This paper was peer-reviewed for scientific content.
Pages 588-593. In: D.E. Stott, R.H. Mohtar and G.C. Steinhardt (eds). 2001. Sustaining the Global Farm. Selected papers from the 10th International Soil Conservation Organization Meeting held May 24-29, 1999 at Purdue University and the USDA-ARS National Soil Erosion Research Laboratory.

Effects of Soil Strength, Texture, Slope Steepness and Rainfall Intensity on Interrill Erosion of Some Soils in Taiwan

Jen-Chen Fan and Min-Fon Wu*

ABSTRACT

The relationships between slope steepness, soil properties, rainfall intensity and interrill soil erosion rate were analyzed in this study. The soils for these erosion tests were collected from six sites distributed across the island of Taiwan. The samples were remolded and prepared in boxes with a width of 0.75m and a length of 0.5m. Slope steepness was 10, 25, 50 and 100%. Rainfall intensities were 35, 60, 90, and 120mm hr^{-1}. The rainfall simulation used in this study was a modification of the programmable rainfall simulators developed by Fan and Lovell (1987). The rainfall simulator was shown to be more effective and the uniformity coefficient of the simulator rainfall was 93.7%. Kinetic energy per unit of the simulated rainfall was 0.2092 MJ ha^{-1} mm^{-1} (793 foot-ton acre^{-1} inch^{-1}). Test items included sieve analyses, fall cone shear tests and interrill soil erosion tests. Using the obtained data, regression analyses were conducted to fit the soil erosion prediction models proposed by previous researchers and the authors. General equations for evaluating interrill soil erosion rate from rainfall intensity, soil shear strength, clay content and slope steepness were developed.

INTRODUCTION

In the past two decades, a number of soil erosion prediction models were developed. Some of the models, such as CREAMS and WEPP, need to input more detailed data input or parameters relevant to interrill soil erosion. Foster et al. (1977) proposed a model in which interrill erosion rate is a function of interrill soil erodibility, raindrop impact and interrill subflow, and slope steepness. A number of research studies relevant to the three factors have been investigated. In some studies, it was proposed that interrill soil erosion rate was highly related to rainfall intensity (Meyer, 1981; Watson and Laflen, 1986; Guy et al., 1987). For the slope steepness factor, a power of the sine value of the slope steepness was used in most studies (Singer and Blackard, 1982; Foster, 1982; Watson and Laflen, 1986; McIssac et al., 1987). However the natural logarithm of the slope steepness and the natural logarithm of the sine value of the slope steepness were also used (Rubio-Montoya and Brown, 1984; Liebenow et al., 1990). In studies of the interrill soil erodibility factor, shear strength of the soil (Al-Durrah and Bradford, 1981) and clay content (Meyer, 1981; Elliot et al., 1989) were used as significant parameters in the prediction models.

There are quite a few research studies regarding to interrill soil erosion in the world. However, on Taiwan, the topography is steep and the geological condition is relatively complicated; and the island of Taiwan is located in a subtropical area. There were very few studies on interrill soil erosion on such steep slopes and more particularly the soils of Taiwan. In this study, soil samples were collected from six sites, which were quite evenly distributed across Taiwan, and soil erosion tests were conducted by using simulated rainfall, to develop equations for predicting interrill soil erosion more accurately.

EXPERIMENTAL METHOD

Calibration of Rainfall Simulator

The rainfall simulator used in this study was a modification of the one developed by Fan and Lovell (1987). The nozzles of Veejet 80100 were used. The pressure of nozzles and fall height of raindrops were 4.22 t m^{-2} (6 psi) and 2.44 m (8 ft) respectively. Under such conditions, the average size of raindrops was 2.26 mm, the maximum diameter of raindrops was 3.79 mm, the kinetic energy per unit depth of rainfall was 0.2092 MJ ha^{-1} mm^{-1} (793 foot-ton acre^{-1} inch^{-1}) (proposed by Fan and Wu, 1996) which is very close to the value of 0.2114 MJ ha^{-1} mm^{-1} (800 foot-ton acre^{-1} inch^{-1}) proposed by Meyer and McCune (1958). In the study, the test box was placed under the center of two adjacent troughs. The rainfall intensities in the test box and measured point were calibrated. The calibration results showed that the coefficient of uniformity of the rainfall intensity inside the test box was up to 93.7% and the average rainfall intensity in the test box was highly related to that measured point.

