A Conceptual Event-Tree Model for Coseismic Landslide Dam Hazard Assessment

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Abstract

Earthquakes may trigger a series of multiple cascading geohazard phenomena. For example, coseismic landslides may block rivers and form landslide dams, which occur frequently in tectonically active mountains with narrow and steep valleys. The catastrophic release of water masses from landslide-impounded lakes is capable to produce outburst floods and debris flows, causing loss of lives, housing and infrastructure. Quantifying the probability of these cascading phenomena following a triggering event has been a main research challenge. This study creates a conceptual event tree model for hazard assessment of earthquake-induced landslide dams, with the involvement of many discussions amongst specialists in different fields. Event tree (ET) is a graphical, hierarchical and tree-like representation of possible events, which has been successfully applied in the volcano hazard assessment, but the application in landslide research is rather limited. We attempt to elaborate the event tree model by applying it in estimating the hazard of landslide dams induced by the Wenchuan earthquake. The model starts from a scenario-earthquake on a known possible active faults; the model then progressively assesses the susceptibility to coseismic landslides and landslide dams, and, finally, provides an estimate of dam-break flood hazard. According to the literature and our best understanding of the seismic hazard, we suggested or proposed possible methods to estimate the probabilities at successive nodes, the cascading events.

Keywords

Wenchuan earthquake • Event-tree model • Landside dam • Hazard assessment

Introduction

On May 12, 2008, a devastating earthquake of magnitude M_w 7.9 hit China's Sichuan province. The quake, originating in the Longmen Shan fault zone at the eastern margin of Tibetan Plateau, was the country's largest seismic event in more than 50 years. In addition to the immediate devastation through shaking, the earthquake triggered more than 60,000 destructive landslides (Görüm et al. 2011) over an area of 35,000 km^2; the landslides caused about one-third of the total number of fatalities. More than 800 landslides during the earthquake blocked rivers, and thus produced numerous quake lakes that posed a serious threat to people downstream (Fan et al. 2012a, b).

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K. Sassa et al. (eds.), *Landslide Science for a Safer Geoenvironment*, Vol. 3,
DOI 10.1007/978-3-319-04996-0_93, © Springer International Publishing Switzerland 2014

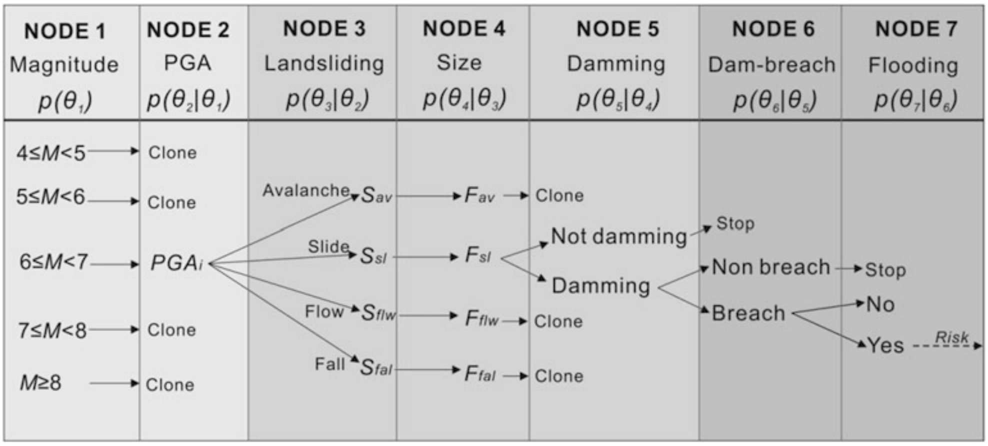

Fig. 1 A conceptual event tree scheme for the earthquake-triggered geohazards. The seven steps of estimation progress from general to more specific events, which are explained in the text. Note that any branch that terminates with "Clone" is identical to the subsequent central branch. For example, at NODE 1, the other magnitude bins are identical to the central $6 \leq M < 7$ branch. At NODE 2, the PGA stands for the peak ground acceleration that is commonly used to represent amplitude of ground shaking. At NODE 3, the S_{av}-S_{fal} represents the spatial probability (susceptibility) of different types of landslides ($_{av}$ = avalanche, $_{sl}$ = slide, $_{flw}$ = flow, $_{fal}$ = fall types) given specified seismic source parameters (i.e. magnitude, fault type and length, PGA etc). At NODE 4, the F_{av}-F_{fal} means the size-frequency distribution of different types of landslides

