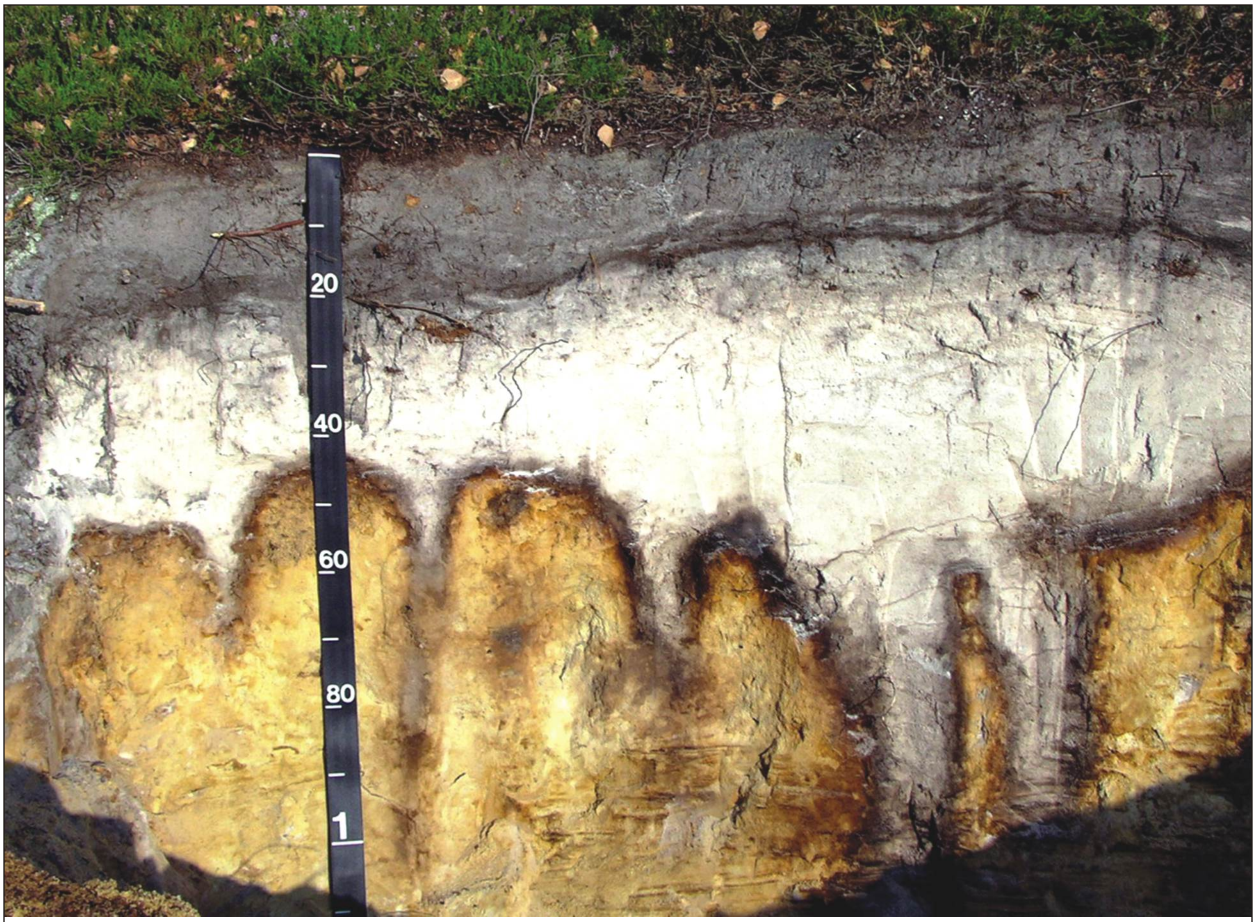


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# Effect of Rock Fragments Cover on Distance of Rill Erosion Initiation and Overland Flow Hydraulics

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## ABSTRACT

Rock fragments on the soil surface protect the soil against erosive agents. However, the effect of rock fragments cover on rill initiation is not well documented. The objective of this study was to evaluate the effect of rock fragment cover and the rate of flow discharge on distance and time rill initiation. The investigation was conducted using a flume with 6 m length, 0.5 m width and 3% gradient. The treatments included rock fragment cover (0, 10, 20, 30%) and three levels of flow discharge (3, 6, 9 L $min^{-1}$). The results showed that the surface cover of rock fragment had significant effect on different erosion processes, as well as rill initiation. Moreover, results indicated that velocity of water flow and the Froude number decreased but the Manning roughness coefficient increased (0.012-0.115 $m^{-1}$/3 sec) with an increase in rock fragment cover, whereas the Reinhold's number remained nearly the same with a small variation among different rock fragment cover percent. This variable was increased with increasing flow discharge. In addition, distance and time of rill initiation increased with a rise in rock fragment cover and diminished with increasing flow discharge.

