Review and Perspectives on Methodology for Landslide Hazard Analysis

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Abstract

Landslide hazard analysis aims at quantitatively evaluating the probability of landslide failure within a specified period of time and within a given region. It is different from a landslide susceptibility analysis which only classifies a region into several successive classes with different potential of landsliding. This study reviews mainly for rain-induced landslide hazard. Similar methodology may also be applied to earthquake-induced landslides.

There are three different approaches in modern landslide hazard analysis. (1) Deterministic approach by an infinite slope model and a hydrological model with parameters pre-calibrated by a set of landslide data is applied, and a return-period rainfall may be used as final input for a hazard map. (2) Probabilistic approach by the Poisson model with annual landslide rate at a slope unit derived from a multi-temporal landslide inventory is applied, and an annual exceedence probability of certain magnitude of landslide failure at a specific slope is provided. (3) Statistical approach by a multi-stage of analysis, including an event-based landslide susceptibility analysis, a probability of failure analysis, a rainfall frequency analysis, and a final analysis, is used for hazard mapping.

All the three approaches may be used for regional landslide hazard mapping, but, there are some shortages in each kind of approach. The deterministic approach requires soil strength, soil depth, and hydrological parameters, which are difficult to collect in a large region. The probabilistic approach requires a long-period landslide data, which may be insufficient length of historical records, incompleteness in inventory, and a possible mixing of extreme events and/or earthquake disturbance. The statistical approach looks better as comparing with the weakness of the other two approaches, but, there still are some further developments needed to predict landslide magnitude and run-out distance which are very important in risk assessment.

Keywords: Landslide inventory, Landslide susceptibility, Landslide hazard, Hazard mapping

1. Introduction

There always had some problems on landslide susceptibility/hazard evaluation in the past. These included: (1) the problem of attempting to quantify landslide hazard over larger areas, (2) challenge of mixing landslide types in the analysis, (3) to use a multi-temporal landslide inventory or an event landslide inventory, (4) the selection of mapping unit in the analysis, and also, (5) the selection of the analytical method (Guzzetti et al., 1999; Aleotti et al., 1999; Brenning, 2005; Van Westen et al., 2006; Lee and Fei, 2015).

Varnes et al. (1984) defined the landslide hazard as “the probability of occurrence within a specified period of time and within a given area of a potentially damaging phenomenon”. Landslide hazard analysis (LHA) is a regional hillslope stability analysis concerning the probability of instability at any given point within a specified period of time. It aims at quantitative evaluation of spatial-temporal probability of landslide at a given slope. Landslide susceptibility analysis (LSA) only classifies a region into several successive classes with different potential of landsliding, and is different from LHA.

There are mainly three different approaches in modern LHA. (1) Deterministic approach by an infinite slope model and a hydrological model (Montgomery and Dietrich, 1994; Iverson, 2000; Claessens et al., 2007). (2) Probabilistic approach by the Poisson model with annual landslide rate at a slope unit derived from a multi-temporal landslide inventory (Guzzetti et al., 2005). (3) Statistical approach by a multi-stage of analysis, including an event-based susceptibility analysis, a probability of failure analysis, a rainfall frequency analysis, and a final analysis, is used for hazard mapping (Lee and Fei, 2015, Lee et al., 2008). A comparison of these three approaches and an overview of recent developments in the landslide hazard analysis and mapping at medium scales will be given. Which kind of approach is more appropriate and more promising in the further development of LHA will also be discussed.

It is clear that temporal probability is an important component in the LHA. Some previous studies, although include the wording like hazard or risk, are actually involving susceptibility only, and are not included in the present review.

2. Comparison of Different Approaches

2.1 Deterministic approach

Deterministic approach performs hazard analysis by an infinite slope model and a hydrological model with parameters pre-calibrated by a set of landslide data, and a return-period rainfall may be used as a final input for the hazard map (Montgomery and Dietrich, 1994; Iverson, 2000; Claessens et al., 2007).

