

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
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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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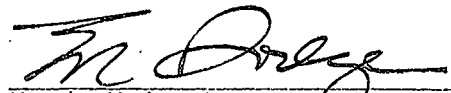
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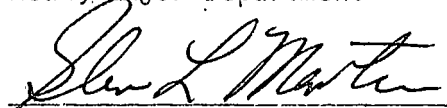
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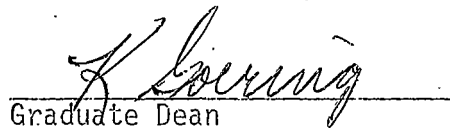
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ABSTRACT

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, 90, 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.

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:

$$T_0 = \gamma R S_0 \qquad (1)$$

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:

$$T_0 = \gamma d S_0 \qquad (2)$$

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:

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

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:

$$E_t = 0.2\ S^{0.7}\ T\ I^{2.2} \qquad (5)$$

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:

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

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		1	80	85	90	95
F6-2		2	95	80	85	90
F6-3	6.0	3	90	95	80	85
F6-4	in/hr	4	85	90	95	80
F45-1		1	80	85	90	95
F45-2		2	95	80	85	90
F45-3	4.5	3	90	95	80	85
F45-4	in/hr	4	85	90	95	80
F3-1		1	80	85	90	95
F3-2		2	95	80	85	90
F3-3	3.0	3	90	95	80	85
F3-4	in/hr	4	85	90	95	80
F15-1		1	80	85	90	95
F15-2		2	95	80	85	90
F15-3	1.5	3	90	95	80	85
F15-4	in/hr	4	85	90	95	80

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

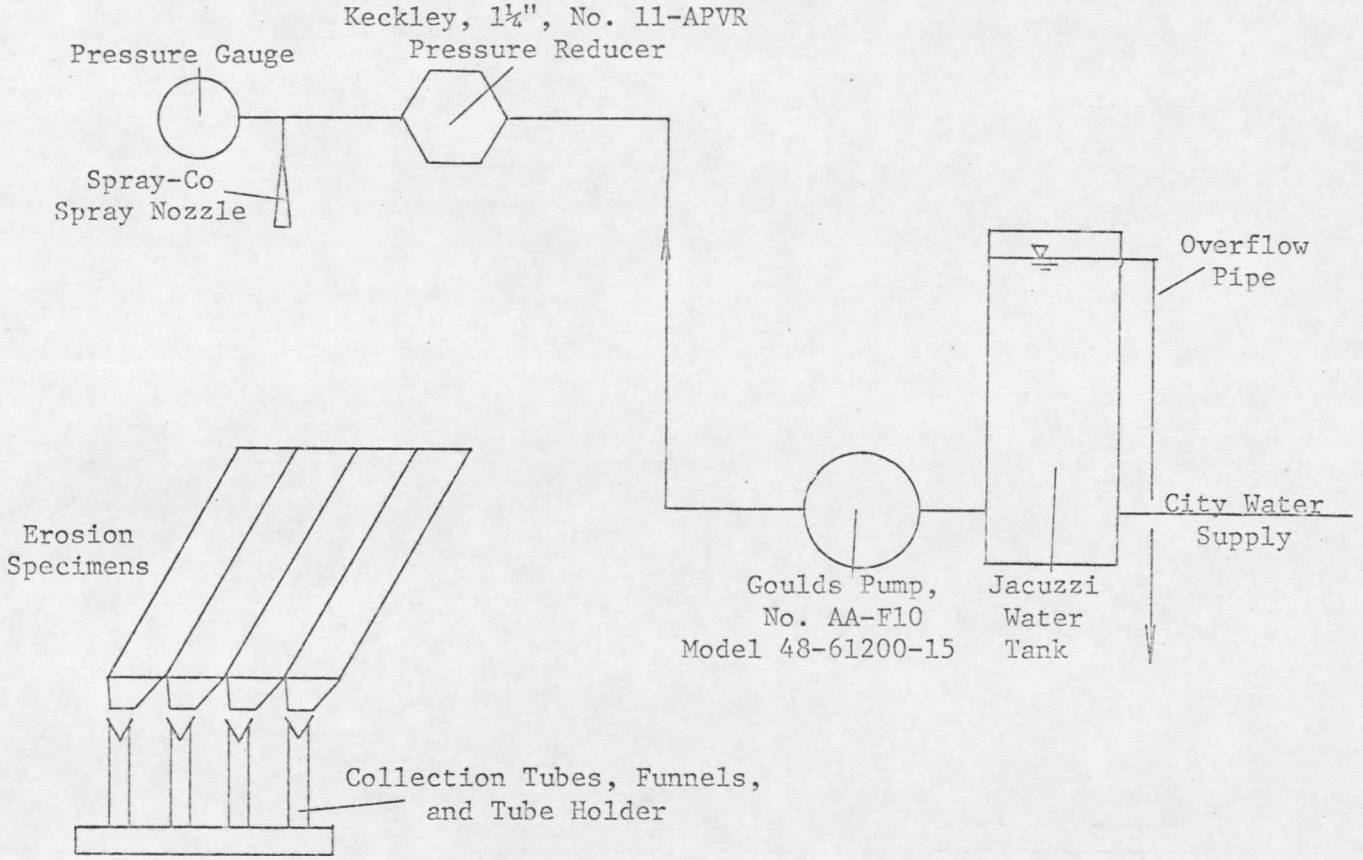


Figure 1. Schematic diagram of the test device.

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,

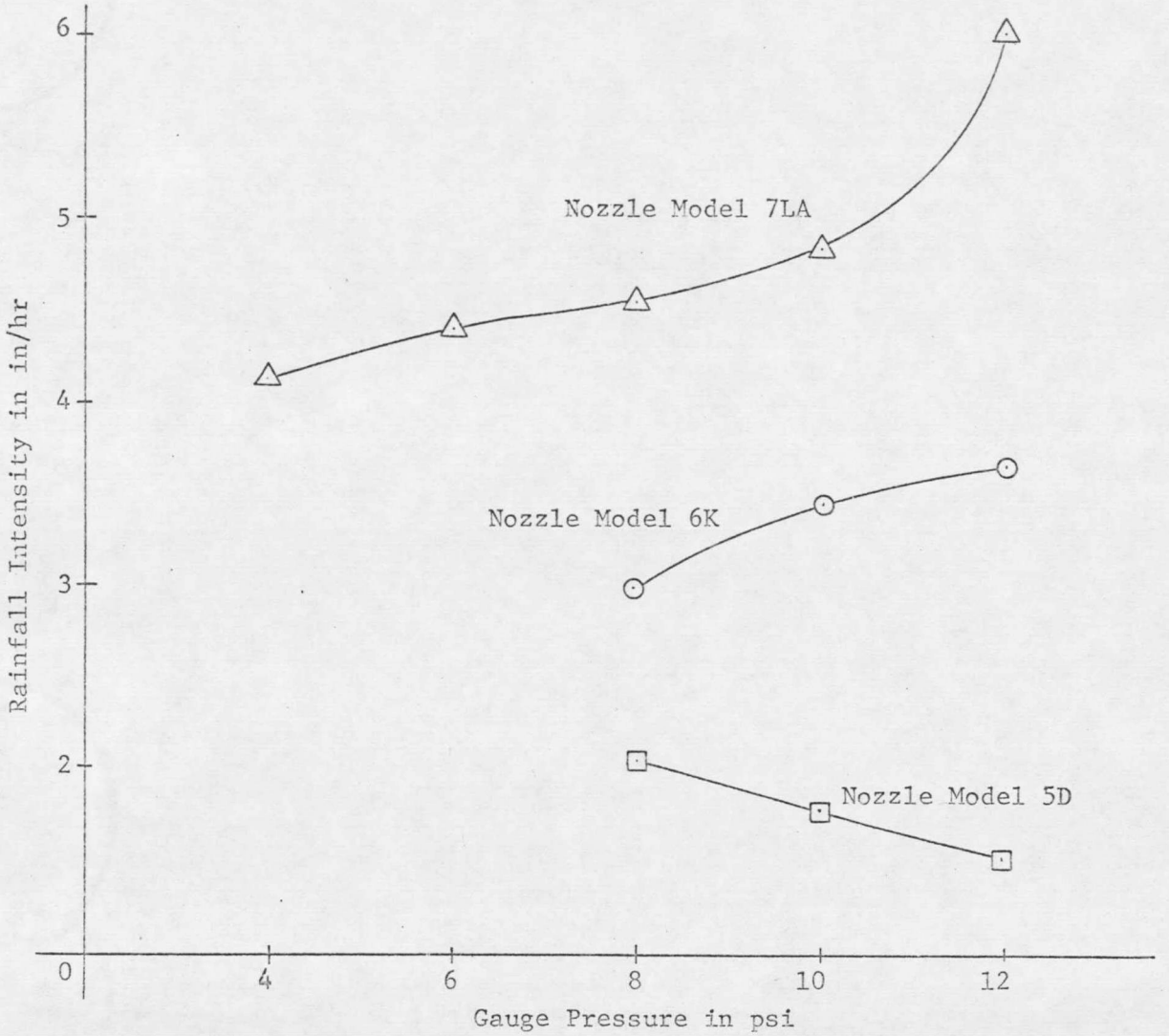


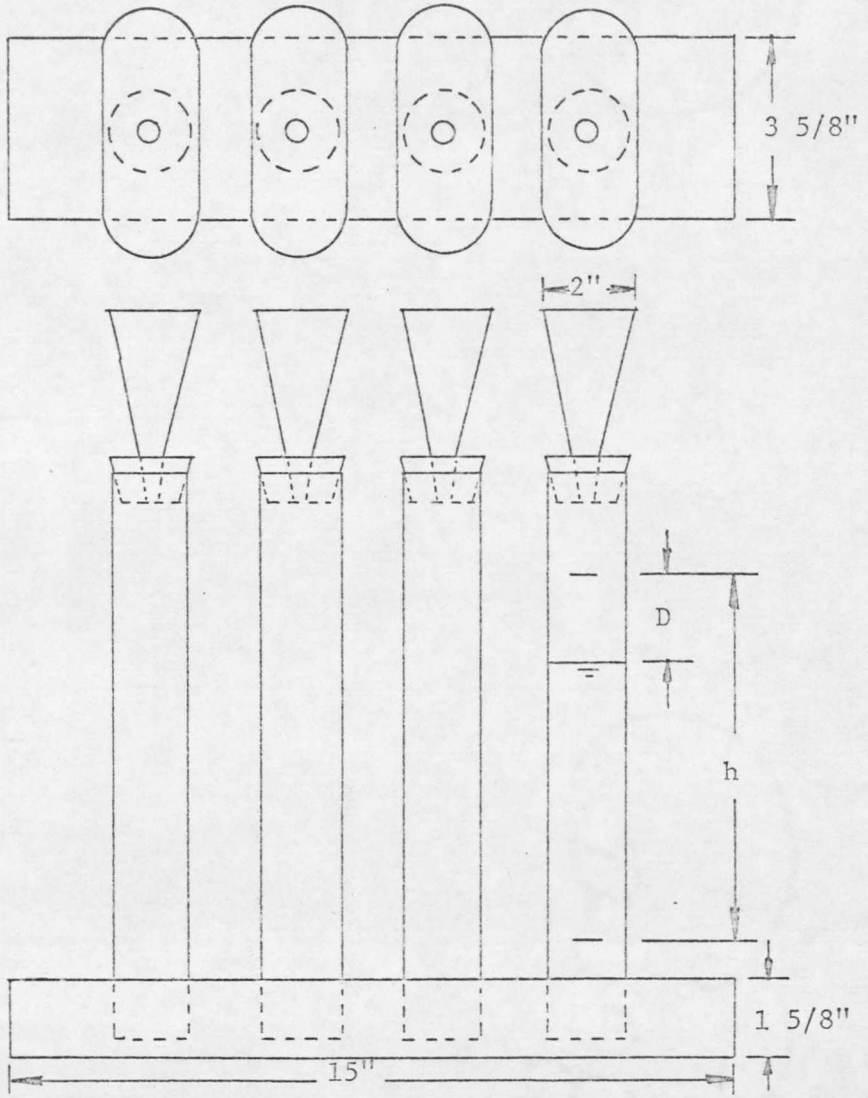
Figure 2. Rainfall intensity as a function of line pressure for selected Spray-Co nozzles.

