Probabilistic modelling of landslide frequency due to coalescence of earthquake and rainfall events

Modélisation probabiliste de la fréquence des glissements de terrain due à la coalescence des séismes et des précipitations

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ABSTRACT: Although landslides induced by the interaction of rainfall and earthquake have been documented in the literature. Hazard assessment of such landslides is commonly not undertaken at present since the effects of different triggering factors are usually analysed individually and managed separately. In this paper, a procedural method has been developed which can assess the landslide frequency due to single hazardous events as well as consider the existence of an interaction between the events and their potential consequences. Landsliding is related to the frequency characteristics of rainfall loads and earthquake events.

RÉSUMÉ : Bien que les glissements de terrain induits par l'interaction des précipitations et des tremblements de terre aient été documentés dans la littérature. L'évaluation des risques de tels glissements de terrain n'est généralement pas entreprise à l'heure actuelle, car les effets de différents facteurs déclenchants sont généralement analysés individuellement et gérés séparément. Dans cet article, une méthode procédurale a été développée qui permet d'évaluer la fréquence des glissements de terrain dus à des événements dangereux uniques ainsi que de considérer l'existence d'une interaction entre les événements et leurs conséquences potentielles. Les glissements de terrain sont liés aux caractéristiques de fréquence des charges de pluie et des événements sismiques.

KEYWORDS: landslides, rainfall, earthquake, probability

1 INTRODUCTION

Landslide hazard is the probability of damaging phenomenon occurrence within a specified period in a given area (Varnes 1984). It has been observed that majority of the methods for landslide hazard assessment only identify the areas susceptible to landslides ("where") and does not provide the information on "when" landslides can occur (Zhou et al. 2018; Wang et al. 2020). However, the time horizon of landslide occurrences plays a crucial role in the landslide risk management. Hence, the estimation of temporal probability becomes essential.

Poisson model is employed to estimate the temporal probability of landslides (Crovelli 2000). The probability of h landslides occurrence during time t is given by:

$$P(H(t)=h)=\exp(-\lambda\, t)\,\frac{(\lambda t)^h}{h!}\qquad h=0,1,2,3\,.... \tag{1}$$

Where λ is the rate/frequency of landslide occurrence. In the literature, frequency of rainfall and earthquake-induced landslides are estimated using different approaches (Caccavale et al. 2017; Bojadjieva et al. 2018). The use of different procedures and reference units is a major setback in the case of frequency estimation of landslides which could occur as a result rainfall and earthquake events occurring simultaneously or one after the other. Studies conducted by Zhang et al. (2014) and Chian and Wilkinson (2015) have reported the occurrence of numerous landslides due to the interaction of rainfall and earthquake events. Sassa (2005) underscored the fact that the consideration of multiple triggering factors and their potential mutual interactions is a necessity for landslide risk reduction. Therefore, the main objective of this study is to propose an approach for hazard assessment of landslides induced by the interaction of rainfall and earthquake events.

2 METHODOLOGY

The study area is geographically located in the north-eastern state of Arunachal Pradesh in India (Figure 1). The area is located near the famous Tawang Monastery. The landslide complex has a long history of slope instability problems which dates back to the 1990s. Based on the multiple field surveys and reports from local agencies, landslides were reported on September 1996, July 2010, November 2010 and September 2012.

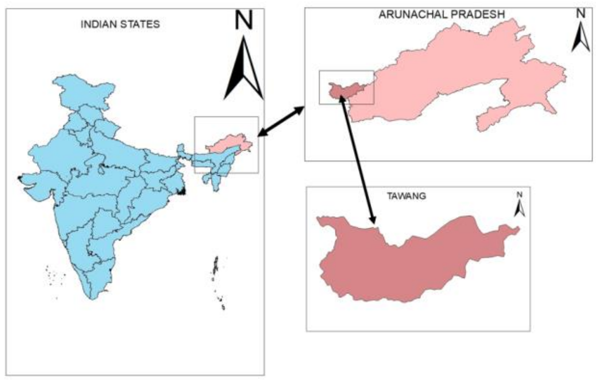

Figure 1. Study area

To estimate the temporal probability of landslides, it is important to establish the relationship between triggering factors and the incidence of landslides. In this context, Forecasting of Landslides Induced by Rainfall (FLaIR) model is employed to relate landslide occurrences with rainfall events (De Luca and Versace 2016). A model similar to the FLaIR model is developed to account for the effects of earthquake loads and is termed as FLaIE (Forecasting of Landslides Induced by Earthquake). FLaIR/FLaIE model establishes the critical threshold for landslide which provides an estimate of the probability of occurrence of rainfall/earthquake events that can trigger landslides. Consequently, the frequency of landslide triggering rainfall and earthquake events are correlated with the frequency of landslide events.