This physical-based method is theoretically perfect, but it is practically doubtful. Because it requires soil strength, soil depth, and hydrological parameters, and these are difficult to collect in a large region.

2.2 Probabilistic approach

Like conventional seismic hazard analysis for earthquake magnitude, the probabilistic approach for landslide hazard proposed by Guzzetti et al. (2005) is very similar with. It used annual landslide rate at a slope unit derived from a multi-temporal landslide inventory and applied the Poisson model to find an annual exceedence probability of certain magnitude of landslide failure at each slope unit over a median-sized drainage basin.

The including of landslide magnitude in LHA is first proposed in this study. Their methodology is simple and straightforward. However, the time span of the landslide inventory may be not long enough to cover an active period and a calm period so that the meaning of the result is reduced. And also, the completeness of the inventory may be difficult to achieve. Mixing of extreme events and/or earthquake disturbance is also possible and makes the inventory complicated for use.

2.3 Statistical approach

Conventional multivariate statistical analysis via discriminate analysis or a logistic regression for landslide susceptibility is a kind of statistical approach. Among the statistical methods, the event-based LSA introduced by Lee et al. (2008) is a recent progress which may be possible for further development and upgrade to LHA, because certain return-period rainfalls can be input into the susceptibility model, and makes the model temporal meaningful.

In the event-based LSA, using the susceptibility model and the training data, a probability of failure and susceptibility relationship can be built, and the probability of failure curve can be used to map landslide spatial probability of the study region. Therefore, spatial probability and temporal probability are both taken into account. The outcome is a landslide probability of failure map under a certain return-period rainfalls and this would be a kind of landslide hazard map (Lee and Fei, 2015).

This kind of landslide hazard model is good for mapping landslide hazard, prediction of landslide failure probability under a rain event, decision making for regional planning, site selection, hazard mitigation, and estimation of sediment yield for a drainage basin after a rain event. However, there still are some further developments needed to predict landslide magnitude and run-out distance which are very important in risk assessment.

2.4 Comparison and discussions

Not resemble previous LSAs, all the three approaches are capable of hazard mapping over large areas. This is because LHAs present consistent hazard-level under certain return-period or annual exceedence probability over a large region.

As to the types of landslide involved, the deterministic approach and the statistical approach are designed for the type of shallow landslide only, whereas the probabilistic approach is not restricted to shallow landslides; deep landslides are not excluded in the analysis. Flow type of landslide, lateral spread, and slope deformations are excluded in all of the three approaches. Separation of different types of landslide, and to build a hazard model for a type of landslide are deemed necessary in the landslide hazard study of a region.

A multi-temporal landslide inventory is required in the probabilistic approach, whereas an event landslide inventory is used both in the deterministic approach and the statistical approach. The latter is much easier to prepare than the formal, not to mention that to prepare a long-period and complete landslide inventory is almost impossible. This is especially true for earthquake-induced landslides.

In the deterministic approach and the statistical approach, grid-cells are used for the analysis, whereas slope-units are used in the probabilistic approach. The formal has a higher resolution (about $100m^2$ a unit), and the latter has a lower resolution (about $100000m^2$ a unit). But, hazard-level in the formal is discrete, that in the latter is compacted and is easy to be used in hazard management and land use. This may means that vectorization and compaction of the discrete grid-cells in the deterministic approach and the statistical approach would be necessary. This is strongly recommended to be considered in the future studies.

Which kind of approach is more appropriate and more promising in the further development? First, the improvement of data quality in the deterministic approach may be a control of further development of this method. In-depth review and ideas should be necessary, and the consideration of multivariate geostatistical interpolation may be one of the possible solution. Second, to prepare a long-period and complete landslide inventory is not easy in most countries. Unfortunately, this method is also highly controlled by the data itself, and is limited for further development. The statistical approach requires only an event landslide inventory accompanying the trigger factors and other data set to build the hazard model. This is deemed more appropriate in conventional usage in every county. However, the statistical approach requires enough number of rain gauge stations, so that a better interpolation of rainfall distribution can be drawn in the study region. The shortage of the statistical approach is also that landslide magnitude and run out distance cannot be predicted at the present stage and reserve further development.