**Key words:** Flume, Golestan province, Iran, loess soils, rill erosion

## INTRODUCTION

Rill erosion is a major participant to soil loss from crop land area. Other erosion types, such as inter-rill, splash, or tillage erosion often lead to translocation of soil within the field (Parsons *et al.*, 2004). Rill erosion has not only a serious importance for on-site effects of erosion but also for off-site effects and environmental concerns. The critical states for rill formation have been the focus of many researchers. Horton (1945) conceptualized the idea of rill formation threshold condition and later, Schumm (1956) used the concepts of the belt of no erosion and constant of channel maintenance to describe the distance from slope summit to the point of rill initiation. The threshold for rill initiation was defined by Kirkby (1978) as when duration of runoff exceeds this point, rill formation may take place. Torri *et al.* (1987) set a criterion to define the rill formation as when an incised rill is at least 5 cm long, 0.5 cm deep and 1 to 2 cm wide. Continuous development of the rill after its formation depends on the flow type. During the rill formation process, incised rills are formed as the result of detachment and transport of soil particles by concentrated flow.

Soil surface conditions as roughness, vegetation, rock fragments cover (Guo *et al.*, 2010), rain characteristics and topography (Moghaddam and Saghafi, 2008) play important roles in the control soil water erosion and initiation rills and gullies. A number of studies have showed that rock fragments cover has a significant effect on runoff and soil erosion. All these studies reported that runoff and erosion decrease with increasing rock fragments cover (Agassi and Levy, 1991; Chow *et al.*, 1992; Nyssen *et al.*, 2001; Martinez-Zavala and Jordan, 2008; Guo *et al.*, 2010). The soil surface can be protected by rock fragments cover against the impacts of raindrops, surface sealing, detachment and transport of soil particles (Martinez-Zavala and Jordan, 2008). So, the rock fragment cover on the soil surface reduces the total sediment yield (Rieke-Zapp *et al.*, 2007). The effects of rock fragments on eroding environment are: (1) protection of soil surface from direct impact of raindrops and soil particles detachment (2) decreasing the physical degradation of the soil surface and (3) increasing the surface roughness and delaying overland flow and thus reducing detachment and transport capacity of the run off (Poesen and Lavee, 1994; Abrahams *et al.*, 2001). Rock fragment surface cover can influence rill initiation because of its effects on soil erosion processes. Studying the distance and time of rill initiation can be useful in soil conservation practices, such as determining of the appropriate intervals in plant works, terracing and other conservation structures. The distance to rill initiation, on bare soil, decreases with increasing the slope steepness (Yao *et al.*, 2008) and critical flow for rill initiation decreased with an increasing slope degree (Farmanullah *et al.*, 1998). Rieke-Zapp *et al.* (2007) indicated Without rock fragments in the soil, rill incision continued over time and headcutting increased for experiments with few or no rock fragments in the soil. A few studies have focused on surface cover and how it affects rill formation. The purpose of present study was to investigate the effect of rock fragment surface cover on the distance and time of rill formation and understanding the relationship between the flow discharge and rock fragments cover in rill initiation.

## MATERIALS AND METHODS

The experiment was conducted in the Laboratory of rainfall and runoff simulation, Soil Conservation and Watershed Management Research Institute, Tehran, Iran. A runoff simulator with a sloped plot (6×0.5 m) was used (Fig. 1). The plot was initially prepared in a horizontal

Fig. 1: A view of flume

position. A 10 cm layer of coarse sand was uniformly placed in the bottom of the plot box; drainage holes in the bottom provided free drainage. On the top of the sand layer, a silty-loam soil (loess) was packed loosely and evenly to a depth of 20 cm. The soil texture was 20% clay, 69% silt and 11% sand. The soil was obtained from the root layer of a cultivated field located in the Loess Plateau area in Golestan province, Iran. The soil was air-dried, crushed and sieved with a 10 mm screen and then was packed in the plot to reach a bulk density of about 1.3 g $cm^{-3}$. During the packing process, a Rollers method was used to pack the soil uniformly in the plot. After packing, the soil surface was smoothed manually with a rake. Then rock fragments with 7 to 8 mm diameter were randomly distributed on the soil surface. The soil was saturated from below and allowed to equilibrate for 24 h, while the plot remained in a horizontal position to ensure a uniform initial soil moisture profile.

