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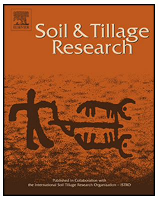

Influence of ridge height, row grade, and field slope on soil erosion in contour ridging systems under seepage conditions

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ABSTRACT

Seepage in contour ridge systems is a common phenomenon that can exacerbate soil erosion, however, the characteristics of soil erosion under seepage conditions in contour ridge systems are not clear. The objective of this study was to analyze the soil erosion process under seepage conditions and quantify the effects and interactions between the ridge height, row grade, and field slope on runoff and sediment yield. Twenty-three treatments for these three factors were arranged by an orthogonal rotatable central composite design. A new type of experimental plot for simultaneously changing the row grade and field slope and creating seepage conditions was used to imitate the microtopographic relief of contour ridge systems. In each run, seepage samples from the row sideslope were collected every 2 min for 60 min, and then artificial rainfall simulation was performed for 30 min during which runoff samples were collected every 1 min. The results showed that four soil erosion sub-processes were observed, including interrill erosion, headward erosion, contour failure, and rill erosion. Second-order polynomial regression models predicted the sediment yield ($R^2 = 0.74$) better than the runoff ($R^2 = 0.56$). Interactions between these factors did not significantly affect the runoff or sediment yield even at $p < 0.1$. The row grade and field slope exerted a greater effect on the sediment yield than on the runoff, whereas the ridge height influenced the runoff more with an increasing positive effect. The effect of these three factors on sediment yield revealed a convex curve with an increasing factor value. The field slope exhibited a greater increasing effect before the maximum sediment yield occurred and a greater decreasing effect after that than the other two factors did. The maximum runoff and sediment yield occurred at similar row grades (7.5° and 7.1°, respectively) and field slopes (10.9° and 10.8°, respectively). However, the minimum runoff occurred at a ridge height of 6.7 cm, and the maximum sediment yield at a ridge height of 12 cm. The findings have important implications for assessing and modeling soil erosion in contour ridge systems.

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1. Introduction

Seepage, defined as the reemergence of soil water at the surface, has been highlighted recently for producing areas susceptible to erosion on hillslopes (Chu-Agor et al., 2008; Huang and Laften, 1996) and stream banks (Fox et al., 2007b; Karmaker and Dutta, 2013), which are considered the dominant source of river sediment in many areas (Fang et al., 2012; Fox and Wilson, 2010; Shi et al., 2013). Under seepage conditions, water-saturated soil looses its matric suction, which effectively reduces the stress of surface soil particles (Vandamme and Zou, 2013; Al-Madhhachi et al., 2014). In addition, the exfiltration gradient can work against gravitational forces, further decreasing the effective stress (Huang and Laften, 1996). The seepage flow itself possesses erosive power, and fine particles can be eroded through the voids between coarse grains, significantly increasing hydraulic conductivity and decreasing soil strength (Ke and Takahashi, 2012). Nouwakpo et al. (2010) observed that the average erodibility under seepage regimes was 5.64 times larger than that under a drainage regime, and the critical shear stress decreased dramatically as the hydraulic gradient increased from negative to positive (Nouwakpo et al., 2010). The effect of the hydraulic gradient on soil strength has also been confirmed by Ke and Takahashi (2012).

Recent laboratory studies and field observations have demonstrated that the decrease in soil stress and increase in erodibility caused by seepage can exacerbate soil erosion (Fox et al., 2007b; Huang and Laften, 1996; Nouwakpo and Huang, 2012; Zheng et al., 2000). Huang and Laften (1996) observed that at a 5% slope, the

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sediment concentration was six times higher for a surface under 20 cm seepage pressure compared with that of a surface drained for seven days, and the seepage could accelerate headcut development. Zheng et al. (2000) observed that sediment delivery was three to six times greater in artesian seepage conditions than under drainage conditions with run-on runoff feeding. The erosion rate was 2.1 times higher in seepage conditions than in drainage conditions under high rainfall and run-on intensity (6.8×10^{-4} $m^{-3}\,s^{-1}$), and the channel erosion rates were doubled under seepage conditions (Nouwakpo and Huang, 2012). Fox et al. (2007b) identified a maximum seepage of 1.0 L min^{-1} and sediment concentration of 100 g L^{-1} at a stream bank site in the Goodwin Creek watershed and observed at least three bank collapses due to the seepage-erosion-initiated undercutting of the bank. Wilson et al. (2007) and Midgley et al. (2013) studied seepage in situ and confirmed that seepage erosion was an important factor in streambank failure. Field observations revealed that seepage can induce the development of rills, leading to more soil loss than interrill erosion (Valentin et al., 2005), and this phenomenon was also verified by laboratory studies by Huang and Laften (1996).

