslide mass conducts and displaces fall, slip, topple, or flow. The typical landslide types in Malaysia are rotational and translational slides, rock falls and debris flow.

Table 1-2: The abbreviated version of Varnes classification of slope movements (Varnes, 1978)

TYPE OF MOVEMENT		TYPE OF MATERIAL		
		BEDROCK	ENGINEERING SOILS	
			Predominantly Coarse	Predominantly Fine
Falls		Rockfall	Debris fall	Earthfall
Topples		Rock topple	Debris topple	Earth topple
Slides	Rotational	Rockslide	Debris slide	Earth slide
	Translational			
Lateral spreads		Rock spread	Debris spread	Earth spread
Flows		Rock flow	Debris flow	Earth flow
Complex		Combination of two or more principle type of landslide		

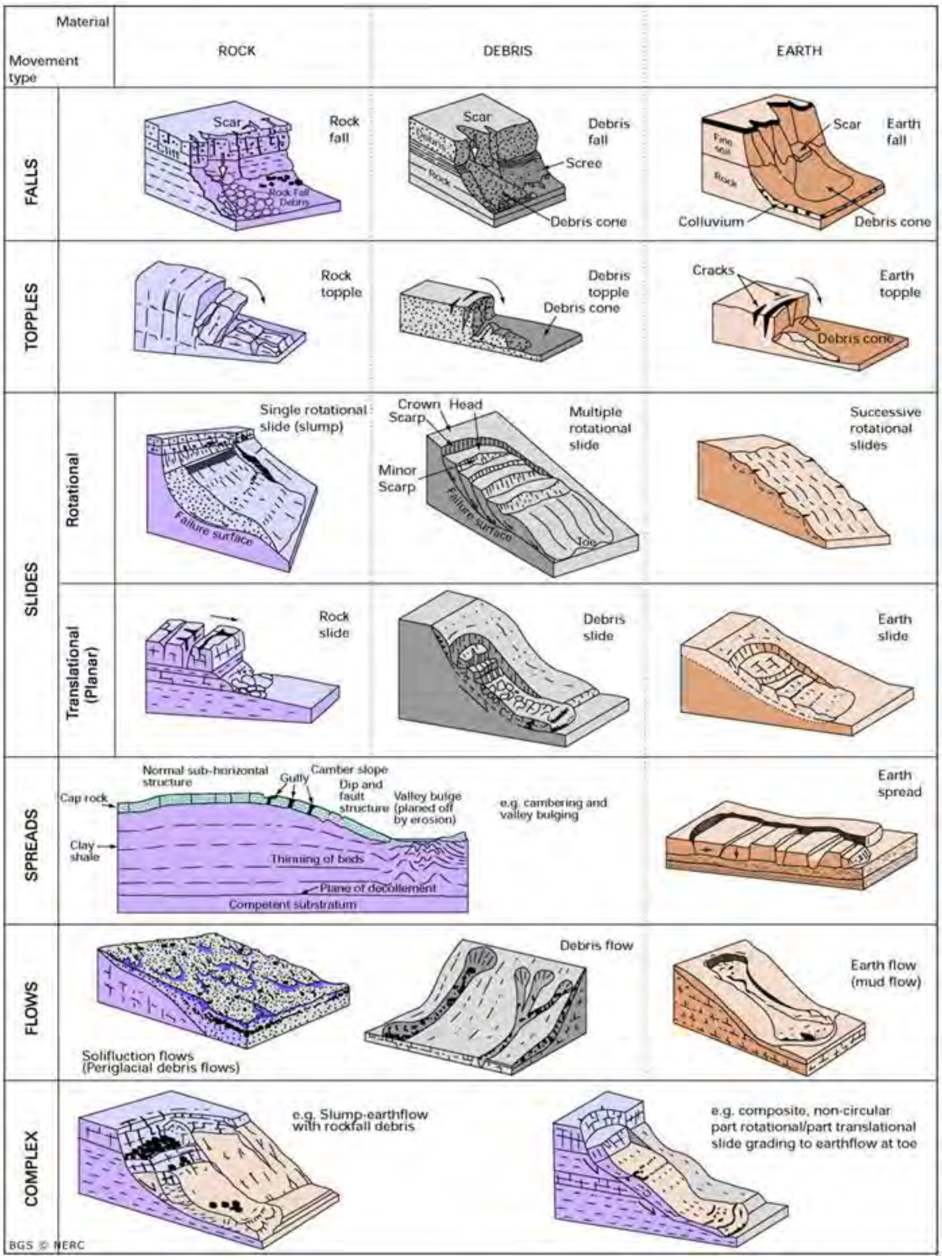

Figure 1-2: Landslide movement types based on Varnes slope movement classification (British Geological Survey (BGS), 2017)

1.4.2 Critical Infrastructure

Critical Infrastructure (CI) is defined as "infrastructures whose services are so vital that their disruption would result in a serious, long-lasting impact on the economy and the society". Critical infrastructures include energy supply, transportation, information and telecommunication, water and solid waste systems (World Economic Forum, 2017). These systems are vulnerable to extreme climate change, as most are built on the assumption that the climate is stationary (Klein Tank et al., 2009). Besides, they are highly interconnected and heavily dependent on each other, so a disturbance can cascade through all these systems and affect the entire critical infrastructure system's functioning (Rinaldi et al., 2001).

Examples of critical infrastructure under vulnerability or element-at-risk where landslide vulnerability assessment is used in land use planning are in Table 1-3.

Table 1-3: Vulnerabilities or elements-at-risk for infrastructure assessment

Physical Vulnerability or Element-at-risk	Suggested Infrastructure for Assessment
Residential land development	i. New urban areas ii. Redevelopment of urban areas iii. Subdivision of rural land
Residential development controls in existing urban areas potentially affected by landsliding	i. Within the local government area ii. Citywide
Development of important Infrastructure	i. Hospitals, schools, fire brigades, and other emergency services ii. Critical communication infrastructure iii. Major lifelines, such as transport, water, and gas pipelines and electricity power lines
Development of new or redevelopment of existing highways, roads, and railways	i. Rural roads ii. Urban main roads iii. Urban subdivision roads
Dam	i. Dam construction to control river flooding and debris flow along the identified potential river channel, with main dams (sabo dams, comb dams) at the upper stream and check dams at the mid-low stream

SECTION 2: LANDSLIDE RISK ANALYSIS FRAMEWORK

The landslide risk analysis framework involves susceptibility, hazard, exposure, and vulnerability analysis for CI. A vulnerability index (VI) will be generated through these processes to establish vulnerability and risk maps. This map could assist construction stakeholders in evaluating the risk associated with the planning permission and development planning.

2.1 Landslide Risk Analysis Framework

Figure 2-1 shows a detailed Landslide Risk Analysis Framework showing the adopted indicator-based method (IBM) analysis. The Landslide Analysis Framework comprises distinct stages, each contributing to a comprehensive understanding of landslide risk. By systematically analyzing susceptibility, hazard, exposure, vulnerability, and risk, this approach provides valuable insights for informed decision-making and risk management strategies. The key components and processes include:

1. **Susceptibility Analysis**
   a) The analysis utilizes environmental factors and landslide inventories for spatial probability determination (linear-based or area-based).
   b) Environmental factors include geological factors, soil type, land use, and hydrology (rainfall intensity).
   c) Landslide inventory includes historical records with location, type, time, magnitude, and related activities.
   d) The critical step in susceptibility analysis is generating a comprehensive landslide inventory based on reliable data and study area size.

2. **Hazard Analysis**
   a) Reveals the magnitude of threatening processes, past, recent, and future landslides.
   b) Hazard maps depict landslide types, extent, and hierarchy of hazards.
   c) The analysis considers susceptibility maps/analysis and landslide triggering factors (rainfall data and/or earthquake).

3. **Exposure Analysis**
   a) Based on data gathered on location, element-at-risk, and public values (including population, buildings, infrastructure and factories).
   b) The analysis can identify elements that are vulnerable to the impact of hazards.

4. **Vulnerability Analysis**
   a) Assesses the likelihood of elements that could be damaged when exposed to hazards.
   b) Elements considered: Infrastructures (C), surrounding environment (E), landslide intensities (I), and population (P).
   c) The analysis methods include vulnerability curves, matrix, and indicator-based methods (IBM).

5. **Risk Analysis**
   a) Risk analysis integrates susceptibility, hazard, exposure, and vulnerability analysis.
   b) There are three approaches to analyzing risk:
      i. Quantitative approach: Combines hazard, vulnerability, and values for risk determination.
      ii. Qualitative approach: Utilises risk matrix to classify risks.
      iii. A semi-quantitative: This framework emphasizes the semi-quantitative method for vulnerability analysis and risk classification. A heuristic approach is considered in this framework based on on-site data and expert judgement.

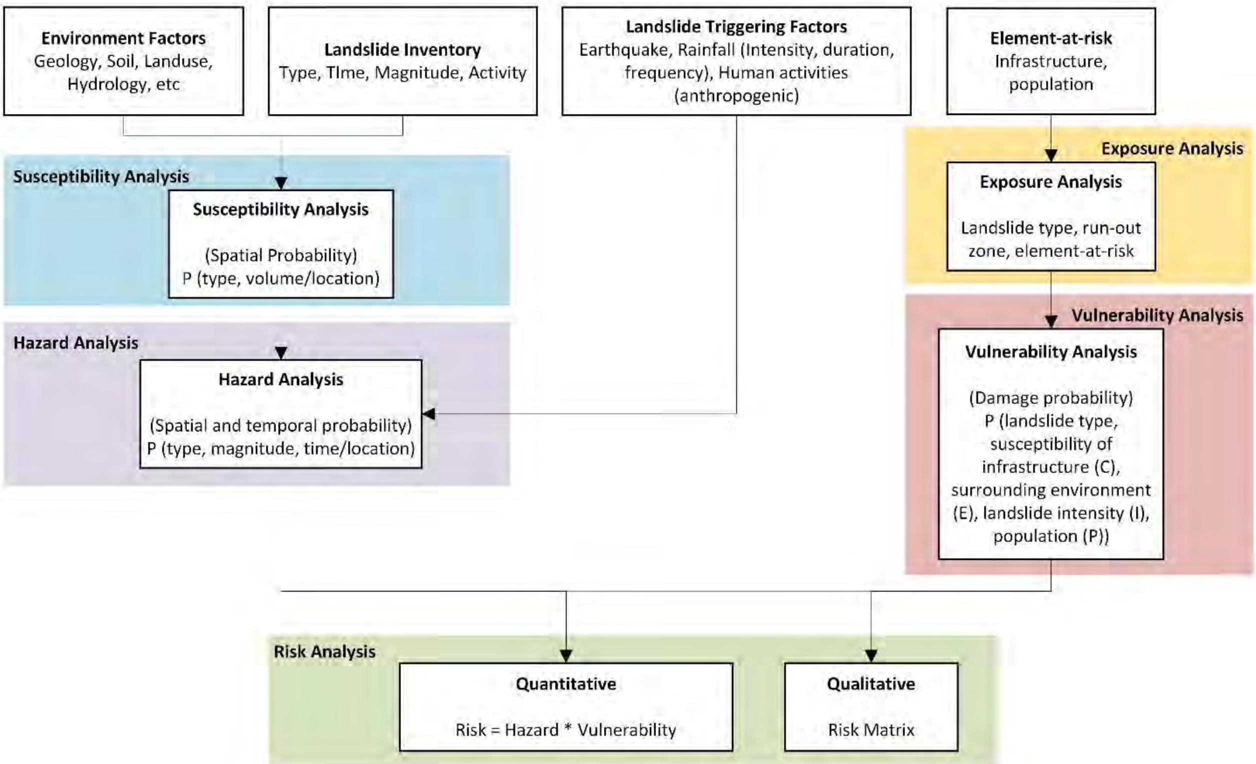

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Figure 2-1: Flow chart of landslide risk analysis showing the adopted indicator-based method of analysis

2.2 Landslide Hazard Analysis Framework

Figure 2-2 shows the landslide hazard analysis framework. Landslide hazard analysis is conducted by selecting a suitable analysis condition (linear-based or area-based). Input data is collected based on environmental factors, landslide inventory and triggering factors. Depending on the data quantity and quality, the susceptibility and hazard analysis can be done using quantitative, qualitative or semi-quantitative approaches.

