# Landslide Susceptibility Mapping Using Bayesian Conditional Probability Model at An Linh Commune, Tuy An District, Phu Yen Province, Vietnam

## Élaboration de la carte de risques de glissement de terrain sur la commune de An Linh, district de Tuy An, province de Phu Yen, à l'aide d'un modèle Bayesien de probabilité conditionnelle

Son N.T.
*Tuy Hoa Industrial College, Phu Yen Province, Vietnam*

Ha P.T.S.
*Facutly of Geology and Petroleum Engineering, Ho Chi Minh City University of Technology, Ho Chi Minh City, Vietnam*

Son L.M.
*flatGEO Consulting Co., Ltd.*

ABSTRACT: Landslide phenomenon at An Linh commune, Tuy An district, Phu Yen province is more and more severe year after year. The prediction of a highly landslide susceptibility zone will support the government and local residents to save their properties. In this paper the authors carried out the landslide susceptibility mapping at An Linh commnune using the deterministic approach with knowledge-driven methods and the stochastic approach with data-driven methods. The deterministic approach is conducted using traditional survey, field investigation, geophysical survey… to evaluate not only geotechnical properties of rock and soil materials but also the mechanism of landslide phenomenon in the studied area. The stochastic approach with probability methods is chosen to evaluate the weights of influence factors such as the elevation, aspect, slope angle, distance to roads and distance to drainages, geology and topographical wetness index of the materials. Landslide susceptibility zonation is developed using the model of Bayesian conditional probability with different criteria for weighting factor calculation integrated with GIS analytical tools. Landslide susceptibility maps from different models are validated with the current landslide inventory to select the most reasonable model for the study area.

RÉSUMÉ : Les glissements de terrain sont devenus de plus en plus fréquents sur la commune de An linh, district de Tuy An, province de Phu Yen, au cours des dernìeres années. Les auteurs ont réalisé une carte de risques de glissement de terrain sur la commune An Linh selon une approche déterministe fondée sur une connaissance experte et à l'aide d'une approche stochastique basée sur les données. L'approche déterministe est conduite à partir des méthodes de reconnaissance, d'observation du terrain, de prospection géophysique… afin de quantifier non seulement les propriétés géotechniques du sol et de la roche mais aussi le mécanisme de glissement de terrain dans la région concernée. L'approche stochastique fondée sur les modèles statistiques est choisie pour évaluer le poids de facteurs d'influence comme l'altitude, l'aspect, la pente, la distance aux cours d'eau, la distance aux voies routières, et au drains, les paramètres géologiques, et l'indice de l'humidité des sols. Le zonage des risques de glissement de terrain a été développé en utilisant un modèle de probabilité conditionnelle de Bayes avec différents critères de calcul du poids des variables, en intégrant les outils analytiques de SIG. Les cartes de risques élaborées selon ces modèles ont été validées à l'aide de l' inventaire des glissements actuels afin de choisir le modèle le plus approprie pour ce site.

KEYWORDS: Landslide susceptibility; Bayesian conditional probability; Stochastic model.

## 1 INTRODUCTION

The study area locates at An Linh commune, Tuy An district, Phu Yen province in the south central coast of Vietnam (see Fig. 1).


Figure 1. Location of the study area

During the past few years, landslides often occur in the study area after heavy and long rains. This phenomenon damages roads and construction works and results in serious cracks in the residential areas that in turn affect to human lives. Therefore the landslide prediction is an urgent task for scientists to support the government in planning and save human lives of local residents.

### 1.1 *Geographic characteristics*

An Linh area which has hill and mountain landscape locates on the eastern side of Van Hoa highland whose elevation of 12 ~ 500m. In that area, hills are rounded and have steep slopes, decorated by narrow valleys which follow along north-south direction. The ground surface which inclines to the north is a bare area with basaltic boulders or cobbles. This topographic landscape is favorite for erosion progress and stimulate landsliding and cracking process.

The study area belongs to the monsoon tropical region with oceanic climate. The annual precipitation is approximate 2000mm. Especially in the rainy season the precipitation can reach 70 ~ 80% the annual precipitation. Furthermore, the precipitation concentrates in a short time – only one or two months at the end of a year.