Foster's collection tube holder was replaced by the one shown in Figure 3. One holder was provided for every four collection tubes and the collection tubes remained in their respective holder throughout the test. One of the tube holders, containing four tubes fitted with funnels, was in the collecting position throughout the duration of the test.

The test was started by placing a tube holder with four clean collection tubes with funnels in the collecting position and starting the rainfall. At specified time periods, 1.5 minutes for runs F6-1 through F3-4 and 3.0 minutes for runs F15-1 through F15-4, the tube holder and full tubes were replaced with a new tube holder and four clean tubes also fitted with funnels. The consecutive replacement of full tubes by clean ones was continued until 60 minutes of runoff had been collected.

At the end of the test, the collection tubes were measured for volume and weighed. All of the collection tubes were then oven dried at 110°C for 48 hours and weighed. For each tube, the total wet weight, total dry weight, and the distance measurement for volume were recorded.

Observations of the condition of the specimen surfaces were recorded after the test and photographs of the soil surfaces were taken. Typical photographs of the erosion specimens are shown in Figure 4. Three moisture samples were taken from each of the erosion specimens to determine the change in water content during the test.



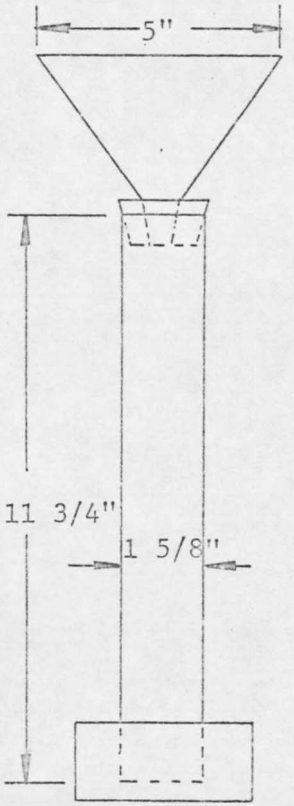
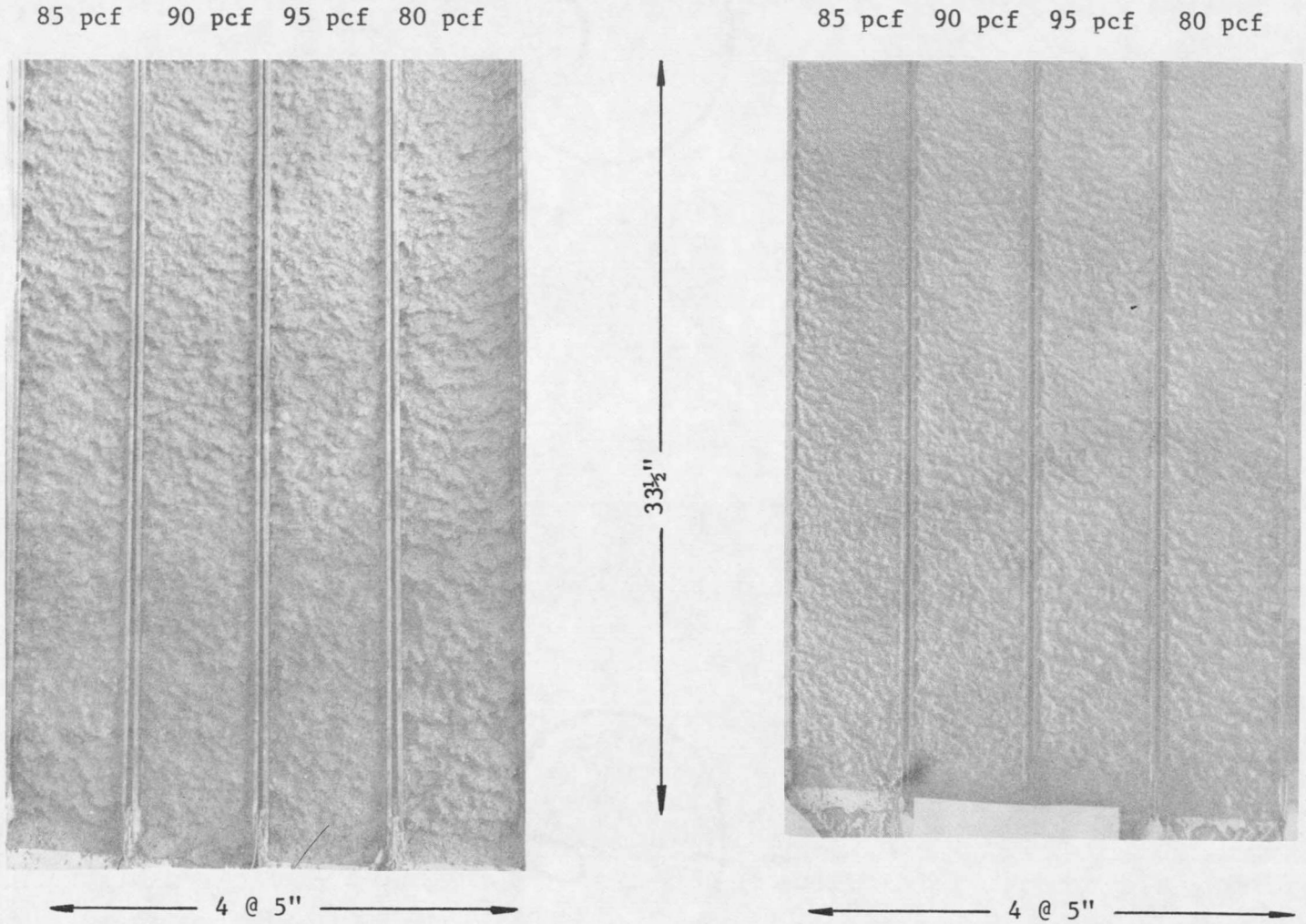


Figure 3. Collection tubes and holder.



(a) Run Number F3-4
Intensity = 3.0 in/hr

(b) Run Number F15-4
Intensity = 1.5 in/hr

Figure 4. Surfaces of eroded specimens after duration of 60 minutes.

Results of the Tests

The weight of soil and volume of water in the tubes was determined from equations reported by Foster (1967). Using the oven dry weight, the equations are:

$$W_s = W_{dry} - W_{tube} \tag{7}$$

where: W_s is the dry weight of the soil in gm,

W_{dry} is the weight of the tube plus the dry weight of the soil in gm, and

W_{tube} is the weight of the tube in gm; and

$$V_w = \frac{W_t - W_s - W_{tube}}{\gamma_w} \tag{8}$$

where: V_w is the volume of water in the tube in cc,

W_t is the total weight of soil, water, and tube in gm, and

γ_w is the unit weight of water in gm/cc.

The amount of soil and water in the tubes can also be determined by knowing the unit weight of the water and the specific gravity of the soil solids. The equations are:

$$W_s = \frac{(250h - 200D)\gamma_w G_s + (W_{tube} - W_t)hG_s}{(1 - G_s)\, h} \tag{9}$$

where: h is the distance between the calibration marks on the tube in mm, as shown in Figure 3,

D is the distance from the top calibration mark to the bottom of the meniscus in mm, as shown in Figure 3,

G_s is the specific gravity of the soil solids; and

$$V_w = (W_t - W_s - W_{tube}) \,/\, \gamma_w. \tag{10}$$

At the beginning of each test, there was a time difference between the start of simulated rainfall and the start of noticeable runoff from the specimens into the collection tubes. The times from the start of simulated rainfall to the first runoff for each specimen are shown in Table II.

The weight of soil solids, computed from Equation (7), was found to be a function approximately linear with time, as shown in Figure 5. This linearity is verified by the high correlation coefficients (see Table III) between the weight of soil solids and time. The results of linear least squares analyses for the average weight of soil solids eroded as a function of the rainfall duration, for each unit weight at each rainfall intensity, are also shown in Table III.

TABLE II. TIMES TO FIRST RUNOFF.

Run No.	80 pcf		85 pcf		90 pcf		95 pcf	
	Min	Sec	Min	Sec	Min	Sec	Min	Sec
F6-1	1	50	2	10	1	35	0	30
F6-2	1	40	1	50	0	40	0	25
F6-3	1	40	1	15	0	30	0	45
F6-4	1	30	1	15	0	35	0	20
F45-1	1	25	1	15	0	45	0	35
F45-2	1	15	1	00	0	40	0	25
F45-3	1	30	0	50	1	05	0	25
F45-4	1	30	1	10	0	40	0	30
F3-1	1	55	1	40	1	10	0	50
F3-2	1	40	1	10	0	50	1	55
F3-3	1	00	1	15	1	10	0	55
F3-4	1	20	1	10	1	10	0	40
F15-1	9	00	5	00	4	30	2	25
F15-2	4	30	4	45	5	00	4	15
F15-3	4	00	4	35	4	30	4	00
F15-4	7	30	6	00	4	00	3	00

