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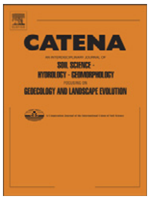

The influences of row grade, ridge height and field slope on the seepage hydraulics of row sideslopes in contour ridge systems

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ABSTRACT

Seepage plays an important role in soil erosion in contour ridge systems. Seepage generated from subsurface flow causes hillslope instability by reducing the soil shear strength and mobilizing soil particles and can produce cave-like features called seepage undercuts that can lead to contour failure. As the main threat to contour plowing, seepage results in large amounts of soil erosion due to row grade. Models used to predict seepage over a time series will provide a basis for modeling soil erosion resulting from seepage in contour ridging systems. Understanding seepage and its effects will advance our knowledge regarding seepage erosion mechanisms in contour ridge systems. In this study, 23 treatments were arranged using an orthogonal rotatable central composite design to model a seepage time series, build a simple seepage prediction model and investigate the effects of row grade, field slope and ridge height on seepage discharge.

Most of the seepage discharge time series followed an S-shaped curve. The seepage discharge processes were fit by an exponential model with a determination coefficients (R^2) greater than 0.995. Furthermore, the physical meaning of the exponential model was consistent with the experimental results. The seepage discharge continuously increased before the inflection point and then decreased. Finally, the seepage discharge approached a steady value. The maximum seepage discharge growth rate was achieved within 14 min, and the seepage discharge became steady within 106 min. Second-order polynomial regression models were used to determine the total and predicted steady seepage discharge using independent variables of row grade, field slope and ridge height, which produced R^2 values of 0.66 ($p < 0.05$) and 0.68 ($p < 0.05$), respectively. Ridge height and row grade significantly affected ($p < 0.05$) the total and predicted steady seepage discharge. Field slope (and its related factors) was ignored because it had no significant effects on seepage discharge. The effects of row grade resulted in a concave curve with an increasing factor value, and ridge height exerted a positive linear effect on seepage discharge.

1. Introduction

Soil surface hydraulics can play important roles in soil erosion. Laboratory studies have shown that sediment delivery under artesian seepage conditions is three to six times greater than that under drainage conditions with run–on and runoff feeding (Zheng et al., 2000). The average erodibility may be 5.64 times greater under seepage regimes than under drainage regimes (Nouwakpo et al., 2010). In addition, field observations revealed that seepage could induce rill formation, which could result in more soil loss and may be a dominant process in rill and gully hillslope and stream bank erosion (Crosta and Prisco, 1999; Sultan et al., 2004; Valentin et al., 2005; Pornprommin et al., 2010; Rao et al., 2011). Seepage causes hillslope instability, primarily by reducing the soil shear strength and mobilizing soil particles (Huang and Laflen, 1996; Simon and Curini, 1998; Simon et al., 1999; Fox et al., 2007b; Wilson et al., 2007; Chu-Agor et al., 2008; Fox and Wilson, 2010; Ke and Takahashi, 2012; Karmaker and Dutta, 2013; Vandamme and Zou, 2013). Seepage often results from a perched water table above a restrictive layer and is mainly generated from pipe flow (Fox et al., 2010; Midgley et al., 2013). The generation of pipe flow often accompanies larger subsurface flow (Wilson et al., 2007). Subsurface flow, which triggers internal erosion, can alter the strength of the soil (Fox et al., 2010). Meanwhile seepage under positive hydraulic gradients (upward directed flow) occurs under exfiltration conditions, and positive pore water pressures reduce the effective stress between solid contacts (Huang, 1998; Wilson et al., 2007; Nouwakpo et al., 2010). Seepage exfiltration can produce cave-like features called seepage undercuts, which can become larger and lead to cantilever failures. These processes are known to occur at numerous geographical locations (Karmaker and Dutta, 2013). Seepage on hillslopes can produce areas that are susceptible to surface erosion, particularly near the bottom of the slope, and can

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accelerate headcut development (Coates, 1990; Huang and Laflen, 1996; Huang, 1998; Fox et al., 2007d; Wilson et al., 2007). Incorporating groundwater seepage into models to quantify soil erodibility will make the model more applicable to fluvial erosion (Al-Madhhach et al., 2014). Many researchers have studied seepage-induced soil erosion by using stream bank failure models (Fox et al., 2007a; Lasage et al., 2008; Lindow et al., 2009), such as the novel particle-based bluff morphology model (BMM) (Huang, 1998) and the finite element model, which was developed to analyze the generation of overland flow on infiltration surfaces (Motha and Wigham, 1995).

Contour ridge tillage has been used worldwide because of its many advantages, such as enhancing rainwater harvesting (Barton et al., 2004; Patil and Sheelavantar, 2004; Li et al., 2007; Mansour and Mohammad, 2009; Stevens et al., 2009), improving soil physical conditions (Hatfield et al., 1998; Lamb et al., 1998; Lowery et al., 1998; Barbosa et al., 2009), protecting soil from erosion (Gupta et al., 1990; Jr. et al., 2001; Liu et al., 2006; Mert et al., 2006), and reducing the need for labor (Lal, 1990; Materechera and Mloza-Banda, 1997). To effectively reduce soil erosion, several techniques have recently been developed, including plastic-covered ridge and furrow rainfall harvesting (PRFRH) systems (Thapa et al., 1999; Li et al., 2001; Li et al., 2008) and contour ridge tillage systems with natural grass barrier strips (Thapa et al., 1999). In northern China, contour ridge systems, which are considered the most effective tillage systems, are widely used on sloping land (Sombatpanit et al., 1995; Liu et al., 2006; Liu et al., 2010).

