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LABORATORY TESTS OF EROSION DEPENDENCE ON PROPERTIES OF SOILS AND RAINFALL[1]

Hu Liu, Theodore G. Cleveland, and Keh Han Wang[2]

ABSTRACT: One hundred and sixty-two rainfall-induced soil erosion tests were conducted to assist in predicting soil loss and subsequent increase in total suspended solids leaving a highway construction site during a rainfall event. A rainfall simulator and a water flume were constructed for the tests. Soil shear strength, compressive strength, rainfall intensity, and soil bed slope were treated as variables during the experiments. The soil with a higher shear strength resisted soil erosion better than lower strength soils. Soil loss was nearly independent of shear strength at low rainfall intensity but at high intensities, the shear strength was more important in resisting soil loss. Lower soil loss can be expected for cohesive soils if the compressive strength is high.
(KEY TERMS: soil erosion; shear strength; compressive strength; rainfall intensity; rainfall simulator; slope.)

INTRODUCTION

The sediment yield of a highway construction site can be 10 times that of cultivated land, 200 times that of grassland, and 2000 times that of a forest land under similar conditions, which suggests that highway construction activities can significantly increase the soil erosion potential and the total suspended loads to the receiving water bodies during rainstorms (USGS, 1969).

Suspended solids serve as a transport mechanism for pollutants that can pose a threat to human health and the environment. The Nationwide Urban Runoff Program considered the total suspended solids as an indicator of other pollutants including heavy metals, oxygen depleting pollutants, and nutrients commonly found in stormwater discharges (U.S. EPA, 1983). High lead and cadmium concentrations are associated with the fine grained soils of 20 to 50 microns and polycyclic aromatic hydrocarbons are adsorbed by the soil particles within 6 to 60 micron range (Xanthopoulos and Augustin, 1992). More than half of the particles collected in typical stormwater samples were found to have sizes ranging from 6 to 60 microns. In a study of 89 stormwater samples from the Dallas-Fort Worth Metroplex, more than 85 percent of the particles were smaller than 30 microns (Pechacek, 1993). This study and unpublished reports from other studies in Texas indicate that the potential for pollutant transport by suspended solids in stormwater is significant.

Suspended solids in stormwater come from soil eroded by rainfall and overland flow. Apart from increasing the total suspended solids load to stormwater, highway construction also generates runoff pollution when chemicals, fertilizers, oils, and litter are washed off and carried to streams, rivers, lakes, and bays during rainstorms. Storm water runoff from industrial activities is regulated via the National Pollutant Discharge Elimination System. Highway and other construction contractors must have their Storm Water Pollution Prevention Plan (SW3P) approved before the construction phase starts. Temporary Sediment Control (TSC) is a very common component of a SW3P and the soil erosion estimation is the basis for design and installation of TSCs.

The goal of this study is to develop a relationship between the soil erosion volume and field measurable data including rainfall intensity, slope, antecedent soil shear strength, and soil compressive strength. Ultimately such data may provide an alternative to the Universal Soil Loss Equation to predict soil loss from a highway construction site during a rainfall event. In this article, results of 162 experiments are presented. Experimental conditions and numbers are

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[2]Respectively, Graduate Research Assistant and Associate Professors, Department of Civil and Environmental Engineering, Univ. of Houston, Houston, Texas 77204-4801 (E-Mail/Cleveland: cleveland@uh.edu).

shown in the Table 1. We observed from the experiments that higher rainfall intensity produced more erosion; soils with a higher shear strength, on the average, exhibited lower soil erosion; soil loss appears to be independent of shear strength at low rainfall intensity; and soil compressive strength plays a role in soil loss.

LITERATURE REVIEW

The erosion processes can be divided into two types: (a) interrill erosion, and (b) rill erosion. In the interrill area, raindrops may impact on either bare soil surface or on soil surface cushioned by sheet flow. Raindrop impact is the dominant detachment agent under this condition. The detached soil particles are usually dispersed into or onto surface water and are kept in suspension by surface overland flow which transports soil particles down the slope or to rills.

Rill flow is flow in shallow channels (rills). It has deeper water depth than interrill areas and is effective in transporting soil particles. The dominant detachment mechanism in rill flow is the traction force of the water on the rill bed (Tan, 1989).

Prediction of erosion is still largely based on empirical methods requiring considerable hydrologist judgment. Wischmeier and Smith (1958) suggested an energy based prediction. They found that the product of kinetic energy and the maximum 30 minute intensity was the best single rainfall parameter for prediction of soil loss. Later they developed the widely used method of predicting soil erosion, the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978).

The USLE provided the first tool for systematic soil erosion prediction and is widely used. Williams (1975) modified the USLE by replacing the rainfall energy factor R with a runoff factor, and proposed the modified universal soil loss equation (MUSLE). Renard *et al.* (1991) introduced the revised universal soil loss equation (RUSLE), that adjusted all the factors in USLE based on extensive review of the database of USLE, analysis of data not previously included in the USLE, and theory describing fundamental hydrologic and erosion processes. The RUSLE is currently the tool used by United States Department of Agriculture (USDA) in predicting agricultural soil erosion by water (USDA, 1996).

Haji *et al.* (1988) argued that the Universal Soil Loss Equation and its derivatives involved so many variables that it was very difficult to adopt for estimating the magnitude of erosion. Additionally, the dependence on factors that are based on hydrologist judgment and experience, rather than direct measurements makes the USLE based tools difficult to rely upon for certain kinds of practical problems. In response, researchers have tried to correlate directly measurable characteristics of rainfall, runoff, soil and soil erosion.

