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The effects of slope length and slope gradient on the size distributions of loess slides: Field observations and simulations

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ABSTRACT

In this study, we characterize and consider the effects of slope length and slope gradient on the size distributions of loess slides. To carry out this study, we employ data on 275 loess slides within Zhidan County, Central Loess Plateau, China. These data were collected in the field and supplemented by the interpretation of remote sensing images. Both the field observations and slope stability analysis show that loess slide size increases with the slope length. Slide sizes is significantly correlated with slope length, showing a power law relationship in both cases. However, the simulation results show that slope gradient is not associated with loess slide size. The main part of the link between slope gradient and slide size seen in the observations is only apparent, as indicated by the strong connection between slope gradient and length. Statistical analysis of the field observations reveals that slope gradient decreases with increasing slope length, and this correlation interferes with the potential relationship between landslide sizes and slope gradient seen in the field observations. In addition, the probability densities of the areas of loess slides occurring on slopes of different slope lengths are determined using kernel density estimation. This analysis shows that slope length controls the rollover of the frequency-size distribution of loess slides. The scaling exponent increases with slope length.

1. Introduction

Loess sediments cover approximately 10% of the earth's surface (Liu, 1985). Loess is extensively distributed in the arid regions of China, and it accounts for approximately 6.6% (631,000 km^2) of the total area (Liu, 1985; Tu et al., 2009). Loess landslides, which are a major and common engineering problem, are a persistent threat to human activities in loess-covered terrain (Derbyshire, 2001; Xu et al., 2013). Increases in population, unplanned urbanization and the excavation of slopes to produce road cuts amplify the impact of loess landslides (Derbyshire, 2001; Zhang and Liu, 2010). Meanwhile, owing to the high costs of controlling these landslides through engineering measures and rational land-use planning, casualties and economic losses are becoming more severe in steep mountainous regions (Derbyshire, 2001).

Proper characterization of the size distributions of landslides is extremely important in determining landslide hazard (Guzzetti et al., 2005), quantifying the integrated effects of erosion and sediment yield caused by landslips (Hovius et al., 2000; Stark and Hovius, 2001; Martin et al., 2002; Brardinoni and Church, 2004; Guthrie and Evans, 2004; Hungr et al., 2008; Chen, 2009) and evaluating the magnitude of landslide events (Hungr et al., 1999; Guzzetti et al., 2002; Malamud et al., 2004a; Van Den Eeckhaut et al., 2007; ten Brink et al., 2009).

Topography affects slope hydrological processes and thus slope stability, as has been studied by several researchers (Sidle and Onda, 2004; Gao and Maro, 2010; Xu et al., 2013). Frattini and Crosta (2013) examined the effects of topography on the distribution of landslide size using the virtual tiling method and investigated the effects of material properties on landslide size through 2D limit equilibrium slope stability analyses. Similarly, Liu and Koyi (2013) noted that landslide size increases with increasing material strength. Katz et al. (2014) studied the controls on the sizes and geometries of individual landslides using a numerical two-dimensional discrete element model and found that landslide size increases with decreasing slope gradient for a given material strength. Chen et al. (2016) performed a study of the controls on landslide size using limit equilibrium simulations and stated that sliding volume increases with decreasing slope gradient. However, controversy regarding on the relationship between landslide size and slope gradient still exists. In particular, few studies have examined landslide size with respect to slope length. Thus, it is very necessary to ascertain the controls on landslide size using field observations and develop a proper simulation model to enable understanding of the field observations.

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Considerable research has addressed landslide size distributions, and a rollover effect has been identified below a certain threshold within landslide frequency-size distributions (Guzzetti et al., 2002; Malamud et al., 2004a). Many empirical observations have shown that landslide size distributions obey a power-law (fractal) correlation for large landslides (Brunetti et al., 2009; Frattini and Crosta, 2013). Some authors have attributed the rollover effect to undersampling and influence of soil moisture, topography and material properties (Pelletier et al., 1997; Stark and Hovius, 2001; Malamud et al., 2004a; Frattini and Crosta, 2013). Though the frequency distribution of landslides shows a power-law scaling for landslides with sizes greater than the threshold, the causes of the rollover effect are not clearly understood (Guzzetti et al., 2002; Frattini and Crosta, 2013).

In the present study, the effects of slope length and slope gradient on the size distributions of loess slides are evaluated. We quantify the response of loess slide size to slope length and slope gradient using a power-law form and a containing field observations of 275 loess slides. In addition, a 2D slope stability analysis using the general limit equilibrium method is performed to reproduce the field observations. Finally, the rollover effect of the loess slide probability distribution is analysed using kernel density estimation, and the contributing factors to the rollover effect are also considered.

2. Materials and methods

2.1. Study area

Zhidan County is bounded by the latitudes 36°21′23″–37°11′47″ N and the longitudes 108°11′56″–109°3′48″ E, and it covers an area of approximately 3781 km^2 in the central part of the Loess Plateau of northern China (Fig. 1). This area contains rugged and steep mountainous terrain, which arises from the combined effects of intermittent tectonic uplift, valley incision and soil erosion on hillslopes (Gao et al., 2016). The elevations within the area range from 1054 to 1714 m above sea level; the mean and standard deviation of these elevations are 1427.40 m and 103.64 m, respectively. The area experiences a typical temperate continental monsoon climate, and the mean annual rainfall and air temperature are 524.5 mm and 7.8 °C, respectively. The amount of rainfall that occurs in different seasons varies significantly. Inspection of the historical precipitation record indicates that approximately 56% of the annual precipitation falls in the rainy season (June to August), and mass movements and severe water erosion also occur during this season. The river network has a dendritic pattern. A dense drainage network dissects the basin, which has a drainage density of 3.3 km^{-1}.

