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Effect of Soil Cohesion on Critical Flow for Rill Initiation under Different Slope Conditions

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Abstract

Experiments to investigate the effect of soil cohesion under steady and uniform flow conditions were carried out in a laboratory flume at different slope degrees. Six samples of soils, four sandy and two loam soils were used. From the relationship of critical flow, slope and particle diameter, an equation was derived, which can be expressed as: $qc = a (\mathrm{Sin}\ \theta)^m$. The equation shows that the basic response of decreasing critical flow with an increase in slope degree is the same for both loam and sandy soils. However, due to water stable aggregates and soil cohesion, the critical flow is greater in loam soils as compared to the critical flow in non cohesive sandy soils. The derived empirical relationships can be used to assist the effect of soil cohesion on rill initiation and can therefore contribute to the development of physically based rill erosion models.

Key words: Soil cohesion, critical flow, rill initiation, slope

Introduction

Various factors are believed to influence soil erodibility and in turn rill processes and development. Some of these factors influence the soil capacity to infiltrate rain and therefore help determine the amount and rate of runoff, some influence its capacity to resist detachment and transport by the erosion forces of the falling raindrops and flowing water and therefore determine the soil content of runoff. The interrelation of these variables is highly complex. Any factor/property that prevents or make difficult soil detachment or transportation, reduces the soil erodibility.

These factor can be classified as internal and external factors. Internal factors include soil properties, such as interaction effect of percent silt, percent sand, clay ratio, particle size distribution, aggregate stability, soil density, soil structure, soil cohesion, organic matter, oxides of iron (Fe_2O_3), aluminum (M_2O_3) and silicon (SiO_2). External factors may include slope aspects and flow discharges.

An unstable air-dried aggregate is wetted, rapidly it slakes into smaller sub-units which may also be aggregates. Slaking is common and occurs in a wide range of 50115 where the aggregates are not strong enough to withstand the pressure of entrapped air in capillaries or the pressure due to swelling. Tisdale and Oades (1982), reported that severe slaking with little or no dispersion is serious, particularly when the soils are irrigated, because the slaked layers limit infiltration of water and emergence of seedlings. Luk (1979), reported that percentage of water stable aggregates greater than 0.5 mm diameter was found to be the most significant soil property explaining soil loss and is consistent with the fact that erosion rate depends on the resistance of the aggregates to dispersion and the size of the water stable aggregates for entrainment by splashing or runoff. Bryan (1987), reported that the processes and rate of interrill erosion also depends on factors such as, soil texture, aggregation characteristics, surface roughness, susceptibility to crusting and the presence and density of organic debris. He further stressed that experiments on fine grained cohesive soils with varied chemical characteristics are particularly important, so that the full complex range of aggregation dynamics can be incorporated in general concepts of rill evolution. Chaney and Swift (1984), reported a highly significant correlations between aggregate stability and organic matter, indicating that organic matter is mainly responsible for the stabilization of aggregates in the soils.

In addition to other soil properties, soil erodibility can be determined by soil texture, by the active surface area of particles and the more homogeneous the granulation, the smaller is the resistance of the soil to erosion. Further, large particles are resistant to transport because of the greater force required to entrain then and that fine particles are resistant to detachment because of their cohesiveness. Clay generally acts as cementing and aggregating agent. Large stable aggregates resist both detachment and transportation. Secondary lime and certain iron compounds bind clay and other soil grains together in quite stable form and so these soils may be resistant to erosion. Soils low in organic matter and high in silt and very fine sand are susceptible to erosion due to relatively less stable aggregates.

This study describes the effect of soil cohesion by comparing the critical flow for rill initiation for loam soils with the critical flow for rill initiation for sandy soils under similar experimental conditions. The derived empirical relationships can be used to assist the effect of soil cohesion on critical flow for rill initiation and can therefore, contribute to the development of physically based rill erosion models.