Sample preparation

In this study, the soils for the erosion tests were collected from six sites, which were quite evenly distributed across Taiwan. At each site, the soil was collected from the Ap horizons. The properties of the soils are as shown in Table 1. The collected soils were first air-dried, and sieved. The soil finer than 2 mm was collected and remolded in a stainless steel test box, with a length of 0.5 m, a width of 0.75 m and a depth of 0.2 m. The procedures for remolding were as follows:

1. The test box was placed horizontally, and coarse sand was used to fill the test box up to a depth of 0.1 m.
2. The test box was then filled with the sieved soil to the top of the box.

*Jen-Chen Fan and Min-Fon Wu, Department of Agricultural Engineering, National Taiwan University, No. 1, Sec. 4, Roosevelt Rd., Taipei, Taiwan. *Corresponding author: fjc@upland.ae.ntu.edu.tw

3. The test box with coarse sand and the soil inside was then filled with water from the hole at the bottom of the box by gravity. The water level was kept the same as that of the soil surface for 24 hours.
4. The water in the test box was drained freely.
5. The test box was then inclined so that the slope steepness of the soil surface was 12%. The soil in the test box settled naturally for 120 days.

Erosion Tests Using Simulated Rainfall

The interrill erosion tests using simulated rainfall were conducted on soil samples which were collected from six sites, at slopes of 10, 25, 50 and 100% (i.e. 5.7, 14.0, 26.6, and 45.0 degrees), and intensities of 35, 60, 90 and 120 mm/hr. That is to say, 24 test boxes (6 soils x 4 slope gradients) of soil samples were used in this study, and 96 combinations (6 soils x 4 slope gradients x 4 intensities) of erosion tests were carried out. The details of the experimental set-up are illustrated in Figure 1. Each combination of erosion test was conducted twice. If the difference of the results between the two tests was greater than 5%, one more test was conducted additionally. The procedure of the interrill soil erosion test was as follows:

1. The test box was adjusted to the desired slope steepness.
2. The height of rainfall simulator was adjusted, so that the average fall height from nozzle to the soil surface was 2.44 m.
3. Plastic boards with a height of 0.5 m were placed at the four sides of the erosion box to intercept the splash of the water drops and soil particles. Under the plastic boards, there were gutters for collecting the water drops and soil particles.
4. The rainfall simulator was started to run for 30 minutes to wet soil preliminarily. The intensity applied was 25 mm/hr.
5. The simulated rainfall was stopped for 5 minutes. In this interval, the plastic boards and gutters were cleaned.
6. The rainfall simulator was started again. The desired rainfall intensities of 35, 60, 90, and 120 mm/hr were applied. Each of them was applied for 15 minutes. During the erosion test, containers with a volume of 2 liters were used for collecting samples of rainfall, runoff and splash at a time interval of 5 minutes. After the test with a given rainfall intensity was completed and before the next test with another rainfall intensity started, the rainfall simulator was stopped for 5 minutes, so that the sampling container and the soil particles on the plastic boards could be collected.
7. Two pieces of thin walled metal rings with a diameter of 85 mm, a height of 55 mm and a thickness of 1mm were used to collect two undisturbed soil sample randomly in the test box. Then, a Swedish fall cone was used to penetrate the soil samples in saturated conditions. The penetration depths were measured six times and the average value calculated. Using these values, the undrained shear strengths of the soil were obtained.
8. A new soil sample was used to replace the old one, and the procedures from 1 to 8 were repeated.

Table 1. Soil characteristics.

