VULNERABILITY MAPPING AND ANALYSIS: AN IMPLEMENTATION IN GEOHAZARD AREAS IN SABAH

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KEY WORDS: Landslide vulnerability, Geospatial, Landslide risk

ABSTRACT:

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 study, the landslide vulnerability mapping and analysis were made on two element-at-risks namely buildings and roads. Based on field observations, building and road construction materials have been classified into 22 and 5 construction materials respectively. The field visits were made on specific areas based on candidate buildings and roads as chosen during the landslide exposure analysis and mapping. The vulnerability values for these element-at-risks were expressed using expert opinion. Four experts have been interviewed with separate sessions. The experts were also supplied with local information on the landslides occurrences and photos of element-at-risk in Kundasang and Kota Kinabalu. The vulnerability matrices were combined based on the weighted average approach, in which higher weight was assigned to panel with local expert (landslides and damage assessment), wide experience in landslide vulnerability analysis, hazard and risk mapping. Finally, the vulnerability maps were produced for Kundasang and Kota Kinabalu with spatial resolution of 25cm. These maps were used for the next step i.e. landslide risk mapping and analysis.

1. INTRODUCTION

One of the most critical steps towards 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). Ideally vulnerability is influenced by various factors including physical, economic, environmental, institutional and human factors.

The degree of loss for element-at-risk is also dynamic which changes over time. The value of vulnerability is scale dependent, which most cases only cover specific site or area of interest. Furthermore, coping capacity is one of the important factors that should be considered in determining vulnerability. The capacity is a combination of all strength and resource available within a community or organization that can reduce the level of risk or the effect of a disaster. Capacity may include physical, institutional, social or economic means as well as skilled personal or collective attributes such as leadership and management.

Input to a vulnerability model could be qualitative (described with words), semi-quantitative (ranked on a relative scale, also denoted categorical) or quantitative (described as a dimensionless number between 0 and 1). Most of the vulnerability assessment methods agreed that vulnerability is dependent on both acting agent (physical impact of a hazard event) and the element-at-risk (structural or physical characteristics of the vulnerable object). It has been discussed previously that vulnerability has been defined in a variety of ways (Uzielli et al., 2008). 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).

Prior to introducing vulnerability methodology, Ciurean, et al. (2013) properly distinguish the component of vulnerability into social and physical vulnerability. Social vulnerability focuses on indicator, based methods where this indicator is defined as ‘a variable which is an operational representation of a characteristic or quality of a 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 with a hazard of natural’. 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.

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This contribution has been peer-reviewed.
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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:

i. 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.);
ii. 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;
iii. 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);
iv. The variability in spatial and temporal vulnerability;
v. 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; and
vi. Non-physical factors influence the vulnerability of people (e.g. early warning, hazard and risk perception, etc.).

Numerous studies have been done by previous researchers to accurately quantify landslides vulnerability. 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).

The semi-quantitative approach reduces level of generalization in the qualitative method (Dai et al., 2002). The methods are flexible 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 Leone et al. (1996) damage matrices were suggested based on damaging factors and the resistance of the elements at risk to the impact of landslides. 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).

Li et al. (2010) estimated landslide vulnerability based on the quantitative approach, which requires detailed information on the landslides intensity (e.g. average velocity of landslide) and building structure (e.g. materials, age, state of maintenance and etc.) for each landslides area and building footprints. The vulnerability curve models however still require further calibration in other areas or against expert judgements. Guillard-Gonçalves et al. (2016) used a semi-quantitative 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).

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. 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.

The holistic approach of vulnerability assessment incorporates all types of vulnerability and coping capacity. On the other hand, the technical approach of vulnerability assessment focuses on the physical vulnerability, which aims at defining the degree of lost for a particular physical element-at-risk for example buildings and roads. In this study, the landslide vulnerability for Kundasang and Kota Kinabalu were based on the technical vulnerability approach. Methods for measuring physical vulnerability can be grouped into empirical and analytical models. The empirical approach can be further divided into analysis of observed damage, expert opinion and score assignment. The first approach is based on the collection and analysis of statistics of damage that occurred in recent and historic events, which requires very intensive data collection and long period of systematic data collection and analyses. The expert opinion is heavily based on interviewing groups of experts in assigning the vulnerability values. Based on the expert experiences the percentage damage is assigned for the different structural types having different intensities of hazard. The analytical approaches require complicated and time-consuming study on the behaviour of buildings and structures based on engineering design criteria, analyzing e.g. seismic load and to derive the likelihood of failure, using computer-based methods from geotechnical engineering. This study was supported supported by several main objectives as follow:

i. Identify and characterize element-at-risk in the study area;
ii. Generation of vulnerability value for each element-at-risk; and
iii. Generation of vulnerability map using geospatial approach.

2. STUDY AREA

2.1 Location of study area

Two (2) study areas were selected in order to pursue the objectives of this study. One study area was located in Kota Kinabalu, Sabah and the other study area was situated in Kundasang, Sabah as shown in Figure 1.

