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Landslide susceptibility mapping along the Ho Chi Minh route in central Vietnam: AHP approach applied to a humid tropical area

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ベトナム国中部，ホーチミンルート沿いの地すべり発生危険度の地図化 －湿潤熱帯地域における AHP の適用－

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Abstract

Landslide is considered as one of the hazardous phenomenon that often occurs in the mountainous region of center area of Vietnam. The prediction of land sliding sensitivty for mitigation should be requireed by fact. This paper focuses on the spatial analysis of landslide susceptibility in this area. For analyse landslide related causative factor maps are derived such as slope angle, type of rock, fault density, distance to the road, land use and precipitation. Landslide causative factor maps were created using GIS, in which each one was alocated in to classes. An analytical hierarchical process is used to combine these maps for landslide susceptibility mapping. As the results, a landslide susceptibility zonation map with 4 landslide susceptibility classes, i.e low, moderate, high and very high susceptibility for potential landslid, is derived based on the inventory map of observed landslide since 2006 to 2013. The landslide susceptibility map indicates that 82.66% total number of occurred landslides, which have been reported fall into highly and very highly susceptible zone. Even there was limited matter concerning relevant, scale and available data, the landslide susceptibility map of this study for corridor along this road is credible for landslide mitigation.

地すべりはベトナム中部の山岳地帯における一つの災害発生要因として常に留意さ

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れる現象である．斜面災害の軽減のためのアプローチとして，事実関係に基づいて斜面の滑動しやすさを予測することが必要である．本稿では当該地域を対象として，地すべり発生のしやすさに関する空間解析を行った．地すべり発生の原因となり得る，斜面傾斜，岩種，断層密度，道路からの距離，土地利用，降水量の要因の地図情報をGIS上でデータベース化し，地すべり発生関連要因地図を整備し，それぞれと地すべり災害の発生状況を照らし合わせた．これらをもとにAHP的な手法を用いて地すべり災害の発生可能性を評価・クラス分けすることとした．その結果，地すべり発生の可能性を，「極めて高い・高い・中程度・低い」の4つにクラス分けし，同時に2006年から2013年に亘って調査された斜面災害地データとの対照を行った．その結果，地すべり発生箇所総数の82.66％が「極めて高い」と「高い」の領域に重なっていた．今回用いたデータや手法が適用できる範囲は限られていると思われるが，地すべり災害の軽減を考える一つの手法として今後も検討を重ねていくことが必要である．

Key words: *Landslide, Mountainous region,Susceptibility map, Identifying map, Vietnam*

1. Introduction of natural characters of study area

Vietnam the land is a typical sloping country, the geological and tectonic status has very complicate. Bordered by the Pacific Ocean, it is also influenced by the monsoon climate, with high average annual rainfall, and complex geological structures with rugged landscape. Landslides are the most important "natural hazard", especially in northern and central Vietnam.

The study area is a zone that includes Ho Chi Minh (HCM) route corridors in the center of Vietnam, where the landslides are regarded as frequent and dangerous phenomena causing widespread economic damage to the transportation sector and local residents. The strategic route of HCM is nearly 1800 km long from Hoa Lac (Hanoi) to HCM City. This route is a part of the North-South expressway master plan approved by the Vietnamese government. The target of the study section is approximately 300 km of HCM route, which begins from the junction with national Highway No. 9 (at the cable stay Bridge Dakrong-Quang Tri Province) to Dong Loc, Dak Glei Kontum Province. In this research, the study area is a zone limited by a distance of 20 km offset to both sides from the center-line of HCM route, extending northwest and southeast between the latitudes of 16° 40'N and 15° 30'N and longitudes of 106° 15'E and 106° 50'E; extends to three provinces of Quang Binh, Hue, and Quang Nam. The study area is presented in Fig. 1.

Regarding topography and landforms, because of the geology structure of the Truong son Mountains located along the west side of the area, terrain of the three described provinces was lower from west to east and is divisible into terrain of three types: (1) medium to high mountain areas, distributed in the west from the top of the Truong Son range to

Fig. 1. Location of the study area.

domain hill bowl area; (2) midlands and narrow delta along the study area; followed by (3) the coastal areas. The HCM route lies mainly in the medium to high mountain area, located in western Vietnam, close to the Lao border, with average elevation of 700–2000 m. The highest summit reaches 2,598 m (Ngoc Linh Mountain). The terrain surface shows strong cleavage because of erosion, weathering, and tectonic action.

The geomorphology of the Vietnam midlands is generally divided into two regions. Region 1 includes the provinces of Quang Tri and Thua Thien-Hue, except the areas of Bach Ma National Park. Mountains here are concentrated in the northeast-southwest, parallel to the coast. The main rivers also follow the water convergence of these mountains. Region 2 includes the area of Bach Ma National Park and of Quang Nam province, which extend west–east. The study area spreads along the longitudes and has geomorphologic character of both described regions. The south of the study area corresponds to cuesta landforms with homoclinal structure.

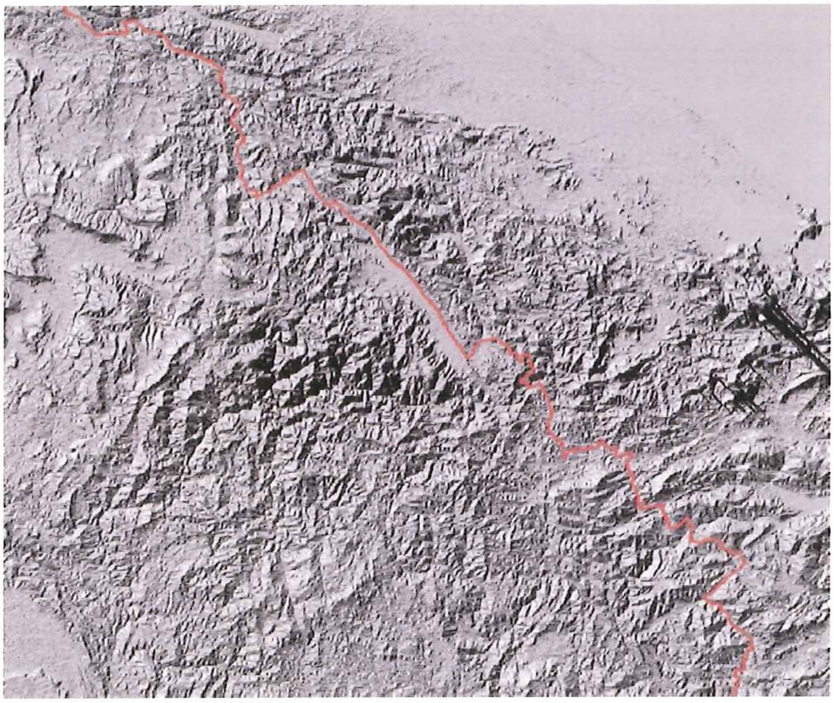

Fig. 2. Topography and landform of the study area.

The regional climate of study area is classifiable into three basic climate zones: Quang Tri province - a tropical monsoon climate zone resembling the northern Vietnam climate; Quang Nam province - the southern tropical climate zone; and Hue as the transitional one. They also have similar characters. The average annual temperatures of the study area are 20–28℃, with occasional temperatures of 40℃-41℃ in Hue during summer. The average annual precipitation is 2,200–2,600 mm, although it can reach 4,000 mm in Bach Mã, Thừa Lưu Mountains, Quang nam Province (Tien DV 2013). The storm season extends from the June through November every year. During September and October, the number of tropical storms coming to these provinces is greatest. Tropical temperatures, high humidity, the weathering with very high density vegetation hide evidence of natural phenomena that took place in the past. Most signs of past slide activity are difficult to observe.

Locating on the Truong Son block of on geology structural blocks map, the geology along the HCM route is dominated by Paleozoic sedimentary rocks such as limestone, shale, slate, and tuff in northern areas including A Luoi, with Palaeozoic metamorphic rocks such as schist and gneissic granite in the central areas including Prao, and Mesozoic sedimentary rocks consisting of sandstone with coal seams, mudstone, and conglomerate in the south. Additionally, in some areas, granite is exposed, exhibiting hornfels and gneissic granite on the edges (granite/gneiss). For the degree of weathering, brown to yellow soil is regarded as strong. Soil containing gravel is also strong. Rock with partially open cracks is regarded as weak and fresh bedrock does not weather (Abe- SATREPS Workshop 2014). Rock type contributions of the study are presented in Fig. 9.

The study area is located in the center of Vietnam, which is an area with extreme climate, affected by heavy rains, high jagged terrain, and complex geological structures, as described. In such natural conditions, landslides are common natural phenomena occurring on this place during the rainy season.

2. Landslides occurring along the HCM Road and Data survey results

After traffic operations, since 2004, along the HCM route in the study area, many slope failures have occurred. Hereinafter they are described as landslides. According to historical data accumulated through 2013, 604 landslides of different sizes were recorded along the road.

According to survey data from the Institute of Geology and Minerals (Tran Tan Van 2006), 167 landslides occurred along the HCM route in 2004. After the rainy seasons of 2006 and 2009, the Research Institute of Transport Science and Technology (ITST) conducted numerous investigations of slope failures. The numbers of landslides were recorded respectively as 178 and 248 landslides (Tien DV,2010). In 2013, with the thin scope of Project Development of Landslide Risk Assessment Technology along Transport Arteries in Vietnam, which was done by ITST and ICL, 15 additional landslides were recorded.