Tan (1989) suggested a parameter, the eroding pressure that is a function of terminal raindrop velocity, water density, surface water depth and rain drop diameter. Kamalu (1992) reported that the runoff rate becomes dominant on long runs or steep slopes (9 percent or above). The interactive combination of rainfall and runoff was dominant over other erosion predictors on intermediate slopes (5-7 percent). Huang and Bradford (1993) conducted an empirical analysis of slope and runoff factors and concluded that the effects of slope on sediment loss rate depended on runoff intensity and vice versa, suggesting that the derivation of independent slope and runoff factors to predict soil erosion is impossible. Le Bissonnais *et al.* (1993) found that initial moisture greatly influences detachment and transport of soil particles and therefore interrill erosion.

A measure of the mechanical resistance of a topsoil to raindrop and runoff detachment is the shear strength, which can be measured with a cone penetrometer or a vane shear device. A soil's shear strength is influenced by the bulk density, moisture content and external factors such as land use and topography. Fan (1987) reported that for compacted and saturated soils, the soil erodibility factor decreases with increasing critical shear stress. Le Bissonnais *et al.* (1993) found that the shear strength is greatly influenced by both moisture and structure of the soil.

TABLE 1. Experimental Conditions.

Condition	Slopes (percent)	Rainfall Intensities (mm/h)	Soils	Total Cases
Non-Compacted Soil	0.1, 0.5, and 1	12.7, 25.4, 50.8, and 101.6	1, 2, 3, 4, 5, and 6	72
Compacted Soil	0.1, 0.5, and 1	12.7, 25.4, 50.8, 76.2, and 101.7	1, 2, 3, 4, 5, and 6	90
Total				**162**

Field experiments conducted by Wang *et al.* (1994) revealed that shear strength has an inverse relationship with erodibility of loess soils in terms of interrill and rill erosion processes.

MODEL CONSTRUCTION AND EXPERIMENTAL PROCEDURE

Rainfall intensity, soil bed slope, antecedent soil shear strength, and compressive strength were selected as the physical variables for the experimental study of the soil erosion. These variables can be measured easily and quickly on a highway construction site. Only bare soil is considered because this work is focusing on soil erosion at construction sites.

In this study, rainfall was generated by a nozzle-type rainfall simulator. Unlike hanging yarn and tubing tip formers, nozzles are more likely to duplicate the drop size distribution of natural rainfall (Mutchler and Hermsmeier, 1965). The simulator consists of a wooden frame and a group of 1.27 cm diameter PVC pipes with small holes of 0.08 cm drilled every 2.54 cm. The rainfall simulator was suspended from the ceiling of the laboratory, covered an area of 0.81 square meters, (94.7 cm x 86.4 cm), and could produce rainfall with intensities as high as 250 mm/h. To help ensure a uniformly distributed drop pattern, a 50 Hz vibrator was operated to vibrate the simulator during the tests. The water supply was controlled by a valve and monitored by a flow meter. A flume was used to hold the soil and direct the runoff. The flume is 4.8 m long and 1.2 m wide. Soils were placed into a smaller square box in the top end of flume, which is 0.66 m^2 in area. The soil bed was fully covered by the rainfall from the simulator above. The flume was mounted on three adjustable supports, allowing the slope to be adjusted within the range of 0-1.3 percent.

Figure 1 is a diagram of the rainfall simulator and accompanying flume. The soil sample was placed at one end of the flume, the slope adjusted, and the simulator activated during the experiments. The top edge of the flume is the datum used for soil loss measurements.

The uniformity of the drop pattern was tested and adjusted. Thirty-six, 600-milliliter beakers were placed in the flume under the simulator to collect raindrops while different rainfall intensities were applied. The volume of water in those beakers was measured, and the simulator was repeatedly adjusted until water volumes in each beaker were identical. The flowmeter was calibrated directly to rainfall intensity.

One hundred drops were collected in a graduated jar to estimate the mean raindrop diameter. Assuming spherical drops, the mean value of calculated raindrop diameter was 6.7 mm, with a standard deviation of 0.5 mm. The mean raindrop diameter was practically invariant over all intensities tested. The size of natural raindrops ranges from close to zero to about 7 mm in diameter, and the median diameter of raindrops tends to increase with rainfall intensity (Meyer, 1988). Thus, the distribution of raindrops in the present work is oversized compared to natural rain, but within the range of naturally observed raindrop sizes.

The average height from the rainfall simulator to the soil bed was 1.80 m. The average velocity of a raindrop falling to the soil surface is 5.94 m/s, and the kinetic energy of rainfall at intensities of 12 and 120 mm/h are 0.059 and 0.59 J/m^2-s, respectively. For natural rainfall at the same intensities, the mean diameters of raindrops are 2.12 and 3.58 mm, respectively (Finkel, 1986). The corresponding terminal velocities are 6.68 and 8.51 m/s, respectively, and the kinetic energies are 0.073 and 1.21 J/m^2-s. Thus, the simulator under-represents the impact forces by 20 percent to 50 percent depending on the rainfall intensity. Therefore, the soil eroded from this simulation is less than that during the natural rainfall expected under field conditions.

