SCHOOL OF
CIVIL ENGINEERING

INDIANA
DEPARTMENT OF HIGHWAYS

JOINT HIGHWAY RESEARCH PROJECT

Final Report

FHWA/IN/JHRP-88/4 - /

PREDICTION OF EROSION
ON CUT OR FILL SLOPES

Jen-Chen Fan

PURDUE UNIVERSITY

JOINT HIGHWAY RESEARCH PROJECT

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FINAL REPORT

PREDICTION OF EROSION
ON CUT OR FILL SLOPES

TO: H. L. Michael, Director
Joint Highway Research Project

January 26, 1988

FROM: C. W. Lovell
Joint Highway Research Project

Project: C-36-36R

File: 6-14-18

Attached is the Final Report of the HPR Part II study titled "Prediction of Erosion on Cut or Fill Slopes." The report was prepared by Dr. Jen-Chen Fan, Graduate Research Assistant, under my direction.

Dr. Fan's principal activities were the redesign of the rainfall simulator to operate effectively on slopes as steep as 50% and the operation of this simulator on newly graded highway slopes near Putnamville and near Evansville.

Dr. Fan found that rill and interrill erosion on such slopes does not continue to increase with slope steepness, but reaches a maximum and then decreases. This is an extremely important finding, since it shows that conventional use of the Universal Soil Loss Equation (USLE) will greatly overestimate the erosion losses on most highway slopes.

Recommendations are made for values of S (slope) factors and K (soil erodability) factors for highway slopes in Indiana. Examples of the proper use of the Universal Soil Loss Equation for engineering purposes are also provided.

Sincerely,

C. W. Lovell
Research Engineer

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16. Abstract <p>Previous research relative to the Universal Soil Loss Equation (USLE) and rainfall simulators are reviewed. A programmable rainfall simulator was modified and successfully operated on highway slopes with slope steepness from 9% to 50% at Putnamville and Evansville, Indiana in 1985 and 1986. Special techniques were introduced for preparation of the test plots and operation of the simulator.</p> <p>Distribution of the simulated rainfall intensity and its effects on soil erosion were studied under conditions of different nozzle heights, different slope steepnesses and different nozzle tilting angles.</p> <p>The slope steepness factor was extended from 18% to 50%. The soil erodibility factor was measured and compared with that proposed by previous researchers.</p> <p>A rotational shear device was modified and operated to obtain critical shear stresses of soil samples to rate the soil erodibility factor.</p> <p>- Examples are given for predicting soil erosion on highway slopes at five locations in or around the state of Indiana, using the USLE.</p>			
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ON CUT OR FILL SLOPES

by

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Joint Highway Research Project

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The contents of this report reflect the views of the author who is responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

Purdue University
West Lafayette, Indiana

January 26, 1988

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Finally, the author gives all thanks, praises and glory to God in the name of the Lord Jesus Christ. As the Scripture says:

"The LORD is my shepherd, I shall not be in want."

"Because I know whom I have believed, and am convinced that he is able to guard what I have entrusted to him for that day."

"To him who sits on the throne and to the Lamb be praise and honor and glory and power, forever and ever!"

"Amen!"

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HIGHLIGHT SUMMARY

A rainfall simulator was modified and successfully operated on highway slopes with steepnesses from 9% to 50% at Putnamville and Evansville, Indiana in 1985 and 1986. Modifications of the structure frame, special techniques for preparation of the test plot and special operating sequences of the rainfall simulator were also developed.

Theoretical and experimental approaches were developed to study distribution of the simulated rainfall intensity and its effects on erosion under different conditions. The conditions included different nozzle heights, slope steepnesses and nozzle tilting angles for single nozzles and group nozzles. The predicted values were found to be reasonably close to the measured data. It was found that average intensity is not sensitive to nozzle height and tilting angle, but increases with slope steepness.

From the field erosion tests on highway slopes at Evansville, the slope steepness factor, S , of the Universal Soil Loss Equation was extended to 50% from 18%. The S factor appears to reach a maximum value of 1.5 at a slope steepness of 20%. The S factor of the site on a 2 to 1 slope at Putnamville was estimated to be 1.50 to 1.75. Erosion rate was found to be very sensitive to discharge rate, but not sensitive to slope steepness. The soil erodibility factor by measurement is lower than that from the nomograph of Wischmeier, Johnson and Cross (1971) because of the compaction effect.

A rotational shear device was modified and successfully operated in 1986 and 1987. It was found that for compacted and fully (or nearly fully) saturated soil samples, the soil erodibility factor decreases with critical shear stress. Critical shear stress is not recommended for use in determination of the soil erodibility factor for soils with low densities, or low cohesion or high permeabilities.

Using the Universal Soil Loss Equation and findings in this study, examples of predicting soil erosion on highway slopes at five different locations in or around the state of Indiana are given.

CHAPTER 1

INTRODUCTION

Sediment occurring through soil erosion has been found to be an important factor in causing water pollution. Because of growing environmental awareness, there is increasing concern with soil erosion. Regulations to limit the amount of soil sediment permitted in streams are becoming more common. Therefore, increased attention to measurement and control of erosion on construction sites has become essential. The control of erosion can produce for significant construction costs. Increase in the accuracy of prediction of soil erosion can help to reduce overdesign and accordingly, reduce the costs for erosion control.

Erosion of highway slopes is most severe during and immediately after construction. However, measured data or equations for predicting soil erosion on highway slopes are very limited. Equations available for predicting erosion have been developed, mainly, for agricultural uses. Slope steepnesses of highway slopes are usually much greater than those of agricultural lands. In addition, soils on highway slopes are usually

much more dense and cohesive than those for agricultural uses. The amount of soil erosion on highway slopes is expected to be different from that predicted by using equations developed for agricultural uses.

The main purpose of this study is to measure and develop prediction techniques for soil erosion on highway slopes.

In Chapter Two, previous research relative to the Universal Soil Loss Equation (USLE) and rainfall simulators are reviewed. The USLE is currently the most widely used equation in the world for predicting soil erosion .

To measure soil erosion on highway slopes with steepnesses from 0 to 50%, a programmable rainfall simulator was modified. Modifications of the simulator, special techniques for preparing the test plots and special operating sequences of the rainfall simulator are described in Chapter Three.

Chapter Four presents theoretical and experimental approaches developed for predicting distribution of the simulated rainfall intensity and its effects on erosion under different conditions. The conditions include different nozzle heights, slope steepnesses and nozzle tilting angles.

After the samples and data were collected from the field erosion tests at the test sites, a number of laboratory tests and data analyses were undertaken. In Chapter Five, the laboratory tests, data analyses, results and discussions are described. Conclusions and recommendations are also made.

To study the relationship between the soil erodibility factor and critical shear stress, a rotational shear device was modified. Modifications of the device, preparation of the soil sample, operating procedures, results and conclusions are shown in Chapter Six.

Chapter Seven shows examples of predicting soil erosion on highway slopes at five different locations in or around the state of Indiana using the USLE and the findings in this study. The five locations are Evansville, Crawfordsville, Greencastle, Cincinnati and Bloomington.

A summary, general conclusions and overall recommendations of this study are shown in Chapter Eight.

CHAPTER 2

LITERATURE REVIEW

2.1 The Universal Soil Loss Equation (USLE)

For more than 50 years, scientists have tried to predict the soil erosion loss by water. Cook (1936) selected three major variables. They were:

- [1] The susceptibility of the soil to erosion, or "soil erodibility".
- [2] The water factor, or so called "potential erosivity".
- [3] The protection factor or "cover protectivity" which is afforded by vegetative cover.

Zingg (1940) first began to use empirical equations for soil erosion prediction. The relationship he recommended was:

$$A = C S^{1.4} L^{0.6} \quad (2.1)$$

where

A = average soil loss per unit area from a land slope
of unit width, (lb/ft²)

C = a constant of variation

S = steepness of land slope, (%)

L = horizontal length of land slope, (ft)

Smith (1941) added a supporting practice factor, P, to the equation. The equation was:

$$A = C S^{1.4} L^{0.6} P \quad (2.2)$$

where

C = constant of variation which combines the effect of weather, soil, crops, or rotation and treatment

A, S, L = same as Equation (2.1)

P = supporting practice factor

Musgrave (1947) introduced the factor of rainfall intensity to prediction of erosion loss. The equation recommended by Musgrave was:

$$E = (0.00527) I R S^{1.35} L^{0.35} P_{30}^{1.75} \quad (2.3)$$

where

E = the soil loss, mm per year

I = the inherent erodibility of a soil at 10 percent slope and 22 meter slope length, mm per year

R = a vegetal cover factor

S = degree of slope, percent

L = length of slope, meters

P₃₀ = the maximum 30 minute rainfall, mm

Smith and Whitt (1947) proposed an equation for soil loss (A) in terms of slope (S) as follows:

$$A = a + b S^{1.33} \quad (2.4)$$

where a and b were constants.

Smith and Whitt (1948) also presented an additional equation in the form

$$A = C S L K P \quad (2.5)$$

where

A = the average annual soil loss

C = the average annual rotation soil
loss from plots

S, L, K and P = the dimensionless multipliers to
adjust the plot soil loss, C,
for slope steepness, length,
soil group, and supporting practice

Van Doren and Bartelli (1956) proposed an erosion equation which was

$$A = f(T, S, L, P, K, I, E, R, M) \quad (2.6)$$

where

A = annual estimated soil loss

T = measured soil loss

S = steepness of slope

L = length of slope

P = practice effectiveness

K = soil erodibility

I = intensity and frequency of 30 minute rainfall

E = previous erosion

R = rotation effectiveness

M = management level

By 1956, more than 7500 plot-years and 500 watershed-years of erosion research data were compiled from 36 locations in 21 states. Smith and Wischmeier (1957), Wischmeier and Smith (1958), and Wischmeier, et al. (1958) re-evaluated the various factors affecting soil loss, and the widely used soil loss prediction method called the Universal Soil Loss Equation (USLE) was developed. It will be described in more detail later.

Hudson (1961) proposed an erosion equation which was

$$E = T S L P M R \quad (2.7)$$

where

E = erosion

T = soil type factor

S = slope gradient factor

L = length factor

P = agronomic or agricultural practice factor

M = mechanical protection factor

R = rainfall factor

Elwell (1977) developed a Soil Loss Estimation System for Southern Africa. It was

$$Z = K C X \quad (2.8)$$

where

Z = predicted mean annual soil loss

K = mean annual soil loss, from a standard field plot 30 m x 10 m at a 4.5 percent slope for a soil of known erodibility under bare fallow

C = the ratio of soil loss from a cropped

plot to that from the standard plot

X = the ratio of soil loss from a plot of length L and slope S to that from the standard plot

Currently, the most widely used method of soil loss prediction in the United States is the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978). It is

$$A = R K L S C P \quad (2.9)$$

where

A = the computed soil loss (ton per acre)

R = the rainfall and runoff factor

(hundreds of foot-tonf * inch per
acre * hour)

K = the soil erodibility factor (ton * acre
* hour per hundreds of acre * foot-tonf
* inch)

L = the slope length factor

S = the slope steepness factor

C = the cover and management factor

P = the support practice factor

The USLE was derived from statistical analysis of 10,000 plot-years of data from natural runoff plots and

the equivalent of 1000 to 2000 plot-years of data from rainfall simulators.

The USLE was developed from an arbitrarily defined "unit" plot. A unit plot is one 72.6 feet (22.13 meters) long at 9% slope, which is kept continuously fallow and tilled up and down slope. L, S, C and P factors are ratios of soil loss from any given set of conditions to that of a unit plot. Therefore, the L, S, C and P factors in the USLE are dimensionless, but A, R and K are not. Consequently, under unit plot conditions the USLE reduces to $A = RK$.

All values which were published in English units can be converted to metric units by the methods described by Foster et al. (1981).

Wischmeier (1972) analyzed 2,300 plot year samples and found the accuracy of USLE prediction was that the mean annual soil loss was 11.3 tons and 53% of the data were in the range of 11.3 ± 1 tons, 84% in 11.3 ± 2 tons and 95% in 11.3 ± 4.6 tons.

Soil losses computed with the USLE will generally be most accurate for medium-textured soils, slope lengths of less than 400 ft, gradients of 3 to 18%, and consistent cropping and management plot studies. The farther these limits are exceeded, the greater will be

the probability of significant extrapolation error.

2.1.1 The Rainfall and Runoff Factor (R)

Cook (1936) listed the parameters affecting the potential erosivity. They were:

- [1] The amount of rainfall
- [2] The rates of rainfall
- [3] The velocities of the raindrops
- [4] The amount of surface runoff
- [5] The rates of surface runoff
- [6] The slope of the surface

The kinetic energy of a single raindrop hitting the soil surface is a function of its size (mass) and velocity at the time of impact. Both size and velocity of raindrops depend upon the rainfall intensity. Using a flour pellet technique, Laws and Parsons (1943) measured raindrop size distributions as a function of intensity for natural rainstorms in the Washington, D.C. area. They concluded that the median raindrop diameter varies with the 0.2 power of intensity. They also concluded that raindrop diameter distributions are bell shaped for

all rainfall intensities measured, but that the distribution spread increases with intensity. Marshall and Palmer (1948) obtained similar results, using radar echoes of dyed filter paper exposed to raindrops to determine diameters.

Laws (1941) and Gunn and Kinzer (1949) found the raindrop terminal velocity was logarithmically related to raindrop diameter.

Wischmeier and Smith (1958) combined raindrop diameter and velocity data to determine the kinetic energy of rainfall. They proposed:

$$E = 916 + 331 \log_{10} I \quad (2.10)$$

where

E = kinetic energy per inch of rainfall (foot-tons per acres * inch)

I = rainfall intensity (inches per hour)

Multiplication of E and the total amount of rainfall (inches) give the total kinetic energy.

Wischmeier and Smith (1958) found that EI_{30} , the multiplication of kinetic energy (E) and the maximum 30 minute intensity (I_{30}), was the best single rainfall parameter for prediction of soil loss.

Meyer and McCune (1958) developed a rainfall simulator for field erosion tests using the flat pattern nozzles of 80100 Veejet to spray raindrops. The 80100 Veejet nozzle with a pressure of 6 psi and a fall height of 8 ft from the nozzle to the soil surface gave a drop velocity at impact very near to the terminal velocity of most natural raindrops. The R factor proposed for the artificial rainfall simulation was:

$$R = 800 \cdot V \cdot I / 100 \quad (2.11)$$

where

R = the rainfall and runoff factor (hundreds of foot-tonf * inch per acre * hour)

V = amount of rain (inches)

I = rainfall intensity (inch/hour)

Wischmeier (1959) provided more detailed information for the soil loss versus EI_{30} regression. For the tested plots, the EI_{30} term explained 72% to 97% of the variation in soil loss for single storms. Up to 94% of the average annual soil loss from these plots could also be explained.

Mutchler and Hansen (1970) studied the raindrop impact force on a surface layer of water. They found as water depth increases from zero to about 0.3 drop

diameter, the forces increase, but for greater depth of water, the forces decrease. When water depth exceeds approximately three drop diameters, drop impact forces on the soil surface and subsequent soil detachment are negligible. Therefore, raindrop impact is important for interrill erosion, but not for rill and larger channel erosions (Foster, Young, Romkens and Onstad, 1984).

Foster, Meyer and Onstad (1977a) replaced R with a term defined as:

$$R_m = 0.5 EI_{30} + 0.5 a V_u \sigma_{pu}^{1/3} \quad (2.12)$$

where

R_m = combined storm erosivity from rainfall
and runoff (megajoule * mm/hectare
* hour)

EI_{30} = single storm EI erosivity value
(megajoule * mm/hectare * hour)

a = a coefficient to be determined

V_u = volume per unit area (mm)

σ_{pu} = storm peak runoff rate per unit
area (mm/hour)

This equation reflects the erosion contribution of both raindrop impact and runoff. They then compared estimated soil loss using the conventional R factor and

the modified factor, R_m , for an agricultural watershed from which actual soil loss had been measured for seven years. During this time, 55 storms produced soil loss. Analysis showed that soil loss predicted with the modified R factor had half the variance (when compared to actual soil loss) as did the conventional R factor.

Wischmeier and Smith (1978) and Foster and Meyer (1975) found that energy per unit depth of rainfall varies approximately with the 0.14 power of rainfall intensity. Total energy for a storm is:

$$E = \sum_{m=1}^n e_m \Delta V_m \quad (2.13)$$

where

E = total energy of the storm

e_m = energy per unit depth of rainfall for
the intensity of each depth increment
of rainfall, ΔV_m

n = number of increments used to
describe the rainstorm

The R factor in the USLE is the average annual summation of each individual storm erosivity value, EI_{30} . E is the total kinetic energy of a storm (foot-tons per acre) and I_{30} is the maximum 30 minute intensity

(inch/hour) of the storm. However, storms which produced less than 0.5 inches (12.7 mm) of total precipitation and occurred more than six hours after a previous storm are not included in the summation unless more than 0.25 inches (6.3 mm) of rain fell within 15 minutes (Wischmeier and Smith, 1978).

Using a rainfall simulator, Meyer (1981) found that the interrill erosion varies with the square of rainfall intensity, but drop size seldom varies with intensity. He suggested that for a storm of constant intensity, the erosivity factor, r_i , be:

$$r_i = i^2 T \quad (2.14)$$

where

i = rainfall intensity

T = storm duration

Since storm amount, V , is $i \cdot T$:

$$r_i = V \cdot i \quad (2.15)$$

Therefore, storm energy, E , is almost directly proportional to storm amount, V , because unit energy, e , varies only slightly with intensity, i . If the maximum 30-minute intensity is assumed to be a characteristic

intensity for a storm, the EI erosivity factor is almost directly proportional to the V^*i erosivity factor. Thus, the volume of rainfall and the maximum 30-minute intensity are the two most important general measures of rainfall erosivity. These two variables were as good as EI for describing erosion from fallow plots (Foster et al. 1982a).

Nearing, Bradford and Holtz (1986) measured water-drop impact forces for 3.31, 3.83, 4.51 and 5.25 mm diameter drops falling from a height of 14.0 m onto piezo-electric transducers with rise times of 2 and 5 μ s. It is found that peak forces occurred within 13 to 21 μ s of initial contact, ranged from 1.0 to 3.8 N, and decreased to 0.5 N after approximately 100 μ s. From the force measurements and an approximation of water drop contact area, average pressures under impact were calculated as a function of time, and decreased to 100 kPa after 50 μ s.

Wischmeier and Smith (1978) suggested that the R value for thaw or snowmelt (R_s) be obtained by taking 1.5 times the local December-through-March precipitation. Thus the total R factor will include the rainfall R factor and R_s .

2.1.2 The Slope Length Factor (L)

Zingg (1940) measured total loss versus slope length. He concluded that, on the average for all plots tested, total soil loss was proportional to slope length raised to the 1.6 power, and that soil loss per unit plot area was proportional to slope length raised to the 0.6 power. He further concluded that exponent differences between plots were attributable to antecedent moisture content, infiltration rates, and runoff.

Musgrave (1947), as mentioned before, proposed 0.35 as the average exponent of slope length for soil loss per unit plot area.

Smith and Wischmeier (1957) obtained 0.46 as an average value of the exponent on unit plots.

Wischmeier, Smith and Uhland (1958) proposed using 0.5 ± 0.1 for conservation planning in the North Central States. They emphasized the high degree of variability of this exponent. Some locations had exponents equal to zero while others had values as high as 0.74. Difference in runoff appeared to be the factor determining differences in the exponent. Exponents often varied more from year to year on the same plot than between plots.

Wischmeier and Smith (1965) used the following equation to determine the slope length factor, L , to adjust soil loss from a given uniform slope length to that of unit plot 72.6 feet (22.13 meters) long.

$$L = (\lambda/72.6)^m \quad (2.16)$$

where

λ = the slope length, feet

m = an exponent dependent on slope steepness

It was recommended that m be set at 0.5 for slopes greater than 5%, 0.4 for slopes of 3.5 to 4.5%, 0.3 for slopes of 1 to 3% and 0.2 for slopes on uniform slopes less than 1%.

Foster et al. (1977a) showed that m increases as rill erosion (F_t) increases relative to interrill erosion (I_t) and therefore all factors which influence the ratio F_t/I_t affect the exponent m .

Foster et al. (1981) pointed out the USLE may not be applied to slopes shorter than 5 meters and certainly does not apply to slopes as short as 1 meter.

2.1.3 The Slope Steepness Factor (S)

Most early researchers used a rational rather than

polynomial equation to relate soil loss to slope steepness. The form of the rational equation was

$$A \propto S^b \quad (2.17)$$

where

A = soil loss

S = a measurement of degree of slope

b = an exponent

Zingg (1940) used a coded soil loss and percent slope (tangent) for S and obtained 1.60 as an average value of the exponent b. Musgrave suggested 1.35 as the value.

Smith and Whitt (1947) recommended 1.33 as the b value. The steepness used was 3%.

Wischmeier and Smith (1978) used the following equation to determine the slope steepness factor, S, to adjust soil loss from a given slope steepness to that of a unit plot at 9% slope.

$$S = 65.41 \sin^2 \theta + 4.56 \sin \theta + 0.065 \quad (2.18)$$

where θ is the slope angle. The same authors (1965) used the tangent of the slope angle instead of the sine. This increases the accuracy of the equation for slopes

steeper than 20% because raindrop impact erosivity is a function of the sine not the tangent of the slope, and differences between sine and tangent become significant above 20%. The steepnesses for the data are less than 18%, where the differences between tangent and sine are not significant.

Foster and Wischmeier (1974) developed a method to evaluate the slope steepness factors for irregular slopes. The slope was divided into segments. Each of them had a uniform slope. The combined factor, LS, can be calculated from:

$$LS = \frac{1}{\lambda_e} \sum_{j=1}^n \frac{S_j \lambda_j^{m+1}}{(22.1)^m} - \frac{S_j \lambda_{j-1}^{m+1}}{(22.1)^m} \quad (2.19)$$

where

S_j = the steepness factor for j^{th} segment

λ = the length from the top of the slope to the lower end of the segment, meters

m = the slope length exponent dependent on the degree of slope in the j^{th} segment

n = number of segments

λ_e = the overall slope length, meters

Use of this equation will produce higher values of LS for convex slopes and lower values of LS for concave

slopes. The predicted soil loss was more accurate than the conventional uniform slope LS factor, when comparing this equation to data collected by Young and Mutchler (1969) on uniform, concave and convex slopes.

The S factor used by Foster (1982) for interrill erosion analysis is:

$$S = 2.96 (\sin\theta)^{0.79} + 0.56 \quad (2.20)$$

Stein et al. (1983) proposed the S factor for two mine topsoils in Indiana. For the sites of Ayshire mine of Amax Coal Co. which is approximately 15 miles northeast of Evansville, the value is:

$$S = 12.784 \sin\theta - 0.146 \quad (2.21)$$

for the sites of the Solar Sources, Inc. which is approximately 6.2 miles east of Petersburg, the value is:

$$S = 10.742 \sin\theta + 0.037 \quad (2.22)$$

McCool and George (1983) proposed an equation for dry farmed croplands in the Pacific Northwest as given by

$$S = (\sin\theta / \sin 5.14^\circ)^{0.7} \quad (2.23)$$

where

S = slope steepness factor

θ = slope angle

Hart (1984) estimated the soil loss on mountain rangeland in Utah using a conventional S factor and that proposed by McCool and George (1983). It was found that for steep slopes of 32% with high intensity rain on wet soil, the S factor by McCool and George was much more accurate.

After studying the S factors proposed by several researchers, McCool et al. (1987) recommended that the S factor be

$$S = 10.8 \sin\theta + 0.03 \quad \theta < 5.14^\circ \quad (2.24)$$

$$S = 16.8 \sin\theta - 0.50 \quad \theta > 5.14^\circ \quad (2.25)$$

2.1.4 The Cover and Management Factor (C)

The cover and management factor, C , in the USLE is the ratio of soil loss from land cropped under specified conditions to the corresponding loss from clean-tilled continuous fallow (which is land that has been tilled and kept free of vegetation for more than 2 years). This factor is designed to combine the effect of all the

interrelated cover and management variables (Wischmeier and Smith, 1978).

2.1.5 The Support Practice Factor (P)

The support practice factor, P, in the USLE is the ratio of soil loss with a specific support practice to the corresponding loss with up-and-down-slope culture. Support practices include contouring, contour stripcropping, terracing and stabilized water channels (Wischmeier and Smith, 1978).

2.1.6 The Soil Erodibility Factor (K)

The erodibility factor, K, in the USLE is a quantitative value experimentally determined. This factor is designed to include all the soil properties that affect soil erosion. Before the USLE was developed, researchers attempted to relate soil properties to measured overall erosion.

Kibler and Busby (1970) defined soil erodibility as inherent susceptibility of soil particles to detachment and transport by raindrops and runoff.

Middleton (1930) was one of the earliest researchers who attempted to analyze the soil properties that affect soil erosion. Instead of quantifying erodibility, he tried to find soil characteristics to classify

soils as "erodible" or "nonerodible". He considered dispersion ratio to be the most significant criterion in distinguishing between erodible and nonerodible soils. The dispersion ratio is the ratio of suspension percentage to the total silt plus clay. The method for determining suspension rate was described by Middleton (1930). The other important soil characteristics were angle of repose, plasticity number, percolation rate, organic matter content, total exchangeable bases and determination of slaking value.

Baver (1933) indicated that two factors influencing runoff and erosion were the capacity of the soil to absorb water and the permeability of the soil. The most significant parameter found was the degree of aggregation, because the rate of water absorption and permeability were highly related to this parameter, i.e. the degree of aggregation increased with porosity and the rate of water absorption and percolation.

Lutz (1935) selected Iredell sandy clay loam and Davidson clay for a study of the physical soil properties that affect erosion. Field tests results showed that Iredell sandy clay loam was an erodible soil and Davidson clay, a relatively nonerodible soil. Laboratory test results showed that the differences in their erodibility were primarily due to the degree of

aggregation of the finer fraction.

Peele (1937) stated that the rate of water percolation is a more accurate index of the erodibility of a soil than is the water absorption capacity of that soil.

Peele et al. (1945) and Anderson (1954) continued to study soil properties in relation to erodible and nonerodible classifications. Their results showed that the aforementioned soil properties tended to differ for erodible and nonerodible soils.

Olson et al. (1962) determined soil erodibility with the Meyer-McCune (1958) rainfall simulator. It was one of the first attempts to establish values for the soil erodibility factor, K, in the USLE. The K factor was determined by dividing the measured total soil loss, A, by the other factors of the USLE. It was:

$$K = \frac{A}{E \cdot I_{30} \cdot L \cdot S \cdot C \cdot P} \quad (2.26)$$

They did not try to relate the soil properties to the determined K factor which ranged from 0.23 to 0.67 (ton · acre · hour/hundreds of acre · foot-tonf · inch) on selected Corn Belt soils.

Olson and Wischmeier (1963) determined K factors for 20 soil types represented by U.S. Department of

Agriculture runoff and erosion research stations located in the eastern half of the United States, from natural rainfall plots. The values of K factor ranged from 0.02 to 0.69. The two soils with the lowest K values were characterized by having a high percentage of very coarse material on the surface. For the other 18 soil types, it was found that medium textured soils were the most erodible and erodibility decreased with increasing amount of sand or clay.

Barnett, Rogers, Holladay and Dooley (1965) determined soil erodibilities with a rainfall simulator for 13 soils on 33 individual sites in the Southern Piedmont and Coastal Plains areas of Georgia and South Carolina. Silt loam was found to be most erodible. Then, in decreasing order of erodibility, were sandy clay loam, sandy loam, loamy sand and sand.

Dash (1968) measured erosion on saturated consolidated samples with a vertical jet apparatus, and on nearly saturated compacted samples with a flume section. An erosion index was introduced to rate soil erodibility. The erosion index generally increased with water content, but decreased with clay percentage. The index was not sensitive to the Reynolds Number used.

Bhasin (1969) measured erosion rates with a verti-

cal water jet on various soil samples under different treatments. It was found that erosion rate increased with water contents, sand-grundite ratio, velocity of the eroding jet, diameter of the jet, the amount of suspended sand in the eroding flow and temperature of eroding water. It was also found that erosion rate decreased with the distance between jet origin and soil sample, length of mixing time of sand, grundite and water, length of curing time of the mixed soil, and as the sand constituent tended toward the well-graded state. Vane shear strength was also applied to relate soil erosion rate. It was found that erosion rate decreased with vane shear strength, when the vane shear strength was lower than a certain value.

In a 5-year field, laboratory, and statistical study including 55 selected Corn Belt soils, Wischmeier and Mannering (1969) tried to relate soil properties to erodibility. An equation with 24 variables was proposed to estimate the K factor at 90% confidence limits of ± 0.04 . Erodibility was found to be very sensitive to small change in particle size distribution.

Wischmeier, Johnson and Cross (1971) proposed a nomograph to estimate soil erodibility using five soil parameters, namely, percent silt, percent sand, organic matter content, structure and permeability. The

nomograph is shown in Figure 2.1. The procedure to estimate the K factor on the nomograph was given as follows:

- [1] Find the sum of percent silt (0.002-0.05 mm) and percent very fine sand (0.05-0.1 mm).
- [2] Use the value of the sum to enter from the left side of Fig. 2.1.
- [3] Proceed to points representing the percent sand (0.10-2.0 mm), percent organic matter, structure and permeability.

The classifications of structure code and permeability are given in the reference "Soil Survey Manual" of the United States Department of Agriculture Handbook No. 18 (1951) listed in the references.

If the fraction of silt and very fine sand does not exceed 70%, the K factor of the soil can be estimated by calculation shown as follows:

$$K = 2.1 M^{1.4} (10^{-4}) (12-a) + 3.25(b-2) + 2.5(c-3) \quad (2.27)$$

where

$$M = (\text{percent silt} + \text{very fine sand}) \cdot (100 - \text{percent clay})$$

Figure 2.1 Soil erodibility nomograph of Wischmeier, Johnson, and Cross (1971)

- a = percent organic matter
- b = structure code
- c = profile permeability class

Wischmeier, Johnson and Cross (1971) also developed a weighting procedure to determine the average annual K factor from simulated rainfall studies. It is:

$$K_{ave} = \frac{13 A_d + 4 A_w + 3(A_w + A_v)}{13 EI_{30d} + 4 EI_{30w} + 3(EI_{30w} + EI_{30v})} \quad (2.28)$$

where

K_{ave} = average annual K factor

A = total soil loss adjusted to a unit plot
by the L, S, C and P factors

EI_{30} = as previously defined

d,w,v = dry, wet and very wet runs of rainfall
simulation, respectively

After analyzing a number of studies by other researchers on causes and mechanisms of cohesive soil erosion, Paaswell (1973) concluded that physicochemical indexes give better information on soil structure which is necessary to interpret soil potential behavior. He also concluded that structural indexes such as previous stress history, particle orientation and ability to swell must be defined to establish relative erodibility

of a given soil and comparison with other soils.

Roth, Nelson and Romkens (1974) developed an equation and a nomograph to determine soil erodibility. The equation is:

$$K_{\text{PRED}} = 0.3214 + (20.167)(10^{-5})X_{12} - 0.14440X_{31} - 83686X_{21} \quad (2.29)$$

where

K_{PRED} = predicted soil erodibility

X_{12} = M-value as defined by Wischmeier,
Johnson and Cross (1971)

X_{31} = sum of the Fe_2O_3 and Al_2O_3
contents

X_{21} = SiO_2

The nomograph constructed from the equation is shown in Figure 2.2. The procedure of using the nomograph is similar to that of Wischmeier, Johnson and Cross (1971).

The equation and nomograph by Roth et al. (1974) could be used on subsoils with little or without organic content and with clay contents beyond the range of those used to develop the equation proposed by Wischmeier et al. (1971).

Procedure: With appropriate data, enter scale at left and proceed to points representing the soils % sand (0.1-2mm), % $(\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3)$ content and % (SiO_2) content, in that sequence. Interpolate between plotted curves.

Figure 2.2 Soil erodibility nomograph of Roth, Nelson, and Romkens (1974)

After reviewing the pertinent literature on soil erosion, Veon and Miller (1977) concluded that the nomograph developed by Wischmeier, Johnson and Cross (1971) gave the best estimate of soil erodibility for most of soils, and the nomograph developed by Roth, Nelson and Romkens (1974) was suggested for use for soils with higher clay content and low organic matter content.

Young and Mutchler (1977) developed an equation to predict soil erodibility from 13 Minnesota soils. The equation was:

$$K = -0.204 + 0.385 X_1 - 0.013 X_2 + 0.247 X_3 + 0.003 X_4 - 0.005 X_5 \quad (2.30)$$

where

X_1 = aggregate index which is the ratio of
2-9 mm aggregates to all the rest

X_2 = the percentage of montmorillonite

X_3 = bulk density

X_4 = percent silt plus very fine sand

X_5 = dispersion ratio

The R^2 value was 0.90. Among the five variables, aggregate index and the percentage of montmorillonite are considered most significant because they explained 75% of the variation in K.

Stein et al. (1983) used a rainfall simulator to collect erosion data from EI plots at three reclaimed mined sites and unmined sites in southern Indiana. They found that reclaimed mined soils had higher K values than unmined soils and most of the field measured K values were higher than the predicted values from the nomograph proposed by Wischmeier et al. (1971).

2.2 Rainfall Simulators

2.2.1 Introduction

A rainfall simulator is a piece of equipment used to simulate natural rainfall. It mainly consists of the following parts:

- [1] Drop-former and spraying system: to form and spray the water drops of a desirable drop size distribution, intensity and water drop velocity. It is considered to be the heart of the simulator.
- [2] Frame: to keep the whole structure of the simulator stable, and supply a fall height for drops to achieve terminal velocities.
- [3] Water tank and hoses: to store and supply the water needed for simulated rainfall.

- [4] Power system: to supply the power needed for the system.
- [5] Simulator controller: to control the operation of a simulator.

To study soil erosion, a number of rainfall simulators have been developed since the 1930's. The advantages of simulated rainfall to measure erosion, as Meyer (1965) described them, are:

- [1] More rapid results: The time required to set conclusive results is much shorter (1-2 years). For natural rainfall, it usually takes 10 to 20 years.
- [2] More efficient: Test plot maintenance prior to application of such artificial storms is much easier.
- [3] More controlled: The necessary conditions, e.g. intensities, durations, topographies and surface treatments, can be well regulated.
- [4] More adaptable: In addition to greater control for field studies, simulated rainfall is readily adaptable to highly controlled laboratory research. Erosion studies which would be impossible to properly control in the field, e.g.

temperature, humidity and wind, can often be conducted in the laboratory using the rainfall simulator. Such studies present the possibility for major advances in understanding of basic erosion processes.

However, rainfall simulators have quite a few limitations. Mech (1965) pointed out a number of these:

- [1] Modeling limitations: Some of the factors, such as wind, light, temperature, humidity, vegetative influences, soil surface, and soil moisture, may be very significant but are difficult to simulate.
- [2] The cost for equipment is relatively high.
- [3] The device requires a number of persons to transport, assemble, operate and disassemble.
- [4] The plots studied are usually too small.