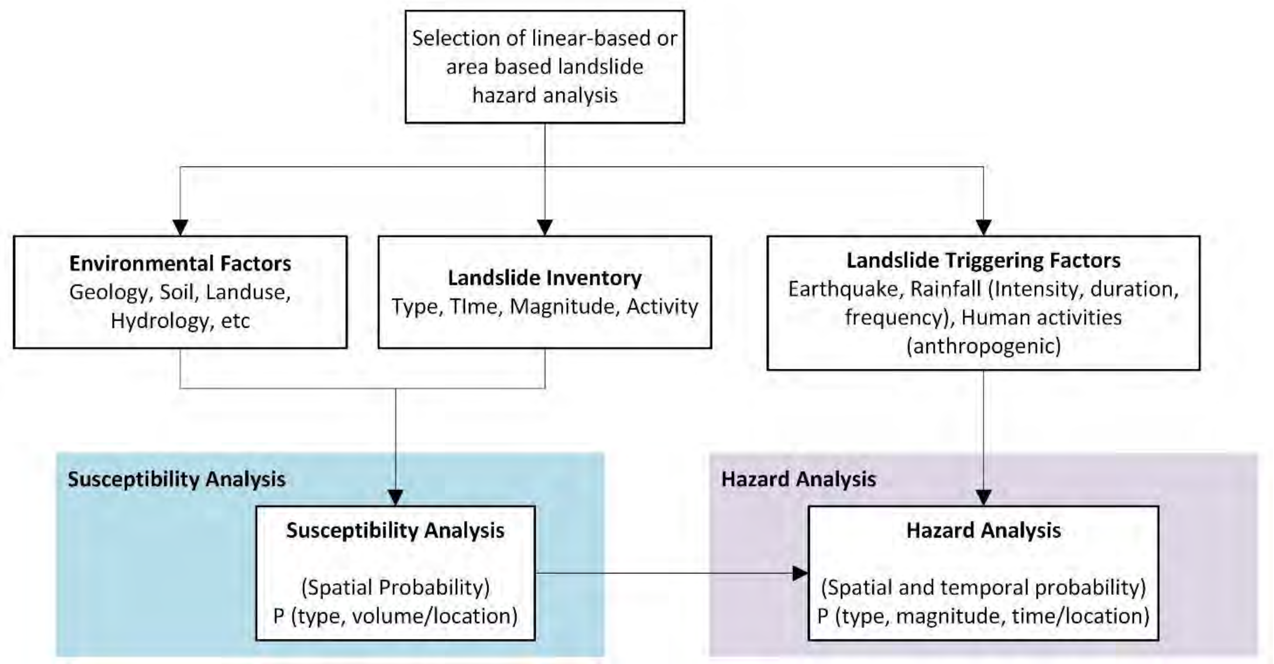

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Figure 2-2: Landslide Hazard Assessment Framework

2.3 Landslide Vulnerability Analysis Assessment Framework

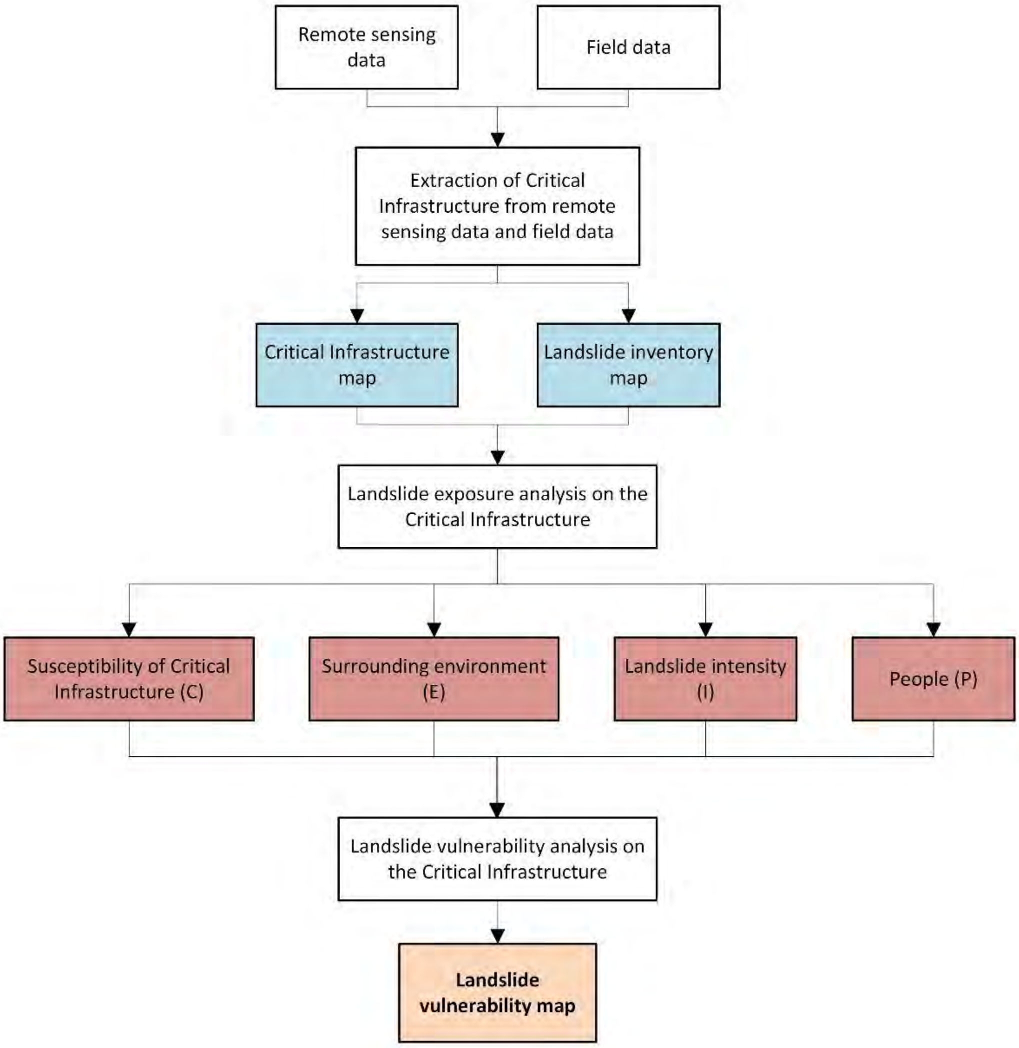
Figure 2-3 shows the landslide vulnerability analysis method and processes.

Landslide vulnerability analysis follows a geospatial-based analysis approach comprising seven stages:

1) Acquisition of remote sensing data and field observations of the location.
2) Extraction of CI from remote sensing data and field data.
3) Creation of landslide inventory and CI maps using data from remote sensing and field observations.
4) Landslide exposure analysis on CI.
5) Generate CI maps based on vulnerability cluster (C, E, I and P) maps.
6) Landslide vulnerability analysis on the CI.
7) Development of landslide vulnerability map for each CI.

Landslide vulnerability analysis is based on the semi-quantitative approach of IBM. The indicator is grouped into four clusters:

i. Critical Infrastructure susceptibility (C).
   - Indicates CI susceptibility to specific landslide hazard intensity based on physical characteristics.
ii. Surrounding environment (E).
   - Considers existing mitigation measures and elements in the vicinity impacting landslide on the CI.
iii. Intensity of landslide hazard (I).
   - Assesses the impact of specific landslide hazard intensity on a given CI.
iv. Susceptibility of individuals affected by damaged CI (P).
   - Analyses effects on residents, road users, downstream populations near dams, and utility service disruptions.



**The colour used in the figure is consistent with all framework figures in this section.*

Figure 2-3: Vulnerability analysis framework encompassing the landslide vulnerability assessment approach

2.4 Landslide Risk Classification Matrix

This section describes the development of the risk classification matrix in qualitative analysis. A risk analysis matrix is employed, aligning with the prevailing literature and practice in landslide risk analysis using a qualitative method. The risk equation is adjusted to accommodate hazard and vulnerability elements.

$$R = H\,x\,V \tag{1}$$

where R = risk, H = hazard, and V = vulnerability.

The proposed measurement method is derived from the Australian Geomechanics Society's Qualitative Measures of Likelihood of Landsliding (Hazard Measurement) and Qualitative Measures of Consequences to Property (Vulnerability Measurement), as exemplified in Table 2-1 and Table 2-2 (Fell et al., 2005). A combination between Table 2-1 and Table 2-2 produces a risk assessment matrix suitable for risk classification. It is based on modifying the risk assessment matrix by Ko Ko et al. (1999) and Fell et al. (2005). The combined likelihood results in a risk assessment matrix divided into five risk index classes from very low risk (VL) to very high risk (VH).

Table 2-1: Hazard measurement – qualitative measures of the likelihood of landsliding (modified after Fell et al., 2005)

Level	Descriptor	Description
A	Very High	The event is expected to occur
B	High	The event will probably occur under adverse condition
C	Moderate	The event could occur under adverse condition
D	Low	The event could occur under very adverse condition
E	Very Low	The event is conceivable but only under exceptional circumstances

Table 2-2: Vulnerability measurement – qualitative measures of consequences to property (modified after Fell et al., 2005)

Level	Descriptor	Description
1	Very High	Structure completely destroyed or large-scale damage requiring major engineering works for stabilization
2	High	Extensive damage to most of the structure or damage extending beyond site boundaries, requiring significant stabilization works
3	Moderate	Moderate damage to some of the structure or a significant part of the site requires large stabilization works
4	Low	Limited damage to a part of the structure or a part of the site requires some reinstatement or stabilization works
5	Very Low	Little damage

Table 2-3: Risk Analysis Matrix (modified after Ko Ko et al., 1999 and Fell et al., 2005)

Likelihood (hazard)	Consequences to property (Vulnerability)				
	Very High	**High**	**Moderate**	**Low**	**Very Low**
Very High	VH	VH	H	H	M
High	VH	H	H	M	M
Medium	H	H	M	M	L
Low	H	M	M	L	VL
Very Low	M	M	L	VL	VL

Legend:

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

SECTION 3: LANDSLIDE VULNERABILITY ASSESSMENT

Landslide vulnerability assessment plays a crucial role in understanding the susceptibility of critical assets to landslides and their associated impacts. This assessment relies on comprehensive geospatial approaches, including inventory analysis, critical infrastructure and hazard mapping. Generating a landslide inventory map involves several steps, utilizing high-resolution Digital Elevation Model (DEM) data combined with contour overlays to delineate landslide areas and attributes. Similarly, critical infrastructure maps are crafted through remote sensing techniques and supervised image classification processes. This mapping provides a foundation for the subsequent landslide exposure analysis, identifying vulnerable infrastructure within the landslide and run-out zones. The hazard mapping process combines inputs such as landslide inventory, causal factors, and trigger elements, focusing on climate-related aspects such as rainfall and seismicity. The outcome is a hazard map presenting varying levels of hazard. By integrating these geospatial methodologies, this study delves into the intricate realm of landslide vulnerability analysis, fostering a comprehensive understanding of the techniques and their implications for effective risk mitigation.

3.1 Data Requirement

Geospatial data shall be utilized to extract and characterize the CI in the study area using various image processing and spatial analysis methods. Table 3-1 shows the data requisite for vulnerability analysis. The output from the landslide hazard and vulnerability project in the study area will generate a landslide risk map. However, the landslide hazard information's applicability will rely heavily on the quality of the hazard map and the need for the proposed vulnerability method.

Table 3-1: Data requirement for vulnerability and risk analyses

Type of Data	Source of Data	Data Information
Critical Infrastructure	In-situ drone-surveyed remotely sensed data, such as LiDAR	Geometric features, footprints, height, size, and length of the CI
	Fieldwork inspection	in-situ vulnerability indicators, and population
Slope information	In-situ drone-surveyed remotely sensed data, such as LiDAR	Slope gradient, slope aspect, plan curvature, stream network, and watershed
	Fieldwork inspection	Classification of the slope, geology, condition of the slope face, drainage system, slope distress, slope stabilization, the scale of failure, slope geometry

Topography map	Department of Survey and Mapping Malaysia (JUPEM)	Slope angle, road, river, contour, and DEM
Aerial photo	Department of Survey and Mapping Malaysia (JUPEM), private sector	Detailed visualization of the study area
Landslide inventory	Department of Mineral dan Geoscience Malaysia (JMG) (Area-based), Public Works Department (PWD) (Linear-based)	Type of landslide, initiation or accumulation area, dimensions of the landslide (length, width, depth), the volume of the landslide, landslide damage, and hazard potential
Landslide hazard map	Department of Mineral dan Geoscience Malaysia (JMG) (Area-based), Public Works Department (PWD) (Linear-based)	Hazard classes (i.e. very low, low, medium, high, and very high) for a specific type of landslide

3.2 Development of Inventory, Critical Infrastructure, Exposure Analysis and Hazard Maps

Table 3-2 summarises the development of inventory, CI, exposure analysis and hazard maps. Detailed explanations of the development of each map are provided in Appendix A.

Table 3-2: Summary of Development of Inventory, CI, Exposure Analysis and Hazard Maps

Map	Data or input	Description
Inventory Map	Hillshade extracted from a high-resolution DEM	For visualization, contours are superimposed on the DEM to show landslide areas, potential run-out zones, and intricate attributes.
Critical Infrastructure Map	High spatial resolution remote sensing data.	Data is used to create Critical Infrastructure maps using parametric and non-parametric algorithms like maximum likelihood, artificial neural network, and support vector machine.
Exposure Analysis Map	Critical Infrastructure map and inventory map	The landslide exposure analysis involves identifying the exposed Critical Infrastructure within the landslide and run-out zones.
Hazard Map	Landslide inventory, causal factors and triggering factors	The landslide hazard map features five distinct categories, ranging from very low to very high.

3.3 Generation of Landslide Vulnerability Cluster Maps

The landslide vulnerability cluster maps are generated depending on the type of CI identified from the Critical Infrastructure maps and the landslide types obtained from the landslide inventory map. The suitable weight value for each landslide cluster's indicators and sub-indicators should be determined and stored in each polygon of the CI in the Critical Infrastructure map. Table 3-3 shows a general description of C, E, I and P cluster maps. All maps are shown in Appendix B.