It is well known that earthquakes may trigger a series of multiple cascading geohazard phenomena. Quantifying the probability of these cascading phenomena following a triggering event is an important research challenge. Event trees (ET) are recognized as a useful framework for discussing, from a probabilistic point of view, all the possible outcomes of adverse events (Newhall and Hoblitt 2002). Basically, an ET is a graphical, hierarchical and tree-like representation of possible events in which branches are logical steps from a general prior event through increasingly specific subsequent events (intermediate outcomes) to final outcomes. In this way, an event tree shows the most relevant possible outcomes produced by the interactions among different hazardous events, i.e. cascading effects.

Marzocchi et al. (2004) developed the Bayesian event tree (BET) based on the event tree scheme created by Newhall and Hoblitt (2002), because the Bayesian approach can estimate the uncertainty and determine the posterior probability on the basis of a prior probability distribution. BET is regarded as a flexible tool to quantify the probabilities of any specific series of events, by combining all the relevant available information such as theoretical models, empirical and deterministic models, prior knowledge and beliefs, monitoring data and any kind of historical data. This method has been well developed and widely applied in the short- and long-term volcanic hazard assessment (i.e. Marzocchi et al. 2010). However, few studies have been done on applying the event tree approach in landslide hazard assessment (i.e. Wong et al. 1997), let alone the application in seismically triggered geohazards.

A Conceptual Event-Tree Model for the Coseismic Landslide Dam Break Flood Assessment

A conceptual ET model for the earthquake-triggered hazard sequence was constructed, after many discussions with specialists in different fields (Fig. 1). A conditional probability, written in the form of $p(\theta_n|\theta_{n-1})$, is the probability of event n given that event $(n-1)$ has occurred. As defined by Newhall and Hoblitt (2002), the probability of any outcome, $p(\theta_n)$, is the product of the probability of an initial event, $p(\theta_1)$, and all further conditional probabilities, as shown in Eq. (1). The possible events at each node do not need to be mutually exclusive or exhaustive.

$$p(\theta_n) = p(\theta_1) \cdot p(\theta_2|\theta_1) \cdot p(\theta_3|\theta_2) \cdot \ldots \cdot p(\theta_n|\theta_{n-1}) \quad (1)$$

In the conceptual ET model, we define the probability for the subsequent outcomes at each node as follows:

$p(\theta_1)$ Probability that a given magnitude earthquake will be triggered by known active faults (seismogenic zones) in a region of interest;

$p(\theta_2|\theta_1)$ Probability that, given seismic source parameters (i.e. magnitude, distance to seismic source, fault type, geometry etc.) and site-specific parameters, the peak ground acceleration (PGA) in a certain area will reach a specified value;

$p(\theta_3|\theta_2)$ Probability that, given above seismic source parameters and ground motions, landslides with a specified type will happen in a certain area;

$p(\theta_4|\theta_3)$ Probability that, given the certain type of landslide occurrence, it will be of a specified size (in terms of landslide area or volume);

$p(\theta_5|\theta_4)$ Probability that, given a specified landslide size and type, the landslide will reach and block a river with a certain width, forming a landslide dam;

$p(\theta_6|\theta_5)$ Probability that, given a landslide dam formation, it will break;

$p(\theta_7|\theta_6)$ Probability that, given the dam breach, it will cause flooding to the exposures at downstream.

The ET starts from an assumed earthquake from known possible seismogenic faults, progressively develops to more specific levels, therefore it can also be called a scenario-based ET. Note that NODE 1 focuses on different known active fault zones (the seismic sources on which future earthquakes are likely to occur); NODE 2 is about ground motion variation in a region, which can be terrain or geological-unit based considering the site amplification effects; NODE 3 estimates the spatial probability (susceptibility) of coseismic landslides, which are normally grid-based; NODE 4 and 5 are specific for each potential landslide site; NODE 6 is then focusing on individual landslide dams; and NODE 7 is different for each area downstream of a potential dam site. NODE 2, 3 and 7 are spatial maps with probabilities, while the probability of the other nodes can be estimated as a single value. The ET can be extended for risk assessment by adding some nodes at the right side of NODE 7, for example, the probability that there will be exposed individuals or buildings given a specified flooding area; the probability that, given a certain type of elements at risk, the degree of damage (vulnerability) will reach a certain value; and the probability that losses will be caused by a specified flood.