Materials and Methods

The effect of soils cohesion on critical flow for rill initiation was studied at college of Agriculture Ehime University Japan, in a laboratory flume 135 cm long, 13.5 cm wide and – cm deep, set at varying slopes of 4, 6, 8, 10 and 12 degrees and subjected to varying inflow discharges. Six soils, four sandy and two loam soils were used. Particle size distribution of the experimental soils was determined by hydrometer method and water stable aggregates were determined by wet sieving method. The physical properties of the soils are shown in Table 1. For each experiment, the soil was filled in the flume with a known amount and constant bulk density. At the up-slope end water was fed into the flume at a known discharge and a constant water head was maintained at the bottom of the flume to regulate the sub-surface flow. The soil was saturated before staring the experiment. Then each run was started with less amount of supplied water and it was gradually increased. The surface and sub-surface flows were measured with graduated cylinder at the down-slope end of the flume. The run was continued for sufficient time until rill started to initiate and at least a rill of size length 5 cm, width 1-2 cm and depth 0.5 cm was developed. The surface flow at this stage was defined as critical flow for rill initiation. The critical flow, sub-surface flow and the given discharge were determined at rill initiation. For each soil the experiment was replicated at least four times under the slope of 4, 6, 8, 10 and 12 degrees, respectively. The data were statistically analyzed by using Microsoft Excel and applying power equations.

Results and Discussion

Effect of slope on critial flow for rill initiation: The relationship between slope and critical flow for loam and different sandy soils is shown in Fig. 1. The basic response of decreasing critical flow with an increase in slope degree was the same for both the loam and sandy soils. For all the soils used in the experiments the observed critical flow required for nil initiation decreased with an increase in slope degree as shown in Fig. 1 and 2. Figure 2 shows the best fit for the data, as an application of some kinds of regression equations, power equation was the best with higher correlation coefficient between critical flow and sin 0. The effect of slope on critical flow was the same for both sandy and loam soils and the following equation was derived:

$$q_0 = a\,(\sin \theta)^m \qquad (1)$$

Where:
q_0 = Critical flow for rill initiation in $m^3/(s.m)$.
0 = Slope in degrees.
m = Regression coefficient.
a = A parameter depending on soil characteristics.

The values of "a" and "m" for different soils are shown in Table 2. The derived regression equations show that the effect of slope on critical flow for rill initiation is independent of particle diameter, because the regression coefficient "m" is almost constant for all the soils used in this experiment.

Effect of soil type on critical flow for rill initiation: Particle diameter also affected the critical flow for nil initiation, as particle diameter increased, the observed critical flow for rill initiation also increased. For example the critical flow for loam soil 2 mm with mean particle diameter d (0.312 mm) for 4 to 12 degree slope ranged from 2.30×10^{5} $m^3/(s.m)$ to 1.04×10^{5} $m^3/(s.m)$, while the critical flow required for rill initiation for loam soil 1 mm with mean particle diameter d (0.216 mm) ranged from 1.07×10^{5} $m^3/(s.m)$ to 0.44×10^{5} $m^3/(s.m)$ for slope range of 4-12 degrees as shown in Table 3.

As far as the effect of soil type is concerned, the critical flow for nil initiation for loam soil under 2 mm with mean particle diameter d (0.312 mm) is almost equal to the critical flow for Mass soil and Beach sand under 1 mm with mean particle diameter d (0.46 mm) each. Although, in case of sandy soils i.e., Mass and Beach sand soils the mean particle diameter d is greater than the mean particle diameter of loam soils, but the critical flow is almost the same for both loam and sandy soils. This shows that the critical flow is greater in loam and sandy soils. This shows that the critical flow is greater in loam soils as compared to the critical flow in sandy soils.

As compared to sandy soils, the greater critical flow for nil initiation for loam soils under 2 and under1 mm may be due to the reason that, the proportion of water stable aggregates in the range of 0.02 to 0.25 mm is more in loam soils as compared to the proportion of these particles in Beach sand and Mass soil, as in Beach and Mass soils much of the aggregates are larger than this range shown in Table 4.

In case of Beach sand and Mass soil the proportion of water stable aggregates in the range of 0.02 to 0.25 mm is small, as much of the aggregates of these soils are larger than this range. Tisdall and Oades (1982) reported that aggregated in the range of 0.02 to 0.25 mm diameter consist largely of particles 0.002 to 0.02 mm diameter bonded together by various cements including persistent organic materials and crystalline oxides and highly disturbed aluminosilicates. These aggregates are very stable against disruption by rapid wetting and mechanical disturbance partly, because they are small, and also because they contain several types of binding agents whose effects are additive. Koh and Sato (1988) studied the mechanism of nil initiation and rill development, they also suggested soil properties such as cohesion and aggregate stability as important factors for determining critical flow for rill initiation.