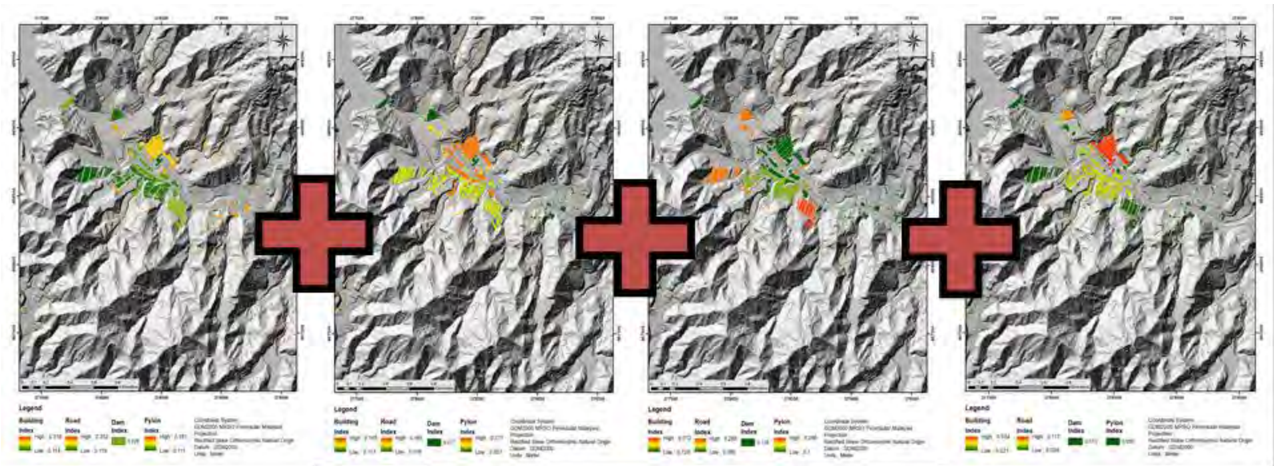
The landslide vulnerability clusters include:
- Susceptibility of the Critical Infrastructure (C)
- Surrounding Environment (E)
- Landslide Intensity (I)
- People (P)

Table 3-3: Summary of Development of Inventory, Critical Infrastructure, Exposure Analysis and Hazard Maps

Map		Description
Critical Infrastructure Susceptibility (C) Map	i.	The Critical Infrastructure map provides essential information regarding the geographical positioning of CI elements.
	ii.	Identify the specific information associated with each indicator and sub-indicator based on each critical infrastructure polygon.
	iii.	The weightage of each indicator and sub-indicator of CI polygons is determined.
Surrounding Environment (E) Map	i.	The Surrounding Environment (E) cluster map generation focuses on how surrounding land features affect critical infrastructure's landslide vulnerability.
	ii.	This process is shown when slope-related risk mitigation reduces CI vulnerability to landslides.
	iii.	The indicators and sub-indicators associated with the Surrounding Environment (E) cluster are examined within a specific spatial range delineated around each polygon representing CI.
Intensity of Landslide Hazard (I) Map	i.	Considers three pivotal indicators:
	o	the accumulation height of the landslide,
	o	landslide thickness
	o	landslide volume
	ii.	Due to the lack of deterministic analyses or surveys at the site, such as geophysics or soil investigation, it is important to note that expert judgement and estimates play a big role in this process. These things make the assessment more complex.
People Affected (P) by Damaged CI Map	i.	The People Affected (P) cluster map is created to understand how CI service disruptions affect the community.
	ii.	Disrupted or damaged CI services could affect the surrounding community. This understanding underpins risk management and informed decision-making.

3.4 Generation of the Landslide Vulnerability Map for Critical Infrastructure

Cluster maps C, E, I, and P are combined to gain a complete understanding of Critical Infrastructure vulnerability to landslides. Equation 1 calculates the Landslide Vulnerability Index, incorporating data from clusters C, E, I, and P. The Vulnerability Index is classified into known vulnerability classes to understand the vulnerability of Critical Infrastructure. The procedure is made simpler by using Figure 3-1 as a visual aid to comprehend how cluster maps are combined.



Map of C cluster Map of E cluster Map of I cluster Map of P cluster

Figure 3-1: Combination of all cluster maps

SECTION 4: LANDSLIDE VULNERABILITY INDEX AND RISK CLASSIFICATION FOR CRITICAL INFRASTRUCTURE

4.1 Determination of Landslide Vulnerability Index

Assessing the vulnerability of landslides is essential for risk analysis, as it reveals elements susceptible to hazards and their associations with potential damages. Vulnerability, measured from 0 (no loss) to 1 (total loss), indicates the extent of event loss to elements-at-risk. Vulnerability indicators offer operational insights into susceptibility, coping capacity, and resilience. In data-scarce areas, the IBM uses relative vulnerability. This section explains the landslide vulnerability index calculation and describes the vulnerability class for specific CI.

Figure 4-1 illustrates the determination of the Landslide Vulnerability Class. The steps are described as follows:

i. Determination of the Critical Infrastructure (CI) and landslide type
ii. The indicators are selected based on C, E, I and P components:
    a) C – Susceptibility of Critical Infrastructure (CI)
    b) E – Surrounding environment
    c) I – Intensity of landslide hazard
    d) P – Susceptibility of People
iii. The sub-indicators are selected. The indicator will be determined based on weightage.
iv. Vulnerability C, E, I or P Cluster Map is generated based on indicator weightage.
v. Calculation of Vulnerability Index
vi. Determination of Vulnerability Class
vii. Vulnerability Index, Class and Description
viii. Vulnerability Map generated based on Vulnerability Class

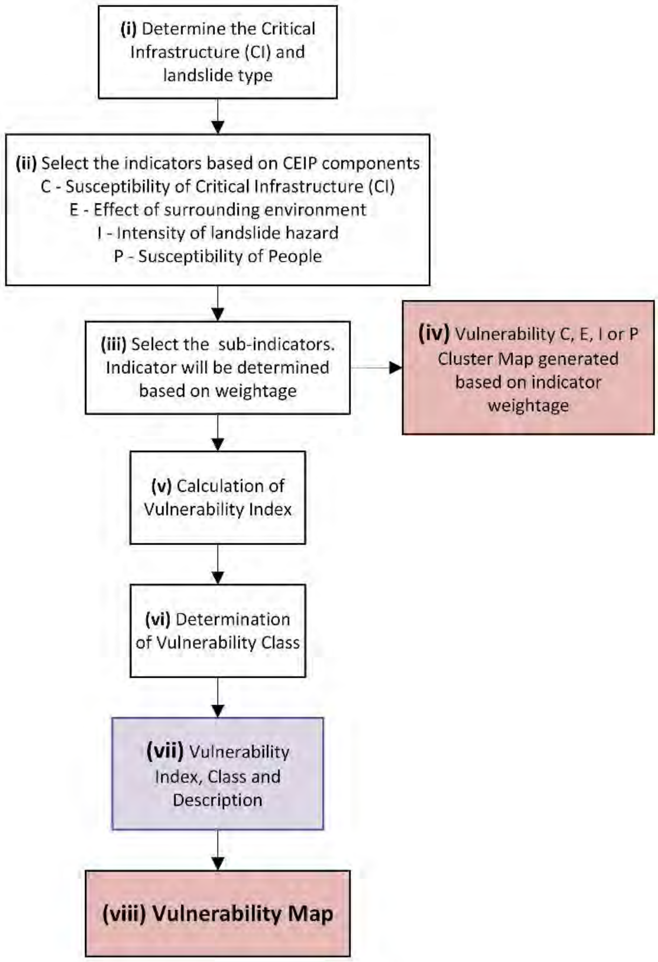


Figure 4-1: Determination of the Landslide Vulnerability Class

4.2 C, E, I and P Indicators, Sub-indicators and Weightage

The selection and determination of suitable cluster indicators and sub-indicators' weightages were made through forums with stakeholders including local authorities, government agencies and professionals with vast experience in Malaysia landslide hazards.

The recommended cluster indicators and sub-indicators are shown in Appendix C and Appendix D. Appendix C shows the group cluster indicators (C, E, I and P) for CI under the translation/rotational landslide type. Appendix D shows CI cluster indicators (C, E, I, and P) under the debris flow type. All tables mentioned show indicators, sub-indicators and weightage relevant to a particular landslide type based on expert judgment and local stakeholders' input. Figure E-1 in Appendix E shows an example of the vulnerability assessment of a building exposed to a translational landslide. The vulnerability of a building-residential for translational landslide type constitutes four clusters, i.e. C, E, I and P with respective indicators, sub-indicators and weightage.

4.3 Cluster Weightage Matrix and Descriptions

The weightage distribution for each cluster C, E, I, and P components must represent each component's degree of contribution towards developing the Vulnerability Index. The vulnerability of any CI shall exist due to two main components i.e landslide hazards and Critical Infrastructure. The cluster weightage value matrix is, as shown in Table 4-1.

Table 4-1: Cluster weightage value matrix

Cluster	Cluster weightage value
Critical Infrastructure (C)	0.33
Surrounding Environment (E)	0.18
Landslide Intensity (I)	0.36
People inside Building (P)	0.13
Total	**1.0**

4.4 Landslide Vulnerability Classes for Critical Infrastructure

Each landslide vulnerability index for a specific CI is classified into five (5) classes, i.e., very low, low, medium, high and very high landslide vulnerability. The class is given a detailed description of the damages and the process that causes the damage (Table 4-2). Different sets of indicators and sub-indicators are defined for a combination of CI and landslide types. This CIS divides the CI into building and residential, road, dam and utility towers.

Table 4-2: Landslide Vulnerability Class for Critical Infrastructures

Critical Infrastructure	Vulnerability Class				
	Very low (0.01-0.19)	**Low (0.20-0.39)**	**Moderate (0.40-0.69)**	**High (0.70-0.89)**	**Very high (0.90-1.00)**
Building and residential	Slight non-structural damage, stability not affected, furnishing or fitting damaged, and no human casualty expected	Cracks in the wall, stability not affected, reparation not urgent and slight injuries of people in the building	Strong deformations, huge holes in the wall, cracks in supporting structures, stability affected, doors and windows unusable, severe injuries and evacuation necessary	Structural breaks, partly destructed, reconstruction of destructed parts, death is highly likely (severe injury), and evacuation necessary	Severely damaged structure or totally destructed, evacuation necessary, complete reconstruction and death is almost certain
Road	Slight damage of road and does not affect any traffic problem	No structural damage with minor repairable damage and slightly affect traffic	No structural damage, major damage requiring major repair work and severe effect on road traffic	Structural damage that can affect the stability and functionality of the road, partly unusable road and requires road diversion	Heavy damage seriously compromising the structural integrity: partial or total collapse of the road, totally unusable road and immediate road diversion is required
Dam	Slight damage of dam and does not affect any problem to the community	No structural damage – minor repairable damage and slightly affect the dam operation	No structural damage –major damage requiring major repair work and severe effect on the dam operation	Structural damage that can affect the stability and functionality of the dam and partly disrupted dam operation	Heavy damage seriously compromising the structural integrity: partial or total collapse of the dam, totally disrupted dam operation and immediate evacuation is required for the community living downstream
Utility Tower	Slight damage of utility and does not affect its operation	No structural damage – minor repairable damage and slightly affect the operation	No structural damage –major damage requiring major repair work and severely affect the operations of such utility	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	Heavy damage seriously compromising the structural integrity: partial or total collapse of the road, a total collapse of utility operation and immediate backup operation is highly required

APPENDIX A Generation of Lanslide Hazard Map

a) Generation of the Landslide Inventory Map

The Landslide Inventory Map, as depicted in Figure A-1, is generated through the adept utilization of hillshade extracted from high-resolution Digital Elevation Model (DEM) data. The DEM is adeptly superimposed with contours, a crucial step aimed at facilitating comprehensive visualization encompassing the delineation of landslide areas, potential run-out zones, and intricate attributes characterizing each landslide. The vulnerability map includes multiple classifications, ranging from very low to high.

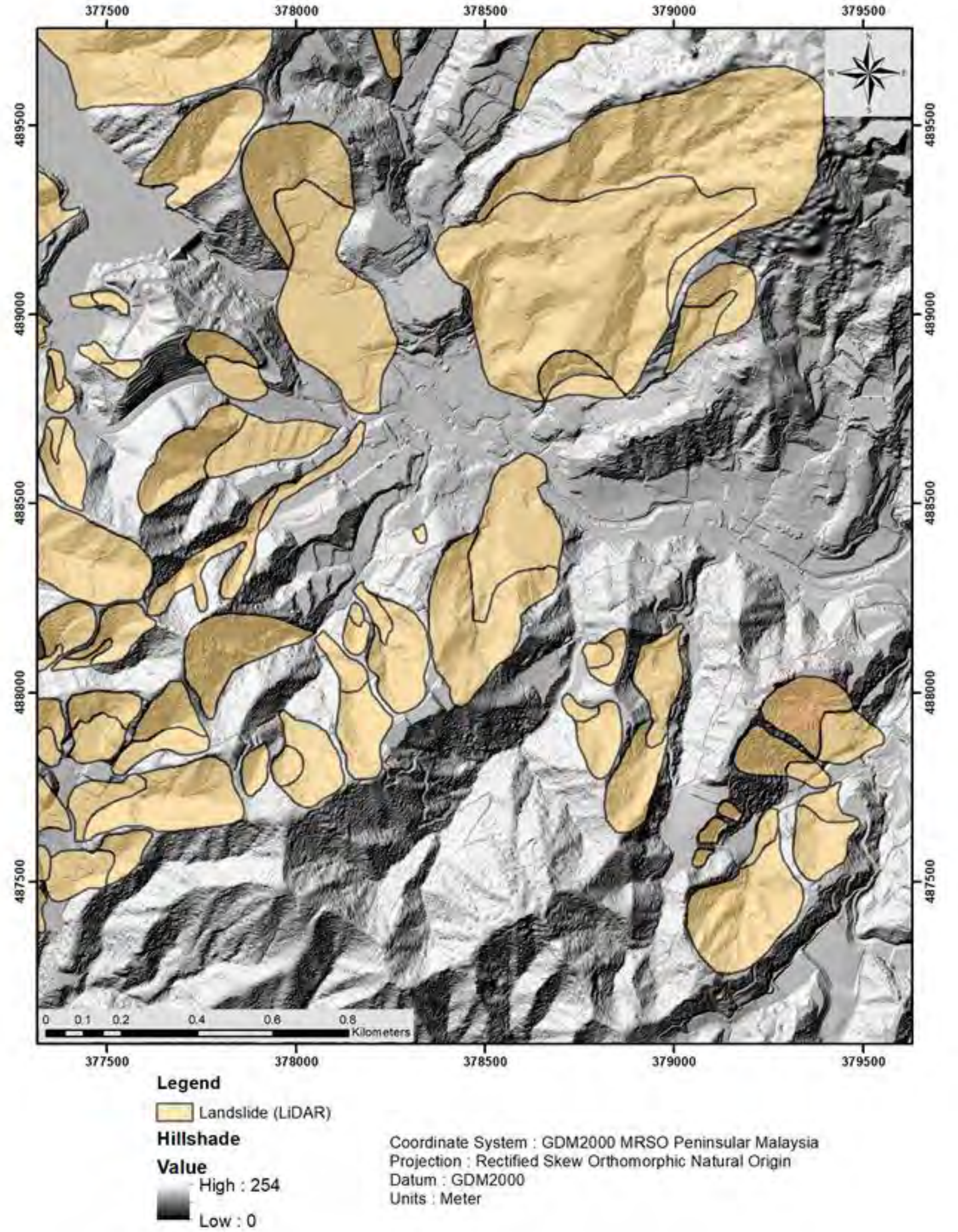


Figure A - 1: Example of derived landslide inventory map of Lembah Bertam, Cameron Highlands.

b) Generation of the Critical Infrastructure Map

The Critical Infrastructure maps boundary created using high-resolution remote sensing data should be delineated manually or based on the digital image classification process. The generation of Critical Infrastructure maps using a digital image processing approach should be based on the supervised image classification process. Various parametric and non-parametric algorithms, such as maximum likelihood, artificial neural network, and support vector machine, can produce Critical Infrastructure maps using high spatial resolution remote sensing data. The classified remote sensing data is in raster format and should be converted into vector format for the next data processing stage. The classified remote sensing data are in raster format and should be converted into vector format in the next data processing stage. Figure A-2 shows the Critical Infrastructure map of Lembah Bertam, Cameron Highlands.