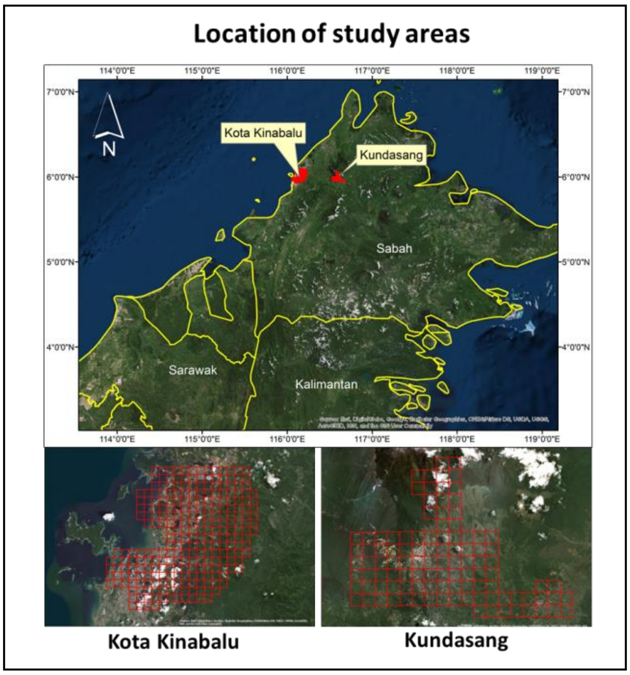


Figure 1. Location of the study area

Based on Figure 1, both of study areas located to the North of Sabah, East Malaysia. It is located approximately between longitude E 116°00’0” to E 116°30’0” and latitude N 5°50’0” to N 6°10’0” in between the South China Sea to the west and the Crocker Range to the east. The study areas cover approximately 106 km^2 and 265 km^2 for Kota Kinabalu and Kundasang, respectively.

2.2 Geological Setting of Study Area

2.2.1 Kota Kinabalu: Kota Kinabalu is the state capital of Sabah which located on the north-west coast of Borneo facing the South China Sea. This area encompassed by the Crocker Ridges which consists of complex land formation and may give negative prospect to any land development activity (Roslee et al., 2012). According to Tongkul (1989), Kota Kinabalu were located at “weak zones”. Weak zones were defined as fault zone whixh prevalently comprise of different size of sedimentary blocks installed in fine grain sedimentary materials, for example, shale and mudstone (Tating et al, 2015). The existing of this zone was due to the previous tectonic activities and their essence may relate to landslide episodes in natural slope and slope failure in road cut slope. In addition, this area prone to landslide incidents due to the pressure of development activities that encourage rapid slope cut works or reclamation for road construction, infrastructures, and other developments especially at hilly areas with expansive populace (Roslee et al., 2012).

2.2.2 Kundasang: Kundasang is located in the Northwest of Ranau, Sabah (Figure 1). Generally, this area is well-known for its unstable hilly area. This area was selected due to the abundance occurences of landslides caused by natural and anthropogenic factors. The hilly terrain and ridges with an elevation of more than 1500 m above mean sea level with combinations of steep slopes was the consequence of violent tectonic activities in the past (Tating, 2006). The area is in a typical tropical climate, large amount of rainfall throughout the year. The annual rainfall ranges from 1920 mm to 3190 mm (average 2075 mm) (Tating et al, 2013). Kundasang area consists of three (3) types of lithology; Pinasouk gravel, Trusmadi formation and Crocker formation. On 5 June, an earthquake measuring 6.0 Mw occurred in Sabah that had triggered the debris flow which caused the disruption of roads, houses and the vegetation along the channel (Wikipedia, 2015). It is said that the earthquake was caused by movement on a SW-NE trending normal fault and the epicenter was near Mount Kinabalu. The shaking caused massive landslides around the mountain (Tongkul, 2015). Rocks located beneath Kundasang vary in age and type, which are the rock starting from Paleocene-Eocene rocks to alluvial rock. Three formations are present and include Trusmadi Formation, Crocker Formation and Quaternary sediment (Tongkul, 1987). Mensaban fault zone is located on the eastern side of Kundasang area which intersects with Crocker fault. The mass movements in Kundasang area can be the result of active movement in Crocker and Mensaban fault zones.

3. METHODOLOGY

In this study, landslide vulnerability assessment was implemented based on the technical vulnerability approach. The flow chart in Figure 2 shows the overall methodology used in this study. Several main phases involved as follows:

i. Data collection and data pre-processing;
ii. Landslide element-at-risk mapping and analysis;
iii. Landslide exposure mapping and analysis; and
iv. Landslide vulnerability mapping and analysis.