The treatments included rock fragment cover (0, 10, 20, 30%), each with three levels of flow discharge (3, 6, 9 L $min^{-1}$) that were tested at the 3% slope (the slope was same as the field). Each test was conducted 24 h after the saturation and pre wetting. The time of rill initiation was from runoff entry to plot until Primary rill formation moment. In each experiment, runoff and sediment samples were collected every minute until rill formation time. Runoff volumes and sediment mass were determined. Flow velocity was measured using a dye-tracing technique (potassium permanganate). The surface velocities ($V_m$) were converted to average velocity of flow profile (V) using the formula:

$$V = aV_m \tag{1}$$

where, a is a coefficient equal to 0.67 (Li *et al*., 1996).

Rill widths were measured with a ruler during the experiments. Each experiment ended, when a rill channel (at least 5 cm long, 0.5 cm deep and 1 to 2 cm wide was formed (Torri *et al*., 1987) (Fig. 2 a, b). After each test, the rills locations were determined throughout the profile accurately, by laser distance meter. The average distances of all rills in a test were used as distance to rill initiation for subsequent calculations.

The critical point of rill formation is the time when a small pit appears on the soil surface during the test that later develops into a rill. The critical conditions of rill formation are related to hydraulic

(a) (b)

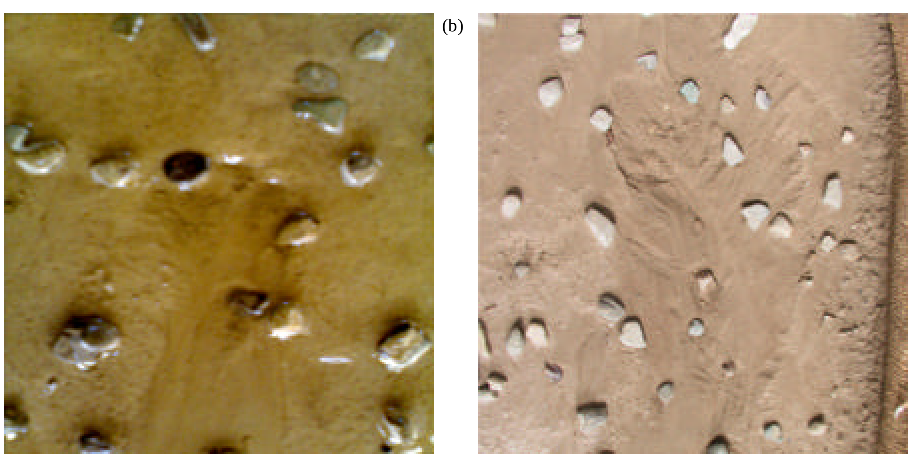

Fig. 2(a-b): Rill initiation in surface rock fragment covers parameters of the surface flow. When the strength and velocity of flow reaches a critical point, the soil particles miss the ability to remain in place and are detached by the overland flow. Two important hydraulic properties of the overland flow for rill formation are the shear stress and velocity. The values of these two parameters can be defined at the point of rill formation as $\tau_i$ and $V_i$, respectively. Soil critical shear stress ($\tau_c$) can be estimated assuming it the same as the shear stress ($\tau_i$) of the overland flow at the point of rill formation. In reality, the shear stress ($\tau_i$) of overland flow at the point of rill formation is greater than but very close to soil critical shear stress ($\tau_c$) because soil detachment has already occurred when the values related to the rill formation are measured in the experimental run.

Soil critical shear stress:

$$\tau_i = \tau_c = pgh_i \tag{2}$$

where, $\tau_i$ is shear stress (pa),p is water density (kg m$^{-3}$) with water temperature being taken into account, g is gravity acceleration (m sec$^{-2}$), S is sin ($\alpha$), in which $\alpha$ is slope angle and $h_i$ is flow depth (m):

$$h_i = \frac{q}{v_i} \tag{3}$$

where, q is unit flow discharge (m$^2$ sec$^{-1}$) and $v_i$ is average surface flow velocity (m sec$^{-1}$).

The Reynold's (Re) and Froude numbers (Fr) were calculated by Eq. 3 and 4, respectively:

$$Re = \frac{vh}{\vartheta} \tag{4}$$

$$Fr = \frac{v}{\sqrt{gh}} \tag{5}$$

where, $\mathbf{v}$ is kinematic viscosity (1.01×10$^{-6}$ m$^2$ sec$^{-1}$) and g is the gravity acceleration (m sec$^{-2}$).