Another reason of greater critical flow for loam soils may be due to the fact that aggregation is associated with greater micro-relief, increased surface detention and retarding runoff. Verhaegen (1984) also reported negative correlation between aggregate stability and splash and wash loss. He further found positive correlation between sand content and splash and wash loss and showed that the quantity of splash material increases, where there is a higher sand content. Wischmeier and Meyer (1973) and Young and Mutchler (1977) also found a positive correlation between sand content and sheet and nil erosion. They explained this by the fact that aggregate stability and the resistance to crusting decreased by an increasing sand content. May be due to this reason, that the larger portion of Beach sand and Mass soil is comprising of sand content so as compared to loam soils the critical flow is smaller for these soils.

Comparison of the observed critical flow for loam soils with critical flow calculated by empirical equation derived for sandy soils: For sandy soils, an equation was derived for

Table 1: Some physical properties of the experimental soils

Soils	Mean diameter d (mm)	d_{50} (mm)	Specific gravity	Dry density (g cm^{-3})	Silt + Clay (%)	Sand (%)
Masa soils 1 mm	0.46	0.43	2.67	1.40	6.05	93.95
Masa soils 2 mm	0.77	0.64	2.68	1.43	6.04	93.96
Beach sand 1 mm	0.46	0.41	2.66	1.45	6.22	93.78
Beach sand 2 mm	0.78	0.60	2.67	1.48	6.22	93.78
Loam soils 1 mm	0.216	0.078	2.62	1.36	50	50
Loam soil 2 mm	0.312	0.08	2.65	1.36	50	50

Table 2: Regression coefficients based on the relationship between slope ans critical flow for rill initiation

Soils	Regression coefficient (a)	Regression coefficient (m)	r-values
Masa soils 1 mm	0.379	-0.751	1.00
Masa soils 2 mm	0.999	-0.745	1.00
Beach sand 1 mm	0.311	-0.795	1.00
Beach sand 2 mm	0.911	-0.785	1.00
Loam soils 1 mm	0.144	-0.827	0.994
Loam soil 2 mm	0.343	-0.716	0.996

Table 3: Comparison of the critical flow required for rill initiation for some of the soils used in the experiment

Slope degree	Masa soil mean diameter d (0.46 mm) q_c = m^3/(s.m)	Beach sand mean diameter d (0.46 mm) q_c = m^3/(s.m)	Loam soil mean diameter d (0.312 mm) q_c = m^3/(s.m)	Loam soil mean diameter d (0.216 mm) q_c = m^3/(s.m)
4	0.50×10^5	2.55×10^5	2.30×10^5	1.07×10^5
6	2.06×10^5	1.89×10^5	1.76×10^5	0.71×10^5
8	1.69×10^5	1.51×10^5	1.36×10^5	0.58×10^5
10	1.41×10^5	1.25×10^5	1.25×10^5	0.47×10^5
12	1.23×10^5	1.07×10^5	1.04×10^5	0.44×10^5

Table 4: Water stable aggregates of the experimental soils

Soils	0-0.1	0.1-0.25	0.25-0.5	0.5-1	1-2
Diameter (mm)					
Loam soil 2 mm	44.81	63.55	80.79	93.67	100
Masa soil 2 mm	10.31	21.12	40.15	70.14	100
Beach sand 2 mm	3.13	18.1	43.89	68.98	100
Loam soil 1 mm	48.32	70.95	89.1	100	
Masa sand 1 mm	13.08	28.97	57.47	100	
Beach sand 1 mm	4.23	23.78	62.18	100	

Table 5: Observed and predicted critical flow for the loam soils

Slope degree	Tota flow q_1 = m^3/(s.m)	Critical flow observed q_0 = m^3/(s.m)	Critical flow predicted q_c = m^3/(s.m)
Loam soil under 2 mm			
4	3.06×10^{-6}	2.30×10^{-5}	1.22×10^{-6}
6	2.67×10^{-6}	1.76×10^{-5}	0.893×10^{-6}
8	2.10×10^{-6}	1.36×10^{-5}	0.720×10^{-5}
10	210×10^{-6}	1.25×10^{-5}	0.604×10^{-5}
12	1.58×10^{-6}	1.04×10^{-5}	0.526×10^{-5}
Loam soil under 1 mm			
4	1.48×10^{-6}	1.07×10^{-5}	0.582×10^{-5}
6	0.98×10^{-6}	0.71×10^{-5}	0.427×10^{-6}
8	0.83×10^{-6}	0.58×10^{-5}	0.342×10^{-5}
10	0.68×10^{-6}	0.47×10^{-5}	0.289×10^{-6}
12	0.68×10^{-6}	0.44×10^{-5}	0.251×10^{-6}