In particular, four sections of this road required special attention because of heavy landslide appearance. They are Section 1 includes Road section on Dak Rong, Ta Rut district, and the 8 km long Peke Pass. Section 2 includes 25 km of two pass sections of A Roang, A Luoi, Thua Thien Hue province. Section 3 includes Adich-Alo Section, Quang Nam province. Section 4 includes Alo-Xaoi Section. Based on data of the investigation, a landslide distribution map was established as basic data for this study. A landslide distribution map of the study area with the four described sections is displayed in Fig. 3. Most slope failures were cut-slopes of roads that collapsed under the direct impact of rain. Regarding the type of movement, they were divisible into three main categories as slides (32.1%), falls and toppling (55.9%), and flows (11.9%). Typical landslide images are portrayed in Fig. 4.

3. Landslide Survey Results and causative factors

To ascertain why landslides have occurred so often in this area and to elucidate the main reasons for their appearance, a large site survey of 604 artificial slope failures was done. The weights of landslide causative factors were considered by experts. To assess landslide

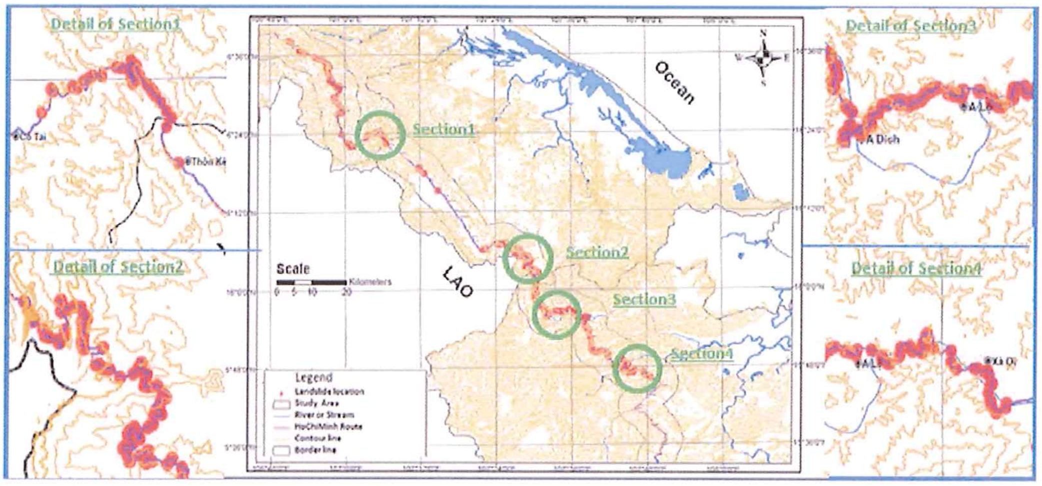

Fig. 3. Landslide distribution map of the study area and four severe landslide sections.

Fig. 4. Photographs of landslides, which often occur on the HCM route in Vietnam: A (N15° 48' 10.6", E107° 53' 07.1") Translation, B (N16° 24' 07.4", E107° 04' 54.1") gully, C (R: N16° 23' 46.5", E107° 05'59.6") rotational, and D (N15° 53' 36.9", E107° 04' 54.1") rock fall.

susceptibility, the identification of causative factors, which are classifiable as dynamic factors (e.g. pore water pressure) and passive factors (e.g. rock structure), might also be considered in terms of their roles as pre-conditioning factors (e.g. slope angle), preparatory factors (e.g. deforestation), and triggering factors (e.g. rainfall) usually targets of the study.

Actually, the landslide process depends on many factors such as topography and geomorphology, geology, climate, and human impact. However, for a concrete study of this zone, based on relevance, availability and scale of map (Slide and Ochiai 2006), necessary factors should be used. Therefore, as objects of analysis for this study, minor and indirect factors were ignored in favor of factors such as elevation, slope angle, land use, rock type, total annual average precipitation, fault density, and distance to the road.

Principles of analyses to evaluate the weight of each factor, which contribute to the sensitiveness of occurred landslides. From survey results, positions of respective landslides were recorded. Six maps of causative factors as described were created from available data, in which each causative factor was divided to different classes. The relation of different classes of each sensitive factor and number of occurred landslides (NOL) and density of occurred landslides (DOL) were studied. Actually, NOL is an important index for consideration because landslides were only recorded along the road, which runs over a certain area of study area, not the entire area. Therefore, a second index represents the landslide number that occurred per unit of area as DOL giving out. Then GIS technology was imported for analyses.

Natural slope Angles

Regarding topography, the slope angles, slope type, and the dynamic processes on the slopes strongly influence the slope stability, particularly on steep terrain, because of the concentration of the surface and sub-surface water. This slope angle is a principal causative or trigger factor because the steeper a slope is, the greater is the risk of land sliding because of higher shear forces induced by gravity. Therefore, the use of a typical geomorphological factor as a natural slope angle is necessary for the landslide risk assessment.

A digital elevation model (DEM) of study area with a resolution of 50 m × 50 m was digitized from the available 1:50,000 scale topographic map. Figure 5 shows the digital elevation model of the study area. Based on the digital elevation model, a slope angle map of the entire study area was derived using the slope function of ILWIS 3.0. It is shown in Fig. 6. A slope angle map of the study area was classified into six different classes groups separately following the classification, which was defined by many researchers of landslides and geomorphology throughout the world as follows: flat-gentle slope (< 3°), fair slope (3-8°), moderate slope (8-15°), fairly moderate slope (15-30°), steep slope (30-45°), and very steep slope (>45°).

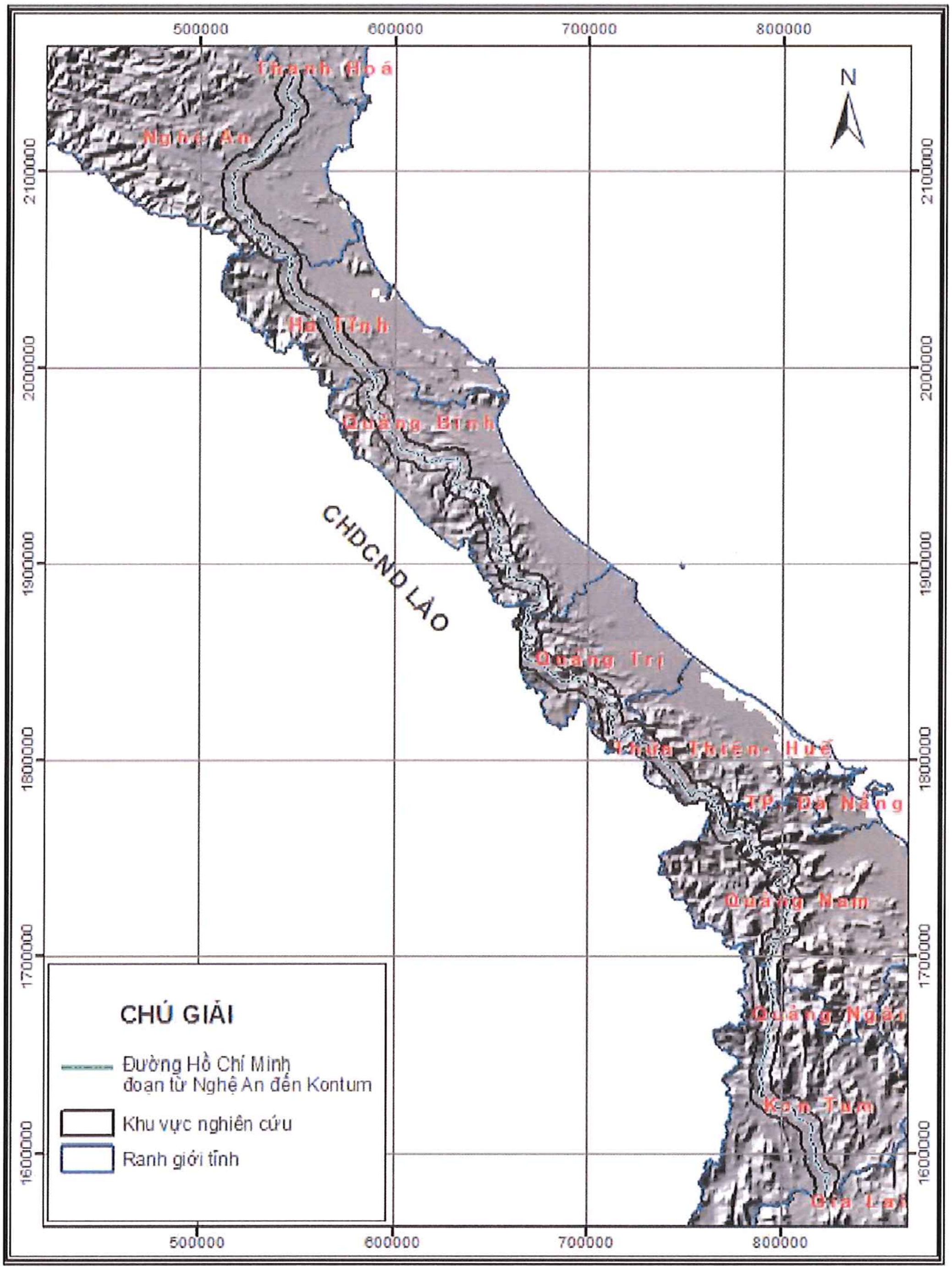

Fig. 5. Digital elevation model of the study area.