Table 2 shows the texture and the classifications of six different soils used in the laboratory experiments. Soil 1 is a 20-40 sieve washed pure sand; Soil 2 is a bentonite clay; Soil 3 is a 30 percent bentonite and 70 percent sand mixture (dry volume ratio); Soil 4 is a soil collected from a highway construction site at NASA Road 1 in Houston, Texas; Soil 5 is from the National Geotechnical Test Site at the University of Houston, Houston, Texas; and Soil 6 is from a highway construction site at the intersection of Highway 59 South and Beltway 8, Houston, Texas. Three artificial soils were selected to study the impact of different soil properties because washed sand was considered a non-cohesive soil and bentonite was considered a cohesive soil. The real soils were selected from three geographically separate locations as representative of local conditions.

Rainfall intensities between 12 and 120 mm/h are usually of the greatest importance in natural rainfalls (Meyer, 1988). Therefore, five different rainfall intensities, 13, 25, 51, 76, and 102 mm/h, were selected to represent the ranges of rainfall for the current study. The rainfall duration is 30 minutes, based on the work of Wischmeier and Smith (1958), who showed that the product of kinetic energy and 30-minute intensity was the best single rainfall parameter for predicting soil loss. Typically highway slope grades

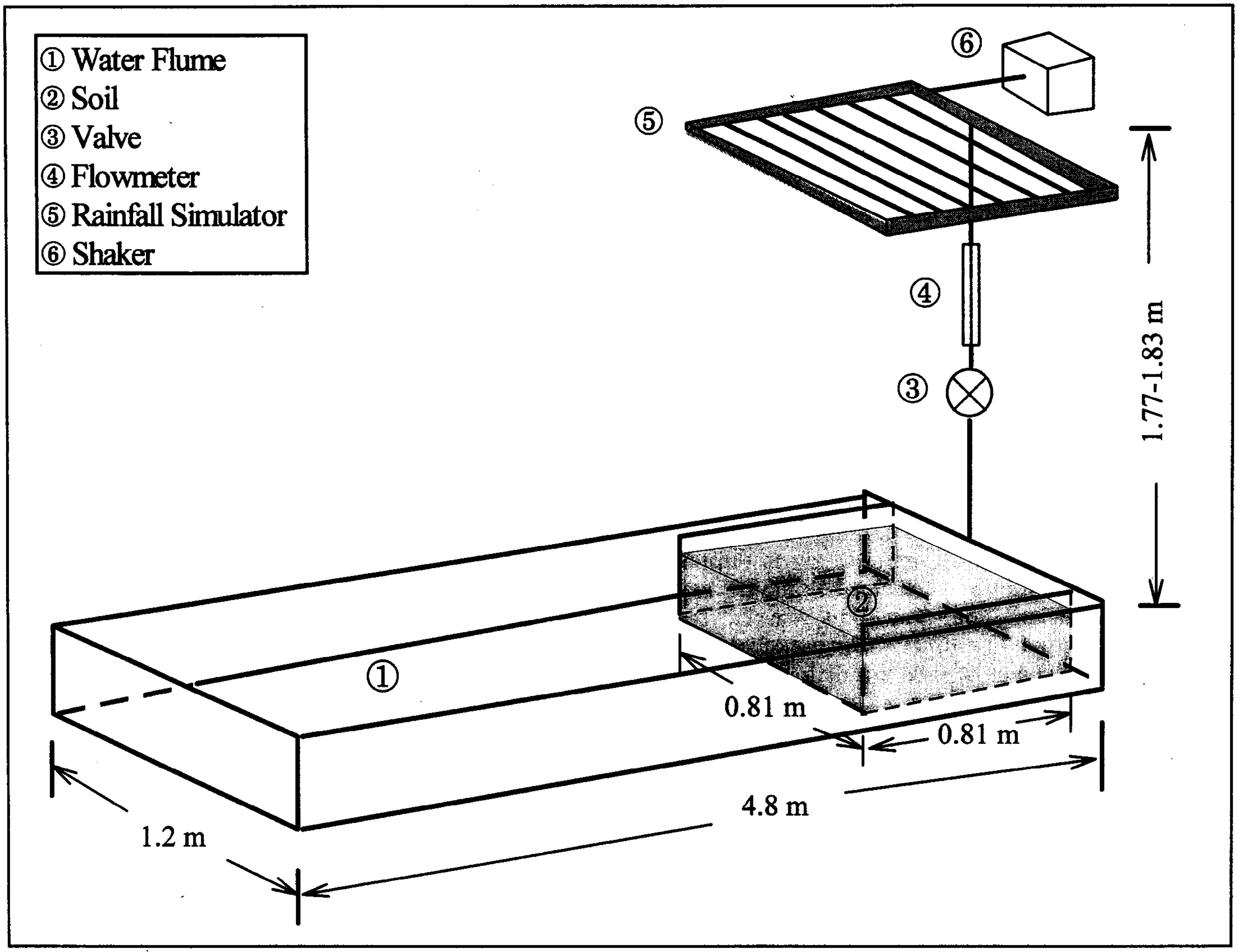

Figure 1. Rainfall Simulator Schematic.

TABLE 2. Soil Textural Properties.

