The effect of unit weight and rainfall intensity on the erosion of unprotected slopes
by Dale Leroy Rowlison

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Civil Engineering
Montana State University

Abstract:
Laboratory tests were performed on a fine grained soil to determine the effect of rainfall intensity and soil unit weight on the rate of erosion of the soil. This study was a continuation of the work of Foster (1967), who investigated the effects of slope and soil unit weight on the rate of erosion.

The rainfall intensities used in this study were 1.5, 3.0, 4.5, and 6.0 in/hr and the soil unit weights were 80, 85, SO, and 95 pcf. The slope was held constant at 1.5:1. The runoff water and eroded soil particles were collected and the weight of the soil solids and volume of runoff water were computed.

The results of this study indicate that, for a constant slope, there is a rainfall intensity for which the erosion rate is a maximum. The maximum occurs within the range of natural rainfall intensities. The effect of the soil unit weight is relatively small for a constant slope, but the trend is that the erosion rate decreases as the unit weight increases.

The results and analyses of this study and Foster's study indicate that the rate of erosion of a cohesive soil is dependent on the slope of the soil surface and the depth of flow of water over the surface. The rate of erosion is limited by the smaller of soil particle detachment rate or particle transportation rate.

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CHAPTER I

INTRODUCTION

Water erodes both natural and man-made slopes. Because most man-made slopes are engineering structures (e.g., earth dams and highway embankments), the engineer is interested in minimizing erosion-caused damage to these structures. It is particularly important to minimize erosion immediately after construction while natural protection, such as vegetation, is developing on the slope.

Because the variables influencing the erosion of steep, unprotected slopes have not been studied in detail, there is a need to isolate the effects of soil and rainfall characteristics on erosion. The investigation, of course, must be conducted over that range of each parameter found in practice under natural conditions.

The investigation described in this paper is a segment of a continuing study designed to isolate the parameters that affect erosion, with the quantitative prediction of the amount of soil that will erode from a steep, unprotected slope being the ultimate goal of the study. Prior to the quantitative prediction, it will be necessary to formulate an hypothesis that qualitatively defines the effect of the governing parameters on erosion.

The particular segment of the investigation reported herein was to evaluate the relative effects of rainfall intensity and soil unit weight on erosion. A laboratory investigation was performed in which a simulated rainfall was applied to the surface of a soil specimen and the runoff from the specimen was collected. The simulated rainfall intensities were 1.5, 3.0, 4.5, and 6.0 in/hr and the soil unit weights were 80, 85, 90 and 95 pcf. Four replications of each unit weight-intensity combination were made.

CHAPTER II

REVIEW OF LITERATURE

Erosion may be thought of as the detachment of particles from a soil surface and the transportation of the detached particles to a new location. Ekern (1954) found that detachment of the particles from the soil surface, rather than the ability of the runoff water to carry the particles, limits the amount of erosion. It should not be construed from such a statement that the transportation of the soil is not important; under certain conditions the ability of the runoff water to carry particles could be the limiting erosion criterion. Ekern's work was conducted on a slope of 16 percent, which is a relatively flat slope when considering engineering structures.

Soil detachment can be caused by the runoff water or by the impact of rainfall. According to Henderson (1966), water flowing in an open channel creates a shear stress on the channel bed. The average shear stress on the channel bed, T_0, is:

$$T_0 = \gamma R S_0 \tag{1}$$

where: γ is the unit weight of water,

R is the hydraulic radius of the channel, and

S_0 is the slope of the channel bed.

Equation (1) assumes small slopes, a hydrostatic pressure distribution, and uniform flow. For a depth of flow, d, which is small compared to the width of flow, the hydraulic radius approaches the depth of flow, and Equation (1) becomes:

$$T_0 = \gamma d S_0 \tag{2}$$

Although Equation (2) is only valid for small slopes, it should give the shear stress within an order of magnitude for greater slopes. In overland flow, because the depth of flow is small compared to the width, the resulting shear stress is small compared to the shear strength of a cohesive soil. For example, using typical values from this study (γ = 62.4 pcf, S_0 = 0.75, d ≃ 0.01 ft) in Equation (2), the shear stress is 0.47 psf, which is very small compared to 1600 psf which is the shear strength of the soil used in this study. Therefore, a relatively small amount of material should be detached from the surface of a cohesive soil as a result of the shear stresses due to overland flow.