Water systems strongly develop with Cai river and Ho Lo river in the west and the east respectively. Both rivers form a hydrological network distributed evenly in the study area.

### 1.2 *Geological characteristics*

A general stratigraphy of the study area composes of following formations:

Table 1. Brief description of geological formations

| Formation | Composition |
|---|---|
| Phong Hanh formation ( $\varepsilon - Sph$ ) | Quartzite of blocky structure, quartz-sericite schist |
| Mang Yang formation ( $T_2my$ ) | Boulders, cobbles, sandstone, siltstone and claystone, blocky structure, thick bedding |
| Kon Tum formation ( $N_2kt$ ) | Green, dark grey, greenish grey basalt, bubble or porosity structure, fracturing; diatomite, clay with diatomite, basalt with interbedded clay |
| Dai Nga formation ( $N_2 - Q_1đn$ ) | Greenish grey, dark grey basalt, blocky structure, fracturing |
| Quaternary formation | Boulders, cobbles, gravel, sand, silt, clay |

### 1.3 *Landslide characteristics*

Landslide occurs mainly at low areas with elevations less than 200m and gentle slopes (slope angles vary from 5° to 20°) in heavily weathered rocks which compose of clay, swelling clay with diatomite… Landscape after sliding forms terraces with many fractures on the ground surface. Landslide exposures usually locate at positions associated with hydrological factors. There are water flows at the toe of slopes in massive landslides. The shear strength of soils within landslide areas is rather low (cohesions vary from 12 to 17kPa, friction angles from 10° to 13°).

### 1.4 *Landslide causes*

The fieldwork study shows some of causes of landslides in the study area:

- Heavy landslides ususally occur at geological structures which compose of clay, clay with diatomite underlying thin heavily weathered basaltic layers. Soils and rocks at landslide areas are different in permeability, swelling, strength (weak soils overlay hard rocks).
- The erosion process occurs at the toe of slopes and piping develops due to the surface run off and underground water flow.
- Heavy and long rains cause rocks and soils swelling or liquefaction that in turn cause the volume change suddenly.
- Human activities also take part in the landslide trigger: the forest clearance, reservoir and rice field preparation… Those activities result in loosing strength at the toe of slopes.

## 2 LANDSLIDE SUSCEPTIBILITY MAPPING

### 2.1 *Theoretical Background*

Nowadays there are two common groups of methods for landslide prediction:

a) Knowledge-driven methods: those methods are based on experiences of experts and rely on empirical relationships.

b) Data-driven methods: those methods analyse collected data and establish models based on the inherent relationship of data. This approach, especially, Bayesian conditional probability method will be applied for the landslide susceptibility mapping in this research. In Bayesian conditional probability method, the likelihood of event D given the presence of factor B can be expressed as the prior probability:

$$P\{D \mid B\} = \frac{P\{D \cap B\}}{P\{B\}} = P\{D\}\frac{P\{B \mid D\}}{P\{B\}} \tag{1}$$

On the contrary, the unlikelihood of event D given the presence of factor B is the probability:

$$P\{\bar{D} \mid B\} = \frac{P\{\bar{D} \cap B\}}{P\{B\}} = P\{\bar{D}\}\frac{P\{B \mid \bar{D}\}}{P\{B\}} \tag{2}$$

where

| | |
|---|---|
| $P\{D \mid B\}$ | the likelihood of event D given the presence of factor B |
| $P\{\bar{D} \mid B\}$ | the unlikelihood of event D given the presence of factor B |
| $P\{B \mid D\}$ | the likelihood of factor B given the presence of event D |
| $P\{B \mid \bar{D}\}$ | the likelihood of factor B given the absence of event D |
| $P\{D \cap B\}$ | the probability of the presence of both event D and factor B |
| $P\{B\}$ | the probability of the presence of factor B |