Soil	Gravel > 2 mm (percent)	Sand 2 mm < s < 50 um (percent)	Silt 50 um < s < 2 um (percent)	Clay < 2 um (percent)	Classification USDA[1]	Classification USGS[2]
Soil 1	0.00	100.00	0.00	0.00	Sand	Sand
Soil 2	0.00	22.22	73.37	4.40	Silty Loam	Sandy-Silt
Soil 3	0.00	83.21	15.84	0.95	Loamy Sand	Sand
Soil 4	7.44	19.43	53.70	19.43	Silty Loam With Gravel	Sandy-Silt
Soil 5	1.16	57.64	28.38	12.82	Sandy Loam	Silty-Sand
Soil 6	17.63	48.41	26.47	7.49	Gravelly Sandy Loam	Silty-Sand

[1]Soil Survey Manual, U.S. Dept. Agriculture Handbook, No. 18, 503 pp. (USDA, 1951).
[2]U.S. Geological Survey, Water-Supply Paper 1662-D (USGS, 1967).

range from 0.2 to 2 percent. These values are based on a highway grade survey conducted by the author for the southern U.S. Steeper grades exist, but represent less than 1 percent of highway miles. Therefore, the flume was operated at three slopes: 0.1 percent, 0.5 percent, and 1.0 percent, which are typical slopes found at highway construction sites. The surface of the soil was kept parallel to the bottom of the flume for each test.

Soil erosion simulations were conducted in two different phases. Loosely packed soil was used in the first phase. In the second phase, soils were compacted while other conditions were intentionally kept the same to study the impact of increased shear strength and compressive strength. Table 1 displays the different controlled experimental conditions.

Before each rainfall simulation, the antecedent shear strength was measured at several locations on the soil surface using a vane type shear stress meter. The arithmetic mean of these measurements was recorded as the shear strength of the soil sample. Following a similar procedure, the antecedent compressive strength was measured by a pocket penetrometer on the soil surface.

The initial soil level relative to a datum was measured at 64 points covering the soil surface. A selected intensity of rainfall was applied for 30 minutes. Flowmeter readings were taken every three minutes during the test to ensure that the rainfall intensity was applied correctly. If the flowmeter reading was too high or too low, the valve was adjusted to maintain the desired flowmeter reading. After the applied rainfall event, the soil level at each referenced point was remeasured. Erosion volume was then determined from the difference of soil level before and after the rainfall event (a traditional cut-and-fill calculation). This cut-and-fill approach to determine soil erosion was used because the flume is long relative to the soil block and not all of the soil reached the end of the flume during an experiment. In addition to this reason, soil collection in field trials is not practical as a matter of routine, while the measurements to make cut-and-fill type calculations can be made quickly using global positioning system (GPS) elevations, especially for a large construction site with multiple drainages. The dry density of the soil was used to convert the volume change to mass loss for comparison with other methods of erosion prediction.

RESULTS AND DISCUSSION

The unit soil volume loss in this work is defined as the soil loss volume per unit area. The results indicate that higher rainfall intensity produces more erosion. This well established relationship occurs because the higher rainfall intensities generate higher traction forces from overland flow and increase drop impact forces on the soil surface.

Figure 2 shows the relationship between unit soil volume loss and shear strength at different rainfall intensities. Five sets of data are shown in this plot. Each data set represents a series of experimental measurements for all soil samples at different rainfall intensities. The linear regression equations corresponding to the line segments shown on Figure 2 describing the soil volume loss versus the shear strength are presented in Table 3. A trend is suggested that soils with high shear strength, on the average, exhibited lower erosion volumes than low strength soils. It is known that the soil shear strength is related to the interparticle attractive forces in the soil. The higher the shear strength, the greater the traction stress required to dislodge the particles, thus higher rainfall intensities are required to produce more soil volume loss for a given soil strength. The plot suggests that for low rainfall intensity, soil volume loss is somewhat independent of the shear strength, while at high intensities the shear strength plays a more important role in resisting soil volume loss.

Figure 3 displays the relationship between unit soil volume loss and compressive strength at different rainfall intensities. Again, the plot indicates five sets of data collected in the model test. An inverse linear correlation between soil volume loss and compressive strength was also observed. The linear regression equations for each data set are described in Table 4. In Figures 2 and 3, the most scattered points are contributed by Soil 1, the pure sand. It is believed that this result occurs because when sand is compacted, a high compressive strength results, but being noncohesive, high loss occurs under high rainfall intensities. Soil 3 is also very sandy, however, the 30 percent volume of bentonite increased this soil's cohesiveness; therefore, the behavior is different from that of Soil 1.

In this study the unit soil volume loss was not affected by the soil bed slope, which is different from other researcher's results; however, the magnitude of slopes in this work are not large enough to show any impact of the slope differentiation.

Figures 2 and 3 show that the soil volume loss depends on the shear strength, compressive strength and rainfall intensity but less affected by the bed slope. Like prior research, no single variable appeared to be a useful predictor.

