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Occurrence probability assessment of earthquake-triggered landslides with Newmark displacement values and logistic regression: The Wenchuan earthquake, China

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ABSTRACT

The Newmark displacement model has been used to predict earthquake-triggered landslides. Logistic regression (LR) is also a common landslide hazard assessment method. We combined the Newmark displacement model and LR and applied them to Wenchuan County and Beichuan County in China, which were affected by the $M_{s.}$ 8.0 Wenchuan earthquake on May 12th, 2008, to develop a mechanism-based landslide occurrence probability model and improve the predictive accuracy. A total of 1904 landslide sites in Wenchuan County and 3800 random non-landslide sites were selected as the training dataset. We applied the Newmark model and obtained the distribution of permanent displacement (D_n) for a 30 × 30 m grid. Four factors (D_n, topographic relief, and distances to drainages and roads) were used as independent variables for LR. Then, a combined model was obtained, with an *AUC* (area under the curve) value of 0.797 for Wenchuan County. A total of 617 landslide sites and non-landslide sites in Beichuan County were used as a validation dataset with *AUC* = 0.753. The proposed method may also be applied to earthquake-induced landslides in other regions.

1. Introduction

Large earthquakes often trigger landslides, which may result in serious disasters (Keefer, 1984; Jibson, 2007; Wang et al., 2007; García-Rodríguez et al., 2008). Landslides may cause casualties and economic losses (Lee, 2005; Nadim et al., 2006; Pourghasemi et al., 2012). For example, the May 12, 2008, Wenchuan earthquake triggered approximately 15,000 geohazards, including landslides, rockfalls, and debris flows (Yin et al., 2009), which caused many fatalities and economic devastation (Yin et al., 2009; Huang and Fan, 2013). The occurrence probability modelling of landslides is important for safety planning, disaster management, hazard mitigation, and rehabilitation planning.

Newmark (rigid-block) analysis is widely used to estimate coseismic slope behaviours (Jibson, 2007). Newmark (1965) proposed a displacement model of a landslide as a rigid friction block that slides on an inclined plane when subjected to base accelerations from an earthquake. Wilson and Keefer (1983) applied a dynamic numerical model based on the Newmark analysis of seismic slope stability to investigate the dynamics of seismically induced landslides. Jibson (2007) collected 2270 strong-motion records from 30 worldwide earthquakes and constructed four different regression models to estimate the Newmark displacement as a function of the critical acceleration, critical acceleration ratio and Arias intensity. Regression models are more suitable for regional-scale seismic landslide hazard mapping than site-specific designs. Hsieh and Lee (2011) applied the Newmark displacement model to soil and rock slope displacement by using data from the 1999 Chi-Chi earthquake in Taiwan. Wang and Lin (2009) also used this model to calculate the displacement in the area that was affected by the Chi-Chi earthquake and ascertained that landslides tended to occur in regions that were displaced by more than 5 cm.

Some statistical methods have also been applied to the prediction of landslide susceptibility, including generalized linear models and various complicated nonlinear models such as the frequency ratio (Yilmaz, 2009; Pradhan and Lee, 2010), logistic regression (LR) (Ohlmacher and Davis, 2003; Ayalew and Yamagishi, 2005; Lee, 2005; Bai et al., 2013), factor analysis (Marko, 2006), cluster analysis (Melchiorre et al., 2008), and soft computing techniques such as artificial neural networks (ANN) (Yesilnacar and Topal, 2005; Nefeslioglu et al., 2008), support vector machines (SVM) (Yao et al., 2008; Yilmaz, 2010) and fuzzy logic (Pourghasemi et al., 2012). These approaches enable the mapping of landslide hazard areas (Pradhan, 2010).

Some research shows that the performance of LR in landslide susceptibility assessment is better than that of bivariate statistics (BS), the frequency ratio, ANN and SVM (Lee, 2005; Xu et al., 2012). Therefore, we selected LR as a representative of the statistical analysis models. The influential factors that are used for mapping landslide susceptibility

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include the geology, topography, human activities, hydrology, vegetation cover and soil (Parise and Jibson, 2000; Kamp et al., 2008; Nefeslioglu et al., 2008; Yao et al., 2008; Eeckhaut et al., 2011; Zhu et al., 2014). The effects of earthquakes, such as intensity and peak ground acceleration (*PGA*), have also been considered to assess the susceptibility of earthquake-triggered landslides (García-Rodríguez et al., 2008; Kamp et al., 2008).

This research applies both the Newmark displacement model and LR. The Newmark model is designed for ideal slopes and does not consider all of the aforementioned influential factors. LR ignores the dynamic mechanisms of landslides. A related question is whether the permanent displacement values that are derived from the Newmark model are significantly influential on earthquake-triggered landslides. The purposes of this research are to discuss this issue, to determine other influential factors, and to develop an occurrence probability model of earthquake-induced landslides.

2. Study areas

The areas that were examined in this study are Wenchuan and Beichuan Counties in Sichuan Province, China. Fig. 1 shows the locations of the two counties that experienced the highest intensity shocks during the Wenchuan earthquake.