Nevertheless, Neff (1979) concluded that, "...There is no other tool available that will quickly and efficiently provide the necessary data when and where it is (sic) needed."

2.2.2 Types of Rainfall Simulators

According to the drop-forming method, simulators can be divided into three types - hanging yarns, tubing tips and nozzles (Mutchler and Hermsmeier, 1965).

2.2.2.1 Hanging Yarns

Parsons (1943) mentioned that a rainfall simulator, which was called a dripolator or a stalatometer, was made using hanging-yarn drop formers.

Ellison and Pomerence (1944) showed the construction details of a rainfall simulator using the hanging-yarn method. The drop formers were built with a regular spacing to give a uniform distribution of intensity over the test area. Drop size depended upon the hanging-yarn size, and was limited to drops with diameters larger than 4 mm.

2.2.2.2 Tubing Tips

Ekern and Muckenhirn (1947) used a simulator which was made of 22-gage hypodermic needles set in a 10-quart aluminum container on a 1-inch grid. Drop size could be changed by enclosing the needles in various sizes of glass tubing. The height needed for a drop to achieve a terminal velocity was about 35 ft.

Mutchler and Moldenhauer (1963) used telescoping pieces of tubing to construct a laboratory rainfall simulator.

Both hanging yarns and tubing tips have the same limitations. The height for attaining at least 95% of terminal drop velocity is about 5 meters for a drop of 2 mm diameter, and about 7.8 meters for a drop of 4 mm diameter (Laws, 1941). Compared to hanging yarns, tubing tips are more suitable for drop forming because they provide a larger range and a greater precision of drop sizes. The terminal drop velocities for the drops of 2 mm and 4 mm diameter are 6.5 and 8.7 m/s, respectively.

2.2.2.3 Nozzles

When nozzles are used for drop forming, there are two basic problems:

1. The median drop size tends to be too small, although the drop size distribution may be similar to natural rainfall.
2. The flow rate tends to be too high.

The first problem may be solved by overlapping the nozzle spray patterns. The second problem can be solved by moving the spray pattern off the plot area, or operating

the nozzle intermittently to provide an off-and-on spray (Mutchler and Hermsmeier, 1965).

Duely and Hays (1932) mentioned the use of an ordinary sprinkling can as a nozzle. Lowdermilk (1930) used Skinner irrigation systems and Skinner nozzles (trade and company names), which consisted of two horizontal pipes fitted with orifices and placed on each side of a set of plots. Nichols and Sexton (1932) used Skinner catfish nozzles to produce rainfall simulation. Craddock and Pearse (1938) used 1/32-in. orifice nozzles. The rainfall intensity was obtained by oscillating the nozzles and delivery pipes to move the spray pattern back and forth across the slope.

Beginning in 1936, Dr. Lowdermilk instructed the group of Soil Conservation Service workers at the Hydraulic Laboratory of the National Bureau of Standards in the construction of a suitable nozzle for rainfall simulation. Their efforts resulted in the well-known type D, E and F rainfall simulators (Parsons, 1943).

Meyer and McCune (1958) developed a rainfall simulator which has come to be known as the "USDA rainulator". The rainfall simulator is made of aluminum to minimize the weight and prevent corrosion by weathering. It is simple to separate, assemble, operate and tran-

sport because the individual pieces can be disassembled into long, narrow and easily loaded shapes. The rain-fall simulator has been successfully used to analyze (qualitatively and quantitatively) soil erodibility, as affected by crop cover, residue management, runoff and the like.

The design for the selected nozzles and their operation are:

- [1] Nozzle: Spraying System Company 80100 Veejet.
- [2] Height: 8 feet above the soil surface.
- [3] Spraying direction: Vertical downward. This can minimize wind distortion. The interference by wind is negligible up to wind velocities of 10 mph.
- [4] Nozzle pressure: 6 psi. This pressure imparts a nozzle velocity of approximately 22.3 fps to the drops. This velocity, plus the fall of 8 ft from the nozzle to the soil surface, results in a drop velocity at impact very near to the terminal velocity of most natural rain drops.
- [5] Distance between nozzles: 5 ft parallel by 6 ft perpendicular to the long dimension of the spray

pattern. The 5 foot distance provides the necessary overlap to give the best intensity distribution at the height and pressure used. Intensity variation within the 5 ft distance is less than 20 percent.

[6] Distance that nozzles are spraying during movement: 6 ft. Therefore, one nozzle stops spraying at the same point that the preceding one began.

[7] Type of movement: Reciprocating, with nozzles moving back and forth across slope.

[8] Intensities: 2 1/2 in/hr and 5 in/hr.

Each unit of the rainulator covers an effective area of 18 ft across the slope by 15 ft down the slope. The rainulator sets can be combined; as many as twelve units have been so used. The combination is 3 units across the slope by 4 units down the slope. These 12 units can cover 3 plots 75 ft long.

The rainfall impact energy per unit of rainfall for the intensity of 2 1/2 in. per hour, e , is approximately 800 foot-tons per acre $\cdot$ in. (0.21104 Mi/ha $\cdot$ mm). This is about 76% of the impact energy (1050 foot-tons per acre $\cdot$ in. or 0.27699 Mj/ha $\cdot$ mm) of the natural rainfall at the same intensity. It is about 77% of the impact

energy (1037.32 fot-tons per acre-in or 0.27365 Mj/ha*mm) of the rainfall at the same intensity as calculated from Equation (2.10).

Barnett and Dooley (1972) and Young and Burwell (1972) compared the erosion potential between simulated and natural rainfall. They concluded that both soil loss and EI_{30} for simulated rainfall were about 78% of those of natural rainfall. Therefore, the soil loss per EI_{30} unit was the same. The use of the rainulator for runoff plot research was described in detail by Meyer (1960).

Swanson (1965) developed a rotating-boom rainfall simulator. It is comparatively cheap and easy to operate, separate, assemble and transport. The spraying nozzles are the 80100 Veejet, which is the same as for the Meyer-McCune rainfall simulator. It has been used to apply rainfall at 5 in. per hour intensity on two parallel plots on a 6% slope. Each plot is 35 ft long and 12 ft wide. However, the intensity is not very uniform all over the plots. Apart from this problem, it can not be combined into larger groups as can the Meyer-McCune simulator.

Bubenzer and Meyer (1965) developed a small simulator for laboratory studies. The device consists of

three 80100 Veejet nozzles which spray downward from a height of 8 ft to a plot approximately 2 ft wide by 10 ft long. However, the test results are not available for comparison with those from field tests.

Moldenhauer (1965) proposed a procedure for studying soil characteristics in the laboratory using disturbed samples and simulated rainfall. In this study, he provided a rather complete method and procedure, and described problems to be solved as well. For example, the problems include the difficulty of maintaining the equilibrium moisture content of the soil sample during sieving and sample preparation in the laboratory. It is also difficult to simulate field moisture suction. This is attempted by placing the soil sample on a bed of glass beads and applying suction to the bed. Unfortunately, there are no supporting data to correlate laboratory and field measurements.

Grierson and Oades (1977) developed a rainfall simulator for field studies of runoff. The nozzles used were Spraying Systems Fulljet 1HH12 or 1 1/2 H30. Both types can provide the rainfall with a uniformity coefficient greater than 80%. The uniformity coefficient (C_u) is defined as follows:

$$C_u = 100 \cdot (1.0 - \frac{\sum x}{mn}) \quad (2.31)$$

where

m = mean value

n = number of observations

x = deviation of individual observation from the
mean

The larger nozzles (1 1/2 H30) are better than the smaller nozzles (1HH12) in uniformity. The simulator is mounted on a two-wheeled trailer towable by either car or tractor. The simulator is small and easy to handle. The intensity, drop size and drop velocities of the simulated rainfall are within the range of natural rainfall. However, the simulator can cover a test plot of only 1 m square, which is probably too small to simulate real erosion by rainfall.

Meyer and Harmon (1979) developed a multiple-intensity rainfall simulator for erosion research on row sideslopes and especially for use on row crops in farm fields. The nozzles used were 80150 and 80100 Veejet. The fall of 3 meters, plus the pressure of 6 psi, gives a terminal velocity of 8.8 m/s, which is almost the same as that of natural rainfall, with the raindrop diameter greater than 4 mm (Gunn and Kinzer, 1949). Under this condition, the 80150 nozzle provides a unit impact

energy, e , of 0.275 Mi/ha²mm and the 80100 nozzle provides 0.200 Mi/ha²mm. When compared with McGregor and Mutchler's (1977) rainfall data from the midsouth area of the U.S., these data showed that the impact energy for spray from the 80150 nozzle is about the same as that of natural rainfall at intensities greater than 25 mm/hr. The 80100 nozzle produces about 73% of the desired impact energy at intensities greater than 25 mm/h. The simulator requires three persons to assemble and disassemble. Test results have shown it can provide useful data on row-sideslope erosion, runoff rates and sediment size distributions.

Foster, Eppert and Meyer (1979) developed a programmable rainfall simulator for field plots. The nozzles used were 80100 Veejet instead of 80150 Veejet, which provides an impact energy nearly equal to that of natural rainfall. The reasons for using the 80100 Veejet nozzles were:

- [1] to provide a standard for comparing results from the simulator with those from the several other simulators that use the 80100 Veejet nozzles
- [2] to use smaller and lighter pumps, wiring and generator; this is an important consideration because weight is critical.

The simulator was designed and constructed by modifying the Meyer-McCune rainulator. The differences are as follows:

- [1] It is designed for plots 4 m wide by 11 m long (or even longer).
- [2] The fall height is 2.44 m and the spacing of nozzles is 1.1 m.
- [3] The median drop size is 2.25 mm.
- [4] It uses oscillating nozzles and recirculates excess water within individual trough units.
- [5] Each trough is independent of other troughs so that variable intensities in time and space can be programmed on the industrial process controller.
- [6] Even though the spray from the nozzles is intermittent, the 0.9 second delay between spray application at a 30 mm/h intensity and 0.5 second delay at 60 mm/h are short enough to have minimal effects on infiltration, runoff and erosion.
- [7] The simulator is light. For each simulator unit, there are 4 troughs. Each of them weighs about 175 lb (121 lb, Foster et al., 1982b) without a drive box. The drive box weighs about 25 lb.

Half of the U-frame weighs about 50 lb. The electrical cable from the distribution panel to a 4 trough unit is 166 lb for a 200 ft cable.

[8] Typical disassembly, moving and assembly time for the programmable simulator is 30 minutes. It requires about 4 persons to handle.

[9] Each programmable simulator costs \$66,000 which is comparatively expensive (Foster et al., 1982b).

Floyd (1981) developed a mobile rainfall simulator for small plot field experiments. The nozzles used were the 80100 Veejet, and the spray from the nozzles is intermittent. The simulator also includes an oscillating boom housing. It covers an area of 7 m by 4 m, which consists of 3 test plots (2 m x 1 m each). In each plot, the intensity is 27 mm/h with a coefficient of variation of 11.3%. The drop size distribution is similar to natural rainfall at the same intensity, but is deficient in drops of diameter greater than 3.5 mm. The velocity at impact is about 68% of natural rainfall terminal velocity.

CHAPTER 3

RAINFALL SIMULATOR AND FIELD EROSION TESTS

3.1 Introduction

Agriculturalists were the first to be concerned with soil loss, because the greater the soil loss, the greater was the potential loss of productivity and of profits. Therefore, equations for predicting soil erosion loss have been, mainly, developed for agricultural uses. Today, because of increased environmental awareness of stream pollution, studies have been initiated on construction sites. Strict laws or regulations now limit the amount of soil sediment permitted in streams. Therefore, measurements and controls of erosion on construction sites become essential. Erosion control can account for significant construction costs. Increase in the accuracy of prediction of soil erosion can help to eliminate excessive overdesign and therefore to cut the cost for erosion control.

Sediment due to soil erosion has been found to be an important factor in causing water pollution. Construction areas without protective covers have also been found to be a large source of soil erosion, and to yield

quite a lot of sediment (Morgan and Nalepa, 1982). Further, construction areas with steep slopes and large areas, e.g. highway embankments, can yield much sediment. The steepness of highway soil slopes usually varies from 0 to 50%.

It is possible to use the Universal Soil Loss Equation (USLE) by Wischmeier and Smith (1978), as described in Chapter 2, which is widely applied for prediction of soil erosion, for highway slopes.

However, the USLE has been developed, mainly, for agricultural uses. For the USLE, as reported by Wischmeier and Smith (1978), the slope steepness varied from 3% to 18%, which is less than usual highway slope steepnesses.

The values of the S factor proposed by Wischmeier and Smith (1978), Foster (1982), Stein et al. (1983), McCool and George (1983) and McCool et al. (1987) are as shown in Equation (2.18), and Equation (2.20) to Equation (2.25). The curves of the S factor vs. slope angle (θ) for the equations are shown in Figure 3.1.

All of the data sets used to develop the equations consist of a slope steepness range from 0.1 to 18%. Application of the equations to slopes greater than 18% is an extrapolation beyond the observed data.

Figure 3.1 The S factor vs. slope angle

In Figure 3.1, it is obvious that the differences among these curves are very large. The six curves intersect at $\theta = 5.14^{\circ}$ (9% slope), where $S = 1$. But for other angles, especially the angles greater than 10 degrees (17.6% slope), the differences are significantly large.

Therefore, it is necessary to run tests and establish the S factor for slopes steeper than 18%. To achieve this goal, a rainfall simulator was modified and successfully operated on highway slopes with steepnesses from 9% to 50% at Putnamville and Evansville, Indiana in 1985 and 1986.

3.2 Design and Construction of Rainfall Simulator

The rainfall simulator was designed and constructed by modifying a programmable rainfall simulator which was developed by Foster et al.(1982b), as described in Chapter 2. To install and operate the rainfall simulator safely and effectively on highway slopes from 0% to 50%, and to achieve accurate test results, the following modifications were necessary.

1. Wedges were used to keep the troughs horizontal on all the test plots.

2. Hinges were added to allow the half U-shape frames to rotate, and bracings adjustable to different slope steepness were also used to keep the whole structure vertical and stable.
3. The design wind speed was 20 mph, which is much higher than the previous limiting workable wind speed of 10 mph.
4. Footings were made of aluminum pipes 2 inches in diameter and 4 feet in length, and were designed to bear the horizontal and uplift load under the application of design wind speed.
5. Bearing plates 1 foot square were designed to connect the legs of rainfall simulator and the footings, and to bear the weight of the entire structure.

They are shown in more detail in Figure 3.2 to Figure 3.5.

3.3 Preparation of Test Plots

The sites for field erosion tests were selected on highway slopes at Putnamville and Evansville with the desirable slope steepnesses and slope lengths. The materials and compaction of the soils were controlled to be rather homogeneous for the two selected highway

Figure 3.2 Overview of the rainfall simulator

Figure 3.3 Side view of the rainfall simulator on a 2 to 1 slope

Figure 3.4 Wedges were used to keep the troughs horizontal on a 2 to 1 slope

Figure 3.5 Bearing plates were used to connect the footing and the legs of the rainfall simulator on a 3 to 1 slope.

slopes. The test plots were prepared as shown in the following sequences.

1. Using a bulldozer or grader, the soil surfaces of the selected test sites were scraped to insure that they were smooth and uniform slopes with the desired lengths (Figure 3.6).
2. All the sites were covered by plastic sheets to prevent both plant growth and erosion from material rainfall. During the heat of the day, the plastic sheets were removed to allow evaporation and to reduce the initial moisture content (Figure 3.7).
3. For each site, three test plots were selected on smooth and uniform slopes. There were two sizes for the test plots, namely, 10 feet wide by 35 feet long along the slope and 10 feet wide by 15 feet long. The layouts of the plots representing the borders, footings, "plot ends", et al. are as shown in Figure 3.8 to Figure 3.11.
4. The bottom of the plot was set off by a "plot end" which was a 10 inch wide strip of heavy gage steel driven vertically into the soil. Since the compacted cohesive soils on highway slopes were very

Figure 3.6 One of the sites at Evansville (3 to 1 slope) was scraped to be smooth and uniform.

Figure 3.7 The plots were covered by plastic sheets.

Figure 3.8 Layout of test site (35 feet long)

Figure 3.9 Layout of test plot (35 feet long)

Figure 3.10 Layout of test site (15 feet long)

(a) PLAN (ALONG THE SLOPE)

(b) PROFILE

Figure 3.11 Layout of test plot (15 feet long)

hard, chain saw were used to cut the soils vertically to a depth of about 7 to 8 inches to enable the plot ends to be driven into the soils (Figure 3.12).

5. The test plot was bordered on the sides and top by 8 inch high corrugated steel strips, which were driven about 4 inches into the soil. Two strips had at least 6 inches of overlap to prevent the water from flowing into or out of the plot. Since the soils were very hard, concrete saws (Figure 3.13) were used to cut the soils vertically to a depth of about 2 inches to enable the corrugated steel strips to be driven into the soils.
6. Using a backhoe, a hole was excavated at the bottom of the plot with a size as shown in Figure 3.14. The hole was for the runoff to drain and for equipment for measuring the rate of runoff to be installed (Figure 3.15).
7. For each plot, four or eight 2 inch ID pipes, 4 feet long, were driven vertically into the soil to a depth of 3 feet and 6 inches at the desired locations (Figure 3.16).
8. Four or eight bearing plates were set as in Figure 3.17.

Figure 3.12 A plot end was driven into the soil.

Figure 3.13 A concrete saw was used to cut the soil to enable the strips to be driven into the soil.

Figure 3.14 Top view of plot end

Figure 3.15 A backhoe was used to excavate a hole for draining the runoff.

Figure 3.16 A footing was driven into the soil.

Figure 3.17 Eight bearing plates were set for the plot.

Figure 3.18 A calibrated flume was set horizontally under the plot end and the gutters.
A hydrograph was installed by the flume as a stage recorder.

9. Gutters were connected to the plot end for collecting the runoff from the plot at the bottom of the test plot.
10. A calibrated flume (with the type of 18.3 centimeter HS) was set horizontally under the plot end and the gutters. The flume with a hydrograph on it was to measure the discharge rate of the runoff (Figure 3.18).
11. Two rails were set at about 4 inches outside of the sides of the plot to support a rillmeter (Figure 3.19) and to measure the cross-section of the plot which was 10-ft wide. The rillmeter consisted of 241 pins with a length of 2 feet and a diameter of $1/8$ inch. The pins were spaced at $1/2$ inch intervals on an 11-ft wide metal board painted black. The top of each pin was painted white so that when the elevations of the two rails at any cross-section were known, photographs of the white-headed pins reflected the cross-section.
12. Ditches 6 inches wide by 3 inches deep were dug along the top and the two sides of the plot to drain the water outside of the plot.

Figure 3.19 A rillmeter on the two rails was used to measure the cross-section of the plot.

Figure 3.20 All the parts of the simulator, equipment, connections, etc. were packed on a truck.

3.4 Operation of Rainfall Simulator

After modifying the rainfall simulator and when the sites were ready to be tested, all the parts of the simulator, equipment and connections, etc., necessary for the field erosion tests were packed on a special truck and transported to the sites (Figure 3.20). The operating sequences of the rainfall simulator are as follows.

1. The parts of the rainfall simulator were unloaded on a flat and dry highway shoulder close to the test plots.
2. The rainfall simulator was assembled on the highway shoulder. It took 5 to 6 persons to accomplish this. The frames, wedges and troughs of the simulator were installed in order (Figure 3.21 and Figure 3.22).
3. After preparation of the test plot, the rainfall simulator was lifted up and transported to the selected positions using a crane (Figure 3.23). Two units of the rainfall simulator were necessary for a 35-ft long section (downslope). The first unit was lifted up and transported to the lower half of the test plot. For a 15-ft long slope

Figure 3.21 Frames of the rainfall simulator were assembled on a highway shoulder.

Figure 3.22 The installation of the frames, wedges, and troughs was accomplished.

Figure 3.23 The rainfall simulator was lifted up and transported from a highway shoulder to a test plot (illustrated for a 3 to 1 slope).

Figure 3.24 The heights of the troughs were adjusted (illustrated for a 2 to 1 slope).

(downslope), one unit was sufficient.

4. The simulator was connected to the bearing plates using bolts and nuts. The legs of the simulator were adjusted to be vertical and the heights of the nozzles in the troughs were adjusted to be 8 feet above the soil surface. The ends of the troughs with sumps were 1 or 2 inches lower than the other ends, to allow the water to flow into the sumps (Figure 3.24).
5. One ladder was set at each side of the plot so that the researchers could safely walk up or down during the rainfall simulation testing (Figure 3.25).
6. A water truck with a capacity of 7,000 gallons and a water pump capable of delivering 1500 gallons of water per hour at 40 psi were used for the water supply (Figure 3.26). They were transported to places close to the plot.
7. Hoses, pipes and manifolds were used to connect the water truck, the pump, and the troughs. This became the water supply system of the test (Figure 3.27). The water pressures in the troughs were set at 6 psi.

Figure 3.25 Ladders were used so that the researchers could safely walk up or down.

Figure 3.26 A water truck and a pump were for water supply.

Figure 3.27 The connection of hoses, pipes manifolds, the pump and the water truck became the water supply system of the test.

Figure 3.28 A generator (close to the upper deck) was used for power supply and a panel (by the generator) as the controller.

8. A 15000 watt, 120 and 240 volt AC generator was used for power supply. A panel with computer programs available to control the water spraying system was used as the controller. The generator and the panel were transported to the places close to the plots (Figure 3.28). The power supply and the computer program were appropriately selected. Using cables, the generator, the panel and the motors in the troughs were connected.
9. An extra inflowmeter was set at the top of the plot to simulate runoff from the upslope area (Figure 3.29).
10. The soil surface of the plot was cleaned up and ready for tests.
11. A long narrow fiber-glass roof and a tent were used to cover the plot end to prevent raindrops from falling on the gutters, equipment and researchers (Figure 3.30).

3.5 Procedures of Field Erosion Tests

For each erosion test in the field, the sequence of rainfall simulation consisted of a one hour "dry run", a 30 minute "wet run", a 30 minute "very wet run", and a 40 minute "extra inflow run". The targeted intensity

Figure 3.29 An extra inflowmeter was set at the top of the plot.

Figure 3.30 A roof and a tent were used to cover the plot end, etc.

for each run was 2.5 inches/hour. The dry and wet runs were separated by a one hour wait, and the wet, very wet and extra inflow runs by a 15 minute data collection period. The extra inflow run was to study rill erosion by adding three successively higher rates of clear water to the top of the plot. After an initial ten-minute simulated rain (2.5 inches/hour), each inflow rate was successively applied for ten minutes.

Before, during and after the rainfall simulation test, there were a number of activities. They are described as follows:

- A. Gravimetric moisture content test. Before the rainfall simulation test and after each run, for a total of 5 times, soil samples were collected for gravimetric moisture content tests. Each time, samples were collected from locations in the test plot. The samples were sealed immediately and tested as soon as possible.
- B. Field density test. Before the dry run, three field density tests were undertaken using the drive cylinder method (AASHTO, 1974, T204-74). The locations were at 5, 17.5 and 30 feet from the bottom of the plot.

- C. Soil sampling for laboratory erosion tests, etc. For each test plot, 50 lb of soil sample was collected for the laboratory rotational shear tests, specific gravity tests using the boiling method (AASHTO, 1974, T100-74), grain size distribution test using the sieve analysis method (AASHTO, 1974, T27-74) and the hydrometer method (AASHTO, 1974, T88-72), etc. distribution tests, etc.
- D. Slope steepness measurement. Before running the erosion test on each plot, a level survey was made to define elevations at 5 foot intervals on both sides of the plot.
- E. Slope cross-section measurement. For each plot a rillmeter was used to measure the cross-section of the slope before erosion testing and after each run, i.e., 5 times in all.
- F. Surface vane shear test. Before each erosion test, the surface vane shear was measured at three different locations: 5, 17.5 and 30 feet from the bottom of the plot. The shear device consisted of 8 vanes which were located radially on a 1-in. diameter stainless steel plate. Each vane was 5/16-in. long, 3/16-in. wide and 1/32-in. thick. On the other side of the 1-in. diameter plate,

were a spring and a gage for measuring torques and accordingly, the shear stresses. The maximum shear stresses were determined by pushing the vanes into the soils to a depth of 3/16 inches and rotating the gage until the soils failed.

- G. Runoff measurement. To determine the rates of runoff vs. test time, two collecting gutters attached to the plot end diverted runoff and transported sediment to a calibrated flume with an attached stage recorder. Traces created by the stage recorder were analyzed to determine the rates of runoff vs. test time and total runoff volume.
- H. Micro-topographic measurement. To measure the micro-topography, two cameras and selected reference points were used. The sensitivity of measurements was about 0.5 cm. Black and white photographs were taken before, during and after each run (Figure 3.31).
- I. Water supply line pressure reading. These readings were to insure that the simulated rain was being applied as close to the targeted 2.5 inches/hour intensity as possible. This was done in every run, and the pressure was maintained between 35 and 40 psi.

Figure 3.31 Two cameras on the two aluminum channel beams

Figure 3.32 A one-liter jar was used to collect the sample.

- J. Sampling for sediment concentration of the runoff. For this purpose, one-liter jars were used to collect the samples (Figure 3.32). The samples were collected at every 2.5 minutes for extra inflow runs, but at every 5 minutes for the other runs. The runoff and sediment concentration data were used to determine the total soil loss for each run.
- K. Flow velocity and eroded aggregate size distribution test. Flow velocity were measured by inserting dye at 10, 20 and 30 feet from the bottom of the plot and by measuring the length of time which was required for the first dyed water to flow a distance of 10 feet (Figure 3.33). This was done at 36 and 56 minutes in the dry run, at 16 minutes in the wet and very wet runs, and at 6, 16, 26 and 36 minutes in the extra inflow run. A special container was used to collect the water with eroded aggregates. This was done just prior to flow velocity measurement, to insure that no dye would be collected. The samples were used for analysis of the grain size distribution.
- L. Average applied intensity measurement. To deter-

Figure 3.33 Dye was used to measure flow velocity.

Figure 3.34 Rain gages were placed at random in the plot to measure the average applied intensity.

mine the average applied intensity, about 70 rain gages were placed at random in the plot after each completed erosion test (Figure 3.34). Then a simulated rainfall was run for 30 minutes. Therefore, using the readings of the rain gages, the average applied intensity was determined. The procedures of field erosion tests are illustrated in Figure 3.35.

3.6 Description of the Sites of Field Erosion Tests

Three test plots at Putnamville, Indiana and twelve test plots at Evansville, Indiana, were selected to run field erosion tests. These test plots were on newly constructed highway slopes, without any cover, management or support practice (Figure 3.36 and Figure 3.37).

The three test plots at Putnamville had 50% slopes. Each plot was 10 feet wide and 35 feet long along the slope.

There were four test sites at Evansville, Indiana, and each site had three test plots. The slope steepnesses at sites No. 1, 2, 3 and 4 were 50%, 33.3%, 16.7% and 9.1% respectively. The test plots of site No. 3 were 10 feet wide by 15 feet long along the slope, while the other test plots were 10 feet wide by 35 feet long along the highway slopes.

Figure 3.35 Sequence of the erosion test in the field

Figure 3.36 The test site at Putnamville, Indiana

Figure 3.37 One of the test sites at Evansville, Indiana

The soil conditions of the test plots at Putnamville, such as the source of the soil, field density, and water content were controlled to be approximately the same. Similarly, the soil conditions of the 12 test plots at Evansville were also controlled to be essentially constant. As a result the soil erodibility factor was essentially constant. Especially, for the sites at Evansville, the slope steepness was designed to be the only variable, so that the slope steepness factor could be established for slopes for 9% to 50%.

The soil parameters are collected and shown in Chapter 5.

3.7 Summary

1. A rainfall simulator was modified and successfully operated on highway slopes with steepnesses from 9% to 50% at Putnamville and Evansville, Indiana in 1985 and 1986. Modifications included: changing the structure frame; its anchorage and wedges for supporting the troughs, and keeping them horizontal on steep slopes; and footings and bearing plates for bearing various loads due to wind and the weight of the rainfall simulator.
2. Special techniques were developed for preparation

of the plot surface, its borders, plot ends, etc. These are detailed in this chapter.

3. Special operating sequences of the rainfall simulator were developed for the field erosion tests, on steep slopes. They included transporting the rainfall simulator from one test plot to another using a crane, ladders for researchers to walk up or down during the rainfall simulation testing, etc.

CHAPTER 4

PREDICTION OF DISTRIBUTION OF RAINFALL INTENSITY ON DIFFERENT SLOPES USING RAINFALL SIMULATOR

4.1 Introduction

As mentioned in Chapter 3, the rainfall simulator used for this study was developed by modifying a programmable rainfall simulator which was developed by Foster et al. (1982b). The water spraying system used is the same as that developed by Foster et al. (1982b). and that developed by Meyer and McCune (1958). When using this water spraying system, the R factor is proposed by Meyer and McCune (1958) as described in Chapter 2. However, the rainfall intensity distribution and the R factor are for slopes which are not steep. If rainfall intensity distribution changes with slope steepness, the R factor will change as well, especially for steep slopes.

Since the R factor is directly related to rainfall intensity and its distribution, it is necessary to know the rainfall intensity distribution on steep slopes. When the rainfall simulator is used on slopes, the troughs or nozzles may be tilted and the heights of them may be changed. These two variables affecting the

rainfall intensity distribution should also be studied.

For the above purposes, a study has been theoretically and experimentally accomplished on prediction of the rainfall intensity distribution under the conditions of different nozzle heights, slope steepnesses and nozzle tilting angles.

4.2 Theoretical Approach

4.2.1 Derivation of the Equations

Foster (1978, attached in Appendix A) calculated the trajectory of water-drops released from a nozzle. The equations used were:

$$y = h_o - v_o t + (v_o - v_{1y}) \frac{v_o}{g} (1 - e^{-gt/v_o}) \quad (4.1)$$

$$x = \frac{v_o v_{1x}}{g} (1 - e^{-gt/v_o}) \quad (4.2)$$

where

h_o = nozzle height above ground

v_o = terminal velocity of a given drop under
a given atmospheric condition

v_{1x} = horizontal velocity component of drop
at the nozzle

v_{1y} = vertical velocity component of drop
at the nozzle

θ_1 = initial trajectory angle

t = time

x = horizontal distance of drop from nozzle
at time t

y = vertical distance of drop above ground at
time t

They are illustrated in Figure 4.1.

The following assumptions were also made:

T_a = Temperature of air = 70°F

ρ_a = Mass density of air = 2.33×10^{-3}
slugs/ft³

μ_a = Dynamic viscosity of air = 3.82×10^{-7}
lbf·sec/ft²

γ_w = Density of water = 62.4 lbf/ft³

g = Acceleration due to gravity = 32.2 ft/sec²

ρ_w = Mass density of water = 1.94 slugs/ft³

d = Median drop size = 2.25 mm = 7.38×10^{-3} ft

v_1 = Initial velocity = 22.3 ft/sec

(The values of d and v_1 were from

Special Report No. 81 by Meyer, 1958)

v_o = Terminal velocity for a given median
drop size (2.25 mm) and an atmospheric
condition given as above

= 23 ft/sec [from Laws (1941)]

$e = 2.718285$

Figure 4.1 Trajectory of a water-drop released from a nozzle and falling on flat ground.

Figure 4.2 Trajectory of a water-drop released from a nozzle and falling on flat slope

Then, Equation (4.1) and Equation (4.2) become:

$$y = h_o - 23 \cdot t + 0.7143(23 - 22.3 \cos \theta_i)(1 - e^{-1.4t}) \quad (4.3)$$

$$x = 15.9286 \sin \theta_i (1 - e^{-1.4t}) \quad (4.4)$$

where the units of y and x are in feet, θ_i in degrees and t in seconds.

Now, the relationship between x and y on the slope with a steepness of α is:

$$y = \alpha x \quad (4.5)$$

Figure 4.2 shows the trajectory of water drop released from a nozzle and falling on a slope.

$$\begin{aligned} \text{Let } f(t) &= y - \alpha x \\ &= h_o - 23 \cdot t + 0.7143(23 - 22.3 \cos \theta_i)(1 - e^{-1.4t}) \\ &\quad - \alpha \cdot 15.9286 \sin \theta_i (1 - e^{-1.4t}) \end{aligned} \quad (4.6)$$

$$\begin{aligned} f'(t) &= \frac{df(t)}{dt} = -23 + (23 - 22.3 \cos \theta_i) e^{-1.4t} \\ &\quad - \alpha \cdot 22.3 \sin \theta_i \cdot e^{-1.4t} \end{aligned} \quad (4.7)$$

For any angle θ_i and a nozzle height h_o , the time for a drop to reach the slope surface from the nozzle can be calculated using Newton's method. The steps are as follows.

1. Assume an initial value of t (say $t = 0.5$ seconds).
2. Calculate $f(t)$.
3. Calculate $f'(t)$.
4. Calculate $t_{\text{new}} = t - \frac{f(t)}{f'(t)}$
5. Use t_{new} as t and repeat step 2 to 4 until $f(t)$ is close to zero.

After the time, t , is found, y and x can be easily calculated. The distance along the slope, x_s , can also be calculated as follows.

$$x_s = \sqrt{x^2 + y^2} \cdot \frac{x}{|x|} \quad (4.8)$$

Using a computer program, the aforementioned calculations can be done in a faster, easier and more accurate way. A computer program called `intla.f` is written and attached in Appendix B for analyzing the trajectory of drops of simulated rainfall under the conditions of different nozzle heights, slope steepnesses and nozzle tilting angles.

Using this computer program and a set of data with nozzle height, $h_0 = 8$ ft, slope steepness, $stp = 0\%$ and nozzle tilting angle, $tilt = 0$ degree, the horizontal distances of drop from nozzle at impact for initial trajectory angles θ_1 , from -45 to 45 degree are calculated and shown in Appendix C. The values of initial trajectory angle, θ_1 , and nozzle tilting angle, $tilt$, are defined to be zero at the vertical line, negative for those at the downslope side and positive for those at the upslope side.

The results in Appendix C are almost exactly the same as those in Figure A.3 by Foster (1978) in Appendix A. For example, the horizontal distances from nozzle center for initial trajectory angles of -30 and 20 degrees in Appendix C are -3.394 and 2.219 ft respectively. The distances in Figure A.3 are about the same.

4.2.2 Distribution of Simulated Rainfall Intensity

To obtain the distribution of simulated rainfall intensity, the results proposed by Meyer (1958, Figure 4.3) using 80100 Veejet nozzles are used.

As mentioned in Chapter 2, the Veejet nozzles of type 80100 direct downward and move perpendicular to the long dimension of their spray patterns. And the nozzles are spaced at 5-foot intervals. The arrangement of the

Figure 4.3 Typical distributions of simulated rainfall intensity for single nozzle and composite nozzles which are spaced at 5-foot intervals (by Meyer, 1958)

Veejet nozzles are the same in this chapter. Although the rainfall intensity is expressed on a horizontal base, the distance is along the slope for convenience, through the chapter.