Loess is a homogeneous, porous, friable and predominantly silt-sized sediment type that forms through the accumulation of wind-blown silt (Liu, 1985; Frechen, 2011). Loess particles primarily range from coarse to medium silt (0.01–0.06 mm) (Derbyshire, 2001). Vertical joints and large pores are well developed in loess (Derbyshire, 2001; Qiu et al., 2017). The study area is underlain by a thick Quaternary loess deposit. The late Pliocene Red Clay overlies a pre-Tertiary base and ranges in thickness from 20 to 50 m. The middle Pleistocene Lishi Loess overlies the Red Clay and is approximately 60–100 m in thickness. The lower part of the Lishi Loess contains paleosols and calcareous nodules. The late Pleistocene Malan Loess, which lies atop the Lishi Loess, is widely distributed in Zhidan, and it has thicknesses of approximately 10–30 m (Liu, 1985; Derbyshire et al., 1991; Derbyshire, 2001). The main exposed outcrops are of loess deposits. The pre-Tertiary units are exposed only at the toes of slopes in the bottoms of deep river valleys. Area with relief of <200 m covers >85% of the study area, and most of the landslides are observed within these low-relief areas. According to the field observations, all of the loess slides actually occurred in the loess substrate. None of the slides are cut in other pre-Tertiary basement rocks. Only a few of the loess slides move along a bedrock surface.

2.2. Landslide data

The Loess Plateau can be considered to be relatively homogeneous from a geological point of view (Liu, 1985). The area's highly fragmented topography, which is very prone to sliding, was caused by the intermittent tectonic uplift that started during the middle

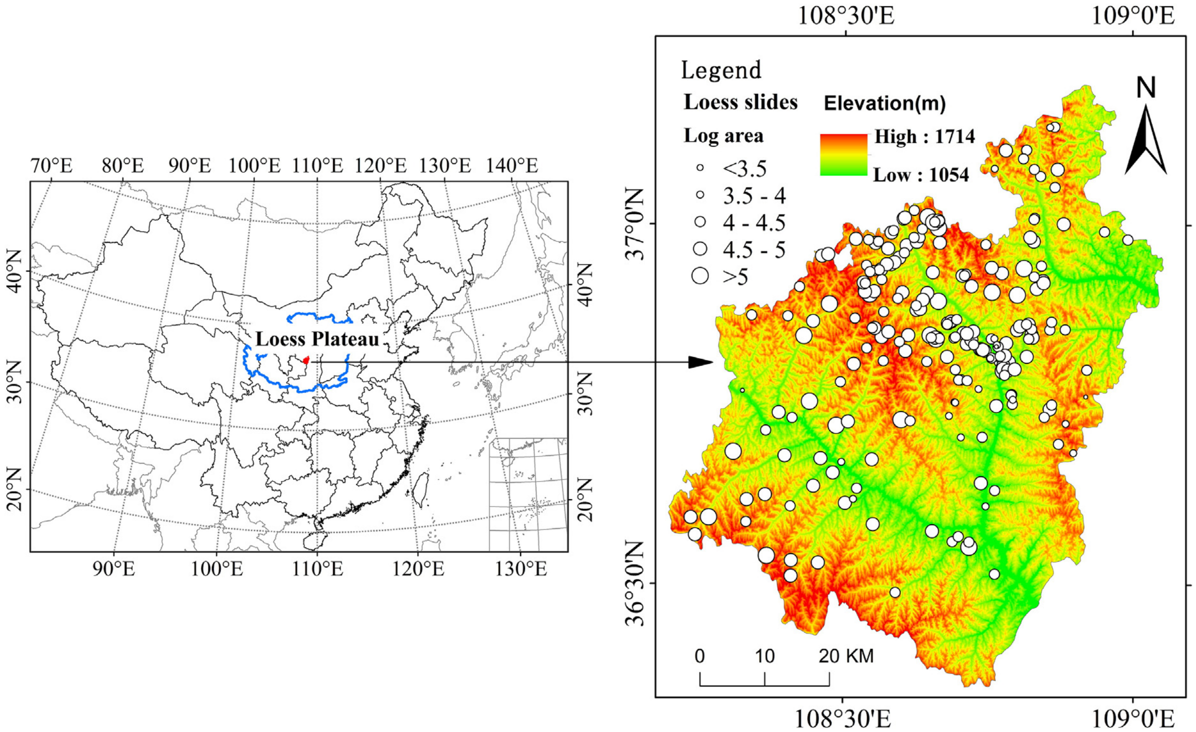

Fig. 1. Location of the study area in Zhidan County, Shaanxi province, China. Red polygon in the figure denotes the study area. The sizes of the white dots represent the log-transformed areas of the loess slides.