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Size distribution of loess slides in relation to local slope height within different slope morphologies

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ABSTRACT

Loess slides are widespread and dangerous gravity-induced surface processes on the Loess Plateau of north-central China. The local slope height and slope morphology have been considered as important conditioning factors for landslide susceptibility mapping. However, the quantitative relationship between landslide size and local slope height within different slope morphologies is not very clear. In this study, an inventory of 155 loess slides was developed based on detailed field investigation and remote sensing image interpretation. Statistical analysis and GIS were applied to find the quantitative relationships between the size of these loess slides and local slope height in different types of slope morphologies. The analysis shows that the relationship between the loess slides volume and area exhibits a similar trend within different types of slope morphologies. In addition, the analysis demonstrated that loess slides are more frequent on local slope height from 40 to 100 m. Stepped slopes with higher pore water pressure are prone to sliding, and approximate 34.19% of total loess slides occur in these stepped slopes. Moreover, the analysis shows that the mean loess slide area and volume rapidly increase with increasing local slope height. Furthermore, the result underlines the fact that both the local slope height and the slope morphology are two fundamental factors that control the occurrence as well as size distribution of loess slides. The loess slide size remarkably increases with increasing local slope height within every type of slope morphologies. These findings indicate that local slope height can limit the loess slide size and their spatial extent. Moreover, we quantified the correlation between the loess slide size and local slope height using power law form, and the scaling exponents of the correlations are different within different slope morphologies.

1. Introduction

Landslide events, as a complex natural phenomenon and the associated hazard often result in severe damage to society in mountainous and hilly environments around the world (Varnes, 1984; Turner and Schuster, 1996; Malamud et al., 2004). In particular, the frequency of landslide has been on an increasing trend in recent years, and human beings are being more prone to the hazards associated with these natural events as a result of rapid population growth accompanied by growing pressures on these natural environments (Anbalagan and Singh, 1996; Larsen and Torres-Sánchez, 1998; Aleotti and Chowdhury, 1999). Steep topography and frequent extreme weather conditions, combined with human disturbances, make the loess area prone to sliding (Derbyshire et al., 1991, 1995; Zhang et al., 2012). Since the last couple of decades, severe loess landslides that occur with little warning are particularly challenging for communities, threatening lives and infrastructure (Derbyshire, 2001; Zhang et al., 2009; Xu et al., 2013).

Loess covers around 10% of the world's land surface, and there exists a remarkable similarity concerning the geological and geotechnical characteristics of these loess all over the world (Liu, 1985; Derbyshire and Mellors, 1988). In China, loess covers an area of approximately 631,000 km^2, i.e. about 6.6% of the total area of the country (Liu, 1985). Loess is homogeneous, clastic, principally silt-sized sediment that is formed by the accumulation of wind-blown dust with a bonded strength, high porosity and low values of bulk density (Derbyshire et al., 1991; Fredlund and Rahardjo, 1993; Derbyshire, 2001; Tu et al., 2009; Xu et al., 2012, 2015). The particles of the loess range from coarse to medium (0.01–0.06 mm), where quartz grains account for over half of the particles (Liu, 1985; Derbyshire, 2001). The vertical jointing in loess are natural sub-surface piping systems that affect the hydrology of the area (Derbyshire, 2001). Moreover, collapsible loess disaggregates instantaneously when locally saturated (Liu, 1985; Derbyshire, 2001), indicating that loess is very sensitive to water. Moisture content can strongly influence the shear strength of loess soil, which has been shown by experiments involving artificial rainfall and ring-shear tests

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(Derbyshire et al., 1994; Tu et al., 2009; Zhang et al., 2013; Xu et al., 2015). Topography (such as slope morphology, elevation, aspect, slope angle, etc.) greatly influences the slope hydrological conditions and stability (Gao et al., 2011; Zhu, 2012; Gao et al., 2016; Zhang et al., 2014). Thus, topographic attributes have also been investigated as key factors of loess landslides (Zhang and Liu, 2009; Zhang et al., 2012, 2014). Furthermore, numerical modeling has been applied by various researchers for the stability analysis of loess landsides (Xu et al., 2013; Wang et al., 2014a, 2014b).

The size distribution of landslides within a given geological and geographic area provides valuable insight into the fundamental processes of landslide dynamics, for determining landslide hazard, and for estimating the contribution of landslides to the sediment yield of rivers basins (Stark and Hovius, 2001; Chaytor et al., 2009). Published literatures indicate that the landslide frequency is nonlinearly related to landslide size (Malamud et al., 2004; Korup et al., 2007). The landslide size distribution in turn is influenced significantly by topographic factors (Ayalew and Yamagishi, 2004; Broothaerts et al., 2012). Thus, understanding the correlation between causal factors and size distribution is most important to address the key question relating to how landslides and local topography dynamically interact (Guthrie and Evans, 2004a, 2004b; Korup et al., 2007; Zhang et al., 2014).

Local slope height and slope morphology are often considered as the two most important parameters and substantial conditional factors for landslide susceptibility assessment (Gökceoglu and Aksoy, 1996; Ayalew and Yamagishi, 2004; Guzzetti et al., 2006; Saito et al., 2009). Although previous studies have analyzed the size distribution of landslides in different class intervals of conditioning factors, only few have focused on quantitative relationship between landslide size and local slope height and slope morphologies. Thus, it is very necessary to quantify the relationship between size distribution of loess slides and local slope height within the different slope morphologies in order to forecast landslide scale more precisely as well as to improve probabilistic prediction models for landslide hazard.

