Multi-stage Statistical Landslide Hazard Analysis: Earthquake-Induced Landslides

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Abstract

Landslides are secondary or induced features, whose recurrence is controlled by the repetition of triggering events, such as earthquakes or heavy rainfall. This makes seismic landslide hazard analysis more complicated than ordinary seismic hazard analysis and requires multi-stage analysis. First, susceptibility analysis is utilized to divide a region into successive classes. Then, it is necessary to construct the relationship between the probability of landslide failure and earthquake intensity for each susceptibility class, or find the probability of failure surface using the susceptibility value and earthquake intensity as independent variables. Then, hazard analysis for the exceedance probability of earthquake intensity is performed. Finally, an analysis of the spatial probability of landslide failure under a certain return-period earthquake is drawn. This study uses data obtained from the Chi-Chi earthquake-induced landslides as input data set to perform the susceptibility analysis and probability of failure surface analysis. A regular probabilistic seismic hazard analysis is also conducted to map different return-period Arias intensities. Finally, a seismic landslide hazard map is provided.

Keywords

Landslide • Event landslide inventory • Landslide susceptibility • Seismic landslide hazard • Earthquake-induced landslides • Arias intensity

Introduction

Unlike seismic ground motions, landslides are secondary or induced features that can be triggered by an earthquake or a storm. Their recurrence is controlled by the repetition of the triggering events and so, analysis is not as simple as with earthquake occurrence. Therefore, different approaches must be considered, as well as multi-stage analysis.

Seismic landslide hazard analysis, as introduced by Jibson et al. (2000), is actually multi-stage analysis, including Newmark analysis, and probability of failure analysis. Its product is a map showing probability of seismic triggering of landslides given the Northridge-earthquake shaking conditions in part of the Oat Mountain quadrangle. A further study has been made applying the Newmark and probability of failure analysis method in Taiwan where the 475-year earthquake intensity was used to construct a seismic landslide hazard map of the Kuohsing quadrangle (Liao 2004; Liao and Lee 2009).

Lee et al. (2008a) proposed a statistical approach to determine the earthquake-induced landslide susceptibility and probability of landslide failure. This approach is similar to Jibson et al.'s (2000) with only the susceptibility stage being different; the former uses a statistical method and the latter uses a deterministic method. Lee (2013b) made an attempt to construct a 475-year seismic landslide hazard map. This paper used the Chi-Chi earthquake-induced landslide data as the training data set to develop a susceptibility model and a probability of failure curve, and further used a 475-year return-period Arias intensity map to construct a 475-year seismic landslide hazard map for the whole of Taiwan.

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However, this approach has a weak point in that the hazard map may include the probability contributed from causative factors and produces a non-zero probability at zero earthquake intensity. To remedy this problem, a new landslide probability of failure relationship must be further developed.

The present study seeks to improve upon Lee's method (2013b) by developing a probability of failure surface instead of a probability of failure curve. The new relationship should avoid mixing the contribution from causative factors. Using this new probability of failure surface and a 475-year return-period Arias intensity map, a new 475-year seismic landslide hazard map for the whole of Taiwan is constructed. The seismic landslide hazard map might reveal the landslide spatial probability at each pixel given a certain earthquake return-period.

Methodology

Susceptibility Model

Our statistical seismic landslide susceptibility analysis method basically follows Lee et al. (2008a). Effective selection of the landslide causative factors and triggering factors should evaluate: (1) the difference between landslide and non-landslide groups; (2) probability of failure curve of a factor; (3) success rate curve of a factor (Lee 2013a). Effective factors are then tested for normality and independence, and the final selection of factors is made.

The construction of a statistical landslide susceptibility model may be performed using a multivariate statistical method (Carrara 1983; Ayalew and Yamagishi 2005; Eeckhaut et al. 2006; Greco et al. 2007). Discriminate analysis was selected in Lee et al. (2008a) to build their susceptibility model with causative factors, triggering factor and an event-based landslide inventory. However, in routine analysis of landslide susceptibility for many different drainage basins in Taiwan in recent years (e.g., Lee and Fei 2011), it has been found that logistic regression is better for three reasons: (1) the shape and concentration of data points in the probability of failure curve are always better when the logistic regression method is used; (2) logistic variables can be used in the logistic regression for categorical data, like the lithology and slope aspects; and (3) although normality is also required in logistic regression, it is not as serious as in discriminate analysis (Lee 2013b). Therefore, the logistic regression method is adopted in the present study.