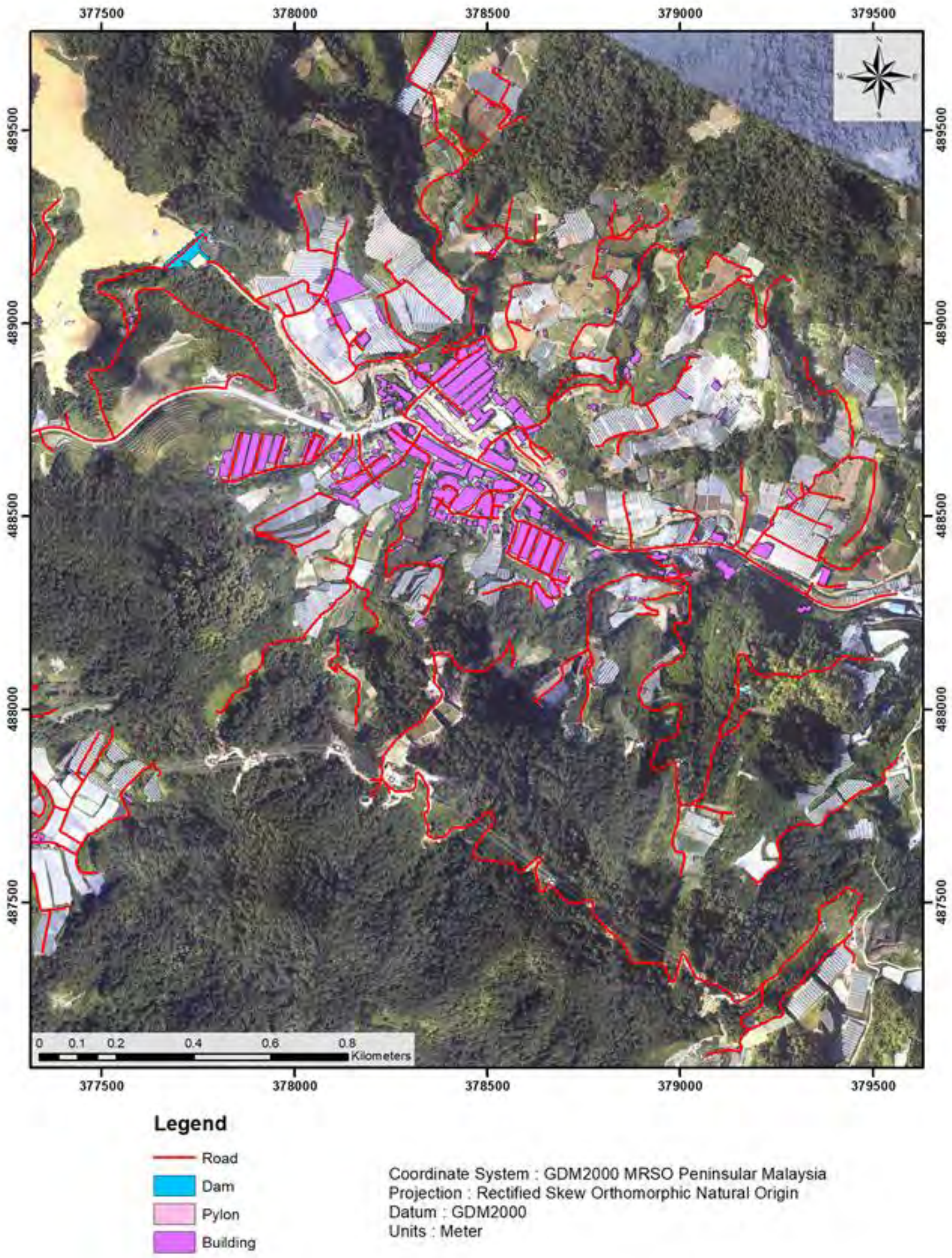


Figure A - 2: Critical Infrastructure map of Lembah Bertam, Cameron Highlands

c) Landslide Exposure Analysis of Critical Infrastructure Map

The landslide exposure analysis involves identifying the exposed Critical Infrastructure within the landslide and run-out zones. The Critical Infrastructure map is overlaid with the landslide inventory map. Critical Infrastructure is marked based on its location, either within the landslide and run-out zones or outside. Figure A-3 shows the landslide exposure map of Lembah Bertam, Cameron Highlands.

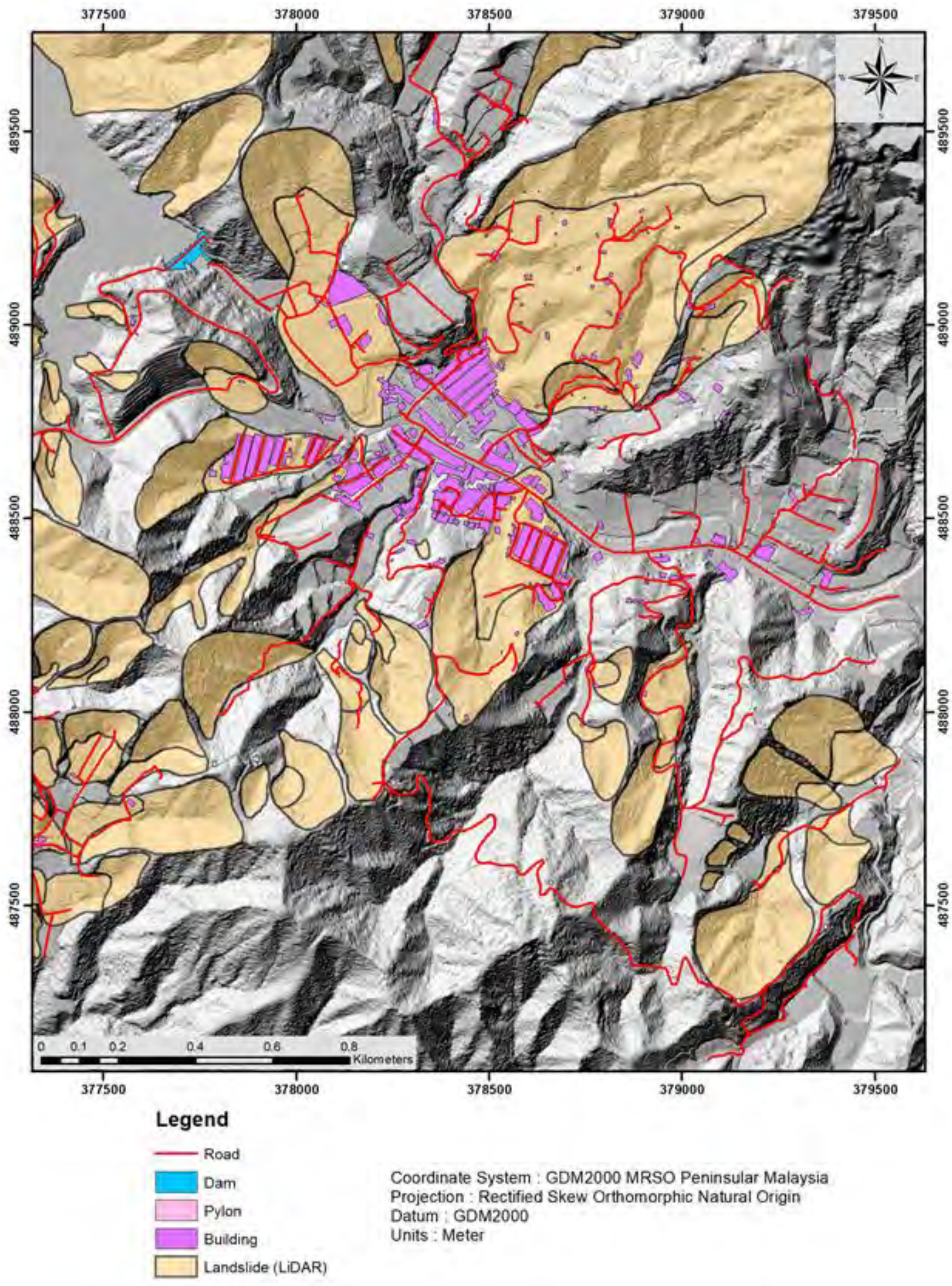


Figure A - 3: Landslide exposure map of Lembah Bertam, Cameron Highlands

d) Landslide Hazard Mapping

A landslide hazard map is formulated through the consolidation of three pivotal inputs:

- Landslide inventory
- Landslide causal factors
- Landslide triggering factors

These factors predominantly encompass climate-related elements, including rainfall and seismicity.

Figure A-4 shows an example of a landslide hazard map. The landslide hazard map features five distinct categories, ranging from very low to very high. Various sources, such as LiDAR and high-resolution satellite imagery, provided geospatial data to develop landslide hazard maps. For verification, a field data collection mission may be planned.

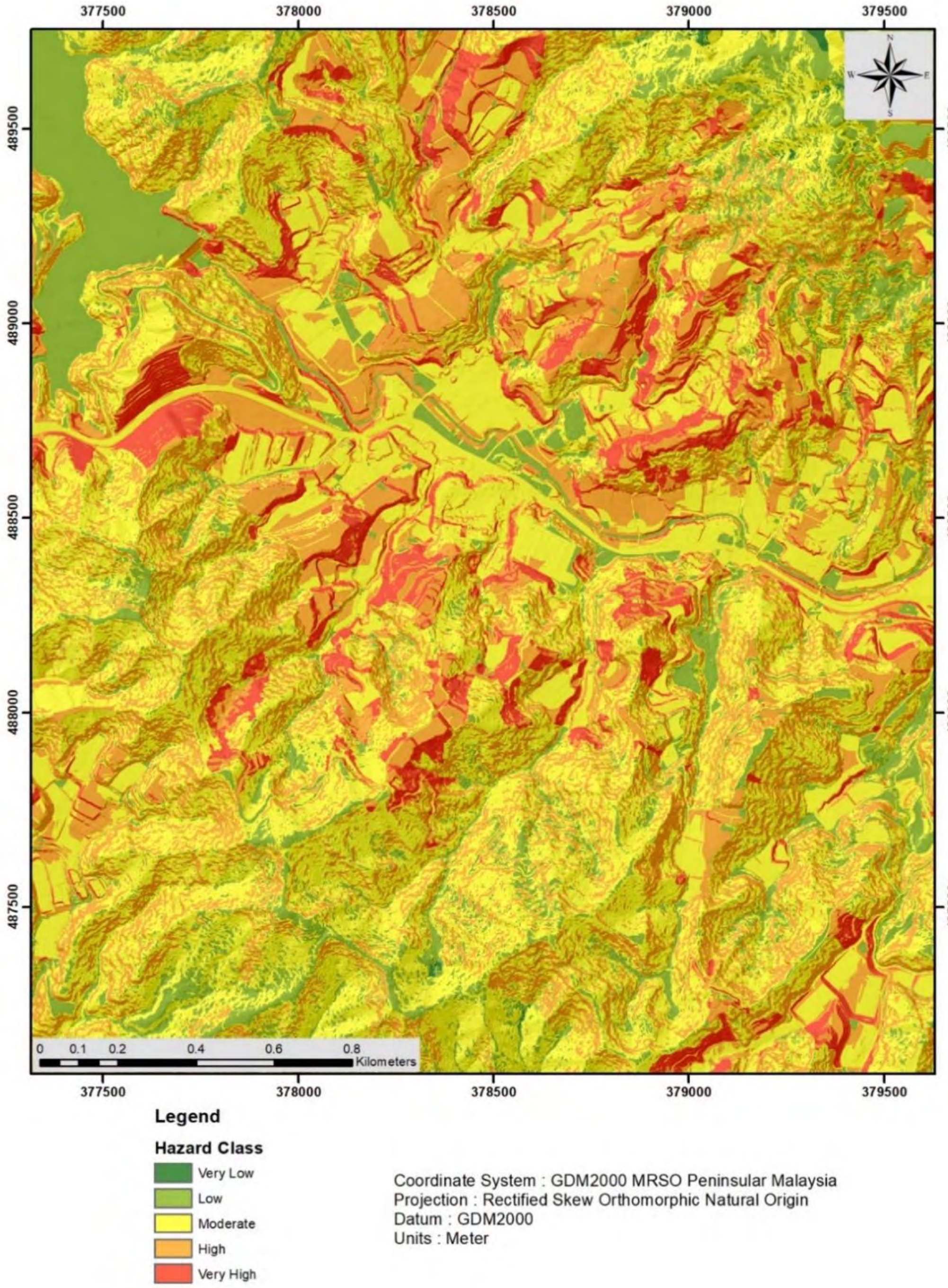


Figure A - 4: Example of a landslide hazard map for Lembah Bertam, Cameron Highlands, Pahang, Malaysia (Department of Mineral and Geoscience Malaysia [JMG], 2018)

APPENDIX B Generation of the Landslide Vulnerability Map for Critical Infrastructure

a) Generation of Critical Infrastructure Susceptibility (C) Map

- The focus of susceptibility of the Critical Infrastructure (C) map generation is to effectively characterize the susceptibility of Critical Infrastructure, encompassing the consideration of all indicators belonging to the C cluster.
- The Critical Infrastructure map provides essential information regarding the geographical positioning of Critical Infrastructure elements.
- A dedicated map for cluster C is generated for each Critical Infrastructure to ensure specificity.
- A crucial step involves determining the detailed information associated with each indicator and sub-indicator, tailored to the unique attributes of every critical infrastructure polygon.
- Weightage assignment constitutes a vital facet, with each indicator and sub-indicator of individual critical infrastructure polygons assigned appropriate weightage values.
- Figure B-1 visually encapsulates the outcomes, illustrating the cluster C map corresponding to the critical infrastructure entities.

