APPLICATION OF LIKELIHOOD RATIO MODEL FOR LANDSLIDE SUSCEPTIBILITY MAPPING USING GIS AT LAI CHAU, VIETNAM

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Abstract: The aim of this study was to evaluate the susceptibility from landslides in the Lai Chau region of Vietnam, using Geographic Information System (GIS) and remote sensing data, focusing on the relationship between tectonic fractures and landslides. Landslide locations were identified from an interpretation of aerial photographs and field surveys. Topographic and geological data and satellite images were collected, processed, and constructed into a spatial database using GIS data and image processing techniques, and a scheme of the tectonic fracturing of the crust in the Lai Chau region was established. In this scheme, Lai Chau was identified as a region with low crustal fractures, with the grade of tectonic fracture having a close relationship with landslide occurrence. The factors found to influence landslide occurrence were: topographic slope, topographic aspect, topographic curvature, distance from drainage, lithology, distance from a tectonic fracture and land cover. Landslide prone areas were analyzed and mapped using the landslide occurrence factors employing the probability–likelihood ratio method. The results of the analysis were verified using landslide location data, and these showed a satisfactory agreement between the hazard map and existing landslide location data.

Keywords: Landslide, Susceptibility, GIS, Likelihood ratio, Verification

1. INTRODUCTION

Landslides are dangerous natural disasters, which happen suddenly, and cause considerable destruction. Recent widespread landslides and debris flows in the northern mountainous areas of Vietnam have caused a large loss of life and property. In particular, in Lai Chau province during 1994 and 1996, high magnitude landslides occurred frequently due to heavy rainfalls. A study of the causes of landslides for forecasting, zoning, and determining measures for mitigation of the loss caused by landslides is, therefore, of primary importance and urgency. Through a scientific analysis of landslides, we can assess and predict landslide-susceptible areas, and thus, decrease landslide damage through proper preparation. To achieve this aim, landslide hazard analysis techniques have been applied, and verified in the chosen study area, the Lai Chau province of Vietnam. Elucidation of the characteristics of the tectonic fractures of the earth's crust in the Lai Chau province and their relationship with landslides were the objectives of this study, for explaining the causes and mechanism of these natural disasters. The Geographic Information System (GIS) software packages, ArcView 3.2 and ARC/INFO v.8.1 (NT version), were used as the basic analysis tools for spatial management and data manipulation.

The landslide susceptibility analysis entailed collecting data, making a spatial database, extracting landslide-related factors, calculating the likelihood ratios, overlaying factors, making landslide susceptibility maps, and verifying the maps.

2. CHARACTERISTICS OF THE FRACTURES IN THE EARTH'S CRUST IN THE STUDY AREA

The earth's crust in the Lai Chau region has been deformed many times, especially during the recent neotectonic, and tectonic movements are widely developed. The tectonic movements are characterized by lateral displacements and by vertical movements, which caused the earth's crust to form strong fractures, and which have created different zones with different fracture sizes, degrees of fracture, and fracture orientation. Strongly fractured zones are always weak geological zones, and are candidate areas for geological hazards, such as landslides. By choosing suitable coefficients and performing calculations using GIS data, a scheme showing the degree of tectonic fractures of the earth's crust in the Lai Chau area on the 1:250,000 scales has been drawn up. This shows an interesting general view of the characteristics of the tectonic fractures. The main characteristics of the density field of the tectonic fissures is the alternation of zones that have density fields in a long linear form, with one zone that has a density field in an inlaying form oriented along a different direction, which was formed by an anomaly of oval forms or other complicated form. In general, zones with a high degree of anomaly ($M > 1.65$ km/km^2) are linear, are long stressed types, coincide with a large fault, and act as boundaries that divided zones with different density field structures. Based on the difference in the field fracture densities, and on the morphology of an anomaly and its distribution rule in space, the Lai Chau province can be divided into two different zones. The boundary between these zones is a zone that has a high density along the longitudinal direction, and coincides with a deep fault that differentiates Lai Chau from Dien Bien as the eastern and western areas. In each area, different zones can be distinguished. The eastern region is characterized by a higher degree of crust fractures than the western area, especially in the northeastern zone of the Pa Tan–Thuan Chau area.

