Prediction of Mountain Road Closure Due to Rainfall-Induced Landslides

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ABSTRACT: The implementation of landslide probability analysis was undertaken in order to evaluate the impact of landsliding on closures of major mountain road networks in Guoshin Township in central Taiwan. To achieve this objective, an event-based landslide probability analysis method was adopted to establish a landslide prediction model using a set of training data from the landslides triggered by Typhoon Mindulle in July 2004. Landslide causative factors and triggering factors were selected in a logistic regression scheme so that the criteria for successfully distinguishing landslides from non-landslides were established. Landslide occurrence probability was mapped in the whole study area as well as along the road route. Locations of high potential for landslide occurrence were thus highlighted along the road route and were proposed for road closure during typhoon events. At last, the proposed locations for road closure were validated by historical road closures caused by subsequent typhoons after Typhoon Mindulle. Validation results show that the proposed model could be used in predicting road closures due to storm-induced landslides.

INTRODUCTION

Rainfall-induced landslides easily result in the closure of the trunk road network. When rock falls occur, roads might be closed in only one direction, causing long delays to the traveling public and truckers. However, when a major slide occurs that closes all lanes, traffic may have to backtrack and detour via other routes for an additional distance. Roads might be closed for months while repairs are made. Road closures due to landslides cause economic impacts and hinder evacuation for mitigation of disasters. These disasters also might damage vehicles and injure people. Landslides triggered by heavy rainfall are the most common hazards throughout Taiwan.

Rainfall-induced landslides have been research subjects for many years (Cardinali et al. 2006; Lee et al. 2008), however, very seldom have researchers discussed the probability of road closures due to landslides. It can be expected that natural hazards causing closure of roads are invariably of low probability and consequently the availability of historical data are limited. Because of this lack of information, there is a high degree of uncertainty in estimations of road closure (Dalziell et al. 1999). With recent publicity and a high public sentiment on road closures, the Directorate General of Highways of Taiwan developed a disaster information system for road management. The system provides information about road closure. However, the information only indicates places where road closures will most likely reoccur, but gives no indication of their likelihood of reoccurrence. In other words, the probability of road closure based on historical closure locations and other road sections is not available.

In this study, the probability maps of landslide occurrence were used to predict road closure. A number of vulnerable areas on the trunk road network throughout Guoshing Township were identified. Roads considered priority for evacuation were evaluated and ranked according to the probability of road closure.

STUDY AREA

The study area of Guoshing Township is located in the central part of Taiwan, covering an area of 175 km^2 that is predominantly hilly or mountainous. The five major roads in Guoshing Township are shown on Figure 1. The area experiences a subtropical climate defined by a distinct rainy season from May through August and dry season from October through March. The average annual precipitation in the study area is about 2200 mm, with an average of 149 rainy days per year. The precipitation during rainy season is 73% of annual precipitation.

Elevations in Guoshing Township range from 300 m to 1,200 m, with generally rugged topography. Geologically, the study area is covered with Quaternary and Tertiary formations. In hilly terrain, the rocks consist of weakly-cemented Pliocene and Pleistocene mudstone, sandstone and conglomerate, while, in mountainous terrain, the rocks consist of better-indurated Eocene, Oligocene and Miocene, sandstone, shale, argillite and quartzite.

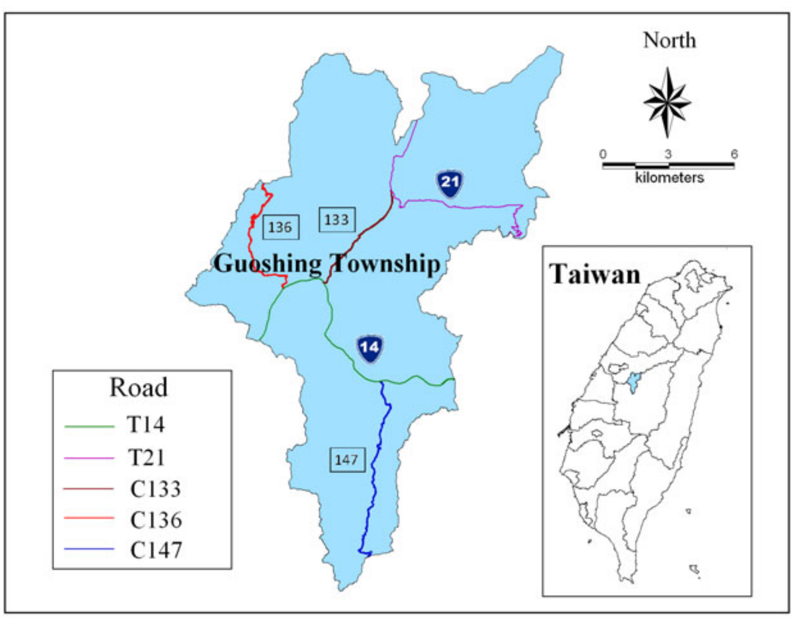

FIG. 1. Study area of Guoshing Township.