The Manning roughness coefficient (n) was calculated as follow:

$$n = V^{-1} S^{1/2} R^{2/3} \tag{6}$$

where, n is manning roughness coefficient (m$^{-1}$/3 sec), V is mean surface flow velocity (m sec$^{-1}$), S is average slope steepness (sine of slope angle) and R is hydraulics radius (m).

## RESULTS AND DISCUSSION

Water and sediment is trapped by rough surface because it contains many barriers that decrease the flow velocity. Increasing the percentage of rock fragment cover in this study increased the surface roughness and manning roughness coefficient (Table 1). Poesen *et al.* (1990) and Guo *et al.* (2010) reported similar results at flume and field experiments, respectively. Increasing rock fragment cover, decreased the Froude number but had not significant effect on Reynold's number (Table 1). Also increasing the rate of flow discharge, decreased the Froude number and increased the Reynold's number.

The soil critical shear stress values ranged from 0.18 to 1.55 Pa, with an average of 0.87 Pa. (Fig. 3). A value of soil critical shear stress for the rock fragment cover treatments was higher than blank. A trend line added to Fig. 3 for the 6 L min$^{-1}$ discharge, indicates a high correlation. Figure 3 indicates that surface roughness's and hydraulic forces may be contributed to shear stresses of increasing rock fragment cover. These results are comparable with some other investigations conducted under various conditions. Despite differences in soil type, plot size and methodologies, the critical shear stress values obtained in this study were either within the range of that of the other reports. For example, Laflen *et al.* (1991) studied 56 soil types and obtained a shear stress range from 0 to 6.64 Pa. Yao *et al.* (2008) reported a critical shear stress range from 1.33 to 2.63 Pa for loess soils at the moment of rill initiation.

Distance to rill formation values are presented in Table 2. The rills developed when soil critical shear stress was exceeded the surface roughness induced shear resistance. Figure 4 shows that distance to rill initiation increased with increasing rock fragment cover and decreased with increasing flow discharge rate. These results are similar to those reported by Renard *et al.* (1997) which assumed that rill erosion is insignificant in slope lengths shorter than 4.5 m at a field.

Table 1: The flow hydraulic properties at different rock fragment cover and flow discharge

| Flow discharge (L min$^{-1}$) | Rock fragment cover (%) | Average flow depth (mm) | Flow velocity (cm sec$^{-1}$) | Reynold's No. | Froude No. | Manning roughn. coef. (m$^{-1}$/3 sec) |
|---|---|---|---|---|---|---|
| 3 | 0 | 0.6 | 16.1 | 83.4 | 2.24 | 0.012 |
| | 10 | 1.2 | 8.3 | 82.6 | 0.84 | 0.033 |
| | 20 | 1.5 | 6.4 | 79.6 | 0.58 | 0.049 |
| | 30 | 2.0 | 5.0 | 82.9 | 0.39 | 0.074 |
| 6 | 0 | 1.2 | 16.4 | 162.5 | 1.66 | 0.017 |
| | 10 | 2.2 | 9.1 | 163.5 | 0.68 | 0.042 |
| | 20 | 3.0 | 6.7 | 165.8 | 0.43 | 0.071 |
| | 30 | 3.8 | 5.3 | 166.3 | 0.30 | 0.104 |
| 9 | 0 | 1.5 | 19.6 | 253.2 | 1.73 | 0.016 |
| | 10 | 2.9 | 10.4 | 256.8 | 0.66 | 0.046 |
| | 20 | 4.2 | 7.2 | 247.9 | 0.39 | 0.081 |
| | 30 | 5.3 | 5.7 | 241.6 | 0.28 | 0.115 |

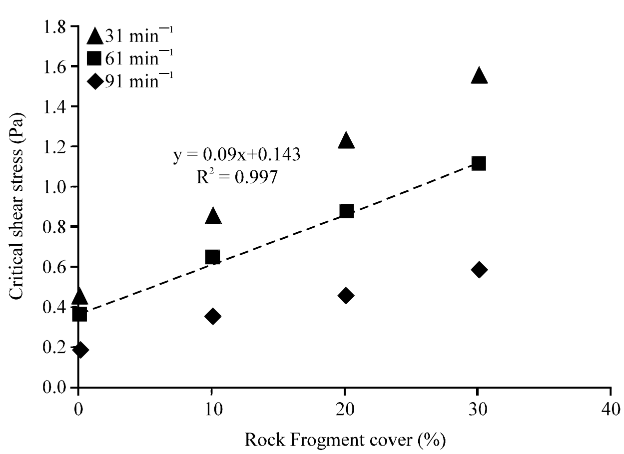


Fig. 3: Relationships of flow critical shear stress, rock fragment and flow discharge