Soil detachment is also caused by the impact of a raindrop striking the soil surface. If the stress of the impact is greater than the stresses producing interparticle bond, soil particles will be dislodged from the soil surface. Because the total volume of raindrops striking the soil is related to the rainfall intensity, the initial motion of the soil particles is dependent on the intensity.

Wischmeier, *et al.*, (1958) found a significant relationship between soil loss and the characteristics of rainfall during a storm. The interaction of energy and intensity was found to be a better indicator of soil loss than either the energy or the intensity alone. Wischmeier, *et al.*, related rainfall intensity to the kinetic energy of a storm by:

$$KE = 916 + 331 \log_{10} I \quad (3)$$

where: KE is the kinetic energy in ft-ton/acre-in, and

I is the intensity in in/hr.

Wischmeier, *et al.*, studied natural storms for which the intensity varied from 1.0 to 6.0 in/hr and the slopes of the soil varied from 3 to 20 percent.

Because the transporting capacity of the runoff water is dependent on the depth and velocity of flow and because the depth and velocity are related to the intensity of the rainfall, the intensity is an important factor in particle transportation.

Because both detachment and transportation of the soil particles are dependent on the rainfall intensity, intensity is an important variable contributing to erosion.

Many investigators have made general observations with regard to the relationship of erosion and rainfall intensity. Between 1940 and 1946 the U. S. Department of Agriculture published a series of technical bulletins on the subject of erosion control. While no functional relationships between erosion and rainfall intensity were developed, the observations that were made are of qualitative value. Daniel, *et al.*, (1943) reported that rainfall intensity is the most important factor affecting runoff, while total rainfall and duration of rainfall, considered separately, have a relatively small effect on erosion. Copely, *et al.*, (1944) found that soil losses are closely related to rainfall intensity, but are not proportional to the total rainfall. Borst, *et al.*, (1945) concluded that increased summer rainfall intensity caused greater soil losses. Pope, *et al.*, (1946) found that large soil losses are related to high intensities of rainfall and are not due to large amounts of rainfall alone. In all of these studies only natural storms were considered. The rainfall intensity varied from 1.0 to 6.0 in/hr; these intensities were the maximum for any 5-min period in a storm. The ground surfaces were natural, and in most cases protected; the ground slopes ranged from 3 to 25 percent.

Conner, *et al.*, (1930) relating erosion to intensity during natural storms, defined low intensity (less than 0.75 in/hr) periods of a storm as "normal" and high intensity (greater than 0.75 in/hr) periods as "torrential." For the same total rainfall, the storms with longer periods of torrential rain created greater soil loss. The slopes Conner, *et al.*, studied were natural and varied from 1 to 3 percent.

Ellison (1947) found that the splash rate of a sandy soil could be expressed as:

$$E = V^{4.33} d^{1.07} I^{0.56} \qquad (4)$$

where: E is the relative amount of soil, by weight, splashed in a 30 min period in gm,

V is the impact velocity of the raindrops in ft/sec,

d is the drop diameter in mm, and

I is the rainfall intensity in in/hr.

The rainfall intensities were 4.8 and 8.1 in/hr, the drop diameters varied from 3.5 to 5.1 mm, and the drop velocities varied from 12.0 to 18.0 ft/sec.

An analysis of variance of Craddock's, *et al.*, (1938) data showed that rainfall intensity was only exceeded by vegetal cover in influencing erosion of a soil. The highest intensity was 1.8 in/hr and protected ground slopes varied from 3 to 30 percent.

Neal (1938) investigated the effects of length and degree of slope, and intensity and duration of rainfall on soil erosion. The effect of each variable was determined by varying one parameter and holding all others constant. The soil was a "silt-loam" and was compacted in layers to a unit weight of 78 pcf in a container 12 ft by 3.63 ft by 2.16 ft. Rainfall was simulated by oscillating sprinklers to give an even rainfall distribution over the soil. Neal varied the rainfall intensities from 0.9 to 4.0 in/hr and the slope varied from 1 to 16 percent. Based on one replicate for each parametric value, Neal concluded that the dry weight of eroded soil could be determined from:

$$E_t = 0.2\ S^{0.7}\ T\ I^{2.2} \tag{5}$$

where: E_t is the total weight of eroded soil in tons/acre,

S is the slope of the soil surface in ft/ft,

T is the duration of rainfall in hr, and

I is the rainfall intensity in in/hr.