A multiple-variable regression analysis was performed to develop predictive models. A linear additive model and a product model were proposed. The linear model can be expressed as:

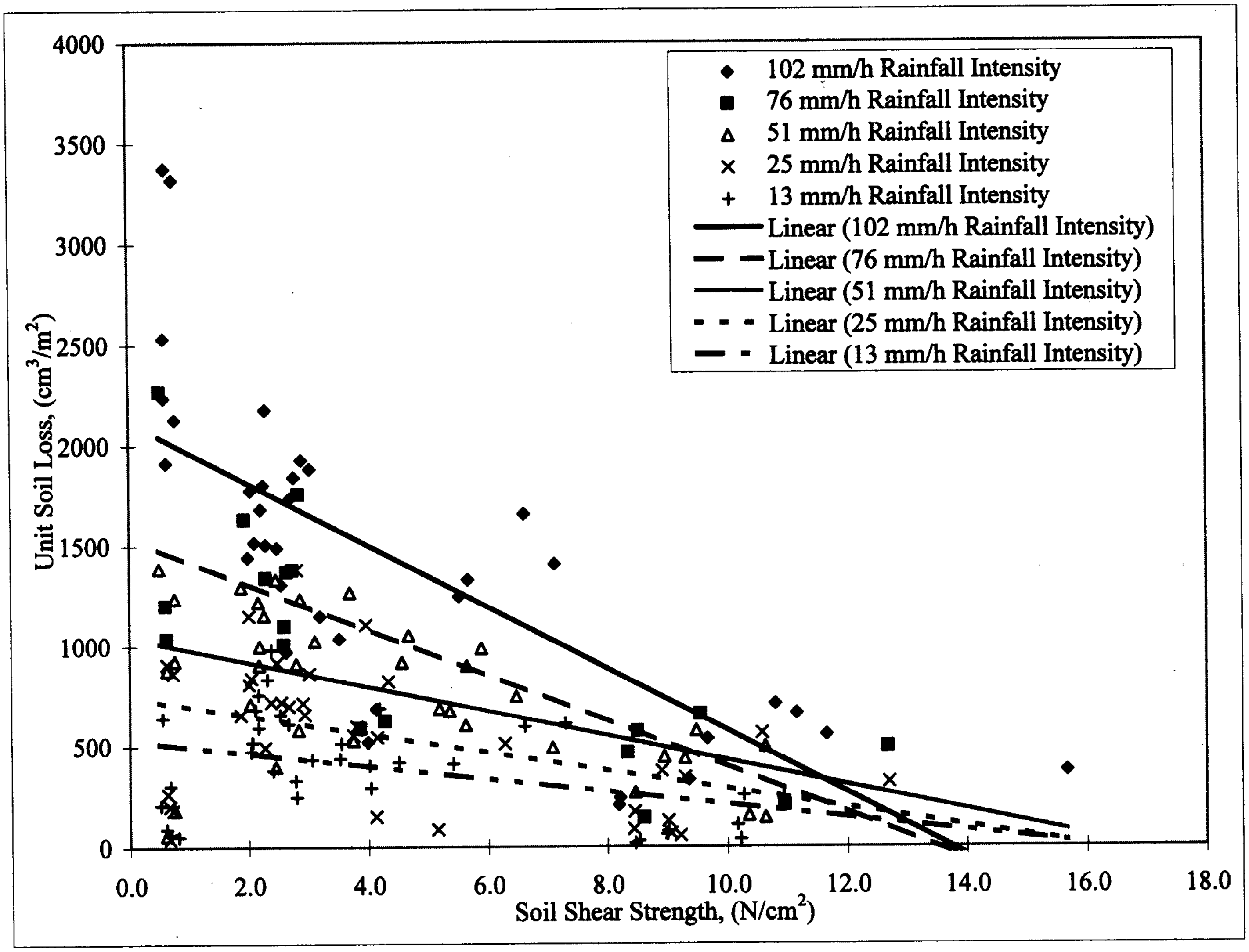

Figure 2. Unit Soil Loss and Shear Strength.

$$U = \beta_0 + b_1 S_0 + b_2 \tau + b_3 \sigma + b_4 I \qquad (1)$$

where U is a 30-minute soil mass loss with units of g/m^2 (the unit soil volume loss was converted to mass loss by using the dry density of soils, so that the estimated unit soil losses could be compared with losses predicted other methods); S_0 is percent slope of the soil bed; τ is shear strength; and σ is compressive strength (they both have units of N/cm^2); I is the rainfall intensity in mm/h; and β_0, b_1, b_2, b_3, and b_4 are regression parameters. The product model is:

$$U = \beta_0 (S_0)^{b_1} (\tau)^{b_2} (\sigma)^{b_3} (I)^{b_4} \ , \qquad (2)$$

where b_1, b_2, b_3, b_4, and β_0 are regression parameters.

TABLE 3. Regression Equations for Figure 2.

Data for 102 mm/h rainfall	$y = -154.22x + 2119$	$R^2 = 0.56$
Data for 76 mm/h rainfall	$y = -114.1x + 1538.1$	$R^2 = 0.60$
Data for 51 mm/h rainfall	$y = -61.528x + 1044$	$R^2 = 0.27$
Data for 25 mm/h rainfall	$y = -45.602x + 742.36$	$R^2 = 0.19$
Data for 13 mm/h rainfall	$y = -31.961x + 527.87$	$R^2 = 0.16$

The product model is similar to USLE and its derivatives, in that it predicts loss as the product of various factors. Unlike USLE methods, the factors are field measurable, geotechnical and other variables. The product model was selected for further study because it is consistent in formulation with earlier models, and at zero rainfall it predicts zero erosion