3. SPATIAL DATABASE USING GIS AND REMOTE SENSING

3.1. Landslide data

For probabilistic landslide susceptibility analysis, an accurate detection of the location of landslides is very important. The application of remote sensing methods, such as aerial photographs and satellite imagery is used to obtain significant and cost-effective information on landslides. In this study, 1:10,000-1:50,000 scale aerial photographs taken in 1981-2000 were used to detect the locations of landslide. The landslide locations detected by photo interpretation were verified by fieldwork. Recent landslides were observed in aerial photographs as a break in the forest canopy, as bare soil, or other geomorphic characteristics typical of landslide scars. For example, head and side scarps, flow tracks, and soil and debris deposits below a scar. In all, 173 landslides were mapped in an area of 16,904km^2 when assembling the database to assess the surface area and number of landslides.

3.2. Fracture data

The number of fractures of the earth's crust is understood in terms of the bedrocks destroyed by different tectonic faults systems. The tectonic fissures were caused by tectonic movements of the earth's crust under the influence of tectonic stress. There have been long and complicated cycles of tectonic activity, and the earth's crust in the study area was differentiated into different tectonic blocks of different thickness and sizes, which move differently to each other. It is at the boundaries of these different blocks that lateral inhomogeneities of the earth's crust occur in the recent texture schemes, and these were used to study the degree of fracture of the earth's crust in the area.

To establish a scheme for studying the degree of fracture of the earth's crust, it is necessary to define an informatics level of the tectonic fault zones, lineament sets, tectonic fractures of the region, and to identify the scope of tectonic fissures of the region. The tectonic faults of different classes and sets of lineaments were interpreted from satellite images, such as Landsat TM images, in combination with 1:33,000-scale aerial photo-visual interpretation and using other geological mapping data. Because our aim was to study the degree of the earth's crust fractures, small faults with lengths >2.5 km were identified as much as possible during the interpretation. The lineaments were closely related to the geological faults, and therefore, a variety of signs was used during the interpretation of the lineaments: photographic tone shape, texture, structure, and morphology from the photographs.

All the above factors for lineament textures were put on a 1:250,000-scale topographic map to form a dense set that had different spatial distributions reflecting a scheme of the earth's crustal fractures in the study area, and this allowed us to study the fractures in the form of a density field. Therefore, the linear map was a map of the tectonics of the fissures of the area, and was also the basis for studying the tectonic fractures in the form of a density field. For impartiality and for homogenous purposes, during the calculations of the linear textures, the maps were divided into three classes: (i) linear textures coinciding with a deep fault, which are old and play a role in dividing different continental crusts, (ii) linear textures that coincide with a large fault, which divide massive tectonic zones, and (iii) other linear textures. Each class was assigned a suitable coefficient during the calculations and the establishment of the density field scheme. The density indicator used was the ratio of the lengths of all the tectonic fissures (calibrated according to the coefficient) per square unit. The calculations were carried out using GIS data, which meant performing the calculations four times. After the calculations had been carried out, an average density degree of the region (the average value) was established for the Lai Chau province, for example, M = 1.1 km/km^2.

3.3. Earth's surface data (slope, aspect, curvature, soil, and land cover)

Contour and survey base points were extracted by having their elevation values read from a 1:50,000-scale topographic map and a DEM were constructed. The DEM had a resolution of 30 m, and using the DEM, the slope angle, slope aspect, and slope curvature values were calculated. The soil data were constructed from a soil map, and land cover data were classified from LANDSAT TM images using an unsupervised classification method and from field surveys. Eleven classes, including urban, water, forest, agricultural areas, and barren areas were extracted for land cover mapping.

4. APPLICATION OF THE PROBABILISTIC METHOD AND ITS INTERPRETATION

4.1. Methodology

The relationship between landslide occurrence areas and landslide-related factors can be distinguished from the relationship between areas where landslides did not occur and landslide-related factors. A likelihood ratio was used to represent this distinction quantitatively in this study. The likelihood ratio for a given attribute used was the ratio of the probability of a landslide occurring to the probability of a landslide not occurring. Therefore, if the ratio is greater than unity, then a high correlation exists between a landslide occurrence and the given factor's attributes, and if the ratio is less than unity, then a low correlation exists between a landslide occurrence and the given factor's attributes. A table was constructed for each landslide-related factor to calculate the likelihood ratios, and the area ratios for a landslide occurrence to a landslide non-occurrence were calculated for a range or type of each factor. In addition, the area ratio for a range or type of each factor to the total area was also calculated. Finally, the likelihood ratios for a range or type of each factor were calculated by dividing the landslide occurrence ratio by the area ratio. The relationship between areas of landslide occurrence and the landslide-related factors could be distinguished from the relationship between areas where landslides did not occur and the landslide-related factors. To represent the distinction quantitatively, the likelihood ratio was used in this study.