2.1 *Critical threshold*

FLaIR/FLaIE model links the rainfall/earthquake loads to landsliding. The model accomplishes this by performing convolution between transfer function and rainfall intensity/arias intensity which yields the slope mobility function {F(t)}.

$$F(t) = \int_0^t \Psi(t-\tau)\, R(\tau)\, d\tau \quad (2)$$

Where R(t) is rainfall intensity/arias intensity and Ψ(t) is the transfer function. F(t) has the same units as R(t). Slope mobility function is related to landslide occurrence via the equation presented below:

$$P(L_t) = 0 \quad if \;\; F(t) < F_c \quad (3)$$

$$1 \; if \; F(t) \geq F_c \quad (4)$$

Where Fc is the critical mobility function. Exceeding this value indicates mobilisation of a landslide. But for F(t) values less than Fc, the probability of landslide is null. The model needs calibration for selecting the right transfer function and validation of the model is required to ensure its successful application in the study area.

2.2 *Temporal probability of landslides*

As rainstorms or earthquakes capable of triggering landslides occur at random times and cause landsliding, the frequency analysis of triggering rainfall and earthquake events will lead to the estimation of landslide frequency. The proposed method relates the landslide occurrence frequency with the frequency of those rainstorm or earthquake events that can trigger landslides in the study area. Landslides are assumed to occur as a Poisson process. Hence, the inter-arrival time between consecutive landslide events will be an exponentially distributed random variable (Wu and Swanston 1980). The inter-arrival time (τ) or return period is the difference between times of successive landslide events, such that for a sequence ti (i= 1,2,3…), the return period is given by τ = ti+1 – ti where ti and ti+1 are the times at which landslides occur. The probability distribution function of τ is given by:

$$p(\tau) = \lambda \exp(-\lambda \tau) \quad (5)$$

Where λ is the rate of landslide occurrence or the reciprocal of the mean landslide return period. With the rate of landslide occurrence estimated, the exceedance probability of experiencing landslides in the study area in a given time interval can be evaluated using the following equation:

$$P(H(t) \geq 1) = 1 - \exp(-\lambda t) \quad (6)$$

3 APPLICATION TO THE STUDY AREA

FLaIR/FLaIE model is calibrated to identify the type of transfer function suitable for the landslide complex. The Gamma type transfer function is selected and is given by:

$$\psi(t) = \frac{t^{\alpha-1}\exp(-\frac{t}{\beta})}{\beta^{\alpha}\,\Gamma(\alpha)} \quad (7)$$

Where α is a dimensionless parameter which indicates the delay in the system response pertaining to loads and β (day) describes the temporal extent. α = 1 and β = 15 days has been identified for rainfall case while α = 10-6 and β = 350 days for earthquake case. For calibrating the model, rainfall data and sequence of earthquake events during the period 2010 to 2012 are used. Figures 2(a) and 3(a) show the Ψ(t). Slope mobility function is evaluated by performing convolution between rainfall/earthquake time series and Ψ(t). Figures 2(b) and 3(b) present the slope mobility function from 2010 to 2012.

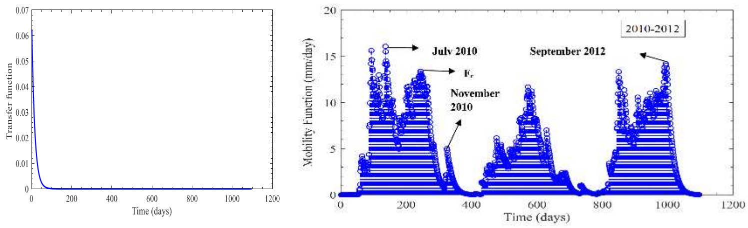

Figure 2. 2(a) Transfer function 2(b) Mobility function induced by rainfall.

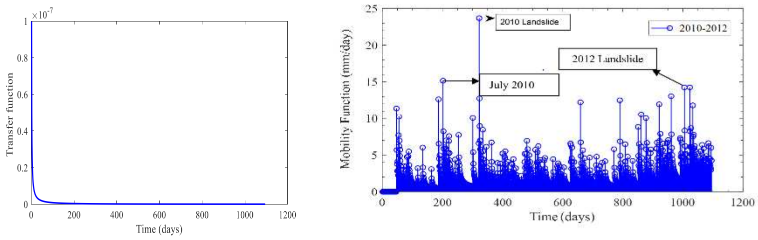

Figure 3. 3(a) Transfer function 3(b) Mobility function due to earthquake.

The critical mobility function is identified as Fc = 12.84 mm/day. The results derived from FLaIR and FLaIE models highlight that the November 2010 landslide was earthquake-induced landslide. However, it is noted that at the time of July 2010 and September 2012 landslides, the critical value was exceeded under rainfall as well as seismic conditions. This implies that these landslides occurred when several independent events such as rainfall and earthquake occurred at around the same time and caused landslide. Hence, the July 2010 and September 2012 landslides occurred due to multiple triggering factors.