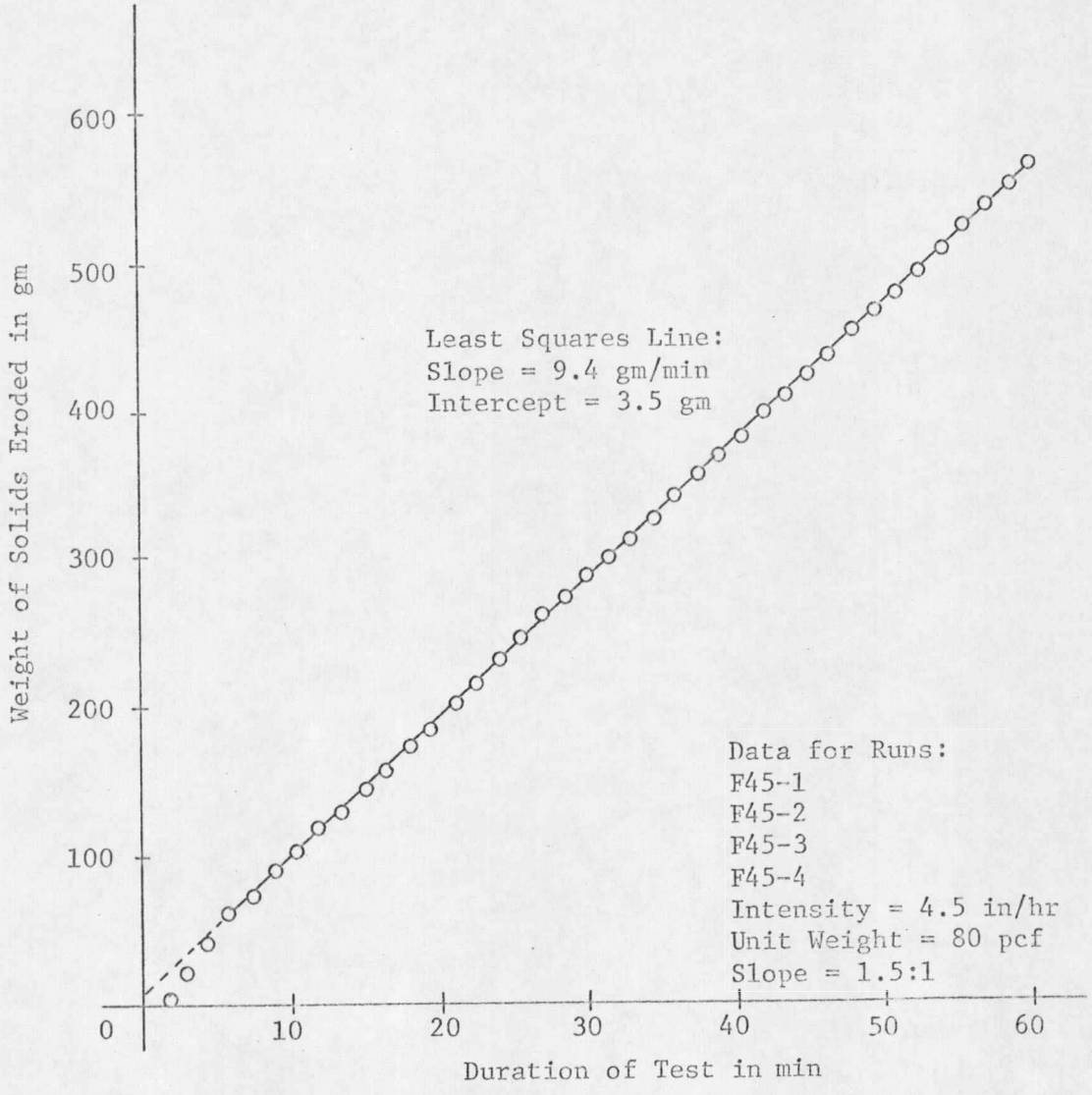


Figure 5. Typical least squares line representing the relationship between weight of solids eroded and duration of rainfall.

TABLE III. AVERAGE WEIGHT OF SOIL SOLIDS ERODED AS A FUNCTION OF TIME.

Intensity, in/hr	Unit Weight, pcf	Slope, gm/min	Intercept, gm	Correlation Coefficient
6.0	80	7.2	-8.3	0.9997
	85	6.8	-3.6	0.9997
	90	5.6	28.1	0.9997
	95	5.6	57.0	0.9998
4.5	80	9.4	3.5	0.9997
	85	7.4	15.5	0.9998
	90	7.0	31.3	0.9999
	95	6.9	46.9	0.9999
3.0	80	3.6	2.5	0.9997
	85	3.7	5.3	0.9998
	90	4.3	15.5	0.9999
	95	4.4	26.6	0.9999
1.5	80	0.3	-3.2	0.9638
	85	0.4	-3.7	0.9793
	90	0.5	-2.0	0.9878
	95	0.6	-1.2	0.9892

CHAPTER IV

ANALYSIS AND DISCUSSION OF RESULTS

Observations of the Soil Surfaces

On all soil surfaces there was more soil material removed from the edge of the channels at the soil-steel boundary than in the longitudinal center of the channels. Foster (1967) attributed this discontinuity to the reduced flow resistance of the steel which increased the water velocity at the boundary. The higher velocity water at the boundary eroded more soil than the lower velocity water near the longitudinal axis of the specimen. Foster also suggested that after compaction the soil rebounded slightly in the center of the specimen and the created gradient caused more water to run to the side of the channel, thus increasing the erosion at the specimen edge.

The erosion at the boundary decreased as the unit weight of the soil increased. Because the strength of a cohesive soil generally increases as the unit weight increases, the reduced erosion at the edge of the higher unit weight specimens indicates that less erosion occurs, with the same erosion potential, on the soils with greater shear strength.

A distinct ripple pattern was observed on the surface of each erosion specimen. As the intensity of the rainfall increased, the amplitude of the ripples decreased as shown in Figure 4.

Volume of Runoff Water

Factorial analyses of variance were employed to determine the effect of replication, intensity, unit weight, and intensity-unit weight

interaction on the volume of runoff water. The results of these factorial analyses are shown in Table IV.

The factorial analyses indicate that the rainfall intensity has a highly significant effect on the volume of runoff water at all rainfall durations. It is rational that rainfall intensity is highly significant because the application of more water to the soil surface should result in more water running off.

The unit weight of the soil affected the volume of runoff water at a high significance level during the first 12 minutes of the tests, at a much lower level at 24 minutes, and was not significant thereafter. The high significance at early time periods is because the infiltration of water into the soil is inversely proportional to the unit weight of the soil (i.e., a soil of lower unit weight will allow faster percolation of water than a soil of higher unit weight). After a period of time, the specimens became saturated near the surface; thus further percolation was inhibited, and all specimens produced the same volume of runoff water at a constant rainfall intensity. The difference in the infiltration rates for the various unit weights is reflected in the time for the first runoff to occur after the start of the run, as shown in Table II. In nearly every test, the higher unit weight specimens produced the earliest noticeable runoff.

The interaction of intensity and unit weight, with respect to the volume of runoff water, was not significant at any rainfall duration,

TABLE IV. ANALYSES OF VARIANCE FOR VOLUME OF RUNOFF WATER.

Time	Source	df	Sum Squares	Mean Squares	F	Sig. Level
12 Min	Replication	3	200988	66996	3.3	5%
	Intensity	3	16021563	5340521	272.5	½%
	Unit Wt.	3	384550	128183	6.3	5%
	Interaction	9	44092	4899	.2	-
	Error	45	914114	20314		
	Total	63	17565307			
24 Min	Replication	3	709160	236386	2.8	10%
	Intensity	3	58919590	19639863	233.0	½%
	Unit Wt.	3	609670	203223	2.4	10%
	Interaction	9	195620	21735	.3	-
	Error	45	3794790	84328		
	Total	63	64228830			
36 Min	Replication	3	1213050	404350	2.2	10%
	Intensity	3	128800900	42933663	240.0	½%
	Unit Wt.	3	593990	197996	1.1	-
	Interaction	9	502830	55870	.3	-
	Error	45	8028970	178421		
	Total	63	139139830			
48 Min	Replication	3	1955500	651833	2.1	-
	Intensity	3	228082900	76027633	239.4	½%
	Unit Wt.	3	528500	176166	.6	-
	Interaction	9	856600	95177	.3	-
	Error	45	14321300	318251		
	Total	63	245744800			
60 Min	Replication	3	2578000	859333	1.7	-
	Intensity	3	360942400	120314130	244.0	½%
	Unit Wt.	3	401100	133700	.3	-
	Interaction	9	1342800	149200	.3	-
	Error	45	22261700	494704		
	Total	63	387526000			

indicating that the intensity and unit weight are independent variables.

Replication was significant at the 12 minute duration, at a much lower level at the 24 and 36 minute durations and was not significant thereafter. Because there is no test evidence that replication had an effect on the volume of runoff water after a duration of 36 minutes, the error due to differences in replicates was subdued after that time.

Weight of Soil Solids Eroded

The weight of soil solids eroded was examined with a factorial analysis at specified rainfall durations. The results of these analyses are given in Table V.

At all times during the investigation the rainfall intensity had a highly significant effect on the weight of solids eroded. This continued significance is because the rainfall intensity is closely related to the detachment of the soil particles from the soil surface and is also closely related to the transportation of the particles after detachment.

The unit weight of the soil was significant for the first 12 minutes and at a lower level at 24 minutes duration of rainfall. The early significance of the unit weight of the soil agrees with the findings of Foster (1967) who attributed the decrease in significance to the loosening of all the soil surfaces until a uniform unit weight was reached in the top layer of the soil.

The interaction of unit weight and rainfall intensity, with re-

TABLE V. ANALYSES OF VARIANCE FOR WEIGHT OF SOLIDS ERODED.

Time	Source	df	Sum Squares	Mean Squares	F	Sig. Level
12 Min	Replication	3	3257	1085	3.0	5%
	Intensity	3	128816	42938	117.8	½%
	Unit Wt.	3	5968	1989	5.4	½%
	Interaction	9	2136	237	.6	-
	Error	45	16437	365		
	Total	63	156616			
24 Min	Replication	3	6439	2146	2.3	10%
	Intensity	3	390126	130042	140.0	½%
	Unit Wt.	3	7693	2564	2.8	10%
	Interaction	9	5777	641	.7	-
	Error	45	41767	928		
	Total	63	451804			
36 Min	Replication	3	7540	2513	1.6	-
	Intensity	3	767435	255811	159.1	½%
	Unit Wt.	3	6854	2284	1.4	-
	Interaction	9	15322	1702	1.1	-
	Error	45	72254	1605		
	Total	63	869407			
48 Min	Replication	3	10254	3418	1.3	-
	Intensity	3	1246333	415444	156.0	½%
	Unit Wt.	3	6537	2179	.8	-
	Interaction	9	31391	3487	1.3	
	Error	45	119584	2657		
	Total	63	1414101			
60 Min	Replication	3	13378	4459	1.1	-
	Intensity	3	1850134	616711	154.9	½%
	Unit Wt.	3	9918	3306	.8	-
	Interaction	9	52964	5884	1.5	-
	Error	45	179242	3983		
	Total	63	2105637			

spect to the weight of soil solids eroded, was not significant at any time during the test, implying that the unit weight and rainfall intensity are independent variables.

Replication was not significant after the first 24 minutes. Again, the lack of test evidence that replication affects the weight of solids eroded indicates that the error due to differences in replication was subdued after an intermediate duration.

The relationship between the weight of solids eroded and the volume of runoff water was approximately linear, as shown in Figure 6. The high correlation coefficients for weight of solids and volume of water verify the approximate linearity (see Table VI). The results of linear least squares analyses for the weight of soil solids, as a function of volume of runoff water for each unit weight at each rainfall intensity, are given in Table VI.