Landslides are secondary or induced features, whose recurrence is controlled by the repetition of triggering events, such as earthquakes or heavy rainfalls. Therefore, LHA may be separated into at least two stages, that is a spatial probability stage and a temporal probability stage. This is true both in the deterministic approach and in the statistical approach. The multi-stage procedure in the above-mentioned statistical approach is deemed necessary.

3. Recent Progress in Statistical Approach

3.1 Basic susceptibility of a region

When event landslide inventory and triggering factors are used in building a susceptibility model, the susceptibility model is dependent on the event itself. However, if we extract the component of the triggering factors from the model, then the model becomes event independent, provided that the triggering factor is an independent factor having only small correlation coefficient with each causative factor.

An event-independent susceptibility model is tested to be a basic susceptibility model in Lee et al. (2004), and in our recent studies. Different event-independent susceptibility model for the same region are similar in pattern, and is similar also to a susceptibility model built by a multi-temporal landslide inventory at that region (Fig. 1). On this basis, we can use an event-independent susceptibility model to represent the susceptibility of the region with confidence.

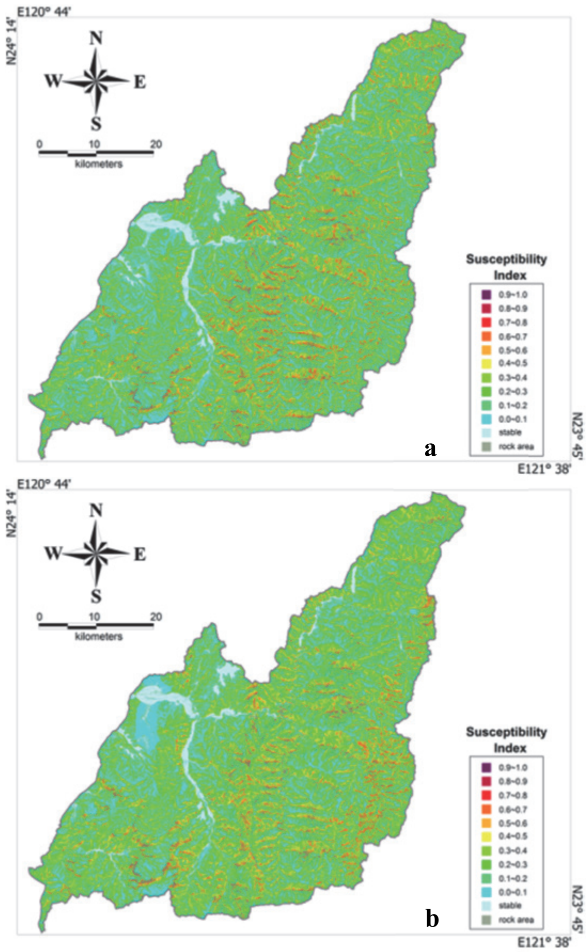

Fig. 1 Basic susceptibility map at mountain terrain of the Choswei River catchment in central Taiwan, (a) that from event-independent model of Typhoon Toraji event, (b) that from multi-temporal landslide inventory.

3.2 Probability of failure surface

We tested the relationship between probability of failure and rainfall intensity, as well as total rainfall at each event-independent susceptibility bin. It was found that the relation is good; the probability of failure increases with an increase in the rainfalls and also an increase in the susceptibility. A fitting surface of probability of landslide failure using a rainfall parameter and the event-independent susceptibility as two independent variables was done. The result is shown in Fig. 2 and equations 1 and 2 as follows:

$$y = 26.815\lambda\,(1 - e^{-3.758\lambda^{0.760}})(1 - e^{-2.0175(\frac{x_1}{100})^{1.836}})\,, \qquad [1]$$

$$y = 32.357\lambda\,(1 - e^{-3.843\lambda^{0.768}})(1 - e^{-1.6835(\frac{x_2}{2000})^{2.445}})\,, \qquad [2]$$

where x_1 is the maximum rainfall intensity in minimeter, x_2 is the total rainfall in minimeter; y is the probability of landslide failure, and λ is the basic susceptibility. Equation 1 is for maximum rainfall intensity and eq. 2 is for the total rainfall of an rain event.