Probability of Failure Surface

The construction of a probability of failure curve for the susceptibility values is simple: simply plot the mean probability of failure value at each susceptibility bin and fit a curve. A probability of failure surface is intended to show relationship between the probability of failure and Arias intensity at each susceptibility bin, and to obtain the fit to the surface using the Arias intensity and susceptibility as two independent variables. Note that the susceptibility values used here indicate the event-independent susceptibility without a triggering factor.

A landslide spatial probability map may be produced by transferring the event-independent susceptibility values and Arias intensities to the probability of failure by using a probability of failure surface. When Arias intensities from the training event are used, one can produce a hazard map that reflects the earthquake event. The use of the Arias intensities for a specific earthquake scenario, produces a hazard map that reflects the scenario earthquake.

Temporal Probability of Landslides

Since seismic landslides are induced by earthquakes, their recurrence is controlled by the repetition of the earthquake event. Therefore, we must know the likelihood of earthquake recurrence or the annual exceedance probability of earthquake ground motions. This may be obtained through regular probabilistic seismic hazard analysis (PSHA) (Wong et al. 2004) with a set of fault source models in addition to the regional source models (Cheng et al. 2007) and a proper set of Arias intensity attenuation equations (Lee et al. 2012).

An Arias intensity map for a certain level of exceedance probability or return period for earthquakes is the objective of the PSHA, and this comprises the input data for the seismic landslide hazard mapping. This is commonly a 475-year return period or 10 % exceedance in 50 years. However, there may be other choices of return period or exceedance probability, like a 950-year return period or a 10 % exceedance in 100 years. If the Arias intensities of a 475-year earthquake are used, the hazard map reflects the 475-year earthquake, and may be called a 475-year seismic landslide hazard map.

Both for establishing a susceptibility model and in hazard mapping, the Arias intensity should be topographically corrected. The present study uses the empirical formula proposed by Lee et al. (2008a) for topographic correction of the Arias intensity.

Data

Basic Data

The basic data used in the present study include: 10 m high resolution SPOT images, a 5-m grid digital elevation model (DEM), 1/5,000 photo-based contour maps, 1:50,000 geologic maps, and earthquake strong-motion records. Digital geological maps (1:50,000) were obtained from the Central Geological Survey, Taiwan. All the vector layers were converted into raster cells of 20 m × 20 m in size and this resolution was used for all subsequent processing and analysis for each landslide factor and the hazard model.

Chi-Chi Landslide Inventory

False-color SPOT images were used for landslide recognition. Landslides were recognized and digitized in GIS and attributes assigned to establish a landslide map table. Each landslide table was then checked in the field and modification was made. An event-triggered landslide was identified by comparing the pre-event and post-event landslide inventories, to produce an event-based landslide inventory. The Chi-Chi earthquake event-based landslide inventory is shown in Fig. 1. For a detailed description of the new Chi-Chi landslide inventory, please refer to Lee (2013a).

Results

Event-Based Susceptibility Model

The Chi-Chi earthquake induced shallow landslides (Fig. 1) and Arias intensities were actually used in the susceptibility analysis. Due to the fact that an event landslide inventory and a triggering factor of the event are used in the development of the susceptibility model, this is called an event-based susceptibility model (Lee et al. 2008a, b).

Causative factors used in the susceptibility model include the following: slope gradient, slope aspect, terrain roughness, slope roughness, total curvature, total slope height, and lithology. For a detailed description of the causative factors and the triggering factor, please refer to Lee (2013a).