Combining the computed results in Appendix C with Meyer's results in Figure 4.3, two assumptions are made. They are:

- [1] Under the condition of nozzle height, $h_o = 8$ ft, slope steepness, $stp = 0\%$ and nozzle tilting angle, $tilt = 0$ degree, the minimum initial trajectory angle (θ_1) = -35° , the minimum horizontal distance (x) = -4.007 ft, the maximum initial trajectory angle (θ_1) = 35° , and the maximum horizontal distance (x) = 4.007 ft. The minimum and maximum initial trajectory angles will not change under any conditions.
- [2] For any values of nozzle height, slope steepness and nozzle tilting angles, the rainfall amount, ΔV , between two θ_1 angles ($\Delta\theta$) is constant. For example, the rainfall amount between the angles (θ_1) of -35° and -34° is ΔV_1 for $h_o = 8$ ft, $stp = 0\%$ and $tilt = 0$ degree. The same rainfall amount, ΔV_1 , is used between the two θ_1 's, -35° and -34° , for any values of h_o , stp and $tilt$.

Using Meyer's results, a computer program, `inth4.f`, attached in Appendix D, is written for calculating and plotting the distribution of simulated rainfall intensity for both single nozzles and composite nozzles, with any given values of nozzle height, h_0 (ft), slope steepness, stp (%), and nozzle tilting angle, $tilt$ (degree).

Using the computer program, selected distributions of simulated rainfall intensity under different conditions are plotted as shown in Figure 4.4 to Figure 4.8.

The distributions of simulated rainfall intensity for both single nozzles and composite nozzles in Figure 4.4 are almost exactly the same as those in Figure 4.3 by Meyer (1958). From the data of Figure 4.4 to Figure 4.8, certain findings are demonstrated.

- [1] The average relative intensity (dimensionless) increases with slope steepness, e.g. the average relative intensity is 0.945 for $h_0 = 8$ ft, $stp = 0\%$ and $tilt = 0$ degree in Figure 4.4; 0.960 for $h_0 = 8$ ft, $stp = 18\%$ and $tilt = 0$ degrees in Figure 4.5; and 0.995 for $h_0 = 8$ ft, $stp = 33\%$ and $tilt = 0$ degree. When nozzle height and nozzle tilting angle are given, the average relative intensity, I_{ave} , can be determined as follows:

Figure 4.4 Relative intensity vs. distance along slope for nozzle height = 8 ft, slope steepness = 0 % and nozzle tilting angle = 0 degree

Figure 4.5 Relative intensity vs. distance along slope for nozzle height = 8 ft, slope steepness = 18 % and nozzle tilting angle = 0 degree

Figure 4.6 Relative intensity vs. distance along slope for nozzle height = 8 ft, slope steepness = 33 % and nozzle tilting angle = 0 degree

Figure 4.7 Relative intensity vs. distance along slope for nozzle height = 9 ft, slope steepness = 50 % and nozzle tilting angle = 0 degree

Figure 4.8 Relative intensity vs. distance along slope for nozzle height = 9 ft, slope steepness = 50 % and nozzle tilting angle = 5.5 degree

$$I_{ave} = \sqrt{1 + s^2} \cdot I_{ave \text{ at } s = 0} \quad (4.9)$$

where s = slope steepness.

[2] Average relative intensity is not sensitive to nozzle height and nozzle tilting angle.

[3] Average intensity and the distributions of the simulated rainfall intensity for single nozzles and composite nozzles can be calculated and plotted for any values of nozzle height, slope steepness and nozzle tilting angle, if the distributions of the simulated rainfall intensity for single nozzles are given under a given condition.

4.2.3 Effect of the Distribution of Simulated Rainfall Intensity on Soil Erosion

For a bared slope without any support practice, Foster (1982) used the following equations to determine detachment rate.

$$\frac{dq_s}{dx} = D = D_r + D_i \quad (4.10)$$

$$D_r = a(\tau - \tau_{cr})^b \quad (4.11)$$

$$D_i = 0.0138 K_i \cdot i^2 \cdot [2.96 (\sin\theta)^{0.79} + 0.56] \quad (4.12)$$

where

q_s = sediment load (kg/m²h)

x = distance along the slope (m)

D = detachment (or deposition) rate ($\text{kg}/\text{m}^2 \cdot \text{h}$)

D_r = rill erosion rate ($\text{kg}/\text{m}^2 \cdot \text{h}$)

D_i = interrill erosion rate ($\text{kg}/\text{m}^2 \cdot \text{h}$)

a and b = constants

τ = average shear stress of the flow channel due to rill for a given location (N/m^2)

τ_{cr} = critical shear stress of the soil to rill erosion (N/m^2)

K_i = soil erodibility factor for detachment by raindrop impact ($\text{kg} \cdot \text{h}/\text{N} \cdot \text{m}^3$)

i = rainfall intensity (mm/h)

θ = slope angle to rill (degree)

If the average rainfall intensity on a slope is known, rill erosion rate will not be affected much by the distribution of the simulated rainfall intensity because the runoff rate on the slope will be about the same. However, interrill erosion rate may be influenced by the distribution of the rainfall intensity because in Equation (4.12), interrill erosion rate is proportional to the square of rainfall intensity. If the slope is divided into many small areas, in a small time period, the total interrill erosion rate is equal to the sum of the interrill erosion rates of all the small areas. Assume that the distribution of the simulated rainfall intensity across the slope does not change. The slope

is then divided into many small segments. The interrill erosion rate on the slope can be determined as follows:

$$D_i = \frac{\sum_{j=1}^n 0.0138 K_i [2.96(\sin\theta)^{0.79} + 0.56] \cdot i_j^2 \cdot \Delta x_j}{\sum_{j=1}^n \Delta x_j} \quad (4.13)$$

where

n = the total number of the segments on the slope

i_j = the intensity on the j^{th} segment

Δx_j = the length of the j^{th} segment

From Equation (4.13), if the intensity is uniform on the slope, the interrill erosion rate is equal to that obtain from Equation (4.12). If the intensity is not uniform, the interrill erosion rate will be greater than that obtained from Equation (4.12).

To study the effect of the distribution of simulated rainfall intensity on interrill erosion rate, two computer programs, namely, `inth9.f` and `inth10.f`, are written and attached in Appendices E and F. In the two programs, there are three variables, namely, nozzle height, slope steepness and nozzle tilting angle. The program of `inth9.f` is for calculating and plotting the ratios of the sum of the square of the simulated

rainfall intensity under the condition of different nozzle heights from 5 to 10 ft, a given slope steepness and a given nozzle tilting angle, to that under the basic condition. The basic condition is: nozzle height = 8.0 ft, slope steepness = 0% and nozzle tilting angle = 0 degree. The program of inth10.f is for calculating and plotting the ratios of the sum of the square of the simulated rainfall intensity under the condition of nozzle tilting angles from -10 to 10 degree, a given nozzle height and a given slope steepness, to that under the basic condition.

The following descriptions explain the two programs in more detail.

- [1] To be consistent with the definition of natural rainfall intensity, the intensity on the slope is considered to be on a horizontal base. Therefore, the length of a slope is considered to be a horizontal base.
- [2] Each segment of the slope is 0.1 ft long and the total length of the slope is 5.0 ft because the intensities are same every 5 ft interval. The two lengths are along the slope and then adjusted to horizontal length according to the steepness of the slope.

[3] A basic value of the sum of the square of the simulated rainfall intensity is calculated under the basic condition and then adjusted for the same average intensity and the same horizontal length as that on the slope.

[4] Relative sum of the square of intensity means the ratio of the sum of the square of intensity under a given nozzle height, slope steepness and nozzle tilting angle to the adjusted basic value mentioned above. Relative sum of the square of intensity is the factor called F_{d1} , which affects the interrill erosion rate because of the distribution of rainfall intensity.

Using the program of `inth9.f`, the relationships between the relative sum of the square of intensity and nozzle height (5 to 10 ft) are calculated and plotted in Figure 4.9 to Figure 4.12. For each figure, the nozzle tilting angle is 0 degree and the nozzle height is from 5 to 10 ft, because the minimum and maximum nozzle heights of the rainfall simulator are about 5 and 9.25 ft respectively. Four slope steepnesses, namely, 0%, 18%, 33.3% and 50% are used for the four figures. From the figures, certain trends may be described as follows:

Figure 4.9 Relative sum of square of intensity vs. nozzle height for slope steepness = 0 % and nozzle tilting angle = 0 degree

Figure 4.10 Relative sum of square of intensity vs.
nozzle height for slope steepness = 18 %
and nozzle tilting angle = 0 degree

Figure 4.11 Relative sum of square of intensity vs.
nozzle height for slope steepness = 33.3 %
and nozzle tilting angle = 0 degree

Figure 4.12 Relative sum of square of intensity vs. nozzle height for slope steepness = 50 % and nozzle tilting angle = 0 degree

- [1] Relative sum of the square of intensity, the F_{di} factor, decreases with nozzle height. For nozzle heights greater than 8 ft, the F_{di} factor does not change much. It is reasonable because the intensity for higher nozzle height is expected to be more uniform.
- [2] The F_{di} factor increases with slope steepness, when nozzle height and nozzle tilting angle are kept constant. For example, when nozzle height = 8 ft and nozzle tilting angle = 0 degree, the F_{di} factors for slope steepnesses of 0%, 18%, 33.3% and 50% are 1.000, 1.017, 1.058 and 1.125 respectively. It is also found that when the nozzle height is given, the F_{di} factor can be determined by the following equation:

$$F_{di} = \sqrt{1 + s^2} \cdot F_{di} \text{ at } s = 0 \quad (4.14)$$

where s = slope steepness.

Using the program of `inthl0.f`, the relationships between relative sum of the square of intensity, the F_{di} factor, and nozzle tilting angle (-10 to 10 degree) are calculated and plotted in Figures 4.13 to 4.16. For each figure, nozzle height is 8 ft and nozzle tilting angle is from -10 to 10 degree, because the minimum and

Figure 4.13 Relative sum of square of intensity vs. nozzle titling angle for nozzle height = 8 ft and slope steepness = 0 %

Figure 4.14 Relative sum of square of intensity vs.
nozzle titling angle for nozzle height
= 8 ft and slope steepness = 18 %

Figure 4.15 Relative sum of square of intensity vs.
nozzle titling angle for nozzle height
= 8 ft and slope steepness = 33.3 %

Figure 4.16 Relative sum of square of intensity vs.
nozzle titling angle for nozzle height
= 8 ft and slope steepness = 50 %

maximum tilting angles of the rainfall simulator are about -8.5 and 8.5 degrees respectively. Four slope steepnesses, namely 0%, 18%, 33.3% and 50% are used for the four figures. From the figures, results are described as follows:

- [1] The F_{di} factor increases very little or does not change at all with nozzle tilting angle.
- [2] The F_{di} factor increases with slope steepness, when nozzle height and nozzle tilting angle are kept constant. For example, when nozzle height = 8 ft and nozzle tilting angle = 8 degrees, the F_{di} factors for slope steepnesses of 0%, 18%, 33.3% and 50% are 1.000, 1.017, 1.058 and 1.126 respectively. It is also found that when the nozzle tilting angle is given, the F_{di} factor can be determined by Equation (4.14).

4.3 Laboratory Tests

To measure distributions of simulated rainfall intensities for different nozzle heights, slope steepnesses and nozzle tilting angles, a series of tests was performed in the National Soil Erosion Laboratory at Purdue University, West Lafayette, Indiana in 1986.

4.3.1. Preparation of Equipment and Materials

The following equipment and materials were prepared for the tests.

- [1] Rainfall simulator: It was the same as that used in the field as described in Chapter 3 except instead of being supported by four legs, it was hung using four wires. These wires could be lowered or lifted so that the desired nozzle heights and slope steepnesses could be obtained. The simulator consisted of four troughs which were identified by number (1,2,3,4).
- [2] Wedges: There were two kinds of wedges according to their functions. One was made of aluminum to keep the troughs horizontal as described in Chapter 3. The other one was made of wood to provide desired nozzle tilting angles. The wood wedges consisted of two angles, namely, 2.862 degrees (5%) and 5.711 degrees (10%) as shown in Figures 4.17 and 4.18.
- [3] Wood slope: Two structures made of wood were used to provide the slopes with desired slope steepnesses (Figure 4.19). Each structure was 8 ft wide, 10 ft long and 3.5 in. thick. The two

Figure 4.17 Wood wedges with an angle of 2.862 degrees (5 %)

Figure 4.18 Wood wedges with an angle of 5.711 degrees (10 %)

Figure 4.19 The wood slope was supported by timber posts.

Figure 4.20 The wood boards were adjusted to be horizontal.

structures made a slope with a width of 8 ft and a length of 20 ft. Using timber posts, the slope was supported to have four different slope steepnesses. They were 0%, 16.7%, 33.3% and 50%. On the two structures, wood boards of 8 ft length, 5.5 in. width and 0.75 in. thickness were used to support the containers for collecting the raindrops during tests. The wood boards were fixed at the upper sides using copper hinges at a space of 6 inches. The lower sides were free so that the boards could be adjusted to be horizontal for different slope steepnesses using nuts and threaded rods through the holes on the boards (Figure 4.20).

- [4] Containers: Hundreds of plastic containers were used to collect the raindrops during the tests. The containers with an opening of $4\frac{3}{8}$ inches in diameter and a height of about 6 inches were spaced at 6-inch intervals across and along the slope.

4.3.2 Procedures of Laboratory Tests

Presented in the following are the procedures of laboratory tests for measuring distributions of the simulated rainfall intensities.

- [1] The wedges, if necessary, were set up with troughs to keep the troughs horizontal or provide the desired nozzle tilting angles.
- [2] The wood slope was set up, and its location and slope steepness were adjusted to be correct. The wood boards were adjusted to be horizontal by using levels.
- [3] The heights of troughs were adjusted to provide a desired nozzle height by adjusting the four wires as shown in Figure 4.21.
- [4] The plastic containers were placed on the wood boards at 6-inch intervals.
- [5] Targeted rainfall intensity ($2 \frac{1}{2}$ inches/hour) and running period was selected on the controller (Figure 4.22) as described in Chapter 3. Then, the test started.
- [6] After the simulated rainfall, the volume of each plastic container was measured and recorded. They are shown in more detail in Figures 4.23 to 4.26.

The tests of the distributions of the simulated rainfall intensities were done in an order shown in the following:

Figure 4.21 The heights of troughs were adjusted.

Figure 4.22 A programmable panel was used as a controller.

Figure 4.23 A rainfall intensity distribution test
on a 0 % slope

Figure 4.24 A rainfall intensity distribution test
on a 6 to 1 slope

Figure 4.25 A rainfall intensity distribution test on a 3 to 1 slope

Figure 4.26 A rainfall intensity distribution test on a 2 to 1 slope

- [1] Tests for the single troughs, trough No. 1, 2, 3 and 4 respectively, under the basic condition, which is nozzle height = 8.0 ft, slope steepness = 0% and nozzle tilting angle = 0 degree.
- [2] Tests for the group troughs to get composite distributions under the basic condition.
- [3] Tests for the single troughs, and then the group troughs, under the conditions of different nozzle heights, slope steepnesses and nozzle tilting angles.

The measured data and their comparisons with the predicted values are shown in the next section.

4.4 Measured Data and Their Comparison with Predicted Values

The measured data for the single troughs, trough No. 1, 2, 3 and 4, under the basic condition are shown in Figure 4.27 to Figure 4.30. For troughs No. 1, 2, 3 and 4, all minimum initial trajectory angles are -36 degrees, and the maximum initial trajectory angles are 35, 35, 38 and 35 degrees respectively.

Using the measured data in Figures 4.27 to 4.30 and the aforementioned theoretical approach, two computer

Figure 4.27 Distribution of intensity at the center line of trough No. 1 under the basic condition

Figure 4.28 Distribution of intensity at the center line of trough No. 2 under the basic condition

Figure 4.29 Distribution of intensity at the center line of trough No. 3 under the basic condition

Figure 4.30 Distribution of intensity at the center line of trough No. 4 under the basic condition

programs, namely, `sincur.f` and `grocur.f`, are written and attached in Appendices G and H. The programs, `sincur.f` and `grocur.f`, are for calculating and plotting the distribution of simulated rainfall intensity for single troughs and group troughs respectively with any given values of nozzle height, h_0 (ft), slope steepness, stp (%), and nozzle tilting angle, $tilt$ (degree).

The measured data and the predicted distributions of intensity for trough No. 1 under different conditions are plotted in Figure 4.31 to Figure 4.34. In each figure, a condition is given. For the four conditions, the nozzle heights are 8, 10, 8 and 8 ft respectively, the slope steepnesses are 0, 0, 16.7 and 50% respectively, and the nozzle tilting angles are 5.711, 0, 0 and 0 degree respectively.

The four figures show that the measured data and the predicted distributions of intensity are very similar.

The measured data and the predicted distributions of intensity for group troughs, troughs No. 1, 2, 3 and 4 in an increasing order of height or from left to right, under different conditions are plotted in Figure 4.35 to Figure 4.39. In each figure, a condition is given. For the five conditions, the nozzle heights are

Figure 4.31 Distribution of intensity at the center line of trough No. 1 for nozzle height = 8 ft, slope steepness = 0 % and nozzle tilting angle = 5.711 degrees

Figure 4.32 Distribution of intensity at the center line of trough No. 1 for nozzle height = 10 ft, slope steepness = 0 % and nozzle tilting angle = 0 degrees

Figure 4.33 Distribution of intensity at the center line of trough No. 1 for nozzle height = 8 ft, slope steepness = 16.7 % and nozzle tilting angle = 0 degrees

Figure 4.34 Distribution of intensity at the center line of trough No. 1 for nozzle height = 8 ft, slope steepness = 50 % and nozzle tilting angle = 0 degrees

Figure 4.35 Distribution of intensity at the center line of group troughs for nozzle height = 8 ft, slope steepness = 0 % and nozzle tilting angle = 0 degrees

Figure 4.36 Distribution of intensity at the center line of group troughs for nozzle height = 8 ft, slope steepness = 0 % and nozzle tilting angle = -2.862 degrees

Figure 4.37 Distribution of intensity at the center line of group troughs for nozzle height = 10 ft, slope steepness = 0 % and nozzle tilting angle = 0 degrees

Figure 4.38 Distribution of intensity at the center line of group troughs for nozzle height = 8 ft, slope steepness = 50 % and nozzle tilting angle = 0 degrees

Figure 4.39 Distribution of intensity at the center line of group troughs for nozzle height = 9 ft, slope steepness = 50 % and nozzle tilting angle = 5.711 degrees

8, 8, 10, 8 and 9 ft respectively, the slope steepnesses are 0, 0, 0, 50 and 50% respectively, and the nozzle tilting angles are 0, -2.862, 0, 0 and 5.711 degrees respectively.

The five figures show that the measured data and the predicted distributions of intensity are very similar except for certain measured data which may be due to splashing or dropping directly from the troughs instead of spraying from the nozzles.

4.5 Summary and Conclusions

To study distribution of the simulated rainfall intensity and its effects on erosion under different conditions, theoretical and experimental approaches were developed. The conditions include different nozzle heights, slope steepnesses and nozzle tilting angles for single nozzles and group nozzles. From the predicted and measured results, it can be concluded:

- [1] A theoretical approach may be developed for predicting distribution of the simulated rainfall intensity and its effects on erosion. The predicted values using this approach and the measured data are reasonably close.

- [2] Using the theoretical approach and the written computer programs, average intensities and distributions of rainfall intensity for single nozzles or composite nozzles can be calculated and plotted for any values of nozzle height, slope steepness and nozzle tilting angle, if distributions of the rainfall intensity for single nozzles are given under a given condition.
- [3] Average intensity increases with slope steepness. When nozzle height and nozzle tilting angle are given, the average intensity, I_{ave} , can be determined by Equation (4.9). It is

$$I_{ave} = \sqrt{1 + s^2} \cdot I_{ave \text{ at } s = 0}$$

where s = slope steepness.

- [4] Average intensity is not sensitive to nozzle height and nozzle tilting angle.
- [5] The relative sum of the square of intensity, called the F_{d1} factor, which affects the interrill erosion rate because of distribution of rainfall intensity, decreases with nozzle height. For nozzle heights greater than 8 ft, the F_{d1} factor does not change significantly.

[6] The F_{di} factor increases very little or does not change at all with nozzle tilting angle.

[7] When nozzle height and nozzle tilting angle are known, the F_{di} factor can be determined by Equation (4.14). It is

$$F_{di} = \sqrt{1 + s^2} \cdot F_{di} \text{ at } s = 0$$

where s = slope steepness.

For example, when nozzle height = 8 ft and nozzle tilting angle = 0 degree, the F_{di} factor is 1.00 for slope steepness = 0%, and 1.12 for slope steepness = 50%.

CHAPTER 5

LABORATORY TESTS, DATA ANALYSES, RESULTS AND DISCUSSIONS OF THE SAMPLES AND DATA COLLECTED FROM THE FIELD EROSION TESTS

5.1 Introduction

After the samples and data were collected from the field erosion tests at Putnamville and Evansville as discussed in Chapter 3, a number of laboratory tests and data analyses were undertaken. They included moisture content, field density, specific gravity, Atterberg limits, grain size distribution, organic matter content, soil classification, slope steepnesses of the tested plots, slope cross-section, surface vane shear, discharge rate of runoff, micro-topographic measurement, sediment concentration of the runoff, total erosion of each run, flow velocity, eroded aggregate size distribution and average applied rainfall intensity of the field erosion tests.

Tests of sediment concentration of the runoff and eroded aggregate size distribution, and data analyses of slope cross-section, discharge rate of runoff, and total erosion of each run are described in the next section.

Calculations and results of the above-mentioned tests and data analyses, discussions and conclusions are also presented in this chapter.

Tests of the rotational shear device on the soil samples collected from the tested sites are discussed in Chapter 6.

5.2 Laboratory Tests and Data Analyses

5.2.1 Tests of Sediment Concentration of the Runoff

After the samples of the runoff for sediment concentration tests were collected in the one liter jars as mentioned in Chapter 3, they were sealed so that no evaporation would occur and were placed in the laboratory to allow the suspended sediment to settle. The total weight of each sample was measured and the clear water was removed carefully so that no sediment was lost. The samples were dried in ovens until the weights did not change in 24 hours. The dried samples were weighed (Figure 5.1) and accordingly the sediment concentration of each sample was determined.

An example of sediment concentration test results is shown in Table 5.1.

Figure 5.1 The dried samples in one liter jars were weighed.

Figure 5.2 Equipment for wet sieving

Table 5.1 An example of sediment concentration test result

Plot Number : E11... (2:1-slope)
Location : Evansville

time (Min)	bottle number	field jar weight (gram)	jar tare weight (gram)	soil+can weight (gram)	soil weight (gram)	water weight (gram)	sediment percent

DRY RUN							
3.550	V417	1342.70	114.91	239.16	124.25	1103.54	11.25922
5.525	V418	1094.25	114.17	193.50	79.33	900.75	8.80711
10.025	V419	1202.50	115.13	185.22	70.09	1017.28	6.88994
15.200	V420	1269.75	113.40	177.91	64.51	1091.84	5.90838
20.033	V421	1239.98	114.34	168.56	54.22	1071.42	5.06057
25.033	V422	1225.11	115.10	163.00	47.90	1062.11	4.50989
30.025	V423	1233.84	115.10	158.67	43.57	1075.17	4.05238
35.025	V424	1204.38	114.36	153.90	39.54	1050.48	3.76399
40.025	V425	1175.60	115.19	153.11	37.92	1022.49	3.70859
45.025	V426	1202.85	115.07	151.67	36.60	1051.18	3.48180
50.025	V427	1177.53	115.68	149.83	34.15	1027.70	3.32295
55.025	V428	1197.70	114.43	147.27	32.84	1050.43	3.12634
60.700	V429	1209.50	114.05	140.78	26.73	1068.72	2.50112
WET RUN							
1.533	V430	1209.71	115.80	126.19	10.39	1083.52	0.95891
3.117	V431	1176.61	115.67	132.41	16.74	1044.20	1.60314
5.025	V432	1150.44	113.86	135.15	21.29	1015.29	2.09694
10.025	V433	1187.77	115.08	139.45	24.37	1048.32	2.32467
15.025	V434	1145.93	114.97	138.68	23.71	1007.25	2.35393
20.025	V435	1110.67	114.99	138.75	23.76	971.92	2.44465
26.517	V436	698.58	115.38	129.16	13.78	569.42	2.42001
30.550	V437	1149.79	114.16	133.78	19.62	1016.01	1.93108
VERY WET RUN							
1.708	V438	1235.12	114.83	136.46	21.63	1098.66	1.96876
3.033	V439	1148.23	114.49	133.77	19.28	1014.46	1.90052
5.042	V440	1145.84	115.46	135.54	20.08	1010.30	1.98753
10.042	V441	1192.33	114.47	137.76	23.29	1054.57	2.20848
15.033	V442	1218.02	115.61	138.66	23.05	1079.36	2.13552
20.025	V443	1181.30	115.04	138.90	23.86	1042.40	2.28895
25.033	V444	1235.46	113.76	141.29	27.53	1094.17	2.51606
30.200	V445	1125.68	114.18	134.40	20.22	991.28	2.03979
EXTRA INFLOW RUN							
1.533	V446	1104.86	114.71	128.75	14.04	976.11	1.43836
3.033	V447	1151.03	114.44	130.10	15.66	1020.93	1.53390
5.033	V448	1143.72	115.25	131.89	16.64	1011.83	1.64455
7.608	V449	1197.13	113.88	132.59	18.71	1064.54	1.75757
10.025	V450	1181.08	115.66	134.79	19.13	1046.29	1.82836
12.517	V451	1127.82	114.67	135.78	21.11	992.04	2.12794
15.017	V452	1061.75	115.20	130.42	15.22	931.33	1.63422
17.525	V453	1086.09	115.45	133.69	18.24	952.40	1.91516
20.008	V454	1113.70	114.84	131.58	16.74	982.12	1.70448
22.508	V455	1059.89	114.11	134.08	19.97	925.81	2.15703
25.008	V456	1084.39	114.94	137.39	22.45	947.00	2.37064
27.508	V457	1132.82	105.67	130.40	24.73	1002.42	2.46703
30.008	V458	1054.54	106.88	129.41	22.53	925.13	2.43533
32.508	V459	1081.70	106.10	133.83	27.73	947.87	2.92551
35.008	V460	1047.41	106.96	140.33	33.37	907.08	3.67884
37.508	V461	998.80	106.06	134.96	28.90	863.84	3.34553
40.267	V462	1148.63	107.17	132.83	25.66	1015.80	2.52609

5.2.2 Tests of Eroded Aggregate Size Distribution

As mentioned in Chapter 3, special containers were used to collect the samples for the test of eroded aggregate size distribution. The capacity of the containers was 3 quarts. The volume of each sample was measured first and then a wet sieving method (Figure 5.2) was used to analyze the eroded aggregate size coarser than 0.05 mm and to avoid breaking the aggregates (Gee and Bauder, 1986). For the aggregates finer than 0.05 mm, a method of grain size distribution analysis, called the pipet method, was applied. To perform the pipet test (Gee and Bauder, 1986), the weight of each sample with water and aggregates finer than 0.05 mm contained in a bucket was measured. Using a hand stirrer, the sample was agitated to be uniform for one minute. The stirrer was made by joining a brass rod about 50 cm long to the center of a 6-cm-diameter plate of thin plastic sheeting. At a certain elapsed test time and a certain depth in the sample, a specimen of 25 ml was taken to represent the aggregates coarser than a certain size. After the specimen of 25 ml was carefully dried and weighed on a balance with a sensitivity of 0.0001 gram, the total weight of the aggregate coarser than the certain size was determined from the weight of the dried aggregates and the ratio of the weight of the

total sample to that of the 25 ml specimen. Next, the aggregate size distribution was determined. The sizes used for wet sieving were Sieve No. 4(4.76 mm), 10(2.00 mm), 20(0.84 mm), 40(0.42 mm), 100(0.149 mm), 200(0.074 mm) and 400(0.037 mm) (U.S. Bureau of Standards). The sizes selected for the pipet method were 0.010 and 0.002 mm.

An example of the results of the eroded aggregate size distribution is shown in Figure 5.3.

5.2.3 Data Analyses of Slope Cross-Section

After the survey readings on the two rails of each tested plot were taken, the elevations on the rails at every 5-ft intervals were computed. An example of the results is shown in Table 2. Using these data, a computer program and digitizing equipment (Figure 5.4), the cross-sections of each plot at every 5-ft interval were determined. The slides of the slope cross-section measurement mentioned in Chapter 3 were projected from the back of the digitizing equipment using a slide projector, so that the pictures on the screen of the digitizing equipment were larger and more clear.

A003

depth of sampling - 10. cm
 volume of pipet - 24.90 ml
 volume of suspension - 5588.19 ml

hydrometer jar number - 1.
 salt factor - 0.
 oven dry weight - 72.40 grams
 percent moisture - 0.

	1 particle size (mm)	2 sand weight (gram)	3 crucible number	5 crucible + clay weight (gram)	4 crucible weight (gram)
1	4.000	0.26			
2	2.000	0.66			
3	1.000	0.89			
4	.500	1.10			
5	.212	0.82			
6	.125	2.49			
8	.010		783	24.02840	23.79380
9	.002		790	24.65130	24.61030

A003

size (mm)	percent passing	cum. percent passing
4.000	0.40	100.00
2.000	0.90	99.60
1.000	1.20	98.70
.500	1.50	97.50
.212	1.10	96.00
.125	3.40	94.90
.050	18.80	91.50
.010	60.00	72.70
.002	12.70	12.70

Percent
Passing

Figure 5.3 A result of eroded aggregate size distribution

Table 5.2 An example of the results of elevation measurements on the two rails

PROFILE MEASUREMENT (ENGLISH UNIT RESULTS)

Plot Number : E11...(2:1-slope)
 Location : Evansville
 Date : 8/08/86
 Elevation of Bench Mark : 397.092 feet
 Survey reading of Bench Mark : 5.280 feet

	LEFT SIDE		RIGHT SIDE
Steepness :	50.663 %		49.585 %
Average steepness :		50.124 %	

DATA OF SOIL PROFILE

Distance (feet)	Reading (feet)	Slope (%)	Distance (feet)	Reading (feet)	Slope (%)
35.000	1.835	0.	35.000	2.066	0.
30.000	4.110	51.095	30.000	4.208	47.411
25.000	6.332	49.608	25.000	6.402	48.832
23.000	7.239	50.883	23.000	7.310	50.954
16.000	10.364	49.890	16.000	10.470	50.591
9.000	13.438	48.880	9.000	13.511	48.232
4.000	15.682	50.222	4.000	15.770	50.643
1.000	17.201	58.716	1.000	17.170	52.764
Plot End	17.708		Plot End	17.700	

DATA OF RAIL PROFILE

Distance (feet)	Reading (feet)	Slope (%)	Distance (feet)	Reading (feet)	Slope (%)
32.000	2.948	0.	32.000	3.203	0.
23.000	6.945	49.568	23.000	7.067	47.538
12.000	11.821	49.451	12.000	11.960	49.666
2.000	16.318	50.348	2.000	16.452	50.278

LEFT SIDE			RIGHT SIDE		
Distance (feet)	Reading (feet)	Elevation (feet)	Distance (feet)	Reading (feet)	Elevation (feet)
RESULTS OF SOIL PROFILE					
35.000	1.835	400.537	35.000	2.066	400.306
30.000	4.110	398.262	30.000	4.208	398.164
25.000	6.332	396.040	25.000	6.402	395.970
20.000	8.578	393.794	20.000	8.664	393.708
15.000	10.803	391.569	15.000	10.904	391.468
10.000	12.999	389.373	10.000	13.077	389.295
5.000	15.233	387.139	5.000	15.318	387.054
0.	17.707	384.665	0.	17.637	384.735
Plot End	17.708	384.664	Plot End	17.700	384.672

RESULTS OF RAIL PROFILE

Distance (feet)	Reading (feet)	Elevation (feet)	Distance (feet)	Reading (feet)	Elevation (feet)
35.000	1.616	400.756	35.000	1.915	400.457
30.000	3.836	398.536	30.000	4.062	398.310
25.000	6.057	396.315	25.000	6.208	396.164
20.000	8.275	394.097	20.000	8.401	393.971
15.000	10.491	391.881	15.000	10.626	391.746
10.000	12.720	389.652	10.000	12.858	389.514
5.000	14.969	387.403	5.000	15.104	387.268
0.	17.217	385.155	0.	17.350	385.022

Figure 5.4 Digitizing equipment

5.2.4 Data Analysis of Discharge Rate of Runoff and Total Erosion of Each Run

To determine the rates of runoff vs. elapsed test time, the traces created by the stage recorders were used. One of the traces is shown in Figure 5.5. Since the flumes were calibrated, the discharge rate at any time was then determined. For example, the flumes used at Evansville were Flume No. 6 and 7. The calibration curves of the two flumes can be represented by the following equations. For Flume No. 6:

$$fr = 2013.2 \cdot y^{2.0155} \quad \text{for } y \leq 0.1519 \quad (5.1)$$

$$fr = 2534.2 \cdot y^{2.1376} \quad \text{for } y > 0.1519 \quad (5.2)$$

For Flume No. 7:

$$fr = 1252.2 \cdot y^{1.8840} \quad \text{for } y \leq 0.1071 \quad (5.3)$$

$$fr = 2313.1 \cdot y^{2.1587} \quad \text{for } y > 0.1071 \quad (5.4)$$

where fr = discharge rate (lb/min)

y = y stage (ft)

Using the traces, the data of sediment concentration, the digitizing equipment and a computer program, the discharge rates of runoff and sediment rates vs. time, and total erosion rates of each run were computed in a faster, easier and more accurate way. A result is

Figure 5.5 A trace created by stage recorder

shown in Table 5.3 as an example.

5.3 Calculations and Results

5.3.1 General Data and Results of Field Erosion Tests

Soil properties and the results of moisture content tests of the test sites at Evansville and Putnamville are shown in Table 5.4 and Table 5.5. The data obtained and results from the field erosion tests are shown in Table 5.6. The obtained data and their calculation in Table 5.6 are described as follows. Item 1 through Item 9 and Item 13 are measured data. Item 10, the rainfall and runoff factor, R , is calculated using Equation (2.11) proposed by Meyer and McCune (1958).

For Item 11, the lengths of slopes are considered to be horizontal lengths, i.e. the length on a horizontal base, l_h , is:

$$l_h = l_s / (1 + s^2)^{0.5} \quad (5.5)$$

where l_s = slope length along the slope
 s = slope steepness

This is consistent with rainfall intensities, since rainfall intensities are also considered to be on horizontal bases.

