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Susceptibility assessment of debris flows using the analytic hierarchy process method — A case study in Subao river valley, China

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ABSTRACT

Many debris flows have occurred in the areas surrounding the epicenter of the Wenchuan earthquake. Susceptibility assessment of debris flows in this area is especially important for disaster prevention and mitigation. This paper studies one of the worst hit areas, the Subao river valley, and the susceptibility assessment of debris flows is performed based on field surveys and remote sensing interpretation. By investigating the formation conditions of debris flows in the valley, the following assessment factors are selected: mixture density of landslides and rock avalanches, distance to the seismogenic fault, stratum lithology, ground roughness, and hillside angle. The weights of the assessment factors are determined by the analytic hierarchy process (AHP) method. Each of the assessment factors is further divided into five grades. Then, the assessment model is built using the multifactor superposition method to assess the debris flow susceptibility. Based on the assessment results, the Subao river valley is divided into three areas: high susceptibility areas, medium susceptibility areas, and low susceptibility areas. The high susceptibility areas are concentrated in the middle of the valley, accounting for 17.6% of the valley area. The medium susceptibility areas are in the middle and lower reaches, most of which are located on both sides of the high susceptibility areas and account for 45.3% of the valley area. The remainders are classified as low susceptibility areas. The results of the model are in accordance with the actual debris flow events that occurred after the earthquake in the valley, confirming that the proposed model is capable of assessing the debris flow susceptibility. The results can also provide guidance for reconstruction planning and debris flow prevention in the Subao river valley.

1. Introduction

The Wenchuan earthquake, which occurred on 12 May 2008, caused more than 15,000 geohazards, the majority of which were rock avalanches and landslides (Huang and Li, 2008). Such landslides and avalanches provide a considerable amount of loose materials for debris flows, which are expected to be more frequent and in the active period of the next 20–30 years (Cui et al., 2011). Thus, the susceptibility assessment of debris flows is of great significance to disaster prevention and mitigation in earthquake-prone areas.

Assessment factors and methods are vital to assessing the debris flow susceptibility. Li et al. (2006, 2009a) demonstrated that the events of debris flow correlate with particular stages of the basin evolution. The rock hardness determines the ability to provide loose materials and then influences the occurrence frequency of debris flows (Lu et al., 2011). Zhang et al. (2008) ranked the common rocks based on their susceptibility to debris flow in ascending sequence, i.e. basalt, argillaceous limestone, dolomite, slate, Quaternary deposit, sandstone, siltstone, phyllite, and mudstone. Tang and Liang (2008) argued that phyllite and slate were especially prone to forming debris flows in the Beichuan earthquake area. With regard to the assessment method, based on a conditional probability model, Tang (2005) and Zou et al. (2012) analyzed the spatial susceptibility of debris flow in the Nujiang River basin of Yunnan and the Upper Yangtze River basin, respectively. Carrara et al. (2008) developed and compared five models (statistical approach vs. physically based approach) for predicting the debris flow occurrence in an alpine area. They found that all of the statistical models were reliable and robust, while the physically based model had low predictive power. Then, Luca et al. (2011) presented an evolution of gullying susceptibility using bivariate and multivariate statistical models, and found the latter had more predictive power in gullying susceptibility. After the Wenchuan earthquake, many researches were also conducted on the susceptibility and

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activities of debris flow in earthquake areas (Liu et al., 2009; Tang et al., 2012; Wang et al., 2013; Liu et al., 2014).

The Subao river valley is located in the worst hit area of the Wenchuan earthquake. The Beichuan reverse fault, considered as the seismogenic fault (Burchfiel et al., 2008; Li et al., 2008, 2009b; Xu et al., 2008), passes through the valley. The earthquake induced many landslides and rock avalanches. On 24 September 2008, a rainstorm triggered a group of large debris flows in the valley, causing 11 deaths and significant damages (Tang and Liang, 2008; Tang et al., 2009; You et al., 2010). After that, several debris flows occurred every year in the valley, seriously threatening the post-disaster reconstruction. The valley has become one of the highest susceptibility areas of debris flow.

This paper describes the formation conditions of debris flows in the Subao river valley, based on field surveys and remote sensing images. Then, we build a model based on the ArcGIS platform to assess the debris flow susceptibility in the valley area.

2. Study area

2.1. Valley overview

The Subao river valley is located to the west of Leigu town, approximately 8 km south of Beichuan county (Fig. 1). The valley covers an area of 72.2 km^2, and the river is 16.5 km long. The river, in the middle of the catchment area, flows from west to east. In the valley, the highest point is 2312 m and the relative relief is 1597 m, with a mean relief ratio of 9.28%. The channel is mainly U-shaped, with a width varying from a few meters to several tens of meters.