Logistic regression is used in the susceptibility analysis and the results of this analysis include a logistical function and the coefficients,

$$\ln\left[\frac{p}{1-p}\right] = \begin{array}{l} 0.089L_1 + 0.259L_2 - 0.538L_3 + 0.550L_4 - \\ 0.067L_5 - 1.179L_6 - 0.435A_1 - 0.172A_2 + \\ 0.209A_3 + 0.288A_4 + 0.345A_5 - 0.339A_7 - \\ 0.715A_8 + 1.068F_1 + 0.184F_2 + 0.137F_3 + \\ 0.827F_4 + 0.234F_5 + 1.220F_6 - 2.331. \end{array} \quad (1)$$

where L_1–L_7 are lithological units; F_1–F_5 are causative factors; F_6 is a triggering factor; and p is the occurrence probability. During the establishment of the logistic equations, the input p is 1 for a landslide grid and 0 for a

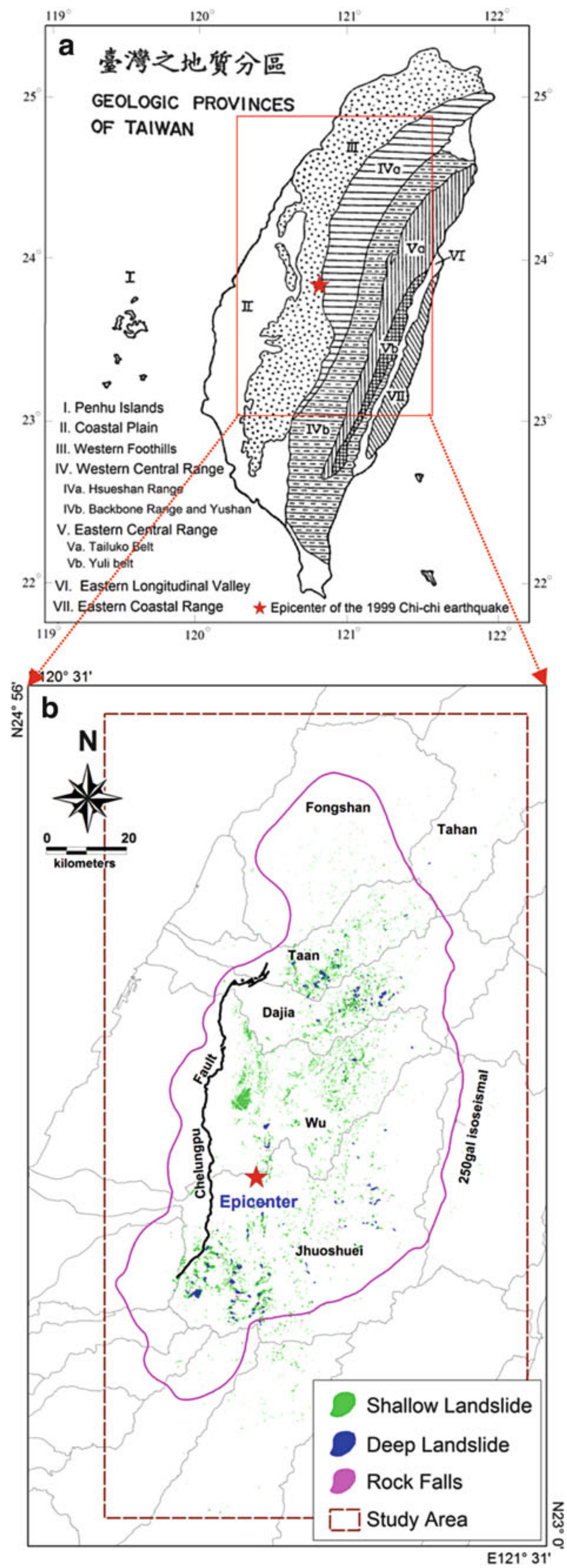

Fig. 1 Landslides triggered by the 1999 Chi-Chi earthquake: (**a**) index map showing the geology of Taiwan; (**b**) landslide distribution (the *red star* indicates the epicenter of the Chi-Chi earthquake)