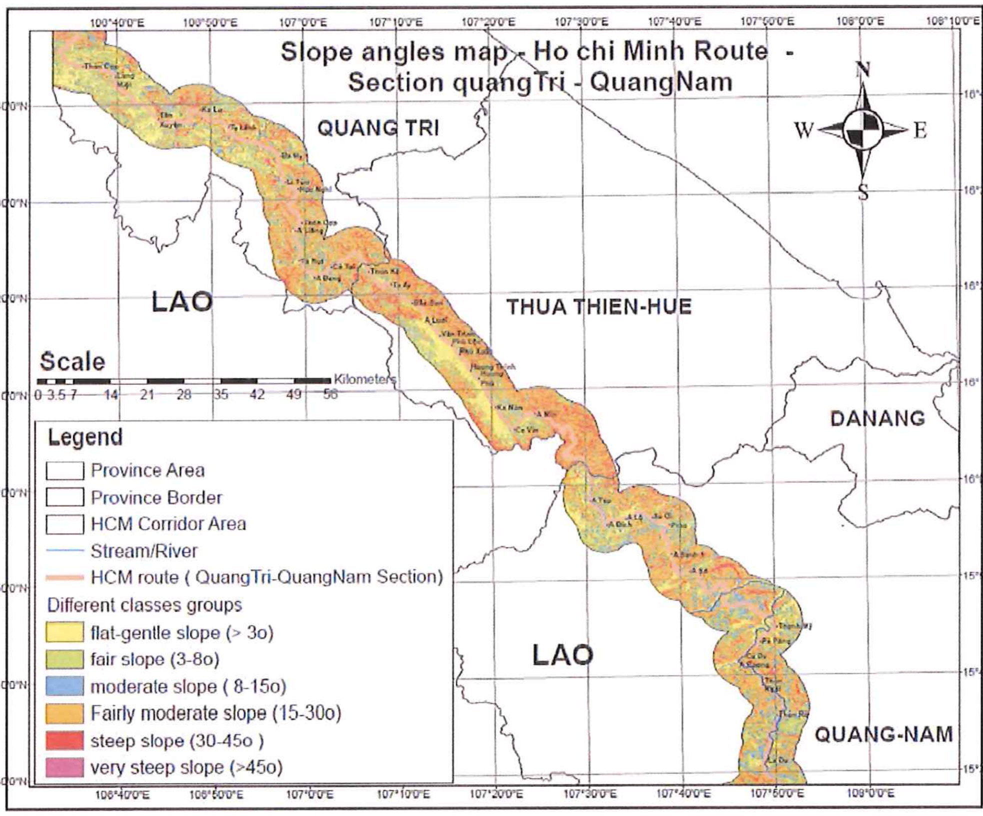

Fig. 6. Slope angle map of the study area, showing zone with flat-gentle slope (< 3°), fair slope (3–8°), moderate slope (8–15°), Fairly moderate slope (15–30°), steep slope (30–45°) and very steep slope (>45°).).

From the locations of slope failures that occurred on different class zones of natural slope angles, we were able to recognize that NOL and DOL increase when the natural slope angle increases. At the natural slope angle as 30–45°, NOL is highest. At the zone of flat-gentle slope angle (> 3°), most landslides are caused by the failure of artificial slopes, which were created from excavation of natural slopes to facilitate road construction. That is an explanation for the quite high NOL index that was recorded. At a very steep slope angle (>45°) zone, where most road designers prevent road-alignment because of difficulty in stable cutting of the slope, the NOL index is small. Result of the study is present in Table 1.

Fault density

The fault density factor represents the shattering of rock. It is defined by the total fault length in a certain area (usually by 1 km^2). Varnes et al. (1984) concluded that the degree of fracturing and shearing takes an important role in determining slope stability. Fault density is usually considered in landslide assessment.

A digital fault density map of the study area was calculated based on taking the total number length of faults per unit area from the faults model of the available 1:200,000 scale

Table 1. Analysis Result of NOL and DOL index with Slope Angle classes

Slope Angle classes	NOL	Area (km^2)	DOL
[1] Flat-gentle slope (< 3°),	113	432,422	0.261
[2] Fair slope (3-8°),	82	347,838	0.236
[3] Moderate slope (8-15°)	85	531,828	0.160
[4] Fairly moderate slope (15-30°)	105	236,595	0.444
[5] Steep slope (30-45°)	213	937,005	0.227
[6] Very steep slope (> 45°)	7	20,19	0.347

Table 2. Analysis Results of NOL and DOL index with Fault Density Classes.

Fault density classes	NOL	Area (km^2)	DOL
[1] <=150 m/km^2	0	25.93	0.000
[2] 150-300 m/km^2	125	554.15	0.226
[3] 300-4500 m/km^2	169	802.12	0.211
[4] >=450 m/km^2	311	1,122.21	0.277

geological map created by the Department of Geology, Ministry of Natural Resources, published in 2005. In this study, for calculation of the fault density, the method of Inverse distance to a Power, Kriging, Minimum curvature (Shepard) from ARCGIS 10.0 is used. A fracture density map of the study area along the HCM road corridor is portrayed in Fig. 7. To facilitate the assessment of the relation between fault density and the current state of landslides in the study area, the fault density map was classed into four separate groups as follows: <= 150 m/km^2, (150-300) m/km^2, (300-450) m/km^2 and (>= 450) m/km^2. The map of the fault density distribution of the study area is presented in Fig. 8.

Table 2 - Analysis Results of NOL and DOL index with Fault Density Classes

The analysis results of value NOL and DOL index belonging to separate fault density class zones is presented in Table 2. A high number of fault density or shattering of the rock is associated with large numbers for NOL and DOL.

Geology

Geology is an important causative factor group for landslide assessment because slope instability and regolith material of different types are strongly associated (Sarkar et al. 1995; Slidle and Ochiai 2006). Four causative factors of the geology group related to land sliding are usually studied: tectonic structure, crust, engineering geology, and hydrogeological factors (Tran Tan Van et al. 2006). However this study emphasizes investigation of the relation between the occurrences of landslides and engineering geology.

Regarding engineering geology, the mechanical and mineral chemistry characteristics are closely related to stability of slopes in which cutting intensity is a mechanical property

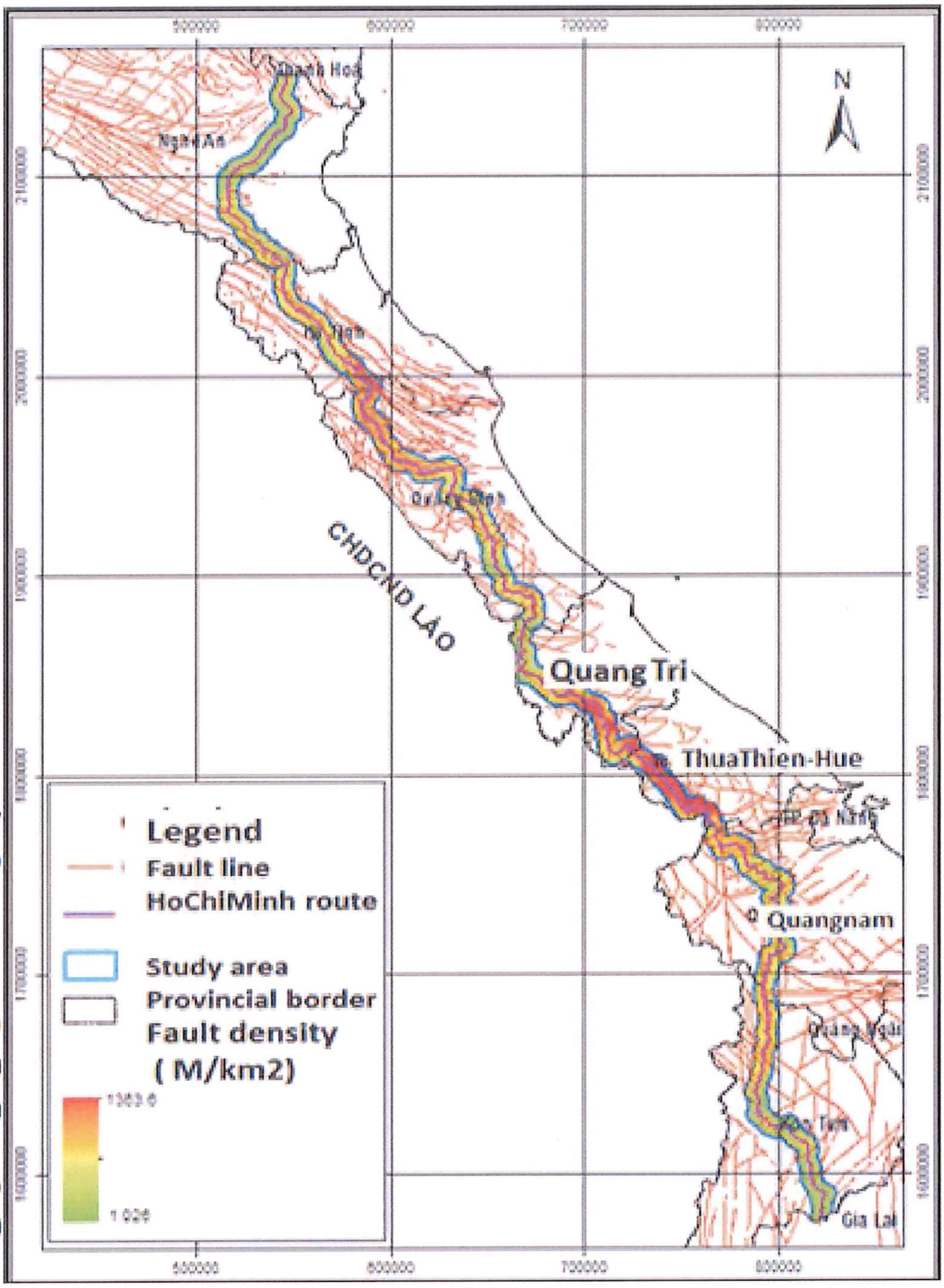

Fig. 7. Fracture density map of the study area of HCM road corridor.