Sample	Soil type	Particle size distribution			τ
		%Clay	%Silt	%Sand	KN m^{-2}
Linkou	Silty Clay Loam	34.6	57.1	8.3	3.08
Taiping	Silty Loam	8.4	54.8	37.8	6.62
Tienliao	Silty Loam	12.8	71.2	16	2.96
Tungmen	Sandy Loam	1.8	39.6	58.6	6.77
Chimei	Silty Loam	8.8	63.8	27.4	3.63
Peinan	Loam	8.8	48.5	42.7	5.98

Figure 1. Experimental set-up.

RESULTS AND DISCUSSION

For the test boxes used for interrill soil erosion test in this study, there was no buffer area to compensate for the splash losses from the central test area. However, the interrill erosion in this study consisted of both the wash loss from the soil sample surface and splash loss outgoing to the plastic boards. In some previous studies such as those by Poesen et al. (1990) and Bradford and Foster (1996), buffer areas were designed and used to compensate for splash losses. If the buffer area is large enough to fully compensate for splash loss, the interrill erosion is considered to be better evaluated. However, in this study, if the incoming splash loss is considered to be equal to outgoing splash loss, the interrill erosion might be slightly overestimated, because, in reality, the soil particles due to incoming splash might not be completely eroded. In this study, 218 sets of data in total were obtained from 96 combinations of erosion tests multiplied by two tests for each combination plus 26 additional tests because the differences between replications were too great. The interrill erosion rate was further normalized to the slope length that gave a horizontal projection of 500 mm by assuming a linear normalization