3.1 *Critical rainfall and earthquake threshold*

The combinations of rainfall intensity (I) and duration (D) which result in the critical value of mobility function are identified. A Power law is used to model the relationship between I and D and the rainfall threshold is given by:

$$I = 43.5\, D^{-0.368} \quad (8)$$

Where I is in mm/day and D is in days. The critical threshold for seismic event is arias intensity nearly 1.3 m/sec. This implies that the earthquake events with arias intensity greater than 1.3 m/sec are capable of triggering landslides in the study area.

3.2 *Temporal probability of landslides induced by the interaction between rainfall and earthquake*

Landslides occurrence due to the unfortunate combination of rainfall and earthquake is not uncommon in the study area. It is evident from the cases of landslides in July 2010 and September 2012. The landslides occurred when the conditions of criticality were satisfied for both rainfall and earthquake case individually, and the time frame for their potential interaction is within 15 days. Due to the random nature of landslides, the occurrence of landslides is modelled as a Poisson Process.

The algorithm adopted for evaluating the rate of landslide occurrence, in this case, is presented below:

1) Set a time step t
2) Identify rainfall events which lie above the critical rainfall threshold.
3) Evaluate the return period of rainfall event.

4) Select the earthquake events which yield arias intensity greater than 1.3 m/sec.
5) Probability of landslide triggering rainfall event occurring in the current year is evaluated, ζΔt.
6) The occurrence probability of landslide triggering earthquake event in the current year, ϕΔt is determined.
7) Generate a uniform random variable.
8) If the values ζΔt and ϕΔt are greater than the random number generated, landslide triggering rainfall and earthquake event will occur in the current year.
9) Since the time window for potential landslide occurrence, in this case, is 15 days. The probability that the triggering earthquake event occurs within 15 days of the occurrence of triggering rainfall event can be estimated using conditional probability concepts. Let E and R denote the earthquake and rainfall events respectively. Based on conditional probability rule, the probability that the triggering earthquake event will occur given that triggering rainfall event has occurred is given by:

$$P(E|R) = \frac{P(E \cap R)}{P(R)} \quad (9)$$

Where P(R) is the probability that triggering rainf all event occurs and P(E∩R) is the probability th at triggering rainfall and earthquake events occur within 15 days. If the value of P(E│R) is greater than the random number generated in step (8), a landslide occurs due to multiple factors.
10) The inter-arrival time between consecutive landsli de events is determined.
11) Proceed to next time step t = t+Δt.

Figure 4 shows the PDF of the return period of landslides due to multiple factors. Figure 5 presents the temporal probability of landslides induced by the coalescence of rainfall and earthquake at different exposure time.

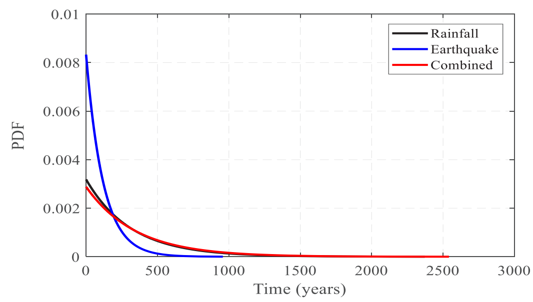

Figure 4. Probability distribution function (PDF)

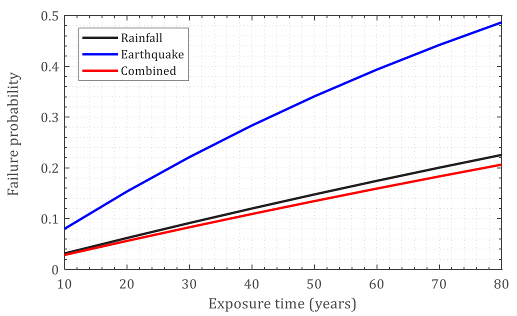

Figure 5. Temporal probability of landslides at different exposure time.

It is observed that the PDF of landslides due to multiple factors is very similar to that of rainfall-induced landslides. This is because triggering earthquake events occur more frequently than triggering rainfall events, so landslides due to multiple factors can only occur when the occurrence of triggering earthquake events coincides with the occurrence of triggering rainfall events. Hence, the proposed method is capable of estimating the rate of occurrences due to different factors and provides an approach for a comprehensive landslide hazard assessment.

4 CONCLUSIONS

This study estimated the rate of landslide occurrence due to multiple triggering factors by associating landslide frequency with the recurrence interval of rainstorm and earthquake events capable of triggering landslides. The FLaIR and FLaIE models predict landslide movements through mobility function. For the case study considered, the models are effective in predicting landslides. Critical thresholds are developed for rainfall as well as seismic loading conditions. The threshold assists in estimating the frequency of landslide triggering rainfall and earthquake events. With the frequency of triggering rainfall and earthquake events known, an algorithm is developed to compute rate of landslide occurrence. PDF of landslide return period is generated by assuming that the landslide events are random point events and follow the Poisson process.The method is applied to a study area located in the North-Eastern region of India. It may be worth noting that the method can be applied to any region around the world by identifying appropriate mathematical model to relate landslide events with triggering factors.

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