4.2. Relationship between tectonic fracture zones and landslides

The formation and development of landslides and debris flows have occurred at various times under the influence of different factors: rock composition, slip and strike of rock, relief morphology, recent movements, weathering of the crust, climate, and vegetation. In general, landslide formation mechanisms and development are very complicated. A necessary condition for the formation of debris flow is a large enough source of material, and mainly results in a landslide on slopes after concentrated heavy rain. Without a landslide, debris flow never occurs.

If we scrutinize the area where landslides have occurred, then we can observe that not all landslides cause debris flow. Debris flow only occurs when landslides occur in the increasingly highly fractured zones, and when sliding materials are of different sizes, from fine clay to very large blocks of bedrock. In the Muong Lay, Saham, and Sa Long areas, where large debris flows have occurred, one can observe that there are large rock boulders in the debris material. This is chaotic material, created from a plug phenomenon, which formed a series of contemporary lakes. When a lake was ruptured, then it caused the rupture of other lakes in a domino effect that formed a very strong debris flow with devastating effect.

To characterize this, the proximity to the largest fracture was identified by buffering. It can be seen that as the distance from a fracture line increases, then the landslide frequency generally decreases. Below a distance of 2,000 m, the ratio was >2, indicating a high probability of landslide occurrence and above a distance of 2,000 m, the ratio was 0.73. The proximity to the second largest fracture was also identified by buffering. It can be seen that there was no distinct relationship between landslide occurrence and distance from the fracture in this case. The proximity to the smallest fracture was also identified by buffering. It can be seen that as the distance from a fracture line increases, the landslide frequency generally decreases. Below a distance of 800 m, the ratio was >1, indicating a high probability of landslide occurrence, and above a distance of 800 m, the ratio was <1, except for some intervals.

All the above-mentioned phenomena, especially the materials, can be observed only in the different degrees of tectonic fractures of the earth's crust. A detailed study of the areas where landslides and debris flows have occurred in the Lai Chau province had supported this conclusion. It is clear that landslides, debris flows, and tectonic fractures have a close spatial relationship. Therefore, a scheme of the tectonic fractures of the earth's crust at Lai Chau is an important tool for forecasting and zoning areas where debris flow can occur. The results of our study form a basis for the planning of stable development of the region.

From a different viewpoint, when we contrast debris flow and our scheme of the tectonic fractures of the earth's crust at Lai Chau, it is evident that there is a close relationship between the degree of fracture and the size of the debris flows. The devastating debris flows always happen in the large fracture zones that have large-sized debris. These are very dangerous for the Lai Chau area, where the Lai Chau–Dien Bien fracture zone of the earth's crust has increased along the sub-longitude direction, with M >1.65–3.2 km/km^2, along with the Tuan Giao–Deo Hoa fracture zone and other fracture zones heading in the northwest–southeast direction.

4.3. Relationship between the earth's surface data and landslides

Factors such as slope, aspect, curvature, soil, and land cover were evaluated using the likelihood ratio method to reveal the correlation between landslide locations and these factors in the study area. The probabilistic approaches were based on the observed relationships between each factor and the distribution of landslides.