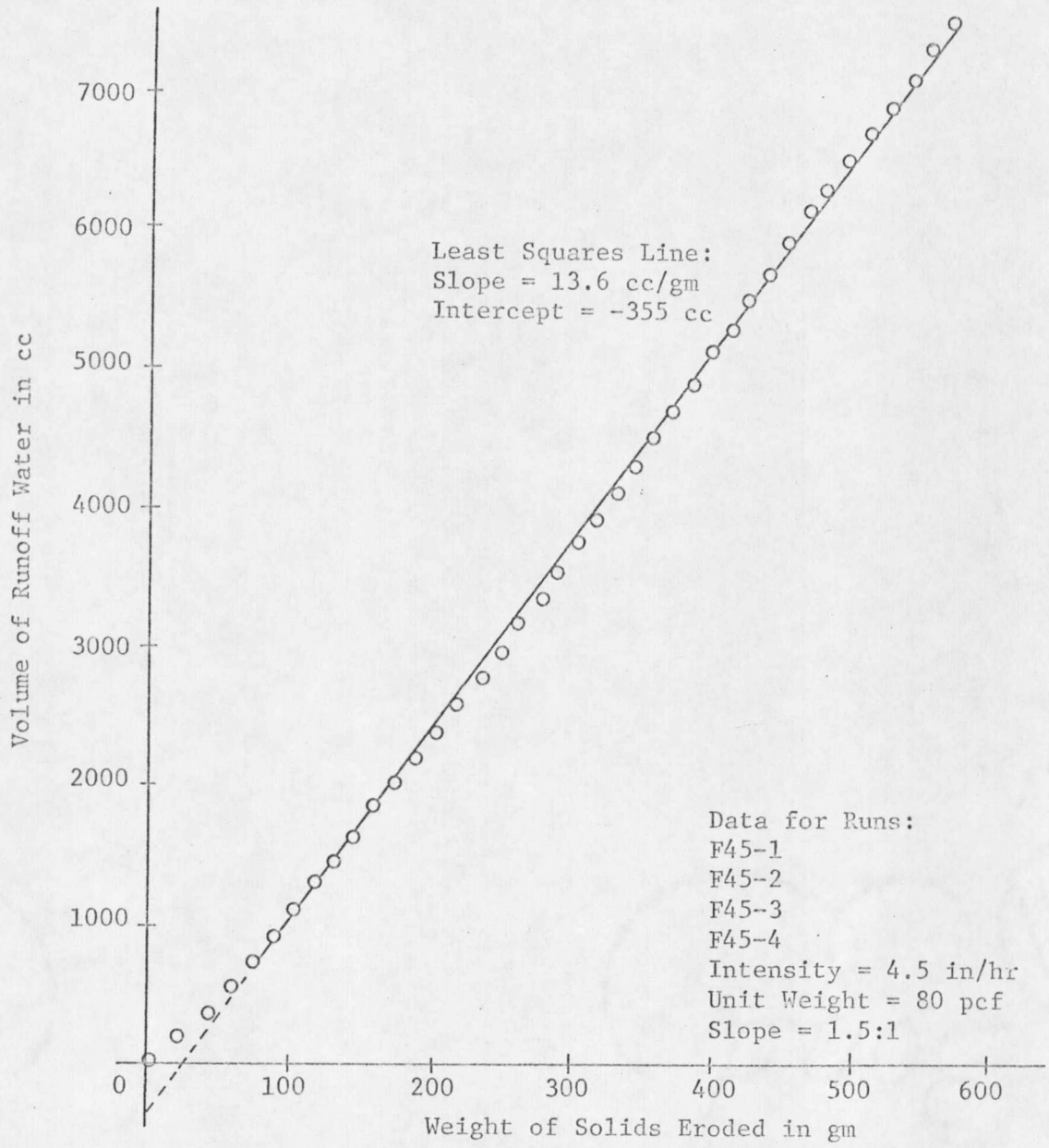


Figure 6. Typical least squares line representing the relationship between volume of runoff water and weight of solids eroded.

TABLE VI. WEIGHT OF SOIL SOLIDS AS A FUNCTION OF VOLUME OF RUNOFF WATER.

Intensity, in/hr	Unit Weight, pcf	Slope, gm/cc	Intercept, cc	Correlation Coefficient
6.0	80	21.4	-342	.9985
	85	21.9	-412	.9985
	90	25.4	-1067	.9985
	95	25.9	-1696	.9958
4.5	80	13.6	-335	.9992
	85	16.8	-484	.9983
	90	18.4	-754	.9968
	95	18.6	-985	.9945
3.0	80	29.9	-392	.9977
	85	29.4	-420	.9985
	90	26.3	-638	.9963
	95	25.4	-817	.9945
1.5	80	127.0	71	.9799
	85	94.1	56	.9889
	90	75.1	-80	.9839
	95	59.3	-102	.9766

Adjusted Weight of Solids

Because different slopes of constant slope length have different projected areas, the volume of water caught on a flatter slope will be greater than the volume of water caught on a steeper slope for a constant intensity of rainfall. The relationship is shown graphically in Figure 7.

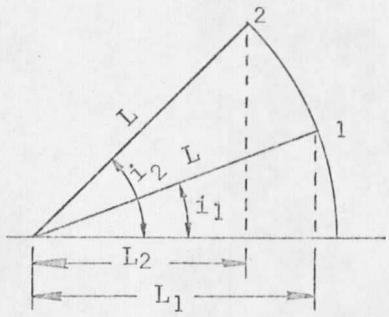


Figure 7. Slope relationships for volume of water adjustment.

From the geometry of Figure 7:

$$L = \frac{L_1}{\cos i_1} = \frac{L_2}{\cos i_2} \tag{11}$$

Multiplying by the intensity, I:

$$\frac{L_1 I}{\cos i_1} = \frac{L_2 I}{\cos i_2} \tag{12}$$

Because all specimens are of equal width, the product of the length and the intensity is the relative volume of water on the surface for a given rainfall duration, or:

$$\frac{V_1}{\cos i_1} = \frac{V_2}{\cos i_2} \tag{13}$$

where: V_1 and V_2 are the volumes of water on surfaces one and two, respectively.

Selecting the horizontal as a reference (i.e., $i_1 = 0$), the adjusted volume of water on surface 2 is:

$$V_{2(adj)} = \frac{V_2}{\cos i_2} \tag{14}$$

where: $V_{2(adj)}$ is the adjusted volume of water on surface 2.

Using the relationship for weight of soil solids as a function of volume of water, the weight of solids can also be adjusted to the horizontal reference:

$$W_{s(adj)} = (V_{2(adj)} - b) / m \tag{15}$$

where: $W_{s(adj)}$ is the adjusted weight of solids,

m is the slope of the least squares line given in Table VI, and

b is the intercept of the least squares line given in Table VI.

The adjusted weight of solids was nearly linear with the duration of rainfall, as shown in Figure 8, and as indicated by the high correlation coefficients (see Table VII). The adjusted erosion rates were found from the slopes of the linear least squares analyses applied to the adjusted weights of solids and the duration of rainfall. The correlation coefficients and the results of the least squares analyses are shown in Table VII.

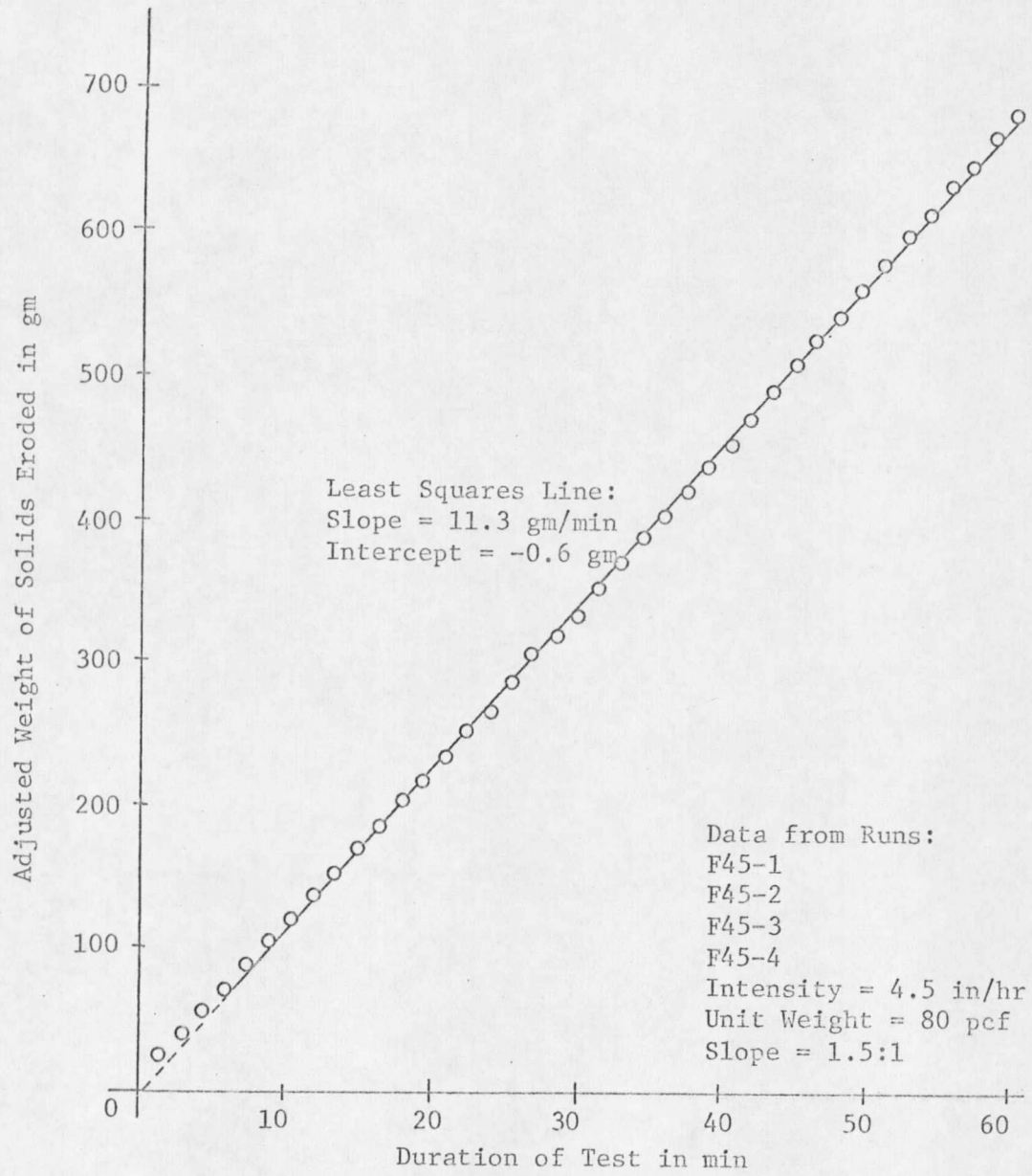


Figure 8. Typical least squares line representing the relationship between adjusted weight of solids and duration of rainfall.

TABLE VII. ADJUSTED WEIGHT OF SOIL SOLIDS AS A FUNCTION OF TIME.

Intensity, in/hr	Unit Weight, pcf	Slope, gm/min	Intercept gm	Correlation Coefficient
6.0	80	8.7	-13.2	.9997
	85	8.1	-8.1	.9997
	90	6.7	24.4	.9997
	95	6.8	55.3	.9998
4.5	80	11.3	-.6	.9997
	85	8.9	12.9	.9998
	90	8.4	29.3	.9999
	95	8.3	45.7	.9999
3.0	80	4.3	.4	.9997
	85	4.4	3.5	.9998
	90	5.2	13.4	.9999
	95	5.3	25.5	.9999
1.5	80	.3	-3.7	.9638
	85	.5	-4.3	.9793
	90	.6	-2.6	.9898
	95	.8	-1.8	.9892

Discussion of Results

The relationships between adjusted erosion rate and rainfall intensity are shown in Figure 9. From the shapes of the curves, it is evident that there is a rainfall intensity for which the erosion rate is a maximum. This erosion rate is within the range of intensities which have been measured in natural storms.