Table 5.3 A result of discharge rate and
sediment rate vs. time and total erosion
of a dry run

EVANSVILLE PLOT NO. E11 - DRY RUN (E11SD)

Erosion Analysis in English Units

Time (Min)	Stage (feet)	Discharge Rate (lb/Min)	Sediment Rate (fraction)	Sediment Rate (lb/Min)
0.	0.	0.	0.	0.
3.550	0.161	44.871	0.11259	5.052
5.525	0.186	61.423	0.08807	5.410
10.025	0.189	63.713	0.06890	4.390
15.200	0.191	64.851	0.05908	3.831
20.033	0.192	65.691	0.05061	3.325
25.033	0.188	62.984	0.04510	2.841
30.025	0.190	64.286	0.04052	2.605
35.025	0.193	66.049	0.03764	2.486
40.025	0.194	66.830	0.03709	2.479
45.025	0.192	65.792	0.03482	2.291
50.025	0.196	68.305	0.03323	2.270
55.025	0.191	64.935	0.03126	2.030
60.000	0.198	70.067	0.03010	2.109

Flume Number = 7
Total Discharge = 3747.390 (lb)
Total Sediment = 178.426 (lb)

Table 5.4 Soil properties of the test sites

Item of Test	Location of Site and Site No.	Evansville				Putnamville
		1 (2 to 1 slope)	2 (3 to 1 slope)	3 (6 to 1 slope)	4 (11 to 1 slope)	
Specific Gravity		2.754	2.776	2.762	2.773	2.712
Atterberg Limits	Liquid Limit (%)	38.9	38.6	36.7	41.3	30.9
	Plastic Limit (%)	24.3	24.5	22.1	22.6	20.7
	Plastic Index (%)	14.6	14.1	14.6	18.7	10.2
Grain Size Distribution (% Finer)	4.76 mm (#4)	100.	100.	100.	100.	97.
	2.00 mm	100.	100.	100.	100.	94.
	0.100 mm	91.	91.	85.	88.	67.
	0.074 mm (#200)	89.	88.	80.	84.	63.
	0.05 mm	85.	84.	77.	81.	60.
Organic Content (%)		36.	31.	29.	32.	17.
Soil Classification	USCS	CL	CL	CL	CL	CL
	AASHTO	A-6 (close to A-7)	A-6 (close to A-7)	A-6 (close to A-7)	A-7 (close to A-6)	A-4 (close to A-6)
	USDAC	Silty Clay Loam (close to Clay Loam)	Silty Clay Loam (close to Clay Loam)	Clay Loam (close to Silty Clay Loam)	Silty Clay Loam (close to Clay Loam)	Loam

Table 5.5 Results of moisture content tests (unit = %)

Sites		Before Dry Run	After Dry Run	After Wet Run	After Very Wet Run	After Extra Inflow Run
Evansville	Site 1 (2:1)	16.49	19.07	18.50	19.70	19.28
	Site 2 (3:1)	9.72	15.05	15.53	17.72	19.71
	Site 3 (6:1)	14.18	15.74	15.99	17.01	17.45
	Site 4 (11:1)	13.80	17.28	17.49	18.84	20.55
Putnamville	(2:1)	17.48	18.05	19.65	19.26	19.32

Table 5.6 Data and results from erosion tests

Item No.	Items		Evansville				Putnamville
			Site 1	Site 2	Site 3	Site 4	
1	Field Density (PCF)		109.0	110.5	108.3	109.9	106.8
2	Dry Run (60 minutes)	(a) Erosion (lb) (b) Discharge (lb)	185.41 (3538.7)	197.24 (3297.2)	83.57 (1483.8)	190.70 (3548.3)	454.81 (3406.3)
3	Wet Run (30 minutes)	(a) Erosion (lb) (b) Discharge (lb)	43.56 (1781.8)	80.34 (1782.9)	27.73 (777.4)	58.66 (1803.2)	105.45 (1801.9)
4	Very Wet Run (30 minutes)	(a) Erosion (lb) (b) Discharge (lb)	44.13 (1849.5)	49.62 (1792.1)	20.94 (756.3)	51.14 (1802.8)	97.16 (1877.7)
5	Extra Inflow Run	1st 10 min. (a) Erosion (lb) (b) Discharge (lb)	10.48 (619.9)	9.14 (501.9)	5.29 (237.9)	16.25 (608.7)	33.69 (571.0)
6		2nd 10 min. (a) Erosion (lb) (b) Discharge (lb)	27.07 (1494.1)	34.14 (1660.4)	20.65 (994.1)	38.63 (1576.1)	77.65 (1564.9)
7		3rd 10 min. (a) Erosion (lb) (b) Discharge (lb)	50.45 (2126.2)	79.93 (2272.9)	34.40 (1220.6)	63.93 (2241.7)	113.82 (2494.5)
8		4th 10 min. (a) Erosion (lb) (b) Discharge (lb)	124.78 (3764.8)	155.65 (3403.2)	46.52 (1595.8)	109.37 (3913.3)	82.44 (3951.1)
9	Rainfall Intensity, I (in/hr)		2.500	2.175	2.389	2.203	2.720
10	Factor of Rainfall & Runoff for One Hour Rain, R		50.00	37.85	45.66	38.83	59.19
11	Length of Slope on Horizontal Base, l_h (ft)		31.273	33.203	14.809	34.843	31.338
12	Factor of Slope Length, L		0.6563	0.6763	0.4516	0.6928	0.6570
13	Slope Steepness, s (%)		50.254	33.347	16.099	9.419	49.735
14	Area of Test Plot on Horizontal Base, A_h (sq. ft.)		312.73	332.03	148.09	348.43	313.38
15	Factor of Cover & Management, C		1.0	1.0	1.0	1.0	1.0
16	Factor of Support Practices, P		1.0	1.0	1.0	1.0	1.0
17	Previous Approx. of S Factor (Assume $S = 1.0$, when slope steepness = 9.419%)		0.853	1.187	1.354	1.0	—
18	Factor of Slope Steepness, S		0.880	1.222	1.395	1.03	—

For Item 12, the slope length factor, L , is calculated using Equation (2.16) by Wischmeier and Smith (1965).

Item 14, areas of test plots on horizontal bases, A_h , are calculated by multiplying the widths of test plots (10 feet) by Item 11, slope lengths on horizontal bases.

For Item 15, the cover and management factor, c , is 1.0 by definition because none of the test plots was covered or managed.

For Item 16, the support practice factor, P , is also 1.0 by definition because none of the test plots had any support practice.

5.3.2 Calculation of the S Factor

To calculate the soil erodibility factor, K , Equation (2.28) by Wischmeier et al. (1971) is applied. It is:

$$K_{ave} = \frac{13A_d + 4A_w + 3(A_w + A_v)}{13EI_{30d} + 4EI_{30w} + 3(EI_{30w} + EI_{30v})}$$

where K_{ave} = average soil erodibility of all runs
(ton·acre·hour per hundreds of acre·
foot-tonf·inch)

$A_{d,w,v}$ = adjusted erosion of dry, wet and very wet run (tons per acre)

E = total storm energy in Equation (2.10)

$I_{30d,w,v}$ = the maximum 30-minute intensity of dry, wet and very wet run

The term of EI_{30} is the R factor. Therefore, the term of EI_{30} can be replaced by the R factor in Equation (2.28). Assume the rainfall intensities, I , the slope length factor, L , the slope steepness factor, S , and the area of the test plot on a horizontal base, A_h , are the same in dry, wet and very wet runs. Then, Equation (2.28) can be written as follows:

$$K_{ave} = \frac{\frac{13 \cdot T_d}{L \cdot S \cdot A_h \cdot C \cdot P} + \frac{7 \cdot T_w}{L \cdot S \cdot A_h \cdot C \cdot P} + \frac{3 \cdot T_v}{L \cdot S \cdot A_h \cdot C \cdot P}}{18 \cdot R} \quad (5.6)$$

where

$T_{d,w,v}$ = total erosion in dry, wet and very wet run (tons)

$$R = EI_{30d} = 2EI_{30w} = 2EI_{30v}$$

$$A_{d,w,v} = \frac{T_{d,w,v}}{L \cdot S \cdot A_h \cdot C \cdot P}$$

Since the C and P factor are 1.0 for all the cases in this study, Equation (5.6) can be written as follows:

$$K_{ave} = \frac{1}{18 \cdot R \cdot L \cdot S \cdot A_h} (13T_d + 7T_w + 3T_v) \quad (5.7)$$

When using the data in Table 5.6, Equation (5.7) becomes:

$$K_{ave} = \frac{1}{18 \cdot R \cdot L \cdot S \cdot A_h} (13\hat{T}_d + 7\hat{T}_w + 3\hat{T}_v) \cdot 21.78 \quad (5.8)$$

where

K_{ave}, R, L, S = same as those in Equations (2.28),
(5.6) and (5.7)

$\hat{A}_h$ = area of test plot on horizontal
base, in square feet

$\hat{T}_{d,w,v}$ = total erosion in dry, wet
and very wet run (lb)

$$1 \frac{1b}{ft^2} = 21.78 \frac{tons}{acre}$$

Assuming $S = 1.0$ when slope steepness is 9.419%,
the soil erodibility is then calculated using Equation
(5.8).

$$\begin{aligned} K_{ave} &= \frac{13 \times 190.70 + 7 \times 58.66 + 3 \times 51.14}{18 \times 38.83 \times 0.6928 \times 1.0 \times 348.43} \times 21.78 \\ &= 0.3928 \text{ (ton} \cdot \text{acre} \cdot \text{hour per hundreds} \\ &\quad \text{of acre} \cdot \text{foot-tonf} \cdot \text{inch)} \end{aligned}$$

From Equation (5.8), the slope steepness factor can
be calculated as follows:

$$S = \frac{1}{18 \cdot R \cdot L \cdot K_{ave} \cdot A_h} (13T_d' + 7T_w' + 3T_v') \cdot 21.78 \quad (5.9)$$

Assuming the soil erodibility factors are the same for all of the sites at Evansville, the previously approximated S factors for the other slopes are calculated and shown as Item 17 of Table 5.6.

Using these data, a curve representing the relationship between the previously approximated S factor and slope steepness is established as shown in Figure 5.6.

The S factor at a slope steepness of 9% has been chosen as unity by researchers for years. To be consistent with this, from Figure 5.6, the S factor of the 9.419% is then adjusted to be 1.03.

Applying Equation (5.8), the soil erodibility of Site 1 at Evansville is then found to be 0.38 ton·acre·hour / hundreds of acre·foot-tonf·inch. Again, assuming the soil erodibility factors are the same for all of the sites at Evansville, the S factors for the other slopes are calculated and shown as Item 18 of Table 5.6. Using these data, a curve showing the relationship between the S factor and slope angle is established and shown in Figure 5.7.

Figure 5.6 Previous approximated S factor vs. slope steepness for the sites at Evansville, Indiana

Figure 5.7 The S factor vs. slope angle for the sites at Evansville, Indiana

5.3.3 Flow Velocities of the Runoff

As mentioned in Chapter 3, flow velocities of the runoff were measured by inserting dye at 10, 20 and 30 feet from the bottom of the plot and by measuring the length of time which was required for the first dyed water to flow a distance of 10 feet. The results of flow velocity tests are shown in Table 5.7.

5.3.4 Surface Vane Shear

Before the field erosion tests, since the soil surfaces of the plots were relatively dry, the soils were very hard. The results of surface vane shear tests were mostly more than 10 kg/cm^2 which is the capacity of the device. After dry runs, wet runs and very wet runs, the soils became soft and the results were mostly equal or close to zero. However, the soil erosion does not increase when the surface vane shear decreases. Therefore, it was decided not to use surface vane shear to relate soil erodibility, and this will not be discussed further.

5.3.5 Slope Cross-Section

For each plot, a rillmeter was used to measure the cross-section of the slope before erosion testing and after each run, i.e., 5 times in all. Typical results

Table 5.7 Results of flow velocity tests (unit = fps)

Sites	Distance From the Bottom of the Plot (ft)	Dry Run at		Wet Run at - 17 min.	Very Wet Run at - 17 min.	Extra Inflow Run at			
		- 37 min.	- 57 min.			- 6 min.	- 16 min.	- 26 min.	- 36 min.
Evansville	Site 1 (2:1)	10-0	1.23	1.06	1.12	0.98	1.57	2.01	2.48
		20-10	0.93	1.07	1.00	1.05	1.60	2.07	2.61
		30-20	0.61	0.59	0.78	0.73	1.77	2.96	2.63
	Site 2 (3:1)	10-0	1.14	0.91	0.86	0.86	1.74	1.10	2.30
		20-10	1.08	0.89	0.87	0.77	1.59	1.84	2.31
		30-20	0.55	0.59	0.52	0.57	1.81	1.93	2.25
	Site 3 (6:1)	10-0	0.40	0.37	0.39	0.39	0.94	1.04	1.14
		20-10	0.63	0.52	0.70	0.54	0.99	1.07	1.21
		30-20	0.69	0.55	0.56	0.61	1.08	1.20	1.49
	Site 4 (11:1)	10-0	0.43	0.46	0.41	0.40	1.04	1.22	1.60
		20-10	0.91	1.11	1.05	1.11	2.00	2.22	2.86
		30-20	0.74	0.77	0.80	0.95	2.00	2.50	3.13
Putnamville (2:1)	30-20	0.56	0.61	0.56	0.67	-	1.67	2.00	2.50

are shown in Figure 5.8 to 5.12. The five figures show the cross-sections at 10 feet from the bottoms of the plots. The data are for : a 2 to 1 slope, a 3 to 1 slope, a 6 to 1 slope and an 11 to 1 slope at Evansville; and for a 2 to 1 slope at Putnamville.

5.3.6 Micro-Topographic Measurement

Using two cameras and selected reference points, micro-topographic measurement were performed at the sites of Evansville. The sensitivity of this equipment was about 0.5 cm. However, the test plots at Evansville, during field erosion tests, did not have apparent rills developed. For instance, the total erosion in dry, wet and very wet runs of Site 3 at Evansville was 132.24 lb (60.0 kg). The field density of Site 3 was 108.3 pcf (1.736 kg/cm^3). The area of the plot was 148.1 ft^2 (13.76 m^2). Therefore, the average eroded thickness of the plot should be 0.0082 ft (0.25 cm), which is less than the sensitivity of the equipment. During and after erosion tests, the soils might tend to swell and this makes the changes of the elevations of the plots even smaller. The results of the measurements are not significant, and are not discussed further.

Figure 5.8 The result of cross-section measurement at 10 ft from the bottom of a plot on a 2 to 1 slope at Evansville

Figure 5.9 The result of cross-section measurement at 10 ft from the bottom of a plot on a 3 to 1 slope at Evansville

Figure 5.10 The result of cross-section measurement at 10 ft from the bottom of a plot on a 6 to 1 slope at Evansville

Figure 5.11 The result of cross-section measurement at 10 ft from the bottom of a plot on a 11 to 1 slope at Evansville

Figure 5.12 The result of cross-section measurement at 10 ft from the bottom of a plot on a 2 to 1 slope at Putnamville

5.3.7 Manning's Roughness Coefficient (n)

To calculate Manning's roughness coefficient, n , the following data are used.

1. discharge rate at the time when the flow velocity was measured (on traces created by the stage recorder or Table 5.3 as an example)
2. flow velocity at the section (in Table 5.7)
3. cross-section measurement (on Figures 5.8 to 5.12 as examples)
4. slope steepness in Table 5.6

Manning's formula is written as follows.

$$V = \frac{1.49}{n} R^{2/3} (S_e)^{1/2} \quad (5.10)$$

where

V = the mean velocity (fps)

R = the hydraulic radius (ft)

S_e = the slope of energy line

n = Manning's roughness coefficient

Manning's n value can be calculated as follows.

$$n = \frac{1.49}{V} R^{2/3} (S_e)^{1/2} \quad (5.11)$$

To determine the hydraulic radius, R , two assumptions are made. The first is that flow is assumed to be concentrated, i.e. all flows are rills and water flows only at the lowest part of any cross-section. The second is that all flows are considered to be sheet flows, i.e. the thicknesses of the flow along the cross-section are same.

The results of Manning's roughness coefficient, n , based on the two assumptions are then calculated and shown in Tables 5.8 and 5.9.

5.3.8 Eroded Aggregate Size Distribution

Typical results of eroded aggregate size distribution of the sites at Evansville and Putnamville are shown in Figures 5.13 to 5.17. The samples for the five tests were collected in the very wet runs of the test plots on a 2 to 1 slope, a 3 to 1 slope, a 6 to 1 slope and an 11 to 1 slope at Evansville, and on a 2 to 1 slope at Putnamville.

5.3.9 Analysis of Erosion Due to Extra Inflow

The main purpose of extra inflow runs is to simulate the runoff from upper slope areas to the test plots, from which the relationships between discharge rate and erosion rate may be obtained. It is assumed

Table 5.8 Manning's roughness coefficient, n , of the test sites (assumed concentrated flow)

Sites	Distance from the Bottom of the Plot (ft)	Dry Run at		Wet Run at - 17 min.	Very Wet Run at - 17 min.	Extra Inflow Run at			
		- 37 min.	- 57 min.			- 6 min.	- 16 min.	- 26 min.	- 36 min.
Evansville	Site 1 (2:1)	5	0.0424	0.0446	0.0431	0.0530	0.0678	0.0442	0.0350
		15	0.0680	0.0648	0.0725	0.0760	0.0753	0.0674	0.0556
		25	0.0822	0.0896	0.0682	0.0829	0.0813	0.0360	0.0190
	Site 2 (3:1)	5	0.0410	0.0567	0.0534	0.0513	0.0505	0.0281	0.0278
		15	0.0349	0.0417	0.0414	0.0430	0.0371	0.0249	0.0230
		25	0.0701	0.0633	0.0824	0.0621	0.0633	0.0267	0.0318
	Site 3 (6:1)	5	0.0663	0.0703	0.0688	0.0734	0.0780	0.0400	0.0365
		5	0.0466	0.0598	0.0349	0.0505	0.0443	0.0327	0.0311
		15	0.0388	0.0519	0.0474	0.0410	0.0416	0.0270	0.0242
	Site 4 (11:1)	25	0.0492	0.0448	0.0494	0.0493	0.0499	0.0257	0.0251
		5	0.0644	0.0523	0.0719	0.0649	-	0.0383	0.0401
		15	0.0967	0.1138	0.1021	0.0849	-	0.0432	0.0340
Putnamville (2:1)	25	0.1004	0.0879	0.1190	0.0809	-	-	-	-

Table 5.9 Manning's roughness coefficient, n , of the test sites (assumed sheet flow)

Sites	Distance from the Bottom of the Plot (ft)	Dry Run at		Wet Run at - 17 min.	Very Wet Run at - 17 min.	Extra Inflow Run at			
		- 37 min.	- 57 min.			- 6 min.	- 16 min.	- 26 min.	- 36 min.
Evanaville	Site 1 (2:1)	5	0.0109	0.0176	0.0145	0.0146	0.0151	0.0117	0.0100
		15	0.0126	0.0127	0.0122	0.0106	0.0085	0.0169	0.0086
		25	0.0146	0.0090	0.0071	0.0106	0.0094	0.0081	0.0046
	Site 2 (3:1)	5	0.0086	0.0122	0.0135	0.0130	0.0107	0.0081	0.0091
		15	0.0073	0.0100	0.0107	0.0124	0.0097	0.0090	0.0089
		25	0.0139	0.0122	0.0171	0.0116	0.0105	0.0070	0.0089
	Site 3 (6:1)	5	0.0169	0.0192	0.0167	0.0173	0.0169	0.0126	0.0116
		5	0.0130	0.0176	0.0108	0.0164	0.0118	0.0115	0.0127
	Site 4 (11:1)	15	0.0084	0.0118	0.0116	0.0103	0.0105	0.0092	0.0099
		25	0.0121	0.0104	0.0126	0.0130	0.0132	0.0088	0.0091
	Putnamville (2:1)	5	0.0145	0.0104	0.0144	0.0106	-	0.0094	0.0149
		15	0.0144	0.0163	0.0162	0.0129	-	0.0087	0.0098
		25	0.0187	0.0157	0.0219	0.0132	-	-	-

A097

size (mm)	percent passing	cum. percent passing
4.000	0.	100.00
2.000	0.20	100.00
1.000	0.60	99.80
.500	0.70	99.20
.212	0.50	98.50
.125	2.80	98.00
.050	15.10	95.20
.010	65.70	80.10
.002	14.40	14.40

Percent
Passing

Figure 5.13 Eroded aggregate size distribution in the very wet run of the plot on a 2 to 1 slope at Evansville

A012

size (mm)	percent passing	cum. percent passing
4.000	0.80	100.00
2.000	1.10	99.20
1.000	1.40	98.10
.500	1.10	96.70
.212	0.60	95.60
.125	3.30	95.00
.050	16.00	91.70
.010	61.20	75.70
.002	14.50	14.50

Percent
Passing

Figure 5.14 Eroded aggregate size distribution in the very wet run of the plot on a 3 to 1 slope at Evansville

A062

size (mm)	percent passing	cum. percent passing
4.000	0.10	100.00
2.000	0.40	99.90
1.000	1.00	99.50
.500	0.90	98.50
.212	0.70	97.60
.125	3.20	96.90
.050	18.10	93.70
.010	61.40	75.60
.002	14.20	14.20

Percent
Passing

Figure 5.15 Eroded aggregate size distribution in the very wet run of the plot on a 6 to 1 slope at Evansville

A029

size (mm)	percent passing	cum. percent passing
4.000	0.10	99.90
2.000	0.70	99.80
1.000	1.10	99.10
.500	1.30	98.00
.212	1.10	96.70
.125	3.30	95.60
.050	16.90	92.30
.010	60.90	75.40
.002	14.50	14.50

Percent
Passing

Figure 5.16 Eroded aggregate size distribution in the very wet run of the plot on a 11 to 1 slope at Evansville

G009

size	percent	cum.
(mm)	passing	percent
4.000	3.40	100.00
2.000	2.80	96.60
1.000	4.60	93.80
.500	14.40	89.20
.212	8.80	74.80
.125	8.40	66.00
.050	27.80	57.60
.010	29.00	29.80
.002	0.80	0.80

Percent
Passing

Figure 5.17 Eroded aggregate size distribution in the very wet run of the plot on a 2 to 1 slope at Putnamville

that the average erosion rate occurs at the middle of the test plot and the average discharge rate includes only the discharge passing the middle line of the test plot.

Therefore, using the data in Table 5.6, average erosion rates ($\text{lb/ft}^2 \cdot \text{hr}$), D , average discharge rates ($\text{lb/ft} \cdot \text{sec}$), q , values of $\sin\theta$ and rainfall intensities can be obtained as shown in Table 5.10. The relationship between erosion rate and discharge rate for different slopes is plotted on Figure 5.18.

5.3.10 Soil Erodibility from the Nomograph of Wischmeier, Johnson and Cross

Using the data on Table 5.4 and Table 5.6, and the nomograph by Wischmeier, Johnson and Cross (1971) in Figure 2.1, the soil erodibilities of the sites at Evansville and Putnamville are determined and shown in Table 5.11. In this table, soil structures and permeabilities are estimated from the data of site investigation and the reference "Soil Survey Manual" of the United States Department of Agriculture Handbook No. 18 (1951).

Table 5.10 Data for analysis of erosion due to extra inflow

Sites at Evansville	Erosion Rate D	Discharge Rate q	Sin θ	Rainfall Intensity I
	(lb/ft ² ·hr)	(lb/ft ² ·sec)		(in./hr)
Site 1 (2 to 1 Slope)	0.20	0.052	0.449	2.50
	0.52	0.197	0.449	2.50
	0.97	0.303	0.449	2.50
	2.39	0.576	0.449	2.50
Site 2 (3 to 1 Slope)	0.17	0.042	0.316	2.18
	0.62	0.235	0.316	2.18
	1.44	0.337	0.316	2.18
	2.25	0.525	0.316	2.18
Site 3 (6 to 1 Slope)	0.22	0.020	0.159	2.39
	0.84	0.146	0.159	2.39
	1.39	0.184	0.159	2.39
	1.89	0.246	0.159	2.39
Site 4 (11 to 1 Slope)	0.28	0.051	0.094	2.20
	0.67	0.212	0.094	2.20
	1.10	0.323	0.094	2.20
	1.88	0.602	0.094	2.20

Figure 5.18 Erosion rate vs. discharge rate

Table 5.11 Soil erodibilities of the sites from the nomograph and the field erosion tests

	Evansville				Putnamville
	Site 1 (2:1)	Site 2 (3:1)	Site 3 (6:1)	Site 4 (11:1)	
% Silt (0.002-0.05 mm)	49	53	48	49	43
% Very Fine Sand (0.05-0.1 mm)	6	7	8	7	7
% Silt + Vfs	55	60	56	56	50
% Sand (0.10-2.0 mm)	9	9	15	12	27
% OM	1.0	1.0	0.8	1.0	0.5
First Approximation of Soil Erodibility	0.27	0.32	0.32	0.30	0.32
Soil Structure	4	4	4	4	4
Permeability	6	6	6	6	6
Soil Erodibility from Nomograph	0.42	0.46	0.46	0.44	0.46
Soil Erodibility from Erosion Tests	0.38	0.38	0.38	0.38	-

Note: The unit of soil erodibility is ton'acre'hour / hundreds of
acre'foot-tonf'inch.

Table 5.12 Relationship between total erosion and erosion due to very wet run

Item No.	Amount of Erosion (1b)	Sites	Evanaville				Putnamville
			Site 1 (2:1)	Site 2 (3:1)	Site 3 (6:1)	Site 4 (11:1)	
1	Dry Run		185.41	197.24	83.57	190.70	454.81
2	Wet Run		43.54	80.34	27.73	58.66	105.45
3	Very Wet Run		44.13	49.62	20.94	51.14	97.16
4	Total (1)+(2)+(3)		273.08	327.20	132.24	300.50	657.42
5	Item 4 Item 3		6.188	6.594	6.315	5.876	6.766

5.3.11 Relationship between Total Erosion and Erosion Due to Very Wet Run

Total erosion means the total amount of erosion in dry, wet and very wet runs. The relationship between total erosion and erosion of very wet runs is shown in Table 5.12, using the data in Table 5.6.

5.4 Discussion

5.4.1 General Soil Properties

From Table 5.4 and Table 5.6, soil properties of the four sites at Evansville are reasonably similar. The soil properties consist of specific gravity, Atterberg limits, grain size distribution, organic matter content and field density. From Table 5.5, before field erosion tests, moisture contents of the four sites at Evansville were at a natural condition level, while the moisture content of Site 2 was drier than this level.

But after very wet run, they were from 17.01% to 19.70% and were reasonably similar. The saturation degrees were from 79.5% to 94.1%. Since the samples for moisture content tests were taken from the top 3 inches of the plots, the degrees of saturation of the soils at greater depths were unknown. The soils at the depth of 3 inches might not be saturated, but the soils near to the surface, e.g., at the top 0.5 inches, were expected to be

fully or nearly fully saturated. The results of grain size distribution in Table 5.4 show that the soil of Site 3 is somewhat coarser. Nevertheless, according to the Unified Soil Classification System (USCS), the American Association of State Highway and Transportation Officials (AASHTO) classification, and U.S. Department of Agriculture Classification (USDAC), they are about the same. Therefore, the soil conditions and soil erodibilities of the tested plots at Evansville are considered to be the same.

5.4.2 The S Factor

In Figure 5.7, for slope steepness less than 18% (10.2 degrees), the S factor is between that defined by McCool and George (1983) and that used by Foster (1982) in Figure 3.1, and is very similar to the S factor by McCool et al. (1986). The S factor proposed by McCool et al. (1986) for application of the USLE in the Pacific Northwest Wheat and Range Region is:

$$S = (\sin\theta / 0.0896)^{0.6} \quad (5.12)$$

where θ = slope angle (degree)

This equation was derived from measured cross sections of rills on slopes ranging from 3 to 53%. But for steepness greater than 18%, the S factor reaches a maximum

value of 1.5 at an intermediate value of slope steepness of 20% (11.2 degrees) and then decreases. This means that erosion due to interrill and rill erosion does not continue to increase with slope steepness. This is very different from the extrapolations of the S factor by previous researchers, but similar to the results by Renner (1936), Horton (1945) and Foster and Martin (1969).

Renner (1936) analyzed the erosion due to rainfall and runoff on the Boise River watershed. He found that on the average, erosion increased with gradient only up to 35% slopes, after which erosion decreased with gradient.

Horton (1945) theoretically analyzed erosional development of streams and their drainage basins. He found that the relationship between erosion and slope gradient was similar to that proposed by Renner(1936). The total eroding force on a slope developed by Horton (1945) is:

$$F_1 = \frac{w_1}{12} \cdot \left(\frac{q_s n x}{1020} \right)^{0.6} \frac{\sin \alpha}{\tan^{0.3} \alpha} \quad (5.13)$$

where

F_1 = the total eroding force (lb/ft²)

w_1 = weight per cubic foot of water in runoff,

including solids in suspension (lb/ft^3)

q_s = the runoff intensity (in/hr)

n = Manning's roughness coefficient

x = distance from the top of the slope (ft)

α = slope angle (degree)

This equation shows that there is a unique slope angle (about 40 degrees) from which the maximum total eroding force will occur.

Foster and Martin (1969) used a rainfall simulator to study the erosion of the soils with different densities on different slopes in a laboratory. He concluded that for a given unit weight of soil, there is a unique slope from which the maximum amount of erosion will occur; and for a given slope, there is a unique unit weight from which the maximum amount of erosion will occur.

The following reasons are also advanced to explain the differences between the measured S factor in Figure 5.7 and the S factor by previous researchers.

[1] Under the conditions of this study, interrill erosion dominates the total erosion.

[2] Interrill erosion decreases with slope steepness.

[3] During dry runs, hydraulic tractive force is considered to be important to transport the loose particles on soil surfaces.

The results plotted in Figure 5.18 may be considered to be supporting evidences for the fact that interrill erosion dominates the total erosion. Figure 5.18 shows that when the discharge rate is less than a certain value, the erosion rate increases very little, or does not increase at all with the discharge rate. Discharge rate is directly related to the length of slope. This means that the slope lengths of the tested plots are too short to allow rill erosion to occur markedly. In fact, during the field erosion tests at Evansville, no apparent rill development was found in dry, wet, very wet and extra inflow runs as illustrated in Figures 5.19 and 5.20.

Figure 5.18 and the data in Table 5.10 can be applied to support the fact that interrill erosion decreases with slope steepness. In extra inflow runs, the runs of the first ten minutes for different slopes are considered to have negligible erosion due to rill erosion. There were no extra inflows, but simulated rain only in these runs. A basic equation for interrill detachment by Foster (1982) is:

Figure 5.19 No apparent rill development was found in the runs on a 2 to 1 slope at Evansville.

Figure 5.20 No apparent rill development was found in the runs on a 6 to 1 slope at Evansville.

$$D_i = 0.0138 K_i \cdot I^2 \quad (5.14)$$

where

D_i = interrill detachment rate ($\text{kg}/\text{m}^2 \cdot \text{hr}$)

K_i = soil erodibility factor for detachment by
raindrop impact ($\text{kg} \cdot \text{hr}/\text{N} \cdot \text{m}^2$)

I = rainfall intensity (mm/hr)

Equation (5.14) can be rewritten as follows:

$$D_i = 9.77 K_i \cdot I^2 \quad (5.15)$$

where

K_i = soil erodibility factor for detachment
by raindrop impact ($\text{lb} \cdot \text{hr}/\text{lb} \cdot \text{ft}^2$)

I = rainfall intensity (inch/hr)

Using Equation (5.15) and the data calculated from Table 5.6 (similar to Table 5.10), interrill erosion rates can be adjusted on the base of rainfall intensity of 2.5 inch/hr as shown on Table 5.13. In this table, the adjusted interrill erosion rate decreases with slope steepness.

As Poesen (1986) pointed out, the following mechanisms may explain this:

Table 5.13 Adjusted interrill erosion rate for
rainfall intensity of 2.5 in./hr

Sites at Evansville	Interrill Erosion Rate D_i (lb/ft ² ·hr)	Discharge Rate q (lb/ft ² ·sec)	Slope Steepness (%)	Sin θ	Rainfall Intensity I (inch/hr)	Adjusted Interrill Erosion Rate (lb/ft ² ·hr)
Site 1 (2 to 1 Slope)	0.201	0.0517	50.254	0.4490	2.500	0.201
Site 2 (3 to 1 Slope)	0.165	0.0418	33.347	0.3163	2.175	0.218
Site 3 (6 to 1 Slope)	0.215	0.0198	16.099	0.1590	2.389	0.235
Site 4 (11 to 1 Slope)	0.280	0.0507	9.419	0.0938	2.203	0.361

- Steeper slopes have smaller amount of raindrop impact, since rain falls vertically.
- The normal component of raindrop impact decreases with increasing slope steepness (cosine effect).
- Low slopes have more opportunity for the occurrence of thin water layer covering the soil surface, through which the compactive force of the impacting raindrops is increased. (Mutchler and Hansen (1970), and Poesen (1983))

Before dry runs, the soil surfaces were naturally dry and had some quantity of loose particles on them. During dry runs, low slopes such as 9.419% may not be able to transport all of the loose particles and those detached by the raindrop impact, even though their interrill detachment magnitude may be more. Therefore, slopes with steepness of 16.099% and 33.347% may have more erosion. However, steep slopes such as 50.254% have the least erosion. Though their hydraulic tractive forces were high enough to transport the loose particles, their interrill detachments were too small. Figure 5.21 is plotted to explain this qualitatively. The measured data on Item 2 of Table 5.6 for the Evansville sites support this. These data show that the erosion rate increases and reaches a maximum value and then

Figure 5.21 Erosion rate vs. slope steepness during dry run

decreases. After the loose particles on dry soil surfaces were nearly totally eroded in dry runs and wet runs, the erosion rates in very wet runs are expected to be less for steeper slopes. The measured data on Item 4 of Table 5.6 support this. Aside from the loose particles on soil surfaces, another reason why dry runs have much higher erosion rates than wet and very wet runs may be the slaking of dry soils at lower water contents.

5.4.3 Flow Velocity of the Runoff

The results of flow velocity tests are shown in Table 5.7. Generally, the velocities in dry runs, wet runs and very wet runs do not change much for the sites at Evansville because there was no apparent rill development, as mentioned previously. However, the velocities of the sites at Putnamville tend to increase from dry runs to wet runs to very wet runs. This may be because rills developed gradually during these runs.

The velocities at the first 10 ft from the bottoms of the plots are the highest, those of the second 10 ft are next, while those of the third 10 ft are the lowest. This is because the discharge rate of runoff decreases from the bottom to the top of the plot. The velocities at the three sections become close in extra inflow runs, especially, at the last 10 minutes in these runs while

the highest rates of extra inflow were applied. This is because addition of rainfall is small relative to bare flow. This ratio is about 1 to 6 as shown in Table 5.6.

The flow velocities for Site 3 at Evansville are the lowest. This is because this site has a shorter slope length (15 ft), while other sites are 35 ft long. The discharge rate of runoff is directly related to the slope length. The discharge rate of runoff for a broad sheet flow can be determined as (Foster et al., 1977b):

$$q = \sigma \cdot x \quad (5.16)$$

where

q = discharge rate per unit width

(volume/unit width/time)

σ = excess rainfall rate (rainfall rate minus infiltration rate) (depth/unit time)

x = distance downslope

For a broad sheet flow, using Manning's formula and Equation (5.16), flow velocity can be determined as:

$$V = \frac{1.27 (\sigma x)^{0.4} (S_e)^{0.3}}{n^{0.6}} \quad (5.17)$$

where

V = flow velocity (length/unit time, ft/sec)

S_e = the slope of energy line

n = Manning's roughness coefficient

From Equation (5.17), flow velocity increases with slope length. This matches the flow velocity test results.