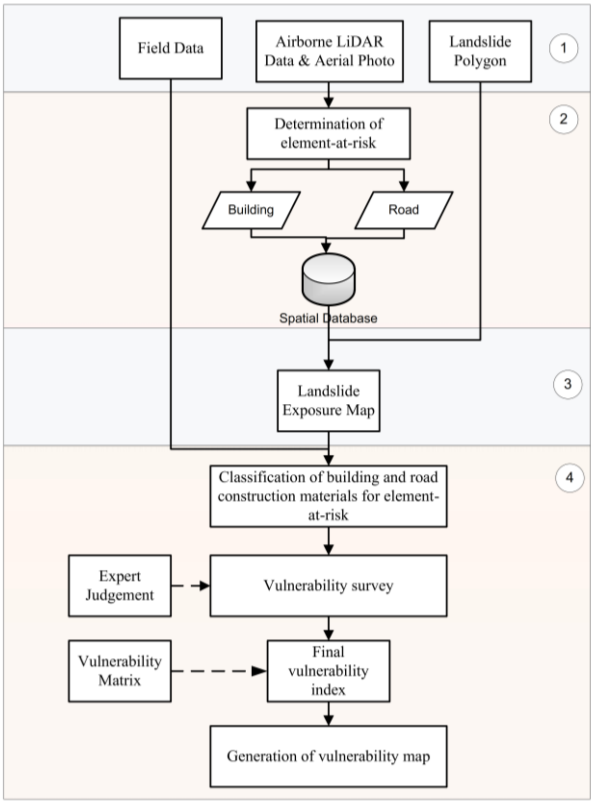


Figure 2. Overall methodology of the study

3.1 Data Collection and Data Pre-processing

As shown in Figure 2, this phase involved various types of data collection such as field data, airborne LiDAR data, and landslide inventory. Field observation were conducted for both areas. For Kota Kinabalu area, observations for buildings and road construction materials were divided into 5 zones while 17 zones for Kundasang. The division process is to ensure effective process of buildings and roads survey during the field work. Special forms were used together with global positioning system (GPS), maps of building footprints and high resolution digital camera to record locations and other important parameters for building and roads. For each observation zone, special database was constructed to store the attributes observed in the field. Airborne LiDAR data and aerial photograph were used for land use and land cover (LULC) mapping. LiDAR point clouds has been classified into ground, building, low vegetation, medium vegetation, high vegetation, road and utilities (electrical and telephone lines). The classification process was also aided by the object-oriented approach on high resolution of aerial orthophoto. Based on the LULC, out of these classified classes, two classes were chosen for element-at-risk components, which are building and road. Apart from building footprint and road, building height is one of the important information in the analysis of element-at-risk. The height was automatically derived from LiDAR-derived Normalized Digital Surface Model (nDSM) and building footprints where each pixel in the nDSM contained values representing height of features. After each individual heights of building footprints were obtained, it was validated randomly by using Google Street View application and field visit in order to maintain consistency and data accuracy. These methods are applied to both Kota Kinabalu and Kundasang areas.

Field observation on the landslide area was executed by recording the information on landslide type, landslide characteristics, building type, construction materials for building and road, damage level and recommended vulnerability values.

3.2 Landslide element-at-risk mapping and analysis

The element-at-risk is one of the crucial components for supporting exposure mapping and analysis. Two classes were chosen for element-at-risk components, which are building and road. The attribute categories for building class are commercial, residential, industrial, public facility, agriculture and institution. Meanwhile, categories of road attribute are state, federal, rural and unpaved roads. All the classified building were further classified into building material classes (22 classes) that has a distinct damage or vulnerability level with different characteristics of landslide. The same method was also used for roads where each class was classified into five road material types. Building and roads were chosen for this study due to the reason that both features are important elements to be considered when dealing with disaster. For example, any damage with building structure will reflect the number of populations or fatalities involved. Road is also essential elements by connecting one place to another and forms as a primary infrastructure for the affected areas to deal with evacuation process or serve as an important platform for a fast disaster relief purposes. Other elements are also important but due to the time limitation, only important elements were considered in this study. Finally, element-at-risk maps for each zone that contained different classes of building and roads materials were produced. These maps were further used to the next phases i.e. landslide exposure mapping and analysis, and landslide vulnerability mapping and analysis.

3.3 Landslide exposure mapping and analysis

In this section, an overview of the Landslide Exposure Mapping and Analysis (LEMA) component was presented. This component is strongly dependent to the other input, such as Landslide Hazard Mapping and Analysis (LHMA) and Landslide Element-at-Risk Mapping and Analysis (LERMA). Exposure indicates the degree to which the elements-at-risk are actually located in an area affected by a particular hazard. Meanwhile, Figure 3 shows the specific methodology of how exposure values of each element-at-risk were obtained.

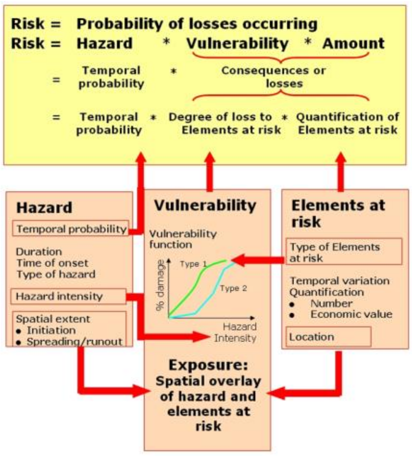


Figure 3. Specific methodology of generating the exposure map (Van Westen, 2008)

Landslide exposure mapping in this study is not meant to assist the determination of vulnerability for element-at-risk, but it helped to prioritize building characterization process compared to other areas with low and no inventory of landslide occurences. By using the information from element-at-risk mapping and landslide inventory, the calculation of exposure map is possible. The method was completed in GIS environment by combining both information with spatial analysis. Landslide exposure mapping and analysis was carried out by looking at the potential areas where the elements are located near to the natural landslides and man-made slope failure. The analysis assumed a landslide (natural landslides and man-made slope failure) will have an effect on the element-at-risk about 100 meters distance. Therefore, any features that lies within the zones were extracted.