Dividing each term by the duration of rainfall, T:

$$E_r = E_t/T = 0.2\ S^{0.7}\ I^{2.2} \tag{6}$$

where: E_r is the rate of soil erosion in T/acre/hr.

In all of the above literature reviewed, the maximum slope was 30 percent. In engineering practice it is not uncommon to find slopes as steep as 100 percent. The low range of slopes, cited in the above literature, limits the value of the investigations with regard to erosion associated with engineering structures. In addition, many of the investigations described have been concerned with protected slopes and with variable rainfall conditions. The maximum rainfall intensities occur for a short duration of the storm and the effects of the intensities cannot be isolated; thus, the validity of these studies to the problem under investigation is questionable.

Foster (1967) investigated the effect of slope and soil unit weight on unprotected slopes. Slopes varied from 33 to 100 percent and unit weights of the soil varied from 80 to 95 pcf. The rainfall intensity was held constant at 6.0 in/hr. Contrary to the findings of other investigators, Foster found that erosion does not increase indefinitely as slope increases, but rather, there exists a slope for which the rate of erosion is a maximum. Foster also found that on flatter slopes, erosion rates were higher for low soil unit weights than for high unit weights. Conversely, Foster found that on steeper slopes, the erosion rates were higher for high soil unit weights than for low unit weights.

Palmer (1963) found a relationship for the impact force of a raindrop on a horizontal surface as a function of the depth of water over the surface. Although Palmer's work involved water over a steel surface, the relationship between impact force and depth of water should be similar for any non-fluid base material.

CHAPTER III

MATERIALS, LABORATORY INVESTIGATIONS, AND RESULTS

Design of the Experiment

In this segment of the long term investigation, the rainfall intensity and soil unit weight were selected as controlled variables, and the slope, slope length, soil material, and rainfall duration were held constant. Rainfall intensities of 1.5, 3.0, 4.5 and 6.0 in/hr were selected to cover the range of intensities normally found in nature. To cover a realistic range, soil unit weights of 80, 85, 90, and 95 pcf were used.

The controlled variables were combined into a factorial set, with four replications of each combination, as shown in Table I.

Testing Procedure

The method of testing used in this investigation is shown schematically in Figure 1. The soil, identified as Gallatin No. 1 by Hogan (1964), was brought to the laboratory from the sample site, air-dried, and broken down to pass a No. 10 U.S. standard sieve.

Because this investigation was a continuation of the work of Foster (1967), the testing procedure and equipment, with a few exceptions, were identical to those reported by Foster. The soil material, erosion specimen preparation, erosion specimen holders, specimen compaction, and sampling tubes were identical to those described by Foster. Based on Foster's experience, the rainfall simulation test device and the sample tube holders were modified.

The water content of the soil was raised to 20 percent. The unit

TABLE I. COMBINATIONS OF CONTROLLED VARIABLES.

Run Number	Intensity	Test No.	Unit Weight in pcf: Channel Position 1	Channel Position 2	Channel Position 3	Channel Position 4
F6-1	6.0 in/hr	1	80	85	90	95
F6-2		2	95	80	85	90
F6-3		3	90	95	80	85
F6-4		4	85	90	95	80
F45-1	4.5 in/hr	1	80	85	90	95
F45-2		2	95	80	85	90
F45-3		3	90	95	80	85
F45-4		4	85	90	95	80
F3-1	3.0 in/hr	1	80	85	90	95
F3-2		2	95	80	85	90
F3-3		3	90	95	80	85
F3-4		4	85	90	95	80
F15-1	1.5 in/hr	1	80	85	90	95
F15-2		2	95	80	85	90
F15-3		3	90	95	80	85
F15-4		4	85	90	95	80

Note: Slope = 1.5:1 for all runs and all specimens.