that strongly influences the stability of natural and artificial slopes. It has no certain value, but is strongly influenced by the load operations occurring on slopes, that are most strongly affected by soil water. The cutting intensity of soil is fundamentally represented by a function of the vertical pressure on the sliding surface (σ), the cohesive force (*C*), and friction angle (ϕ). The relation among these components of the natural characteristics of the soil has also

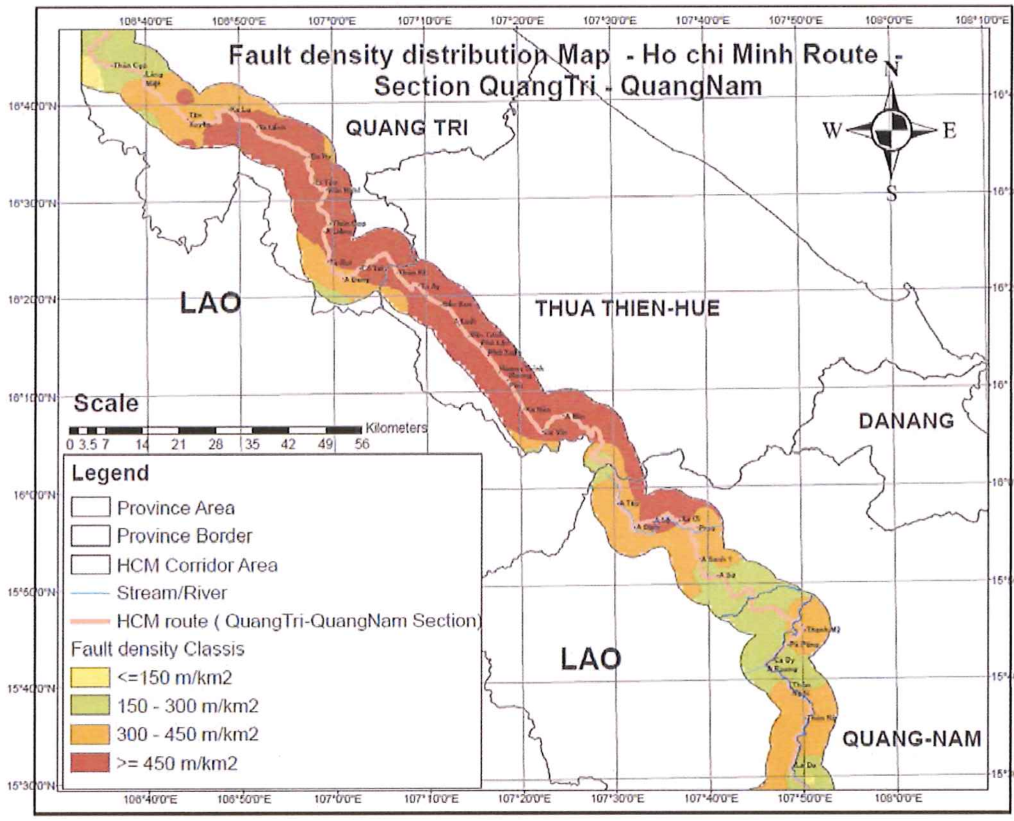

Fig. 8. Fault density distribution map of the study area showing area with <= 150 m/km^2, (150–300) m/km^2, (300–450) m/km^2 and (>= 450) m/km^2.

been examined in many works and has been specified by different rock types.

Based on the available geological map scale of 1: 200,000 created by the Department of Geology published in 2005 under the Ministry of Natural Resources, this study compiled diagrams showing the distribution of these rock types, with bedrock and soils grouped according to the source. Accordingly, the geology of entire area of the HCM road corridor from Quang Binh to Kon Tum section was divided into seven rock types: [1] igneous rocks, [2] Quaternary sedimentary rock, [3] Mesozoic sedimentary rock, [4] limestone, [5] metamorphic rock; [6] metamorphic sedimentary rocks, [7] sedimentary with coal and limestone rock. A diagram of rock type classifications is shown in Fig. 9.

Based on NOL and DOL depending on rock types, we evaluated the sensitivity of each rock type zone to appearance frequency of landslides. Analysis results show sensitivity of each rock type zone from weak to strong, as shown in Table 3.

Precipitation

Landslide causative climate factor group includes Sunny Solar radiation, Cloud, Rain, Air temperature, Relative humidity factor took part in sliding process through surface water, Infiltration into ground, underground water, as a result, landslide initiation mechanism

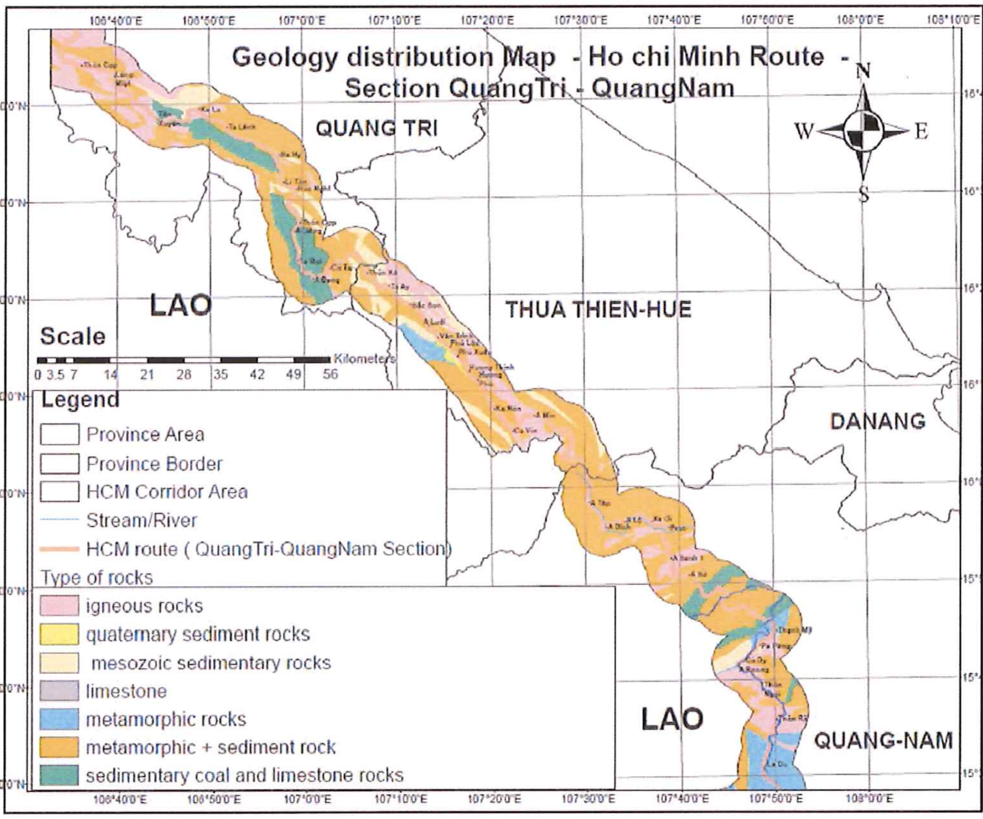

Fig. 9. Classification Rock Map of the HCM study area showing seven rock types: [1] igneous, [2] Quaternary sedimentary, [3] Mesozoic sedimentary, [4] limestone, [5] metamorphic, [6] metamorphic + sedimentary, and [7] sedimentary with coal and limestone.

Table 3. Analysis Result of NOL and DOL index with Types of rock.