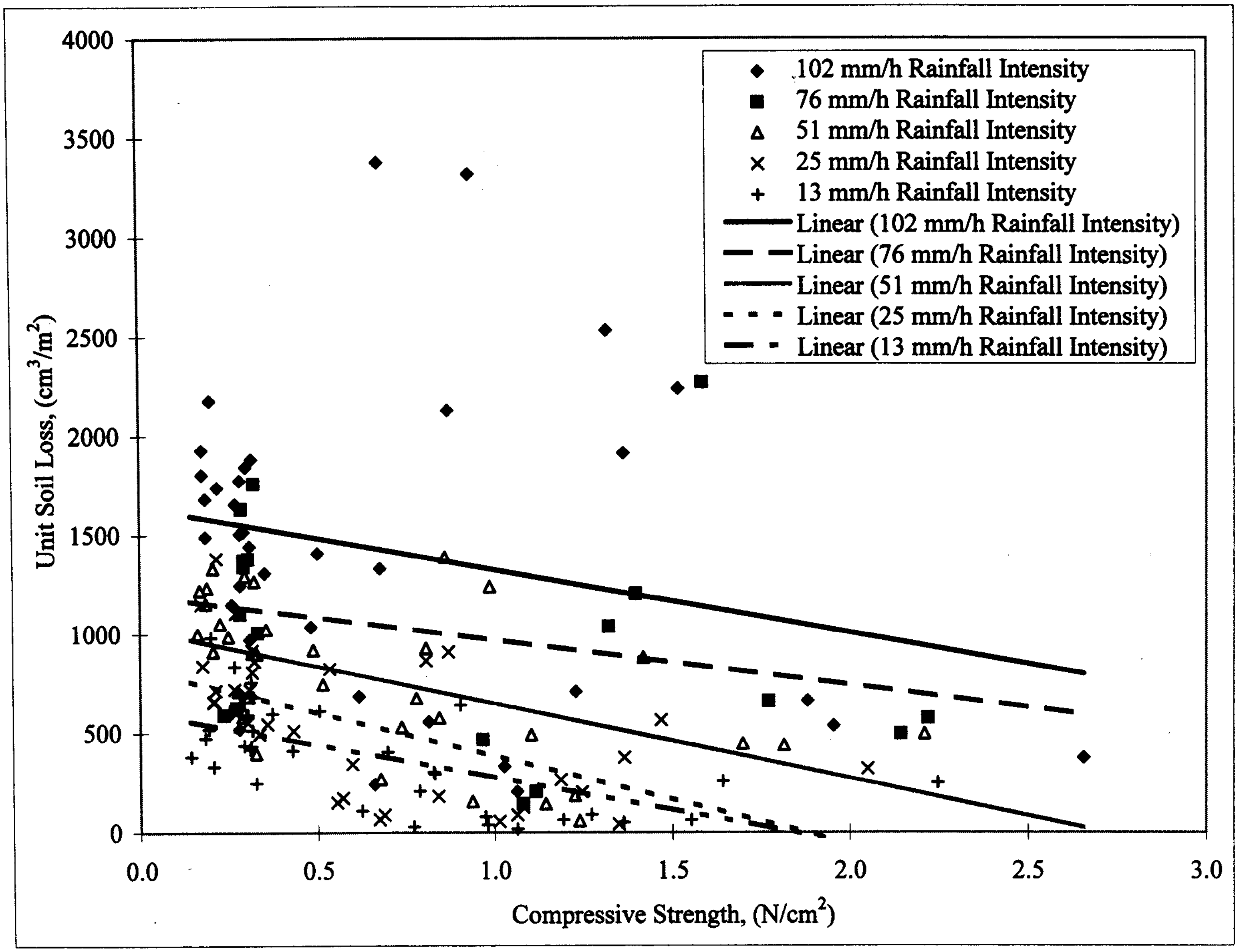

Figure 3. Unit Soil Loss and Compressive Strength.

while the linear model violated this physically intuitive limit.

TABLE 4. Regression Equations for Figure 3.

Data for 102 mm/h rainfall	y = -317.9x + 1641.7	$R^2 = 0.06$
Data for 76 mm/h rainfall	y = -227.94x + 1197.1	$R^2 = 0.08$
Data for 51 mm/h rainfall	y = -377.88x + 1026	$R^2 = 0.28$
Data for 25 mm/h rainfall	y = -437.61x + 822.06	$R^2 = 0.33$
Data for 13 mm/h rainfall	y = -327.66x + 604.38	$R^2 = 0.41$

The RUSLE is the soil erosion prediction tool used by the USDA. It is also used to estimate the soil erosion caused by single rainfall events, despite warnings against this type of application. The Texas Department of Transportation uses a USLE-based soil erosion estimation tool (TXDOT, 1993) that shares the same origins as RUSLE and thus the same limitations.

The RUSLE model is:

$$A = R \cdot K \cdot LS \cdot C \cdot P, \tag{3}$$

where A is the estimation of average annual soil loss in tons per acre caused by sheet and rill erosion, R is the rainfall erosivity factor, K is the soil erodibility factor, LS is the slope length and steepness factor, C is the cover and management factor, and P is the support practice factor. The RUSLE was applied in this research to compare its ability to estimate soil loss during single rainfall events with the product model. In using the RUSLE, the R factor, K factor, and the LS factor were determined using equations and tables in Renard *et al.* (1997). The C and P factors were set equal to 1.

Figure 4 is a plot of the unit soil mass loss predicted by the product model. The regression parameters are summarized in Table 5. The predicted loss calculated by the RUSLE is also plotted in this figure. Both the RUSLE and the product model use the measured data as the x-coordinate, and the predicted loss as the y-coordinate. A perfect prediction would plot all the calculated values along the 45° line shown on the plot, which means that the predicted values are equal to the measured values. In the present work, the data are scattered, with the most scattering observed for Soil 1, the pure sand. Plots for the linear model exhibited similar characteristics and are not presented for the sake of brevity.