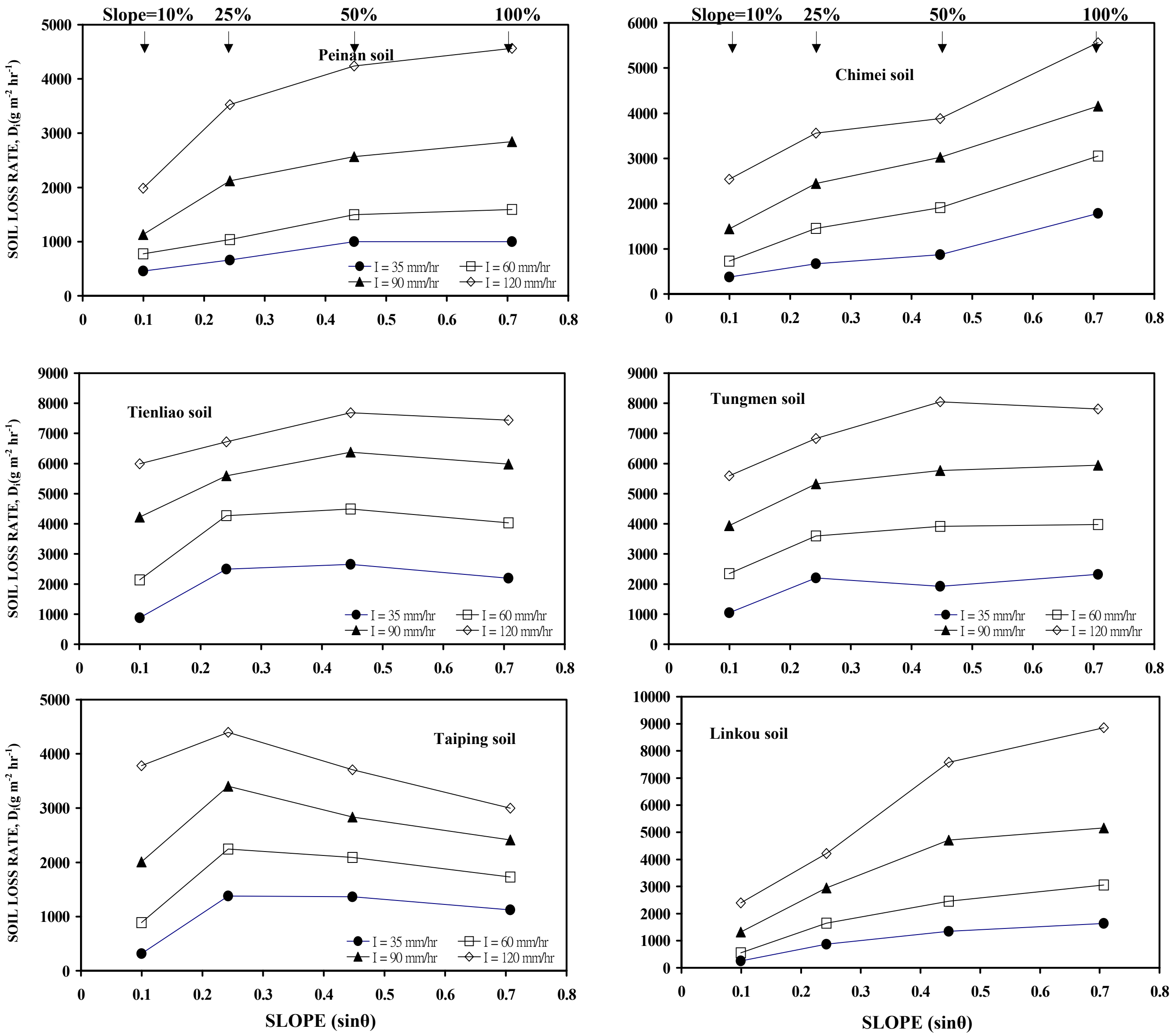

Figure 2. Relationships of interrill erosion rate vs. slope.

factor ($1/\cos\theta$). Finally, the data obtained from shear strength tests and particle size tests of the soils were added, and 96 groups of test data were used for statistical analyses.

The Effects of Slope

To investigate the effects of slope gradients on interrill soil erosion, figures presenting soil erosion rate versus slope steepness for six different soils under the conditions of four different rainfall intensities were plotted as shown in Figure 2. This figure shows that for soils of Tienliao and Taiping, critical slope the steepness existed between 50% and 100%. A maximum interrill erosion rate was found at the critical slope steepness. When the slope steepness was less than the critical value, interrill soil erosion rate increased with slope steepness; however, when the slope steepness was greater than the critical value, interrill soil erosion rate decreased with slope steepness. Similar results were proposed by Foster (1982) and Fan and Lovell (1987 and 1988). Among the slope steepness factors of interrill erosion suggested by previous researchers, the form of a second-degree polynomial proposed by Singer and Blackard (1982) could be used to describe this phenomenon. Using the form of second-degree polynomial, regression analyses were conducted to relate the sine value and interrill soil erosion rate. The results were shown in Table 2. From the results, it was found that a critical slope steepness can be determined not only the soils of Tienliao and Taiping, but also for the soils of Peinan and Chimei.

Table 2. Parameter estimation for the model $D_i = a \sin^2\theta + b \sin\theta + c$

Soil	I	a	b	c	R^2	css (%)
Peinan						
	35	-2189	2714	185	0.98	79
	60	-2358	3320	436	0.98	99
	90	-6028	7529	508	0.98	80
	120	-10070	12157	967	0.98	76
Tienliao						
	35	-13537	12759	-117	0.91	53
	60	-17023	16405	868	0.91	55
	90	-13158	13439	3046	1.00	59
	120	-8631	9491	5067	0.98	66
Taiping						
	35	-8261	7730	-258	0.85	53
	60	-10520	9497	208	0.80	51
	90	-10044	8259	1505	0.61	45
	120	-6246	3433	3636	0.84	29
Chimei						
	35	-4698	5445	741	0.69	71
	60	-8669	9443	1592	0.95	65
	90	-9200	10475	3094	0.96	69
	120	-12486	13826	4297	1.00	66
Linkou						
	35	2672	52	391	0.98	N
	60	500	3251	474	0.98	N
	90	-1687	5626	988	0.98	N
	120	1890	3097	2365	0.96	N
Tungmen						
	35	-3596	5132	-204	1.00	N
	60	-5803	8706	-212	1.00	N
	90	-12577	16547	-239	1.00	87
	120	-13227	21768	158	0.99	N