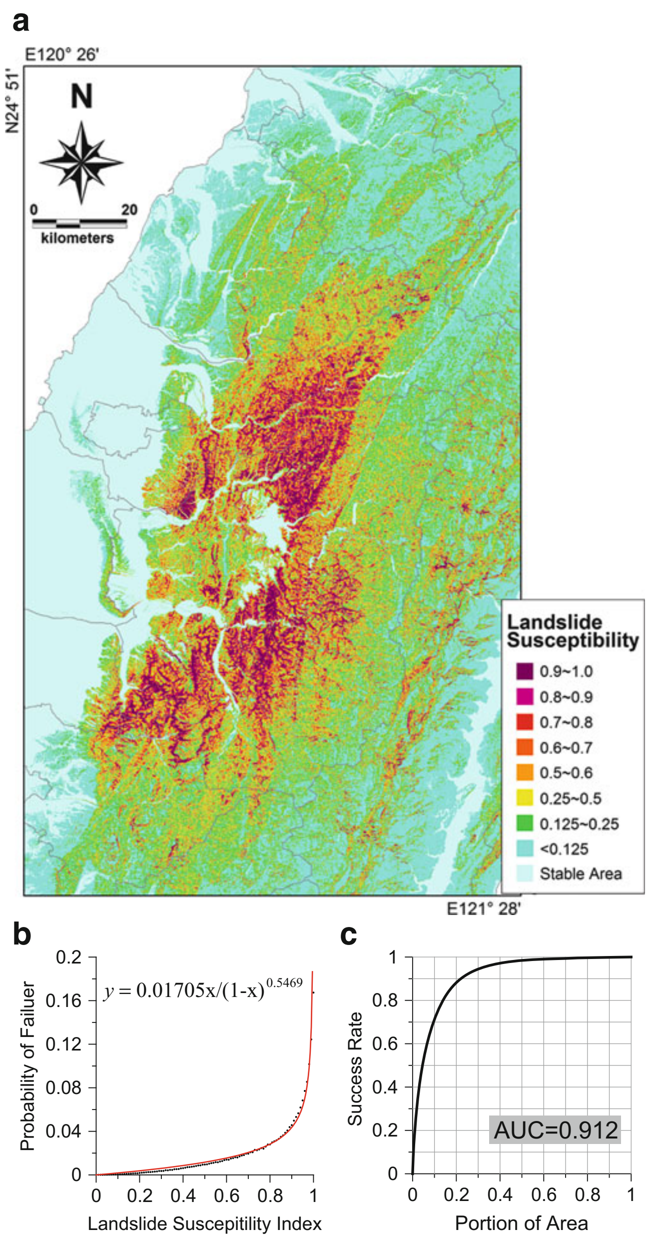

Fig. 2 Susceptibility model for Chi-Chi earthquake-induced landslides: (**a**) event-dependent landslide susceptibility map; (**b**) probability of *failure curve*; and (**c**) *success rate curve*

non-landslide grid. After the regression, when the set of factors is given a score at a grid point, the occurrence probability p at that point is derived. It will be in the range of 0–1. This occurrence probability is taken as a susceptibility index λ in this study. Larger values of an index indicate a higher susceptibility to landslides.

The event-based susceptibility model (Fig. 2) explains the event-induced landslide distribution. The probability of failure curve shows a good fit to the x/(1−x) function (Fig. 2b). The area under the curve (AUC) of the success rate curve can be as high as 0.912 (Fig. 2c). The model is further validated utilizing the Rueili earthquake event landslide inventory (Huang 1999) and Arias intensities; the AUC of the prediction rate curve is 0.769 for the model.

Event Independent Susceptibility Model

The event-based susceptibility model is dependent on the event itself. However, if we extract the triggering factor from the model, then the model becomes event independent, provided that the triggering factor is an independent factor having only small correlation coefficient with any causative factors. This option must be carefully examined before a causative factor is selected.

In this case, the event-based susceptibility model is reduced to an event-independent model by removing the component of the triggering factor from the original model. Here, we call this reduced model an event-independent susceptibility model for the region. Different event-independent susceptibility models for the same region have been compared and good similarity has been found among them (Lee et al. 2004). On this basis, we can use an event-independent susceptibility model to represent the susceptibility of the region with confidence.

Probability of Failure Surface

Starting with testing the relationship between probability of failure and Arias intensity at each event-independent susceptibility bin, it was found that the relation is good; the probability of failure increases with an increase in the Arias intensity and also with an increase in the susceptibility (Fig. 3a). After this finding, it was necessary to find a global fitting surface using the Arias intensity and event-independent susceptibility as two independent variables. The result is shown in Fig. 3b and Eq. (2) as follows:

$$y = 50.316\lambda\left(1 - e^{-12.620\lambda^{1.021}}\right)\left(1 - e^{-0.026x^{2.232}}\right) \quad (2)$$

where x is the corrected Arias intensity; y is the probability of failure, and λ is the event-independent susceptibility.