The velocities for steeper slopes are higher. This is reasonable because slope steepness is a factor affecting flow velocity in Manning's formula, as shown in Equation (5.10).

During extra inflow runs, flow velocities increase from the first 10 minutes to the fourth (last) 10 minutes. This is because the rates of extra inflow, in an increasing order, were applied to the first, the second, the third and the fourth 10-minute sections.

However, there are errors in this measurement. For instance, surface roughness and rill development are very significant for flow velocity. Some plots were more rough than others. Some plots have more rills developed than others. Figures 5.22 and 5.23 show the rills developed during testing at Putnamville, while in Figures 5.19 and 5.20, there is no apparent rill developed during testing at Evansville. Since the measured flow velocities are the fastest parts of the runoff, they can not reflect the representative or mean velocities at those sections.

Figure 5.22 Rills developed in a plot at Putnamville
(top view)

Figure 5.23 Rills developed in a plot at Putnamville
(bottom view)

The development of rills during testing at Putnamville may be part of the explanation for the higher erosion rates at Putnamville relative to those at Evansville as shown in Table 5.6.

5.4.4 Slope Cross-Section

The main purpose of measurement of slope cross-section is to know the changes of the slope cross-sections during field erosion tests so that the process of rill development and the mechanism of erosion may be better known. Typical results of this measurement are shown in Figures 5.8 to 5.12. Originally, the cross-section elevations before the dry run was expected to be the highest, then in a decreasing order, that after the dry run, after the wet run, after the very wet run and after the extra inflow run. However, from the five figures, the results are not as expected. The elevations of the cross-sections for each plot do not show a clear order. In Figure 5.9, the cross-section before the dry run is mostly higher in elevation than others but not in other figures. In Figures 5.10 and 5.11, the cross-sections after the dry run are the lowest. The reasons for this may be described as follows.

- [1] The deflection of the rillmeter may be different for each measurement at the same cross-section. This may be due to wind load or other human errors.

- [2] Penetration of the white-headed pins of the rillmeter into the soils may be different for each measurement at the same cross-section. This may be due to different soil strengths at different times or varying friction of the pins.

- [3] The soils may swell during testing. This may explain why some cross-sections before the dry run are lower in elevation than others.

- [4] The average thickness eroded by water is small. The total amounts of erosion in the dry, wet and very wet runs for Site 1, 2, 3 and 4 at Evansville, and the site at Putnamville are 273.08 lb (123.7 kg), 327.2 lb (148.4 kg), 132.2 lb (60.6 kg), 300.5 lb (136.3 kg) and 657.4 lb (298.2 kg), respectively. The field densities of them are 109.0 pcf (1.747 kg/cm^3), 110.5 pcf (1.771 kg/cm^3), 108.3 pcf (1.736 kg/cm^3), 109.9 pcf (1.761 kg/cm^3) and 106.8 pcf (1.712 kg/cm^3). The areas of the plots are 312.73 ft^2 (29.05 m^2), 332.03 ft^2 (30.85 m^2), 148.09 ft^2 (13.76 m^2),

348.43 ft² (32.37 m²), 313.38 ft² (29.11 m²).

Therefore the average eroded thicknesses of the plots should be 0.00801 ft (0.244 cm), 0.00892 ft (0.272 cm), 0.00824 ft (0.251 cm), 0.00785 ft (0.239 cm) and 0.01964 ft (0.599 cm). These thicknesses may be too small to be reflected clearly using this measurement.

- [5] The errors of the images of white-headed pins may be significant when analyzing the cross-sections using digitizing equipment. The heads of the pins are about 1/4 inch (0.635 cm) which is large compared to the average eroded thickness of the tested plots. The average eroded thicknesses range from 0.239 to 0.599 cm. Therefore, errors of the cross-section elevations seems to be inevitable when tracing the images of the white-headed pins on the screen of the digitizing equipment by hand.

Therefore, these measurements were not used for analyses of rill development and erosion mechanism in this study.

5.4.5 Manning's Roughness Coefficient (n)

The results of Manning's roughness coefficients, n , are shown in Tables 5.8 and 5.9. Table 5.8 shows the results based on an assumption that all flows are concentrated or rill flows. Table 5.9 shows the results

based on an assumption that all flows are sheet flows. The average n value of Table 5.8 is 4.35 times of that of Table 5.9. Especially, during dry, wet and very wet runs, the differences of n values in the two tables are greater. The reason why the n values in Table 5.8 are higher is that they are obtained by assuming all flows are rills. For a given discharge rate and flow velocity, a rill has a larger hydraulic radius, R , compared to a sheet flow. When applying Manning's formula, Equation (5.11), higher hydraulic radii will have higher n values if other factors are constants.

The two assumptions made are two extreme cases. The flows during testing were neither purely rill flows nor purely sheet flows, but between the two cases. Therefore, the n values should be between the values in Table 5.8 and those in Table 5.9. However, the differences between the two tables are large and, further, the errors of flow velocity measurement and cross-section measurement are also significant, as previously mentioned. Therefore, the obtained n values are of limited value. Nevertheless, since the flows of dry, wet, very wet runs at the sites of Evansville were near to sheet flow, the Manning's n values of them in Table 5.9 should be close to the true values.

5.4.6 Eroded Aggregate Size Distribution

Typical results of eroded aggregate size distribution are shown in Figures 5.13 to 5.17. The samples for the five tests were collected at 16 minutes in the very wet runs of the test plots of Sites 1, 2, 3 and 4 at Evansville, and that at Putnamville. The grain size distributions of the eroded aggregates at the four sites of Evansville are reasonably similar. For example, the percents of the samples finer than 0.125 mm for Site 1, 2, 3 and 4 at Evansville are 98.0, 95.0, 96.9 and 95.6, respectively; the percents finer than 0.05 mm are 95.2, 91.7, 93.7 and 92.7, respectively; the percents finer than 0.010 mm are 80.10, 75.70, 75.60 and 75.40, respectively; and the percents finer than 0.002 mm are 14.40, 14.50, 14.20 and 14.50, respectively. This means the soils of the four sites at Evansville are rather homogeneous.

From Figure 5.17, the distribution of eroded aggregate size at Putnamville is very different from those at Evansville.

5.4.7 The Relationships between Erosion Rate and Other Factors

Using the data on Table 5.10 and neglecting the data of the first 10 minute runs in extra inflow runs of

the four sites at Evansville, a regression analysis was performed. The square of the correlation coefficient(r) is 0.7942, when

$$D = 6.9148 (q^{2.25} \cdot (\sin\theta)^{0.27} + 0.1218) \quad (5.18)$$

where

D = erosion rate (lb/ft²·hr)

q = discharge rate (lb/ft²·sec)

θ = slope angle (degrees)

If the data of Site 3 are not included, the square of the correlation coefficient(r) is 0.9442, when

$$D = 5.1406 (q^{0.85} \cdot (\sin\theta)^{0.10} - 0.1108) \quad (5.19)$$

Equation (5.19) is more reasonable than Equation (5.18) because of a higher value of the correlation coefficient.

After analyzing a large set of data, Yang (1972,1973,1976), Yang and Molinas (1982), and Yang and Stall (1976) concluded that unit stream power is the dominant factor in determining the total sediment concentration of streams with alluvial and gravel beds. Yang (1973) and Yang and Song (1979) defined unit stream power P_{us} as the time rate of potential energy dissipation per unit weight of water:

$$P_{us} = \frac{dY}{dt} = \frac{dx}{dt} \frac{dY}{dx} = VS_e \quad (5.20)$$

where

Y = the elevation above datum

x = the longitudinal distance

t = time

V = flow velocity

S_e = the energy gradient and can be approximated
by the slope of the soil surface

Moore and Burch (1986) demonstrated that the unit stream power for sheet flow, P_{us} , is:

$$P_{us} = VS_e = q^{0.4} \frac{S_e^{1.3}}{n^{0.6}} \quad (5.21)$$

where

q = discharge rate per unit width

S_e = the slope of the soil surface

n = Manning's roughness coefficient

In Equation (5.21), unit stream power is very sensitive to slope steepness but not so sensitive to discharge rate. However, in Equation (5.19), erosion rate is strongly sensitive to discharge rate but not sensitive to slope steepness. Equations (5.19) and

(5.21) are very different. Reasons for this are needed to be studied in the future.

According to Figure 5.18, erosion rate is very sensitive to discharge rate, but not sensitive to slope steepness. When the discharge rate is lower than a certain value, the erosion rate does not increase much with discharge rate. Therefore, a critical discharge rate or a critical slope length is expected for a given soil and slope steepness. Beyond that range, erosion rate increases markedly with discharge rate or slope length.

Theoretical supports for this are as follows. Foster et al. (1977b) derived the equations for rill and interrill erosion on a quasi-steady sheet flow where critical stress of the soil was assumed to be zero. The equations were:

$$G = G_r + G_i \quad (5.22)$$

$$G_r = K_r (a S^e) \sigma x^2 \quad (5.23)$$

$$G_i = K_i I (b S + c) x \quad (5.24)$$

where

G = sediment load (mass/unit width/unit time)

G_r = sediment load due to rill erosion

- G_i = sediment load due to interrill erosion
 K_r = soil erodibility factor for rill erosion
 (mass/unit area/erosivity unit)
 a = coefficient in slope effect on rill erosion
 S = slope of land surface at x
 e = exponent effect on rill erosion
 σ = excess rainfall rate (rainfall rate
 minus infiltration rate (depth/unit time)
 x = distance downslope
 K_i = soil erodibility factor for interrill
 erosion (mass/unit area/erosivity unit)
 I = an index of the instantaneous potential of
 rainfall and interrill to cause interrill
 erosion
 b, c = constants for slope effect on interrill
 erosion

Using the above equations, Hussein and Laflen (1982) developed equations for rill and interrill erosion on a rainfall simulation plot. At the top of the plot, a simulated runoff was added. The equations were:

$$G_L = [K_i L - K_r L^2] + 2K_r L X \quad (5.25)$$

or

$$G_L = C + DX \quad (5.26)$$

where

- G_L = sediment load on the length of rainfall simulation plot(L), (mass/unit width/unit time)
 K_i = factor relating to interrill erosion
 L = length of rainfall simulation plot
 K_r = factor relating to rill erosion
 X = sum of the length of rainfall simulation plot(L) and the length(X-L) from which runoff from upper areas is simulated
 $C = K_i L - K_r L^2$
 $D = 2K_r L$

From Equation (5.26), Total erosion rate on the lowest length L of a longer length X is linearly related to the length X. From Equation (5.16), Equation (5.26) can be written as:

$$G_L = C + Dq/\sigma \quad (5.27)$$

where

q, σ = same as those in Equation (5.16)

Equation (5.27) matches the right parts of the curves on Figure 5.18. Equation (5.27) is based on the assumption that critical shear stress of the soil is zero. This may be true for most of agricultural soils.

However, for compacted cohesive soils on highway slopes, critical shear stresses are expected to be greater than zero. For hydraulic tractive stresses below the critical shear stress, erosion is expected to increase very little (or not increase) with stress. For stresses beyond this critical value, erosion is expected to increase rapidly with stress, as shown in Equation (4.11). The above theories support the results on Figure 5.18.

5.4.8 Comparison of the Soil Erodibility by Measurement and that from Nomograph

For the four sites at Evansville, the average soil erodibility from the nomograph of Wischmeier, Johnson and Cross (1971) is 0.44 ton·acre·hour / hundreds of acre·foot-tonf·inch as shown in Table 5.11. However, the measured soil erodibility from erosion tests is 0.38, which is 86% of that from nomograph. This effect may be due to compaction of the soils on highway slopes. The nomograph was mainly developed for agricultural uses. Therefore, the data of compacted soils were not included in this nomograph. It is recommended that for compacted cohesive soils of highway slopes, the soil erodibilities from the nomograph be multiplied by a factor of compaction to obtain the true soil erodibility.

5.4.9 The S Factor of the Site at Putnamville

If the S factor by Wischmeier and Smith (1978) is used to analyze the data of the site at Putnamville, the value of S is calculated to be 15.07 using Equation (2.18). Then, the soil erodibility, K, is calculated to be 0.0457 (ton' acre'hour per hundreds of acre'foot-tonf'inch). This is not reasonable because this value is much less than that of the sites at Evansville, while the soils of Evansville are more cohesive and dense. When Equation (2.25) of the S factor by McCool et al. (1987) is applied, the value of S is 6.981. Then the K value is 0.0987 which is unreasonably low for the same reasons. The upper bound of the K factor for the site at Putnamville is 0.46, from the nomograph as shown in Table 5.11. The lower bound is 0.394 which is the multiplication of 0.46 and 0.856, which is the compaction factor of the sites at Evansville. That is to say, the lower and upper bounds of the S factor of the site at Putnamville are, namely, 1.50 and 1.75 respectively. In any case, the S factors by previous researchers are too high to be applicable in this case.

Compared to the S factor obtained from the tests at Evansville, the S factor of the site at Putnamville is a little bit higher. Accordingly, the S factor may change with soil properties.

From Items 2 to 4, the relationships between erosion and slope steepness are different in the three runs. Therefore, the S factor may change with elapsed time.

From Figure 5.18, the relationships between erosion and slope steepness are different at different discharge rates. Therefore, the S factor may change with discharge rate or slope length.

5.4.10 Relationship between Total Erosion and Erosion Due to Very Wet Run

Before dry runs, the test plots were naturally dry. It is somewhat difficult to simulate the soil conditions from which laboratory tests should be run to obtain indicators of soil erodibilities. It is much easier to simulate the soil conditions before and during very wet runs because the soils are nearly fully saturated. However, the relationship between the total erosion which consists of the total amount of erosion in dry, wet and very wet runs, and the erosion due to very wet run should be identified. Otherwise, the indicators obtained from the tests on fully saturated soils would be of little use.

Item 5 of Table 5.12 represents the division of total erosion by the erosion due to very wet run. The

mean value is 6.348 with a standard deviation of 0.311 and a coefficient of variation of 4.90%. This means that the relationship between total erosion and the erosion due to very wet run is rather constant. If this is true for erosion tests on different conditions, indicators obtained from fully (or nearly fully) saturated soil samples could be used to rate the erosion on partially saturated soils. However, the measured data are very limited. More erosion tests should be performed to obtain more conclusive results.

5.5 Conclusions and Recommendations

5.5.1 Conclusions

1. Soil properties of the four sites at Evansville are reasonably similar. The soil properties consist of specific gravity, Atterberg limits, grain size distribution, organic matter content, field density, moisture content and eroded aggregate size distribution. The soil conditions and soil erodibilities of the tested plots at Evansville are considered to be the same.
2. From the field erosion tests on highway slopes at Evansville, the S factor is extended to 50% (26.57 degrees) from 18% (10.2 degrees) as shown in Fig-

ure 5.7. The S factor reflects the development of rills, and the impact of raindrops, and appears to reach a maximum value of 1.5 at an intermediate value of slope steepness of 20% (11.2 degrees). This means that erosion due to interrill and rill erosion does not continue to increase with slope steepness.

3. The S factor of the site with a slope steepness of 49.735% (26.44 degrees) at Putnamville is estimated to be 1.50 to 1.75 which is much less than that proposed by previous researchers, but close to the S factor proposed in this study as shown in Figure 5.7.
4. For cohesive and compacted soils of the highway slopes at Evansville, total erosion is very sensitive to discharge rate or slope length, but not sensitive to slope steepness.
5. For the erosion tests at Evansville, a critical discharge rate or a critical slope length seems to exist for a given slope steepness. When discharge rate is less than this critical value, erosion rate increases very little or does not increase at all with discharge rate. When beyond this critical value, erosion rate increases markedly with discharge rate.

6. The S factor changes with slope length, soil properties and elapsed time. Accordingly, the S factor is not a factor independent of the others.
7. For cohesive and compacted soils in this study, the soil erodibility factor is less than that from the nomograph of Wischmeier, Johnson and Cross (1971). The effect may be described as the compaction factor.
8. For the field erosion tests in this study, the ratios of total erosion (which consists of dry, wet and very wet runs) to the erosion due to very wet runs are close to a constant. The mean value is 6.348 with a standard deviation of 0.311 and a coefficient of variation of 4.90%.
9. Flow velocities of the runoff were measured. The values are reasonable. The errors present, such as those due to surface roughness and rill development are also discussed.
10. Slope cross-sections of the tested plots were measured and analyzed. The errors are discussed in this chapter. The errors are considered to be too large to be used for analyses of rill development and erosion mechanism.

11. The value of Manning's roughness coefficient, n , is calculated based on two assumptions on flows, namely, rill flows and sheet flows. The n values based on rill flow assumption are about 4.35 times of those based on sheet flow assumption. The n values at dry, wet and very wet runs of the sites at Evansville based on sheet flow assumption are considered to be close to true values.

5.5.2 Recommendations

5.5.2.1 The Soil Erodibility Factor (K)

The soils of the four sites at Evansville are very dense and cohesive. The measured soil erodibility is 0.38 (ton·acre·hour per hundreds of acre·foot-tonf·inch). The soil erodibility predicted from the nomograph by Wischmeier, Johnson and Cross (1971) is 0.44. The difference is 14%. For design purposes, and to be on conservative side, before other indicators are available to predict the K factor more precisely than the nomograph, the nomograph is recommended for use in predicting the K factor of the compacted and cohesive soils on highway slopes in the state of Indiana.

5.5.2.2 The Slope Steepness Factor (S)

Using the S factor for the sites at Evansville in Figure 5.7, the data of the S factor of the site at Putnamville and the S factor proposed by McCool and George (1983), the recommended S factor of highway slopes with compacted and cohesive soils in Indiana is shown in Figure 5.24 and as follows.

$$S = (\sin\theta/\sin 5.14^\circ)^{0.7} \quad \theta < 14^\circ \quad (5.28)$$

$$S = 2.00 \quad \theta > 14^\circ \quad (5.29)$$

The S factor proposed by McCool and George (1983) was for dry-farmed cropland in the Pacific Northwest. Hart (1984) estimated the soil loss on mountain rangeland in Utah and found that for steep slopes of 32% (17.74 degrees) with high intensity rain on wet soil, the S factor by McCool and George was much more accurate than the conventional S factor as mentioned in Chapter 2. Since the S factor by McCool and George was proposed for dry-farmed cropland, the soils of the cropland are considered not so dense and cohesive as those at the sites at Evansville and Putnamville. Therefore, the S factor for highway slopes with compacted and cohesive soils in Indiana should be smaller than that by McCool and George, because rills are more likely to develop in

Figure 5.24 The recommended S factor

weaker soils, and the S factor is expected to be higher for weaker soils for a given slope steepness.

The soils of the four sites at Evansville are very dense and cohesive. The soils at the site of Putnamville are looser and more silty. For design purpose, the recommended S factor is (staying on the conservative side) as shown in Equations (5.28) and (5.29), and Figure 5.24.

5.5.2.3 The Slope Length Factor (L)

Extra inflow was used to simulate the runoff from upper slope areas, from which the relationship between erosion rate and discharge rate or slope length may be obtained. Using the data calculated from Table 5.6 (similar to Table 5.10), the slope length factor, L, is analyzed in Table 5.14. In Table 5.14, Column (1) shows erosion rates at extra inflow runs of the test sites at Evansville and Putnamville. There were four different rates of discharge for each extra inflow run. In an increasing order each rate was applied for 10 minutes as mentioned in Chapter 3. Erosion rates in Column (1) are based on the areas of tested plots. Column (2) represents discharge rates of the runoff passing the middle lines of the plots. Column (3) shows simulated slope lengths. Because there was no extra inflow

Table 5.14 The slope length factors from measurement and the equation by Wischmeier and Smith (1965)

Site	10 Min.	(1) Erosion Rate of the Plot (lb/ft ² ·hr)	(2) Discharge Rate (lb/ft ² ·sec)	(3) Simulated Slope Length (ft)	(4) Erosion Rate of (3) (lb/ft ² ·hr)	(5) Ratio of Erosion Rate of (3) to that of 1st 10 Min. Run	(6) Ratio Using Formula of Slope Length Factor
Site 1 (2:1 Slope)	1st	0.201	0.0517	31.27	0.201	1.000	1.000
	2nd	0.519	0.1974	119.40	0.284	1.413	1.954
	3rd	0.968	0.3027	183.08	0.332	1.652	2.420
	4th	2.394	0.5758	348.26	0.398	1.980	3.337
Site 2 (3:1 slope)	1st	0.165	0.0418	33.20	0.165	1.000	1.000
	2nd	0.617	0.2349	186.57	0.245	1.485	2.371
	3rd	1.439	0.3370	267.67	0.323	1.958	2.839
	4th	2.246	0.5254	417.38	0.330	2.000	3.545
Site 3 (6:1 slope)	1st	0.215	0.0198	14.81	0.215	1.000	1.000
	2nd	0.837	0.1459	109.13	0.299	1.391	2.715
	3rd	1.394	0.1836	137.33	0.342	1.591	3.045
	4th	1.885	0.2462	184.15	0.349	1.623	3.526
Site 4 (11:1 slope)	1st	0.280	0.0507	34.84	0.280	1.000	1.000
	2nd	0.665	0.2120	145.68	0.372	1.329	2.045
	3rd	1.101	0.3229	221.89	0.409	1.461	2.524
	4th	1.883	0.6015	413.34	0.415	1.482	3.444
Putoosville (2:1 slope) (Extra Inflow Run)	1st	0.645	0.0476	31.34	0.645	1.000	1.000
	2nd	1.487	0.2132	140.37	0.833	1.291	2.116
	3rd	2.179	0.3682	242.42	0.843	1.307	2.781
	4th	1.578	0.6109	402.22	0.717	1.112	3.582

applied to the plot in the first 10 minutes of each extra inflow run, the simulated slope lengths are the lengths of the plots. The simulated slope lengths after the first 10 minute runs are adjusted by discharge rates. For example, the simulated slope length of the second 10 minute run of Site 1 at Evansville is calculated as follows.

$$31.27 \times \frac{0.1974}{0.0517} = 119.40 \text{ (ft)}$$

Column (4) shows erosion rates based on the simulated slope lengths. It is conservatively assumed that there is only interrill erosion in the first 10 minutes of extra inflow run. Then the values of Column (4) are calculated by summing interrill erosion and rill erosion and dividing by the simulated slope lengths. For example, for the second 10 minute run of Site 1 at Evansville, the erosion rate of 0.519 (lb/ft²·hr) means the erosion rate of interrill erosion of the plot length (31.27 ft) plus rill erosion due to a length of 119.40 ft and divided by the length of plot (31.27 ft). To obtain the erosion rate based on the simulated slope length, interrill erosion should be added to the whole length. Since the interrill erosion rate is uniform in the simulated slope length, the amount of interrill erosion of [0.201 x (119.40-31.27)] should be added to

(0.519 x 31.27) to be the total erosion of a unit width of the length of 119.40 ft. This total erosion of unit width divided by the slope length (119.40 ft) is the erosion rate of the simulated slope. The calculation is shown as follows.

$$\frac{0.201 \times (119.40 - 31.27) + 0.519 \times 31.27}{119.40} = 0.284 \text{ (lb/ft}^2 \cdot \text{hr)}$$

Column (5) shows ratios of the erosion rates of Column (4) to those of the first 10 minute run at the same time.

Column (6) shows ratios of the slope length factor using Equation (2.16) by Wischmeier and Smith (1965) to those of the first 10 minute run at the same site.

From the values in Columns (5) and (6), the measured slope length factors for longer slopes are lower than those proposed by Wischmeier and Smith (1965). However, the data were measured after the very wet runs, i.e. the soils were nearly fully saturated. The slope length factor may be different when the soils are dry. Nevertheless, when Equation (2.16) is used for the slope length factor, the value is considered to be on the conservative side.

Therefore, Equation (2.16) by Wischmeier and Smith

(1965) is recommended to be used as the slope length factor for predicting soil erosion on highway slopes in Indiana.

5.5.2.4 Studies Suggested to Be Done in the Future

Certain research efforts are recommended in the future for predicting soil erosion more precisely. They are as follows.

1. Research of the raindrop impact and its detachment rate on soil slopes.
2. The soil erodibility factors for interrill erosion and rill erosion.
3. Equations based on the fundamental mechanics for predicting soil erosion, to replace the empirical equations.

CHAPTER 6

TESTS WITH ROTATIONAL SHEAR DEVICE

6.1 Introduction

As mentioned in Chapter 2, soil erodibility is one of the factors affecting slope erosion. Kibler and Busby (1970) defined soil erodibility as inherent susceptibility of soil particles to detachment and transport by raindrops and runoff. Since the 1930's, researchers have attempted to identify indicators to relate soil properties to measured overall erosion. Many of the applications were agricultural in nature.

Dunn (1959) proposed a method to estimate the tractive resistance (or critical tractive shear stress) of cohesive channel beds. The method was based on information obtained from simple soil tests e.g. Atterberg limits, grain size analysis and vane shear values. To measure hydraulic shear resistance, a submerged jet test apparatus was developed.

Moore and Masch (1962) developed a rotating cylinder to directly measure the shear stress distributed uniformly at the surface of a cohesive sediment. Espey (1963) continued this study on selected cohesive

soils, where design and calibration of the apparatus, preparation of soil samples and test procedures were described in some detail.

Grissinger (1966) continued the study by Dunn (1959) and Moore and Masch (1962) on selected clay systems. He concluded that soil stability increased with concentrations of clay minerals, but increased bulk densities had little influence on stability.

Dash (1968) measured soil erosion on saturated consolidated samples with a vertical jet apparatus, and on nearly saturated compacted samples with a flume section. Bhasin (1969) continued this study on various soil samples under different treatments as described in Chapter 2.

Paaswell (1973) evaluated reported studies to determine the factors that initiate and sustain erosion. The test procedures studied included jets, rotating cylinders, tube flow, flumes and field tests. He concluded that generally used soil classification indexes, e.g. plastic index, grain size distribution, had not proved quantitatively useful as erosion predictors. He also suggested certain indexes, e.g. structural indexes, pore fluid indexes, eroding fluid, internal and external force systems, be defined to establish the rate and initiation of erosion.

Arulanandan et al. (1975) used a rotating cylinder developed by Moore, Mash and Espey to relate soil erosion and critical hydraulic shear stress. In this study, the influences of pore and eroding fluid on soil erosion were quantitatively measured. They concluded that a critical shear stress exists for a given clay soil and eroding fluid. For stresses below this critical value, surface erosion is absent or very slow. They also concluded that both the sodium adsorption ratio and the concentration of pore fluid ions affected the critical shear stress for a given soil and when concentrations of salt of eroding fluid were lower than that of pore fluid, critical shear stress decreased due to the swell caused by osmotic influences. They suggested that critical shear stress obtained using distilled water as an eroding fluid were most conservative and most suitable for channel design purposes where rain or snow melt runoff was expected.

Arulanandan et al. (1980) continued this study and attempted to develop a quantitative method to predict the critical shear stress and the erosion rate of natural soil along the stream bank. After testing a wide range of soils, including disturbed and undisturbed samples, they obtained very similar results but did not

develop a quantitative method to predict critical shear stress and erosion rate for undisturbed soils.

Arulanandan and Perry (1983) continued this study and developed a method to quantify the soil erodibility based on the use of critical shear stress developed due to hydraulic flow in the crack zone of a dam.

Chapuis (1986a) and Chapuis (1986b) modified the rotational shear device so that it could accept either intact or remolded cohesive soils. The modifications included improved rotational guidance, a lower system friction, etc. The procedure for measuring eroded mass was also modified to acquire more accurate results.

Van Wijk and Lovell (1987) used a rotational shear device to determine the critical shear stresses and erosion rates of portland cement-stabilized materials for predicting the subbase erosion caused by pavement pumping.

However, the critical shear stress determined by using the rotational shear device had not been used to predict the soil erodibility factor, K , of the Universal Soil Loss Equation. In this study, a rotational shear device was used to determine critical shear stresses of the soil samples collected from the sites at Evansville, Putnamville and at the Throckmorton farm in Indiana. At

the Throckmorton farm site, researchers of the National Soil Erosion Laboratory at Purdue University, have been running field erosion tests for several years. These data and results are discussed and used to rate the soil erodibility factors of the sites at the three different locations.

In this chapter, design and operation of the rotational shear device are described in some detail. Preparation of soil samples, test procedures, results, discussion and conclusions are also included.

6.2 Rotational Shear Device

The principle of the rotational shear device is to use an annular water flow to provide shear stress around a stationary soil sample. The shear stress is rather uniform. The rotational shear device used in this study was similar to that by Chapuis (1986a) and Van Wijk and Lovell (1987), but with certain modifications. The Chapuis device had itself been modified from the device of Moore and Masch (1962) and Espey (1963).

6.2.1 The Rotating Cylinder by Moore and Masch (1962) and Espey (1963)

The rotating cylinder by Moore and Masch (1962) and Espey (1963) is shown in Figure 6.1. A hole in the soil sample was to allow passage of a torque tube. After the

Figure 6.1 Diagram of rotating cylinder test apparatus by Moore and Masch (1962) and Espey (1963)

soil sample was prepared and placed in the rotating cylinder, the rotating cylinder was filled with eroding fluid (water was used). When the external transparent cylinder rotated, the eroding fluid also rotated and provided surface shear stress around the soil sample which was stationary. Because of the rotational shear stress on the soil sample, the torque tube, yoke, brass rod and torque indicator were slightly rotated. The brass rod was used to resist the torque. From the calibration of the brass rod and the reading of the indicator, the applied torque and the shear stress on the soil sample were determined. The relationship between the rotational speed of the device and the applied shear stress was calibrated so that the desired shear stress could be obtained from the applied rotational speed.

The soil sample was nearly fully saturated and weighed before testing. Each time after the device was rotated at a certain rotational speed, i.e. a certain shear stress was applied on the soil sample, for a certain time period, the soil sample was removed from the cylinder, wiped, weighed, and placed into the cylinder again for another test without changing the eroding fluid. Therefore, the concentration of salt and sediment of the eroding fluid and saturation degree of the sample changed with time. These would cause errors in

the test results. Further, moving, wiping and weighing the soil sample might disturb the soil sample and cause errors.

6.2.2 The Rotational Erosion Device Modified by Chapuis (1986a)

The rotational erosion device modified by Chapuis (1986a) is shown in Figure 6.2. The soil sample was mounted between two metallic short cylinders (head and base in Figure 6.2) of the same diameter. The two metallic short cylinders were guided in rotation by ball bearings, and they rotated freely relative to the external cylinder. The rotations of the soil sample and the external cylinder were completely independent. The advantages of the modifications were that the device could accept either intact or remolded cohesive samples and the internal system friction was lower.

To directly measure the torque transmitted by the eroding fluid to the soil sample, a pulley-and-weight system with masses ranging from 0 to 40 g $\pm$ 0.1 g was used. This method could eliminate the errors of torque measurement due to different surface roughnesses of the soils. The previous assumption was that the relationship between rotational speed and torque obtained by using a dummy sample was constant. However, as Aru-

NOTES:

1. ROTATING EXTERNAL CYLINDER
2. SOIL SAMPLE
3. ERODING WATER IN ANNULAR SPACE
4. GUIDING SHAFT FOR INSTALLATION
5. TORQUE MEASUREMENT SYSTEM
6. HEAD
7. BASE
8. ACCESS FOR CLEANING
9. GRAVITY DRAINAGE

Figure 6.2 Rotational erosion device modified by Chapuis (1986a)

lanandan et al. (1975) pointed out, the surface roughness of a soil sample will be variable throughout a test depending on the erosion action.

To measure the eroded mass, the eroding fluid was drained at the end of each test. After this, the fluid with eroded particles was oven-dried, and the eroded mass was directly determined. The cell was filled with the eroding fluid to start a new test. This method could help to reduce the errors due to the changes of the eroding fluid concentration and saturation degree, and disturbance of the soil sample caused by repetitive manipulations. This method could also reduce the inherent friction torque to a range from 0.05 to 0.30 N·cm which was much less than the values present in the previous method.

To avoid shear stress concentration at the interfaces between the soil sample and the two metallic short cylinders (head and base), where the erosion started frequently, cylindrical steel foils were used to protect the contact interfaces.

6.2.3 The Rotational Shear Device Used in This Study

The rotational shear device used in this study was similar to that by Chapuis (1986a), but with certain modifications. The modifications are as follows:

1. Guiding shaft for installation (Figure 6.2):

The shaft previously designed by Chapuis (1986a) was a hollow tube of 5/8-in. OD and 1/2-in. ID. The opening of 1/2-in. diameter was to connect the head metallic cylinder using a small screw. The hollow tube was easily deformed when the small screw was tightened and it resulted in different frictions between the shaft and the rotating cylinder for different tests. To avoid the deformation of the tube, a solid stainless steel rod (Figure 6.3) was used as the shaft. Because of this modification, the rotating external cylinder needed to be longer by 1-1/2 inches (changed from 8 inches to 9-1/2 inches).

2. Interfaces between guiding shaft and the device:

Previously, there was no ball bearing at the interfaces between the guiding shaft and the device. Lubricating oil was used to reduce the friction. A small error in the alignment of the soil sample, the head short cylinder and the shaft would cause a significant friction error. During testing, the vibration of the device could make the friction even larger. To avoid these problems, ball bearings were used to surround the

Figure 6.3 A solid stainless steel rod for transmitting the torque

Figure 6.4 Ball bearings were used at the two interfaces between the guiding shaft and the device to minimize the friction.

shaft at both ends of the interfaces as shown in Figure 6.4. The friction was then reduced to be as close to zero as possible.

3. Torque measurement:

Chapuis (1986a) used a pulley-and-weight system with masses ranging from 0 to 40 g $\pm$ 0.1 g to measure the torque. As Arulanandan et al. (1975) pointed out, the surface roughness and accordingly, the torque changed with elapsed time. Much time was required to measure the torque using the pulley-and-weight system. During testing, because of vibration of the pulley-and-weight system; the error was expected to be large. To avoid these problems, a digital force gage was mounted on the device as shown in Figures 6.5 and 6.6. The capacity of the digital force gage was 250 g $\pm$ 0.1 g. The gage could be set to zero and set to show the maximum force at any time. The advantages of this method are that the torque can be quickly and more accurately measured, so that more readings can be taken to obtain the average value and the error due to vibration can be minimized. Aside from these, a digital force gage can also be connected to a computer to obtain a continuous reading for further analysis.

Figure 6.5 A digital force gage

Figure 6.6 A digital force gage was mounted on the device to measure the torque.

6.3 Preparation of Samples

The soils for rotational shear device tests were collected from the sites at Evansville, Putnamville and Throckmorton Farm in Indiana. The soils at Evansville and Putnamville were newly compacted on highway slopes. The soil at Throckmorton was for agricultural uses without any treatment. The sample preparation was to simulate the soil condition during the field erosion tests. The soils before rainfall simulation were naturally dry. However, dry samples slake before and during rotational shear device tests. Therefore, the samples for rotational testing were prepared at moisture contents close to full saturation.