As the unit weight of the soil decreases, the maximum erosion rate increases, as shown in Figure 9. The strength of a cohesive soil increases as the unit weight of the soil increases, and, therefore, it is rational that the soils of higher unit weight will erode less under the same rainfall conditions.

The data from Figure 9 are shown obversely in Figure 10 as adjusted erosion rate as a function of soil unit weight for a constant intensity. These curves show the independence of the soil unit weight and intensity because the curves are grossly parallel.

There presently is no logical explanation for the maximum erosion rate described in Figure 9. It is therefore necessary to develop an hypothesis which rationally describes the maximum erosion rate.

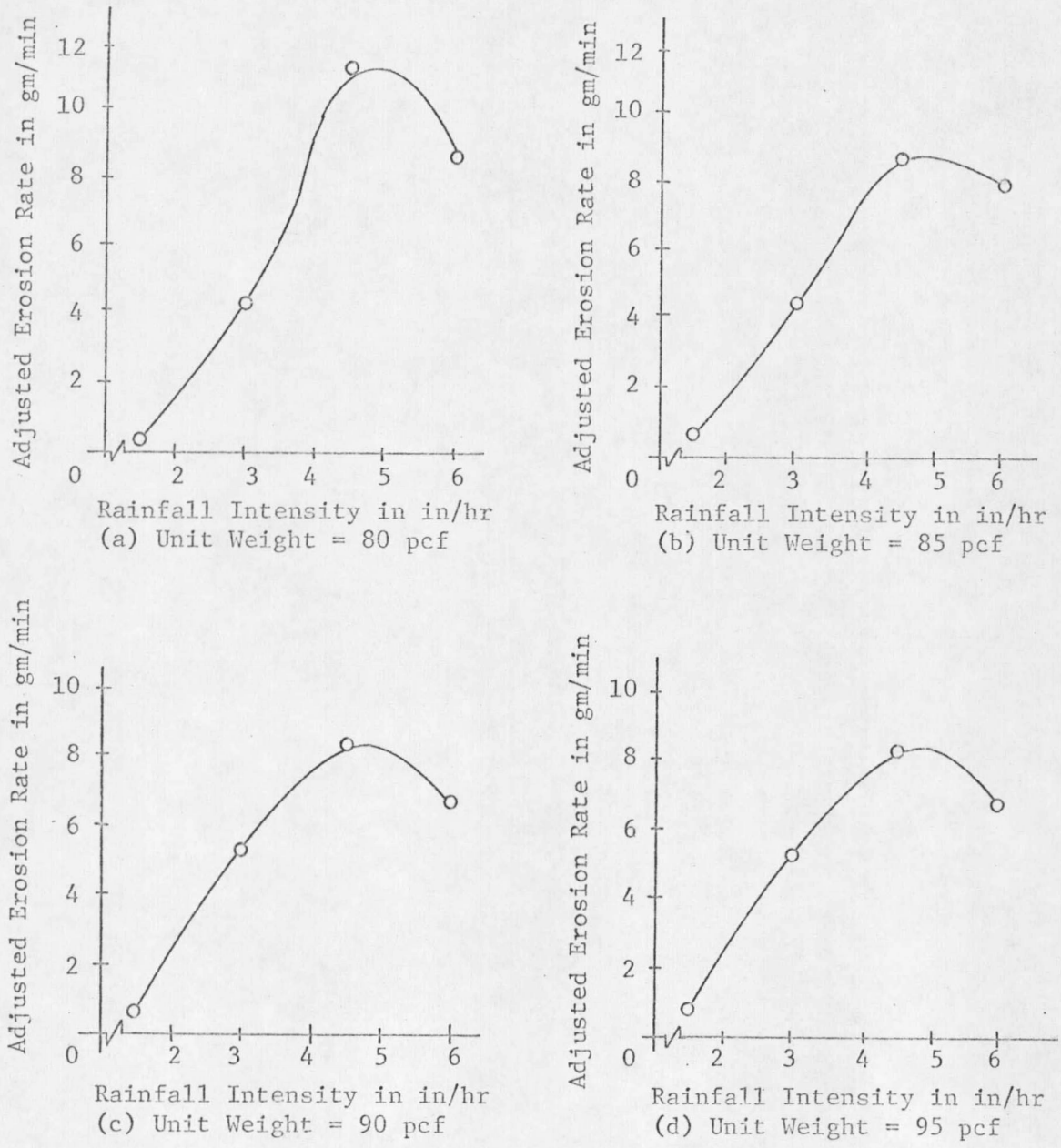


Figure 9. Relationships between rainfall intensity and adjusted erosion rate.

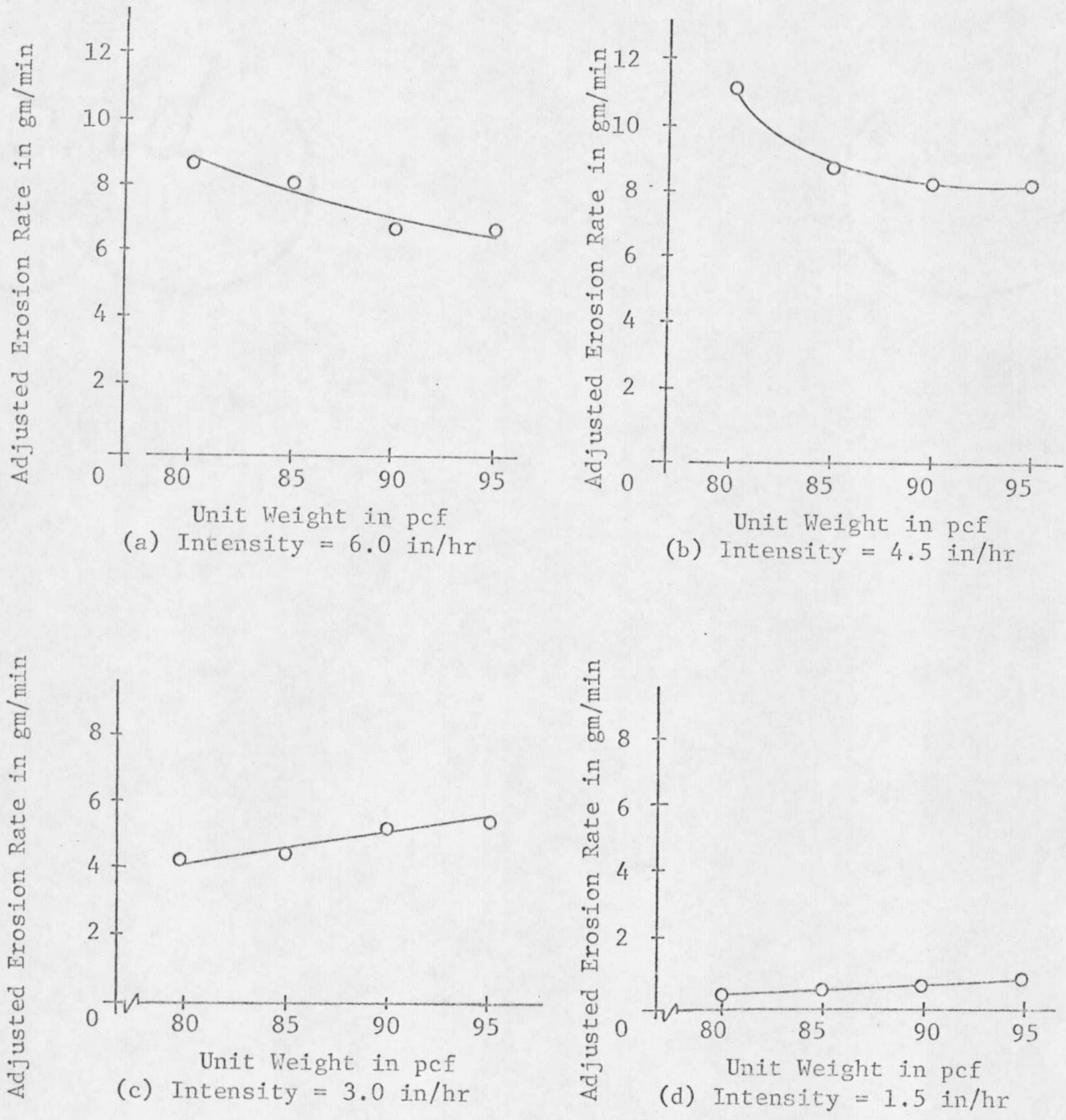


Figure 10. Relationships between unit weight and adjusted erosion rate.

CHAPTER V

AN HYPOTHESIS FOR RATE OF EROSION

Because erosion is a combination of particle detachment and subsequent transportation of the detached particles, a qualitative relationship can be developed between erosion rate and the variables that affect the detachment and transportation of the soil particles. The two variables that will be considered are the slope of the soil surface and the depth of flow of water over the soil surface. Contributing factors to the rate of erosion are as follows:

I. Soil particle detachment
   - A. Detachment due to runoff water
   - B. Detachment due to impact of the rainfall
     1. Impact detachment as depth of flow varies
     2. Impact detachment as slope varies

II. Soil particle transportation
   - A. Transportation due to runoff water
     1. Runoff transportation as depth of flow varies
     2. Runoff transportation as slope varies
   - B. Transportation due to impact of the rainfall
     1. Impact transportation as depth of flow varies
     2. Impact transportation as slope varies.

Soil Particle Detachment

Detachment due to runoff water. - As previously stated, the amount of soil that will be detached from the surface of a cohesive soil as a

result of the runoff from overland flow is relatively small. Therefore, in this hypothesis, the detachment of the soil particles due to the runoff water will be considered negligible.

Detachment due to impact of the rainfall. - The effect of rainfall impact on the detachment of soil particles can be found by considering the work of Palmer (1963). Palmer found that, for a horizontal slope, the impact force of a raindrop varies as the depth of a water layer above the surface, as shown in Figure 11. Because the particle detachment is a function of the impact force, it is rational to assume that the rate of soil detachment is a function of the water layer depth as shown in Figure 12.

As the slope of the soil surface increases, the normal component of the impact force, F_n, decreases. It follows, therefore, that the rate of soil detachment will decrease as the slope increases, as shown in Figure 13. For slopes greater than zero, it is highly probable that the shape of the curve in Figure 12 remains unchanged, but is translated downward. The combined effects of the slope of the soil surface and the depth of water flow over the surface, hypothesized above, result in the potential rate of detachment surface shown in Figure 14.

Soil Particle Transportation

Transportation due to runoff water. - The ability of the runoff water to transport the detached soil particles depends on the depth of water flow over the surface, the slope of the surface, and the velocity

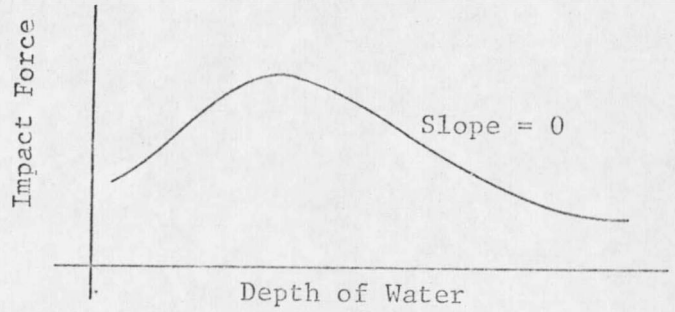


Figure 11. Variation of impact force with depth of water (*After Palmer*, 1963).