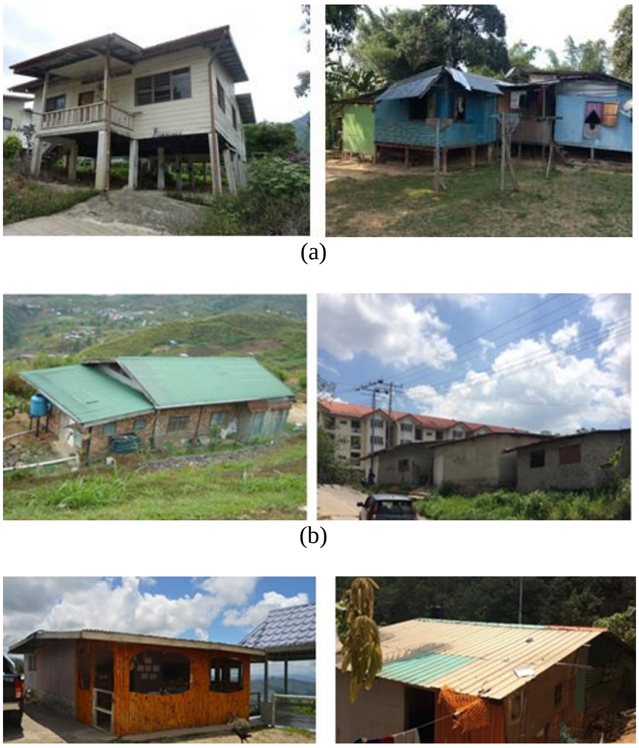
Initially, 50 meters of distance was tested as the buffering distance from the landslides. However, the buffering zone was to small and only few buildings are included in the analysis for both areas. This produced irrelevant results and most likely these features will not be affected by any hazard. In contrast, another test that was done using 200 meters buffering distance and showed that there were too many buildings affected, although these building were actually located very far from the center of the polygons. Therefore, 100 meters buffering distance was deemed as appropriate distance for these areas after considering these factors. Note that other areas with different landslide characteristics might need different buffering values. The best approach is to apply proper landslide runout analysis that accounts detailed landslides characteristics.

3.4 Landslide vulnerability mapping and analysis

In landslide vulnerability mapping and analysis, expert judgement-based method was used to identify vulnerability value for each element-at-risk. For this, severals vulnerability surveys has been conducted with the selected experts. Separate expert-based vulnerability matrices were generated for Kundasang and Kota Kinabalu areas. The experts were selected based on certain criterias as follow:

i. Knowledge on landslides vulnerability mapping and analysis based expert judgment;
ii. Knowledge on landslides risk mapping based on geospatial approach;
iii. Local knowledge on landslides occurrences and their characteristics for Kundasang and Kota Kinabalu;
iv. Coping capacity for different element-at-risk to withstand landslide hazard in Kundasang and Kota Kinabalu; and
v. The impact of different landslide types in Kundasang and Kota Kinabalu on different building and road construction materials.

During the interview session with the experts, the survey form was attached with a document that contains list of building materials and its corresponding pictures. Figure 4 shows the examples of building construction materials in Kundasang and Kota Kinabalu.



(a)

(b)

(c)

Figure 4. Examples for poor wood/zinc/cement-board building with pillar (a), Poor single storey confined brick masonry building (b) and poor single storey wood/zinc/cement-board building (c) for Kundasang (left) and Kota Kinabalu (right) respectively

Each building and road construction material type was crossed with different types of landslides. The vulnerability value for building construction materials is determined based on the damage value as shown in Table 1. The damage level is divided into 5 levels i.e. 1) negligible damage, 2) slightly damage, 3) significantly damage, 4) severely damage and 5) very severe damage. Based on the experience of the experts and damage description, each empty space located in the vulnerability matrix was assigned with the vulnerability value (between 0.0 and 1.0). Roads in Kundasang and Kota Kinabalu are classified into 5 classes, namely 1) highway (well-maintained paved road), 2) federal road (paved road), 3) state road (paved road), 4) rural road (poorly paved road) and 5) unpaved road. The road classes were paired with the above-mentioned types of landslide. Table 2 defines the typical level physical impacts or damages that occurred on road. The damages on the road are classified into 5 groups similar with buildings.

Damage level	Damage class	Description of buildings
1	Negligible damage	No significant damage – slight accumulation of material causing asthetic damage (dirt, chipping paint, etc). Vulnerability value: **0.10-0.29**
2	Slightly damage	No structural damage – minor repairable damage: chipping of plaster, slight cracks, damage to door, windows and stair. Vulnerability value: **0.30-0.49**
3	Significantly damage	No structural damage –major damage requiring complex repair: displacement or partial collapse of walls or panels without compromising structural integrity, highly developed cracks. Evacuation required. Vulnerability value: **0.50-0.69**
4	Severely damage	Structural damage that can affect the stability of the building: out-of-plane failure or collapse of masonry, partial collapse of floors, severe cracking or collapse of sections of structure due to settlement. Immediate evacuation; demolition of the element may be required. Vulnerability value: **0.70-0.89**
5	Very severe damage	Heavy damage seriously compromising the structural integrity: partial or total collapse of the building. Imlerative and immediate evacuation and complete demolition. Vulnerability value: **0.90-1.00**

Table 1. Reference vulnerability for buildings

Damage level	Damage class	Description of buildings
1	Negligible damage	No significant damage. Vulnerability value: **0.10-0.29**
2	Slightly damage	No structural damage – minor repairable damage. Vulnerability value: **0.30-0.49**
3	Significantly damage	No structural damage –major damage requiring major repair work. Vulnerability value: **0.50-0.69**
4	Severely damage	Structural damage that can affect the stability and functionality of the road. Vulnerability value: **0.70-0.89**
5	Very severe damage	Heavy damage seriously compromising the structural integrity: partial or total collapse of the road. Vulnerability value: **0.90-1.00**

Table 2. Reference vulnerability for roads

This expert judgement-based landslide vulnerability assessment is developed based on several assumptions:

i. The locations of element-at-risk i.e. road and building are assumed inside the landslide polygons. However, the specific location for the element-at-risk will only account typical scenario in Kundasang and Kota Kinabalu;
ii. The magnitude of landslides only accounts the typical landslides occurrences in Kundasang and Kota Kinabalu;
iii. Identification of road and building damages due to landslides are based on typical road and building damages in Kundasang and Kota Kinabalu;
iv. Determination of vulnerability value accounts coping mechanism for each element-at-risk. For example, building constructed with light materials and supported by wood pillar would have smaller damage compared to concrete buildings for creeping land movement. This is due to dynamic nature of light material building that has high tolerance with slow movement of landslides compared to concrete buildings; and
v. Damage assessment of road assumes typical thickness of pave and size of carriageway.