The procedures of sample preparation are as follows:

1. The collected soil samples were air-dried in a room with good ventilation for several days.
2. The samples were pulverized using a rubber or plastic hammer.
3. Moisture contents of the air-dried sample were tested.
4. About 2,300 grams of the air-dried sample were

weighed and mixed with a certain amount of deionized water to obtain a moisture content which was about 1% higher than the desired values. The additional 1% of moisture content was for evaporation during mixing and curing.

5. The sample was sealed in a plastic bag and a plastic container (Figure 6.7) and cured for at least two days. Before, during and after curing, moisture contents of the sample were determined to ensure that they were the desired values.
6. The cured sample was compacted to the desired density in a compaction mold, 4-in. diameter and 4.6-in. high.
7. The compacted soil sample with the mold and porous stones at both ends was submerged in the water for increasing saturation and curing (Figure 6.8) for two to three days.

After soaking and cured, the sample was ready for the rotational shear test. The testing procedures are shown in the next section.

6.4 Test Procedures

After the soil sample was soaked and cured, a rota-

Figure 6.7 A soil sample was sealed in a plastic bag for curing.

Figure 6.8 A compacted soil sample was submerged in water for increase in saturation.

tional shear test could be started. The following test procedures include installation of the rotational shear device, setting up the soil sample, running the test and eroded mass measurement.

1. A stainless steel bearing ball of 3/16-in. diameter was placed on the top center of the bottom part of the rotational shear device (Figure 6.9).
2. A round plate (Figure 6.10(a)) 4-in. diameter by 1-in. thick, with one hole on each side, was placed on the bearing ball.
3. Another bearing ball of the same kind was placed in the top hole of the round plate (Figure 6.10(a)).
4. A bottom brass cap (Figure 6.10(b)) of 4-in. diameter with a nut of 1/2-in. diameter on one side was placed on the round plate and the bearing ball as shown in Figure 6.11
5. Before the previously prepared sample was extruded from the mold, a top base cap (Figure 6.12) of 4-in. diameter with one nut of 1/2-in. diameter on one side and four nuts of 1/2-in. diameter on the other side was gently driven into the sample. Since the distance between the four nuts and the

Figure 6.9 Initial condition before setting up rotational shear device

Figure 6.10 (a) Left: A round plate
(b) Right: A bottom brass cap

Figure 6.11 The round plate (Fig. 6.10 (a)) and the
bottom brass cap (Fig. 6.10 (b)) were set.

Figure 6.12 Top brass caps for samples

Figure 6.13 A top brass cap (Fig. 6.12) on a soil sample

soil surface was about 1 inch and the volume of the four nuts was about 6 cm^3 , the error of test results due to this was expected to be small. The soil sample was then extruded from the mold as shown in Figure 6.13.

6. The soil sample with a top brass cap on it was placed on the bottom brass cap (Figure 6.11). Tapes were used at the interfaces between the soil sample and the two brass caps to avoid shear stress concentration at those areas. They are shown in Figure 6.14.
7. A solid stainless steel rod (Figure 6.15(a)) of 1/2-in. diameter by 8-1/2-in. long was fastened on the top brass cap using an allen wrench (Figure 6.15(b)). This is shown in Figure 6.16.
8. A lucite cylinder (Figure 6.17(a)) was set on the rotationally shear device. There were two kinds of lucite cylinders, one was 5-1/2-in. OD, 5-in. ID by 9-1/2-in. long for lower shear stress tests, and the other one was 5-1/2-in. OD, 4-3/4-in. ID by 9-1/2-in. long for higher shear stress tests. In this study, the lucite cylinder for lower shear stress tests was used. They are shown in Figure 6.18.

Figure 6.14 The soil sample with a top brass cap on it was placed on the bottom brass cap.

Figure 6.15 (a) Left: A stainless steel rod,
(b) Right: An allen wrench

Figure 6.16 The stainless rod was fastened on the top
brass cap.

Figure 6.17 Lucite cylinders:

(a) Left: 5.5-in. OD, 5-in. ID,

(b) Right: 5.5-in. OD, 4.75-in. ID

Figure 6.18 A lucite cylinder (Fig. 6.17 (a)) was set around the sample.

9. The upper part of the rotational shear device (Figure 6.19) was set on the lucite cylinder along the square aluminum rod as shown in Figure 6.20.
10. The rotational shear device was fastened tightly using four brass rods (Figure 6.21). The nuts and bolts on the back and side of the square aluminum rod were tightened. They are shown in Figure 6.22.
11. A rotatable pedestal (Figure 6.23(a)) and a force arm (Figure 6.23(b)) were set successively on the rotational shear device along the guiding shaft (Figure 6.15(a)). They are shown in Figure 6.24.
12. A digital force gage (Figure 6.5) with a capacity of 250 ± 0.1 g was mounted on the shear device to measure the torque as shown in Figure 6.6.
13. The cell of the device was filled with deionized water to a level about 1/2-in. higher than the top of the soil sample using 1/8-in. diameter tubing as shown in Figure 6.25. After the tubing was removed, a square-headed bolt (Figure 6.26) was used to seal the hole for filling water.

Figure 6.19 Upper part of rotational shear device

Figure 6.20 The upper part of rotational shear device was set on the lucite cylinder.

Figure 6.21 Four brass rods

Figure 6.22 The rotational shear device was fastened using the four brass rods.

Figure 6.23 (a) Left: A rotatable pedestal for the force arm (b) Right: A force arm

Figure 6.24 The rotatable pedestal and the force arm were set on the device along the guiding shaft.

Figure 6.25 The cell of the device was filled with water.

Figure 6.26 A square-headed bolt was used to seal the hole for filling water.

The reason for using deionized water instead of using a fluid with salt as eroding fluid was that in this study the detachment by raindrops and erosion by runoff were simulated. The critical shear stress obtained from this method using clear water as eroding fluid was most suitable for runoff due to rain, which was also suggested by Arulanandan et al. (1975).

14. When the test was ready to be run, the digital force gage was turned on and set to a zero reading.
15. The switch for air pressure on the panel (Figure 6.27) was turned from "stop" to "run". The motor speed control in Figure 6.27 was set to a desired air pressure.
16. A touchless photo tachometer (Figure 6.28) was used to measure the rotational speed as shown in Figure 6.29.
17. For each test, a rotational speed was applied for five minutes. During the five minutes, one maximum shear stress was measured at one minute intervals. The five maximum stresses were used to determine the average shear stress applied. Usually, six to eight tests were necessary for a soil

Figure 6.27 On the panel, there were a pressure gage (top right), a motor speed control (middle right) and a switch for air pressure (bottom right).

Figure 6.28 A touchless photo tachometer

Figure 6.29 The touchless photo tachometer was used to measure rotational speed.

sample. The tests were under different rotational speeds from very low to high depending on the soil properties. Usually, when the eroding water became very cloudy (Figure 6.30) under a rotational speed, this meant that the shear stress applied was higher than the critical shear stress.

18. After each test, the eroding water was drained from the bottom of the device. The cell was carefully cleaned to insure that no or very little eroded mass was left in the cell. Containers were used to collect the eroding water with eroded particles. The samples were dried in the oven, weighed and the eroded mass was then determined.
19. After testing, the shear device was disassembled (Figure 6.31) and the moisture content of the sample was measured.

6.5 Results and Discussion

6.5.1 Soil Properties

The soils used for rotational shear device tests were collected from the sites of Evansville, Putnamville and Throckmorton Farm in Indiana. Soil properties of the sites are shown in Table 6.1. The soil properties consist of specific gravity, field density, organic

Figure 6.30 The eroding fluid in the cell became cloudy.

Figure 6.31 A soil sample after rotational shear device test

Table 6.1 Soil properties of the sites

Item of Test	Evansville	Putnamville	Throckmorton
Specific Gravity	2.766	2.712	2.658
Field Density (PCF)	109.4	106.9	87.0
Organic Content (%)	0.95	0.5	2.4
Atterberg Limits	Liquid Limit (%)	38.9	30.9
	Plastic Limit (%)	23.4	20.7
	Plastic Index (%)	15.5	10.2
Grain Size Distribution (% Finer)	4.76 mm (#4)	100	97
	2.00 mm	100	94
	0.10 mm	89	67
	0.074 mm (#200)	85	63
	0.05 mm	82	60
Soil Classification	0.002 mm	32	17
	USCS	CL	CL
	AASHTO	A-6 (close to) A-7	A-4 (close to) A-6
	USDAC	Silty Clay Loam	Loam

matter content, Atterberg limits, grain size distribution and soil classification. From Table 6.1, the three soils are very different. The soil at Evansville has the highest specific gravity and field density, while that at Throckmorton has the lowest. The soil at Throckmorton has the highest organic content while that of Putnamville has the lowest. According to grain size distribution and Atterberg limits, the soil at Evansville is the finest and most cohesive, while those at Putnamville and Throckmorton are coarser and not so cohesive, and the values of the two sites are rather close. According to the Unified Soil Classification System (USCS), the three soils are CL. According to the American Association of State Highway and Transportation Officials (AASHTO), the soils at Evansville, Putnamville and Throckmorton are A-6 (close to A-7), A-4 (close to A-6) and A-4, respectively. According to the U.S. Department Agriculture Classification (USDAC), the soil at Evansville is silty clay loam while the other two are loam.

6.5.2 Soil Erodibilities

Soil erodibilities of the three sites obtained from the nomograph by Wischmeier, Johnson and Cross (1971) and field erosion tests are shown in Table 6.2. According to the nomograph, erodibilities of the soils at

Table 6.2 Soil erodibilities of the sites from the nomograph and the field erosion tests

	Evansville	Putnamville	Throckmorton
% Silt (0.002 - 0.005 mm)	50	43	47
% Very Fine Sand (0.05 - 0.1 mm)	7	7	11
% Silt + Vfs	57	50	58
% Sand (0.10 - 2.0 mm)	11	27	26
% Organic Content	0.95	0.5	2.4
First Approximation of Soil Erodibility	0.30	0.32	0.32
Soil Structure	4	4	2
Permeability	6	6	3
Soil Erodibility from Nomograph	0.445	0.46	0.33
Soil Erodibility ₂ from Erosion Tests	0.381	-	-

Notes 1 and 2: Unit = ton'acre'hour/hundreds of acre'foot-tonf'inch

Evansville, Putnamville and Throckmorton are, respectively, 0.445, 0.46 and 0.33 ton·acre hour/hundreds of acre·foot-tonf·inch. From field erosion tests, erodibility of the soil at Evansville is 0.381 while for the other two soils, there are no data directly from field erosion tests. Therefore, the soil erodibility at Evansville is 0.381. The difference of the soil erodibility at Evansville is discussed in Chapter 5. As also discussed in Chapter 5, the upper and lower bounds of soil erodibility at Putnamville are estimated to be 0.46 and 0.394, respectively. The soil erodibility at Putnamville is then estimated to be 0.427, the average of the two bound values. Schroeder (1986) ran field erosion tests at the Throckmorton Farm and calculated the soil erodibility factor, K. The values of the K factor ranged from 0.002 to 0.233 metric ton·hectore·hour/hectare·megajoule·millimeter, or 0.015 to 1.769 ton·acre·hour/hundredsofacre·foot-tonf·inch. The differences were discussed by Schroeder (1986). Since, the soil at Throckmorton was for agricultural uses, the nomograph is considered to be valid for estimating the soil erodibility.

Therefore, the soil erodibility at Throckmorton is estimated to be 0.33 ton·acre·hour/hundreds of acre·foot-tonf·inch as shown in Table 6.2.

Therefore, the soil at Putnamville is estimated to be the most erodible because of lower clay content and organic content. The soil at Throckmorton is estimated to be the least erodible because of higher organic content and lower density from which a higher infiltration rate is contemplated.

6.5.3 Test Results of Rotational Shear Device

Typical test results of the rotational shear device are shown in Figures 6.32 and 6.33. In the two figures, the relationship between erosion rate and shear stress is shown. For each figure, two different slopes are found. Intersection of the two slopes is called the critical shear stress. Below this value, the erosion rate increases slowly with shear stress, while beyond this value, the erosion rate increases rapidly. These are similar to results of previous studies by Espey (1963), Arunanlāndan et al. (1975, 1980 and 1983), Chapuis (1986a) and Van Wijk and Lovell (1987).

All results of rotational shear tests are presented in Table 6.3. This table shows dry densities, moisture contents, saturation degrees, critical shear stresses and erosion rates of the soil samples from the three test sites. Dry densities of the tested soil samples are close to the field densities in Table 6.1. Satur-

Figure 6.32 A typical test result of rotational shear device on the soil sample from the site at Evansville

Figure 6.33 A typical test result of rotational shear device on the soil sample from the site at Throckmorton

Table 6.3 Test results of rotational shear device

Location	Test No.	Dry Density (PCF)	Moisture Content (%)	Saturation Degree (%)	Critical Shear Stress (N/m ²)	Erosion Rate (g/m ² ·sec)
Evansville	1E	108.4	21.12	99.3	1.80	0.22
	1F	109.2	20.85	100.1	1.90	0.90
	1G	110.7	19.75	98.5	2.00	0.60
Putnamville	26A	106.2	20.87	95.4	0.48	1.30
	26B	108.1	20.82	100.0	1.10	0.80
Throckmorton	22A	88.4	31.69	96.0	0.90	0.90
	22B	88.6	31.26	95.3	0.78	0.84

tion degrees range from 95.3 to 100.1% which are nearly fully saturated. Critical shear stresses of the three soil samples from Evansville are respectively 1.80, 1.90 and 2.00 N/m^2 , which are the highest values among the soil samples from the three tested sites. Critical shear stresses of the two samples from Putnamville are respectively 0.48 and 1.10 N/cm^2 . The average value of them is close to that from Throckmorton. The critical shear stress values of the samples from Putnamville have a larger variation. This may be due to different saturation degrees which are 95.4% and 100%. Erosion rates of the samples from Evansville and Putnamville fluctuate very much. From rotational shear device tests, erosion rates are found to be very sensitive to small changes in preparation of soil samples, e.g. compaction and extrusion of the samples, etc.

Critical shear stresses of the samples from Throckmorton are expected to be lower than those in situ because the values obtained using the rotating device in this study are from tests on remolded samples. To obtain critical shear stresses closer to true values, undisturbed and saturated samples are needed. However, it is somewhat difficult to get these samples because of plant roots and other residues.

Because of problems due to slaking and instability of the soil samples, especially for noncohesive or partially saturated or loose samples, tests with the rotational shear device were not always successful. Therefore, rotational shear device tests are suggested only for cohesive, dense and fully (or nearly fully) saturated samples.

6.5.4 Relationship between Soil Erodibility and Critical Shear Stress

One of the main purposes of this study is to predict soil erodibility using critical shear stress values obtained from the rotational shear device tests. Figure 6.34 shows the relationship between soil erodibility and critical shear stress. In this figure, the samples from Throckmorton have lower erodibilities and lower critical shear stresses which was not previously expected. However, the Throckmorton samples are looser with higher organic content, and accordingly, are more permeable. These factors cause lower soil erodibility as discussed in previous studies on the soil erodibility factor in the literature review of Chapter 2. This means that the rotational shear device test does not seem to completely reflect the erosion process due to raindrop and runoff. For example, samples with higher percolation rates in the field have lower erodibilities,

Figure 6.34 Soil erodibility vs. critical shear stress

while those in the rotating cylinder may have higher erosion rates or lower critical shear stresses. Neither can the effect of raindrop detachment be simulated by the rotational shear device.

Nevertheless, for cohesive, dense and fully (or nearly fully) saturated samples with low permeabilities like those from Evansville and Putnamville, critical shear stresses obtained by using the rotational device may be used to determine soil erodibilities. In Figure 6.34, the Evansville samples have higher critical shear stresses and lower soil erodibilities, while the Putnamville samples have lower critical shear stresses and high soil erodibilities. Figure 6.34 may be used to determine soil erodibilities in Indiana, from critical shear stresses obtained using the rotating cylinder test. However, to establish the relationship between the soil erodibility factor and critical shear stress obtained by using the device for a wide range of compacted cohesive soils, on highway slopes, with high densities and low permeabilities, more soil samples with known soil erodibilities are needed for rotational shear device tests.

6.6 Conclusions

1. A rotational shear device developed by Chapuis

(1986a) was modified and successfully operated in 1986 and 1987. The modifications included the guiding shaft for transmitting the torque from the soil sample to the force gage, ball bearings at the interfaces between the guiding shaft and the device for reducing the friction and a digital force gage for measuring the torque. These modifications provided better operation and lower internal friction, and accordingly, increased accuracy of the results.

2. Critical shear stresses were obtained by using the rotational shear device for the samples from Evansville, Putnamville and Throckmorton, Indiana. When shear stress is below the critical value, the erosion rate increases slowly with shear stress, while beyond the critical value, the erosion rate increases rapidly.
3. The rotational shear device test is not recommended for noncohesive or partially saturated or loose soil samples because of problems due to slaking and instability of the soil samples.
4. For compacted cohesive and fully (or nearly fully) saturated samples, the soil erodibility factor decreases with critical shear stress.

5. The rotational shear device test does not seem to reflect completely the erosion process due to raindrop and runoff processes. For example, percolation of water and raindrop detachment cannot be simulated by the test.
6. Critical shear stress may not be used to determine the soil erodibility factor for soils with low densities, or low cohesion or high permeabilities.

CHAPTER 7

EXAMPLES OF PREDICTING SOIL EROSION ON HIGHWAY SLOPES USING THE UNIVERSAL SOIL LOSS EQUATION

7.1 Introduction

The Universal Soil Loss Equation (USLE) has been used for predicting soil erosion on highway slopes since the 1970's. For example, Swerdon and Kountz (1973) and Miller et al. (1981) estimated soil erosion in Pennsylvania and Israelsen et al. (1981a and 1981b) predicted soil erosion in Utah. However, the slope steepness factors which they used were too conservative as mentioned before.

The main purpose of this chapter is to give examples of predicting soil erosion on highway slopes at five different locations in or around the state of Indiana using the USLE and the findings in this study. The five locations are Evansville, Crawfordsville, Greencastle, Cincinnati and Bloomington. Certain assumptions were required for predicting soil losses at the five places, when experimental information was not available.

7.2 Recommended Factors for the USLE

7.2.1 The Rainfall and Runoff Factor (R)

For single storms, the rainfall and runoff factor, R, is recommended as follows:

$$\begin{aligned} R &= EI_{30}/100 \\ &= eVI_{30}/100 \\ &= (916 + 331 \log_{10} I_{30})V \cdot I_{30}/100 \end{aligned} \quad (7.1)$$

where

R = the rainfall and runoff factor (hundreds of foot-tonf·inch/acre·hour)

E = kinetic energy (foot-tonf/acre)

I_{30} = the maximum 30-minute intensity (inch/hour)

e = kinetic energy per unit depth of rainfall
(foot-tonf/acre·inch)

V = depth or amount of rainfall (inch)

For annual values of the rainfall and runoff factor of the state of Indiana, a map by Wischmeier and Smith (1978) is used, as shown in Figure 7.1. The unit is hundreds of foot-tonf·inch/acre·hour·year.

7.2.2 The Soil Erodibility Factor (K)

A nomograph proposed by Wischmeier, Johnson and Cross (1971) as shown in Figure 2.1 is used for determining the soil erodibility factor.

Figure 7.1 Average annual values of the R factor of Indiana (Wischmeier and Smith, 1978)

7.2.3 The Slope Length Factor (L)

Equation (2.16) by Wischmeier and Smith (1965) is used for determining the slope length factor.

7.2.4 The Slope Steepness Factor (S)

For compacted cohesive soils, Equations (5.28) and (5.29) are used for determining the slope steepness factor. For cut slopes, Equation (2.23) is recommended for determining the S factor. For irregular slopes, Equation (2.19) is used for the combined factor LS.

7.2.5 The Cover and Management Factor (C)

The cover and management factor after Wischmeier and Smith (1978) is used. In the state of Indiana, most of the grasses planted on highway slopes are tall fescue and Kentucky blue grass. When the meadow is established without appreciable canopy, the weight of hay is estimated to be 3 to 5 tons per acre for a full year. Using Tables 5-B and 10 in the handbook by Wischmeier and Smith (1978), the C factors are estimated to be 0.004 and 0.003 respectively. A value of the C factor of 0.004 is considered to be conservative.

7.2.6 The Support Practice Factor (P)

The support practice factor by Wischmeier and Smith

(1978) is used. Usually, there is no support practice on highway slopes. Therefore, by definition, the P factor used is 1.0.

7.3 Examples

Estimation of the soil erodibility factor of the highway slopes at the five locations is based on the nomograph by Wischmeier, Johnson and Cross (1971) and reports by the Geotechnical Section, Division of Materials and Tests, Indiana Department of Highways, with certain assumptions. The estimated values are shown in Table 7.1. Because soils on the highway slopes at the five locations are compacted and cohesive, their soil structures and permeabilities are estimated to be "massive" and "very slow", respectively, according to the reference "Soil Survey Manual" of the United States Department of Agriculture Handbook No. 18 (1951). Therefore, their soil structure and permeability code numbers are 4 and 6 respectively. The unit of the soil erodibility in Table 7.1 is $\text{ton} \cdot \text{acre} \cdot \text{hour/hundreds of acre} \cdot \text{foot-tonf} \cdot \text{inch}$.

7.3.1 Example for Evansville

The conditions are given as follows:

Table 7.1 Estimation of the soil erodibility factors

	Evansville	Crawfordsville	Greencastle	Cincinnati	Bloomington
4.76 mm (#4)	100	99	97	95	100
2.00 mm	100	96	94	86	100
0.10 mm	89	70	67	79	80
0.074 mm (#200)	85	61	63	78	74
0.05 mm	82	55	60	70	67
0.002 mm	32	19	17	23	22
Σ Silt + Vfs (0.002-0.1 mm)	57	51	50	56	58
Σ Sand (0.10-2.0 mm)	11	26	27	7	20
Σ OM	0.95	0.6	0.5	0.7	0.9
Soil Structure	4	4	4	4	4
Permeability	6	6	6	6	6
Soil Erodibility	0.445	0.465	0.460	0.425	0.520

Note: The unit of soil erodibility is ton'acre'hour/hundreds of acre'foot-tonf'inch

1. A single storm with a maximum 30-minute intensity of 2.0 inch/hour and a total rainfall amount of 3 inches is assumed.
2. The topographic condition is shown in Figure 7.2. A curb on the highway shoulder prevents runoff from the pavement onto the slope.
3. On the slope, there is no support practice, but tall fescue is planted and well established.

Calculation of soil erosion is as follows:

1. To calculate the R factor using Equation (7.1):

$$\begin{aligned}
 R &= (916 + 331 \log_{10} I_{30}) V \cdot I_{30}/100 \\
 &= (916 + 331 \log_{10} 2.0) \cdot 3.0 \cdot 2.0/100 \\
 &= 60.94 \text{ hundreds of foot-tonf} \cdot \\
 &\quad \text{inch/acre} \cdot \text{hour}
 \end{aligned}$$

2. To estimate the K factor:

The K factor is estimated to be 0.445 ton·acre
 ·hour/hundreds of acre·foot-tonf·inch
 in Table 7.1.

3. To calculate the L factor using Equation (2.16):

$$\begin{aligned}
 L &= (\lambda/72.6)^m \\
 &= (60/72.6)^{0.5} \\
 &= 0.909
 \end{aligned}$$

Figure 7.2 Highway slope at Evansville

(a) NO BENCH ON THE SLOPE

(b) A BENCH WITH A DITCH ON THE SLOPE

Figure 7.3 Highway slopes at Crawfordsville

4. To calculate the S factor using Equations (5.28) and (5.29):

The slope angle is 18.43 degrees which is greater than 14 degrees.

$$S = 2.00$$

5. $C = 0.004$

6. $P = 1.00$

Soil erosion of the slope is:

$$A = R K L S C P$$

$$= 60.94 \times 0.445 \times 0.909 \times 2.00 \times 0.004 \times 1.0$$

$$= 0.197 \text{ ton/acre}$$

7.3.2 Example for Crawfordsville

The conditions are given as follows:

1. An average total amount of rainfall for a full year is assumed.
2. The topographic condition is shown in Figure 7.3a.
3. On the slope, there is no support practice, but Kentucky blue grass is planted and well established.

Calculation of soil erosion is as follows:

1. The R factor is about 187.5 hundreds of foot -
tonf * inch/acre * hour * year from Figure 7.1

2. The K factor is 0.465 from Table 7.1.

3. The L factor is calculated using Equation (2.16).

$$\begin{aligned} L &= (\lambda/72.6)^m \\ &= (80/72.6)^{0.5} \\ &= 1.050 \end{aligned}$$

4. The S factor is determined using Equations (5.28)
and (5.29). The slope angle is 26.57 degrees
which is greater than 14 degrees.

$$S = 2.00$$

5. C = 0.004

6. P = 1.00

Soil erosion of the slope is:

$$\begin{aligned} A &= R K L S C P \\ &= 187.5 \times 0.465 \times 1.050 \times 2.00 \times 0.004 \times 1.00 \\ &= 0.732 \text{ ton/acre * year} \end{aligned}$$

If the slope has a bench with a ditch on it as
shown in Figure 7.3b, soil erosion on the slope can be
calculated as follows:

1. The L factors for the two sections are:

$$L_1 = (30/72.6)^{0.5}$$

$$= 0.643$$

$$L_2 = (50/72.6)^{0.5}$$

$$= 0.830$$

2. The other factors remain the same.

The average erosion of the slope is:

$$A = R K S C P (L_1 \times 30 + L_2 \times 50)/80$$

$$= 187.5 \times .465 \times 2.00 \times .004 \times 1.0 \times (0.643 \times 30 + 0.830 \times 50)/80$$

$$= 0.530 \text{ ton/acre } \cdot \text{ year}$$

This value is less than that of the slope without a bench with a ditch. Therefore, benches with ditches can be used to reduce the slope length and erosion rate on the slope.

7.3.3 Example for Greencastle

The conditions are given as follows:

1. A single storm with a maximum 30-minute intensity of 2.50 inch/hour and a total rainfall amount of 3.5 inches. is assumed.
2. The topographic conditions is shown in Figure 7.4.
3. On the slope, there is no support practice, cover or management.

Figure 7.4 Highway slope at Greencastle

(a) A CONVEX SLOPE

(b) A CONCAVE SLOPE

Figure 7.5 Highway slopes at Cincinnati

Calculation of soil erosion is as follows:

1. To calculate the R factor using Equation (7.1):

$$\begin{aligned}
 R &= (916 + 331 \log_{10} I_{30}) \cdot V \cdot I_{30}/100 \\
 &= (916 + 331 \log_{10} 2.5) \times 3.5 \times 2.5/100 \\
 &= 91.68 \text{ hundreds of foot - tonf} \cdot \\
 &\quad \text{inch/acre} \cdot \text{hour}
 \end{aligned}$$

2. The K factor is 0.460 from Table 7.1

3. The L factor is calculated using Equation (2.16)

$$\begin{aligned}
 L &= (100/72.6)^{0.5} \\
 &= 1.174
 \end{aligned}$$

4. The S factor is determined using Equations (5.28) and (5.29). The slope angle is 18.43 degrees which is greater than 14 degrees.

$$S = 2.00$$

5. $C = 1.00$

6. $P = 1.00$

Soil erosion of the slope is:

$$\begin{aligned}
 A &= R K L S C P \\
 &= 91.68 \times 0.460 \times 1.174 \times 2.00 \times 1.00 \times 1.00 \\
 &= 99.02 \text{ ton/acre}
 \end{aligned}$$

This value of erosion is very high. Therefore, cover and management on the slope is very significant for erosion control.

7.3.4 Example for Cincinnati

The conditions are given as follows:

1. A single storm with a maximum 30-minute intensity of 3.00 inch/hour and a total rainfall amount of 4.00 inches is assumed.
2. The topographic condition is shown in Figure 7.5a.
3. On the slope, there is no support practice, cover or management.

Calculation of soil erosion is as follows:

1. To calculate the R factor using Equation (7.1):

$$\begin{aligned}
 R &= (916 + 331 \log_{10} I_{30}) \cdot V \cdot I_{30}/100 \\
 &= (916 + 331 \log_{10} 3.00) \times 4.00 \times 3.00/100 \\
 &= 128.87 \text{ hundreds of foot} \cdot \text{tonf} \cdot \\
 &\quad \text{inch/acre} \cdot \text{hour}
 \end{aligned}$$

2. The K factor is 0.425 from Table 7.1.
3. The combined LS factor is calculated using Equation (2.19). The slope angle of Segment 1 is 9.46

degrees which is less than 14 degrees. Using Equation (5.28), the S factor of Segment 1, S_1 , is 1.529. The slope angle of Segment 2 is 26.57 degrees which is greater than 14 degrees. Using Equation (5.29), the S factor of Segment 2, S_2 , is 2.00. Using Equation (2.19), the combined LS factor is calculated to be 1.810 as shown in Table 7.2.

4. $C = 1.$

5. $P = 1.$

Soil erosion of the entire slope is:

$$\begin{aligned} A &= R \cdot K \cdot LS \cdot C \cdot P \\ &= 128.87 \times 0.425 \times 1.810 \times 1. \times 1. \\ &= 99.13 \text{ ton/acre} \end{aligned}$$

If the slope is changed to be a concave slope as shown in Figure 7.5b and the other conditions remain the same, soil erosion is calculated as follows:

1. Using Equation (2.19), the combined LS factor is calculated to be 1.675 as shown in Table 7.2.

2. Soil erosion of the slope is:

$$\begin{aligned} A &= R \cdot K \cdot LS \cdot C \cdot P \\ &= 128.87 \times 0.425 \times 1.675 \times 1. \times 1. \\ &= 91.74 \text{ ton/acre} \end{aligned}$$

Table 7.2 Calculation of the combined LS factor
for the slopes at Cincinnati

Slope Type	Segment No.	S_j	m	λ_j (ft)	λ_{j-1} (ft)	$u_2 = \frac{S_j \lambda_j^{m+1}}{(72.6)^m}$	$u_1 = \frac{S_j \lambda_{j-1}^{m+1}}{(72.6)^m}$	$u_2 - u_1$	Segment Length (ft)	LS $\frac{\sum u_2 - u_1}{\lambda_e}$
Convex	1	1.529	0.5	45.0	0.0	54.17	0.00	54.17	45.0	
	2	2.00	0.5	75.0	45.0	152.46	70.86	81.60	30.0	
	Entire Slope							135.77	75.0	1.810
Concave	1	2.000	0.5	30.0	0.0	38.57	0.00	38.57	30.0	
	2	1.529	0.5	75.0	30.0	116.56	29.47	87.09	45.0	
	Entire Slope							125.66	75.0	1.675

Therefore, erosion on a convex slope is higher than that on a concave slope.

If the highway slope on Figure 7.5a is a cut slope and the other conditions remain the same, soil erosion is calculated as follows.

1. To estimate the K factor: Assume grain size distribution and organic matter content of the soil are the same as those in Table 7.1. Since the slope is a natural slope, the soil structure and permeability should be different from those of compacted soils. The soil structure and permeability are assumed to be medium granular and moderate to rapid respectively. According to the nomograph by Wischmeier et al. (1971), the soil structure and permeability numbers are 3 and 5 respectively. Using the same nomograph, the K factor is estimated to be 0.36 ton'acre'hour / hundreds of acre'foot-tonf'inch.
2. To estimate the combined LS factor: Using Equation (2.23), the S factor for Segment 1, S_1 , is 1.529, and the S factor for Segment 2, S_2 , is 3.082.

Using Equation (2.19), the combined LS factor is calculated to be 2.399.

3. Soil erosion of the cut slope is:

$$\begin{aligned} A &= R \cdot K \cdot LS \cdot C \cdot P \\ &= 128.87 \times 0.36 \times 2.399 \times 1.0 \times 1.0 \\ &= 111.30 \text{ ton/acre} \end{aligned}$$

7.3.5 Example for Bloomington

The conditions are given as follows:

1. An average total amount of rainfall for a full year is assumed.
2. The topographic condition is shown in Figure 7.6a.
A curb is on the highway shoulder to divert the water from the pavement.
3. On the slope, there is no support practice, cover, or management.

Calculation of soil erosion is as follows:

1. The R factor is about 193 hundreds of foot - tonf
inch/acre · hour · year from Figure 7.1.
2. The K factor is 0.520 from Table 7.1.

(a) A CURB ON THE SHOULDER

(b) NO CURB ON THE SHOULDER

Figure 7.6 Highway cross-sections at Bloomington

3. The L factor is calculated using Equation (2.16).

$$L = (50/72.6)^{0.5}$$

$$= 0.830$$

4. The slope angle is 9.462 degrees which is less than 14 degrees. The S factor is calculated to be 1.529 using Equation (5.28).

5. $C = 1.00$

6. $P = 1.00$

Soil erosion of the slope is:

$$A = R K L S C P$$

$$= 193 \times 0.520 \times 0.830 \times 1.529 \times 1.00 \times 1.00$$

$$= 127.36 \text{ ton/acre } \cdot \text{ year}$$

If there is no curb on the highway shoulder as shown in Figure 7.6b and the other conditions remain the same, soil erosion is calculated as follows:

1. Modifying the USLE and Equation (2.19), soil erosion can be calculated using the following equation.

$$A = (RCP/\lambda_e) \sum_{j=1}^n K_j \cdot \left[\frac{S_j \lambda_j^{m+1}}{(72.6)^m} - \frac{S_j \lambda_{j-1}^{m+1}}{(72.6)^m} \right]$$

(7.2)

where λ_e , λ_j , and λ_{j-1} are in feet.

Equation (7.2) is for calculating soil erosion of irregular and non-homogeneous slopes.

2. The K factor of Segment 1, K_1 , is assumed to be 0. because the pavement is considered to be nonerodible. The K factor of Segment 2, K_2 , is 0.520 from Table 7.1.
3. The slope angle of Segment 1 is 1.146 degrees which is less than 14 degrees. The S factor of Segment 1, S_1 , is 0.350 using Equation (5.28). The S factor of Segment 2 is 1.529.

Using Equation (7.2), soil erosion is calculated as follows:

$$\begin{aligned}
 A &= (R \cdot C \cdot P / \lambda_e) \left(0 \times \left[\frac{0.350 \times 40^{1.3}}{(72.6)^{0.3}} - \frac{0.350 \times 0^{1.3}}{(72.6)^{0.3}} \right] \right) \\
 &\quad + 0.520 \left[\frac{1.529 \times 90^{1.5}}{(72.6)^{0.5}} - \frac{1.529 \times 40^{1.5}}{(72.6)^{0.5}} \right] \\
 &= 193 \times 1.00 \times 1.00 \times 56.07 / 90. \\
 &= 120.24 \text{ ton/acre} \cdot \text{year}
 \end{aligned}$$

However, this value is the average erosion of the 90-ft slope (including the pavement and the highway slope). Since there is no erosion on the pavement, the

average erosion on the highway slope is calculated as follows:

$$\begin{aligned} A &= 120.24 \times 90./50 \\ &= 216.43 \text{ ton/acre} \cdot \text{year} \end{aligned}$$

This value is higher than that with a curb on the shoulder. Therefore, curbs on highway shoulders can help to reduce the erosion on highway slopes.