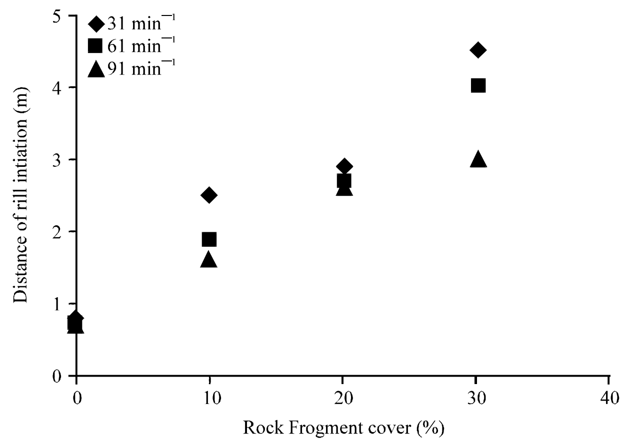


Fig. 4: Relationship between distance to rill initiation and rock fragment cover

Table 2: Experimental data at point of rill initiation

| Flow discharge (L $min^{-1}$) | Rock fragment cover (%) | Distance of rill initiation (m) | Time of rill initiation (min) |
|---|---|---|---|
| 3 | 0 | 0.8 | 7.29 |
| | 10 | 2.5 | 21.3 |
| | 20 | 2.9 | 30.1 |
| | 30 | 4.5 | 60 |
| 6 | 0 | 0.74 | 4.12 |
| | 10 | 1.9 | 15 |
| | 20 | 2.7 | 25.3 |
| | 30 | 4.0 | 48.3 |
| 9 | 0 | 0.7 | 3 |
| | 10 | 1.6 | 13.4 |
| | 20 | 2.6 | 20.4 |
| | 30 | 3.0 | 34.2 |

Table 2 shows quantitatively that the changes in distance to rill initiation were different for varied rock fragment percents and flow discharge rates and that the changes due to the rock fragments were more than that of the flow discharge rates, within the ranges of this experiment. This can be more clearly demonstrated using the relative change rate, defined as:

$$r = \frac{\Delta l_i}{l_0} \times 100 \tag{7}$$

where, r is the percent of distance change to rill formation, $\Delta l_i$ is the change of rill initiation distance because of rock fragment and flow discharge ranges (0 to 30% rock fragment covers in a determined flow discharge rate, or 3 to 9 L $min^{-1}$ flow discharge rates in a determined rock fragment cover) and $L_0$ is minimum value (belong to distance to rill formation of 0% Rock fragment cover in different flow discharge rates, or 3 L $min^{-1}$ flow discharge rate in different rock fragment covers. The results of this sensitivity analysis are given in Table 3. The distance to rill formation has a greater sensitivity to rock fragment covers relative to flow discharge rates, so the effect of rock fragment covers on distance to rill initiation ($L_i$) is more significant than that of flow discharge rates.

Table 3: Distance to rill initiation at different rock fragment covers and flow discharge rates

| | Rock fragment cover change (0-30%) | | | Flow discharge change (3-9 L $min^{-1}$) | | | |
|---|---|---|---|---|---|---|---|
| Factor level | 3 | 6 | 9 | 0 | 10 | 20 | 30 |
| Li change range | 0.8-4.5 | 0.74-4 | 0.7-3 | 0.7-0.8 | 1.6-2.5 | 2.6-2.9 | 3-4.5 |
| r change rate (%) | 462.5 | 440.5 | 328.5 | 12.5 | 36 | 10.3 | 33.3 |
| r average change rate | 410.5% | | | 23.1% | | | |

Since time to rill initiation is the function of soil intrinsic characteristics, morphological conditions of soil surface and runoff, in each experiment, time were recorded when the rill initiation occurred. Table 2 indicates that time to rill initiation, generally increased with increasing the surface rock fragment cover and decreased with increasing flow discharge rate.

## CONCLUSION

The general results of this investigation show that flow discharge rate and rock fragment cover percent, both affect the distance to rill initiation but the effect of rock fragment is more significant. Increased rock fragment cover decreases runoff velocity because of increasing the soil surface roughness and shear resistance. The rill initiation was retarded with increasing the rock fragment cover because of flow velocity and erosivity power. These results are very useful for understanding the mechanisms of rill formation, runoff impact, rock fragment cover effectiveness and help us in conservation practices such as determination of optimum distance for tree planting, channel terraces designing, etc.

These findings are usable for erosion control and soil and water resources conservation in sensitive areas of loess soils.

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