Due to a lack of experimental observations and adequate research tools, the erosion process under seepage conditions has largely been overlooked in prediction models, such as in the Water Erosion Prediction Project (WEPP) (Fox and Wilson, 2010; Nouwakpo and Huang, 2012; Valentin et al., 2005). Recent studies mainly focused on two regimes related to seepage. One regime is the downslope of the slope land, which is modeled by adjusting the level of supply water feeding to the bottom. Seepage and drainage conditions can be created when the water level is higher or lower, respectively, than the soil surface in laboratory conditions (Gabbard et al., 1998; Huang and Laften, 1996; Zheng et al., 2000). Based on the submerged jet test (jet erosion test, or JET) used in situ as well as in the laboratory (Hanson and Simon, 2001; Hanson and Hunt, 2007; Al-Madhhachi et al., 2013), a mini JET with a device to impose seepage forces was developed by Al-Madhhachi et al. (2014) and was considered as an in situ mechanistic approach to investigating soil erosion under seepage conditions. The other regime is soil banks, which can be created by supplying water from the upper side of the soil matrix with a controlled water head (Chu-Agor et al., 2008; Fox et al., 2007a). To study seepage erosion under field conditions, Midgley et al. (2013) created an innovative trench injection system that can provide a constant head on a near-streambank groundwater system that has been successfully used to research seepage-induced streambank erosion and instability. However, another practical regime – the contour ridge system – has not been considered until now. Contour ridging can increase the infiltration of retained rainwater in furrows and result in seepage.

Contour ridging is an effective agricultural practice for soil conservation and crop promotion (Barton et al., 2004; Shi et al., 2004; Stevens et al., 2009). Soil erosion in contour ridge systems has garnered increasing attention because variations in field slope and microtopographic relief can produce ineffective erosion control (Hatfield et al., 1998; Liu et al., 2014; USDA-ARS, 2008). The effects of ridge height, row grade, and field slope on soil erosion before contour failure have been considered to the greatest extent in the Revised Universal Soil Loss Equation, Version 2 (RUSLE2) (USDA-ARS, 2008; Hessel et al., 2003). The ridge height, with a positive effect on water infiltration that results in less runoff and sediment yield, is used to compute the effect of contouring on erosion in the RUSLE2 model. The row grade along the furrows can form some depression areas where runoff accumulates. When the ponded rainwater exceeds the storage within a contour row, overflow occurs and may result in severe ephemeral gully erosion (Flanagan and Livingston, 1995; USDA-ARS, 2008). The conservation function of the contour ridge as the field slope increases is described as a concave curve, increasing from no soil conservation capacity to the greatest conservation benefit and then decreasing to no benefit again (USDA-ARS, 2008).

To analyze the effects and interactions between the row grade, field slope, ridge height and width, and rainfall intensity on soil erosion induced by contouring failure, Liu et al. (2014) conducted 32 rainfall simulation experiments arranged in an orthogonal array. The results revealed that the interaction between the field slope and rainfall intensity had a significant effect on the runoff, and the ridge height was the most important factor for sediment yield. However, this result and the research findings used in the development of the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), RUSLE (Renard et al., 1997), and WEPP (Flanagan and Livingston, 1995) did not consider seepage conditions. Recently, Al-Madhhachi et al. (2014) incorporated seepage forces into the Wilson model (Wilson, 1993) based on JET techniques and developed a new detachment model i.e., the modified Wilson model, for predicting the influence of seepage on soil detachment. Because of the seepage creation method, in which water was supplied to the bottom of the soil matrix by an attached device, more studies on the application of this modified model for the estimation of soil erodibility concerned with seepage in contour ridge systems are necessary. Thus, a better understanding of soil erosion under seepage conditions and its influencing factors in contour ridge systems will advance our knowledge of soil erosion and potentially improve soil erosion modeling and conservation practices. Therefore, this study was undertaken to examine soil erosion under seepage conditions. The specific objectives were to: (i) analyze the soil erosion process under seepage conditions and (ii) quantify the effects and interactions between the ridge height, row grade, and field slope on runoff and sediment yield.

2. Methods and materials

2.1. Experimental design

An orthogonal rotatable central composite design was used to investigate the effects of three influential factors: the row grade, field slope, and ridge height. With this method, the number of treatments required to estimate all of the terms of a second-order polynomial equation can be considerably reduced compared with the full factorial design. Most importantly, the response model coefficients could be uncorrelated and estimated as a function of only the distance from the center and not the direction (St-Pierre and Weiss, 2009). Therefore, this method is widely used in various fields (Domínguez et al., 2010; Hadjmohammadi and Sharifi, 2012; Hou et al., 2009; Tang and Feng, 2006; Zhou et al., 2007). Based on the results of field investigations and previous studies, the minimum and maximum values of these factors at the code values of 1.68 and −1.68 were determined, and then the values at the other code values (i.e., 1, 0, and −1) could be calculated, as shown in Table 1. Here, the code values were determined by the

Table 1
Code values determined by the orthogonal rotatable central composite design and corresponding factor values of row grade, field slope and ridge height.

Code values	Factor values		
	Row grade (°)	Field slope (°)	Ridge height (cm)
1.68	10.0	15.0	16.0
1	8.4	13.0	14.4
0	6.0	10.0	12.0
−1	3.6	7.0	9.6
−1.68	2.0	5.0	8.0

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