* D_i g m^{-2} hr^{-1}
I mm hr^{-1}
css is critical slope steepness
N means cannot find css between 10% and 100%

However, in Figure 2, because for the soils of Peinan, Chimei, Linkou and Tungmen, interrill soil erosion rate didnot decrease remarkably with slope steepness, the slope steepness factor of interrill soil erosion could be represented in other ways. For instance, in the WEPP model, a slope steepness factor equation was proposed for the interrill erosion component. The equation is shown as follows:

$$S_i = 1.05 - 0.85 \exp(-4 \sin\theta) \quad (1)$$

where S_i is the slope steepness factor and θ is slope steepness (degree). The phenomenon that interrill erosion rate increases with slope steepness but the increment due to the change of slope steepness decreases with slope steepness can be described by using this equation.

The Effects of Soil Properties and Rainfall Intensity

To study the effects of soil properties and rainfall intensity on interrill soil erosion rate, the equation form proposed by Meyer (1981) was applied to the data obtained from the erosion tests with each of the four different slope gradients. The results are shown in model A of Table 3. The correlation coefficients (R^2) ranged from 0.58 to 0.65. No matter whether the function was expressed in the form of rainfall intensity to the power of clay content, or was expressed in the form of the product of rainfall intensity and clay content, the correlation coefficients were low, as shown in models A and B of Table 3.

Table 3. Parameter estimation for the model including soil properties and rainfall intensity.

Slope	a	b	c	d	R^2
Model A : $D_i = a\, I^{b-c\,(\%clay)/100}$					
10%	1.16	1.72	0.16	-	0.58
25%	27.9	1.11	0.17	-	0.58
50%	20.3	1.23	0.29	-	0.65
100%	29.3	1.14	0.11	-	0.62
Model B : $D_i = a\, I^b\, (\%clay)^c$					
10%	1.110	1.69	0.055	-	0.58
25%	33.18	1.05	-0.006	-	0.55
50%	24.67	1.21	-0.118	-	0.63
100%	34.32	1.15	-0.112	-	0.65
Model C : $D_i = a\, I^{b-c\,\tau/100}$					
10%	1.71	1.78	3.41	-	0.72
25%	38.1	1.13	2.37	-	0.65
50%	23.5	1.24	1.61	-	0.64
100%	32.2	1.20	1.87	-	0.69
Model D : $D_i = a\, I^b \tau^c$					
10%	4.49	1.64	-0.71	-	0.72
25%	94.3	0.98	-0.48	-	0.65
50%	38.9	1.17	-0.35	-	0.64
100%	57.7	1.11	-0.40	-	0.69
Model E : $D_i = a\, I^{b-c\,(\%clay)/100} \tau^d$					
10%	16.1	1.69	0.85	-1.40	0.93
25%	195	1.11	0.74	-1.10	0.93
50%	125	1.22	0.89	-0.98	0.92
100%	107	1.15	0.53	-0.76	0.80
Model F : $D_i = a\, I^{b-c\,\tau/100} (\%clay)^d$					
10%	5.52	1.92	7.78	-0.42	0.84
25%	105	1.27	6.25	-0.38	0.82
50%	76.4	1.45	6.38	-0.51	0.93
100%	78.3	1.39	5.47	-0.46	0.93
Model G : $D_i = a\, I^b\, \tau^c (\%clay)^d$					
10%	45.9	1.61	-1.61	-0.41	0.83
25%	637	1.01	-1.30	-0.38	0.82
50%	599	1.15	-1.38	-0.52	0.95
100%	478	1.13	-1.19	-0.47	0.95

** D_i g /m^2.hr; I mm/hr; τ KN/m^2; %clay %

A number of previous studies showed that shear strength of the soil was highly related to interrill soil erosion rate. Accordingly, instead of clay content in models A and B, soil shear strength was used to do the regression analyses. The results showed that no matter whether the function was presented in the form of rainfall intensity to the power of shear strength, or was presented in the form of the product of rainfall intensity and shear strength, the correlation coefficients (R^2) improved to a range from 0.64 to 0.72, as shown in models C and D of Table 3. When both clay content and soil shear strength were used, the correlation coefficients (R^2) increased to at least 0.82, as shown in models E, F and G of Table 3. For models E, F and G, for slopes of 10% and as slope of 25%, for model E had better fitting curves. For steeper slopes of 50% and 100%, model G was better.