CHAPTER 8

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

8.1 Summary and Conclusions8.1.1 Rainfall Simulator and Field Erosion Tests

1. A rainfall simulator was modified and successfully operated on highway slopes with steepnesses from 9% to 50% at Putnamville and Evansville, Indiana in 1985 and 1986. Modifications included: changing the structure frame; its anchorage and wedges for supporting the troughs, and keeping them horizontal on steep slopes; and footings and bearing plates for bearing various loads due to wind and the weight of the rainfall simulator.
2. Special techniques were developed for preparation of the plot surface, its borders, plot ends, etc. These are detailed in Chapter 3.
3. Special operating sequences of the rainfall simulator were developed for the field erosion tests, on steep slopes. They included transporting the rainfall simulator from one test plot to another using a crane, ladders for researchers to walk up

or down during the rainfall simulation testing, etc.

8.1.2 Prediction of Distribution of Rainfall Intensity on Different Slopes Using the Rainfall Simulator

To study distribution of the simulated rainfall intensity and its effects on erosion under different conditions, theoretical and experimental approaches were developed. The conditions include different nozzle heights, slope steepnesses and nozzle tilting angles for single nozzles and group nozzles. From the predicted and measured results, it can be concluded:

1. A theoretical approach may be developed for predicting distribution of the simulated rainfall intensity and its effects on erosion. The predicted values using this approach and the measured data are reasonably close.
2. Using a theoretical approach and written computer programs, average intensities and distributions of rainfall intensity for single nozzles or composite nozzles can be calculated and plotted for any values of nozzle height, slope steepness and nozzle tilting angle, if distributions of the rainfall intensity for single nozzles are given under a given condition.

3. Average intensity increases with slope steepness. When nozzle height and nozzle tilting angle are given, the average intensity, I_{ave} , can be determined by Equation (4.9). It is:

$$I_{ave} = \sqrt{1 + s^2} \cdot I_{ave \text{ at } s = 0}$$

where s = slope steepness

4. Average intensity is not sensitive to nozzle height and nozzle tilting angle.
5. The relative sum of the square of intensity, called the F_{di} factor, which affects the interrill erosion rate because of the distribution of rainfall intensity, decreases with nozzle height. For nozzle heights greater than 8 ft, the F_{di} factor does not change significantly.
6. The F_{di} factor increases very little or does not change at all with nozzle tilting angle.
7. When nozzle height and nozzle tilting angle are known, the F_{di} factor can be determined by Equation (4.14). It is:

$$F_{di} = \sqrt{1 + s^2} \cdot F_{di \text{ at } s = 0}$$

where s = slope steepness

8.1.3 Laboratory Tests, Data Analyses, Results and Discussions of the Samples and Data Collected from the Field Erosion Tests

1. Soil properties of the four sites at Evansville are reasonably similar. The soil properties consist of specific gravity, Atterberg limits, grain size distribution, organic matter content, field density, moisture content and eroded aggregate size distribution. The soil conditions and soil erodibilities of the tested plots at Evansville are considered to be the same.
2. From the field erosion tests on highway slopes at Evansville, the S factor is extended to 50% (26.57 degrees) from 18% (10.2 degrees) as shown in Figure 5.7. The S factor reflects the development of rills, and the impact of raindrops, and appears to reach a maximum value of 1.5 at an intermediate value of slope steepness of 20% (11.2 degrees). This means that erosion due to interrill and rill erosion does not continue to increase with slope steepness.
3. The S factor of the site with a slope steepness of 49.735% (26.44 degrees) at Putnamville is estimated to be 1.50 to 1.75 which is much less than that proposed by previous researchers, but

close to the S factor proposed in this study, as shown in Figure 5.7.

4. For cohesive and compacted soils of the highway slopes at Evansville, total erosion is very sensitive to discharge rate or slope length, but not sensitive to slope steepness.
5. For the erosion tests at Evansville, a critical discharge rate or a critical slope length seems to exist for a given slope steepness. When the discharge rate is less than this critical value, the erosion rate increases very little or does not increase at all with discharge rate. When beyond this critical value, erosion rate increases markedly with discharge rate.
6. The S factor changes with slope length, soil properties and elapsed time. Accordingly, the S factor is not a factor independent of the others.
7. For cohesive and compacted soils in this study, the soil erodibility factor is less than that from the nomograph of Wischmeier, Johnson and Cross (1971). The effect may be described as the compaction factor.
8. For the field erosion tests in this study, the

ratios of total erosion (which consists of dry, wet and very wet runs) to the erosion due to very wet runs are close to a constant. The mean value is 6.348 with a standard deviation of 0.311 and a coefficient of variation of 4.90%.

9. Flow velocities of the runoff were measured. The values are reasonable. The errors for this, viz., surface roughness and rill development, are discussed.
10. Slope cross-sections of the eroded tested plots were measured and analyzed. The errors are discussed in Chapter 5. The errors are considered to be too large to be used for analyses of rill development and other details of the erosion mechanism.
11. The values of Manning's roughness coefficient, n , are calculated based on two assumptions of flow, namely, rill flows and sheet flows. The n values based on the rill flow assumption are about 4.35 times of those based on the sheet flow assumption. The n values at dry, wet and very wet runs of the sites at Evansville based on the sheet flow assumption are considered to be close to real values.

8.1.4 Tests with Rotational Shear Device

1. A rotational shear device developed by Chapuis (1986a) was modified and successfully operated in 1986 and 1987. The modifications included a guiding shaft for transmitting the torque from the soil sample to the force gage, ball bearings at the interfaces between the guiding shaft and the device for reducing the friction and a digital force gage for measuring the torque. The modifications provided better operation and lower internal friction, and accordingly, increased accuracy of the results.
2. Critical shear stresses obtained by using the rotational shear device exist for the samples from Evansville, Putnamville and Throckmorton. When shear stress is below this critical value, erosion rates increase slowly with shear stress while beyond the critical value, erosion rate increases rapidly.
3. The rotational shear device test is not recommended for noncohesive, or partially saturated or loose soil samples, because of problems due to slaking and instability of the soil samples.

4. For compacted cohesive and fully (or nearly fully) saturated soil samples, the soil erodibility factor decreases with critical shear stress.
5. The rotational shear device test does not seem to completely reflect the erosion process due to raindrop and runoff. For example, percolation of water and raindrop detachment can not be simulated by the test.
6. Critical shear stress may not be used to determine the soil erodibility factor for soils with low densities, or low cohesion or high permeabilities.

8.2 Recommendations

1. For design purposes, and to be on the conservative side, until other indicators are available to predict the K factor more precisely than the nomograph by Wischmeier, Johnson and Cross (1971), the nomograph is recommended for use in predicting the K factor of the compacted and cohesive soils on highway slopes in the state of Indiana.
2. The recommended S factor for highway slopes with compacted and cohesive soils in Indiana is as follows.

$$S = (\sin\theta / \sin 5.14^\circ)^{0.7} \quad \theta < 14^\circ$$

$$S = 2.00 \quad \theta > 14^\circ$$

3. The L factor by Wischmeier and Smith (1965) is recommended for predicting soil erosion on highway slopes in Indiana.

4. Certain research efforts are recommended in the future for predicting soil erosion more precisely. They are as follows.

[1] Additional research of raindrop impact and its detachment rates on soil slopes.

[2] Separation of soil erodibility into interrill and rill erosion components

[3] Equations based on the fundamental mechanics of soil erosion need ultimately to be developed to replace empirical equations.

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APPENDICES

Appendix A

The Equations Derived by Foster in 1978 for

Trajectory of Water-Drops Released from A Nozzle

The derivation of the equations by Foster in 1978 for trajectory of raindrop released from a nozzle is shown as follows.

Figure A.1 shows the trajectory of a water-drop released from a nozzle. Some of the terms used in this derivation are shown as follows.

h_o = Nozzle height above ground

v_o = Terminal velocity of a given drop under a given atmospheric condition

v_{ix} = Horizontal velocity component of drop at the nozzle

v_{iy} = Vertical velocity component of drop at the nozzle

θ_i = Initial trajectory angle

t = time

x = Horizontal distance of drop from nozzle at time t

y = Vertical distance of drop from nozzle at time t

The following assumptions are also made:

T_a = Temperature of air = 70°F

ρ_a = Mass density of air = 2.33×10^{-3} slugs/ft³

μ_a = Dynamic viscosity of air

Figure A.1 Trajectory of a water-drop released from a nozzle and striking flat ground

Figure A.2 Forces on drop in y direction

$$= 3.82 \times 10^{-7} \text{ lbf} \cdot \text{sec} / \text{ft}^2$$

$$\gamma_w = \text{Density of water} = 62.4 \text{ lbf} / \text{ft}^3$$

$$g = \text{Acceleration due to gravity} = 32.2 \text{ ft} / \text{sec}^2$$

$$\rho_w = \text{Mass density of water} = 1.94 \text{ slugs} / \text{ft}^3$$

$$d = \text{Median drop size} = 2.25 \text{ mm} = 7.38 \times 10^{-3} \text{ ft}$$

$$v_i = \text{Initial velocity} = 22.3 \text{ ft} / \text{sec}$$

(The values of d and v_i are from Special Report No. 81 by Meyer, 1958)

$$v_o = \text{Terminal velocity for a given median drop size (2.25 mm) and an atmospheric condition given as above}$$

$$= 23. \text{ ft} / \text{sec} \text{ [from Laws (1941)]}$$

$$e = 2.718285$$

$$A = \text{Drop effective cross sectional area (assume sphere)}$$

At nozzle, the Reynolds Number is:

$$N_R = \frac{v_i d \rho_a}{\mu_a} = \frac{(22.3)(7.38 \times 10^{-3})(2.33 \times 10^{-3})}{3.82 \times 10^{-7}} = 1004$$

At terminal velocity, the Reynolds Number is:

$$N_R = \frac{v_o d \rho_a}{\mu_a} = 1036$$

The range of Reynolds Numbers is very small.

Therefore, the drag coefficient, C_D , is assumed to be constant.

Drag force, F_D , is:

$$F_D = \frac{1}{2} C_D \rho_a A v^2$$

Since variation in v is small, assume

$$F_D = \hat{C}_D \rho_a A v \quad (\text{where } \hat{C}_D = \frac{1}{2} C_D v)$$

This linear assumption permits

$$\begin{aligned} F_{DX} &= \hat{C}_D \rho_a A v_x \\ &= \sin\theta \cdot F_D = \hat{C}_D \rho_a A v \sin\theta \end{aligned}$$

(Note: Above linear assumption is not permissible with $F_D \propto v^2$.)

and

$$F_{Dy} = \hat{C}_D \rho_a A v_y$$

Forces on drop in y direction is shown in Figure A.2, where

W = weight of drop = γV

V = volume of drop

m = mass of drop

$$W = \gamma V = \gamma \frac{\pi d^3}{6}$$

Net force in y direction is

$$F_y = W - F_{Dy} = m \cdot a_y$$

Acceleration of drop in y direction, a_y , is

$$\begin{aligned} \frac{W}{m} - \frac{F}{m} &= g - \frac{C_D \rho}{\rho_w} \cdot V A v_y \\ &= g - \frac{6 C_D \rho a \pi d^2}{4 \rho_w \pi d^3} v_y = g - \frac{6 C_D \rho a v_y}{4 \rho_w d} \end{aligned}$$

The value of C_D is evaluated as follows.

At v_y = terminal velocity, $a_y = 0$

$$\begin{aligned} g &= \frac{6 C_D \rho a v_o}{4 \rho_w d} \\ C_D &= \frac{4 g \rho_w d}{6 \rho a v_o} \end{aligned}$$

Substituting for C_D

$$\begin{aligned} a_y &= g - \frac{6}{4} \frac{\rho a v_y}{\rho_w d} \left(\frac{4}{6} \frac{g}{\rho_w} \frac{\rho_w d}{v_o} \right) \\ &= g - \frac{g v_y}{v_o} \end{aligned}$$

Note that drag coefficient has been eliminated. Instead acceleration and drop motion is written in terms of ter-

terminal velocity, v_o .

Now, solve for v_y

$$a_y = \frac{dv_y}{dt} = g - \frac{g v_y}{v_o} = g \left(1 - \frac{v_y}{v_o}\right)$$

$$\frac{dv_y}{1 - \frac{v_y}{v_o}} = g dt$$

$$\int \frac{1}{1 - \frac{v_y}{v_o}} dv_y = \int g dt$$

$$-v_o \ln \left(1 - \frac{v_y}{v_o}\right) = gt + c'$$

$$\ln \left(1 - \frac{v_y}{v_o}\right) = \frac{-gt}{v_o} + c \quad [\text{where } c = \frac{-c'}{v_o}]$$

$$\text{at } t = 0, v_y = v_{iy}$$

$$\ln \left(1 - \frac{v_{iy}}{v_o}\right) = 0 + c$$

$$\ln \left(1 - \frac{v_y}{v_o}\right) - \ln \left(1 - \frac{v_{iy}}{v_o}\right) = \frac{-gt}{v_o}$$

$$\ln \left(\frac{v_o - v_y}{v_o - v_{iy}}\right) = \frac{-gt}{v_o}$$

$$\frac{v_o - v_y}{v_o - v_{iy}} = e^{-gt/v_o}$$

$$v_y = v_o - (v_o - v_{iy}) e^{-gt/v_o}$$

$$\frac{dy}{dt} = v_y$$

$$y = \int v_y dt$$

$$y = v_o t + (v_o - v_{iy}) \frac{v_o}{g} e^{-\frac{gt}{v_o}} + c_1$$

$$y = 0 \text{ at } t = 0$$

$$\begin{aligned}
 0 &= + (v_o - v_{iy}) \frac{v_o}{g} + c_1 \\
 c_1 &= - (v_o - v_{iy}) \frac{v_o}{g} \\
 y &= v_o t - (v_o - v_{iy}) \frac{v_o}{g} (1 - e^{\frac{-gt}{v_o}})
 \end{aligned}$$

Or put $y = 0$ at ground

$$y = h_o - v_o t + (v_o - v_{iy}) \frac{v_o}{g} (1 - e^{\frac{-gt}{v_o}}) \quad (\text{A.1})$$

Comparison of Equation (A.1) with Assumption

$$F_D \propto C_D v^2 \text{ with } C_D = \text{constant}$$

Computer simulation program written to solve

$$F_D \propto C_D v^2$$

Assuming $v_o = 23.5 \text{ ft/sec}$, $\theta_1 = 15^\circ$, $h_o = 8 \text{ ft}$

Time for drop to hit ground = 0.362 sec

Time by Equation (A.1) = 0.364 sec

x by computer program where drop hits ground is 1.670 ft

x by equation (to be developed) is 1.655 ft

Therefore, Equation (A.1) is satisfactory.

To Solve for Time When $y = h$

Where $h = \text{some particular value, e.g. } h = 0$

(ground) or $h = 3$ ft.

Use Newton's methods to find where function f crosses 0.

$$f = h - h_0 + v_0 t - (v_0 - v_{iy}) \frac{v_0}{g} (1 - e^{-gt/v_0})$$

When $f = 0$, have t for $y = h$.

Assume a t_e as an estimate of t (use 0.36 for $h = 0$, and 0.23 for $h = 3, 8$ and 10).

Let t_n = new estimate

$$s = \frac{f_n - f_e}{t_n - t_e}$$

f_n at t_n is desired.

$$\text{Then } t_n = \frac{-f_e}{s} + t_e = \frac{-f_e}{\left(\frac{df}{dt}\right)} + t_e$$

$$\frac{df}{dt} = - (v_0 - v_{iy}) e^{\frac{-gt}{v_0}} + v_0$$

When $|f| < \text{set value}$, solution has converged. Solution converges in about 2 to 3 iterations.

To Solve for v_x and x

$$a_x = -F_{Dx}$$

By analysis similar to above

$$\begin{aligned}
 a_x &= -\frac{g v_x}{v_o} \\
 \frac{a v_x}{dt} &= -\frac{g v_x}{v_o} \\
 \frac{dv_x}{v_x} &= -\frac{g dt}{v_o} \\
 \ln v_x &= -\frac{gt}{v_o} + c_2 \\
 v_x &= v_{ix} \text{ at } t = 0 \\
 c_2 &= \ln v_{ix} \\
 \ln v_x - \ln v_{ix} &= \frac{-gt}{v_o} \\
 \ln \left(\frac{v_x}{v_{ix}} \right) &= \frac{-gt}{v_o} \\
 \frac{v_x}{v_{ix}} &= e^{\frac{-gt}{v_o}} \\
 v_x &= v_{ix} \cdot e^{\frac{-gt}{v_o}} \\
 x &= \int v_x dt \\
 x &= -\frac{v_o v_{ix}}{g} e^{\frac{-gt}{v_o}} + c_3 \\
 x &= 0 \text{ at } t = 0 \\
 c_3 &= \frac{v_o v_{ix}}{g} \\
 x &= \frac{v_o v_{ix}}{g} (-e^{\frac{-gt}{v_o}}) \tag{A.2}
 \end{aligned}$$

Nondimensionalize Equation (A.1) and (A.2)

$$\frac{g}{v_o^2} (h_o - y) = \frac{gt}{v_o} - \left(1 - \frac{v_{iy}}{v_o}\right) \left(1 - e^{\frac{-gt}{v_o}}\right)$$

$$\text{Let } y_* = \frac{g}{v_o^2} (h_o - y), \quad a = \frac{v_{iy}}{v_o} \text{ and } t_* = \frac{gt}{v_o}$$

$$y_* = t_* - (1-a)(1 - e^{-t_*}) \quad (\text{A.3})$$

$$\text{Let } x_* = \frac{gx}{v_o^2}, \quad b = \frac{v_{ix}}{v_o} \text{ and } t_* = \frac{gt}{v_o}$$

$$x_* = b(1 - e^{-t_*}) \quad (\text{A.4})$$

Tables can be constructed for Equations (A.3) and (A.4) to give y_* as a function of t_* and a , and x_* as a function of t_* and b . Tables will be valid for all trajectories.

Using Equation (A.1) and (A.2), drop trajectories for $h_o = 8$ ft and $h_o = 10$ ft are calculated and plotted in Figures A.3 and A.4.

Figure A.3 Drop trajectory for nozzle height = 8 ft

Figure A.4 Drop trajectory for nozzle height = 10 ft

Appendix B

A Computer Program, intla.f, for Analyzing
the Trajectory of Drops of Simulated Rainfall Under
the Conditions of Different Nozzle Heights, Slope
Steepnesses and Nozzle Tilting Angles


```

c
c   Program RAINFALL/erohor/int1a.f is for analyzing the trajectory
c   of drops of rainfall simulator.
c
c   dimension angd(100),vix(100),viy(100),t(100),xc(100),yc(100),
c   xs(100),angr(100)
c   pi=3.1416
c
c   read data, h0, stp, tilt
c
c   read *, h0, stp, tilt
c   print 10, h0, stp, tilt
10 format('//5x, 'Height of nozzle = ',f7.2,' ft'//5x,
1  'Steepness of slope = ',f7.2,' %'//5x,
2  'Tilting angle of nozzle = ',f7.2,' degree')
c
c   generate trajectory angle data
c
c   do 110 i=0,90
c   angd(i)=i-45.+tilt
c   angr(i)=angd(i)*pi/180.
c   vix(i)=22.3*sin(angr(i))
110 viy(i)=22.3*cos(angr(i))
c
c   define functions, ft, fd, and use Newton's Method
c
c   do 120 i=0,90
c   t(i)=.5
c   do 115 j=1,100
c   ft=h0-23.*t(i)+0.7143*(23.-viy(i))*(1.-exp(-1.4*t(i)))-
c   &0.01*stp*.7143*vix(i)*(1.-exp(-1.4*t(i)))
c   if(abs(ft).le.0.000001) go to 120
c   fd=-23.+(23.-viy(i))*exp(-1.4*t(i))-0.01*stp*vix(i)*exp(-1.4*t(i))
115 t(i)=t(i)-ft/fd
120 continue
c
c   to calculate the distance of each trajectory angle
c
c   do 130 i=0,90
c   xc(i)=0.7143*vix(i)*(1.-exp(-1.4*t(i)))
c   yc(i)=h0-23.*t(i)+0.7143*(23.-viy(i))*(1.-exp(-1.4*t(i)))
c   xs(i)=sqrt(xc(i)**2.+yc(i)**2.)
c   if(xc(i).ge.0.) go to 130
c   xs(i)=-1.*xs(i)
130 continue
c   write(6,15)
15 format('//5x, 'Trajectory',4x,'Distance Along',6x,'Dropping'/8x,
1  'Angle',9x,'The Slope',9x,'Time'/6x,'(degree)',10x,'(feet)',9x,
2  '(second)'/)
c   do 140 i=0,90
140 print 20,angd(i),xs(i),t(i)
20 format(7x,f7.2,7x,f10.5,7x,f9.6)
c   stop
c   end

```

Appendix CComputed Results of the Program, intla.f, Using ASet of Data with Nozzle Height = 8 Ft,Slope Steepness = 0%, and Nozzle TiltingAngle = 0 Degree

Height of nozzle = 8.00 ft

Steepness of slope = 0.00 %

Tilting angle of nozzle = 0.00 degree

Trajectory Angle (degree)	Distance Along The Slope (feet)	Dropping Time (second)
-45.00	-5.29279	0.453361
-44.00	-5.16052	0.448617
-43.00	-5.02905	0.444021
-42.00	-4.89838	0.439570
-41.00	-4.76853	0.435263
-40.00	-4.63950	0.431096
-39.00	-4.51129	0.427068
-38.00	-4.38391	0.423175
-37.00	-4.25733	0.419415
-36.00	-4.13157	0.415786
-35.00	-4.00662	0.412285
-34.00	-3.88246	0.408910
-33.00	-3.75908	0.405658
-32.00	-3.63648	0.402528
-31.00	-3.51464	0.399518
-30.00	-3.39353	0.396623
-29.00	-3.27316	0.393845
-28.00	-3.15349	0.391179
-27.00	-3.03452	0.388624
-26.00	-2.91621	0.386177
-25.00	-2.79856	0.383839
-24.00	-2.68154	0.381606
-23.00	-2.56513	0.379476
-22.00	-2.44931	0.377449
-21.00	-2.33405	0.375523
-20.00	-2.21932	0.373696
-19.00	-2.10512	0.371967
-18.00	-1.99141	0.370335
-17.00	-1.87817	0.368797
-16.00	-1.76537	0.367354
-15.00	-1.65299	0.366004
-14.00	-1.54100	0.364746

-13.00	-1.42939	0.363579
-12.00	-1.31811	0.362502
-11.00	-1.20715	0.361514
-10.00	-1.09648	0.360615
-9.00	-0.98608	0.359803
-8.00	-0.87591	0.359079
-7.00	-0.76596	0.358441
-6.00	-0.65619	0.357889
-5.00	-0.54658	0.357423
-4.00	-0.43711	0.357042
-3.00	-0.32774	0.356746
-2.00	-0.21845	0.356534
-1.00	-0.10921	0.356408
0.00	0.00000	0.356366
1.00	0.10921	0.356408
2.00	0.21845	0.356534
3.00	0.32774	0.356746
4.00	0.43711	0.357042
5.00	0.54658	0.357423
6.00	0.65619	0.357889
7.00	0.76596	0.358441
8.00	0.87591	0.359079
9.00	0.98608	0.359803
10.00	1.09648	0.360615
11.00	1.20715	0.361514
12.00	1.31811	0.362502
13.00	1.42938	0.363579
14.00	1.54100	0.364746
15.00	1.65299	0.366004
16.00	1.76537	0.367354
17.00	1.87817	0.368797
18.00	1.99141	0.370335
19.00	2.10512	0.371967
20.00	2.21932	0.373696
21.00	2.33404	0.375523
22.00	2.44930	0.377449
23.00	2.56513	0.379476
24.00	2.68154	0.381606
25.00	2.79856	0.383839
26.00	2.91621	0.386177
27.00	3.03452	0.388623
28.00	3.15349	0.391179
29.00	3.27316	0.393845

30.00	3.39353	0.396623
31.00	3.51464	0.399518
32.00	3.63648	0.402528
33.00	3.75908	0.405658
34.00	3.88246	0.408910
35.00	4.00662	0.412285
36.00	4.13157	0.415786
37.00	4.25733	0.419415
38.00	4.38391	0.423175
39.00	4.51129	0.427068
40.00	4.63950	0.431096
41.00	4.76853	0.435263
42.00	4.89838	0.439570
43.00	5.02905	0.444021
44.00	5.16052	0.448617
45.00	5.29279	0.453361

Appendix D

A Computer Program, inth4.f, for Calculating
and Plotting the Distribution of Simulated Rainfall
Intensity for Both Single Nozzle and Composite
Nozzles with Any Given Values of Nozzle Height,
Slope Steepness, and Nozzle Tilting Angle,
Using Meyer's Data in 1958

```

c
c   Program RAINFALL/erohor/inth4.f is for calculating and
c   plotting the distribution of simulated rainfall intensity
c   on a horizontal base(for single and group troughs) using
c   Meyer's data(1958,Special Report #81). This program will
c   generate four files,namely,x,y,yy and yyy, which are
c   written in binary code for plotting graphs.
c       Where x denotes the distance(ft) along the slope,
c           y denotes the distribution of simulated rainfall
c               intensity of the single trough on a
c                   horizontal base,
c           yy denotes the distribution of simulated rainfall
c               intensity of group troughs on a
c                   horizontal base,
c       and yyy denotes the average simulated rainfall intensity
c           on a horizontal base.
c
c   real itn(200),itnm(400),itnma(400),itnmb(400),itnmt(400),
c   & itnms(400),itnmc(400),itnmd(400)
c   dimension angd(100),vix(100),viy(100),t(100),xc(100),yc(100),
c   1xs(100),angr(100),volh(36),vol(100),xsm(400)
c   data volh/0.1092, 0.1086, 0.1077, 0.1067, 0.1054, 0.1040,
a       0.1021, 0.1003, 0.0982, 0.0962, 0.0942, 0.0922,
b       0.0899, 0.0870, 0.0840, 0.0806, 0.0766, 0.0722,
c       0.0679, 0.0636, 0.0580, 0.0524, 0.0474, 0.0410,
d       0.0367, 0.0322, 0.0314, 0.0316, 0.0344, 0.0404,
e       0.0429, 0.0424, 0.0372, 0.0237, 0.0112, 0.0000/
c   pi=3.1416
c   open(unit=1,file="x",status="new",form="unformatted")
c   open(unit=2,file="y",status="new",form="unformatted")
c   open(unit=3,file="yy",status="new",form="unformatted")
c   open(unit=4,file="yyy",status="new",form="unformatted")
c
c   read data, h0, stp, tilt
c
c   read *, h0, stp, tilt
c   print 10, h0, stp, tilt
10  format(////////10x,'Height of nozzle = ',f7.2,' ft'//10x,
1    'Steepness of slope = ',f7.2,' %'//10x,
2    'Tilting angle of nozzle = ',f7.2,' degree')
c
c   arrange simulated rainfall volume on each small area
c
c   do 105 i=35,70
c       j=i-34
105  vol(i)=volh(j)
c       do 107 i=0,34
c           j=70-i
107  vol(i)=vol(j)
c
c   generate trajectory angle data
c
c   do 110 i=0,70
c       angd(i)=i-35.+tilt
c       angr(i)=angd(i)*pi/180.
c       vix(i)=22.3*sin(angr(i))
110  viy(i)=22.3*cos(angr(i))
c
c   define functions, ft, fd, and use Newton's Method
c

```

```

do 120 i=0,70
t(i)=.5
do 115 j=1,100
ft=h0-23.*t(i)+0.7143*(23.-viy(i))*(1.-exp(-1.4*t(i)))-
&0.01*stp*.7143*vix(i)*(1.-exp(-1.4*t(i)))
if(abs(ft).le.0.000001) go to 120
fd=-23.+(23.-viy(i))*exp(-1.4*t(i))-0.01*stp*vix(i)*exp(-1.4*t(i))
115 t(i)=t(i)-ft/fd
120 continue

c
c to calculate the distance of each trajectory angle
c
do 130 i=0,70
xc(i)=0.7143*vix(i)*(1.-exp(-1.4*t(i)))
yc(i)=h0-23.*t(i)+0.7143*(23.-viy(i))*(1.-exp(-1.4*t(i)))
xs(i)=sqrt(xc(i)**2.+yc(i)**2.)
if(xc(i).ge.0.) go to 130
xs(i)=-1.*xs(i)
130 continue
if(xs(0).lt.-10.) go to 900
if(xs(70).gt.10.) go to 950

c
c calculation of rainfall intensity
c
itn(0)=0.
itn(70)=0.
do 150 i=1,69
j=i-1
k=i+1
150 itn(i)=2.*vol(i)/(xs(k)-xs(j))

c
c arrange data of distance & overlapped intensity
c
ixsm0=int(10.*(xs(0)))
xsm(0)=ixsm0/10.
j=0
do 300 i=0,200
xsm(i)=xsm(0)+i*0.1
if(xsm(i).gt.xs(70)) go to 310
285 if(xsm(i).lt.xs(j)) go to 300
k=j+1
if(xsm(i).ge.xs(k)) go to 290
itnm(i)=itn(j)+(itn(k)-itn(j))*(xsm(i)-xs(j))/(xs(k)-xs(j))
go to 300
290 j=j+1
go to 285
300 continue
310 ix=i-1
id=abs(int(xsm(0)*10.))
iu=int(xsm(ix)*10.)
jx1=100-id-1
do 315 i=0,jx1
315 itnms(i)=0.
jx2=jx1+1
jx3=100+iu
do 320 i=jx2,jx3
jx4=i-jx2
320 itnms(i)=itnm(jx4)
jx5=jx3+1
do 325 i=jx5,200

```



```

325 itnms(i)=0.
c
c      Intensity due to the lowest nozzle.(A)
c
      do 350 i=0,200
350  itnma(i)=itnms(i)
      do 355 i=201,350
355  itnma(i)=0.
c
c      intensity due to the second lowest nozzle.(B)
c
      do 360 i=0,49
360  itnmb(i)=0.
      do 365 i=0,200
      kx=50+i
365  itnmb(kx)=itnms(i)
      do 368 i=251,350
368  itnmb(i)=0.
c
c      Intensity due to the second highest nozzle.(C)
c
      do 370 i=0,99
370  itnmc(i)=0.
      do 375 i=0,200
      ky=100+i
375  itnmc(ky)=itnms(i)
      do 378 i=301,350
378  itnmc(i)=0.
c
c      Intensity due to the highest nozzle.(D)
c
      do 380 i=0,149
380  itnmd(i)=0.
      do 385 i=0,200
      kz=150+i
385  itnmd(kz)=itnms(i)
c
c      Overlap the intensity
c
      do 390 i=150,199
      kw=i-150
390  itnmt(kw)=itnma(i)+itnmb(i)+itnmc(i)+itnmd(i)
      do 395 i=0,49
      ka=50+i
      kb=100+i
      kc=150+i
      itnmt(ka)=itnmt(i)
      itnmt(kb)=itnmt(i)
395  itnmt(kc)=itnmt(i)
      itnmt(200)=itnmt(0)
c
c      Plotting the intensity due to single nozzle
c
      xsr=sqrt(1.+(.01*stp)**2.)
      do 400 i=0,200
      x=i*0.1-10.
      y=itnms(i)*xsr
      write(1) x
      write(2) y
400  continue

```

```

c      calculating the mean & standard deviation
c      of overlapped intensity
c
      val=0.
      do 410 i=0,49
410    val=val+itnmt(i)*xsr
        aveitn=val/50.
        var=0.
        do 420 i=0,49
420    var=var+(itnmt(i)*xsr)**2.
        var=(var/50.)-aveitn**2.
        staitn=sqrt(var)
        print 15, aveitn, staitn
15    format(/10x,'Mean of intensity = ',f10.6//10x,
1    'Standard deviation of intensity = ',f10.6)
c
c      plotting the overlapped intensity
c
      do 430 i=0,200
      yy=itnmt(i)*xsr
      yyy=aveitn
      write(3) yy
430    write(4) yyy
      go to 999
900    print 90, xs(0)/xsr
      90    format(/10x,'Nozzles spray too downslope, end =',f10.6,' ft')
      go to 999
950    print 95, xs(70)/xsr
      95    format(/10x,'Nozzles spray too upslope, end =',f10.6,' ft')
999    stop
      end

```

Appendix E

A Computer Program, inth9.f, for Calculating
and Plotting the Ratios of the Sum of the
Square of the Simulated Rainfall Intensity
Under the Condition of Nozzle
Heights from 5 to 10 Feet, A Given
Slope Steepness and A Given Nozzle Tilting
Angle, to that under the Basic Condition

```

c
c Program RAINFALL/erohor/inth9.f is for calculating and
c plotting the ratios of the sum of the square of the
c simulated rainfall intensity on a horizontal base under the
c conditions of different nozzle heights(h0=5 to 10 ft),
c different slope steepnesses(stp), and different nozzle
c tilting angles(tilt), to that under the basic condition
c with h0=8 ft, stp=0 % and tilt=0 degree. The data used was
c presented by Meyer (1958, Special Report #81). This program
c will generate two files, namely, x and y, which are written
c in binary code for plotting graphs.
c   Where x denotes the nozzle height(ft), h0, from 5 to 10
c         feet, and
c         y denotes the ratio mentioned above.
c
c   real itn(200),itnm(400),itnma(400),itnmb(400),itnmt(400),
c & itnms(400),itnmc(400),itnmd(400),msumba
c dimension angd(100),vix(100),viy(100),t(100),xc(100),yc(100),
c ixs(100),angr(100),volh(36),vol(100),xsm(400)
c data volh/0.1092, 0.1086, 0.1077, 0.1067, 0.1054, 0.1040,
a      0.1021, 0.1003, 0.0982, 0.0962, 0.0942, 0.0922,
b      0.0899, 0.0870, 0.0840, 0.0806, 0.0766, 0.0722,
c      0.0679, 0.0636, 0.0580, 0.0524, 0.0474, 0.0410,
d      0.0367, 0.0322, 0.0314, 0.0316, 0.0344, 0.0404,
e      0.0429, 0.0424, 0.0372, 0.0237, 0.0112, 0.0000/
c   pi=3.1416
c   nn=-1
c   open(unit=1,file="x",status="new",form="unformatted")
c   open(unit=2,file="y",status="new",form="unformatted")
c
c   From this line to Statement No.420, this program is to
c   calculate the sum of the square of intensity for the
c   distance from 0 to 5 ft under the condition of
c   nozzle height, h0=8 ft
c   slope steepness, stp= 0 %
c   nozzle tilting angle, tilt=0 degree
c
c   h0=8.
c   stp=0.
c   tilt=0.
c   iflag=1
c
c   print out the condition for basic value
c
c   write(6,('The basic condition: "/"nozzle height = ',
1 f7.2," feet"/"slope steepness = ",f7.2," %"/
2 "nozzle tilting angle = ", f7.2," degree")) h0,
3 stp, tilt
c
c   arrange simulated rainfall volume on each small area
c
c   do 105 i=35,70
c     j=i-34
105   vol(i)=volh(j)
c     do 107 i=0,34
c       j=70-i
107   vol(i)=vol(j)
c
c   generate trajectory angle data
c