To remove the effect of Soil 1, the noncohesive soil, multiple variable regressions were conducted excluding Soil 1 experimental results. Figure 5 is a plot showing the results of this analysis. On this plot the distribution of data points are closer to the ideal line than the case where Soil 1 is included. Comparing the regression parameters for the product model both the β_0 constant and the exponent on the compressive strength change by more than 200 percent while the other parameters change by less than 50 percent. These two changes suggest that the compressive behavior of Soil1 is different than in the cohesive soils.

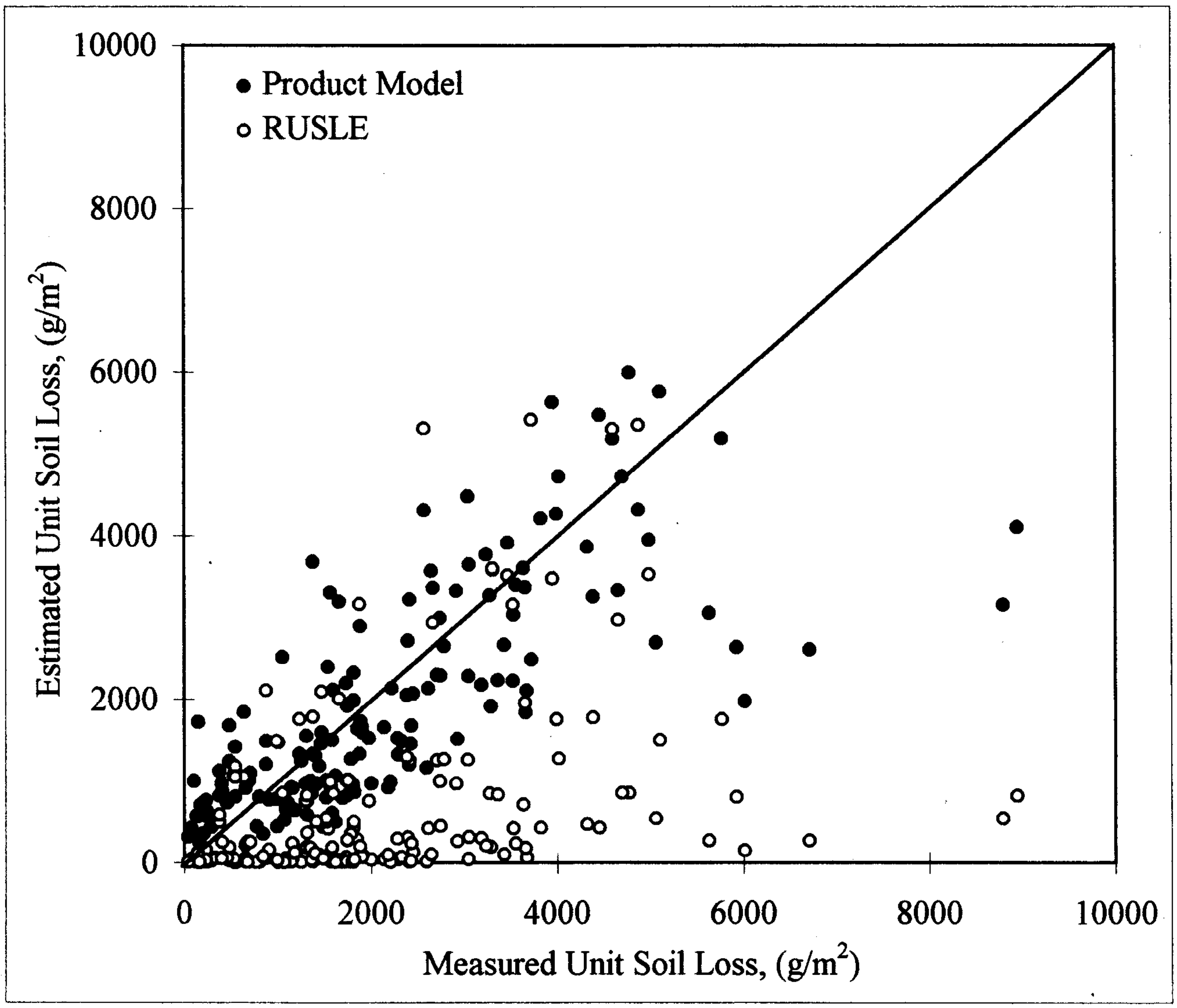

Figure 4. Product Model vs. RUSLE Prediction of Unit Soil Loss (all soils tested).

In all cases the RUSLE underestimated the unit soil loss. Therefore, based on these results, if one were to use the RUSLE to predict event-based losses, then integrate the losses over time to design temporary sediment controls, one would tend to undersize the controls.

CONCLUSIONS

In these experiments we observed that higher rainfall intensity produced more erosion. The soils with a higher shear strength, on the average, exhibited

TABLE 5. Regression Parameters for Product Models.

