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A laboratory study of channel sidewall expansion in upland concentrated flows

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ABSTRACT

Gully erosion contributes large amounts of sediment within watersheds around the world. Gully widening constitutes about 80% of total soil loss, especially in the presence of a plow pan which manifests a less or non-erodible soil layer. Current knowledge on sidewall toe scour (scour arcs) and tension crack processes in gully widening is limited. Thus, simulated channel sidewall expansion tests, where the channel bed was fixed to represent a non-erodible layer, were designed to investigate how inflow rate, slope gradient and initial channel width affect channel widening processes. Soil boxes (2.0 m-long, 0.3 m-wide and 0.5 m-deep) with two slope gradients (15° and 20°), four inflow rates (1.0, 2.0, 3.0 and 4.0 L min^{-1}) and two initial channel widths (4 and 8 cm) were subjected to clear-water overland flow. Photogrammetry was used to detect tension crack and width variations of channels. The results show that sediment delivery and channel width increase with the increase of inflow rate, bed slope and the decrease of initial channel width. Exponential equations were used to predict the channel width time series. Time lag occurred between sediment peak and soil block failure. Toe scour, crack development, sidewall failure and block detachment and transport, in sequence, were the four main processes of channel widening. Basal scour arc length, tension crack length and width decreased with initial channel width and increased with time, flow discharge and bed slope. Basal scour arcs were divided into three patterns according to different shapes in comparison to the failure arcs. Sediment delivery equations based on the disaggregation of concentrated flow entrainment and mass failure were also fitted. This study provides new insight on improving gully erosion measurements and prediction technology.

1. Introduction

Gully erosion, where runoff water accumulates and removes soils from the gully area, is one of the main soil erosion types and a major source of sediment to river systems (FAO, 1965). Depending on morphological characteristics and erosion patterns, gullies can be divided into two types: ephemeral gully and classical gully (Foster, 1986; Castillo and Gómez, 2016). Soil loss by gully erosion represents from 10% to 94% of total water erosion worldwide and it occupies around 60% of the sediment yield in the hilly gully region and more than 80% in the gully region on the Loess Plateau of China (Poesen et al., 2003). Concentrated flow in gully channels erodes fertile soil and fragments croplands, and as a result, gullies become pathways for transporting other pollutants within watershed systems (Castillo and Gómez, 2016).

Physical gully evolution processes include headcut migration, bed incision and sidewall expansion (widening), and each process dominates at different phases of gully development (Bingner et al., 2016). These three processes occur consecutively and interact with each other through feedbacks. Initial gully width is determined by the gully head retreat process. When a non- or less-erodible layer is present in the subsurface in a constant bed slope gully, the concentrated flow begins to erode the base of sidewalls and, consequently, increased gully widening follows (Di Stefano and Ferro, 2011; Wells et al., 2013). Chaplot et al. (2011) reported that sidewall retreat was confirmed to be a main process after headward migration in overall gully evolution and overall erosion in landscapes. Sidewall failure, which provides the main sediment source during the final stage of gully development, contributes as much as 80% of the total eroded sediment from incised

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channels in the loess area of the Midwest United States (Simon et al., 1996) and more than half of the gully volume in New South Wales, Australia (Blong et al., 1982). Various factors such as discharge, slope, soil properties and management conditions significantly influence gully width evolution processes (Bingner et al., 2016). Wells et al. (2013) pointed out that gully width and its widening rate increased as bed slope and discharge increased and corresponding predictive empirical equations of gully widening were formulated.

The processes and mechanisms of gully sidewall collapse are complex and attract much attention (Martinez-Casasnovas et al., 2004; Chaplot et al., 2011; Chen et al., 2013; Wells et al., 2013; Momm et al., 2015; Bingner et al., 2016). However, the failure of gully sidewalls is hard to be fully evaluated because it is influenced by many factors (Bradford and Pies, 1977). Istanbulluoglu et al. (2005) pointed out that gully erosion is most commonly triggered by fluvial erosion, more specifically, the bank failure is attributed to a combination of water erosion (fluvial shearing process) and gravity erosion effects (gravitational mass failure process). Chaplot et al. (2011) indicated that the triggering of gully sidewall failure processes could be attributed to three sub-processes which contribute to total gully sidewall erosion in descending order: by water running along gully sidewalls, transport of soil material by splash and the falling of entire soil blocks. Gravitational mass failure, which is difficult to predict due to its sudden occurrence, begins with sidewall toe scour, ultimately leading to high and unstable sidewalls (Chen et al., 2013). After scouring the gully toe, a tension crack frequently forms on the surface behind the sidewall top lip. These cracks occur when the driving forces, e.g., gravitational force, become larger than the resisting forces, i.e., soil cohesion and friction (Istanbulluoglu et al., 2005; Thomas et al., 2009). The overhanging layers then continue being undermined by fast concentrated flows, and as a result, collapse and gully widening accelerate (Billi and Dramis, 2003; Martinez-Casasnovas et al., 2004; Chen et al., 2013).