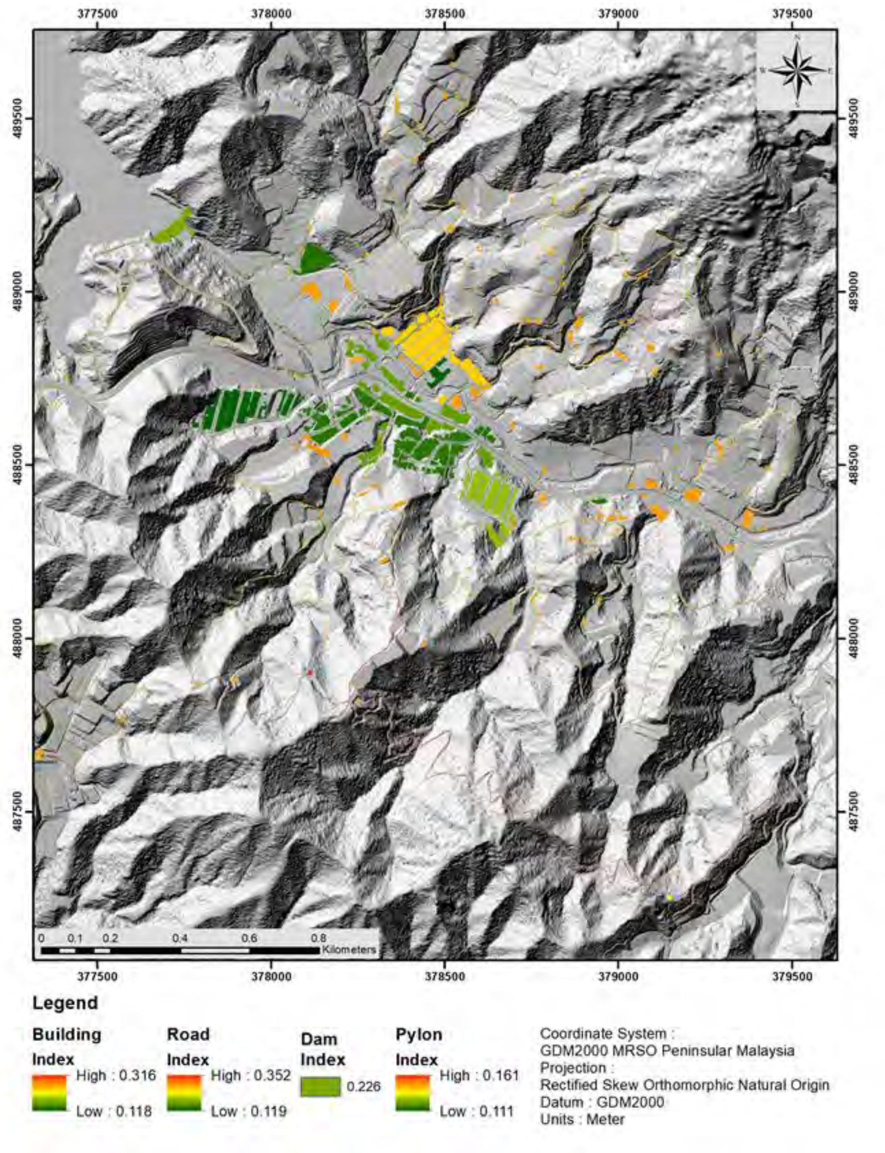


Figure B - 1: Map of cluster C of Lembah Bertam, Cameron Highlands

b) Generation of Surrounding Environment and Mitigation Measures (E) Map

- The primary goal of the Surrounding Environment (E) cluster map generation centres on assessing the impact of surrounding land features upon the vulnerability of critical infrastructure to potential landslides.
- This process is exemplified by instances where measures aimed at mitigating slope-related risks contribute to diminishing the potential impact of a landslide upon critical infrastructure vulnerability.
- The indicators and sub-indicators associated with the Surrounding Environment (E) cluster are examined within a specific spatial range delineated around each polygon representing Critical Infrastructure.
- Precision is ensured by assigning corresponding weight values to both indicators and sub-indicators, aligning with the unique characteristics of each Critical Infrastructure polygon featured on the map.
- The outcomes of this process are visualized in Figure B-2, which portrays the cluster E map corresponding to each Critical Infrastructure.

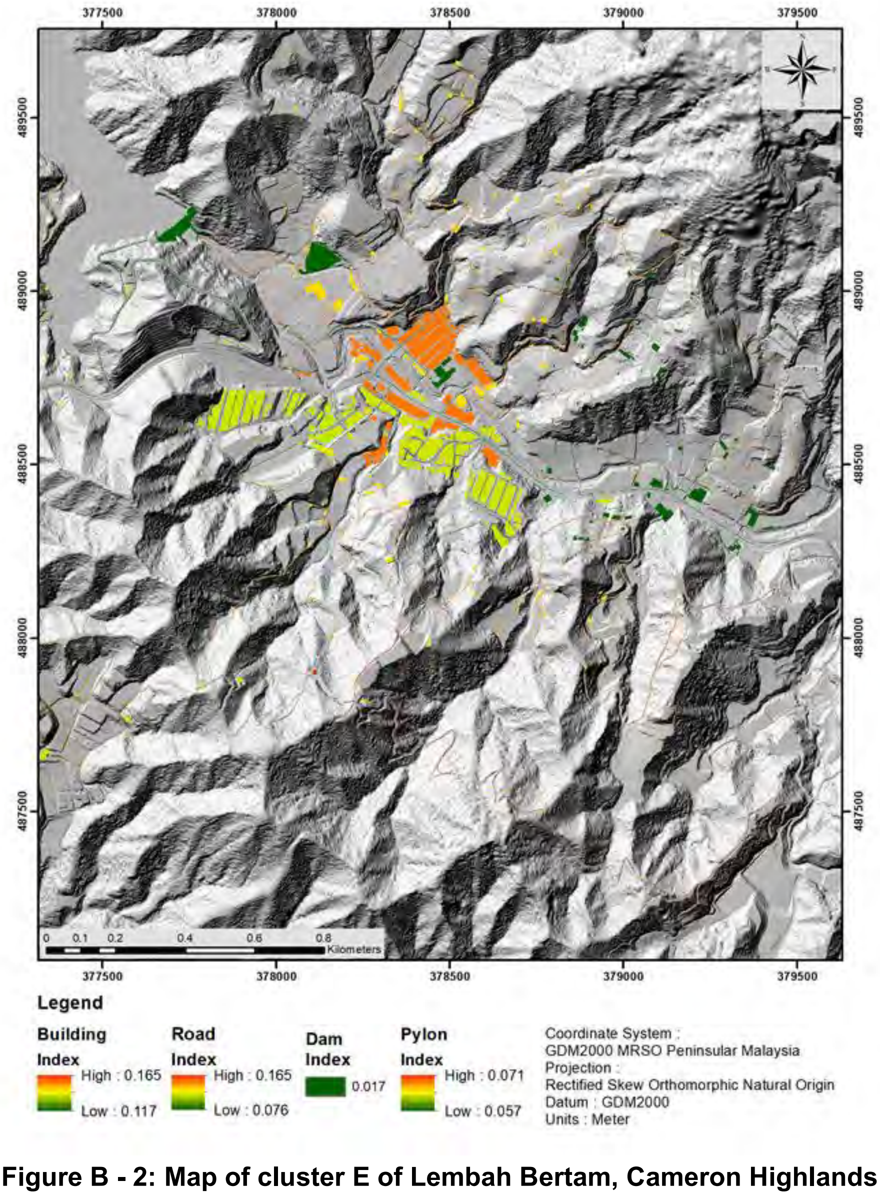


Figure B - 2: Map of cluster E of Lembah Bertam, Cameron Highlands

c) **Generation of Intensity of Landslide Hazard (I) Map**

- The Landslide Intensity (I) cluster map is designed to depict the landslide intensity. Evaluating landslide intensity is paramount in gauging the vulnerability posed to elements-at-risk.
- The process entails selecting and considering three pivotal indicators:
    - o i) the accumulation height of the landslide,
    - o ii) landslide thickness
    - o iii) landslide volume
- The culmination of this process is represented in Figure B-3, which portrays the outcome of landslide exposure analysis for cluster I, focusing on Critical Infrastructure entities within the chosen geographical area.
- The values encapsulated within the landslide intensity are grounded in specific parameters, notably encompassing accumulation height of landslides, landslide thickness, and landslide volume.
- It is important to note that expert judgment and estimation play a pivotal role in this process due to the absence of deterministic analyses or surveys, such as geophysics or soil investigation, conducted at the specific location. These factors contribute to a more nuanced assessment.

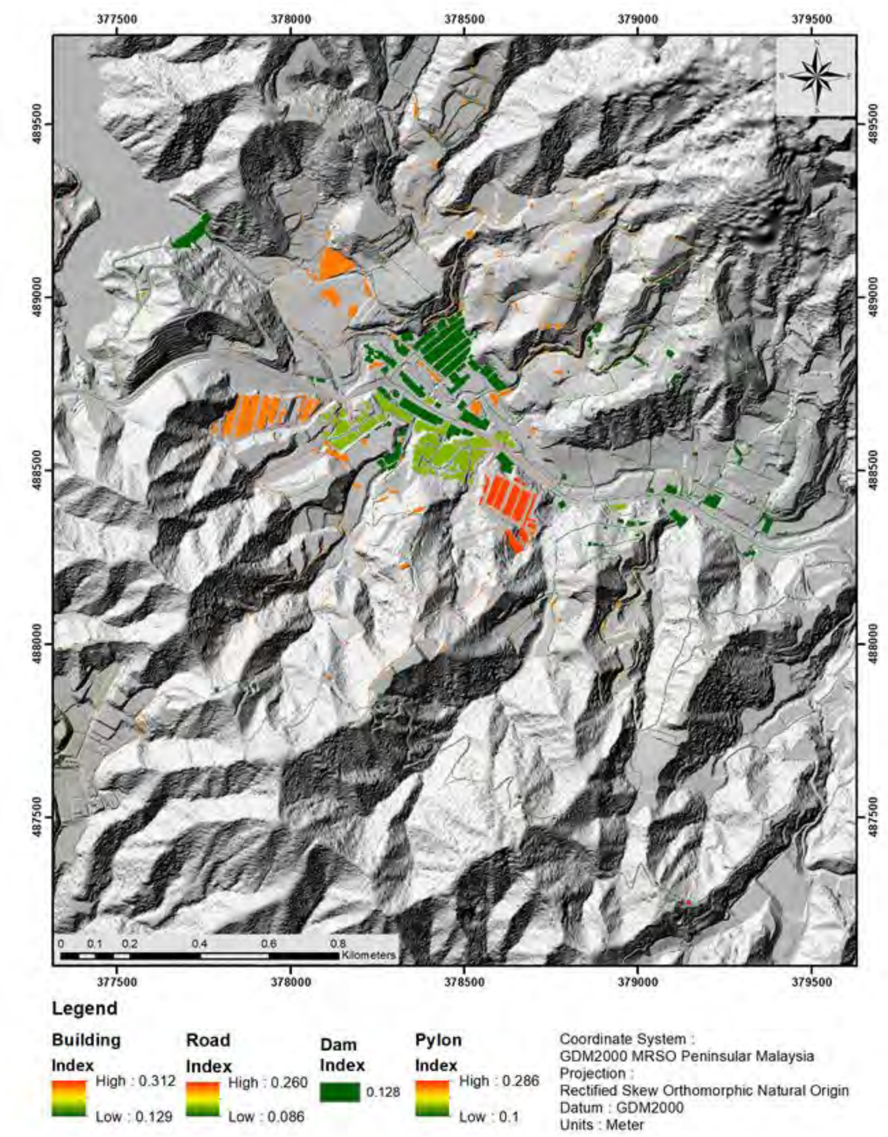


Figure B - 3: Output of cluster I of Lembah Bertam, Cameron Highlands

d) Generation of People Affected (P) by Damaged CI Map

- The People Affected (P) cluster map is created to understand how critical infrastructure service disruptions affect the community.
- Each critical infrastructure polygon's P cluster indicators and sub-indicators are carefully selected. Weightage values for each critical infrastructure polygon support this tailored selection.
- Figure B-4, which shows the map for cluster P in a very clear way, is a representation of the result of this methodical approach. The map shows how critical infrastructure services interact with each other and how they affect each other's Critical Infrastructure.
- Disrupted or damaged critical infrastructure services could affect the surrounding community. This understanding underpins risk management and informed decision-making.