Finally, the final vulnerability map is produced by combining vulnerability matrices filled by the experts. The matrices are combined using weighted arithmetic average as explained in Equation 1 to Equation 3.

$$\{x_1, x_2, \dots, x_n\} \qquad (1)$$

$$\bar{x} = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i} \qquad (2)$$

$$\bar{x} = \frac{w_1 x_1 + w_2 x_2 + \cdots + w_n x_n}{w_1 + w_2 + \cdots + w_n} \qquad (3)$$

where,

w – Weight for each panel or expert
x – Vulnerability matric (building or road) of each panel for Kundasang and Kota Kinabalu
n – Number of panel = 4

The weighted arithmetic average requires weight values for each panel and this is defined based on their experience and knowledge (Table 3). The method ensures the final vulnerability matric will have a strong influence from the panel with higher weight compared to panels with low weight value.

Panel	Weight	Justification
1	0.5	Local expert (landslides and damage assessment), wide experience in landslide vulnerability analysis, hazard and risk mapping
2	0.3	Local expert (landslides and damage assessment), experience in hazard and risk mapping
3	0.2	Wide experience in urban planning
4	0.2	Wide experience in slope management, landslides hazard and risk mapping

Table 3. Weight value for each panel

The landslide types (based on materials and process) as defined in the vulnerability assessment form have been re-classified based on its process that used by the field observation and landslides interpretation processes. The vulnerability matrices obtained by averaging 17 types of landslides into several landslides in Kundasang and Kota Kinabalu. The average value is derived by using a normal averaging method. Since the landslide susceptibility and hazard modelling and mapping have been done based on the combination of all landslide types, the vulnerabilty values assigned for each landslide type should be combined to produce single vulnerability value for each building and road construction material. Therefore, the process involves averaging the vulnerability values using weighted arithmetic average method (Equation 4 to Equation 6). The weighted arithmetic average requires weight values for each landslide type (Table 4) and this is defined based on their percentage in the landslide inventory. The method ensures the final vulnerability value will have a strong influence from the landslide type with higher weight compared to landslides with low weight value.

$$\{x_1, x_2, \ldots, x_n\} \tag{4}$$

$$\bar{x} = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i} \tag{5}$$

$$\bar{x} = \frac{w_1 x_1 + w_2 x_2 + \cdots + w_n x_n}{w_1 + w_2 + \cdots + w_n} \tag{6}$$

where,

w – Weight for each landslide type
x – Vulnerability value of each landslide type for Kundasang
n – Number of landslide type

Process-based types	Weight	
	Kota Kinabalu	Kundasang
Complex	0.06	0.09
Rotational	0.29	0.46
Translational	0.09	0.16
Flow	0.01	0.06
Topple	0.004	-
Fall	0.006	0.03
Unknown	0.54	0.2

Table 4. Weight value for each landslide type for Kota Kinabalu and Kundasang

Vulnerabiltiy map is generated by combining building/road footprint with information on construction materials and the final vulnerability value.

4. RESULTS AND DISCUSSION

4.1 Landslide Element-at-risk Mapping and Analysis

Figure 5 and Figure 6 show the sample of element-at-risk maps for Kota Kinabalu and Kundasang areas that contain two main features i.e. buildings and roads. Both features were stored in special database and each feature was categorized based on different material type. This database was further used in generating the landslide exposure map and landslide vulnerability map.

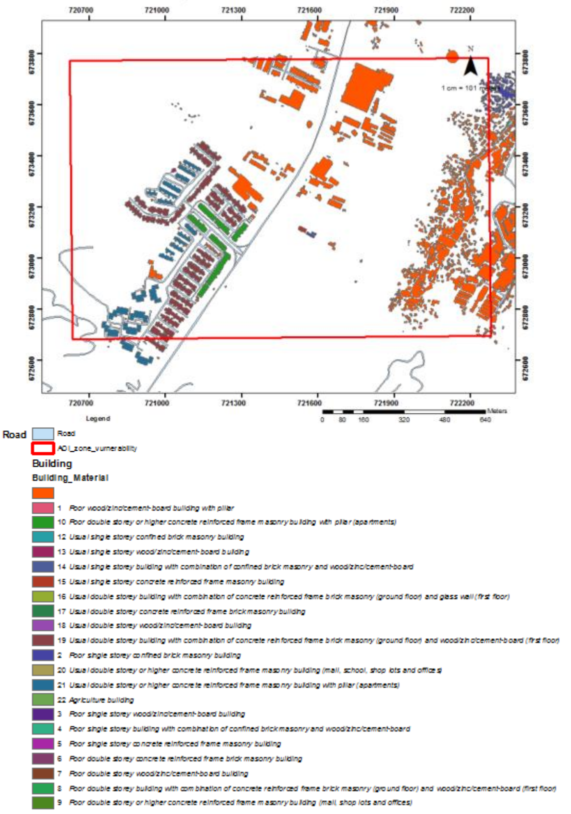


Figure 5. Example of building footprints classified into different building construction materials in Kota Kinabalu