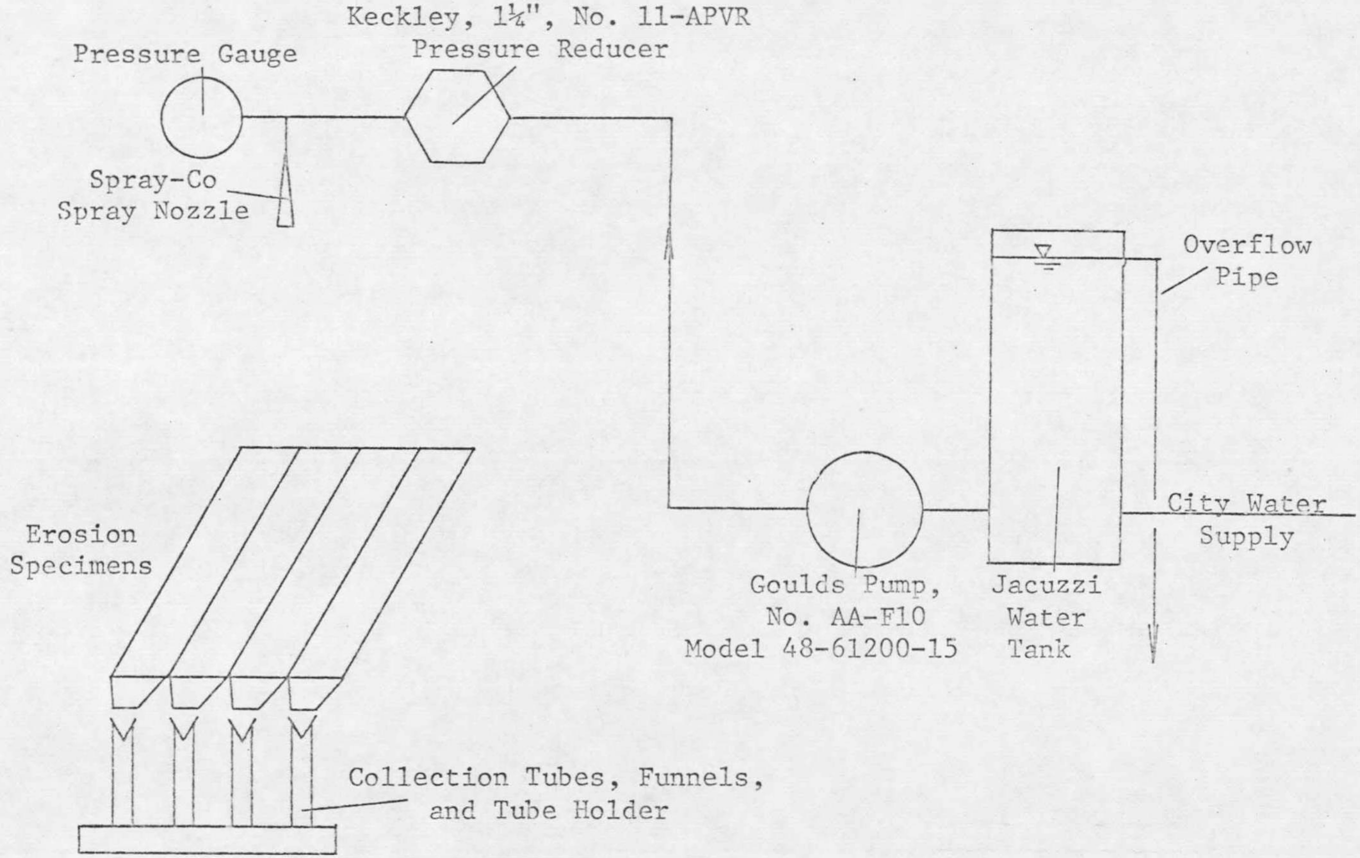

Figure 1. Schematic diagram of the test device.

weight was controlled by placing a known weight of soil in a specimen holder of known volume. The soil placed in the specimen holder was then statically compacted to the desired unit weight. For each run, four erosion specimens were prepared at unit weights of 80, 85, 90 and 95 pcf and placed in the rainfall simulation test device.

The rainfall simulation system used by Foster was altered by removing the top of the Jacuzzi water tank and providing an overflow to maintain a constant pump suction head. The purpose was to eliminate the possibility of water pressures in the tank, other than hydrostatic pressures. Three different nozzles were used to obtain the four simulated rainfall intensities selected in the experimental design. For the 4.5 and 6.0 in/hr intensities, a model 7LA Spray-Co nozzle was used; nozzle models 5D and 6K were used for the 1.5 and 3.0 in/hr intensities, respectively. The three nozzles were calibrated in the same manner employed by Foster and the calibration curves are shown in Figure 2.

There is an apparent anomaly in the calibration curve for nozzle model 5D; as the pressure, and thus the discharge, increases, the intensity decreases. Because the "cone" of the nozzle spray increases in diameter as the pressure increases, the rainfall is spread over a larger area which decreases the rainfall intensity. For this nozzle, the increased cone diameter has a greater effect on the intensity than the increased discharge.

In order to reduce the number of times the tubes were handled,