If there are more datasets (more B factors) involved in the mapping prediction and those datasets are conditionally independent to each other with respect to a set of landslide occurences, the Bayesian conditional probability of event D is expressed by the following formula:

$$P\{D \mid (B_1 \cap B_2 \cap \ldots \cap B_n)\} = \frac{e^{(\log it\{D\} + \sum W^k)}}{1 + e^{(\log it\{D\} + \sum W^k)}} \tag{3}$$

where

$$\log it\{D\} = \ln\frac{P\{D\}}{1 - P\{D\}} \tag{4}$$

$$W^+ = \log\frac{P\{B \mid D\}}{P\{B \mid \bar{D}\}} \tag{5}$$

$$W^- = \log\frac{P\{\bar{B} \mid D\}}{P\{\bar{B} \mid \bar{D}\}} \tag{6}$$

$W^k$ : positive weight ( $W^+$ ) or negative weight ( $W^-$ ) of factor B depending on the presence or absence of factor B

The total weight of all B factors at each pixel on the prediction map is the sum of $W^k$, in which $W^k$ will be the positive weight $W^+$ if the factor B is present or negative weight $W^-$ if B is absent.

The constrast of weight is:

$$C_W = W^+ - W^- \tag{7}$$

### 2.2 *Landslide susceptibility mapping*

After the landslide survey at the end of year 2010, 142 landslide occurences are recorded in which 103 positions are used for the landslide susceptibility prediction by Bayesian conditional probability and 39 occurences are used for the validation. The location of 103 landslide occurrences is presented in Fig 2. Black plus symbols on this figure are landslide occurences.

There are seven factors chosen for the calculation of the landslide probability: elevation (DEM), slope direction (ASPECT), slope angle (SLOPE), geology (GEO), distance to road (DTR), distance to drainage (DTD), topographical wetness

index (TWI). Each factor is classified into several classes; the positive and negative weights of each class for each factor are calculated using an open-source software ILWIS (Integrated Land and Water Information System). To each factor, a class trigger for positive or negative weight is chosen at the class whose contrast reaches the highest value (see highlight classes in Table 2).

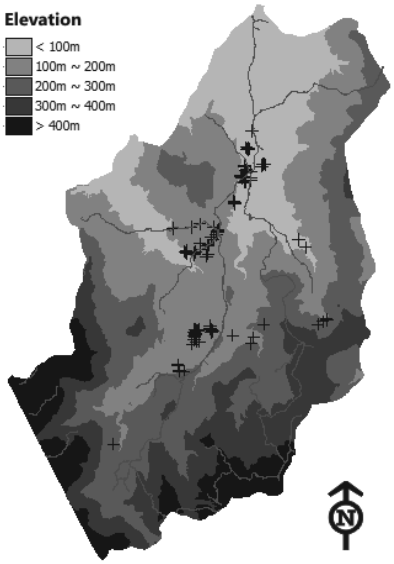


Figure 2. Landslide inventory map for modelling (103 points)

Table 2. Weight values of classes from parameters

| Parameter | Value | $W^+$ | $W^-$ |
|---|---|---|---|
| DEM | 100m ~ 200m | 0.620 | -0.488 |
| ASPECT | West | 0.470 | -0.121 |
| SLOPE | 0° ~ 10° | 0.073 | -0.078 |
| GEO | Claystone, sandstone with diatomite | 1.009 | -1.960 |
| DTR | < 100m | 0.758 | -0.274 |
| DTD | 300m ~ 400m | 0.881 | -0.180 |
| TWI | 4 ~ 6 | 0.137 | -0.077 |

The flow chart of the procedure for landslide susceptibility mapping by Bayesian conditional probability is shown in Fig. 3.

Weights of seven factor maps are calculated and expressed as weight maps and displayed in Fig. 4 to Fig. 10.

The Bayesian conditional probability map is derived from seven factor maps using the formula (3). However the slicing of this probability map into landslide susceptibility zones is not applicable because the ranges of landslide probability on different probability maps from different methods are totally different. Therefore the probability pattern is sliced into susceptibility zones using the ranking of predicted probability value instead of predicted value itself (Chung and Fabbri, 2003). A pixel of highest probability will be assigned the highest rank and pixel of lowest probability will be the lowest rank. After ranking all pixels within the study area, the landslide zoning could be carried out using predefined threshold values of different zones: high, moderate and low susceptibility.

In the study area, those threshold values are 15%, 25% and 60% for the high, moderate and low susceptibility area respectively. The landslide susceptibility map is presented in Fig. 11.