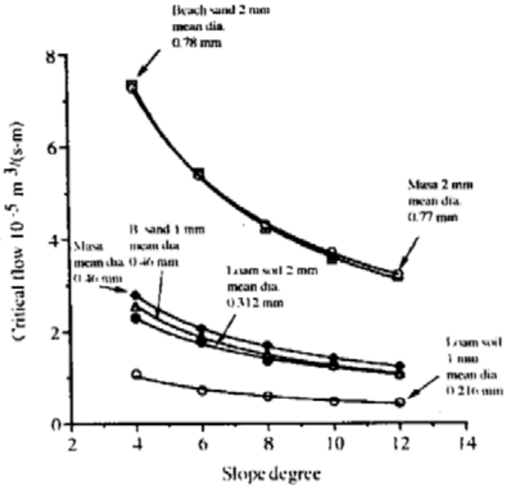

Fig. 1: Relationship of slope and critical flow for the soils used in the experiment

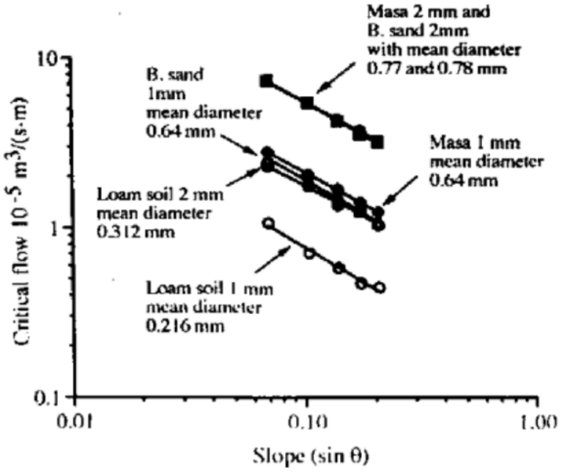

Fig. 2: Relationship of slope and critical flow (graph showing best fit for the data)

the relationship between critical flow, slope and particle diameter under uniform flow conditions as follow.

$$q_0 = 1.63\ (d)^{2.01}\ (\sin\theta)^{0.77} \qquad (2)$$

Where:

q_0 = Critical flow rill initiation in $\times\ 10^{-5}$ $m^3/(s.m)$. Mean particle diameter in m m.
d = Slope in degrees.
m = Regression coefficient.
a = A parameter depending on soil characteristics.

$$q_0 = 1.79\ (d_{50})\ (\sin\theta)^{0.77} \qquad (3)$$

The observed critical flow for loam soils as shown in Table 3 was cross checked against predicted critical flow derived by Eq. (2). Generally, Eq. (2) underestimated the critical flow for rill initiation for loam soils. The observed critical flow for loam soils are almost two times greater than the predicted critical flows by Eq. (2), as shown in Table 5. This increased critical flow in loam soils may be due to stable aggregates, as compared to Mass and Beach sand soils the proportion of water stable aggregates of 0.02 to 0.25 mm is greater in loam soils. For loam soils the following equations were derived.

$$q_0 = 3.20\ (d)^{2.01}\ (\sin\theta)^{0.77} \qquad (4)$$

$$q_0 = 28.10\ (d_{50})\ (\sin\theta)^{0.77} \qquad (5)$$

In case of sandy soils both the diameters i.e. mean diameter d and 50% diameter d_{50} are equally effective. In case of loam soils, if mean diameter d replaced by d_{50}, the parameter "a" in Eq. (4) increases from 3.20 to 28.10. This shows that the individuality of grain is lost when they become fine and grain size no longer has meaning and the critical flow for nil initiation increases because of the cohesion of the clay minerals in loam soils. As already stated, that these stable aggregates resist both detachment and transportation and make the soil more resistant to erosion and larger force in required to move these stable aggregates. That is why critical flow for nil initiation is greater in loam soils as compared to the critical flow for sandy soils.

The second reason of greater critical flow in loam soils may be due to the greater percentage of clay particles in loam soils, because the finer particles are harder to erode due to the cohesiveness of the clay minerals of which they are comprised. It can be concluded that the cohesion of the soil has an important negative influence on rill formation. Because cohesion is brought about by the binding forces acting between the different soil particles and an increase of the binding forces will decrease the sensitivity to erosion. The third reason of greater critical flow in loam soils may be due to the effect of crusting, as in clay and loam soils crust develops after wetting and saturation of these soils. The resistance to erosion may increase due to crust formation.

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