2.2. Topography

Mountains dominate the Subao river valley, which is in the transition area between the front and back of the Longmen Mountains. The valley head is approximately 2312 m wide, falling rapidly to 715 m at the valley mouth. The main channel has a steep gradient with a mean relief ratio of 9.28%. The valley is dominated by steep slopes (Fig. 1). The slope angles are greater than 25°, with some up to 40°–50° or more. The area of steep (25°–35°) and steeper (>35°) slopes is 46.76 km^2, accounting for up to 64.76% of total slope area. Table 1 lists the slope statistic data of the Subao river valley acquired from 1:50000 digital elevation model (DEM).

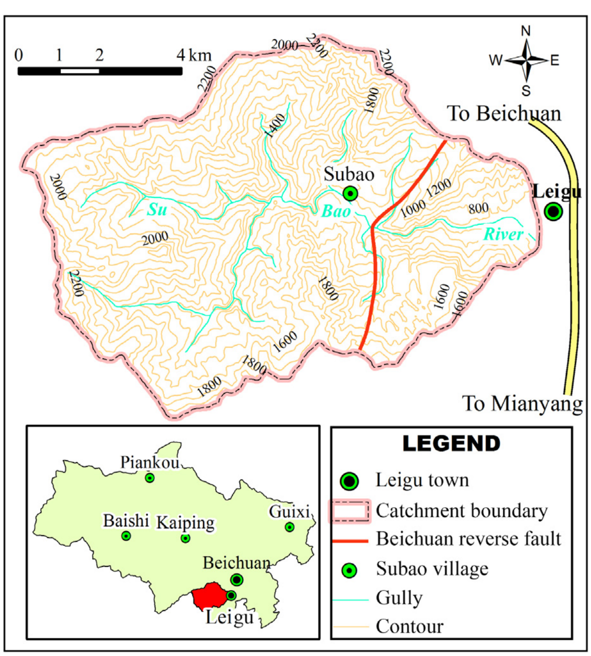

Fig. 1. The location and topographic features of the Subao river valley.

2.3. Geological settings

Fig. 2 shows the Beichuan reverse fault passing through the Subao river valley. The strike of the fault plane is almost northeast in direction (Dong et al., 2006). The motion of this fault is responsible for the uplift of the mountains relative to the lowlands of Sichuan Basin to the east.

The stratum lithology is controlled by the Beichuan reverse fault. The hanging wall in the northwest is mainly composed of Silurian metamorphic rocks, which originated from regional metamorphism with a foliated texture and numerous cracks. The metamorphic rocks, distributed in the middle and upper catchment areas, are composed of phyllite, slate, sandstone, and other similar rocks. The footwall in the southeast is mainly composed of shallow sea phase sedimentary rocks of the middle Devonian period, including limestone, argillaceous limestone, bioclastic limestone, and siltstone. The footwall also contains a small amount of Cambrian siltstone. The rocks of the footwall disperse farther downstream, where there are steep slopes with hard rocks that are resistant to erosion.

According to field surveys and remote sensing images (with a resolution of 0.5 m), it is determined that the Wenchuan earthquake directly induced more than 300 landslides and rock avalanches in the Subao river valley (Fig. 2). Landslides mainly developed in softer rock areas (such as the hanging wall) and rock avalanches mainly occurred in hard rock areas (such as the footwall). These geohazards continue to provide enough loose materials for subsequent debris flows and will last for several decades.

2.4. Climate

The Subao river valley has a mild subtropical humid monsoon climate with four distinct seasons and an average annual temperature of 15.6 °C. The valley has rich rainfalls with an average annual precipitation of 1399.1 mm. The 24-h maximum precipitation was 101 mm, and the 1-h maximum precipitation was 42 mm. Approximately 80% of the rain falls between June and September. Rainstorms, combined with topographic effects, can result in debris flows in the rainy season.

3. Assessment factors

The determination of assessment factors should consider the debris flow formation conditions in the valley. Generally, the formation conditions of debris flow include loose materials, topography and precipitation.

3.1. Loose materials

Loose deposits form an important material basis of debris flow events. Generally, the loose materials are determined by the stratum lithology and geological structures.

Table 1
Slope statistic data of the Subao river valley.

Slope angle (°)	Area (km^2)	Percentage (%)
<15	7.64	10.58
15–25	17.81	24.66
25–35	22.76	31.52
>35	24	33.24
Total	72.21	100