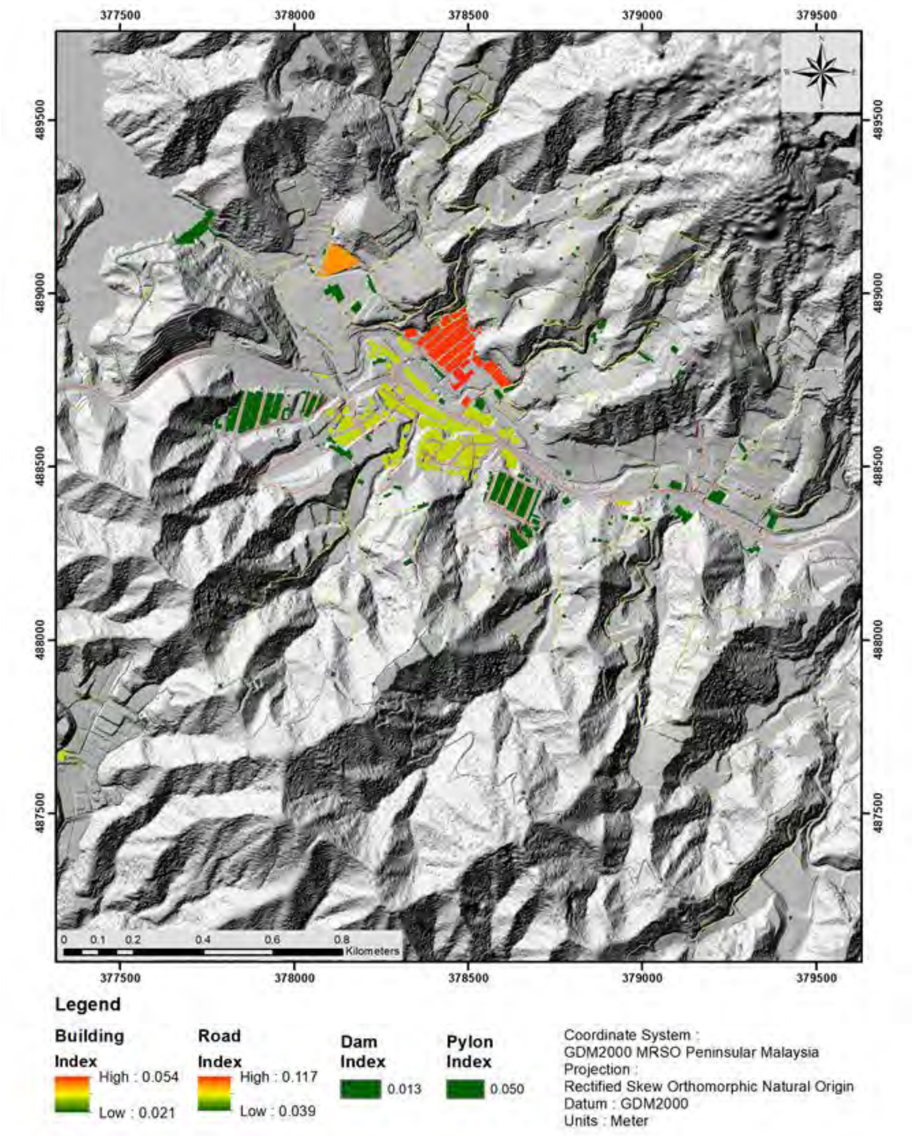


Figure B - 4: Map of cluster P of Lembah Bertam, Cameron Highlands

Generation of the Landslide Vulnerability Map for Critical Infrastructure

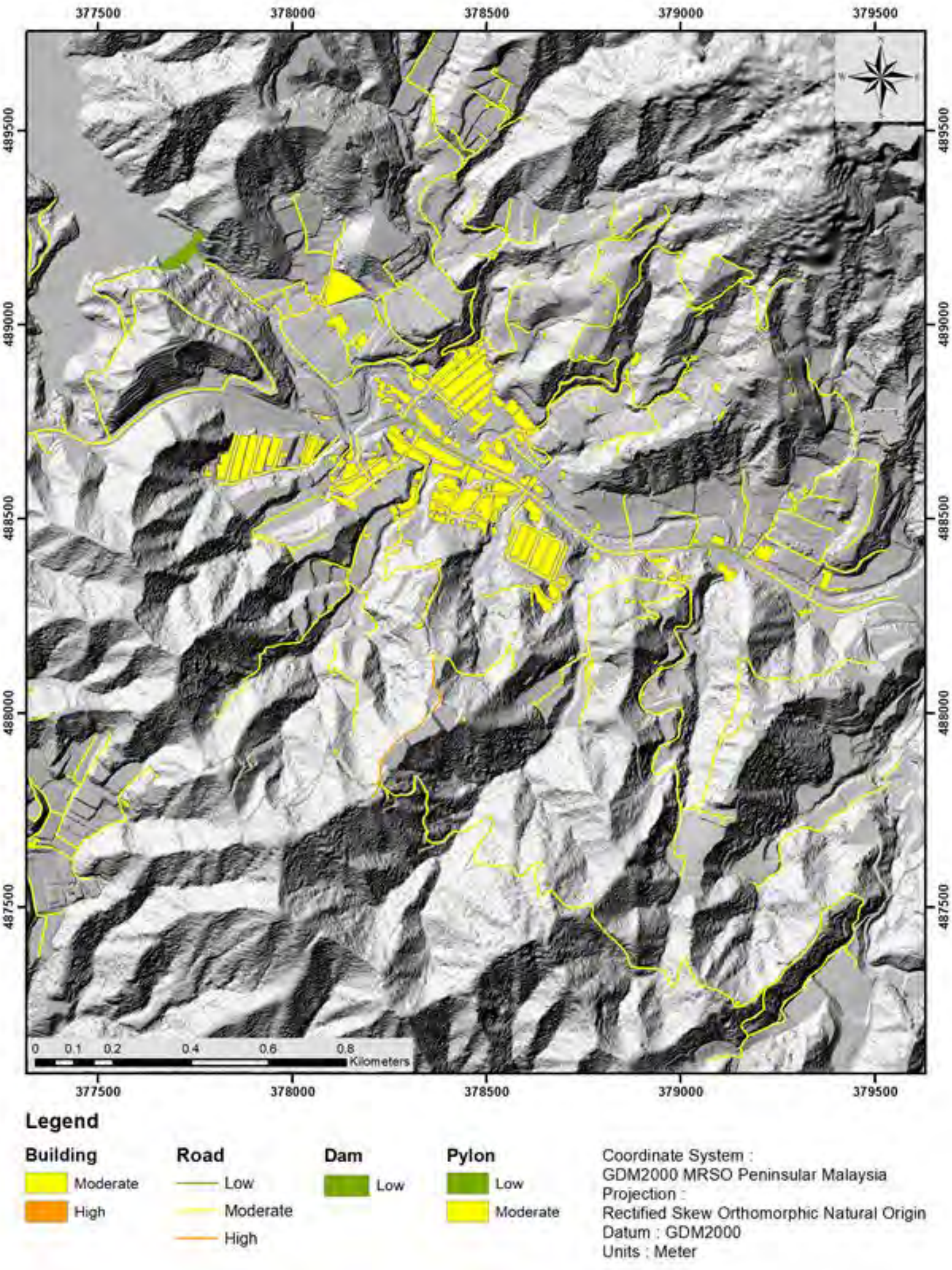


Figure B - 5: Landslide vulnerability map of Lembah Bertam, Cameron Highlands

APPENDIX C Vulnerability Index C, E, I, and P values for Translational/Rotational Landslide

Table C - 1: Indicators, sub-indicators and weight values of CI (building) with landslide type (translational/rotational)

CLUSTER	COMPONENT (WEIGHT)	INDICATOR	INDICATOR (WEIGHT)	SUB-INDICATOR	SUB-INDICATOR (WEIGHT)
SUSCEPTIBILITY OF CRITICAL INFRASTRUCTURE [C]	0.36	STRUCTURAL TYPOLOGY / STRUCTURE CONSTRUCTION MATERIALS	0.14	Steel structure	0.30
				IBS structures	0.40
				Reinforced concrete structure	0.40
				Masonry structure	0.50
				Timber structure	0.70
				Semi lightweight	0.80
				Lightweight	1.00
		BUILDING FOUNDATION DEPTH (LANDSLIDE TYPE VS DEEP FOUNDATION BUILDING)	0.12	Accumulation height/landslide depth <1.5 meter, deep foundation (pile)	0.10
				Accumulation height/landslide depth 1.5 - 5 meter, deep foundation (pile)	0.20
				Accumulation height/landslide depth > 5 meter, deep foundation (pile)	0.40
		BUILDING FOUNDATION DEPTH (LANDSLIDE TYPE VS SHALLOW FOUNDATION BUILDING)		Accumulation height/landslide depth < 1.5 meter, shallow foundation (pad footing)	0.60
				Accumulation height/landslide depth 1.5 - 5 meter, shallow foundation (pad footing)	0.80
				Accumulation height/landslide depth > 5 meter, shallow foundation (pad footing)	1.00
		NUMBER OF FLOOR	0.10	High rise (> 5 storey)	0.20
				Medium rise (2 - 5 storey)	0.50
				Low rise (Single-storey)	0.80
SURROUNDING ENVIRONMENT [E]	0.18	PRESENCE OF PROTECTION	0.07	Engineered protection system	0.10
				Non-engineered protection system	0.40
				Natural / Vegetation protection	0.70
				No protection	1.00
		DISTANCE BETWEEN BUILDING	0.05	> 5 meter	0.10
				3 - 5 meter	0.50
				< 3 meter	0.90
		BUILDING LOCATION	0.06	Building is located at a distance more than height of slope	0.10
				Building is located at a distance within height of slope	0.20
				Building is located at the toe of slope	0.60
				Building is located at the crest of slope	0.80
				Building is located at the mid-height of slope	1.00
LANDSLIDE INTENSITY [I]	0.33	ACCUMULATION HEIGHTS	0.15	< 0.2 meter	0.10
				0.2 meter - 0.5 meter	0.40
				0.5 meter - 2.0 meter	0.70
				> 2.0 meter	1.00
		LANDSLIDE VOLUME	0.18	< 500 meter^3	0.30
				500 - 10,000 meter^3	0.50
				10,000 - 50,000 meter^3	0.70
				50,000 - 250,000 meter^3	0.90
				> 250,000 meter^3	1.00

PEOPLE INSIDE BUILDING [P]	0.13	POPULATION DENSITY	0.04	Low	0.30
				Medium	0.60
				High	0.90
		EVACUATION OF ALARM SYSTEM	0.03	Yes	0.10
				No	1.00
		AGE OF PEOPLE	0.03	Adults	0.20
				Teenagers	0.30
				Children	0.50
				Senior citizen (65 - 74 years old)	0.80
				Senior citizen (75 - 84 years old)	0.90
				Senior citizen (> 85 years old)	1.00
		HEALTH CONDITION	0.03	Health (Good)	0.10
				Health (Poor)	0.50
				Disabled person	1.00

Table C - 2: Indicators, sub-indicators and weight values of CI (road) with landslide type(translational/rotational)

CLUSTER	COMPONENT (WEIGHT)	INDICATOR	INDICATOR (WEIGHT)	SUB-INDICATOR	SUB-INDICATOR (WEIGHT)
SUSCEPTIBILITY OF CRITICAL INFRASTRUCTURE [C]	0.38	ROAD CATEGORY (JKR STANDARD DESIGN)	0.09	R6 (expressway)	0.10
				U6 (urban expressway)	0.10
				R5 (highway)	0.40
				U4 / U5 (urban arterial road)	0.40
				R4 / R5 (primary rural road)	0.60
				U3 / U4 (urban collector road)	0.70
				R3 / R4 (secondary rural road)	0.80
				R1 / R1a / R2 (minor rural road)	0.90
				U1 / U1a / U2 / U3 (urban local street)	0.90
		LOCATION OF ROAD	0.10	Road is located at a distance more than height of slope	0.10
				Road is located at a distance within height of slope	0.30
				Road is located at the toe of slope	0.50
				Road is located at the crest of slope	0.70
				Road is located at the mid-height of slope	0.90
		ROAD MATERIAL	0.09	Rigid pavement / Concrete road	0.10
				Flexible pavement / Bituminous road	0.50
				Unpaved road	0.90
		ROAD MAINTENANCE	0.10	Good maintenance	0.10
				Poor maintenance	0.50
				No	1.00
SURROUNDING ENVIRONMENT [E]	0.17	PRESENCE OF PROTECTION	0.06	Engineered protection system	0.10
				Non-engineered protection system	0.40
				Natural / Vegetation protection	0.70
				No protection	1.00
		PRESENCE OF WARNING SYSTEM	0.06	Yes	0.10
				No	1.00
		ROAD DRAINAGE SYSTEM	0.05	Yes	0.20
				No	0.90
LANDSLIDE INTENSITY [I]	0.32	ACCUMULATION HEIGHTS	0.10	< 0.2 meter	0.10
				0.2 - 0.5 meter	0.50
				0.5 - 2.0 meter	0.70
				> 2.0 meter	0.90

		LANDSLIDE THICKNESS	0.10	< 1.5 meter	0.30
				1.5 - 5 meter	0.50
				5 - 20 meter	0.70
				> 20 meter	0.90
		LANDSLIDE VOLUME	0.12	< 500 meter^3	0.30
				500 - 10,000 meter^3	0.50
				10,000 - 50,000 meter^3	0.70
				50,000 - 250,000 meter^3	0.90
				> 250,000 meter^3	1.00
ROAD USER [P]	0.13	TRAFFIC VOLUME	0.13	(R2 / R1 / R1a / U2 / U1/ U1a (less than 1000 ADT)) - Low traffic volume	0.30
				(R3 / U3 - 3000 to 1000 ADT)	0.50
				(R4 / U4 - 10,000 to 3000 ADT)	0.60
				(R5 / U5 - more than 10,000 ADT)	0.80
				(R6 / R5/ U6 - all traffic volume) - High traffic volume	0.90

Table C - 3: Indicators, sub-indicators and weight values of CI (dam) with landslide type (translational/rotational).