## 2.3 *Validation*

The landslide susceptibility map is validated by using 39 heavy landslide occurences (white plus symbols on Fig. 12). Among them there are 31 points classified as high landslide susceptibility (80% accuracy).

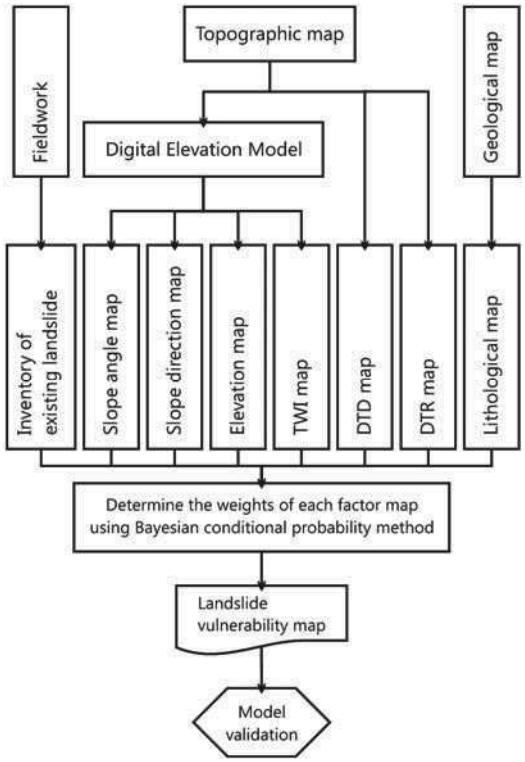


Figure 3. Procedure of landslide susceptibility mapping

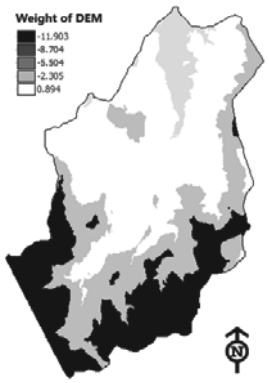


Figure 4. Weight of elevation factor

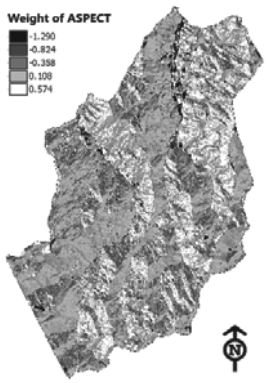


Figure 5. Weight of aspect factor

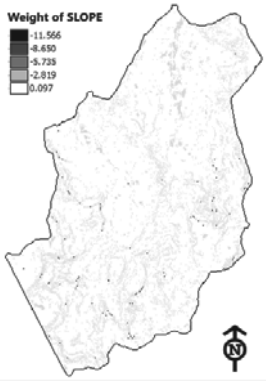


Figure 6. Weight of slope angle factor

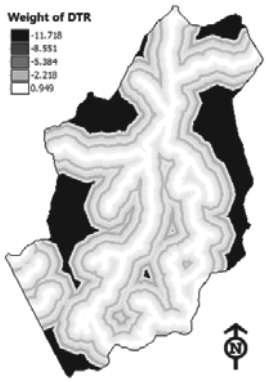


Figure 7. Weight of DTR factor

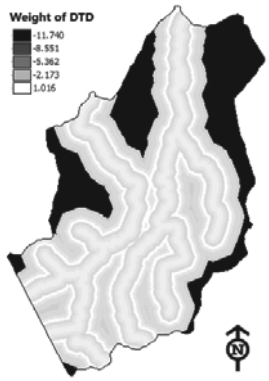


Figure 8. Weight of DTD factor

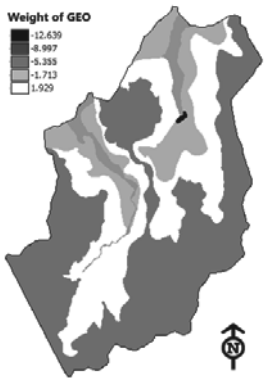


Figure 9. Weight of geological factor

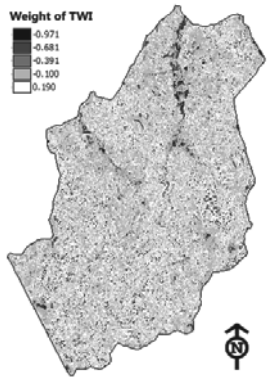


Figure 10. Weight of TWI factor

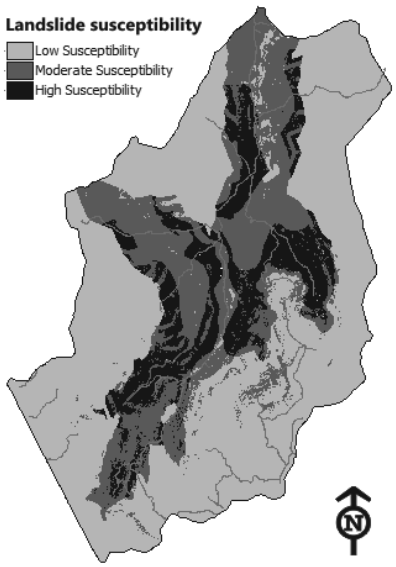


Figure 11. Landslide susceptibility map

## 3 CONCLUSION

a) The landslide susceptibility map shows that most of landslide occurences concentrate at the areas of low elevation (100~200m), gentle slopes (slope angles vary from 5° to 20°), high TWI values (high water accumulation).

b) Landslides are also triggered due to the road construction. The roadway cuts into the slope faces and reduces the stability of slopes. Landslides occurs near the road construction sites (approximate 100m far from roads).

c) Landslides also distribute along the east-west direction which coincides with the direction of narrow valleys of steep slopes in the study area.