Arias Intensity from PSHA

The temporal probability of a seismic landslide hazard model may be accounted for by a triggering factor—namely the hazard level of the Arias intensity in the present study. This may be obtained through conducting a regular PSHA (Wong et al. 2004) with a proper set of earthquake source models and Arias intensity attenuation equations.

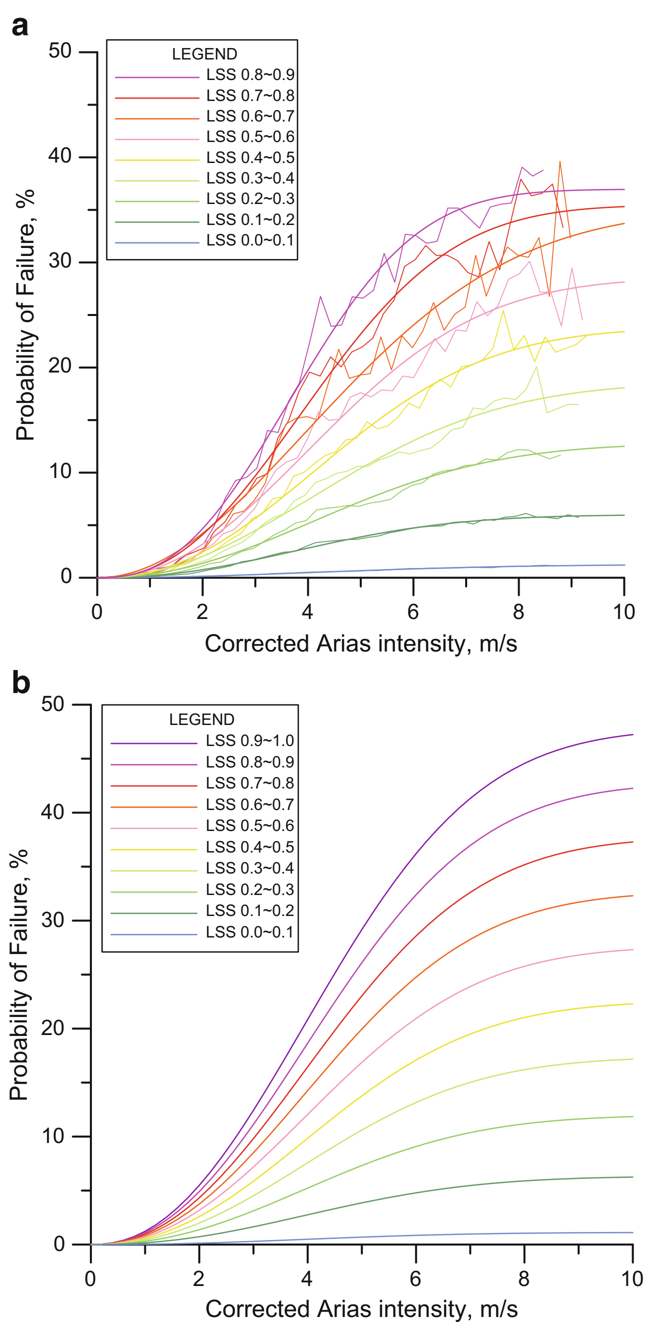

Fig. 3 Probability of failure surface: (**a**) probability of *failure curve* at each event-independent susceptibility bin with data and local fit; (**b**) fit of probability of failure surface, equation shown in the text

I and my students have made efforts to build a modern Taiwan seismic hazard model since the year 2002 (Cheng 2002). This model includes traditional regional sources and model fault sources. In the model, the fault parameters and slip rate for each of the 48 active fault sources are evaluated (Lee 1999; Cheng 2002). Subduction zone interface and intraslab sources are also considered.

The seismic hazard model of Taiwan (Cheng 2002; Cheng et al. 2007) and a new Arias intensity attenuation relationship (Lee et al. 2012) are used in performing the PSHA, to obtain the different levels of exceedance probabilities as well as return periods for Arias intensity for each grid cell in the study region. The attenuation equations used include the relationships for crustal earthquakes, subduction zone interface earthquakes and intraslab earthquakes (Lee et al. 2012; Hsieh 2008).

Both in establishing a susceptibility model and in hazard mapping, the Arias intensity should be topographically corrected. The empirical formula proposed by Lee et al. (2008a) is used for topographic correction of the Arias intensity in the present study.