The Complete Statistical Equation for Interrill Soil Erosion

In this study, development of general equations for evaluating interrill soil erosion rate was an objective.

Therefore, models E and G in which higher correlation were found were selected to be combined with the slope steepness factor in the form of second-degree polynomials as proposed by Singer and Blackard (1982) and exponential function as proposed by Liebenow et al., (1990). After regression analyses using the 96 combinations of test data, four equations were obtained as shown in the following.

$$D_i = 42.91\,(I^{1.23-0.72(\%\,clay)/100})(1+5.63\sin\theta - 4.80\sin^2\theta)\,\tau^{0.97} \qquad R^2=0.88 \tag{2}$$

$$D_i = 175.9(I^{1.16}(1 + 5.45\sin\theta - 4.45\sin^2\theta)\,(\%clay)^{-0.45}(\tau^{-1.3}) \qquad R^2=0.89 \tag{3}$$

$$D_i = 93.71(I^{1.22-0.72(\%clay)/100})(1.28 - e^{-6.08\sin\theta})\tau^{-0.97} \qquad R^2=0.88 \tag{4}$$

$$D_i = 3638 \times I^{1.16} \times (1.32 - e^{-5.14\sin\theta}) \times (\%clay)^{-0.45} \times \tau^{-1.30} \qquad R^2=0.89 \tag{5}$$

where D_i is interrill soil erosion rate ($g \cdot m^{-2} \cdot hr^{-1}$), I is rainfall intensity($mm \cdot hr^{-1}$), Θ is slope angle (degree), τ is soil shear strength ($KN \cdot m^{-2}$) and %clay is clay content (%).

It should be noted that the correlation coefficients of the four equations were rather high (ranged from 0.88 to 0.89) and almost the same. In other words, for the test results in this study, no matter whether the function was expressed in the form of rainfall intensity to the power of clay content, or was expressed in the form of the product of rainfall intensity and clay content, and no matter what the slope steepness factor was presented in the form of second-degree polynomials or exponential function, best fit did not change significantly. Fig. 3 compares measured soil erosion rate versus estimated soil erosion rate using Eq. 4.

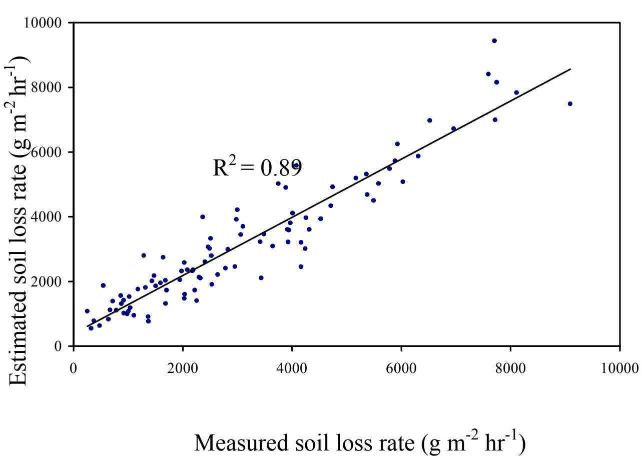

Figure 3. Estimated vs. measured soil loss rate for all plots by Eq. 4.

CONCLUSIONS

In this study, six different soils in Taiwan were collected for interrill soil erosion test. Using regression analyses on the test data, relationships between interrill soil erosion rate, rainfall intensity, soil properties and slope steepness were established. In the erosion tests, the range of rainfall intensity was from 35 mm/hr to 120 mm/hr and the range of slope steepness was from 10% to 100%.