Rock type	NOL	Area (km^2)	DOL
[1] Limestone	0	0.00	0.000
[2] Igneous rock	0	519.30	0.000
[3] Mesozoic sedimentary rock	1	245.02	0.004
[4] Sedimentary with coal and limestone rock	21	254.59	0.082
[5] Metamorphic+sedimentary rock	484	1340.02	0.361
[6] Metamorphic rock	91	138.87	0.655
[7] Quaternary sediment rock	8	7.18	1.114

created and movement occurred. Survey records show that most landslides appeared after rains or storms. Precipitation played a salient role in this causative group factor of climate. Given the same rock type but at different times of a year, the slide probability is completely different because of precipitation. For instance, during the rainy season, the landslides probability is much higher than during the dry season. Landslides occur more frequently during months of high rainfall. In landslide research, the role of precipitation is a major influence on the sliding mechanism. Precipitation is closely associated with landslide initiation because of its influence on runoff and water pressure (So 1971; Stark; Tsukamoto and Ohta 1988). Therefore, the Climate factor Group and rain phenomena are subjects of the study.

However, many parameters can represent rain phenomena such as maximum rainfall intensity, total rainfall per day, rainy hours per day, number of raining days of month, or total annual rainfall. For this study, the average annual rainfall was regarded as appropriate factor and represent for temporal and spatial rainfall distribution. We also use water infiltration into the slope surface.

Precipitation factors used for this study were the average annual rainfall with long-term observations during 1960-2010. Source data were collected from the map the average annual rainfall, scale 1:500,000 of Center of National Hydrometeorology. The map of average annual rainfall of the long-term study area is presented in Fig. 10. However, these precipitation values are continuous values or not split by the group. Therefore, it would be a difficult to evaluate and calculate for landslide susceptibility mapping. In this study, an annual average rainfall map of the year is divided into five groups based on differences in precipitation conditions and climate of the study area as the following (< 2300) m/year, (2300-2600) mm/year, (2600-2900) mm/year, (2900-3200) mm/year and (> 3200) mm/year, is presented in Fig. 11.

From the values of NOL and DOL, one can readily recognize that the sensitivity of landslides increases concomitantly with the increase of annual average rainfall. The analysis result of the relation between different precipitation zones and NOL and DOL is presented in Table 4.

Land use

In the study area, the human effects on landslide processes are diverse, such as deforestation, road construction, and agriculture activities, all of which affect slope stability. However, because of limited ability to investigate and evaluate the causes of all human activities affecting landslides in this study, the author emphasizes the impact of changing vegetation cover and road construction in raising the risk of catastrophic landslides.

Poor farming practices and illegal forest clearing have markedly changed the function of vegetative cover in the study area. Land use, especially vegetation cover, augments slope stability by removing soil moisture through evapotranspiration, and by providing root cohesion to the soil (Greenway 1987).

Based on a 1:500,000 scale vegetation cover map of the study area published by the Ministry of Agriculture and Rural Development in 2010, which classified carpet vegetation into five categories as Defense and special forests, Protected forest land, Special use forest

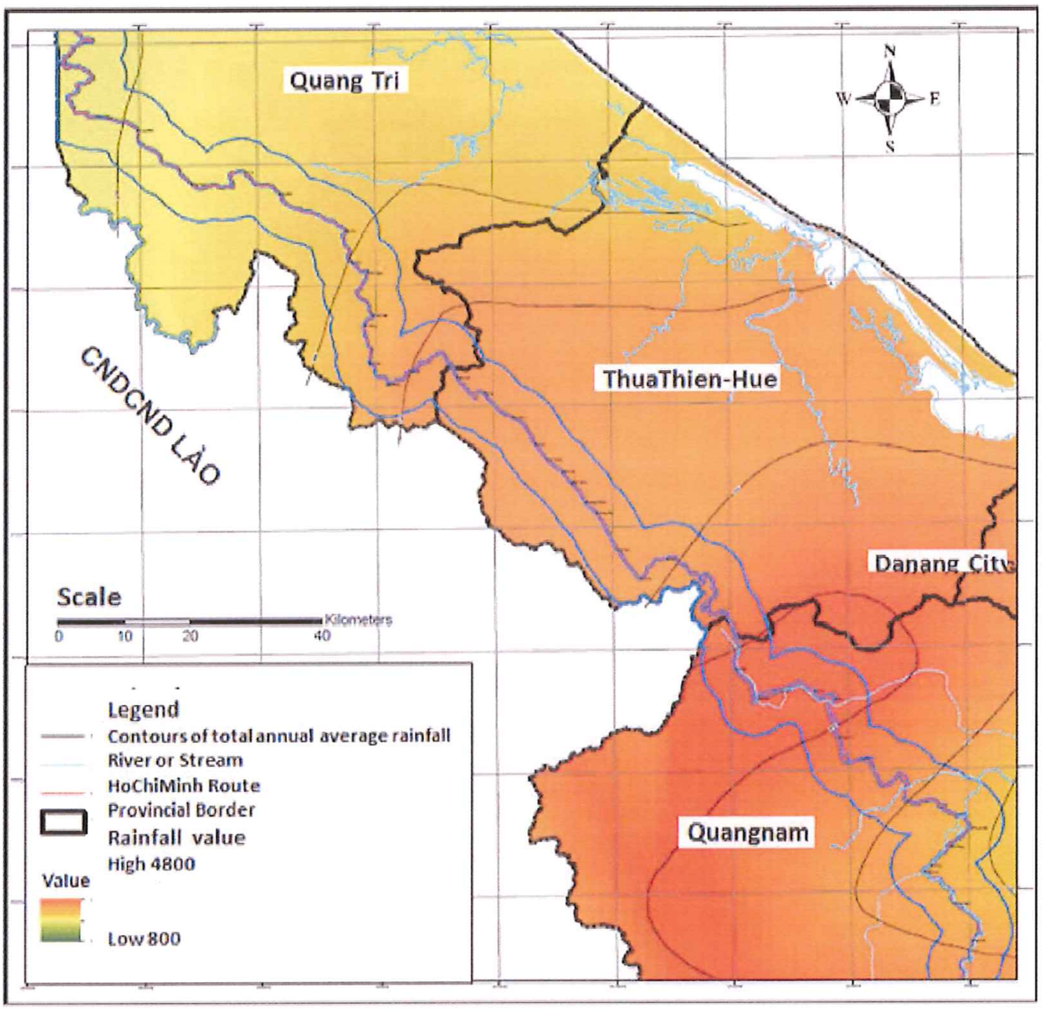

Fig. 10. Diagram showing the rainfall distribution of average annual rainfall, scale 1:500,000 from the Center of National Hydrometeorology.

land, Productive forest land, Agricultural land, a vegetation coverage map was extracted for research. This map is presented in Figure 12. The number of landslides for each forest type was analyzed. The landslide susceptibility rate of vegetation categories zone was evaluated base on NOL and DOL. Table 5 presents the results.

Distant to the road

Regarding road construction activity in mountainous areas, cutting and excavating of natural slopes is the main and common activity. Survey results show that 100% of investigated landslide sites were affected by these activities.

The survey record showed that most landslide phenomena had characteristics of shallow landslides, mainly related to the terrain surface which was strongly weathered. The direction of geological slope layers exhibits the same direction with the cutting slope of the road. A slip surface usually appears at the position of the geological interface or between

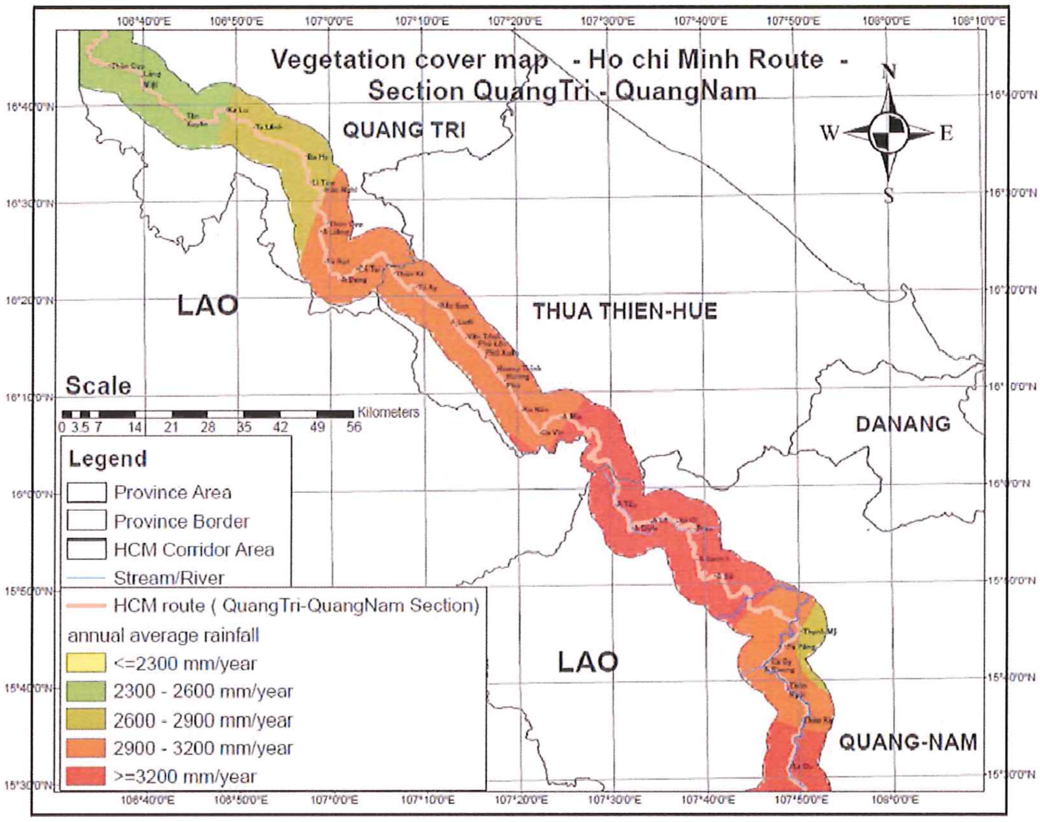

Fig. 11. annual average rainfall map, showing five classes (<= 2300) m/year, (2300–2600) mm/year, (2600–2900) mm/year, (2900–3200) mm/year and (>= 3200) mm/year.