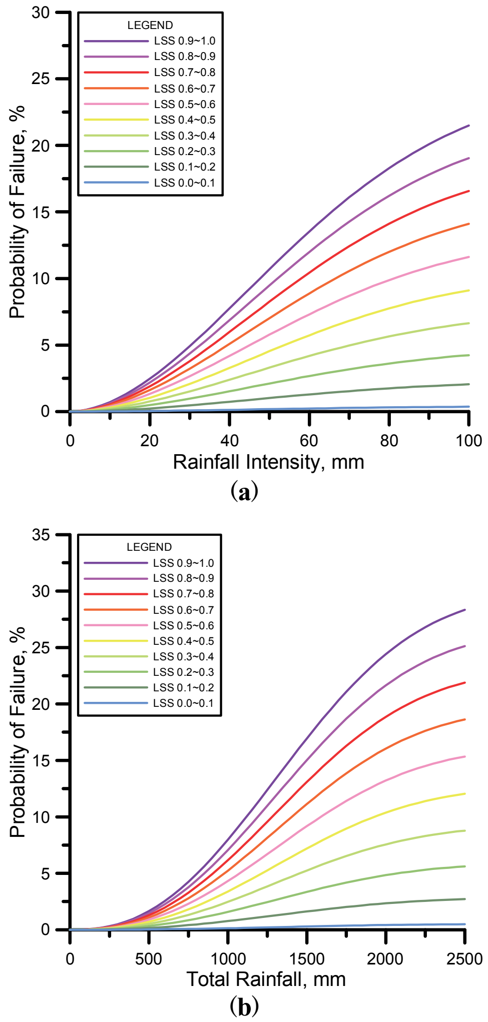

Fig. 2 An example of probability of failure surface from the Kaoping River basin in southern Taiwan, (a) maximum rainfall intensity, (b) total rainfall. Equations are shown in the text.

A global probability of failure surface for two rainfall variables may be built by combining equations 1 and 2. If the two rainfall variables are totally independent, then the square of global probability of failure is the sum of the square of eq. 1 and the square of eq. 2. If the two rainfall variables are totally dependent, then the square of global probability of failure is the product of the eq. 1 and the eq. 2. In actual cases, the two rainfall variables are commonly in between dependent and independent, but have a correlation coefficient between 0 and 1. In the present study, we propose,

$$y = ((1-r)(y_1^{\,2} + y_2^{\,2}) + r(y_1 y_2))^{0.5}, \qquad [3]$$

where y_1 is y of eq. 1, y_2 is y of eq. 2, and r is the correlation coefficient between maximum rainfall intensity and the total rainfall.

The probability of failure surface may be used to map and/or predict landslide spatial probability over the study region under a scenario rain event or return-period rainfalls. Figure 3 is an example of landslide hazard map under 100-year rainfall.

