Geomorphology 125 (2011) 203–213

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

An experimental study on dynamic processes of ephemeral gully erosion in loess landscapes

J.G. Gong [a,*], Y.W. Jia [a], Z.H. Zhou [a], Y. Wang [b], W.L. Wang [c], H. Peng [a]

[a] Department of Water Resources, China Institute of Water Resources and Hydropower Research, Beijing 100038, China
[b] State Key Laboratory of Earth Surface Processes and Resource Ecology, College of Geography and Remote Sensing, Beijing Normal University, Beijing 100875, China
[c] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, CAS and MWR, Yangling, Shaanxi 712100, China

ARTICLE INFO

Article history:
Received 19 June 2010
Received in revised form 21 September 2010
Accepted 22 September 2010
Available online 29 September 2010

Keywords:
Erosion
Hydrodynamics
Runoff
Ephemeral gully
Loess Plateau

ABSTRACT

Ephemeral gully erosion is widespread on the Loess Plateau of China. To provide theoretical support for constructing numerical models and soil-water conservation planning, the hydrodynamic characteristics of ephemeral gully flows were studied by laboratory experiments with a physical model. We firstly concluded that, with the influence of "step-slope-pool" (or "step-pool") terrain on the bottom of gully channels, no obvious or consistent pattern changes were evident in the hydrodynamic parameters along the flow direction. Secondly the change of hydrodynamic parameters during erosion could be classified into an initially fast changing interval followed by a stable period, and the initial adjustment period would become shorter with increasing slope and rainfall intensity. Thirdly ephemeral gully erosion flows were turbulent and changed frequently in space and time between supercritical and subcritical flows. Throughout the experiment, the Reynolds number fluctuated and increased with time. With increasing rainfall intensity and gully slope, the frequency of larger Reynolds numbers increased. In addition, the Froude number also fluctuated, but decreased with time, and the mean Froude number eventually stabilized at ~0.5 at different slope angles and rainfall intensities. Fourthly the distribution of erosional energy was influenced mainly by topography in loess slopes. In the case of 20° slopes, the inverse ratios of dissipation as soil erosion, sediment transport, and flow kinetic energy were relatively stable in time and space during ephemeral gully erosion. Moreover, flow velocity, shear stress, the Darcy–Weisbach friction factor, and the Manning coefficient were influenced by rainfall intensity to a lesser degree during erosion. In the stable interval, for 15° and 25° slopes, shear stress, the Darcy–Weisbach friction factor and Manning coefficient of ephemeral gully flow both increased with increasing rainfall intensity. Flow velocity on the 15° slope decreased initially then increased with increasing rainfall intensity, but flow velocity on the 25° slope decreased with increasing rainfall intensity. Finally the regularity seen in hydrodynamic parameters of ephemeral gully flows occurred despite disturbance from lateral confluences, gravity erosion of the channel bank, and changes in terrain. The sediment transport capacity of ephemeral gully flows increased with USP by a linear function ($r = 0.64$, $n = 99$, $P < 0.01$).

1. Introduction

In recent years, the importance of soil erosion processes has been widely recognized. Based on accurate surveys and detailed study of gully erosion processes near Milledgeville, Georgia, from 1840 to 1938, Ireland (1939) showed that retreat of gully heads had slowed over time, because the heads were within 200–300 ft of the drainage divide and received much less water than they did previously.

Classification of water erosion includes splash, rill, ephemeral gully, and gully erosion. The term "ephemeral gully" was coined by American scholars in the twentieth century as a then newly recognized type of erosion. The official website of the Soil Science Society of America (2010) defines ephemeral gullies as "small channels eroded by concentrated flow that can be easily filled by normal tillage, only to reform again in the same location by additional runoff events."