Non-erodible layers, which have a resistance to erosion greater than that of the overlying soil, often develop due to conventional tillage operations (Wells et al., 2013). The plow depth is often correlated with depth to the non-erodible layer, as the lower edge of the plow or disc tends to compact and smear the soil at that depth. As soil erodes and concentrated flow occurs, incision through the freshly ploughed soil is delayed or halted at the intersection of the plow pan and the above erodible layer (Bingner et al., 2016). Gully widening occurs as a consequence of this intersection and shows an increase in widening rate, as the energy of the flowing water shifts from a vertical force to a horizontal force. Researches on rill and gully erosion, have focused on the sidewall widening processes and mechanisms when plow pans were encountered, and indicated that a platy-structured compact bed which is a less- or non-erodible layer was often formed at the plough depth (Fullen, 1985; Shen et al., 2015). Laboratory studies were designed to investigate the impact of non-erodible layer on gully evolution, especially gully widening (Gordon et al., 2007; Wells et al., 2013).

Research findings on river bank toe-erosion process and its affecting factors (Wang et al., 2016), tension crack formation and development (Hossain et al., 2011), mass failure mechanisms (Darby et al., 2002; El Kadi Abderrezzak et al., 2014) and bank stability simulation (Darby et al., 2002) have laid a foundation for gully sidewall collapse research. However, some of the algorithms that have been developed to determine river/gully width have not taken depth limitation into account so that it may significantly impact the widening prediction where a less erodible layer encountered (Gordon et al., 2007; Wells et al., 2013; El Kadi Abderrezzak et al., 2014; Bingner et al., 2016). The processes that control gully widening such as sidewall toe scour and changes of tension crack with time is still very weak and need to be intensified (Bingner et al., 2016). Understanding of gully bank retreat should be considered by further in-situ and modeling studies (Chaplot, 2013). Improved understanding of gully widening processes is critical to the development of some modules of water erosion prediction models such as CREAMS, EphGEE and AnnAGNPS (Wells et al., 2013; Dabney et al., 2014; Bingner et al., 2016) and is essential in the assessment of conservation practices on controlling gully erosion in agricultural fields.

In this study, channels are formed above a non-erodible layer to investigate channel widening processes with certain inflow volume and varied durations after channel headcut migrating upstream and channel bed finishing undercutting. Scouring tests were implemented to study the effect of slope gradient, inflow rate and initial width on channel widening in the presence of a non-erodible channel bed. The specific objectives of this study were: 1) to determine channel sidewall expansion processes and morphodynamic changes under different experimental designs, 2) to discuss how channel toe scour and tension crack development affect the channel widening process, and 3) to establish a predictive equation for channel width time series.

2. Materials and methods

2.1. Experimental design, materials and setup

This study consisted of 12 experimental runs (non-completely orthogonal experimental design), three factors were considered: four inflow rates (1.0, 2.0, 3.0, 4.0 L min^{-1}), two slope gradients (15° and 20°) and two initial channel widths (4 and 8 cm width with 4 cm depth). The lengths of different experimental runs were in accordance with inflow rates to keep the total inflow volume constant (60 L). For 1.0, 2.0, 3.0 and 4.0 L min^{-1} inflow rate, the lengths of experiments were 60, 30, 20 and 15 min, respectively. Each experimental run included two replicates and the experiments reported here are average values of these two replicates; however, the 8-cm initial channel width was tested with the 20° slope only. The detailed comparisons between experimental design and natural conditions is shown in Table 1 (Zhang, 1983; Zhou and Wang, 1987; Wu and Cheng, 2005; Wang et al., 2014). Four soil boxes measuring 2.0 m-long, 0.3 m-wide and 0.5 m-deep (Fig. 1), containing drain holes with 2 mm diameter (1 cm grid spacing) at the soil box bottom, were used in this study. For each experimental run, soil boxes were selected randomly to prevent the occurrence of systematic error. A runoff outlet at the downstream end of the soil box was used to collect runoff samples throughout the experiment (Fig. 1). A down sprinkler rainfall simulation system (He et al., 2014), consisted of three nozzles, can be set to a range of 30–350 mm h^{-1} rainfall intensity. Flow discharge was controlled by a constant-head water tank fixed 2.5 m above the soil box. To ensure that the regime of concentrated flow entering the initial channel was laminar, energy dissipation practices were applied at the transition section. It was a simulation of the changing process of turbulent flow with high flow velocity of channel headcut to laminar flow with low flow velocity of channel body. Pebbles of different sizes were pasted at the water tank outlet and linen cloth was laid at the junction between water tank and soil box (Fig. 1). Flow energy was dissipated and flow velocity was controlled at the transition section. The adjustable range of inflow rate was

Table 1
Comparisons of gully channels on the Loess Plateau and simulated channels, characteristics of rainfall and topography between natural conditions and experimental design.

Factors	Natural condition	Experimental design
Erosive rainfall intensity (equivalent inflow rate)/mm h^{-1}	10.5–234.8	10, 20, 30, 40
Erosive rainfall duration (experiment length)/min	5–600	15, 20, 30, 60
Slope gradient/°	15–39	15, 20
Width depth ratio	0.24–1.47	1, 2
Less- or non-erodible layer	Plow pan	Non-erodible layer
Depth of non-erodible layer/cm	20–40	4
Soil bulk density/g cm^{-3}	0.93–1.85	1.1 for plow layer, 1.3 below plow layer