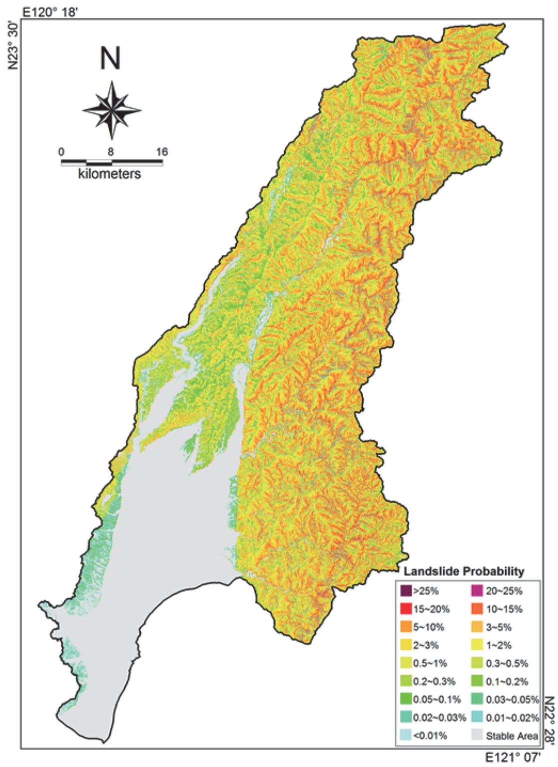

Fig. 3 100-year rainfall landslide hazard map for the Kaoping River basin in southern Taiwan.

3.3 Nationwide large-scale landslide hazard map

In the past, landslide susceptibility analysis was generally limited to a small area and of research purpose. A susceptibility model established for on specific region could not be applied to other areas. This has led to technological stagnation in the research and testing phase.

Based on actual demand, Taiwan started a research program, the Central Geological Survey, in 2003, for the execution of nationwide landslide hazard maps. By the end of year 2013, the whole of Taiwan has been mapped with good results. The statistical approach proposed by our group was developed in this period. For hazard analysis and mapping in a wide region, one needs to take into account heterogeneous features present in the wide area and the consistency of results from different regions. These challenges require the following two methods to be resolved: (1) division of homogeneous zones so that a reliable hazard model can be established for a zone; (2) a consistent hazard level must be chosen so that the results for different regions will be consistent. The statistical approach via an event-based landslide susceptibility model and a probability of failure surface will ensure the consistency of results from different analyses.

A total of 16 river basins and 26 susceptibility models, as well as probability of failure curves, have been built during the period 2007 to 2013. For consistent mapping, a rainfall return-period must be selected. We adopt the 100-year return-period rainfall for the triggering factors and use them in the hazard mapping. A 100-year shallow landslide probability map for the whole of Taiwan (1:50,000 scale and total area 35,873 km^2) is shown in Fig. 4. It shows a consistent hazard level (landslide spatial probability) in the region.

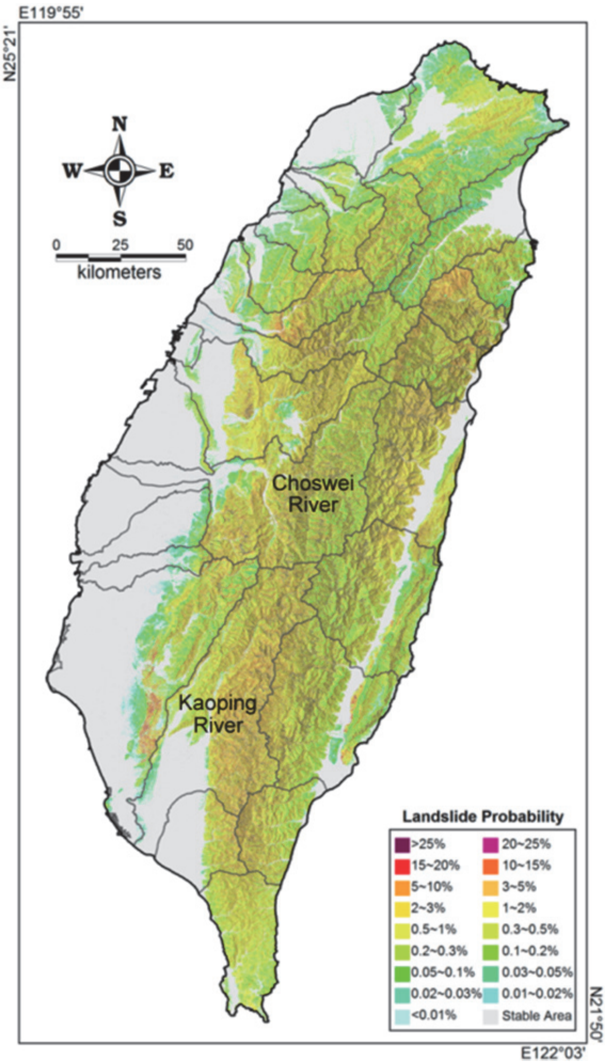

Fig. 4 100-year rainfall landslide hazard map for the whole of Taiwan (modified after Lee and Fei, 2015). Original map scale is 1 to 50,000.