It is believed that contour ridge tillage should always be implemented along contour lines in arid or semi-arid areas (Flanagan and Livingston, 1995; Hatfield et al., 1998; Shi et al., 2004; Stevens et al., 2009). However, in locations with irregular microtopographic relief, it may be impossible to construct ridges that precisely follow contours (Griffith et al., 1990). This problem results in furrow depressions. Thus, rainwater can accumulate in these depressions and lead to further water infiltration in the furrows and water seepage from the row sideslope. In contour ridge systems, the irregular microtopographic relief of the ridge geometry, which is called the row grade, is essential for seepage generation. The seepage running through the ridge soil is similar to the seepage that is generated on the lower hillslope. In this case, the ridge can easily collapse and enhance soil erosion (Liu et al., 2014a; Liu et al., 2014b). Seepage hydraulics plays an important role in the rill erosion process in contour ridging systems.

Soil erosion in contour ridge systems is considered in the revised universal soil loss equation, version 2 (RUSLE2), in which ridge height and row grade factors are used to estimate the subfactors of support practices (P) (Hessel et al., 2003; Liu et al., 2014a). However, the occurrence of soil erosion under seepage conditions is not clearly explained by the RUSLE2 model. Thus, the incorporation of seepage into models to quantify soil erodibility will improve the accuracies of the models when considering particle mobilization and local failure mechanisms during erosion processes (Midgley et al., 2013; Al-Madhhach et al., 2014). Soil properties (e.g., soil aggregation and shear strength) can affect seepage erosion processes, which could influence soil erodibility and rill development (Bryan, 2000). The slope of the restrictive layer is linearly related to the flow rate and time until seepage initiation (Wilson et al., 2007; Fox and Wilson, 2010). By contrast, Bryan et al. (1998) considered that linking rill formation to only seepage processes may be unreliable when conducting simulated rainfall experiments in a general simulated plot with a smooth soil surface. Meanwhile, seepage and pipe flow processes can trigger internal erosion to reduce hillslope stability, and an internal erosion model has been investigated (Huang and Laflen, 1996; Midgley et al., 2013). In contour ridge systems, the field slope, ridge height and row grade are the main factors that affect sediment delivery and runoff under seepage conditions (Liu et al., 2014a; Liu et al., 2014b). Seepage processes play an important role in soil erosion mechanisms. However, few studies have been conducted regarding the contributions of seepage hydraulics mechanisms and seepage prediction. Seepage is an important factor that affects soil erosion, and understanding seepage processes is important for providing basic data for soil erosion research and prediction. Seepage modeling is helpful for understanding the processes that reduce soil stability and the mechanisms of soil erosion. However, seepage may be affected by microtopography and ridge geometry. Therefore, understanding the processes that are responsible for generating seepage and the factors that affect seepage and creating simple prediction models for seepage will improve our ability to model seepage processes when investigating soil erosion in contour ridge systems. The specific objectives of this study are to (i) analyze and model seepage time series and (ii) assess the effects of row grade, ridge height and field slope on seepage discharge to build a simple seepage prediction model.

2. Materials and methods

2.1. Experimental design

The orthogonal rotatable central composite design has been widely used to identify influential factors (Dadkhah, 1991; Zhou et al., 2007; Liu et al., 2015). Relative to a full factorial design and orthogonal array, this method could considerably reduce the number of treatments required for estimating all second-order polynomial regression terms without loss of efficiency. Therefore, this method could reduce testing time, allow for detailed statistical analysis, and help identify primary and monofactor effects (St-Pierre and Weiss, 2009).

Three factors were chosen for testing, row grade, field slope, and ridge height. According to the orthogonal rotatable central composite design, the three-factor quadratic regression orthogonal design table was chosen, as shown in Table 1 (Ding, 1986), and five code values (−1.682, −1, 0, 1, and 1.682) were determined for each factor. Due to the orthogonality of the experimental design, the information matrix

Table 1
The quadratic regression orthogonal design and experimental results.

Treatment No.	Code values			Factor values			Experimental results	
	X_1	X_2	X_3	RG (°)	FS (°)	RH (cm)	Total seepage discharge (L)	Predicted steady seepage discharge (L $\min^{-1}$)
1	1	1	1	8.4	13	14.4	40.938	1.007
2	1	1	−1	8.4	13	9.6	25.312	0.790
3	1	−1	1	8.4	7	14.4	35.064	0.946
4	1	−1	−1	8.4	7	9.6	19.414	0.592
5	−1	1	1	3.6	13	14.4	41.261	1.039
6	−1	1	−1	3.6	13	9.6	28.580	0.738
7	−1	−1	1	3.6	7	14.4	40.654	0.992
8	−1	−1	−1	3.6	7	9.6	21.333	0.633
9	1.682	0	0	10	10	12	31.279	0.918
10	−1.682	0	0	2	10	12	53.520	1.206
11	0	1.682	0	6	15	12	19.605	0.594
12	0	−1.682	0	6	5	12	30.276	0.776
13	0	0	1.682	6	10	16	52.320	1.317
14	0	0	−1.682	6	10	8	15.600	0.464
15	0	0	0	6	10	12	24.664	0.727
16	0	0	0	6	10	12	12.165	0.668
17	0	0	0	6	10	12	21.361	0.650
18	0	0	0	6	10	12	30.744	0.935
19	0	0	0	6	10	12	44.594	0.422
20	0	0	0	6	10	12	22.132	0.977
21	0	0	0	6	10	12	31.286	0.741
22	0	0	0	6	10	12	24.815	0.644
23	0	0	0	6	10	12	15.287	0.942

RG: row grade; FS: field slope; RH: ridge height.