On the Loess Plateau of China, some researchers (Huang, 1953; Zhu and Zhang, 1955) in the 1950s observed that there were many shallow gullies without steep walls, the traces of which cannot be removed after contour plowing. Shallow gully erosion is a transitional erosion type between rill and gully erosion. More recently, researchers (Liu et al., 1988; Zhang et al., 1991; Wang et al., 2003a,b) have emphasized that a shallow gully is an erosion trench formed at the bottom of weak slope incisions scoured by surface runoff. They noted that shallow gullies occur mainly on 15° tilled slopes, and while they have no impact on plowing, they could develop into gullies. Thus, shallow gullies can be treated as part of the extended "ephemeral gullies" group.

---

* Corresponding author. Tel.: +86 10 68785505; fax: +86 10 68785625.
E-mail address: jiaguogong@163.com (J.G. Gong).

0169-555X/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2010.09.016

On the Loess Plateau, especially in hilly areas, ephemeral gullies are the main erosion type and widespread (Zhang and Tang, 1992). They typically occur on slopes between 20 and 60 m below the watershed divide and gully erosion zone. In slope gully systems, ephemeral gullies are the transitional links between rills and gullies (Wang et al., 2003a,b). Ephemeral gullies amount to ~70% of the land surface area between gully areas, and they contribute to 35–70% of the slope erosion mass (Tang, 2004). Ephemeral gullies can broaden the erosion area, increase the ephemeral gully catchment area, and speed up the flow concentration of slope flow. As a result, flow can be collected easily, and erosion energy can be enhanced. Ephemeral gullies provide the energy for full erosion and gully-head development (Wang et al., 2003b).

Ephemeral gully incisions are the main channels of sediment delivery derived from raindrop splash erosion, surface erosion, and rill erosion, and also are the main source of eroded sediments. The hydrodynamic processes of ephemeral gully gouges are important in slope gully systems. According to Wang et al. (2003b), the hydrodynamics of ephemeral gully water flows is similar to that of open channel water flows. The study of hydrodynamic parameters of ephemeral gully water flow has developed widely around the world. Hydromechanical models based on these hydrodynamic parameters can be used to forecast erosion. These studies lend themselves to experimental analysis where estimates of soil erosion can be made in order to investigate hydrodynamic parameters. The pertinent hydrodynamic parameters include flow depth (Merz, 1990), total discharge, discharge per unit width (Meyer et al., 1975; Line and Meyer, 1989), flow shear stress, effective flow shear stress (Lyle and Smerdon, 1965; Torri, 1987; Ghebreiyessus et al., 1994; Nearing et al., 1997), runoff kinetic energy (Bagnold, 1977; Hairsine and Rose, 1992; Elliot and Laflen, 1993; Zhang et al., 2003), effective runoff kinetic energy (Govers, 1992), unit stream power (Yang, 1972; Moore and Burch, 1986), and the Froude number (Fr) (De Ploey, 1983). Other models include the runoff kinetic energy model GUEST (Misra and Rose, 1996), and KYERMO (Hirschi and Barfield, 1988). The U.S. Department of Agriculture developed the ephemeral gully erosion model (EGEM) (Foster, 1990), the only conceptual tool tailored specifically for ephemeral gully erosion. The EGEM comprises a hydrological module and an erosional module. It simulates spatial and temporal changes in gullying and forecasts annual average soil erosion of a single gully, but its adaptability to different regions is low (Casalí et al., 1999; Capra and Scicolone, 2002; Valcárcel et al., 2003; Capra et al., 2005).

Despite decades of research on ephemeral gullies around the world, many unsolved problems still persist in many regions. The Loess Plateau is a plateau that covers an area of 640,000 km² in the upper and middle reaches of China's Yellow River, and in China proper. Since the silty loess soil is highly prone to erosion, it has been called the “most highly erodible soil on earth” (Laflen, 2000). Because field observations can be difficult and hazardous in this part of China, the number of field-based studies on the dynamic process of ephemeral gully erosion on the Loess Plateau is limited. Based on previous field observations, we conducted a simulation experiment that investigated changes in flow patterns, kinematic behavior, and frictional behavior of ephemeral gully flow. Hydrodynamic processes also were analyzed. This study is intended to provide theoretical support for establishing an ephemeral gully erosion model based on hydrodynamic processes in the Loess Plateau, and in other regions of similar soil types.