Models	b_0	b_1	b_2	b_3	b_4	R^2
Product Model for All Soils (Figure 4)	124.4	0.04	-0.28	-0.57	0.72	0.5554
Product Model for Soils Except Pure Sand (Figure 5)	581.2	0.08	-0.67	-0.25	0.59	0.6206

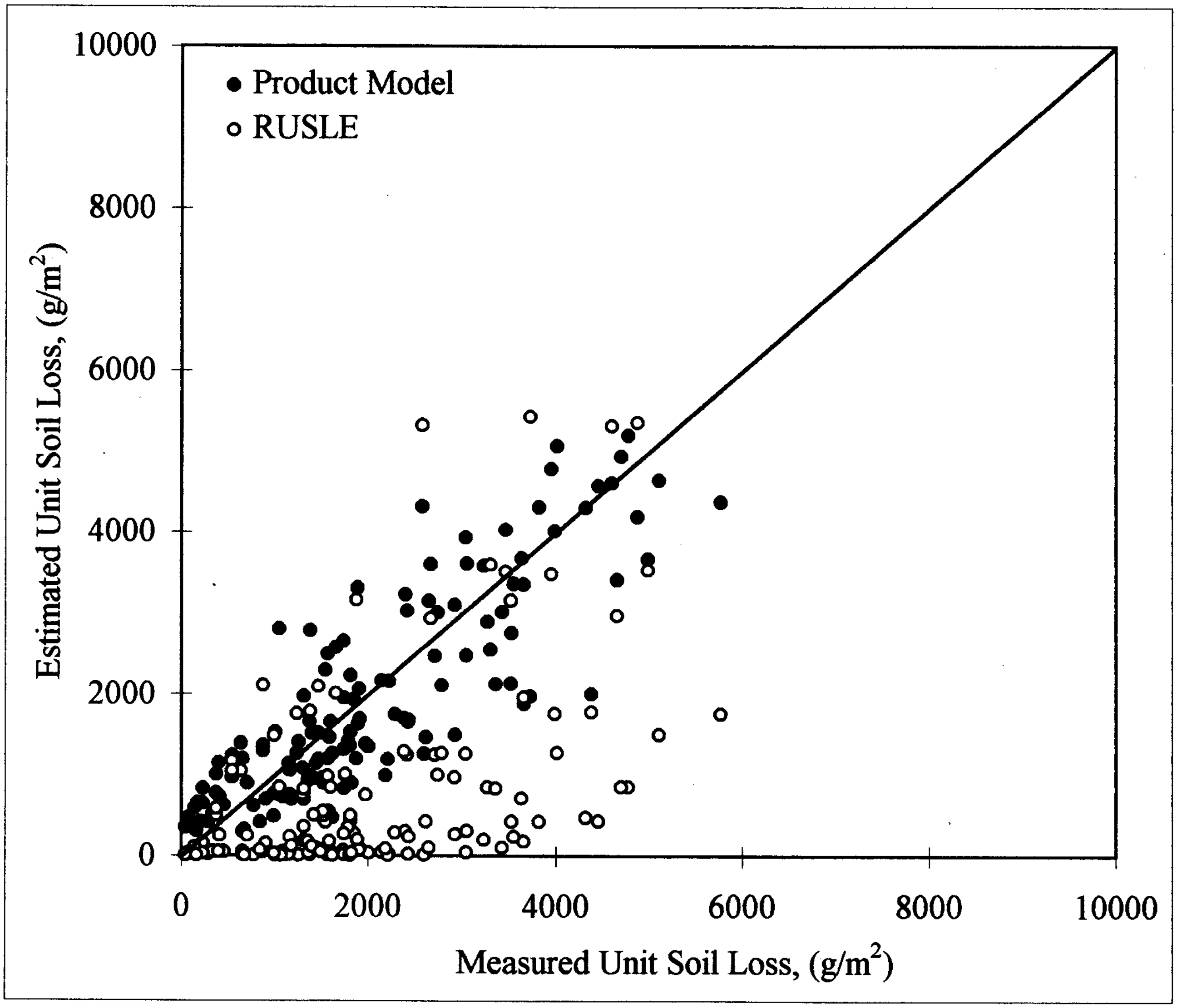

Figure 5. Product Model vs. RUSLE Prediction of Unit Soil Loss (Soil 1 excluded).

lower soil erosion, but soil loss appears to be nearly independent of shear strength at low rainfall intensity. Soils with higher compressive strength exhibited lower soil loss if they were cohesive soils. None of these variables alone is suitable for predicting the soil erosion.

Multiple variable regression suggested that both linear and product models can predict soil erosion better than single parameters. The product model was presented because it is consistent in formulation with earlier models, and at zero rainfall it predicts zero erosion while the linear model violates this intuitive result. The magnitude of the product model exponents can be interpreted in a factor analysis fashion suggesting that the importance of predictive variables decreases in the following order for cohesive soils (ignoring the β_0 parameter): rainfall intensity, compressive strength, shear strength, and slope. The ranking when Soil 1 is included is: rainfall intensity, shear strength, compressive strength, and slope. As indicated in the literature, the RUSLE is not suitable for estimating soil erosion caused by single rainfall event, and thus is a poor tool for estimating soil loss over short construction periods (less than 1 year).

The model presented in this work should be applicable to bare soils whose texture fall into the same texture spectrum of soils tested in this study. More texturally varied soils need to be examined and field scale testing is indicated to expand the applicability of the model. In highway construction planning, the model could be applied directly to a homogeneous slope to estimate the possible soil erosion. The advantage of this model is that the use of directly measurable properties of the soils reduces the need to rely upon non-measurable properties such as erosion control factors, cover and management factors, and support practice factors in predicting soil erosion.

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