```

```

do 110 i=0,70
  angd(i)=i-35.+tilt
  angr(i)=angd(i)*pi/180.
  vix(i)=22.3*sin(angr(i))
110 viy(i)=22.3*cos(angr(i))
113 xsr=sqrt(1.+(0.01*stp)**2.)
c
c   define functions, ft, fd, and use Newton's Method
c
do 120 i=0,70
  t(i)=.5
  do 115 j=1,100
    ft=h0-23.*t(i)+0.7143*(23.-viy(i))*(1.-exp(-1.4*t(i)))-
    &0.01*stp*.7143*vix(i)*(1.-exp(-1.4*t(i)))
    if(abs(ft).le.0.000001) go to 120
    fd=-23.+(23.-viy(i))*exp(-1.4*t(i))-0.01*stp*vix(i)*exp(-1.4*t(i))
115 t(i)=t(i)-ft/fd
120 continue
c
c   to calculate the distance of each trajectory angle
c
do 130 i=0,70
  xc(i)=0.7143*vix(i)*(1.-exp(-1.4*t(i)))
  yc(i)=h0-23.*t(i)+0.7143*(23.-viy(i))*(1.-exp(-1.4*t(i)))
  xs(i)=sqrt(xc(i)**2.+yc(i)**2.)
  if(xc(i).ge.0.) go to 130
  xs(i)=-1.*xs(i)
130 continue
  if(xs(0).lt.-10.) go to 900
  if(xs(70).gt.10.) go to 950
c
c   calculation of rainfall intensity
c
  itn(0)=0.
  itn(70)=0.
  do 150 i=1,69
    j=i-1
    k=i+1
150 itn(i)=2.*vol(i)/(xs(k)-xs(j))
c
c   arrange data of distance & overlapped intensity
c
  ixsm0=int(10.*(xs(0)))
  xsm(0)=ixsm0/10.
  j=0
  do 300 i=0,200
    xsm(i)=xsm(0)+i*0.1
    if(xsm(i).gt.xs(70)) go to 310
285 if(xsm(i).lt.xs(j)) go to 300
    k=j+1
    if(xsm(i).ge.xs(k)) go to 290
    itnm(i)=itn(j)+(itn(k)-itn(j))*(xsm(i)-xs(j))/(xs(k)-xs(j))
    go to 300
290 j=j+1
    go to 285
300 continue
310 ix=i-1
    id=abs(int(xsm(0)*10.))
    iu=int(xsm(ix)*10.)
    jx1=100-id-1

```

```

      do 315 i=0,jx1
315  itnms(i)=0.
      jx2=jx1+1
      jx3=100+iu
      do 320 i=jx2,jx3
      jx4=i-jx2
320  itnms(i)=itnm(jx4)
      jx5=jx3+1
      do 325 i=jx5,200
325  itnms(i)=0.
c
c      Intensity due to the lowest nozzle.(A)
c
      do 350 i=0,200
350  itnma(i)=itnms(i)
      do 355 i=201,350
355  itnma(i)=0.
c
c      intensity due to the second lowest nozzle.(B)
c
      do 360 i=0,49
360  itnmb(i)=0.
      do 365 i=0,200
      kx=50+i
365  itnmb(kx)=itnms(i)
      do 368 i=251,350
368  itnmb(i)=0.
c
c      Intensity due to the second highest nozzle.(C)
c
      do 370 i=0,99
370  itnmc(i)=0.
      do 375 i=0,200
      ky=100+i
375  itnmc(ky)=itnms(i)
      do 378 i=301,350
378  itnmc(i)=0.
c
c      Intensity due to the highest nozzle.(D)
c
      do 380 i=0,149
380  itnmd(i)=0.
      do 385 i=0,200
      kz=150+i
385  itnmd(kz)=itnms(i)
c
c      Overlap the intensity
c
      do 390 i=150,199
      kw=i-150
390  itnmt(kw)=itnma(i)+itnmb(i)+itnmc(i)+itnmd(i)
      do 395 i=0,49
      ka=50+i
      kb=100+i
      kc=150+i
      itnmt(ka)=itnmt(i)
      itnmt(kb)=itnmt(i)
395  itnmt(kc)=itnmt(i)
      itnmt(200)=itnmt(0)
c

```

```

c      calculating the sum of the square of the rainfall
c      intensity for the basic condition, sumbas
c
      if(iflag.gt.1) go to 450
      sumbas=0.
      do 420 i=0,49
420    sumbas=sumbas+(itnmt(i)*xsr)**2.
c
c      read data: slope steepness: stp (%)
c      nozzle tilting angle: tilt (degree)
c
      write(6,('What is the slope steepness(%)?'))
      read *, stp
      write(6,('What is the tilting angle of nozzles(degree)?'))
      read *, tilt
      iflag=2
      go to 510
450    sumsqr=0.
      do 480 i=0,49
480    sumsqr=sumsqr+(itnmt(i)*xsr)**2.
c
c      adjust the value of sumbas to the modified value(msumba)
c      with the condition which has the same average intensity
c      and slope length as that on slope
c
      msumba=sumbas*xsr**2./xsr
      x=h0
      y=sumsqr/msumba
      write(1) x
      write(2) y
510    nn=nn+1
      if(nn.gt.100) go to 999
      h0=5.+ .05*nn
      go to 113
900    print 90, xs(0)/xsr
      90 format(/10x, 'Nozzles spray too downslope, end =',f10.6,' ft')
      go to 999
950    print 95, xs(70)/xsr
      95 format(/10x, 'Nozzles spray too upslope, end =',f10.6,' ft')
999    stop
      end

```

Appendix F

A Computer Program, inth10.f, for Calculating
and Plotting the Ratios of the Sum of the
Square of the Simulated Rainfall Intensity
under the Condition of Nozzle Tilting Angles
from -10 to 10 Degrees, A Given Nozzle
Height and A Given Slope Steepness, to
that under the Basic Condition


```

c
c   Program RAINFALL/erohor/inth10.f is for calculating and
c   plotting the ratios of the sum of the square of the
c   simulated rainfall intensity on a horizontal base under the
c   conditions of different nozzle heights(h0), different slope
c   steepnesses(stp), and different nozzle tilting angles(tilt=
c   -10 to 10 degree),to that under the basic condition with
c   h0=8 ft,stp=0 % and tilt=0 degree. The data used was presented
c   by Meyer (1958, Special Report #81). This program will generate
c   two files, namely, x and y, which are written in binary code for
c   plotting graphs.
c       Where x denotes the nozzle tilting angle(degree), tilt, from
c               -10 to 10 degree, and
c       y denotes the ratio mentioned above.
c
c   real itn(200),itnm(400),itnma(400),itnmb(400),itnmt(400),
c   & itnms(400),itnmc(400),itnmd(400),msumba
c   dimension angd(100),vix(100),viy(100),t(100),xc(100),yc(100),
c   1xs(100),angr(100),volh(36),vol(100),xsm(400)
c   data volh/0.1092, 0.1086, 0.1077, 0.1067, 0.1054, 0.1040,
c   a      0.1021, 0.1003, 0.0982, 0.0962, 0.0942, 0.0922,
c   b      0.0899, 0.0870, 0.0840, 0.0806, 0.0766, 0.0722,
c   c      0.0679, 0.0636, 0.0580, 0.0524, 0.0474, 0.0410,
c   d      0.0367, 0.0322, 0.0314, 0.0316, 0.0344, 0.0404,
c   e      0.0429, 0.0424, 0.0372, 0.0237, 0.0112, 0.0000/
c   pi=3.1416
c   nn=-1
c   open(unit=1,file="x",status="new",form="unformatted")
c   open(unit=2,file="y",status="new",form="unformatted")
c
c   From this line to Statement No.420, this program is to
c   calculate the sum of the square of intensity for the
c   distance from 0 to 5 ft under the condition of
c   nozzle height, h0=8 ft
c   slope steepness, stp= 0 %
c   nozzle tilting angle, tilt=0 degree
c
c   h0=8.
c   stp=0.
c   tilt=0.
c   iflag=1
c
c   print out the condition for basic value
c
c   write(6,('The basic condition:/'nozzle height = ",
c   1 f7.2," feet/"slope steepness = ",f7.2," %"/
c   2 "nozzle tilting angle = ", f7.2," degree')) h0,
c   3 stp, tilt
c
c   arrange simulated rainfall volume on each small area
c
c   do 105 i=35,70
c       j=i-34
c   105 vol(i)=volh(j)
c       do 107 i=0,34
c           j=70-i
c   107 vol(i)=vol(j)
c   108 xsr=sqrt(1.+(0.01*stp)**2.)
c
c   generate trajectory angle data

```

```

c      do 110 i=0,70
        angd(i)=i-35.+tilt
        angr(i)=angd(i)*pi/180.
        vix(i)=22.3*sin(angr(i))
110    viy(i)=22.3*cos(angr(i))

c      define functions, ft, fd, and use Newton's Method
c
c      do 120 i=0,70
        t(i)=.5
        do 115 j=1,100
            ft=h0-23.*t(i)+0.7143*(23.-viy(i))*(1.-exp(-1.4*t(i)))-
50.01*stp*.7143*vix(i)*(1.-exp(-1.4*t(i)))
            if(abs(ft).le.0.000001) go to 120
            fd=-23.+(23.-viy(i))*exp(-1.4*t(i))-0.01*stp*vix(i)*exp(-1.4*t(i))
115    t(i)=t(i)-ft/fd
120    continue

c      to calculate the distance of each trajectory angle
c
c      do 130 i=0,70
        xc(i)=0.7143*vix(i)*(1.-exp(-1.4*t(i)))
        yc(i)=h0-23.*t(i)+0.7143*(23.-viy(i))*(1.-exp(-1.4*t(i)))
        xs(i)=sqrt(xc(i)**2.+yc(i)**2.)
        if(xc(i).ge.0.) go to 130
        xs(i)=-1.*xs(i)
130    continue
        if(xs(0).lt.-10.) go to 900
        if(xs(70).gt.10.) go to 950

c      calculation of rainfall intensity
c
c      itn(0)=0.
        itn(70)=0.
        do 150 i=1,69
            j=i-1
            k=i+1
150    itn(i)=2.*vol(i)/(xs(k)-xs(j))

c      arrange data of distance & overlapped intensity
c
c      ixsm0=int(10.*(xs(0)))
        xsm(0)=ixsm0/10.
        j=0
        do 300 i=0,200
            xsm(i)=xsm(0)+i*0.1
            if(xsm(i).gt.xs(70)) go to 310
285    if(xsm(i).lt.xs(j)) go to 300
            k=j+1
            if(xsm(i).ge.xs(k)) go to 290
            itnm(i)=itn(j)+((itn(k)-itn(j))*(xsm(i)-xs(j))/(xs(k)-xs(j)))
            go to 300
290    j=j+1
            go to 285
300    continue
310    ix=i-1
            id=abs(int(xsm(0)*10.))
            iu=int(xsm(ix)*10.)
            jx1=100-id-1

```

```

      do 315 i=0,jx1
315  itnms(i)=0.
      jx2=jx1+1
      jx3=100+iu
      do 320 i=jx2,jx3
      jx4=i-jx2
320  itnms(i)=itnm(jx4)
      jx5=jx3+1
      do 325 i=jx5,200
325  itnms(i)=0.
c
c      Intensity due to the lowest nozzle.(A)
c
      do 350 i=0,200
350  itnma(i)=itnms(i)
      do 355 i=201,350
355  itnma(i)=0.
c
c      intensity due to the second lowest nozzle.(B)
c
      do 360 i=0,49
360  itnmb(i)=0.
      do 365 i=0,200
      kx=50+i
365  itnmb(kx)=itnms(i)
      do 368 i=251,350
368  itnmb(i)=0.
c
c      Intensity due to the second highest nozzle.(C)
c
      do 370 i=0,99
370  itnmc(i)=0.
      do 375 i=0,200
      ky=100+i
375  itnmc(ky)=itnms(i)
      do 378 i=301,350
378  itnmc(i)=0.
c
c      Intensity due to the highest nozzle.(D)
c
      do 380 i=0,149
380  itnmd(i)=0.
      do 385 i=0,200
      kz=150+i
385  itnmd(kz)=itnms(i)
c
c      Overlap the intensity
c
      do 390 i=150,199
      kw=i-150
390  itnmt(kw)=itnma(i)+itnmb(i)+itnmc(i)+itnmd(i)
      do 395 i=0,49
      ka=50+i
      kb=100+i
      kc=150+i
      itnmt(ka)=itnmt(i)
      itnmt(kb)=itnmt(i)
395  itnmt(kc)=itnmt(i)
      itnmt(200)=itnmt(0)
c

```

```

c      calculating the sum of the square of the rainfall
c      intensity for the basic condition, sumbas
c
      if(iflag.gt.1) go to 450
      sumbas=0.
      do 420 i=0,49
420    sumbas=sumbas+(itnmt(i)*xsr)**2.
c
c      read data: slope steepness: stp (%)
c                  nozzle tilting angle: tilt (degree)
c
      write(6,('What is the nozzle height(feet)?'))
      read *, h0
      write(6,('What is the slope steepness(%)?'))
      read *, stp
      iflag=2
      go to 510
450    sumsqr=0.
      do 480 i=0,49
480    sumsqr=sumsqr+(itnmt(i)*xsr)**2.
c
c      adjust the value of sumbas to the modified value(msumba)
c      with the condition which has the same average intensity
c      and slope length as that on slope
c
      msumba=sumbas*xsr**2./xsr
      x=tilt
      y=sumsqr/msumba
      write(1) x
      write(2) y
510    nn=nn+1
      if(nn.gt.200) go to 999
      tilt=-10.+1*nn
      go to 108
900    print 90, xs(0)/xsr
      90 format(/10x,'Nozzles spray too downslope, end =',f10.6,' ft')
      go to 999
950    print 95, xs(70)/xsr
      95 format(/10x,'Nozzles spray too upslope, end =',f10.6,' ft')
999    stop
      end

```

Appendix G

A Computer Program, `sincur.f`, for Calculating
and Plotting the Distribution of Simulated
Rainfall Intensity for Single Troughs with
Any Given Values of Nozzle Height,
Slope Steepness, and Nozzle Tilting
Angle Using the Measured Data of Single
Troughs under the Basic Condition

```

c
c Program RAINFALL/newhor/sincur.f is for calculating and
c plotting the distribution of the simulated rainfall
c intensity(for single troughs) on a horizontal base using the
c data measured at National Soil Erosion Laboratory at Purdue
c University, West Lafayette, Indiana. This program will generate
c two files,namely x and y, which are written in binary code for
c plotting graphs.
c   Where x denotes the distance(ft) along the slope,
c         y denotes the distribution of simulated rainfall
c           intensity of the single trough on a
c           horizontal base.
c
c   integer tangle
c   real itn(200),minang(4),maxang(4),totang(4)
c   dimension angd(100),vix(100),viy(100),t(100),xc(100),yc(100),
c   1xs(100),angr(100),volh(4,100),vol(100),xsm(100)
c   trough # 1
c   data (volh(1,j),j=1,71)/ 0.074976, 0.223488, 0.562613, 0.868008,
a   1.096560, 1.191722, 1.155552, 1.091390, 1.042177,
a   1.022112, 1.073059, 1.123392, 1.201351, 1.264754,
a   1.327910, 1.376640, 1.466328, 1.555553, 1.630656,
a   1.719072, 1.820556, 1.881432, 1.955407, 2.016394,
a   2.077171, 2.124864, 2.159424, 2.221027, 2.308950,
a   2.397377, 2.485955, 2.548462, 2.585507, 2.609845,
a   2.647978, 2.660356, 2.673461, 2.687304, 2.701649,
a   2.716751, 2.706098, 2.696406, 2.660825, 2.625606,
a   2.617639, 2.583360, 2.549837, 2.503258, 2.483770,
a   2.450956, 2.378668, 2.346494, 2.233440, 2.106264,
a   2.005844, 1.891152, 1.734566, 1.563061, 1.473230,
a   1.368982, 1.305943, 1.256609, 1.178268, 1.156388,
a   1.134472, 1.126663, 1.060924, 1.052698, 0.926856,
a   0.651446, 0.268186/
c   trough # 2
c   data (volh(2,j),j=1,71)/ 0.044986, 0.119194, 0.281306, 0.426648,
a   0.570211, 0.813859, 1.097774, 1.421680, 1.713168,
a   1.873872, 1.891973, 1.769342, 1.676304, 1.598316,
a   1.604558, 1.651968, 1.713000, 1.773876, 1.848077,
a   1.908576, 1.995869, 2.042698, 2.102732, 2.163283,
a   2.236954, 2.270948, 2.344896, 2.406113, 2.480472,
a   2.529101, 2.578027, 2.601007, 2.638004, 2.649190,
a   2.647978, 2.660356, 2.673461, 2.765957, 2.885256,
a   3.027472, 3.205282, 3.209381, 3.187721, 3.140172,
a   3.027472, 2.954304, 2.855286, 2.742931, 2.657366,
a   2.544708, 2.432423, 2.346494, 2.206368, 2.038320,
a   1.951264, 1.822632, 1.693267, 1.604558, 1.556621,
a   1.536612, 1.530622, 1.553112, 1.604148, 1.627510,
a   1.536563, 1.285552, 0.799326, 0.409382, 0.279528,
a   0.148056, 0.074496/
c   trough # 3
c   data (volh(3,j),j=1,74)/0.104966, 0.372480, 0.725474, 1.000416,
a   1.184285, 1.366121, 1.401107, 1.436040, 1.470469,
a   1.476384, 1.482516, 1.502537, 1.522643, 1.556621,
a   1.590726, 1.624435, 1.644480, 1.705650, 1.752955,
a   1.827360, 1.874498, 1.894871, 1.955407, 1.989686,
a   2.037226, 2.058462, 2.106432, 2.247468, 2.572830,
a   2.937445, 3.117308, 3.126463, 3.110483, 3.016404,
a   2.936371, 2.817618, 2.752092, 2.739739, 2.727878,
a   2.723313, 2.719235, 2.604334, 2.529101, 2.440890,
a   2.366452, 2.318400, 2.191266, 2.103802, 2.016394,

```

```

a      1.942014, 1.908310, 1.874498, 1.840896, 1.766544,
a      1.705650, 1.671888, 1.624435, 1.576894, 1.501027,
a      1.452797, 1.418282, 1.397801, 1.377012, 1.327705,
a      1.278076, 1.256663, 1.206256, 1.140422, 1.029840,
a      0.888336, 0.715162, 0.569818, 0.347098, 0.106319/
c      trough # 4
      data (volh(4,j),j=1,71)/ 0.014995, 0.089395, 0.222084, 0.367800,
a      0.497107, 0.653994, 0.823331, 1.077030, 1.399087,
a      1.604148, 1.609589, 1.516579, 1.438828, 1.320348,
a      1.383240, 1.445472, 1.575960, 1.732940, 1.848077,
a      1.908576, 1.968898, 2.015820, 2.049160, 2.109869,
a      2.143747, 2.204546, 2.252160, 2.379672, 2.467278,
a      2.594963, 2.749019, 2.850599, 2.900492, 2.911486,
a      2.923262, 2.922460, 2.935565, 2.949480, 2.963945,
a      2.979239, 2.995099, 2.985776, 2.963790, 2.915874,
a      2.882047, 2.835072, 2.762323, 2.689670, 2.603952,
a      2.477742, 2.351790, 2.265581, 2.152224, 2.024731,
a      1.896683, 1.767816, 1.638202, 1.535396, 1.473230,
a      1.396920, 1.334028, 1.284847, 1.220856, 1.156388,
a      1.033949, 0.924442, 0.784793, 0.643315, 0.470784,
a      0.296112, 0.104294/
      data minang/ -36.00, -36.00, -36.00, -36.00/
      data maxang/ 35.00, 35.00, 38.00, 35.00/
      pi=3.1416
c
c      read data, nflag, ntro, h0, stp, tilt
c
      write(6,('Do you want to study single trough(input 1) or trough"
+ " groups(input 2)?'))
      read *,nflag
      if (nflag .gt. 1) goto 999
      write(6,('which trough do you want to study(input 1-4)?'))
      read *, ntro
      write(6,('what is the nozzle height(ft)?'))
      read *,h0
      write(6,('what is the slope steepness(%)?'))
      read *, stp
      write(6,('what is the tilting angle of the trough(degree)?'))
      read *, tilt
      print 10, ntro, h0, stp, tilt, minang(ntro), maxang(ntro)
10 format(////////10x,'Number of this trough = ',i3, '//10x,
a 'Height of nozzle = ',f7.2, ' ft'//10x,
1 'Steepness of slope = ',f7.2, ' %'//10x,
2 'Tilting angle of nozzle = ',f7.2, ' degree'//10x,
3 'Minimum angle of this trough = ',f7.2, ' degree'//10x,
4 'Maximum angle of this trough = ',f7.2, ' degree')
c
c      arrange simulated rainfall volume on each small area
c
      totang(ntro)=int(abs(minang(ntro))+abs(maxang(ntro)))
      tangle= int(totang(ntro))
      do 105 i=1,tangle
105 vol(i)=volh(ntro,i)
c
c      generate trajectory angle data
c
      do 110 i=0,tangle
      angd(i)=i+minang(ntro)+tilt
      angr(i)=angd(i)*pi/180.
      vix(i)=22.3*sin(angr(i))

```

```

110 viy(i)=22.3*cos(angr(i))
c
c   define functions, ft, fd, and use Newton's Method
c
do 120 i=0,tangle
  t(i)=.5
  do 115 j=1,100
    ft=h0-23.*t(i)+0.7143*(23.-viy(i))*(1.-exp(-1.4*t(i)))-
&0.01*stp*.7143*vix(i)*(1.-exp(-1.4*t(i)))
    if(abs(ft).le.0.000001) go to 120
    fd=-23.+(23.-viy(i))*exp(-1.4*t(i))-0.01*stp*vix(i)*exp(-1.4*t(i))
115   t(i)=t(i)-ft/fd
120  continue
c
c   to calculate the distance of each trajectory angle
c
do 130 i=0,tangle
  xc(i)=0.7143*vix(i)*(1.-exp(-1.4*t(i)))
  yc(i)=h0-23.*t(i)+0.7143*(23.-viy(i))*(1.-exp(-1.4*t(i)))
  xs(i)=sqrt(xc(i)**2.+yc(i)**2.)
  if(xc(i).ge.0.) go to 130
  xs(i)=-1.*xs(i)
130 continue
  if(xs(0).lt.-6.) go to 900
  if(xs(tangle).gt.6.) go to 950
c
c   calculation of rainfall intensity
c
fact=sqrt(1+(0.01*stp)**2)
xsm(0)=xs(0)
xsm(tangle+1)=xs(tangle)
itn(0)=0.
itn(tangle+1)=0.
do 150 i=1,tangle
  xsm(i)=(xs(i-1)+xs(i))/2
  itn(i)=(vol(i)/(xs(i)-xs(i-1)))/12
150 itn(i)=itn(i)*fact
c
c   arrange data for plotting
c
open(unit=2,file="x",status="new",form="unformatted")
open(unit=3,file="y",status="new",form="unformatted")
do 160 i=0,tangle+1
  valuex=xsm(i)
  valuey=itn(i)
  x=valuex
  y=valuey
  write(2) x
  write(3) y
160 continue
go to 999
print 90, xs(0)
90  format('//15x,'Nozzles spray too downslope, end =',f10.6,' ft')
go to 999
print 95, xs(tangle)
95  format('//15x,'Nozzles spray too upslope, end =',f10.6,' ft')
999 stop
end

```


Appendix H

A Computer Program, grocur.f, for Calculating
and Plotting the Distribution of Simulated
Rainfall Intensity for Group Troughs with
Any Given Values of Nozzle Height,
Slope Steepness, and Nozzle Tilting
Angle Using the Measured Data of Single Troughs
under the Basic Condition

```

c
c Program RAINFALL/newhor/grocur.f is for calculating and
c plotting the distribution of the simulated rainfall
c intensity(for group troughs) on a horizontal base using
c the data measured at National Soil Erosion Laboratory at
c Purdue University, West Lafayette,Indiana. This program
c will generate two files,namely, x and y, which are written
c in binary code for plotting graphs.
c Where x denotes the distance(ft) along the slope,
c and y denotes the distribution of simulated rainfall
c intensity of group troughs on a
c horizontal base,
c
c integer tangle
c real minang(7),maxang(7),totang(7)
c real itn(4,100),itnd(4,100),itnc(4,300),itnf(300)
c dimension angd(100),vix(100),viy(100),t(100),xc(100),yc(100),
c xs(100),angr(100),volh(4,100),vol(100)
c dimension ix(4)
c dimension xsm(4,100),xsd(4,100)
c
c trough # 1
c data (volh(1,j),j=1,71)/ 0.074976, 0.223488, 0.562613, 0.868008,
a 1.096560, 1.191722, 1.155552, 1.091390, 1.042177,
a 1.022112, 1.073059, 1.123392, 1.201351, 1.264754,
a 1.327910, 1.376640, 1.466328, 1.555553, 1.630656,
a 1.719072, 1.820556, 1.881432, 1.955407, 2.016394,
a 2.077171, 2.124864, 2.159424, 2.221027, 2.308950,
a 2.397377, 2.485955, 2.548462, 2.585507, 2.609845,
a 2.647978, 2.660356, 2.673451, 2.687304, 2.701649,
a 2.716751, 2.706098, 2.696406, 2.660825, 2.625606,
a 2.617639, 2.583360, 2.549837, 2.503258, 2.483770,
a 2.450956, 2.378668, 2.346494, 2.233440, 2.106264,
a 2.005844, 1.891152, 1.734566, 1.563061, 1.473230,
a 1.368982, 1.305943, 1.256609, 1.178268, 1.156388,
a 1.134472, 1.126663, 1.060924, 1.052698, 0.926856,
a 0.651446, 0.268186/
c
c trough # 2
c data (volh(2,j),j=1,71)/ 0.044986, 0.119194, 0.281306, 0.426648,
a 0.570211, 0.813859, 1.097774, 1.421680, 1.713168,
a 1.873872, 1.891973, 1.769342, 1.676304, 1.598316,
a 1.604558, 1.651968, 1.713000, 1.773876, 1.848077,
a 1.908576, 1.995869, 2.042698, 2.102732, 2.163283,
a 2.236954, 2.270948, 2.344896, 2.406113, 2.480472,
a 2.529101, 2.578027, 2.601007, 2.638004, 2.649190,
a 2.647978, 2.660356, 2.673461, 2.765957, 2.885256,
a 3.044861, 3.205282, 3.209381, 3.187721, 3.140172,
a 3.027472, 2.954304, 2.855286, 2.742931, 2.657366,
a 2.544708, 2.432423, 2.346494, 2.206368, 2.038320,
a 1.951264, 1.822632, 1.693267, 1.604558, 1.556621,
a 1.536612, 1.530622, 1.553112, 1.604148, 1.627510,
a 1.536563, 1.285552, 0.799326, 0.409382, 0.279528,
a 0.148056, 0.074496/
c
c trough # 3
c data (volh(3,j),j=1,74)/0.104966, 0.372480, 0.725474, 1.000416,
a 1.184285, 1.366121, 1.401107, 1.436040, 1.470469,
a 1.476384, 1.482516, 1.502537, 1.522643, 1.556621,
a 1.590726, 1.624435, 1.644480, 1.705650, 1.752955,
a 1.827360, 1.874498, 1.894871, 1.955407, 1.989686,
a 2.037226, 2.058462, 2.106432, 2.247468, 2.572830,
a 2.937445, 3.117308, 3.126463, 3.110483, 3.016404,

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a          2.936371, 2.817618, 2.752092, 2.739739, 2.727878,
a          2.723313, 2.719235, 2.604334, 2.529101, 2.440890,
a          2.366452, 2.318400, 2.191266, 2.103802, 2.016394,
a          1.942014, 1.908310, 1.874498, 1.840896, 1.766544,
a          1.705650, 1.671888, 1.624435, 1.576894, 1.501027,
a          1.452797, 1.418282, 1.397801, 1.377012, 1.327705,
a          1.278076, 1.256663, 1.206256, 1.140422, 1.029840,
a          0.888336, 0.715162, 0.569818, 0.347098, 0.106319/
c  trough # 4
    data (volh(4,j),j=1,71)/ 0.014995, 0.089395, 0.222084, 0.367800,
a      0.497107, 0.653994, 0.823331, 1.077030, 1.399087,
a      1.604148, 1.609589, 1.516579, 1.438828, 1.320348,
a      1.383240, 1.445472, 1.575960, 1.732940, 1.848077,
a      1.908576, 1.968898, 2.015820, 2.049160, 2.109869,
a      2.143747, 2.204546, 2.252160, 2.379672, 2.467278,
a      2.594963, 2.749019, 2.850599, 2.900492, 2.911486,
a      2.923262, 2.922460, 2.935565, 2.949480, 2.963945,
a      2.979239, 2.995099, 2.985776, 2.963790, 2.915874,
a      2.882047, 2.835072, 2.762323, 2.689670, 2.603952,
a      2.477742, 2.351790, 2.265581, 2.152224, 2.024731,
a      1.896683, 1.767816, 1.638202, 1.535396, 1.473230,
a      1.396920, 1.334028, 1.284847, 1.220856, 1.156388,
a      1.033949, 0.924442, 0.784793, 0.643315, 0.470784,
a      0.296112, 0.104294/
    data minang/ -36.00, -36.00, -36.00, -36.00, 3*0./
    data maxang/ 35.00, 35.00, 38.00, 35.00, 3*0./
    pi=3.1416
c
c  read data,  h0, stp, tilt
c
    write(6,('/"what is the nozzle height(ft)?"'))
    read *,h0
    write(6,('/"what is the slope steepness(%)?"'))
    read *, stp
    write(6,('/"what is the tilting angle of the trough(degree)?"'))
    read *,tilt
    print 10, h0, stp, tilt
10  format(////////10x,'Height of nozzle = ',f7.2,' ft'//10x,
1  'Steepness of slope = ',f7.2,' %'//10x,
2  'Tilting angle of nozzle = ',f7.2,' degree'//10x)
c
c  arrange simulated rainfall volume on each small area
c
    do 102 ntro=1,4
    totang(ntro)=int(abs(minang(ntro))+abs(maxang(ntro)))

    tangle= int(totang(ntro))
    do 105 i=1,tangle
105  vol(i)=volh(ntro,i)
c
c  generate trajectory angle data
c
    do 110 i=0,tangle
    angd(i)=i*minang(ntro)+tilt
    angr(i)=angd(i)*pi/180.
    vix(i)=22.3*sin(angr(i))
110  viy(i)=22.3*cos(angr(i))
c
c  define functions, ft, fd, and use Newton's Method
c

```

```

do 120 i=0,tangle
t(i)=.5
do 115 j=1,100
ft=h0-23.*t(i)+0.7143*(23.-viy(i))*(1.-exp(-1.4*t(i)))-
&0.01*stp*.7143*vix(i)*(1.-exp(-1.4*t(i)))
if(abs(ft).le.0.000001) go to 120
fd=-23.+(23.-viy(i))*exp(-1.4*t(i))-0.01*stp*vix(i)*exp(-1.4*t(i))
115 t(i)=t(i)-ft/fd
120 continue

c
c to calculate the distance of each trajectory angle
c
do 130 i=0,tangle
xc(i)=0.7143*vix(i)*(1.-exp(-1.4*t(i)))
yc(i)=h0-23.*t(i)+0.7143*(23.-viy(i))*(1.-exp(-1.4*t(i)))
xs(i)=sqrt(xc(i)**2.+yc(i)**2.)
if(xc(i).ge.0.) go to 130
xs(i)=-1.*xs(i)
130 continue
if(xs(0).lt.-6.) go to 900
if(xs(tangle).gt.6.) go to 950

c
c calculation of rainfall intensity
c
fact=sqrt(1+(0.01*stp)**2)
xsm(ntro,0)=xs(0)
xsm(ntro,tangle+1)=xs(tangle)
itn(ntro,0)=0.
itn(ntro,tangle+1)=0.
do 150 i=1,tangle
xsm(ntro,i)=(xs(i-1)+xs(i))/2
itn(ntro,i)=(vol(i)/(xs(i)-xs(i-1)))/12
150 itn(ntro,i)=itn(ntro,i)*fact
102 continue
open(unit=1,file="x",status="new",form="unformatted")
open(unit=2,file="y",status="new",form="unformatted")
open(unit=3,file="yy",status="new",form="unformatted")

c
c arrange data of distance & overlapped intensity
c
do 403 ntro=1,4
tangle= int(totang(ntro))
ixsm0=int(10.*(xsm(ntro,0)))-1
xsd(ntro,0)=ixsm0/10.
403 continue
do 405 ntro=1,4
tangle= int(totang(ntro))
j=0
do 300 i=0,100
xsd(ntro,i)=xsd(ntro,0)+i*0.1
if(xsd(ntro,i).gt.xsm(ntro,tangle)) go to 310
285 if(xsd(ntro,i).lt.xsm(ntro,j)) go to 300
k=j+1
if(xsd(ntro,i).ge.xsm(ntro,k)) go to 290
ppp=(itn(ntro,k)-itn(ntro,j))*(xsd(ntro,i)-xsm(ntro,j))
itnd(ntro,i)=itn(ntro,j)+ppp/(xsm(ntro,k)-xsm(ntro,j))
go to 300
j=j+1
290 go to 285
300 continue

```

```

310 ix(ntro)=i-1
405 continue
c   do 410 ntro=1,4
c       iix=ix(ntro)
c   do 410 k=0,iix
c       xsc(ntro,0)=xsd(ntro,0)+(4-ntro)*5.
do 415 i=-60,210
do 415 ntro=1,4
itnc(ntro,i)=0.0
415 continue
do 420 ntro=1,4
iix=ix(ntro)
do 420 i=0,iix
kk=i+(xsd(ntro,0)*10.)+(4-ntro)*50.
itnc(ntro,kk)=itnd(ntro,i)
420 continue
do 425 i=-60,210
itnf(i)=0.0
do 425 ntro=1,4
425 itnf(i)=itnf(i)+itnc(ntro,i)
totali=0.
do 427 i=0,150
427 totali=totali+itnf(i)
avei=totali/151
do 430 i=0,150
x=i*0.1
yy=itnf(i)
y=avei
write(1) x
write(2) y
write(3) yy
430 continue
go to 999
900 print 90, xs(0)/xsr
90 format('//10x,'Nozzles spray too downslope, end =',f10.6,' ft')
go to 999
950 print 95, xs(70)/xsr
95 format('//10x,'Nozzles spray too upslope, end =',f10.6,' ft')
999 stop
end

```


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