METHODOLOGY

Study Program

The assessment of road closure is based on a landslide prediction model from an event-based landslide hazard analysis (Lee et al. 2008). In order to develop the model, an event-based landslide inventory was first established using high resolution satellite images before and after a heavy rainfall event. And then the landslide inventory was checked by rectified aerial photographs in a geographic information system (GIS). Some were identified in the study area from field surveys. After checking and attributes assignment, an event-based landslide inventory was established. The event-based landslide inventory was used as train data to establish a logistic regression model against landslide causative factors and triggering factors. Landslide occurrence probability was mapped in the whole study area as well as along the road route using rainfall values of 100 year return period.

In order to estimate a potential landslide failure due to increase of rainfall intensity, rainfall return period of 100 year were used in the landslide prediction model. The probabilities of road closure were based on the probabilities of landslides along mountain roads and the probability maps of road closure were developed.

Data Acquisition

The required data included digital elevation models (DEM), SPOT5 satellite images, aerial photographs, 1:50,000 geologic maps of the study area, GIS road maps, and hourly rainfall records. The DEM with 5m × 5m resolution and 1:50,000 geological maps were obtained from the Central Geological Survey (CGS) Taiwan. The 5m × 5m DEM was used to extract geomorphic landslide causative factors, and 1:50,000 geological maps were used to classify geological regions. SPOT5 images taken prior and after heavy rainfall events were obtained from the Center for Space and Remote Sensing Research, National Central University. Landslides induced by Typhoon Mindulle were interpreted from SPOT5 images. Hourly rainfall data were collected from the Water Resources Agency, Taiwan Power Company, and the Central Weather Bureau to assess the relationship of rainfall and landslide occurrence.

In this study, the heavy rainfall event of Typhoon Mindulle in July 2004 was selected to develop the landslide prediction model. The analyzed rainfall data covered at least 2 days before and after rainfall events and consisted of maximum hourly rainfall and total accumulated rainfall. Hourly rainfall data were gathered from rain gauge stations in and around the study area. The maximum hourly rainfall data, maximum daily rainfall and total accumulated rainfall recorded by rain gauge stations are shown in Table 1. The rainfall data were then spatially interpolated to each 10m x 10m grid cell in the study area using the ordinary Kriging method. Further logistic analysis was based on the 10m x 10m grid-cells unit.

Selection of Factors for Modelling

The landslide prediction model contains factors related to causes of landslides. According to previous studies (Lee et al. 2008), these factors include slope gradient, normalized difference vegetation index (NDVI) (Paruelo et al. 2004), slope roughness, total curvature, maximum elevation, total slope height, maximum hourly rainfall and total accumulated rainfall. The NDVI used in this study was calculated from an image taken prior to Typhoon Mindulle. It is an environmental factor reflecting vegetation cover and land-use. A higher NDVI value means denser vegetation. Slope roughness is defined as the standard deviation of slope gradients. The factor of maximum elevation is probably physically related to weathering ability, which is mainly attributed to wind velocity, rainfall, temperature, and so on. Wind velocity depends on elevation, ground surface roughness, terrain, and atmospheric stability. It increases with a rise in elevation (Disrud 1970). Winds accompanying rains increase the rain's ability to cause soil detachment and clod disintegration, which in turn contributes to shallow landslides. The total slope height is the distance from crest to toe of a slope. The factor of total slope height is physically related to the magnitude of the stress and the pore-water pressure in the lower slope. For long slopes the surface and subsurface water is more likely to be concentrated in the lower slope, causing instability (Lee et al. 2008).

Landslide Prediction Model

In order to predict landslide occurrence, a logistic model was used to develop a landslide prediction model. A logistic model is one of the multivariate analysis models, and is the most important model for categorical response data, especially for binary data. It has the advantages of using variables that are either continuous or categorical, or any combination of both types, and variables do not necessarily have the limitation of normal distributions. The logistic model is expressed as:

$$P = \frac{1}{1 + \mathbf{e}^{-z}} \qquad (1)$$

where P is the probability of an event occurring. In the present situation, Eq. (1) is treated as a landslide prediction model. The value P is the estimated probability of landslide occurrence. The probability varies from 0 to 1. It follows that logistic regression involves fitting an equation of the following form to the data:

$$Z = \alpha + \beta x_i \qquad (2)$$

where α is the intercept of the model, x_i are the independent variables, and β is the coefficient of the independent variable, i.e., the weights of the factors.