Table 4. Analysis Result of NOL and DOL index with total annual average precipitation classes.

Total annual average precipitation classes	NOL	Area (km^2)	DOL
[1] <2300 mm/year	0	0	0.000
[2] 2300–2600 mm/year	1	338.72	0.003
[3] 2600–2900 mm/year	74	365.01	0.203
[4] 2900–3200 mm/year	92	1,049.71	0.088
[5] >3200 mm/year	438	748.27	0.585

?Your numbers above for 2,3,4 are not mutually exclusive

different weathering layers. In such cases, the slip surface usually has a non-large radius. The toe of the rupture surface usually ended up at the middle or end of the cutting slope of the road embankment. However, a few slip surfaces with a large radius, predicted as old landslides, were located under the road embankment. The cutting for road construction disturbed them. For that reason, the sliding movement continued to move with low velocity depending on the water absorption of the sliding block. Numerous cut-slope failures on the HCM road had classification characteristics close with the fall and topple caused by

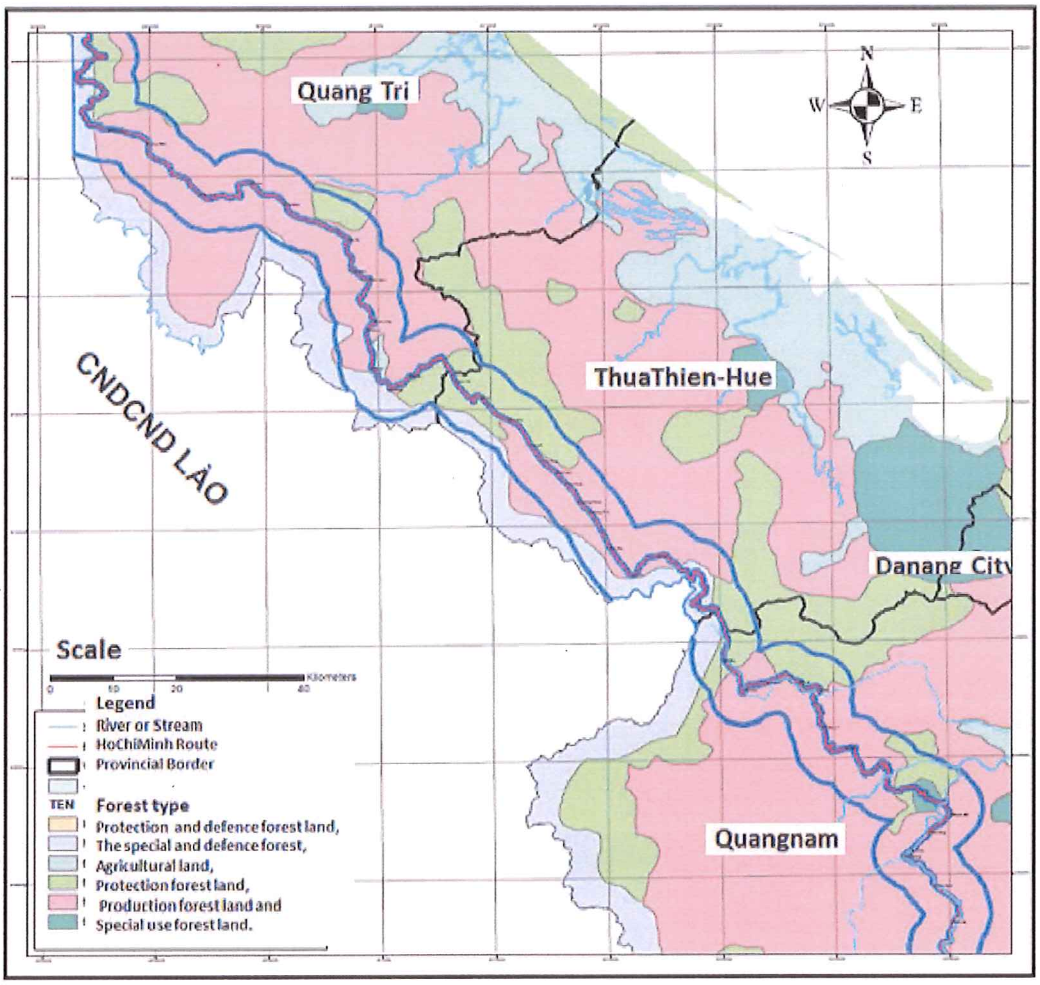

Fig. 12. Vegetation cover map of the study area (1:500,000) created by the Ministry of Agriculture and Rural Development; published in 2010.

Table 5. Analysis results of NOL and DOL index with land use classes.

Land use class	NOL	Area (km^2)	DOL
[1] Special use forest land.	6	72.48	0.083
[2] Agricultural land	2	14.05	0.142
[3] Productive forest land	322	1,700.00	0.189
[4] Protected forest land	126	458.95	0.275
[5] Special and defense forest	149	259.06	0.575

unsuitable cutting slope design and lack of slope protection from water penetration through cracks and strong weathering of the surface layers, with vegetation removed, and the surface partly cut off.

In most landslide cases, the distance from the center of the landslide to the road is

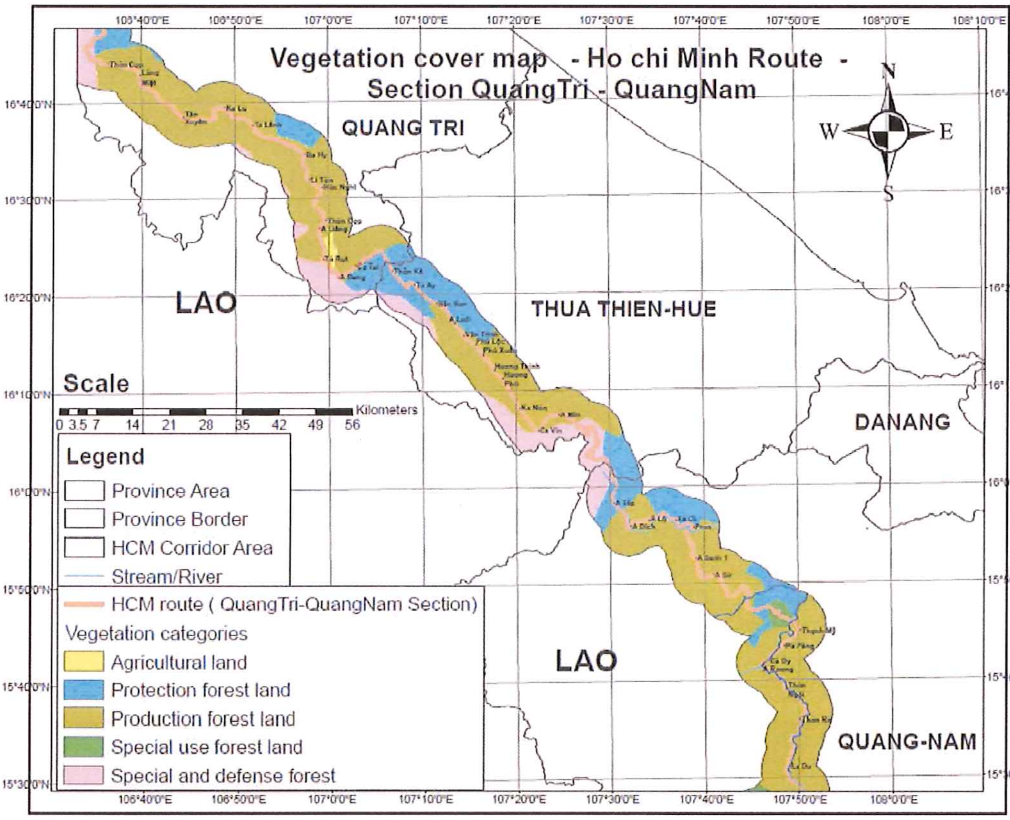

Fig. 13. Vegetation cover map of study area.

regarded as extremely important. To simulate the role of the road construction to landslide risk, the topo-map was used. It classifies the distance to the road centerline into three zones of less than 50 m, from 50-100 m and larger than 100 m. A map of different distances from the center road is present in Fig. 14. The relation between NOL and DOF and difference distance to the road centerline zone was analyzed and recoded. The result is presented in Table 6.