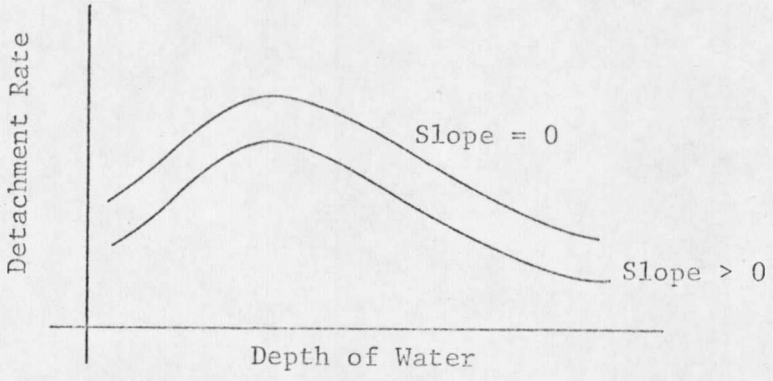


Figure 12. Soil detachment rate due to impact (constant slope)

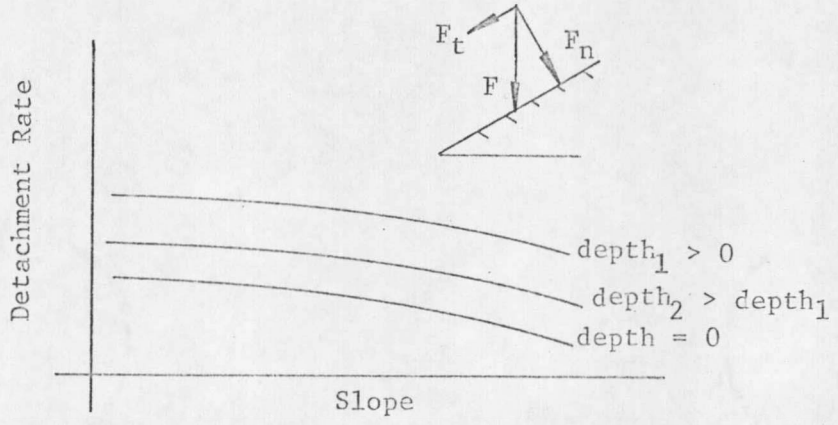


Figure 13. Soil detachment rate due to impact (constant depth).

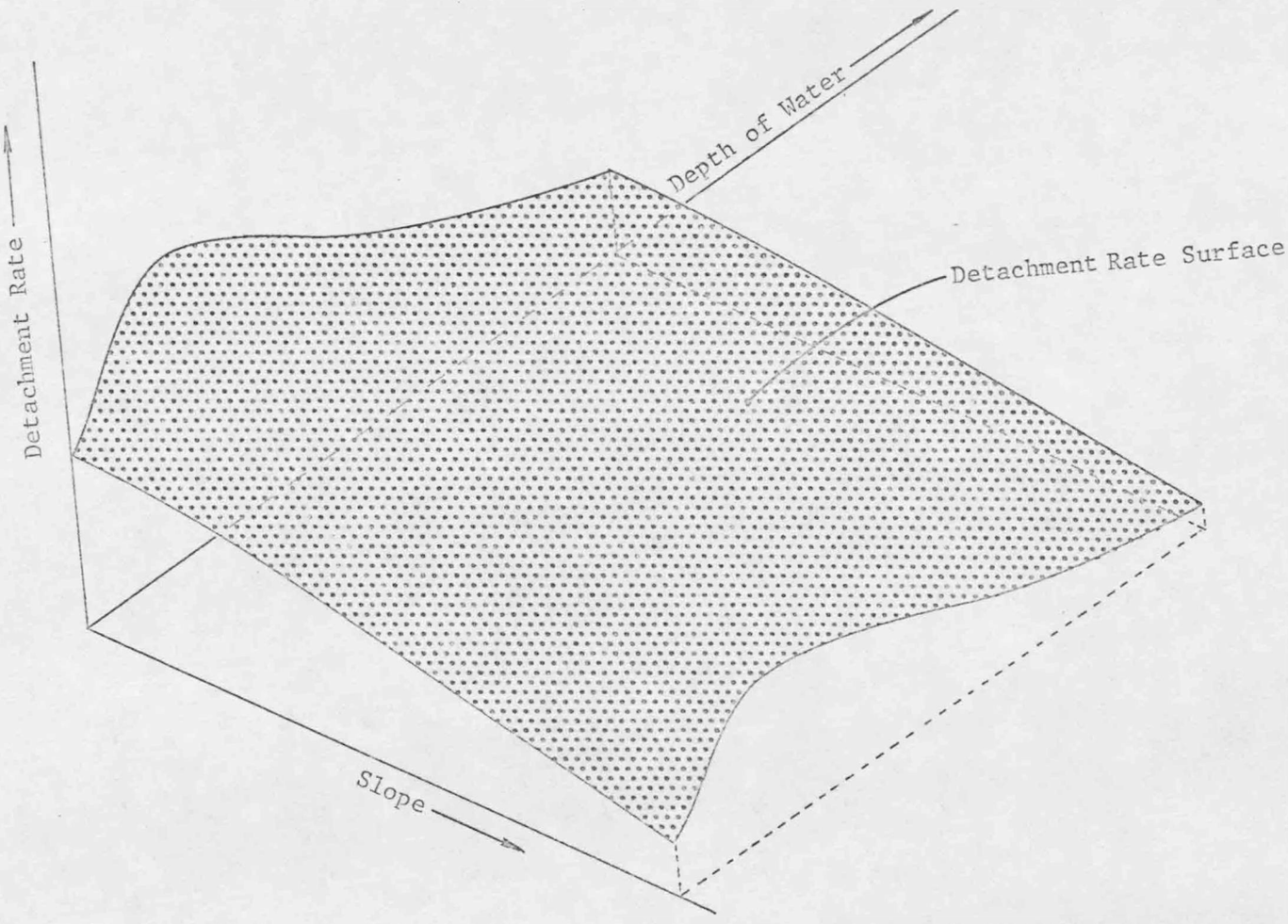


Figure 14. Potential detachment rate surface.

of the water. The velocity, depth of flow, and slope are probably related by some power function similar to Manning's equation:

$$v = K\, d^{a}\, S^{b} \qquad (16)$$

where: v is the velocity in cm/sec,

d is the depth of flow in cm,

S is the slope of the surface in cm/cm, and

K, a, and b are empirical constants.

For a zero slope, because the velocity of flow is zero, there will be no transportation of the soil particles due to the runoff for any depth of flow, as shown in Figure 15. For a constant slope greater than zero, the transportation rate of the particles would increase exponentially as the depth of flow increases, as shown in Figure 15.

For a depth of flow of zero, no transportation will occur for any slope as shown in Figure 16. For a constant depth of flow greater than zero, because the velocity is increasing, the transporting rate of the runoff very probably increases exponentially as the slope increases, as shown in Figure 16.

Transportation due to impact of the rainfall. - Transportation rate of the soil particles due to rainfall impact also is dependent on the depth of flow and the slope of the surface. On a horizontal slope, because the soil particles will be splashed equally in all directions, there will be no net transportation of the particles due

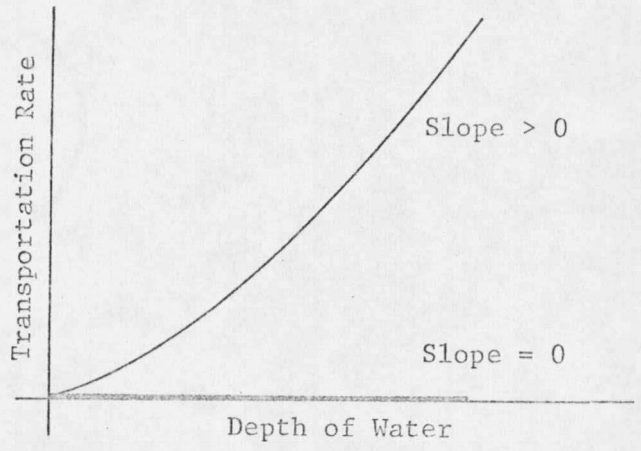


Figure 15. Transportation rate of soil particles due to runoff (constant slope).

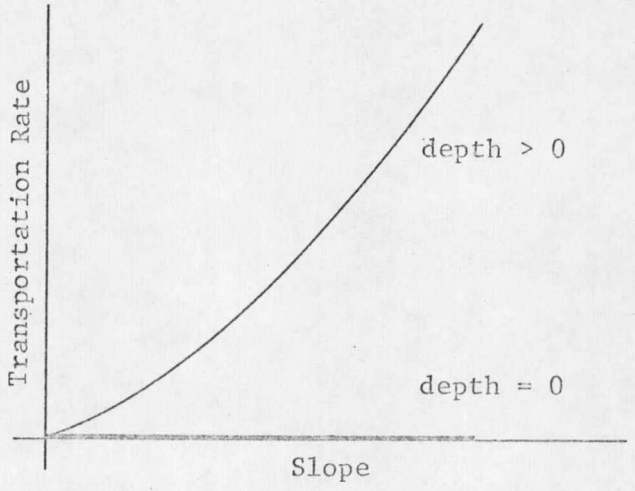


Figure 16. Transportation rate of soil particles due to runoff (constant depth).

to impact for any depth of water, as shown in Figure 17. It is reasonable to assume that the impact varies with the depth of water at a finite slope as well as at a zero slope. Therefore, for a slope greater than zero, the transportation rate of soil particles due to impact will vary with the depth of flow as shown in Figure 17.

For a constant depth of water, a constant impact force, and increasing slope, the tangential component of the impact force, F_t, will increase; therefore, the rate of transportation of the soil particles due to impact will very probably increase as shown in Figure 18.

Adding the common components of downslope transportation rate in Figures 15 through 18, the hypothesized surface of potential transportation rate, shown in Figure 19, is generated.

The Limiting Condition of Erosion Rate

The weight of soil solids that will erode from a soil surface will be controlled by the smaller of detaching capacity or transporting capacity. Stated another way, for a high rate of soil detachment and a low transporting rate, the rate of soil erosion from a slope is limited by the rate of transportation of both the runoff water and impact. Using this limiting condition, the surfaces of Figures 14 and 19 for potential detachment rate and potential transportation rate can be combined into one surface that defines the maximum erosion rate as a function of slope and depth of flow, as shown in Figure 20.

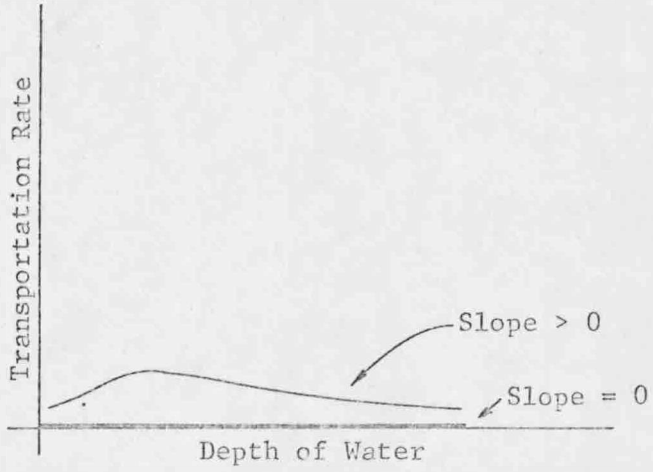


Figure 17. Transportation rate of soil particles due to impact (constant slope).