2.1. Wenchuan County

Wenchuan County (102°51′–103°44′E, 30°45′–31°43′N) is located in the north-western Sichuan Plain, China, and has an area of 4084 km^2. Most of the terrain is mountainous and extends from an elevation of 787 m a.s.l. in the south-eastern region to 6204 m a.s.l. in the western region. Several different climate zones are present in the county because of the mountainous terrain. The mean annual rainfall is approximately 1200 mm, and the most precipitation occurs between July and September. The region is drained by the Minjiang River and its main tributaries, the Zagu'nao and Er Rivers, which have high erosion rates and form deep valleys. The Longmenshan fault is composed of three faults: the Beichuan–Yingxiu fault, Wenchuan–Maoxian fault and Jiangyou–Guanxian fault. The Longmenshan fault is an active thrust-fault at the conjunction of the eastern edge of the Tibetan Plateau and the western margin of the Sichuan Basin (Densmore et al., 2007). The main shock occurred along the Beichuan–Yingxiu fault, and aftershocks spread along the Longmenshan fault zone. The Wenchuan–Maoxian and Beichuan–Yingxiu faults cross the county. The bedrock geology is complicated. Devonian slate that is intercalated with sandstone and limestone outcrops in the nature reserve of Wolong for pandas. Silurian limestone intercalated with sandstone and phyllite outcrop in the north-western area of the county. The eastern portion of the county is underlain by Archean metasedimentary rocks and metavolcanic rocks. Quaternary unconsolidated sediments and weathered volcanic rocks, which facilitate landslide development, are widespread in the study area.

2.2. Beichuan County

Beichuan County (104°26′–104°29′E, 31°35′–31°38′N) is located at the northeast of Wenchuan County and covers an area of 2868 km^2. It is a mountainous area with elevations from 516 to 4693 m a.s.l. The county experienced massive destruction because of its location along the Beichuan-Yingxiu fault, which crosses the eastern region along with the Jiangyou-Guanxian fault. The climate is sub-tropical, humid

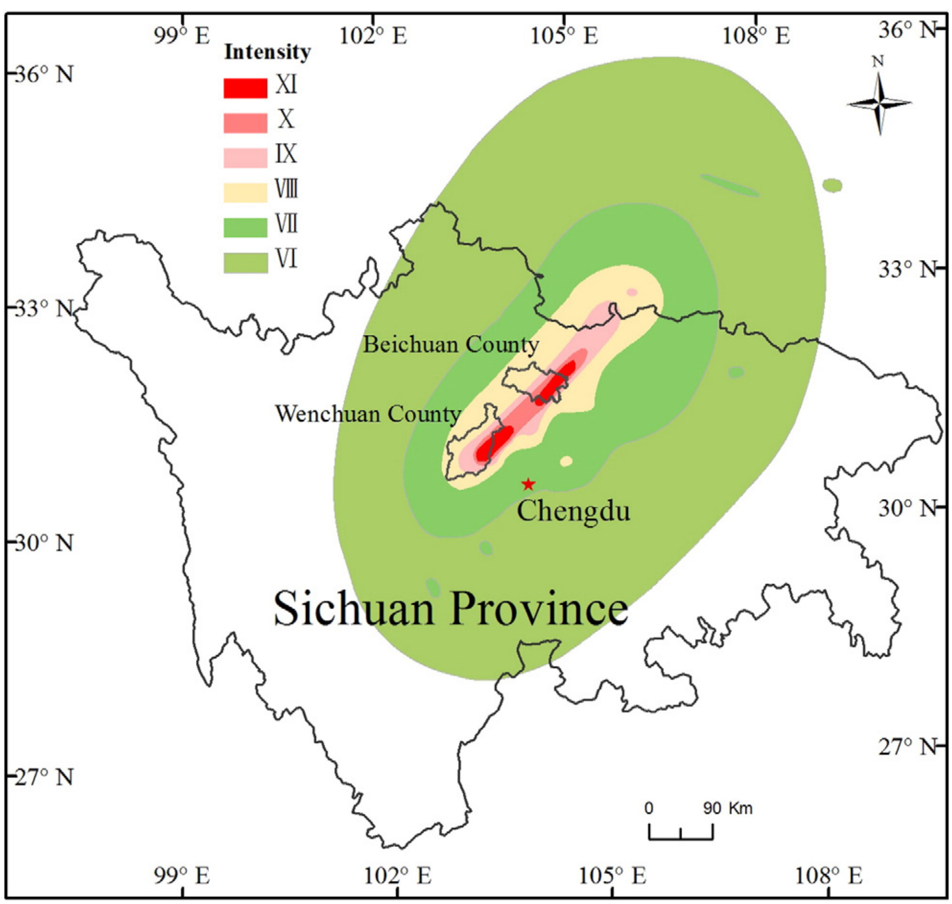

Fig. 1. Location of Wenchuan and Beichuan counties and seismic intensity of the 2008 Wenchuan earthquake. Data source: China Earthquake Administration (http://www.cea.gov.cn/publish/dizhenj/124/202/20120206145932281415010/index.html).