4. Methodology for landslide susceptibility mapping

The analytic hierarchy process (AHP), developed at the Wharton School of Business by Thomas Saaty in the late 1970s (Saaty 1980) is a decision-aiding tool that can facilitate multi-criterion decisions. It enables the derivation of priorities or weights as opposed to arbitrary judgment (Yalcin 2008). This is achieved by structuring decisions as a hierarchy and by deriving weights through pairwise relative comparisons, allowing both objective and subjective considerations without inconsistencies in the decision process. Actually, AHP is based on three principles: decomposition, comparative judgment, and synthesis of priorities

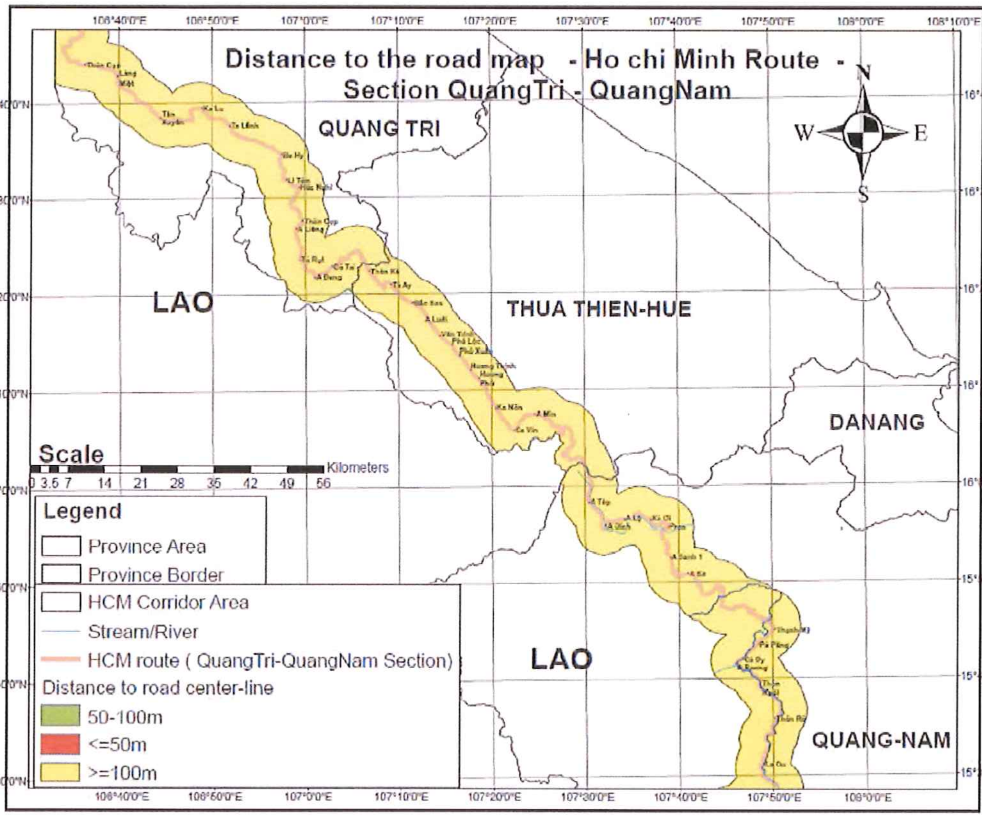

Fig. 14. Distance road map.

Table 6. Analysis Results of NOL and DOL index Distance to the Road Classification.

Distance to the road	NOL	Area (km^2)	DOL
[3] >100 m	40	2,443.17	0.016
[2] 50–100 m	44	30.39	1.448
[1] < 50 m	521	30.85	16.888

(Malczewski 1999). Concepts and techniques in AHP include hierarchical structuring of complexity, pairwise comparisons, redundant judgment, eigenvector calculation for deriving weights, and consistency considerations.

The advantages of using AHP in a landslide analysis are the following: (1) information of all types can be included in the discussion process; (2) judgment is structured so that all the information is considered; (3) discussion rules can be based on experience; (4) once a consensus is reached, weights for each relevant factor are obtained automatically by eigenvector calculation of the decision matrix; and (5) inconsistencies in the decision process can be detected, and hence, corrected. As such, the AHP technique often exhibits higher

Table 7. Scale of preference between two parameters in AHP.

Scale	Degree of preference	Explanation
1	Equally	Two activities contribute equally to the objective
3	Moderately	Experience and judgment slightly favor one activity over another moderately
6	Strongly	Experience and strongly favor one activity over another
7	Very strongly	An activity is strongly favored over another and its dominance is shown in practice
9	Extremely	Evidence of favoring one activity over another is of the highest degree possible of an affirmation
2, 4, 6, 8	Intermediate	Used to represent compromises between the preference in weights 1, 3, 5, 7 and 9
Reciprocals	Opposites	Used for inverse comparison

performance for landslide susceptibility mapping than for other methods (e.g., Akgun et al. 2008). An important shortcoming of AHP is the judgment and ranking of causative factors based on expert opinion, so that subjective preference in the ranking cannot be avoided because it depends upon personal choice and knowledge.

Many studies of landslide susceptibility mapping involving AHP techniques can be found in the literature (Komac 2006; Yalcin 2008; Yalcin et al. 2011; Ladas et al.2007). In most of these earlier works, AHP was commonly used to set weighting factor for landslide causative factor. Only in some studies was AHP also used to assign weight factors for the different classes of each landslide causative factor, e.g. Yalcin 2008 and Yalcin et al. 2011.

In this study, the landslide susceptibility index based on the AHP approach is calculated based on a weighted linear combination of causative factor and classes within causative factor as (Voogd 1983).

$$\mathrm{LSI} = \sum_{j=1}^{N} W_j w_{ij} \tag{1}$$

Therein, LSI stands for the landslide susceptibility index, W_j denotes the weight values of causative factor j. w_{ij} represents the weight value of class i in causative factor j, and N signifies the number of causative factors. Weights W_j and w_{ij} are quantitatively determined by pairwise comparisons and eigenvalues calculations (Saaty 1977). The W_j values are obtained as the normalized principal eigenvector of the matrix that portrays the preferences between different causative factors. Furthermore, the w_{ij} values are normalized principal eigenvectors of the matrix that portrays the preferences between the classes of a causative factor. These matrices are obtained by assigning pairwise preference scales among parameters (factors or classes within a factor), as given in Table 1 (Saaty 2000).

An important feature of AHP is the ability to evaluate the consistency of preference ratings. As a measure of consistency, a consistency index CI is defined as

$$\mathrm{CI} = \frac{\gamma_{\max} - n}{n-1} \tag{2}$$

Therein, $\gamma_{\max}$ is the largest eigenvalue of a preference matrix and its size (number of parameters). The consistency index is compared to a random consistency index RI, the values of which have been tabulated by Saaty (1977) as a function of n, by calculating the consistency ratio CR as shown below.

$$\mathrm{CR} = \frac{CI}{RI} \times 100\% \tag{3}$$

If the value of the consistency ratio is greater than 10%, then the subjective judgment in the pair-wire comparison between parameters is inconsistent. It must be revised.

The process of landslide, which depends on many factors, is divided into four groups: topography-geomorphology, geology, hydrology and artificial actions. However, the causative factors for landslide susceptibility mapping in this study were selected base on the relevance and data availability.

5. Landslide susceptibility map creation and discussion

5. 1. Discussion

According to Table 8, the level of the importance of 6 element cause factors are rated respectively on a tapered scale sliding: Slope angle, Total annual average precipitation, Land use, Rock type, Distance to road, and Fault density. Pairwise comparison work was conducted similarly to the information layers in each element causes of landslide disasters. The paired comparison matrix is the basis for assigning weights W_{ij} for the different layers of information in accordance with the values of eigenvector in each matrix (see Table 8).

Table 8 presents a pairwise comparison matrix of the causative factors. The first column of the matrix compares the Fault density with other factors, which are all regarded as more important. The Slope angle is regarded as the most important. The second column compares Distance to the road with the remaining factors, which are regarded as more important except for Fault density, and so on.

Table 8 shows that (Sub-Table 1) for topographic slope angle, the higher the slope angle, the greater its influence on landslide we can get. Evaluation results of pairwise comparison show that the value weighted eigenvector increases with larger slope angle groups (Sub-Table 2). Similar to the total average annual precipitation, the groups of precipitation have higher values that are conducive to landslides. Weight values for the group precipitation as <2300 mm/year, from (2300–2600) mm/year, from (2600–2900) mm/year, (2900–3200)

Table 8. Pairwise comparison matrix and normalized principal eigenvector for landslide causative factors and for the classes within each factor, as required for applying the AHP method