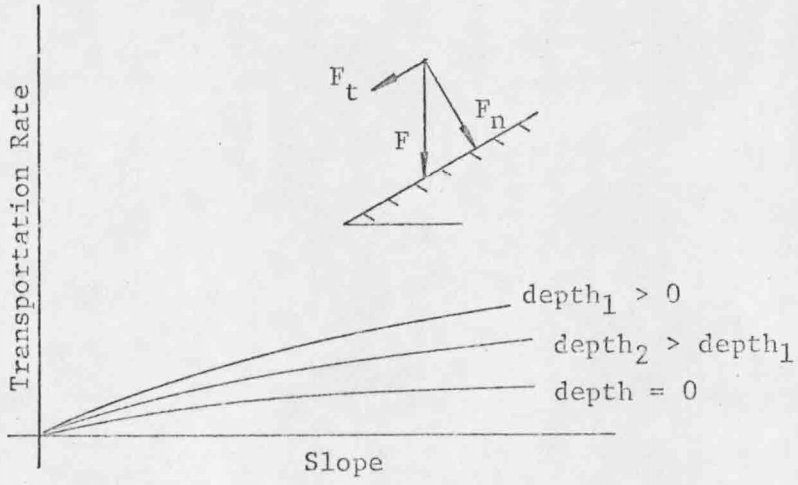


Figure 18. Transportation rate of soil particles due to impact (constant depth).

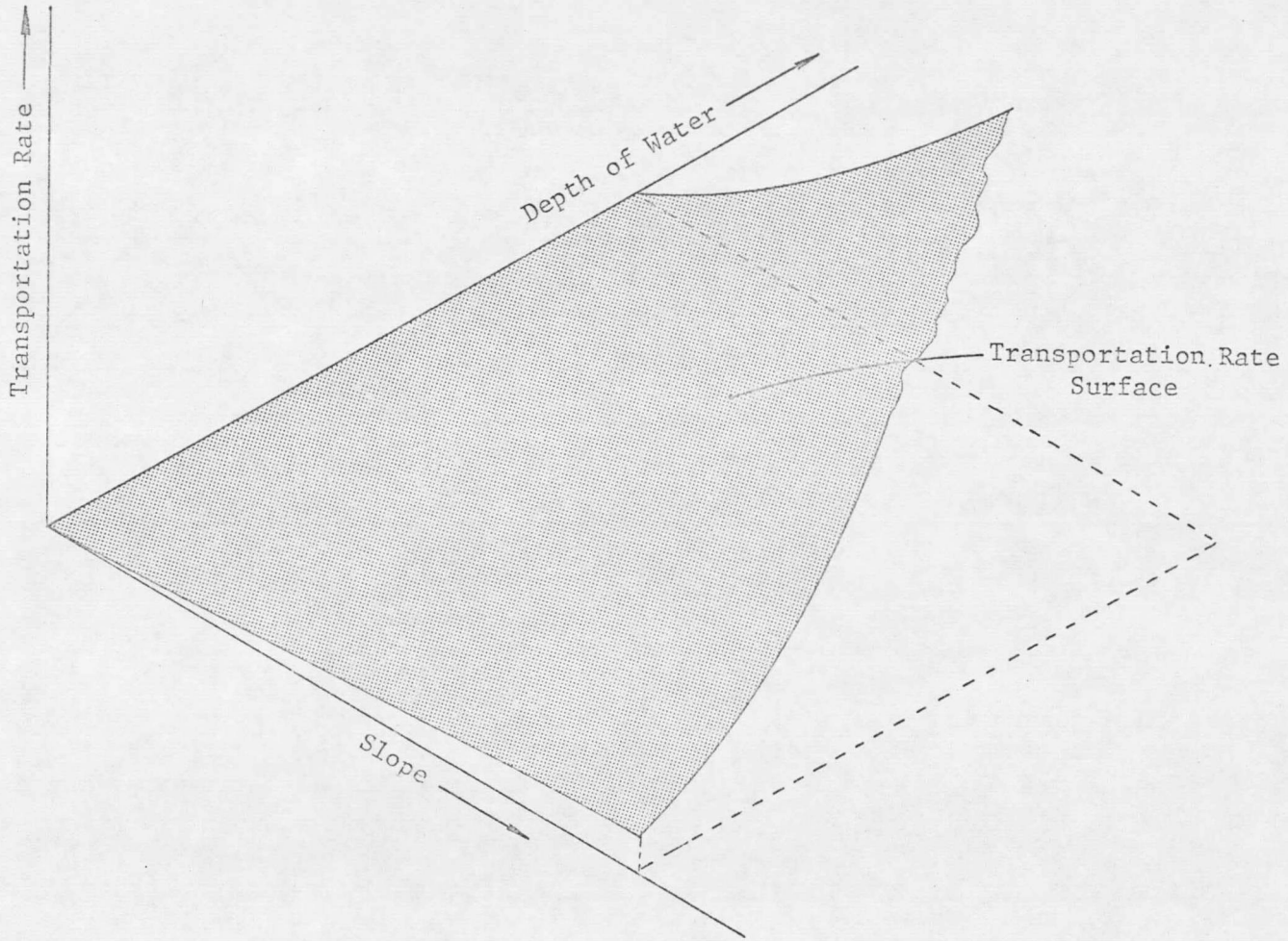


Figure 19. Potential transportation rate surface.

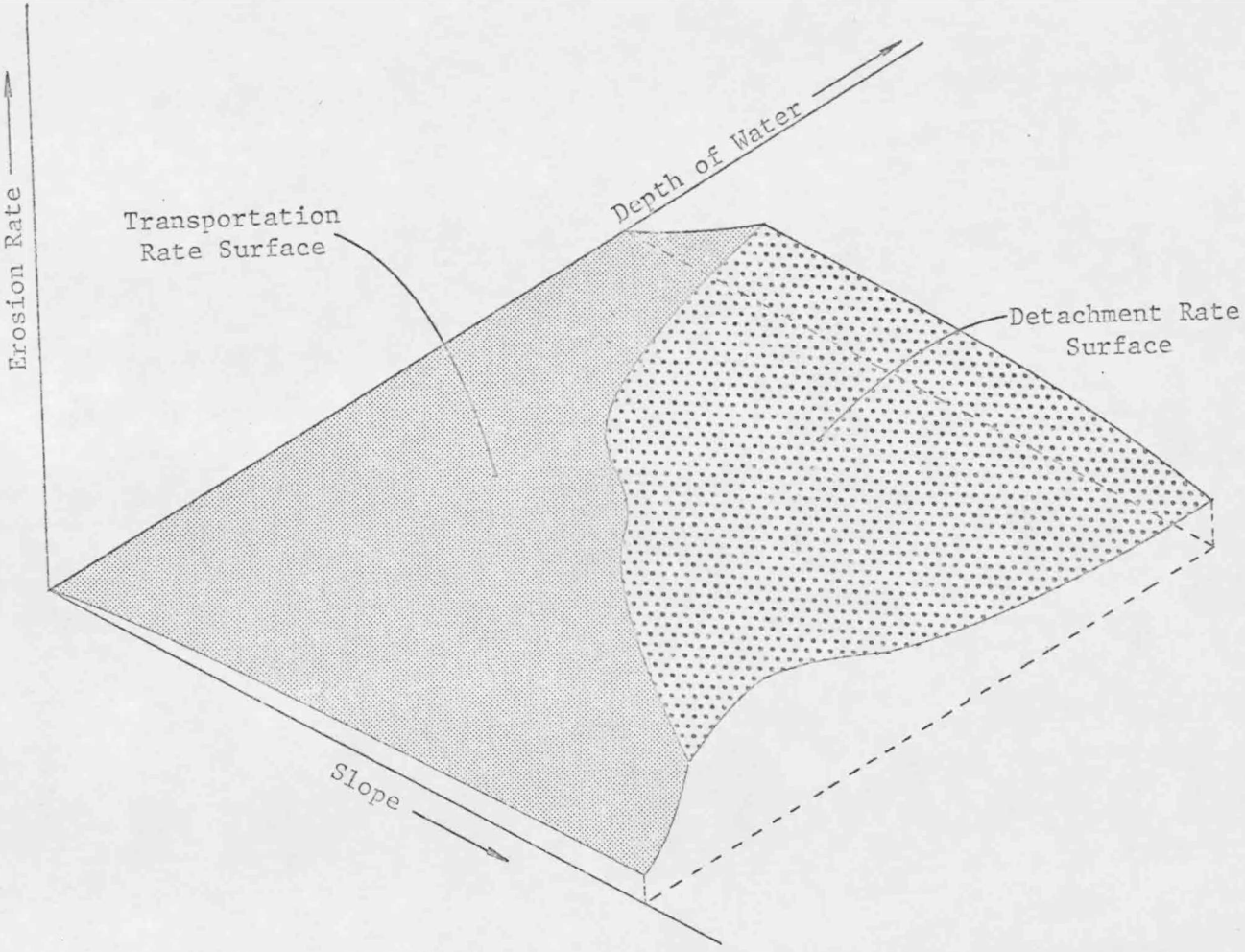


Figure 20. Surface of maximum erosion rate.

Comparison of Erosion Rate Hypothesis with Laboratory Results

The surface of maximum erosion rate presented in Figure 20 satisfies the results of the present investigation and the results of Foster's (1967) study. Foster's results are shown in Figure 21.

In Foster's study, the soil material and rainfall intensity were held constant; the slope of the soil surface and the unit weight of the soil were varied. For a constant rainfall intensity and increasing slope the depth of flow will decrease. This means that Foster's investigation was performed on a surface perpendicular to the slope-depth plane, as shown in Figure 22. Foster found a positive slope for the relationship between slope and rate of erosion at the highest soil unit weight. Considering the detachment rate surface shown in Figure 22 to be that for the highest soil unit weight, the positive slope is represented by the region F-F'. Because a decrease in soil unit weight decreases the strength of a cohesive soil, the detachment rate surface will rise as the soil unit weight decreases. The effect of raising the detachment rate surface is to change the slope of the line in region F-F' to negative, which agrees with Foster's results. Lowering the soil unit weight and raising the detachment rate surface also shifts the maximum erosion rate to the right. Foster found the erosion rate was greatest for low unit weights on flatter slopes, and greatest for high unit weights on steeper slopes, which agrees with the shift of the maximum erosion rate to the right.