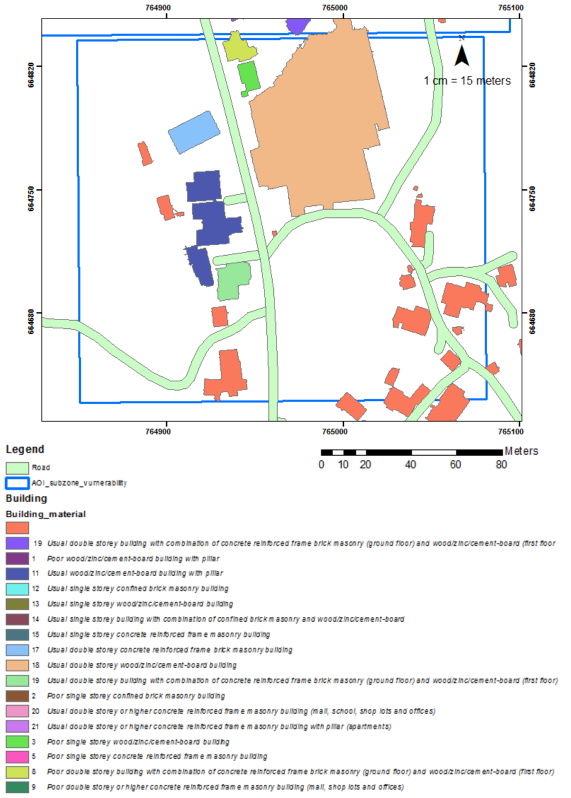


Figure 6. Example of building footprints classified into different building construction materials in Kundasang

4.2 Landslide Exposure Mapping and Analysis

Landslide exposure mapping indicates the degree to which the elements-at-risk are actually located in an area affected by landslides. According to the statistics table as shown in Table 5, 6,146 out of 28,823 total buildings in Kota Kinabalu which is 21.32% of buildings are at risk. As for roads in Kota Kinabalu as shown in Table 6, about half from total length of roads which are 53.15% are at risk. About 345.71 kilometres out of 650.49 kilometres of roads are contained within buffer zone. These buildings and roads which are located 100 meters away from the location of landslides and slope failure are considered as element-at-risk and needs some precautions in order to prevent any casualties.

Kota Kinabalu (Buildings)			
No.	**Buildings Footprint**	**Total**	**Percentage (%)**
1	Total Buildings in Kota Kinabalu	28823	
2	Buildings within landslide and man-made slope failure	6146	21.32

Table 5. Statistics of selected buildings within 100 meters distance in Kota Kinabalu

Kota Kinabalu (Roads)			
No.	**Buildings Footprint**	**Length of roads (km)**	**Percentage (%)**
1	Total length of roads in Kota Kinabalu	650.49	
2	Roads within landslide and man-made slope failure	35.71	53.15

Table 6. Statistics of selcted roads within 100 meters distance in Kota Kinabalu

According to the statistics for Kundasang area as shown in Tables 7 and 8, building and road features within this area are mostly selected as element-at-risk. As 3,769 much of buildings out of 5,805 are located within 100 meters from landslide and slope failure. In terms of percentage, 64.93% is more than half of total buildings are considered as at risk. The situation goes worse for the roads in Kundasang where 198.43 kilometres out of 258.86 kilometres are at risk. In percentage view, as much as 76.66% of roads in Kundasang are located near to landslide and slope failure.

Kundasang (Buildings)			
No.	**Buildings Footprint**	**Total**	**Percentage (%)**
1	Total Buildings in Kundasang	5805	
2	Buildings within landslide and man-made slope failure	3769	64.93

Table 7. Statistics of selected buildings within 100 meters distance in Kundasang

Kundasang (Roads)			
No.	**Buildings Footprint**	**Length of roads (km)**	**Percentage (%)**
1	Total length of roads in Kundasang	258.86	
2	Roads within landslide and man-made slope failure	198.43	76.66

Table 8. Statistics of selcted roads within 100 meters distance in Kundasang

By using information and analysis from element-at-risk and landslide polygon, the calculation of exposure map is possible. The method was completed in GIS environment by overlaying both information. The results of the exposure calculation can be illustrated as landslide exposure maps for Kota Kinabalu and Kundasang areas (Figure 7 and Figure 8).