2. Experimental design

Ephemeral gully formation on the Loess Plateau proceeds as follows. On sloping farmland, rainfall leads to sheet flow, which initiates sheet and rill erosion and concentrated flows. Points of initial incision evolve into erosion gullies in the downslope direction. Since the land is used for agriculture, the gullies then are filled and leveled during plowing. With subsequent rainfall events, the filled gullies are re-initiated at the sites of the original gullies. This alternating erosion and plowing over time produces the unique topography of the Loess Plateau hilly area, termed “imbricated landform” (Fig. 1) (Zhang and Tang, 1992). The factors influencing ephemeral gully formation and development are soil type and texture, rainfall, land slope and shape, and land use.

The experimental loess was located in the hilly region of the Loess Plateau, Ansai County. Initially we built up 10-cm depth samples of fine sand on the bottom of the experimental flume. The loess was passed through a 1-cm sieve, then placed in the experimental flume to a depth of 50 cm (built up in five layers). The two surface layers simulated the plow zone, and were packed at a bulk density of 1.1 g cm^{-3}. The three lower layers were packed at a bulk density of 1.25 g cm^{-3}. The soil particle size distribution is presented in Table 1.

The experimental parameters are presented in Table 2 (Zhang et al., 1991; Zhang and Zhu, 2006; Xiao et al., 2009). Runoff from the upstream catchment area was simulated by controlled release of water. The simulated slope length was 8 m (Fig. 2).

After the soil sample was set up in the flume, and to maintain soil moisture consistency between different experiments, synthetic rain was applied at 15-mm h^{-1} intensity until surface runoff on the slope occurred. The soil sample was then left undisturbed for 24 h. To adjust the rainfall intensity, we covered the flume by placing a plastic film over the experiment. Then, we uncovered the film, and set the “zero” time as the start of flow out of the flume. At the same time, water discharged from above at a set flow rate. Three observation sections were located at 2, 4 and 6 m in the down slope direction. Observation times were at 1, 3, 6, 9, 12, 15, 18, 21, 24, 27, 30, 33, 36 and 39 min after the experiment commenced (Fig. 3). Every experiment was repeated twice, and we took the average of the observed data within 1–30 min.

Observed variables were flow rate (Q, $\mathrm{m}^3\ \mathrm{s}^{-1}$), sediment concentration (S, kg m^{-3}), flow velocity (v, m s^{-1}), flow surface width (w, m) and depth (d, m), gully width and bottom depth (m), and temperature (T, °C) at the outlet.

3. Results

The hydrodynamic parameters studied were the Reynolds Number (Re), Froude Number (Fr), shearing stress (τ, N m^{-2}), unit stream power (USP, m s^{-1}), Darcy–Weisbach friction factor (f), and Manning coefficient (n). The equations were as follows:

$$Re = vR/\eta \tag{1}$$

$$Fr = v/\sqrt{gd} \tag{2}$$

$$\tau = \gamma RJ \tag{3}$$

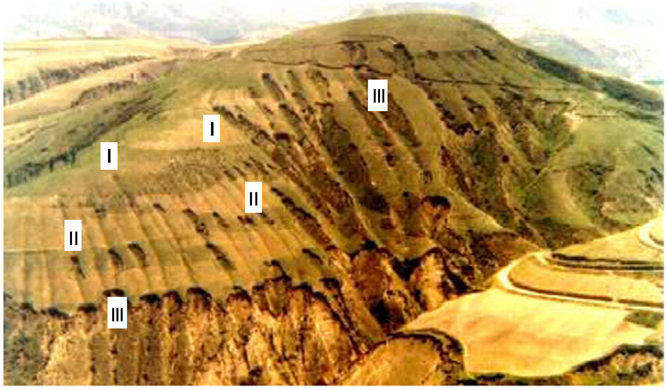

Fig. 1. Typical slope in the hilly region of the Chinese Loess Plateau (Tang, 2004).