General Illustration of the Event-Tree Model

At **NODE 1**, the different earthquake magnitude bins are determined based on the classification of NEIC (National Earthquake Information Center). The earthquakes with the magnitude lower than 4 are not considered, since these hardly triggered any catastrophic landslides according to the review on earthquake-induced landslides by Keefer (2002). $p(\theta_1)$, the magnitude recurrence probability can be estimated by a statistical model, the Gutenberg-Richter magnitude-frequency power-law, using historic earthquake catalog of the known active fault zone.

NODE 2 is the probability of reaching a certain PGA level given specified seismic source parameters and site-specific parameters of a certain area. The intensity and duration of earthquake induced ground shaking at a site is a function of three main factors: earthquake source, medium of propagation as well as physical and geotechnical characteristics of the site denoted as site effects (Kramer 1996; Shafique et al. 2011). The commonly used method for estimating ground motion is a simplified empirical attenuation models based on strong motion data.

NODE 3 is actually the susceptibility assessment of coseismic landslides of a certain type, which can be defined as a function of relevant spatial factors (i.e. seismic, geological, topographic and hydrological factors)

$$S = f\left(L \middle| X_1, \ldots\ldots X_n\right) \tag{2}$$

Equation (2) expresses the joint conditional probability that a given region will be affected by future landslides of a certain type given the n variables $X_1, X_2 \ldots X_n$ in the same region. There are a variety of methods available for landslide susceptibility assessment, including heuristic, deterministic and statistical approaches (see van Westen et al. 2008 for an overview).

NODE 4 is the size probability of a certain type of coseismic landslides. The exact size of landslides is not possible to be predicted beforehand, due to the intrinsic complexity of landslide failure mechanisms, site-specific geomorphology, geological and tectonic setting. In case that there are available landslide inventories or an event-based inventory, the landslide size probability can be assessed by a magnitude (size)-frequency analysis. The landslide size can be fitted to various statistic distributions as reviewed by van den Eeckhaut et al. (2007).

NODE 5 is the probability that a landslide of a certain type and size from a specific area can dam a river with a certain width. This can be solved by the empirical model, together with the landslide susceptibility assessment at NODE 3 and size-frequency distribution at NODE 4. The dam-formation threshold volume for a certain type of landslides was determined based on the empirical runout model as well as the correlation between river width and required damming volume, which allows a landslide to reach and block a river with a certain width.

NODE 6 is the dam-break probability. This node relates to the stability of landslide dams, which is a function of their geometry, internal structure, material properties, lake volume, inflow rate, and seepage processes (Costa and Schuster 1988; Korup and Tweed 2007). We tried to link the landslides and the consequent dam typology to the dam stability (Fan 2013). It is believed that the dams composed by large boulders or almost intact rock strata are more stable than those composed by unconsolidated fine debris.

NODE 7 is the dam-break flood probability. This node requires dynamic hydraulic modelling to estimate the spatial variation of flood parameters. The dam-break flood probability is controlled by the discharge capacity of the river that flows into the dammed lake and the probable flood parameters (flood peak discharge, depth, velocity and duration) that are determined by the lake volume, dam-breach process and downstream terrain. The flood parameters can be estimated by physically–based numerical models and GIS-based hydraulic models as discussed in Fan et al. (2012c).

At the regional scale or in an emergency situation, the NODE 6 and 7 can be combined and simplified in order to rapidly assess the potential hazard of landslide dams.

Discussion

This study presents a basic framework, the “Event Tree Model”, to assess the multi-hazard associated with a high-magnitude earthquake. This approach has been successfully applied in volcanic hazard assessment, but the application in earthquake-induced landslide research still needs to be tested in more regions. Future research is directed towards the improvement of the shortcomings of this method (that lacks a spatial capability), and better illustrating the model by giving a calculation example. Such a model needs to be integrated with GISs to cope with data with dynamical position and attributes. In addition, further effort is needed to assign conditional probabilities, with their confidence boundaries, to each of the primary and secondary branches (nodes).

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