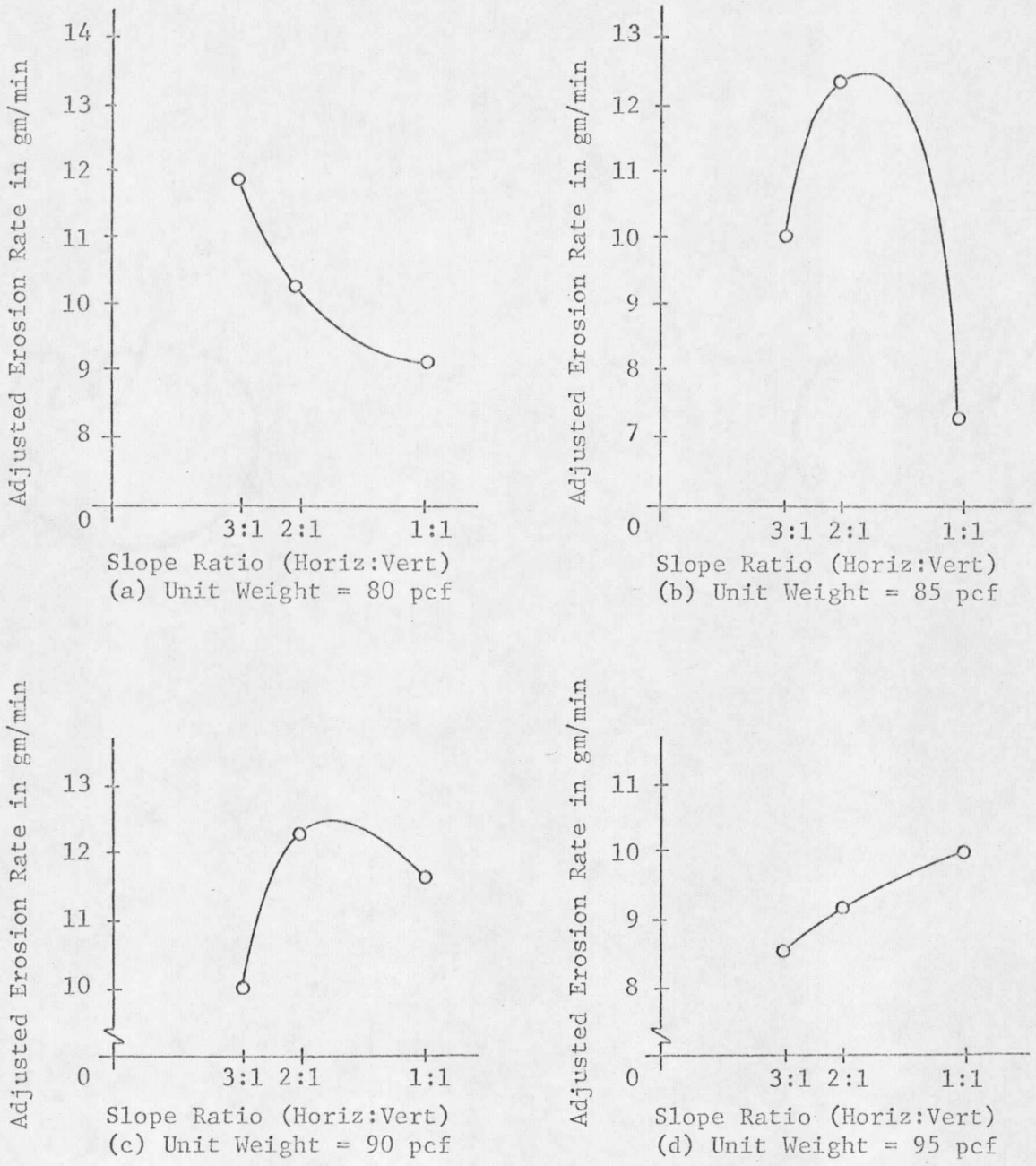


Figure 21. Relationships between slope and adjusted erosion rate. (*After Foster*, 1967).

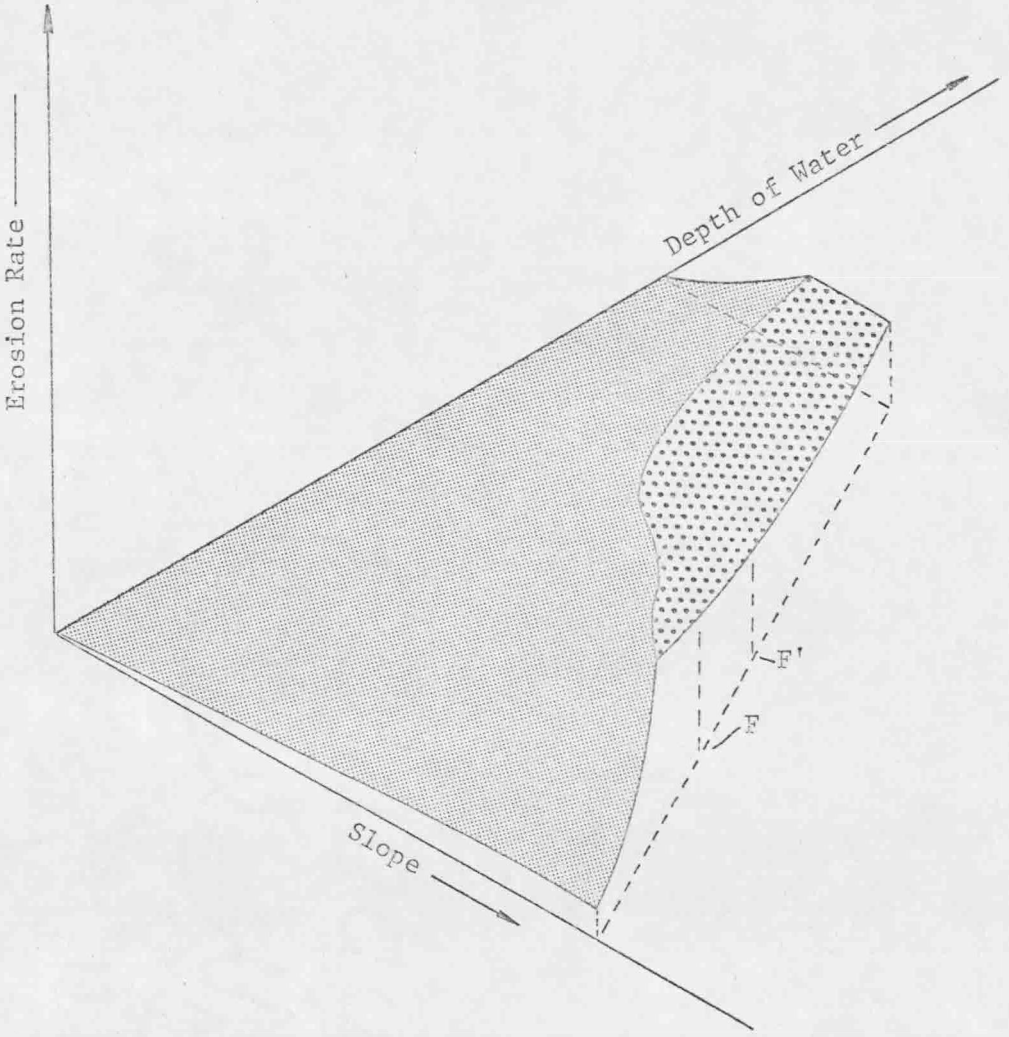


Figure 22. Plane of constant rainfall intensity.

In the investigation described in this paper, the slope was held constant, and the rainfall intensity and soil unit weight varied. Because the slope is constant, the study was performed in a plane perpendicular to the slope axis as shown in Figure 23. As the intensity of rainfall increases, the depth of flow will increase; therefore, the intensity corresponds to the depth of flow axis in Figure 23. The results of this study show that as the intensity of rainfall increases, a maximum rate of erosion will occur (see Figure 9). This condition corresponds to the region R-R' on Figure 23. Considering the detachment surface shown in Figure 23 to be that for the highest soil unit weight, the maximum rate of erosion will increase as the soil unit weight decreases which agrees with the trend shown in Figure 9.

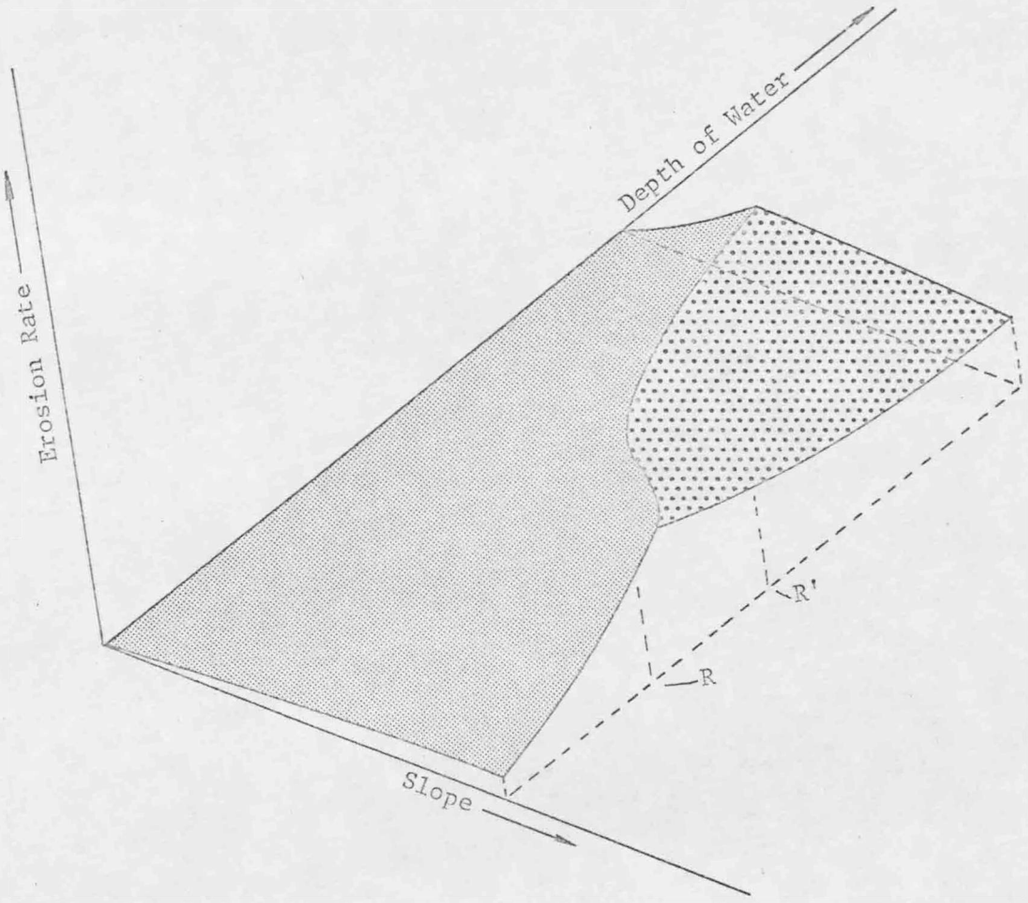


Figure 23. Plane of constant slope.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The results of this investigation indicate that there is an intensity for which the erosion is a maximum and that the maximum occurs within the range of rainfall intensities of natural storms.

The results and analyses of this study and Foster's study indicate that there exists a surface of maximum erosion rate which is a function of the slope, unit weight, and depth of water flow over the soil. The surface of maximum erosion rate is controlled in part by the detachment of the soil particles due to impact and in part by the transporting capacity of both the runoff water and raindrop impact.

Recommendations for Further Study

Based on the results of the two investigations, the following recommendations for further study are made:

1. Analytically investigate the interaction between raindrop impact and flow of water over the surface from a fluid mechanics perspective.

2. Determine the effect of soil parameters on erosion.

3. Evaluate the change in impact force, depth of flow, and flow velocity as slope and rainfall intensity are varied.

4. Improve the testing technique to define, quantitatively, points on the maximum erosion surface.

5. Examine the effect of duration of rainfall on the erosion of the soil.

6. Vary the specimen surface area and depth of specimen to determine any "scale" effect.

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