d) The results of Bayesian conditional probability model and the fieldwork survey show that landslides occur usually in soil layers with high proportion of clay and diatomite clayey soils which are heavily weathered.

e) The Bayesian conditional probability model gives the reliable result of landslide susceptibility for the study area. The validation was conducted for 39 heavy landslide positions which show that there are 31 positions (80% accuracy) located in the high landslide susceptibility zone.

f) The reliability of this model could be improved year after year when new landslide occurences are updated annually in the landslide inventory.

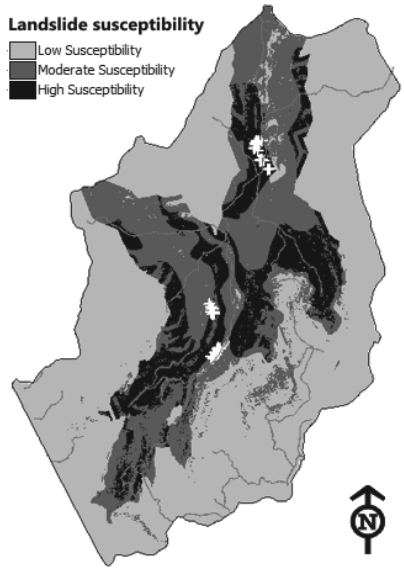


Figure 12. Landslide location for model validation (39 points)

## 4 REFERENCES

Bonham-Carter G.F. 1994. *Geographic Information Systems for Geoscientists: Modelling with GIS*, Volume 13 (Computer Methods in the Geosciences). Pergamon.

Brett G. Dickson et al. 2006. Mapping the Probability of Large fire Occurrence in Northern Arizona, USA. *Landscape Ecology* (21), 747-761.

Chung C.F. and Fabbri A.G. 1999. Probabilistic Prediction Models for Landslide Hazard Mapping. *Photogram Engineering Remote Sensing* (65), 1389-1400.

Chung C.F. and Fabbri A.G. 2003. Validation of Spatial Prediction Models for Landslide Hazard Mapping. *Natural Hazards* (30), 451-472.

Lee S., J. Choi , K. Min. 2002. Landslide Susceptibility Analysis and Verification Using the Bayesian Probability Model. *Environmental Geology* (43), 120-131.

Raul Romero-Calcerrada et al. 2008. GIS analysis of spatial patterns of human-caused wildfire ignition risk in the SW of Madrid (Central Spain). *Landscape Ecology* (23), 341-354.