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Gravity erosion on the steep loess slope: Behavior, trigger and sensitivity

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ABSTRACT

Gravity erosion is a dominant geomorphic process on the widespread steep loess slopes, yet it is not well understood due to the complexity of failure occurrence and behavior. This study conducted a series of experiments in the laboratory to test the stability of different slope geometries and rainfalls and then performed a sensitivity analysis to quantitatively explore the triggering mechanisms of mass failure on the steep loess slope. A topography meter designed by the authors was used to quantitatively measure the process of gravity erosion, and the increase-rate-analysis method presented by the authors was also used to analyze the sensitivity of gravity erosion. The following three types of gravity erosion were observed: landslide, avalanche, and mudslide. In an event of rainfall, various types of gravity erosion might emerge in the same period, and mass failures with the same mode and similar size often adjacently appeared. Sometimes, a group of mass failures might happen on a large, slowly slipping block. Then the increase-rate-analysis method was used to evaluate variations in the gravity erosion with respect to changes in other causal parameters of rainfall duration–intensity and slope height-gradient. Climate-driven factors and topography triggers had prominent influences on gravity erosion. Whether for the total amount or the peak amount in an experiment, the largest sensitivity parameter on both landslides and mudslides was that of rainfall duration. In comparison, topography was relatively less influential. For the total amount in an experiment, the sensitivity parameters of rainfall duration on the landslide and mudslide were 24.9 and 19.5, respectively, while the sensitivity parameter of rainfall intensity on the avalanche was 2.2. For the peak amount in an experiment, the sensitivity parameter of rainfall duration on the landslide and mudslide were 5.5 and 15.6, respectively. Meanwhile the sensitivity parameter of slope gradient on the avalanche was 4.6. The experimental results obtained here provide an insight into the pre-failure mechanisms and processes of steep loess slopes.

1. Introduction

Gravity erosion is a frequent and widespread geomorphological phenomenon, whether in mountainous or urban areas. It is the mass failure on a steep slope, triggered by self-weight. Erosion due to gravitational force occurs under the combined influence of definite hydrologic, geologic, and topographic conditions. Gravity erosion is also an important part of the loss process and is often the first stage in the breakdown and transportation of weathered materials. The phenomena can be classified in part by spatial size and distribution on the ground, or by duration of time that the process acts, or by rate of movement (Shroder and Bishop, 1998; Wang et al., 2014). It may also differ with respect to the thickness of a failed mass, time of failure occurrence, or rotational inclination (Au, 1998). Forms of gravitational erosion include avalanche, landslide, mudflow, and sinkhole formation. Climate and landform play significant roles in the occurrence and behavior of gravity erosion. Gravity erosion generally takes place together with hydraulic erosion, namely, soil loss due to water flowing over the slope, but the mechanism and dynamics of each type of erosion are different. Hence the measures to control hydraulic erosion and gravity erosion are different, and it is essential to quantitatively distinguish the amounts of the failure masses during the same event of rainfall (Xu et al., 2015b).

Most gravity erosion occurs during or just after storms (Ali et al., 2014; Fourie, 1996; Montgomcry and Dietrich, 1994; Peruccacci et al., 2012; Salciarini et al., 2006; Tsai and Yang, 2006). Slope stability problems due to rainfall are often encountered in geotechnical engineering, either in tropic regions with frequent rainfall or in arid regions (Derbyshire et al., 1995; Tsaparas et al., 2002; Tu et al., 2009). Even though an otherwise stable slope may fail due to human-induced factors, such as excavation at the toe or loading due to construction, many slopes simply fail due to rainfall infiltration (Ali et al., 2014; Fourie, 1996). In the area of Three Gorge Reservoir of China, the frequency of rain-induced landslides accounted for 75% of the total geological disasters since building the reservoir (Li et al., 2011). Hence, the determination of geological mechanisms for the occurrence of the rain-induced gravity erosion is a problem of scientific and societal interest.

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Assessment of soil erosion sensitivity is defined as the possibility of soil erosion occurrence and identification of areas susceptible to soil erosion when only considering natural factors (Zhang et al., 2013). The main task in landslide susceptibility assessment is to find out how the causal factors influence the occurrence of landslides (Melchiorre et al., 2011). The mode of rain-induced mass failure strongly depends on the initial state of the slope materials, together with the pore water pressure distribution and magnitude of apparent cohesion due to variations in the soil water content (Lourenco et al., 2006; Zhang et al., 2014). Intense rainfall, soils that are largely non-cohesive as they become saturated, steep terrain, and intense development are considered to be the major causes of the failures. Loss of pore-water suction, erosion, and pore-water pressure build-up at shallow depths are the most common ways through which rainwater affects slope stability, as short-burst rainstorms are common. The scale of a failure event depends on the intensity, area, position, and duration of the triggering rainstorm, whereas the antecedent rainfall has relatively little influence (Au, 1998). The erosional history and the consequent morphology are also much more important except for the trimming induced by occasional very large run-off events (Thornes and Alcantara-Ayala´, 1998).

