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Susceptibility assessment of earthquake-triggered landslides in El Salvador using logistic regression

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Abstract

This work has evaluated the probability of earthquake-triggered landslide occurrence in the whole of El Salvador, with a Geographic Information System (GIS) and a logistic regression model. Slope gradient, elevation, aspect, mean annual precipitation, lithology, land use, and terrain roughness are the predictor variables used to determine the dependent variable of occurrence or non-occurrence of landslides within an individual grid cell. The results illustrate the importance of terrain roughness and soil type as key factors within the model — using only these two variables the analysis returned a significance level of 89.4%. The results obtained from the model within the GIS were then used to produce a map of relative landslide susceptibility.

Keywords: Logistic regression; Slope stability; Landslide susceptibility; Geographical Information Systems (GIS); El Salvador

1. Introduction

An earthquake is a major natural process of high destructive potential, often resulting in both human and material losses as the direct consequence of the seismic phenomenon. However, some processes derived from an earthquake such as liquefaction, landslides, and tsunamis can often be more dangerous than the initial earthquake. The 2004 Southeast Asian tsunami and the 2001 landslides in El Salvador represent good examples. One of the earliest known studies on earthquake-induced landslide hazards was conducted by Keefer (1984), who analysed the types and magnitude of mass movements in tectonically active regions.

Landslides are significant natural hazards in many areas of the world. Each year they cause more than a 100 000 deaths and injuries, with damage costing more than a 1billion USD (Schuster, 1996). In many countries, the economic losses and casualties due to landslides are greater than commonly recognized, and landslides generate a yearly loss of property larger than that from any other natural disaster including earthquakes, floods and windstorms. Generally, landslides are triggered by seismicity or heavy rains. Other possible causes are anthropogenic, including deforestation, road cutting, and mining. The study of earthquake-induced landslides plays an important role in determining seismic risk, as earthquakes and landslides can result in considerable damage to infrastructure, in addition to a massive loss of

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life (Marzorati et al., 2002). In January and February of 2001, El Salvador experienced several destructive earthquakes, which caused hundreds of landslides of various sizes. In this study, we have used a logistic regression model to assess the susceptibility of earthquake-induced landslides for the whole country of El Salvador.

Two factors are important when modelling any natural phenomena in experimental science: data quality and the choice of scientific models. When data are incomplete or inaccurate, natural phenomena are usually analysed intuitively with ad hoc methods (e.g., Anbalagan, 1992; Anbalagan and Singh, 1996). When studying landslides in small geographical areas, methods most often used are GPS measurements, photogrammetry, or detailed field surveys (Casson et al., 2003; Agnesi et al., 2005); however, for larger geographical areas such as an entire country, methods usually used include remote sensing and thematic cartography. Some studies have used satellite imagery as a substitute for large- to medium-scale aerial photography of landslides (Nichol and Wong, 2005; Nichol et al., 2006). The scale of the model depends on the purpose of the investigation and the specifications of the user. Hazard assessment of earthquake-triggered landslides may be developed at different scales or detail levels, ranging from site-specific evaluation to regional studies (Bommer and Rodríguez, 2002). The framework for our study is classified as Grade 2 with a scale of 1:10 000–1:100 000 (ISSMGE, 1999). Our aim is to produce an earthquake-triggered landslide susceptibility map for the entire country of El Salvador, which requires certain data approximations and generalisations. The available data include topographical maps, geological maps (1:100 000), digital cartography (1:25 000), landslide inventories, and the rainfall database. The data were provided by the Servicio Nacional de Estudios Territoriales de El Salvador (SNET), and the Universidad Centroamericana Simeón Cañas (UCA), whose databases are well-documented and useful for both landslide hazard evaluation and model definition.

2. Summary of previous studies

A variety of approaches have been used in mapping slope instability, and they can be classified into qualitative and quantitative methods. Most of qualitative methods tend to be subjective, since they depend on expert opinions and portray hazard levels in descriptive terms (Anbalagan, 1992). Quantitative methods are based on the numerical expression of the relationship between instability factors and landslides, which can be divided into deterministic and statistical. Deterministic methods depend on engineering principles of slope instability, expressed in the factor of safety (Refice and Capolongo, 2002; Zhou et al., 2003). Typical multivariate statistical approaches used to map landslide susceptibility are *discriminant analyses* and *logistic regression.* Brenning (2005) reviewed several methods and found logistic regression with stepwise variable selection an adequate method for the prediction of landslide susceptibility. Lee (2005) also used a logistic regression model to evaluate the hazard of landslides induced by rainfall. The results were verified using remote sensing data and GIS-based landslide locations, and were compared with the results from a probabilistic model. It was demonstrated that a logistic regression model is better than a probabilistic model in terms of hazard prediction.

Logistic regression belongs to the statistical family of generalized linear models, which are all well-suited for analysis of a presence/absence dependent variable. The linear models have been used to predict slope instability (Carrara et al., 1991; Mark and Ellen, 1995; Rowbotham and Dudycha, 1998). Logistic regression has also been applied to landslide susceptibility mapping in various studies including Wieczorek (1996), Atkinson and Massari (1998), Guzzetti et al. (1999), Gorsevski et al. (2000), Lee and Min (2001),Dai et al. (2001), Dai and Lee (2002, 2003), Ohlmacher and Davis (2003), and Ayalew and Yamagishi (2005). The primary objective of logistic regression is to model the probability of appearance of a habitually dichotomic event, the presence/absence of diverse factors, and the significance of this presence/absence. Recently, landslide susceptibility has been studied using rare events logistic regression (Van Den Eeckhaut et al., 2006). This differs from ordinary logistic regression in that it takes into account the high proportion of no non-landslides to landslides. Depending on the proportion of landslides, either one of these analyses could be used.

Despite many efforts, no agreement has yet been reached on the best techniques and methods for landslide susceptibility mapping (Yesilnacar and Topal, 2005). The arguments revolve around comparisons of data from several authors employing different techniques (Guzzetti et al., 2000), to analyze data from diverse terrains at various scales, with different types of inventories and characteristic factors.

The main assumption in slope instability modelling is that the past occurrence of landslides in a specific site is indicative of the potential for future landslides to occur in sites with similar characteristics. By identifying physical parameters contributing to the formation of landslides,