Causative Factor	[1]	[2]	[3]	[4]	[5]	[6]	[7]	Eigenvectors
[1] Fault density	1							0.0287
[2] Distance to the road	2	1						0.040
[3] Rock type	5	3	1					0.0752
[4] Land use	7	5	3	1				0.1292
[5] Precipitation	8	7	4	3	1			0.2875
[6] Slope angle	9	9	5	4	2	1		0.4395
C.i=0.0578								
Sub-Table1-Slope angle								
[1] Flat-gentle slope (> 3°)	1							0.0287
[2] Fair slope (3–8°)	2	1						0.040
[3] Moderate slope (8–15°)	5	3	1					0.0752
[4] Fairly moderate slope (15–30°)	7	5	3	1				0.1292
[5] Steep slope (30–45°)	8	7	4	3	1			0.2875
[6] Very steep slope (>45°)	9	9	5	4	2	1		0.4395
C.i=0.0578								
Table 5-Land use								
[1] Special use forest land.	1							0.3192
[2] Agricultural land	2	1						0.0888
[3] Production forest land	3	2	1					0.1759
[4] Protection forest land	5	4	3	1				0.2731
[5] Special and defense forest	9	7	6	5	1			0.4303
C.i=0.0488								
Sub-Table 3-Rock type								
[1] Limestone	1							0.0238
[2] Igneous rocks	3	1						0.0452
[3] Mesozoic sedimentary rock	3	1	1					0.0452
[4] Sedimentary with coal and limestone rock.	5	3	3	1				0.0955
[5] Metamorphic+sedimentary rocks	7	5	5	3	1			0.1962
[6] Metamorphic rocks	7	5	5	3	1	1		0.1962
[7] Quaternary sediment rock	9	7	7	5	3	3	1	0.3979
C.i=0.0474								
Sub- Table 4-Total annual average precipitation								
[1] <2300 mm/year	1							0.0333
[2] 2300–2600 mm/year	3	1						0.0633
[3] 2600–2900 mm/year	5	3	1					0.129
[4] 2900–3200 mm/year	7	5	3	1				0.2615
[5] >3200 mm/year	9	7	5	3	1			0.5128
C.i=0.0593								
Sub-Table 2-Fault density								
[1] <=150 m/km^2	1							0.0438
[2] 150–300 m/km^2	4	1						0.0885
[3] 300–4500 m/km^2	7	4	1					0.2431
[4] >=450 m/km^2	9	6	3	1				0.6246
C.i=0.060								
Sub-Table 6-Distance to the road								
[3] >=100 m	1							0.1095
[2] 50–100 m	3	1						0.309
[1] <=50 m	5	3	1					0.8516
C.i=0.0018								

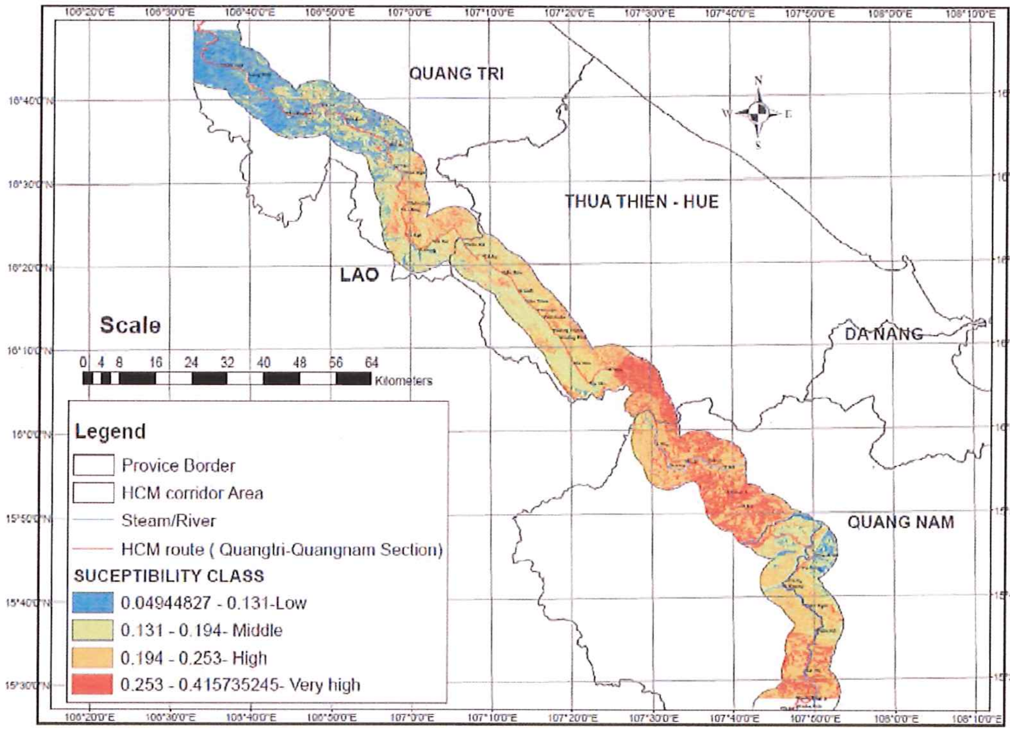

Fig. 15. Landslide susceptibility map of the study area, along HCM from QuangTri to Kontum.

mm/year and >= 3200 mm/year increase respectively as 0.0333, 0.0633, 0.129, 0.2615, and 0.5128 (Sub-Table 3). Weights for the group of fault density also increase with increasing fault density value of the group, as shown in column 2 of the table values eigenvector (Sub-Table 4). The impact of humans on landslide processes through cutting road slopes are represented by the distance to roads: closer to roads, the risk of landslides is higher (Sub-Table 5). Regarding land use, agricultural land is the most favorable for landslides (Sub-Table 6). For different rock types, limestone and igneous rocks are less favorable for landslide occurrence. Mesozoic sedimentary rock and Sedimentary with coal limestone rock, show respectively increasing sensitivity to landslides. At the zone of metamorphic+ sedimentary rocks and metamorphic rocks, landslides mainly occur. Quaternary sediment rock was found to be the most sensitive to landslides. Sub-Table 2 shows weighted values of these different rock types.

Table 8 shows that the CR value is consistently less than 0.1, which indicates the evaluation followed principles of consistency and conformity.

The attribute field W_{ij} was created and assigned to a corresponding column of attributes as described in Table 8. Because values w_j and w_{ij} are calculated in Table 8, using the function "weighted sum" in ArcGIS software to implement equation (1) for the risk index landslide hazard maps, the landslide susceptibility map of the study area, along corridor HCM route from QuangTri to Kontum was established.

The landslide susceptibility mapping was thereby created. The landslide susceptibility zonation map shows four landslide susceptibility classes, i.e., low, moderate, high and very high susceptibility. The map was derived from the inventory map, with observations from 2004-2013.

5. 2. Results of mapping

According to the study results of the landslide susceptibility map of the study area along corridor HCM route from QuangTri to Kontum and with the division of the landslide index of Galang Method applied, the Galang Method was introduced from 2004, with landslide susceptibility divided into four classes from low to very high landslide sensitivity. The number of landslide occurred in lower is a half of higher zone. Overlapping of the landslide distribution map and landslide susceptibility map showed that 26, 80, 255, and 244 landslides in all of 604 recorded landslides were respectively located in low, average, high, and very high susceptibility areas for landslides.

Therefore, 40.40% of the landslides were in the very high susceptibility areas; 42.22% of the landslides occurred in high susceptibility areas; 13.25% of the landslides occurred in middle susceptibility areas; only 4.14% of landslides occurred in low susceptibility areas. Specifically regarding high and very high susceptibility areas, 82.66% all landslides occurred there.

5. 3. Limitations

Landslides in this study were slope failures mainly located along a road. Positions of artificial slope failures were recorded as points measured from an intersection between the landslide boundary and the road. Therefore, landslides spatial arrangements were only distributions along the road. The susceptibility map scale was large, 1:500,000, so the areas and micro-features of respective landslides were not considered.

In general, three basic methods exist for creating a landslide distribution map: collecting historical data, conducting field surveys, and interpreting aerial photos. However, for this study, the field survey method was applied to create a landslide distribution map. Landslide surveys are related to human capabilities of recognizing them in terms of number, space, and time, all of which introduce error.

For susceptibility mapping, aside from the causal factors which were considered, i.e., Slope angle, Total annual average precipitation, Land use, Rock type, Distance to road, and Fault density, other sensitive causal factors such as fault depth, distance to water stream, and alignment were not examined because of their poor relevance and lack of available data sources. Although most landslides occurred in high and very high risk zones, some landslides occurred in other zones, perhaps because of low-probability causes such as slope cutting for road construction.

6. Conclusions

Landslides are regarded as a dangerous phenomenon that often occurs in mountainous regions of Vietnam. They directly affect the lives of the people in the region, destroy traffic infrastructure and road systems. The center section of the HCM route is a mountainous road that is heavily influenced by landslides. Therefore, reducing landslide susceptibility for this important corridor is the target of this study.

Landslides have various possible causes with complex mutual relations. Detailed assessments to ascertain the main causes of each landslide are not feasible in most cases. The selection of causative factors for a landslide susceptibility map is usually based on experts' subjective experience. In this study, to analyze landslide manifestation, causative factors were derived: slope angle, rock type, fault density, distance to the road, land use, and precipitation. Maps for causative factors were created, with causes divided into classes.

Positions of 604 artificial slope failures were found along the HCM route. From them, a landslide distribution was produced. The sensitivity to landslide of each zone of causative factor maps was calculated and then evaluated using NOL and DOL values derived from a comparison of the landslide distribution map and causative factor maps using GIS.

An analytical hierarchical process was used to combine these maps for landslide susceptibility mapping. Consequently, based on the inventory map of observed landslide from 2006-2009, a landslide susceptibility zonation map with four landslide susceptibility classes is derived, with low, moderate, high and very high susceptibility for landslides. This map shows that 82.66% of all landslides have occurred in highly and very highly susceptible areas.

Although limited by matters of map scale and available data, the landslide susceptibility map of this study for corridor along this road is expected to be useful for landslide mitigation.

Acknowledgement

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