CLUSTER	COMPONENT (WEIGHT)	INDICATOR	INDICATOR (WEIGHT)	SUB-INDICATOR	SUB-INDICATOR (WEIGHT)
SUSCEPTIBILITY OF CRITICAL INFRASTRUCTURE [C]	0.38	BASIN / CATCHMENT)	0.06	Very large (> 100 kilometer^2)	0.20
				Large (50 - 100 kilometer^2)	0.40
				Medium (25 - 50 kilometer^2)	0.50
				Small (5 - 25 kilometer^2)	0.60
				Very small (< 5 kilometer^2)	1.00
		RESERVOIR	0.07	Very high (> 30 kilometer^2)	0.20
				High (11 - 30 kilometer^2)	0.30
				Medium (6 - 10 kilometer^2)	0.50
				Low (1 - 5 kilometer^2)	0.60
				Very low (< 1 kilometer^2)	1.00
		DAM DIMENSION (MAIN STRUCTURE - HEIGHT)	0.06	< 5 meter	0.20
				6 - 15 meter	0.30
				16 - 50 meter	0.50
				51 - 99 meter	0.60
				> 100 meter	0.80
		DAM DIMENSION (MAIN STRUCTURE - LENGTH)	0.06	> 300 meter	0.20
				201 - 300 meter	0.30
				101 - 200 meter	0.40
				51 - 100 meter	0.60
				< 50 meter	0.70
		DAM TYPOLOGY/ CATEGORIES	0.07	Sedimentation / Recreational	0.20
				Flood mitigation	0.40
				Irrigation	0.50
				Power generation	0.60
				Water supply	0.80
		DAM CONSTRUCTION MATERIALS	0.06	Reinforced concrete	0.30
				Composite	0.50
				Rockfill	0.60
				Earthfill	0.80
SURROUNDING ENVIRONMENT [E]	0.17	PRESENCE OF PROTECTION	0.09	Fully engineered protection system	0.10
				Partially man-made protection system	0.40
				Natural protection (e.g vegetation)	0.60
				No protection	1.00
		PRESENCE OF WARNING SYSTEM	0.08	Yes	0.10
				No	1.00

LANDSLIDE INTENSITY [I]	0.32	LANDSLIDE VOLUME	0.32	< 500 $meter^3$	0.20
				500 - 10,000 $meter^3$	0.40
				10,000 - 50,000 $meter^3$	0.60
				50,000 - 250,000 $meter^3$	0.80
				> 250,000 $meter^3$	1.00
PEOPLE AFFECTED BY DAM OPERATION [P]	0.13	POPULATION DENSITY	0.13	Low (< 25 people per km^2)	0.10
				Medium (25 - 50 people per km^2)	0.50
				High (> 50 people per km^2)	0.70

Table C - 4: Indicators, sub-indicators and weight values of CI (Utilities Tower) with landslide type (translational/rotational)

CLUSTER	COMPONENT (WEIGHT)	INDICATOR	INDICATOR (WEIGHT)	SUB-INDICATOR	SUB-INDICATOR (WEIGHT)
SUSCEPTIBILITY OF CRITICAL INFRASTRUCTURE [C]	0.30	TYPOLOGY OF UTILITIES	0.07	Telco tower	0.20
				Substation 33KV	0.30
				PMU	0.50
				GRID 132KV (Height 29 meter) (Width 5.7 meter)	0.70
				Hybrid tower (Combination of KV)	0.80
				GRID 500KV (Height 46 - 67 meter) (Width 10.5 - 19 meter)	0.80
				GRID 275KV (Height 34 meter) (Width 7.5 meter)	0.90
		TOWER AND TOWER COMPONENT MATERIAL	0.06	Composite	0.30
				Steel	0.50
				Wood	0.80
		BUILDING STRUCTURE FOUNDATION (TELCO, PMU, SUBSTATION 33KV)	0.04	For surficial landslide, < 1.5 meter	0.20
				For shallow landslide, 1.5 - 5 meter	0.30
				For deep seated landslide, 5 - 20 meter	0.60
				For very deep seated landslide, > 20 meter	0.90
		TOWER STRUCTURE FOUNDATION (132KV, 275KV, 500KV, HYBRID)	0.07	For surficial landslide, < 1.5 meter	0.10
				For shallow landslide, 1.5 - 5 meter	0.30
				For deep seated landslide, 5 - 20 meter	0.60
				For very deep seated landslide, > 20 meter	0.90
		LOCATION OF TOWER	0.06	Toe of slope	0.30
				Top of slope	0.50
				Face of slope	0.90
SURROUNDING ENVIRONMENT [E]	0.15	PRESENCE OF PROTECTION	0.03	Engineered protection system	0.10
				Non-engineered protection system	0.40
				Natural / Vegetation protection	0.70
				No protection (Including Encroachment & ROW)	1.00
		SLOPE MORPHOLOGY (SHAPE)	0.03	Straight	0.30
				Convex	0.50
				Concave	0.90
		PRESENCE OF WARNING SYSTEM	0.02	Yes	0.10
				No	1.00
		DISTANCE OF TOWER FROM THE RIVER	0.03	> 50 meter	0.10
				25 - 50 meter	0.40
				10 - 25 meter	0.70
				< 10 meter	0.90
		PRESENCE OF EROSION	0.04	No erosion	0.10
				Sheet	0.30
				Rill	0.70
				Gully	0.90

LANDSLIDE INTENSITY [I]	0.45	ACCUMULATION HEIGHTS	0.15	< 0.2 meter	0.10
				0.2 - 0.5 meter	0.50
				0.5 - 2.0 meter	0.70
				> 2.0 meter	0.90
		LANDSLIDE THICKNESS	0.16	Surficial deposit, < 1.5 meter	0.10
				Shallow landslide, 1.5 - 5 meter	0.30
				Deep seated landslide, 5 - 20 meter	0.60
				Very deep seated landslide, > 20 meter	0.90
		LANDSLIDE VOLUME	0.14	< 50 meter^3	0.10
				50 - 500 meter^3	0.20
				500 - 10,000 meter^3	0.50
				10,000 - 50,000 meter^3	0.80
				50,000 - 250,000 meter^3	0.90
				> 250,000 meter^3	1.00
PEOPLE AFFECTED BY UTILITIES TOWER OPERATION [P]	0.10	POPULATION DENSITY	0.10	Low (< 25 people per km^2)	0.10
				Medium (25 - 50 people per km^2)	0.50
				High (> 50 people per km^2)	0.70

APPENDIX D Vulnerability Index C, E, I, and P values for Debris Flow Landslide

Table D - 1: Indicators, sub-indicators and weight values of CI (building) with debris flow

CLUSTER	COMPONENT (WEIGHT)	INDICATOR	INDICATOR (WEIGHT)	SUB-INDICATOR	SUB-INDICATOR (WEIGHT)
SUSCEPTIBILITY OF CRITICAL INFRASTRUCTURE [C]	0.36	STRUCTURAL TYPOLOGY / STRUCTURE CONSTRUCTION MATERIALS	0.14	Steel structure	0.30
				IBS structures	0.40
				Reinforced concrete structure	0.40
				Masonry structure	0.50
				Timber structure	0.70
				Semi lightweight	0.80
				Lightweight	1.00
		BUILDING FOUNDATION DEPTH (LANDSLIDE TYPE VS DEEP FOUNDATION BUILDING)	0.12	Accumulation height/landslide depth <1.5 meter, deep foundation (pile)	0.10
				Accumulation height/landslide depth 1.5 - 5 meter, deep foundation (pile)	0.20
				Accumulation height/landslide depth > 5 meter, deep foundation (pile)	0.40
		BUILDING FOUNDATION DEPTH (LANDSLIDE TYPE VS SHALLOW FOUNDATION BUILDING)		Accumulation height/landslide depth < 1.5 meter, shallow foundation (pad footing)	0.60
				Accumulation height/landslide depth 1.5 - 5 meter, shallow foundation (pad footing)	0.80
				Accumulation height/landslide depth > 5 meter, shallow foundation (pad footing)	1.00
		NUMBER OF FLOOR	0.10	High rise (> 5 storey)	0.20
				Medium rise (2 - 5 storey)	0.50
				Low rise (Single-storey)	0.80
SURROUNDING ENVIRONMENT [E]	0.18	PRESENCE OF PROTECTION	0.07	Engineered protection system	0.10
				Non-engineered protection system	0.40
				Natural / Vegetation protection	0.70
				No protection	1.00
		DISTANCE BETWEEN BUILDING	0.05	> 5 meter	0.10
				3 - 5 meter	0.50
				< 3 meter	0.90
		BUILDING LOCATION	0.06	Building is located at a distance more than height of slope	0.10
				Building is located at a distance within height of slope	0.20
				Building is located at the toe of slope	0.60
				Building is located at the crest of slope	0.80
				Building is located at the mid-height of slope	1.00
LANDSLIDE INTENSITY [I]	0.33	ACCUMULATION HEIGHTS	0.08	< 0.2 meter	0.10
				0.2 meter - 0.5 meter	0.40
				0.5 meter - 2.0 meter	0.70
				> 2.0 meter	1.00
		LANDSLIDE VOLUME	0.09	< 500 $meter^3$	0.30
				500 - 10,000 $meter^3$	0.50
				10,000 - 50,000 $meter^3$	0.70
				50,000 - 250,000 $meter^3$	0.90
				> 250,000 $meter^3$	1.00
		LANDSLIDE VELOCITY	0.10	Very rapid (3 meter/minute)	0.90
				Extremely rapid (5 meter/second)	1.00
		LANDSLIDE THICKNESS	0.06	Surficial landslide, < 1.5 meter	0.20
				Shallow landslide, 1.5 - 5 meter	0.40
				Deep-seated landslide, 5 - 20 meter	0.60
				Very deep-seated landslide, > 20 meter	0.80

PEOPLE INSIDE BUILDING [P]	0.13	POPULATION DENSITY	0.04	Low	0.30
				Medium	0.60
				High	0.90
		EVACUATION OF ALARM SYSTEM	0.03	Yes	0.10
				No	1.00
		AGE OF PEOPLE	0.03	Adults	0.20
				Teenagers	0.30
				Children	0.50
				Senior citizen (65 - 74 years old)	0.80
				Senior citizen (75 - 84 years old)	0.90
				Senior citizen (> 85 years old)	1.00
		HEALTH CONDITION	0.03	Health (Good)	0.10
				Health (Poor)	0.50
				Disabled person	1.00

Table D - 2: Indicators, sub-indicators and weight values of CI (road) with landslide type (debris flow)

CLUSTER	COMPONENT (WEIGHT)	INDICATOR	INDICATOR (WEIGHT)	SUB-INDICATOR	SUB-INDICATOR (WEIGHT)
SUSCEPTIBILITY OF CRITICAL INFRASTRUCTURE [C]	0.38	ROAD CATEGORY (JKR STANDARD DESIGN)	0.09	R6 (expressway)	0.10
				U6 (urban expressway)	0.10
				R5 (highway)	0.40
				U4 / U5 (urban arterial road)	0.40
				R4 / R5 (primary rural road)	0.60
				U3 / U4 (urban collector road)	0.70
				R3 / R4 (secondary rural road)	0.80
				R1 / R1a / R2 (minor rural road)	0.90
				U1 / U1a / U2 / U3 (urban local street)	0.90
		LOCATION OF ROAD	0.10	Road is located at a distance more than height of slope	0.10
				Road is located at a distance within height of slope	0.30
				Road is located at the toe of slope	0.50
				Road is located at the crest of slope	0.70
				Road is located at the mid-height of slope	0.90
		ROAD MATERIAL	0.09	Rigid pavement / Concrete road	0.10
				Flexible pavement / Bituminous road	0.50
				Unpaved road	0.90
		ROAD MAINTENANCE	0.10	Good maintenance	0.10
				Poor maintenance	0.50
				No	1.00
SURROUNDING ENVIRONMENT [E]	0.17	PRESENCE OF PROTECTION	0.06	Engineered protection system	0.10
				Non-engineered protection system	0.40
				Natural / Vegetation protection	0.70
				No protection	1.00
		PRESENCE OF WARNING SYSTEM	0.06	Yes	0.10
				No	1.00
		ROAD DRAINAGE SYSTEM	0.05	Yes	0.20
				No	0.90
LANDSLIDE INTENSITY [I]	0.32	ACCUMULATION HEIGHTS	0.08	< 0.2 meter	0.10
				0.2 - 0.5 meter	0.50
				0.5 - 2.0 meter	0.70
				> 2.0 meter	0.90

		LANDSLIDE THICKNESS	0.08	< 1.5 meter	0.30
				1.5 - 5 meter	0.50
				5 - 20 meter	0.70
				> 20 meter	0.90
		LANDSLIDE VOLUME	0.08	< 500 meter^3	0.30
				500 - 10,000 meter^3	0.50
				10,000 - 50,000 meter^3	0.70
				50,000 - 250,000 meter^3	0.90
				> 250,000 meter^3	1.00
		LANDSLIDE VELOCITY	0.08	Very rapid (3 meter/minute)	0.90
				Extremely rapid (5 meter/second)	1.00
ROAD USER [P]	0.13	TRAFFIC VOLUME	0.13	(R2 / R1 / R1a / U2 / U1/ U1a (less than 1000 ADT)) - Low traffic volume	0.30
				(R3 / U3 - 3000 to 1000 ADT)	0.50
				(R4 / U4 - 10,000 to 3000 ADT)	0.60
				(R5 / U5 - more than 10,000 ADT)	0.80
				(R6 / R5/ U6 - all traffic volume) - High traffic volume	0.90

Table D - 3: Indicators, sub-indicators and weight values of CI (dam) with landslide type (debris flow)

CLUSTER	COMPONENT (WEIGHT)	INDICATOR	INDICATOR (WEIGHT)	SUB-INDICATOR	SUB-INDICATOR (WEIGHT)
SUSCEPTIBILITY OF CRITICAL INFRASTRUCTURE [C]	0.38	BASIN / CATCHMENT)	0.06	Very large (> 100 kilometer^2)	0.20
				Large (50 - 100 kilometer^2)	0.40
				Medium (25 - 50 kilometer^2)	0.50
				Small (5 - 25 kilometer^2)	0.60
				Very small (< 5 kilometer^2)	1.00
		RESERVOIR	0.07	Very high (> 30 kilometer^2)	0.20
				High (11 - 30 kilometer^2)	0.30
				Medium (6 - 10 kilometer^2)	0.50
				Low (1 - 5 kilometer^2)	0.60
				Very low (< 1 kilometer^2)	1.00
		DAM DIMENSION (MAIN STRUCTURE - HEIGHT)	0.06	< 5 meter	0.20
				6 - 15 meter	0.30
				16 - 50 meter	0.50
				51 - 99 meter	0.60
				> 100 meter	0.80
		DAM DIMENSION (MAIN STRUCTURE - LENGTH)	0.06	> 300 meter	0.20
				201 - 300 meter	0.30
				101 - 200 meter	0.40
				51 - 100 meter	0.60
				< 50 meter	0.70
		DAM TYPOLOGY/ CATEGORIES	0.07	Sedimentation / Recreational	0.20
				Flood mitigation	0.40
				Irrigation	0.50
				Power generation	0.60
				Water supply	0.80
		DAM CONSTRUCTION MATERIALS	0.06	Reinforced concrete	0.30
				Composite	0.50
				Rockfill	0.60
				Earthfill	0.80
SURROUNDING ENVIRONMENT [E]	0.17	PRESENCE OF PROTECTION	0.09	Fully engineered protection system	0.10
				Partially man-made protection system	0.40
				Natural protection (e.g vegetation)	0.60
				No protection	1.00
		PRESENCE OF WARNING SYSTEM	0.08	Yes	0.10
				No	1.00