It was found that no matter whether the function was presented in the form of rainfall intensity to the power of clay content (which was suggested by Meyer, 1981), or in the form of the product of rainfall intensity and clay content, the best fit for the data did not change very much. When the soil properties of both shear strength and clay content were used for statistical analyses, the agreement between the measured and projected soil loss increased significantly.

It was also found that for some soils, interrill erosion rate at steeper slope was less than that at milder slope. However, for other soils, this phenomenon was not very clear.

ACKNOWLEDGEMENTS

The authors are grateful to the National Science Council, Taiwan, R.O.C. for financial support of this research under Contract No. NSC82-0410-E002-035.

REFERENCES

Al-Durrah, M.M. and J.M. Bradford. 1981. New methods of studying soil detachment due to single water drop impact. Soil Sci. Soc. Am. J. 45:949-953.

Bradford, J.M. and G.R. Foster. 1996. Interrill soil erosion and slope steepness factors. Soil Sci. Soc. Am. J. 60:909-915.

Elliot, W.J., J.M. Laflen, and K.D. Kohl. 1989. Effect of soil properties on soil erodibility. Paper no. 89-2150. ASAE, St. Joseph, MI.

Fan, J.C. and C.W. Lovell. 1987. Measurement of erosion on highway slopes. The 4th Symposium on Environmental Concerns in Right-of Way Management, 427-435. Indianapolis, IN., 25-28 October.

Fan, J.C. and C.W. Lovell. 1988. Slope steepness factor for predicting erosion on highway slopes. In Transportation Research Record 1188, National Research Council, 63-73. Washington, D. C.: TRB.

Fan, J.C. and M.F. Wu. 1996. Design, fabrication, operation, calibration and analysis of a field-scale rainfall simulator in Taiwan. J. of Chinese Soil and Water Conservation 27:1-13.

Foster, G.R., L.D. Meyer and C.A. Onstad. 1977. An erosion equation derived from basic erosion principles. Trans. ASAE 20(4):678-682.

Foster, F.R. 1982. Modeling the erosion process. In Hydrologic Modeling of Small Watersheds, ed. C. T. Haan et al., ch. 8, 297-380. St. Joseph, MI: ASAE Monograph No. 5.

Guy, B.T., W.T. Dickinson, G.J. Wall and R.P. Rudra. 1987. Characterization of interrill transported sediment . ASAE Paper No. 87-2028, ASAE. St, Joseph, MI 49085.

Liebenow, A. M., W. J. Elliot., J. M. Laflen, and K. D. Kohl. 1990. Interrill erodibility: Collection and analysis of data from cropland soils. Trans. ASAE 33:1882-1888.

McIsaac, G.F., J.K. Mitchell and M.C. Hirschi. 1987. Slope steepness effects on soil loss from disturbed lands. Transactions of the ASAE 30:1005-1013.

Meyer, L.D. 1981. How rain intensity affects interrill erosion. Trans. ASAE 24:1472-1475.

Meyer, L.D. and D.L. McCune. 1958. Rainfall simulator for runoff plots. Agricultural Engineering 39:644-648.

Poesen, J., F. Ingelmo-Sanchez, and H.Mucher. 1990. The hydrological response of soil surfaces to rainfall as affected by cover and position of rock fragments in the top layer. Earth Surface Processes and Landforms. 15:653-671.

Rubio-Montoya, D. and K.W. Brown. 1984. Erodibility of stripmine spoils. Soil Science 138:365-373.

Singer, M.J. and J. Blackard. 1982. Slope angle-interrill soil loss relationships for slopes up to 50%. Soil Sci. Soc. Am. J. 46:1270-1273.

Watson, D.A. and J.M. Laflen. 1986. Soil strength, slope and rainfall intensity effects on interrill erosion. Trans. ASAE 29:98-102.