In this study, we first divided the slope morphology into five classes according to vertical profile of slope. Using landslide inventory obtained from the stereoscopic interpretation of aerial photographs and systematic field verifications, we developed an empirical relationship between loess slide volume and area. Furthermore, we analyzed the distribution of loess slides number, area and average area within the local slope height. Finally, we used statistical analysis in the form of power law to quantify the relationship between size distribution and local slope height within different slope morphologies.

2. Study area and geological settings

The study area lies in Shaanxi province of People Republic of China and falls within 35°21′ to 37°30′N and 107°40′ to 110°33′E latitude and longitude respectively (Fig. 1). It covers an area of about 36,712 km^2 of predominantly steep and rugged hilly terrain. The elevation in the study area ranges between 351 m and 1795 m above sea level, with an average of 1238 m (standard deviation = 212 m), while the slope angle varies from 0° to 78°, with a mean value of 16° and a standard deviation of 9°. The study area is drained by the Yellow River along with its major tributaries, the Yan River and the Luo River (Fig. 1). Additionally, there are a number of subsidiary intermittent streams flowing only in the rainy season. Semi-arid climatic condition prevails within the study area and is represented by typical temperate continental monsoon climate with average rainfall of 500 mm $year^{-1}$, average evaporation of 1000 mm $year^{-1}$, and average air temperature of 9.2 °C $year^{-1}$. Precipitation tends to be most abundant in summer (June to August), which account for 57% of annual precipitation (Wang et al., 2014a, 2014b; Zhang and Liu, 2009).

The study area lies in the middle part of the Loess Plateau that is developed on the Mesozoic basement mainly made up of mudstone and sandy mudstone (Liu, 1985; Zhang et al., 2013). Thick Quaternary loess is deposited over the Mesozoic basement rocks (Liu, 1985). The thickness of loess is variable and ranges from a few cm to about 400 m (Derbyshire et al., 1995). Stratigraphically, the loess deposit in the study area can be classified into four units. These are (a) Red Clay (Late Pliocene) overlying the Pre-Tertiary basement rocks; (b) Wucheng Loess (Early Pleistocene) consisting of interbedded calcareous nodule beds and fossil soils, resting over the Red Clay; (c) Lishi Loess (Middle Pleistocene) consisting of loess and palaeosol sequences on top of the Wucheng Loess; and (d) Malan Loess (Late Pleistocene), the upper most layer of the loess deposit consisting predominantly of light grey-yellow silt with large pores, low geotechnical strength and vertical joints (Liu, 1985; Derbyshire et al., 1991, 1995). With the chronological and intermittent rising of the Loess Plateau, the surface of loess is severely incised (Zhao et al., 2000). The resultant landscape is characterized by a fragmented topography, with steep hills and incised valleys (Zhao et al., 2000; Derbyshire et al., 1995). Most prominent landforms are loess platforms, loess-mantled ridges and loess-covered hills (Liu, 1985; Derbyshire et al., 1995).

3. Materials and methods

3.1. Data preparation

Loess landslides are one of the extremely dangerous gravity-induced loess surface processes and are very widespread on the Chinese loess plateau. Most of the landslides in the study area are loess slides (Cruden and Varnes, 1996). The other types such as loess fall and mudflows are significantly less, so we did not considered them for further analyses. The loess slide inventory map was obtained primarily from the stereoscopic interpretation of color aerial photograph from 2010 and 2014 at the scale of 1:10,000, and it was verified in the field through detailed GPS surveys. During the field survey, several loess slides and some important geomorphologic characteristics were observed that were not visible on aerial photographs. The mapped features of the individual loess slides were first converted to digital vector data, and subsequently converted into raster data in ArcGIS with a grid size of 10 × 10 m. In order to minimize errors, two geomorphologists independently identified and mapped loess slides. These two inventories were critically reviewed and merged together.

3.2. Empirical relationship between loess slide volume and area

Estimation of landslide volume is especially difficult (Brardinoni et al., 2003). In this work, mean landslide depth was estimated directly in the field within the ground-surveyed areas. Area was measured directly from aerial photographs and was verified in the field for some loess slides. The volume of individual loess slide was estimated as the product of the area and the mean landslide depth (Brardinoni and Church, 2004; Guzzetti et al., 2009). Though the estimated volume is not very accurate, it is sufficient for the purpose of this work. To test the data spanning multiple orders of magnitude, the empirical data were log-transformed. We adopt a least square linear fitting technique to fit the empirical data between log-transformed values of volume (V) and area (A) of loess slides.

3.3. Terminology and category of slope morphology

In this paper, the local slope height is defined as the vertical distance between the crest and toe of a slope (Fig. 2A) (Gökceoglu and Aksoy, 1996). The slope morphology which is also called curvature is the second derivative of the surface (Meinhardt et al., 2015). The slope morphology is differentiated into plan and profile curvature (Burrough and McDonnell, 1998). In this study, we examined the relationship between loess slides and profile curvature. The slope morphology was divided into five classes: stepped slope (SS), convex slope (CVS), composite slope (CPS), concave slope (CCS) and linear slope (LS). The