In regards to the topographic factors, such as slope, aspect, and curvature, the relationship between landslides and slope, shows that the steeper the slope, the greater the landslide probability. Below a slope of 5°, the ratio was 0.26, (<1, indicating a very low probability of occurrence), and for slopes above 6°, the ratio was >1, indicating a high probability of occurrence. This means that the landslide probability increases with increasing slope angle. As the slope angle increases, the shear stress in the soil or other unconsolidated material generally increases as well. Gentle slopes are expected to have a low frequency of landslides, because of the generally lower shear stresses associated with low gradients. Steep natural slopes resulting from outcropping bedrock, however, may not be susceptible to shallow landslides. In the case of the aspect, landslides were most abundant on south-facing and northeast-facing slopes. The frequency of landslides was lowest on east-facing, west-facing, and northwest-facing slopes (excepting flat areas). The curvature values represent the morphology of the topography. A positive curvature indicates that a surface is upwardly convex at that cell. A negative curvature indicates that a surface is upwardly concave at that cell. A value of zero indicates that the surface is flat. According to the curvature results, the more positive or negative the value is, then the higher is the probability of a landslide occurrence. Flat areas have a low probability value of 0.60. The reason for this is that following heavy rainfall, a convex or concave slope contains more water, and retains it for a longer period. Analysis was carried out to assess the influence of drainage lines on landslide occurrence. The relationship between landslides and the soil is that rocky mountain soil has a probability of 2.30, and ferralic acrisols have a probability of 1.38, with the remaining soils having probabilities <1. The relationship between landslide and land cover is that rocky mountain soils have a probability of 3.18, while areas used for rice and crops have a probability of 2.59. The remaining areas have a probability of <1.

5. LANDSLIDE SUSCEPTIBILITY MAPPING AND VERIFICATION

Using the probability method, we derived the spatial relationship between the location of landslide occurrences and each landslide-related factor. The factors we used that influence landslide occurrences are: the distance from different fractures, topographic slope, topographic aspect, topographic curvature, soil, and land cover. Each of these factors was derived from TM satellite images. The factors were converted to form a 10 x 10 m^2 grid to calculate a landslide susceptibility index (LSI). In the study area, the total number of cells was 1,690,435, and the number of landslide occurrence cells was 175. Using GIS software, the grid was overlain with the geographic coverage for each study area.

The correlation ratings were calculated from analysis of the relationship between landslides and the relevant factors. Therefore, the rating of each factor's type or range was assigned from the relationship between landslide occurrence and each factor's type or range, *i.e.*, the ratio of the number of cells where landslides did not occur to the number of cells where landslides did occur. The LHI was calculated by summation of each factor's ratio value as

LSI = ΣFr (where Fr = the rating of each factor's type or range) (1)

After the calculations, the LSI had a minimum value of 1.93, a maximum value of 15.82, and an average value of 8.02. The standard deviation was 2.32. Analysis of the relationship using the ratio of the area where landslides occurred to the total area was carried out, so that an LHI value of LHI = 8 denotes an average value, because eight factors were used. If the LHI value was >8, then it denotes a higher correlation, and a value <8 denotes a lower correlation. The landslide-susceptibility map was constructed using the LSI value index for interpretation. The index was classified by equal areas, and grouped into five classes.

The susceptibility maps formed using Equation (1) was verified using existing landslide location data. All eight factors were used, and the landslide susceptibility index (LSI) values of nine cases including all the above factors were calculated. For verification, the method was subjected to tests that determine whether its predictions matched the expected results based on knowledge of the factors. The output was compared with the expected changes in the output. Rate curves were created to achieve this. To obtain the rate curves, the calculated LSI values of all the cells in the study area were sorted in descending order. Then, the ordered cell values were divided into 100 classes, with 1% accumulated intervals. The rate curves explain how well the method and chosen factors predict landslides. The areas under the curves were calculated to compare the results. A total area = 1 denotes a perfect prediction accuracy for all cases. The area under a curve can be used to assess the prediction accuracy in a qualitative manner. For example, 10% of the study area where the LSI had a high rank could explain 41% of all the landslides. In addition, 30% of the study area where the LSI had a high rank could explain 68% of the landslides. The area under these curves was 0.7410, and therefore we can state a prediction accuracy of 74.01%.

6. CONCLUSIONS

In the Lai Chau area of Vietnam where landslides are common, our method was applied to study the influence of tectonic fractures on landslide occurrence and debris flows. From our observations, it is clear that landslides and debris flows are geological processes, in which tectonics plays an important role. Our results allow us to distinguish zones with different fractures of the earth's crust. Landslides and debris flows become most dangerous when M >1.6–3.2 km/km^2. The verification of the results is that agreement was found between our susceptibility map and the landslide location data, as the prediction accuracy is 74.01%.