Table 1. Rainfall Record of Typhoon Mindulle in Study Area

Maximum Hourly Rainfall (mm)	Maximum Daily Rainfall (mm)	Total Accumulated Rainfall (mm)	Station Location
101	354	1107	Chiufenershan
84	460	997	Beishan
75	437	830	Shueijangliou
70	407	898	Jangfu
63	464	992	Chingliou
58	254	545	Hsuangtung

EVALUATION OF ROAD CLOSURES

Probability Mapping for Landslides

Table 2 shows the coefficients (apparent weight) of the factors in the landslide prediction model. Equation (1) was calculated to generate a landslide probability map for the entire study area. Figure 2 represents the landslide probability map in the administrative area of Guoshing Township for a 100 year rainfall return period. From Figure 2, the west, upper left and down left parts of Guoshing Township have higher probability of landslide occurrence. This is because west part (west side of Route C136) is on Jou-Jou Mountain, north west (east side of Route C136) on Dahengpingshan Mountain, and south west (west side of Route C147) is Chiufenershan Mountain. After Typhoon Mindulle, many landslides occurred, consequently causing the high probability of failure events in this area.

Probability of Road Closures

Routes T14, T21, C133, C136 and C147 are the primary roads in Goushing Township. Landslides probably lead to closure of these routes and the probability of road closure is defined as the landslide probability along roads. Figure 3 shows the probability of road closure for Routes T14, T21, C133, C136 and C147 for a 100 year rainfall return period. The probability of road closure is between 0 and 1, with 0 corresponding to no road closure that never occurs and 1 to road closure that is certain to occur. In this study, the probability of road closure was categorized into 5 levels, with each level having a different color on the map. Red represents the highest probability (0.8-1.0) of road closure, while dark green represents low probability (0-0.2). Using GIS to categorize levels along the roads the essential construction locations for preventing landslides can be clearly known based on the predicted probability of road closure. Keeping the roads open will lead to lower casualties since people will be able to evacuate from home to shelters when a typhoon approaches. High priority roads for evacuation should consist of roads where there is a low probability of landslide occurrence. The results also can be used in decision making for allotment of medical treatment resources and rescue goods. On Figure 3, there are more locations with a probabilities of road closure greater than 0.6, in Qiangou, Fugui, Ganlin, and Beigang Villages for Routes T14, C136 and T21, respectively, than the other areas.

Table 2. Weights of Factors in Logistic Model

Factors	Weights
Slope gradient	0.653
NDVI	-0.427
Slope roughness	0.392
Total curvature	0.554
Maximum elevation	0.750
Total slope height	0.152
Maximum rainfall intensity	0.433
Total accumulated rainfall	0.485
Constant	-25.059

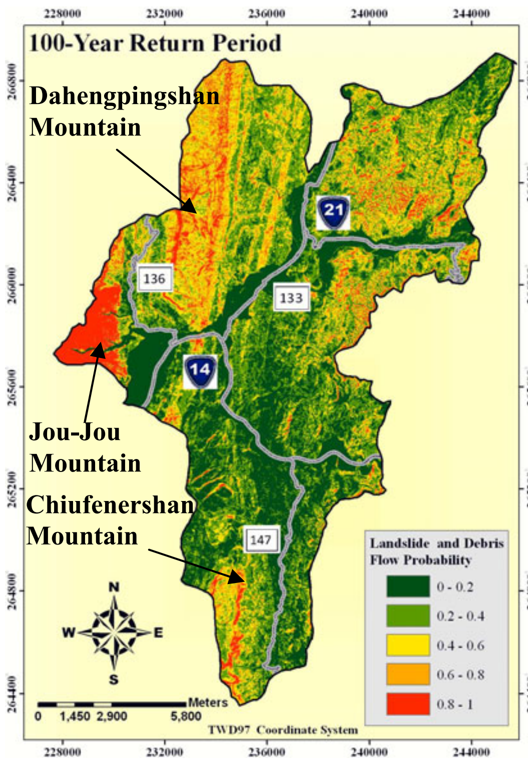

FIG. 2. Landslide probability map of Guoshing Township.