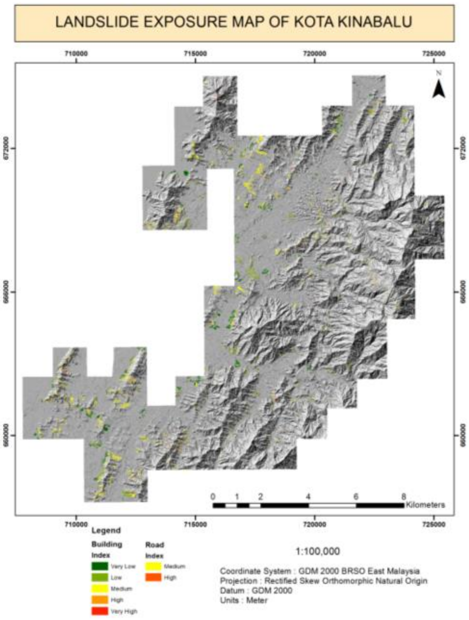


Figure 7. Landslide Exposure map of Kota Kinabalu

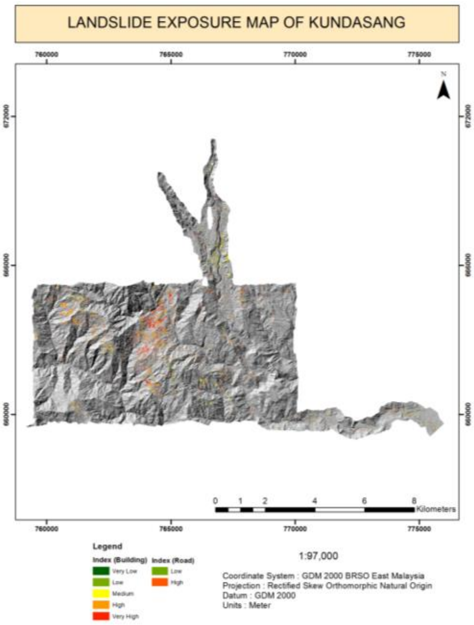


Figure 8. Landslide Exposure map of Kundasang

The exposure level of hazard for building and roads can be summarized in Tables 9 to 12. For building in Kota Kinabalu (Table 9), about half on the buildings in the area were categorized as 'Medium' level (50.52%), which was considered as the highest percentage. This is followed by 21.62% for 'Very Low', 14.61% for 'High' and 12.95% for 'Low'. Building with 'Very High' level of exposure was showing a small percentage (0.29% or 18 buildings) and was the lowest among all.

For road in Kota Kinabalu (Table 10), there were only two levels of exposure which is 'Medium' and 'High', as opposed to the original five classes of hazard levels. From this, about 85% (292.76 km) of the total roads were categorized as 'Medium' and the rests (15% or 52.95 km) were considered as 'High'.

Kota Kinabalu (Building)			
No.	**Level of Exposure**	**Total Buildings**	**Percentage (%)**
1	Very Low	1329	21.62
2	Low	796	12.95
3	Medium	3105	50.52
4	High	898	14.61
5	Very High	18	0.29

Table 9. Level of building exposure toward hazard in Kota Kinabalu

Kota Kinabalu (Roads)			
No.	**Level of Exposure**	**Length of roads (km)**	**Percentage (%)**
1	Medium	292.76	84.68
2	High	52.95	15.32

Table 10. Level of road exposure toward hazard in Kota Kinabalu

For building in Kundasang (Table 11), the highest class was the 'High' exposure level with 43.39% or about 1635 buildings. The second largest was 'Very High' level (26.78%), followed by 'Medium' with 19.64%, 'Low' with 9.71%. Buildings with 'Very Low' were the lowest with 0.48% (about 18 buildings).
In the meantime, for road in Kundasang (Table 12), about 82% or 161.7 km of the road lengths were considered as 'High'. The rests (18% or 36.73 km) were appeared as 'Low'.

Kundasang (Building)			
No.	**Level of Exposure**	**Total Buildings**	**Percentage (%)**
1	Very Low	18	0.48
2	Low	366	9.71
3	Medium	740	19.64
4	High	1635	43.39
5	Very High	1009	26.78

Table 11. Level of building exposure toward hazard in Kundasang

Kundasang (Roads)			
No.	**Level of Exposure**	**Length of roads (km)**	**Percentage (%)**
1	Low	36.73	18.51
2	High	161.7	81.49

Table 12. Level of road exposure toward hazard in Kundasang

In a conclusion, majority of buildings and roads in Kota Kinabalu can be categorized as having 'Medium' level of exposure in terms of hazard while more than half of the buildings and roads in Kundasang area are located at the level of 'High' exposure and above.

4.3 Lamdslide Vulnerability Mapping and Analysis

The final vulnerability map is produced by combining vulnerability matrices filled by the experts. The matrices are combined using weighted arithmetic average as explained in previous section. Table 13 to Table 14 show the final vunerability value for building and road for Kota Kinabalu and Kundasang area.

No	**Building material types**	**Final Vulnerability Value**	
		Kota Kinabalu	**Kundasang**
1	Poor wood/zinc/cement-board building with pillar	0.78	0.76
2	Poor single storey confined brick masonry building	0.76	0.76
3	Poor single storey wood/zinc/cement-board building	0.76	0.76
4	Poor single storey building with combination of confined brick masonry and wood/zinc/cement-board	0.77	0.74
5	Poor single storey concrete reinforced frame masonry building	0.75	0.72
6	Poor double storey concrete reinforced frame brick masonry building	0.74	0.71
7	Poor double storey wood/zinc/cement-board building	0.75	0.72
8	Poor double storey building with combination of concrete reinforced frame brick masonry (ground floor) and wood/zinc/cement-board (first floor)	0.64	0.66
9	Poor double storey or higher concrete reinforced frame masonry building (mall, shop lots and offices)	0.62	0.67
10	Poor double storey or higher concrete reinforced frame masonry building with pillar (apartments)	0.64	0.65
11	Usual wood/zinc/cement-board building with pillar	0.70	0.66
12	Usual single storey confined brick masonry building	0.63	0.60
13	Usual single storey wood/zinc/cement-board building	0.62	0.60
14	Usual single storey building with combination of confined brick masonry and wood/zinc/cement-board	0.58	0.61
15	Usual single storey concrete	0.56	0.56

	reinforced frame masonry building		
16	Usual double storey building with combination of concrete reinforced frame brick masonry (ground floor) and glass wall (first floor)	0.54	0.50
17	Usual double storey concrete reinforced frame brick masonry building	0.49	0.51
18	Usual double storey wood/zinc/cement-board building	0.61	0.53
19	Usual double storey building with combination of concrete reinforced frame brick masonry (ground floor) and wood/zinc/cement-board (first floor)	0.57	0.50
20	Usual double storey or higher concrete reinforced frame masonry building (mall, school, shop lots and offices)	0.46	0.47
21	Usual double storey or higher concrete reinforced frame masonry building with pillar (apartments)	0.45	0.46
22	Agriculture building	0.87	0.86