Because gravity erosion is affected and constrained by so many factors, its quantification is complicated and difficult to achieve. Furthermore, gravity erosion is a stochastic, non-continuous process, and usually occurs as a combination of soil transportation with sheet flow and mass failure on the steep slope (Benda and Dunne, 1997; Keefer and Larsen, 2007). Although, the process is readily observed on natural hill slopes, quantifying it in a natural environment is significantly challenging given the extended timeframe between occurrence of the process, and variability in rainfall, soils, and other factors (Acharya et al., 2011). Site-specific and real-time measurement is almost impossible due to the uncertainty and non-continuity of gravity erosion. Hence the volume of individual failure was normally calculated by multiplying the slide area by the thickness of the slide mass after the rainfall events (Guzzetti et al., 2009; Haflidason et al., 2005). Nevertheless, the calculated volume involves an amount of tinkering, for shallow debris flow scars rapidly heal and are difficult to detect after as few as years (Montgomcry and Dietrich, 1994). Moreover, erosion volumes caused by water and gravity could not be distinguished from the above calculation approaches. Landslide activity maps represent a short-cut in the assessment of mass movement hazards (Parise and Wasowski, 1999). While valuable, these inventory maps usually do not provide information on the timing of the events, making it difficult to correlate landslide occurrences with specific triggering events (Kirschbaum et al., 2010).

The specific processes of rain-induced mass failures are most easily studied and quantified in a flume using a rainfall simulator under controlled laboratory conditions (Acharya et al., 2011). Here, we employed a topography meter designed by us to quantitatively measure the process of gravity erosion, and we utilized the increase-rate-analysis method to analyze the sensitivity of gravity erosion. The experimental activity was focused on processes related to gravity and to the interaction between rainfall and topography.

2. Study area

The Loess Plateau is located in the upper and middle reaches of the Yellow River, covering a total area of 624,000 km^2 (Fig. 1). Most of the area is an arid or semi-arid region with dry air, little clouds, and abundant illumination, but is short of moisture. The average annual precipitation on the Loess Plateau is only 350 to 550 mm, most of which is concentrated in the rainy season of June to September (Xu et al., 2004). Usually, a few short yet intense rainfalls can account for more than 60%, even 90%, of the total precipitation in a year.

Areas of the Loess Plateau, especially the Loess Hill Ravine Region and the Loess Mesa Ravine Region, are severely affected by gravity erosion. All types of mass failure are abundant in the area, and locally cover 30–50% of the land (Wang et al., 1993). In the area, rainstorm-induced gravity erosion frequently occurs, because the undulating terrain on the Loess Plateau is characterized by crisscrossing gullies, the vegetation is so sparse, and especially the loess is collapsible and in vertical joints. On the Loess Plateau, a steep bank with the slope more than 70° in the upper reaches of the small watershed is the main source of gravity erosion. Forms of gravity erosion on the Loess Plateau include avalanche, landslide, earth flow, and creep (Tang, 2004).

3. Method and materials

To classify different failure mechanisms and observe conditions of instability, we conducted a series of gully bank collapse experiments under closely controlled conditions in 2010 and 2012 in the Joint Laboratory for Soil Erosion of Dalian University of Technology and Tsinghua University located in Beijing, China. The landscape simulator consisted of a rainfall simulator and a slope model covering an area of 3.0 m by 3.0 m (Fig. 2). Five runs of rainfall were applied in turn on a conceptual landform with a gentle upper slope of 3° and steep lower slope of 70°–80°. An equal period, 12 h or so, was kept after each rainfall to ensure the approximate value of initial water content. The conceptual slope was made with loess by hand patting. The 50% diameter of soil particles, $D50$, was 52.2 μm, and the specific gravity, γ_s, was 2.56. The physical properties of the model soil was similar to that of the Loess Plateau; that is, distribution of the grain size is close that in Shanxi, Gansu, and Shannxi (Xu et al., 2009). A summary of the tests carried out by us is reported in Table 1.

In this experimental study, the failure style was defined by direct eye observation of the process of soil deformation, and the volume of failure mass was calculated according to the video of the topography meter. Both during and 20 min after the rainfall, slope failure occurrence time, slip mode, type of failure scar, location, and slope failure retrogression behavior were recorded by direct observation and the topography meter (Fig. 2). In contrast to the conventional contact observation instruments, the topography meter could quantitatively measure the random mass failures on the steep slope in dynamic environments. The topography meter emitted a group of parallel lasers to the slope surface and recorded the dynamic variation of the steep slope under rainfall simulation with a video camera. Then the operator could transform the plane figures into 3D graphs to compute the shape of the target surface. By comparing the slope geometries in the moments before and after the erosion incident on the snapshot images, we could obtain the soil erosion data, including the volume of any individual slide masses. The instrument was invented by the authors themselves, and its performance was confirmed in the calibration tests and the landslide experiments (Xu et al., 2015a,b).

Gravitational erosion involved both large-scale mass wasting and smaller-scale erosion. The size of each mass failure was calculated and classified, and then the total amount of all failure masses g_t and the peak value of individual erosion events during a rainfall event g_p were obtained. All failure masses with volume more than 500 cm^3 were considered in the experimental study. To assess the effects of the initial landform geometry on the gravity erosion, we divided experiments into the following eight experimental groups, each of which had the same slope height or gradient:

(1) G1 (experiments L5–8) vs G2 (experiments L1–4). Rainfall intensity in the former experimental group was 0.8 mm/min, while the later was 2.0 mm/min.
(2) G3 (experiments L9–10) vs G4 (experiments L5–6). Rainfall duration in the former experimental group was 30 min, while the later was 60 min.
(3) G5 (experiments L1, 3, 5 and 7) vs G6 (experiments L2, 4, 6 and 8). Slope gradient of the initial lower slope in the former experimental group was 70°, while the later was 80°.
(4) G7 (experiments L1, L2, L5 and L6) vs G8 (experiments L3, L4, L7 and L8). Slope height of the initial lower slope in the former experimental group was 1.0 m, while the latter was 1.5 m.