Seismic Landslide Hazard Map

The event-independent susceptibility model and the probability failure surface together with an Arias intensity map may be used to construct a seismic hazard map. It is capable of landslide prediction during a scenario earthquake event, provided that the earthquake intensity is known for each study grid cell. However, for hazard mapping, a certain temporal probability or return period for earthquake intensity should be adopted. This is commonly a 475-year return period or 10 % exceedance in 50 years. Other choices of return period or exceedance probability, like a 950-year return period or a 10 % exceedance in 100 years, may also be used.

The 475-year topographically corrected Arias intensity map and the event independent susceptibility model are then applied to the probability of failure model to construct a 475-year seismic landslide hazard map for the whole of Taiwan (Fig. 4).

Conclusion and Recommendation

A multivariate statistical approach with logistic regression has been used to analyse the Chi-Chi earthquake-induced shallow landslides and their controlling factors, and to build an event-dependent susceptibility model. The event-independent model (without a triggering factor), the topographically corrected Arias intensity map, and the actual landslides from the Chi-Chi event, are used to construct a relationship, using the event-independent susceptibility and corrected Arias intensity as independent variables, and is fitted with a probability of failure surface. Then, a 475-year corrected Arias intensity map with the event-independent susceptibility model are input

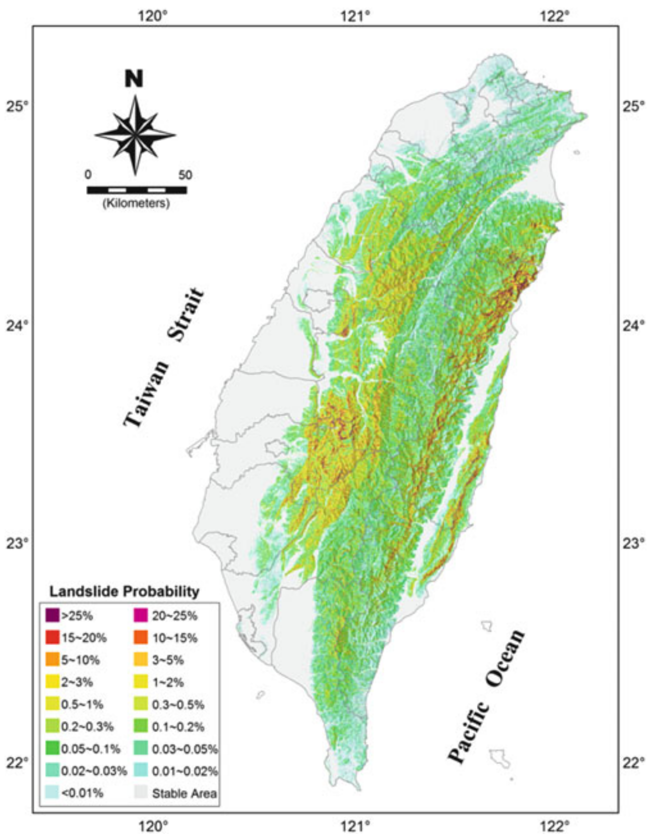

Fig. 4 475-Year seismic landslide hazard map for the whole of Taiwan

into the probability of failure relationship to complete a 475-year seismic landslide hazard map for the whole of Taiwan. The results of the analysis are good, provided that careful validation of the Rueili earthquake-induced landslides is made. We conclude that this statistical approach is feasible for seismic landslide hazard analysis, and that the hazard model can be used to predict landslides after a major earthquake and can be used to produce a seismic landslide hazard map of a wider region.

The statistical approach to seismic landslide hazard has advantages over deterministic methods in that it does not require failure depth, material strength, or groundwater data, and may have a better prediction rate. On the other hand, a deterministic model can be used anywhere once the parameters required by the model are available. The statistical approach, in contrast, may be applicable only in the vicinity of the study region where the model was trained, and may be limited to within or near the earthquake intensity range for which they were trained.

The present proposed hazard model is good for the prediction of landslide spatial probability during an earthquake event, the mapping of the seismic landslide hazard probability for a certain return-period earthquake, decision making for regional planning, site selection, hazard mitigation, and the estimation of sediment products for a drainage basin after an extreme event. However there is still a lack of output in regards to the landslide magnitude which is very important in risk assessment. This problem needs further study.

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