Table 13. Final vulnerability value for building in Kota Kinabalu and Kundasang

No	Road material types	Final Vulnerability Value	
		Kota Kinabalu	Kundasang
1	Highway (Well maintained paved road)	0.43	0.46
2	Federal road (paved road)	0.46	0.49
3	State road (paved road)	0.47	0.50
4	Rural road (poorly paved road)	0.52	0.55
5	Unpaved road	0.61	0.63

Table 14. Final vulnerability value for roads in Kota Kinabalu

Based on derived vulnerability value of element-at-risk i.e. buildings and roads, vulnerabiltiy map was generated by combining building nad road footprint with the information on construction materials and final vulnerability value. Figure 9 and Figure 10 show the vulnerability maps for Kota Kinabalu and Kundasang area, respectively.

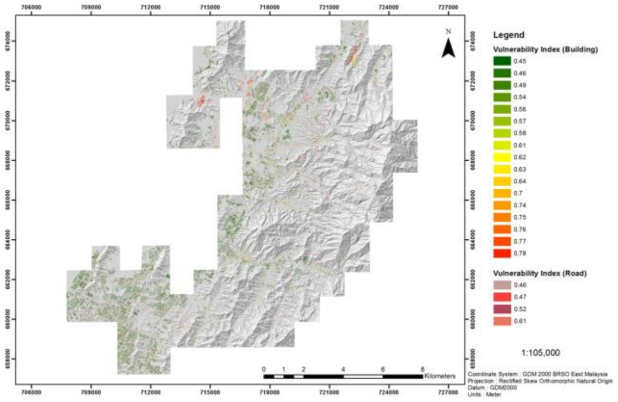


Figure 9. Vulnerability map for Kota Kinabalu

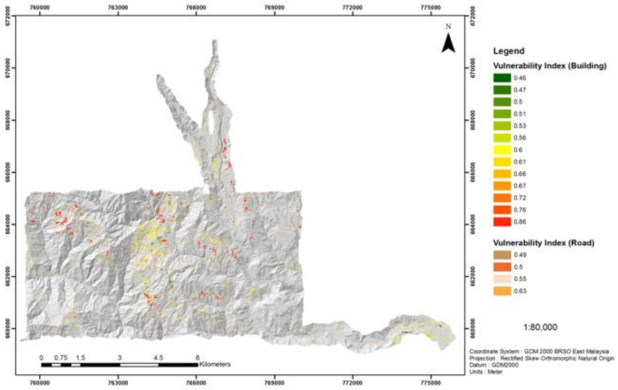


Figure 10. Vulnerability map for Kundasang

5. CONCLUSION AND DISCUSSIONS

The vulnerability assessment and mapping is based on vulnerability matrices generated using expert opinion. The experts have been selected based on several conditions that account their experiences and knowledge on landslide vulnerability and damage assessments. The quality of the vulnerability map relies on the accuracy of LULC classification and mapping. The LULC map has been used to produce element-at-risk map that consists of additional attributes for vulnerability assessment i.e. building and road construction materials. The information on the building and road construction materials were obtained by means of multiple field observations. The final vulnerability maps for Kundasang and Kota Kinabalu have been used successfully for landslide risk mapping and analysis. The vulnerability maps, however, are still subjected to limitations and assumptions. Therefore, there are several recommendations that can be considered for future landslide vulnerability assessment.

i. The expert-based landslide vulnerability assessment should be combined with the damage records due to landslide. Special proforma should be developed and used by the authority to record and assess the related element-at-risk for every landslide incident. This information should also be combined with detailed landslide intensity assessments to produce vulnerability curve for each element-at-risk.
ii. Detailed classification of element-at-risk that accounts damages due to landslides for example building material types should be simplified to reduce its complexity in the vulnerability analysis. Good classification schemes

allow authority to determine the best option for element-at-risk to withstand landslide hazard. Specific coping mechanism for element-at-risk can be identified by carefully analyze the vulnerability curve which allows mitigation measures to be taken at minimum cost and at the same time reduces the landslide risk.

iii. In this study, landslide susceptibility and hazard maps have been produced by combining all landslide types. We recommend separate landslide susceptibility and hazard mapping for different landslide types. This allows separate and detailed analysis on landslide vulnerability.

iv. We also recommend the inclusion of other element-at-risk for landslide vulnerability analysis and mapping. This allows detailed landslide risk mapping that accounts multiple aspect of risks.

One of the important aspects in airborne LiDAR processing is point clouds filtering that aims at separating ground and non-ground laser points. Problems in the filtering process will lead to a problem in LULC mapping for example buildings might be wrongly classified as ground terrain. This will affect the quality of element-at-risk mapping and landslide vulnerability mapping and assessment. In this case, airborne LiDAR filtering process should be done carefully that accounts local condition of specific area. This also requires careful assignment of values for important variables in the filtering algorithm. The results of this filtering process should be supported by strong quality checking (QC) procedures.

ACKNOWLEDGEMENTS

We would like to express our gratitude to Minerals and Geoscience Department for the remote sensing data and experts in the landslides mapping and inventory process. Special thanks to the experts from various departments including Minerals and Geoscience Department, Public Works Department, PLAN@Malaysia, and Universiti Malaysia Sabah and also support from GUP grant vot number Q.J130000.2527.19H43, and Zamalah/ Institutional Scholarship.

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This contribution has been peer-reviewed.
https://doi.org/10.5194/isprs-archives-XLII-4-W9-189-2018