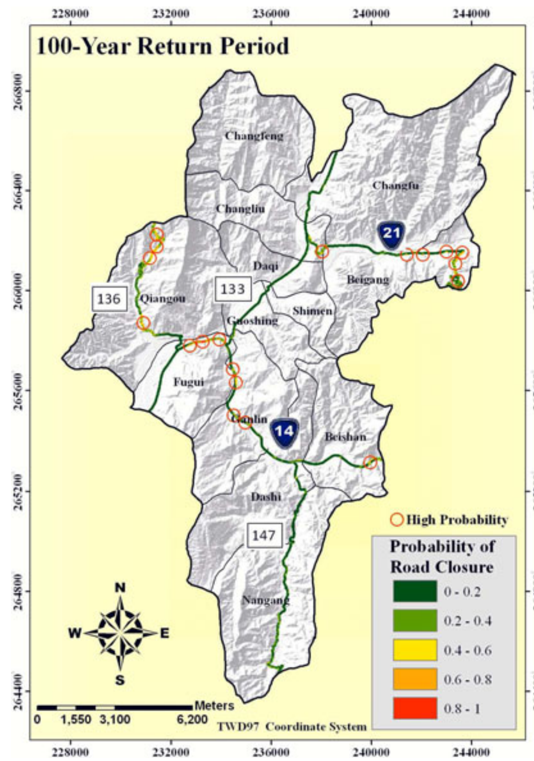

FIG. 3. Probability of road closure of Guoshing Township.

In order to comprehend the variation of the probability of road closure along road thoroughly, the relationships between the probability of road closure and location, as indicated by roadway distance markers are plotted on Figures 4 to 8. The distance marker is a kilometer post along the road. Figure 4 shows that the Route T14 is most likely to close between kilometer marker posts 37.5 to 38.5 km. The probabilities of road closure for this road section are as high as 0.9. In fact, in 2008, Typhoon Sinlaku caused the road closure in post kilometer 37.8 km. For Route T21, the probabilities of road closure are apparently high between marker posts 29 to 30 km, shown in Figure 5. In 2005, Typhoon Matsa caused the road closure in post kilometer 29 km.

Figures 6 and 7 show the probabilities of road closure for Routes C136 and C147, respectively. Obviously, the probabilities of Route C136 are higher than those of Route C147. Route 136 is through more mountainous terrain and there is an abundance of loose soil and rock, which results in the higher probability of a road closing event. On the other hand, although Chiufenershan Mountain has a high probability of landslides, it is far from Route C147, and has less impact on Route C147. In 2005, a heavy rainfall event caused the road closure of Route C136 in post kilometer 49.4 and 54.4 km. From Figures 4 to 6, it seems that the probability of road closure of 0.7 is a threshold where road closure occurs. It is verified by the probabilities of road closure for Route C133, because the probabilities are all less than 0.7, shown in Figure 8, and indeed no events of road closure occur on Route C133.

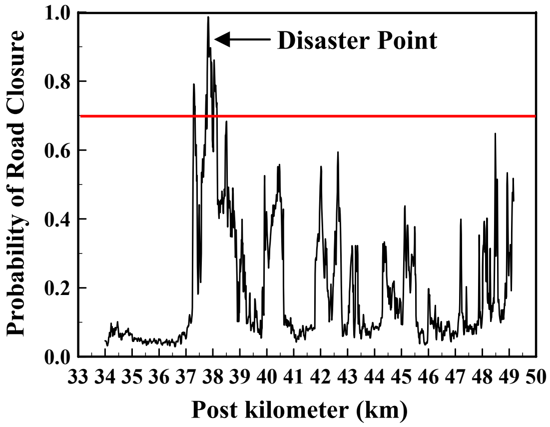

FIG. 4. Probability of road closure for Route T14.

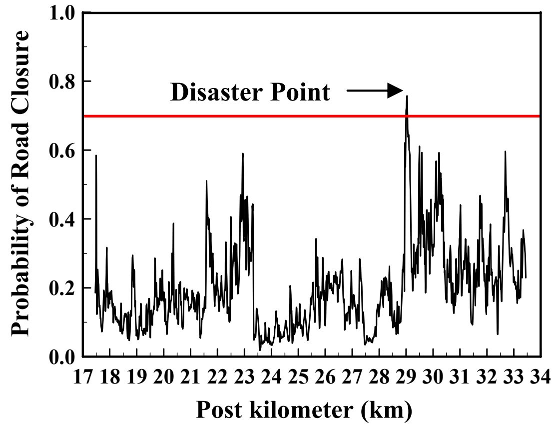

FIG. 5. Probability of road closure for Route T21.