LANDSLIDE INTENSITY [I]	0.32	LANDSLIDE VOLUME	0.14	< 500 $meter^3$	0.20
				500 - 10,000 $meter^3$	0.40
				10,000 - 50,000 $meter^3$	0.60
				50,000 - 250,000 $meter^3$	0.80
				> 250,000 $meter^3$	1.00
		LANDSLIDE VELOCITY	0.18	Very rapid (3 meter/minute)	0.90
				Extremely rapid (5 meter/second)	1.00
PEOPLE AFFECTED BY DAM OPERATION [P]	0.13	POPULATION DENSITY	0.13	Low (< 25 people per km^2)	0.10
				Medium (25 - 50 people per km^2)	0.50
				High (> 50 people per km^2)	0.70

Table D - 4: Indicators, sub-indicators and weight values of CI (Utilities Tower) with debris flow

CLUSTER	COMPONENT (WEIGHT)	INDICATOR	INDICATOR (WEIGHT)	SUB-INDICATOR	SUB-INDICATOR (WEIGHT)
SUSCEPTIBILITY OF CRITICAL INFRASTRUCTURE [C]	0.30	TYPOLOGY OF UTILITIES	0.07	Telco tower	0.20
				Substation 33KV	0.30
				PMU	0.50
				GRID 132KV (Height 29 meter) (Width 5.7 meter)	0.70
				Hybrid tower (Combination of KV)	0.80
				GRID 500KV (Height 46 - 67 meter) (Width 10.5 - 19 meter)	0.80
				GRID 275KV (Height 34 meter) (Width 7.5 meter)	0.90
		TOWER AND TOWER COMPONENT MATERIAL	0.06	Composite	0.30
				Steel	0.50
				Wood	0.80
		BUILDING STRUCTURE FOUNDATION (TELCO, PMU, SUBSTATION 33KV)	0.04	For surficial landslide, < 1.5 meter	0.20
				For shallow landslide, 1.5 - 5 meter	0.30
				For deep-seated landslide, 5 - 20 meter	0.60
				For very deep-seated landslide, > 20 meter	0.90
		TOWER STRUCTURE FOUNDATION (132KV, 275KV, 500KV, HYBRID)	0.07	For surficial landslide, < 1.5 meter	0.10
				For shallow landslide, 1.5 - 5 meter	0.30
				For deep-seated landslide, 5 - 20 meter	0.60
				For very deep-seated landslide, > 20 meter	0.90
		LOCATION OF TOWER	0.06	Toe of slope	0.30
				Top of slope	0.50
				Face of slope	0.90
SURROUNDING ENVIRONMENT [E]	0.15	PRESENCE OF PROTECTION	0.03	Engineered protection system	0.10
				Non-engineered protection system	0.40
				Natural / Vegetation protection	0.70
				No protection (Including Encroachment & ROW)	1.00
		SLOPE MORPHOLOGY (SHAPE)	0.03	Straight	0.30
				Convex	0.50
				Concave	0.90
		PRESENCE OF WARNING SYSTEM	0.02	Yes	0.10
				No	1.00
		DISTANCE OF TOWER FROM THE RIVER	0.03	> 50 meter	0.10
				25 - 50 meter	0.40
				10 - 25 meter	0.70
				< 10 meter	0.90
		PRESENCE OF EROSION	0.04	No erosion	0.10
				Sheet	0.30
				Rill	0.70
				Gully	0.90

LANDSLIDE INTENSITY [I]	0.45	ACCUMULATION HEIGHTS	0.10	< 0.2 meter	0.10
				0.2 - 0.5 meter	0.50
				0.5 - 2.0 meter	0.70
				> 2.0 meter	0.90
		LANDSLIDE THICKNESS	0.13	Surficial deposit, < 1.5 meter	0.10
				Shallow landslide, 1.5 - 5 meter	0.30
				Deep-seated landslide, 5 - 20 meter	0.60
				Very deep-seated landslide, > 20 meter	0.90
		LANDSLIDE VOLUME	0.09	< 50 $meter^3$	0.10
				50 - 500 $meter^3$	0.20
				500 - 10,000 $meter^3$	0.50
				10,000 - 50,000 $meter^3$	0.80
				50,000 - 250,000 $meter^3$	0.90
				> 250,000 $meter^3$	1.00
		LANDSLIDE VELOCITY	0.13	Very rapid (3 meter/minute)	0.90
				Extremely rapid (5 meter/second)	1.00
PEOPLE AFFECTED BY UTILITIES TOWER OPERATION [P]	0.10	POPULATION DENSITY	0.10	Low (< 25 people per km^2)	0.10
				Medium (25 - 50 people per km^2)	0.50
				High (> 50 people per km^2)	0.70

APPENDIX E Landslide Vulnerability Index Calculation

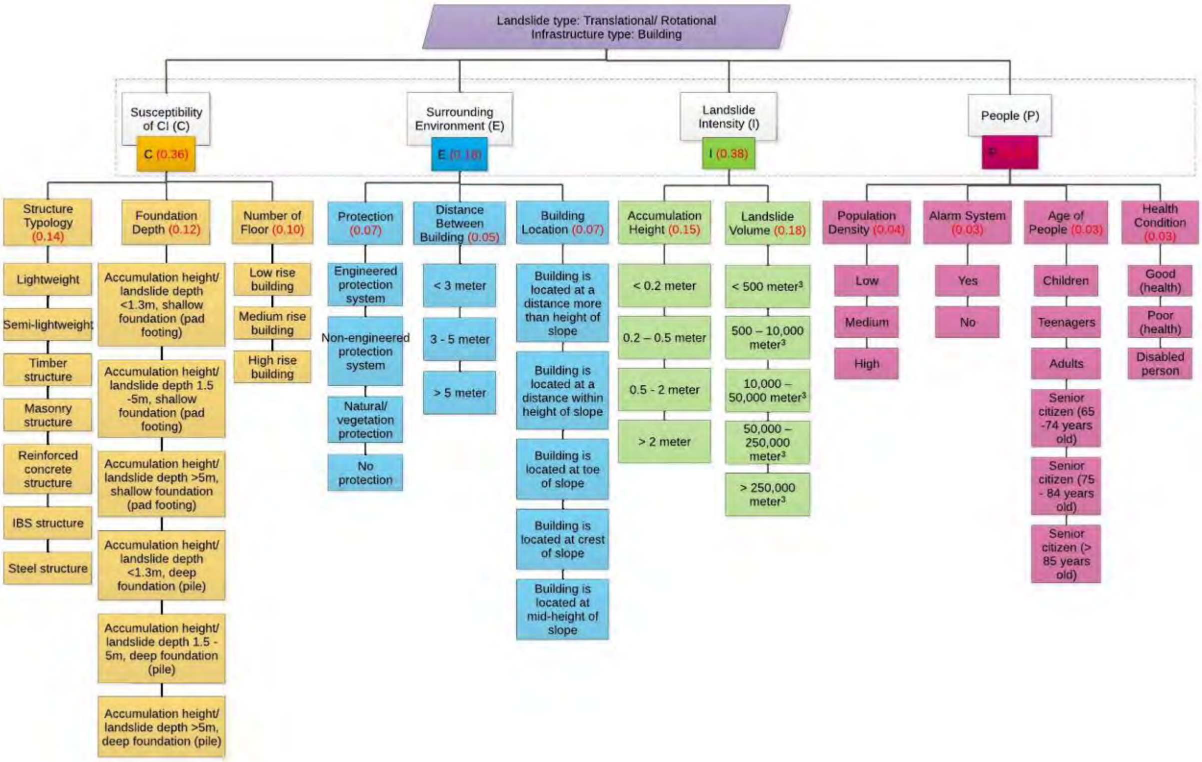


Figure E - 1: Vulnerability assessment of a building exposed to translational/rotational landslide

Vulnerability Index for Critical Infrastructure

An example of a landslide vulnerability assessment based on the recommended cluster weightage values is shown in Table E-1. The landslide vulnerability scenario depicts detailed information on indicators and sub-indicators for building and residential development over the rotational and translational landslide. Each indicator and sub-indicator is given a specific weight value from which the total vulnerability index is calculated. In this scenario, the calculated vulnerability index is 0.20 and classified as a low vulnerability class. Figure E-2 shows the overall process of landslide vulnerability assessment of a particular Critical Infrastructure (building) presumably subjected to translational or rotational landslide hazard in deriving the Critical Vulnerability Index Infrastructure using cluster weightage value matrix as in Table 4-1.

The Vulnerability Index contains a landslide risk assessment, and the resulting score can be found on a scale from 0-1 (total damage). The score contains details about the extent of landslide hazard's consequent losses. An example of Scenario 1 (Critical Infrastructure: building, landslide type: translational/rotational) is shown in Figure E-2. The summation of all yellow box scores is equivalent to the Vulnerability Index for scenario 1. The index is referred to as the vulnerability classes in Table 4-2. The possible degree of the severity of damage to the CI is determined in Figure E-3.

Table E - 1: Example of a landslide vulnerability assessment based on the recommended cluster weightage

Landslide type: Translational/Rotational

CI: Building

Susceptibility of CI (C):

- Structural Typology **(0.14)**: Steel structure **(0.30)**
- Foundation Depth **(0.12)**: Landslide Type Vs Deep Foundation Building:

Accumulation height/landslide depth <1.5 meters, deep foundation (pile) **(0.10)**

- Number of floor **(0.10)**: High rise (> 5 storey) **(0.20)**

Surrounding Environment (E):

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

Landslide intensity (I):

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

People inside the building (P):

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

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

Vulnerability index: 0.185

Class of vulnerability: Very Low

Vulnerability description: Slight non-structural damage, stability not affected, furnishing or fitting damage and no human casualties expected.

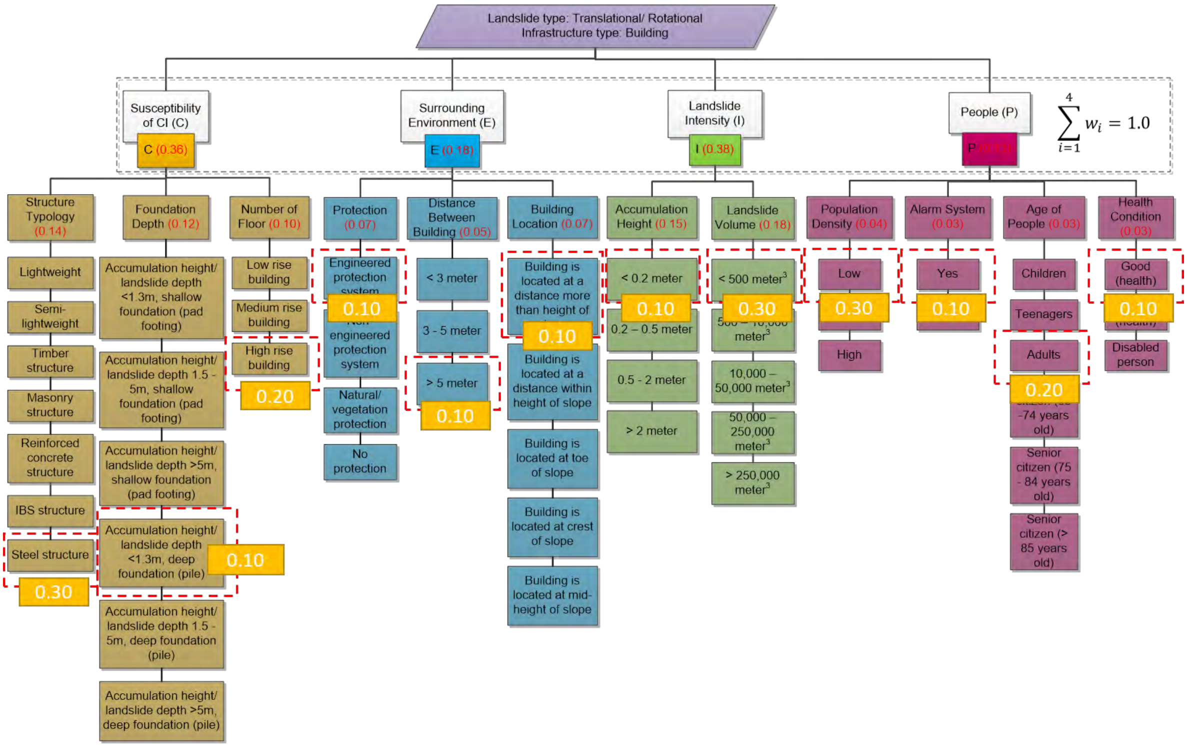


Figure E - 2: Conceptual division of indicators, sub-indicators, and weight values for the landslide vulnerability assessment scenario

Landslide Type: Translational/Rotational

CI Type: Building/Residential $\qquad V = \sum_{i=1}^{m} w_i \times s_i$

Vulnerability Index of the CI

((0.14 x 0.30) + (0.12 x 0.10) + (0.10 x 0.20)) + ((0.07 x 0.10) + (0.05 x 0.10) + (0.07 x 0.10)) + ((0.15 x 0.10) + (0.18 x 0.30)) + ((0.04 x 0.30) + (0.03 x 0.10) + (0.03 x 0.20) + (0.03 x 0.10))

VI = 0.186 (Very Low Vulnerability)

Slight non-structural damage, stability not affected, furnishing or fitting damage, and no human casualties expected.

Figure E - 3: The corresponding Vulnerability Index calculation for the building and residential vulnerability scenario as in Figure E-2

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