Using similar approach, we also complete a nationwide debris-flow hazard map in the same project. A preliminary deep-seated landslide susceptibility evaluation has also been done, and the deep-seated landslide hazard mapping is actively ongoing. For rockfall hazard, it is partly included in the shallow landslide hazard. But, a separate rockfall hazard study, including run out area, is also ongoing.

4. Concluding Remarks and Perspectives

Statistical approach by a multi-stage of analysis, including an event-based landslide susceptibility analysis, a probability of failure analysis, a rainfall frequency analysis, and a final analysis, is deemed best among the three approaches for landslide hazard analysis (LHA) from the practical point of view.

Susceptibility indices are only relative values in a study area where a model was built. Same susceptibility index from two different models do not mean equal potential for landsliding. They even have no relation with each other. However, a probability of landslide failure (PLF) means a kind of hazard level in LHA. Same PLF at different model means same thing: percentage of failed grid-cells from the total grid-cells in a susceptibility bin. When working over a large region, PLFs from different models are consistent in meaning. Therefore, mapping a large region with multi-models will be consistent in result. No seam or no abrupt change will exist at the boundary of two models.

The term “basic susceptibility” was firstly introduced by Lee et al. (2004), and is mentioned now in this study. This term links up the result of a conventional LSA and an event-based LSA, because their basic susceptibility is similar. The basic susceptibility can be used to build a susceptibility, rainfall and PLF relationship, and forms an empirical PLF equation for a region. This could be used in mapping for a scenario rain event or a return-period rainfall.

To optimize the construction of a basic susceptibility model for a region, mixing two or more rain events to build an event-independent landslide susceptibility model, or using multi-temporal landslide inventory to directly build a basic susceptibility model may be considered. Using a long-period multi-temporal landslide inventory to build a basic susceptibility model for a region is best according to our experiences. Mixing two or more rain events in building a basic susceptibility model is second. Using only one event is OK, if no more data is available. By the way, using multi-event landslide data set is good also for constructing a more general probability of failure surface.

For the statistical approach, there still are some further developments needed to predict landslide magnitude and run-out distance which are very important in risk assessment. This is actively studied by a Ph.D. student in our Institute. The analysis of landslide magnitude is basically slope-unit based.

For the deterministic approach, since the soil depth, strength and hydrological data are the controlling factors; to improve the data quality by multivariate geostatistical method may be necessary. The basic susceptibility model may be used as an auxiliary variable in the multivariate geostatistics for better interpolation.

For the probabilistic approach, a long-period landslide inventory is the control. If data covers long enough time span to cover an active period and a calm period, then the result would be meaningful. The completeness of the multi-temporal landslide inventory is another issue. If the inventory is incomplete, the total duration method cannot be applied. Instead of this, the extreme value method may be considered.

For earthquake-induced landslides, a probabilistic approach is not applicable, because of lacking a multi-temporal landslide inventory. Deterministic approach by using Newmark displacement method (Jibson et al., 2000), and statistical approach with the earthquake intensity as a triggering factor (Lee, 2014) are working well. This deterministic approach has similar problem with the above-mentioned one, both are lacking of soil depth and strength data. The statistical approach is again more promising and perspective.

Acknowledgements

This research was partly supported by the Central Geological Survey, Ministry of Economic Affairs, Taiwan, under the Landslide Research Project. The author is much appreciated to the long-term project support so that everything can be carried out smoothly.

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