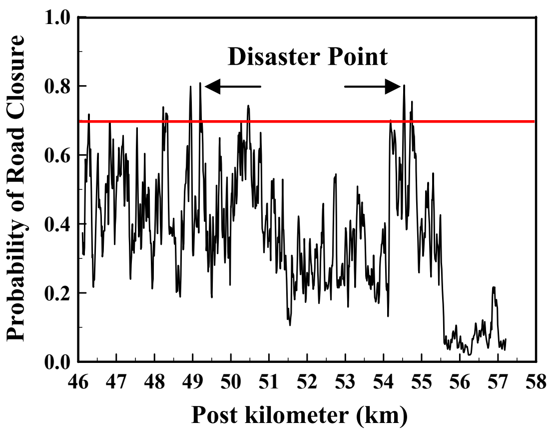

FIG. 6. Probability of road closure for Route C136.

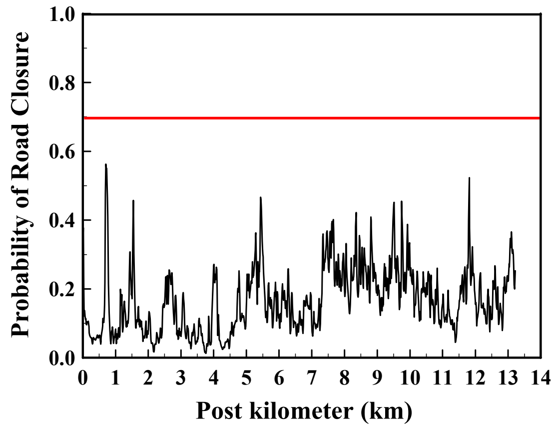

FIG. 7. Probability of road closure for Route C147.

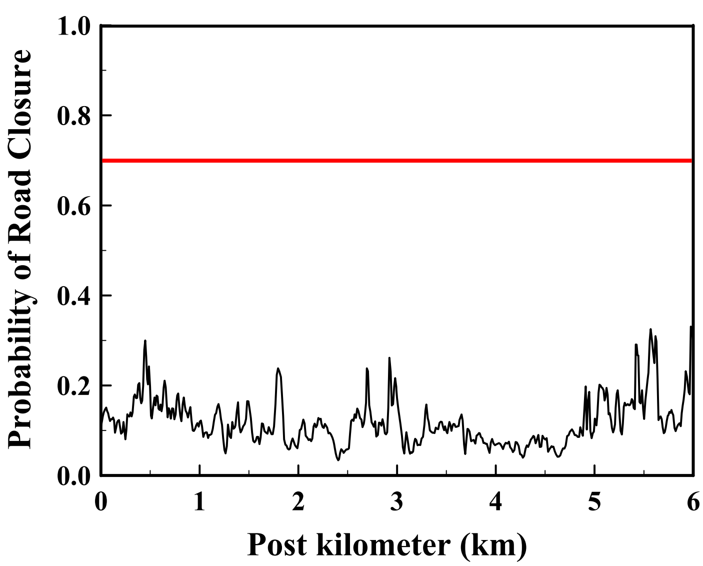

FIG. 8. Probability of road closure for Route C133.

From the above discussion, Route C136 is obviously impacted by landslides. The

Probabilities of road closure of Route C136 are significantly higher than the other Routes. The probabilities of road closure of Routes C133 are lowest compared with the other route's probabilities. The probability of road closure of Route C147 is slightly higher than that of Route C133 and lower than that of Route T21.

Route C133 is a Priority route for typhoon evacuation. Routes C147 and T21 (not including the section from kilometer post 29 to 33 km) are considered Priority 2 and 3 for evacuation. Routes T14 and C136 are easily influenced by landslides and are not suitable routes for evacuation. In practice, people residing in Central and Northern Goushing Township evacuate to the north via Route C133 and connect with T21, while people residing in Southern Goushing Township evacuate to the south via Route C147. Road closure assessment techniques provide a method by which roads for evacuation can be ranked to provide criteria for mitigation.

DISCUSSION AND CONCLUSIONS

The landslide prediction model proposed in this study is mainly for prediction of shallow landslides. It is not valid for prediction of structural controlled landslides in larger scale. Fortunately, the majority of landslides in mountainous areas are shallow landslides, so that a shallow landslide prediction model could be used in the present study. However, a structural controlled landslide may have larger scale in volume and cause longer closure of road; it should be studied also in the field by landslide expert in the future. The application of landslide probability analysis to evaluate the impact of landsliding on closures of major mountain road networks in Guoshin Township in central Taiwan is successful, provided that careful validation using historical road closure data has been done. The road closure assessment techniques proposed in the present study could be used for route selection and road maintenance, as well as hazard mitigation purpose in mountainous areas.

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