SLOPE GRADIENT EFFECTS ON SOIL LOSS FOR STEEP SLOPES

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ABSTRACT. *Data for assessing the effects of slope gradient on soil erosion for the case of steep slopes are limited. Widely used relationships are based primarily on data that were collected on slopes up to approximately 25%. These relationships show a reasonable degree of uniformity in soil loss estimates on slopes within that range, but are quite different when extrapolated beyond the range of the measured data. In this study, soil loss data from natural runoff plots at three locations on the loess plateau in China were used to assess the effect of slope gradient on soil loss for slopes ranging from 9 to 55% steepness. Plot size at each location was 5 m wide by 20 m long, and the soils were silt loams or silty-clay loam. The results indicated that for these plots, soil loss was linearly related to the sine of the slope angle according to the equation: $S = 21.91 \sin\theta - 0.96$, where θ is the slope angle and S is the slope steepness factor normalized to 9%. This relationship was assessed in terms of the limited existing experimental data for rainfall erosion on steep gradients and found to be reasonable for data collected on longer plots, but somewhat different than the data from shorter plot studies. The results of this study would indicate a lesser soil loss at high slopes than does the relationship used in the Universal Soil Loss Equation, but a greater soil loss than predicted by the Revised Universal Soil Loss Equation for steep slopes.*

Keywords. *USLE, RUSLE, soil, slopes.*

The determination of slope steepness factors is an integral part of most soil erosion prediction models. Several scientists have investigated slope steepness effects on soil loss. McCool et al. (1987a) discussed data related to the effects of slope gradient on erosion, as well as the equations that have been developed and used to evaluate slope gradient effects on soil loss. Table 1 is a summary of the principle equations that have been developed to relate soil loss to slope gradient. The reader is referred to McCool et al. (1987a) or the primary references for more detail.

The equations in table 1 use one of two independent variables; either percent of the slope or sine of the slope angle. They also use one of three different functional forms: linear, power, or polynomial. All of these equations were developed using data collected on slopes up to approximately 25%; however, some of them were validated using data collected on steeper slopes. For plots within this slope range, all of these equations provide calculated slope factors which are reasonably consistent in value, however, when the slope is greater than this, the calculated slope factors from these equations are significantly different (fig. 1). Renard et al. (1991) reported that computed soil loss for slopes less than 20% by Universal Soil Loss Equation (USLE) and Revised Universal Soil Loss Equation (RUSLE) are similar. However on steep slopes, computed soil loss is reduced almost by half with the RUSLE equation (Renard et al., 1991). When slope steepness is 50%, the USLE S factor (Wischmeier and Smith, 1978) is 15.2, while the RUSLE S factor (Renard et al., 1993) is only 7.0. RUSLE uses the equations developed and recommended by McCool et al. (1987a). Some studies have been conducted on steep slopes. McCool et al. (1987b, 1993) presented the equation:

$$S = (\sin\theta/0.0869)^{0.6} \qquad (1)$$

that is based on measured field rill erosion data collected from more than 2,100 slope segments ranging in slope from 1.5 to 56%. These data were collected for conditions in the Palouse region of the United States where soil loss was primarily caused by surface flow over thawing soils. This equation predicts low slope steepness factors compared to results from equations derived from rainfall induced erosion experiments. It is used in RUSLE to predict erosion on thawing soils for slopes greater than or equal to 9%.

Another two studies on steep and relatively long slopes ($\geq$ 4.6 m) were conducted under rainfall simulated on highway slopes and in the laboratory. Fan (1987) conducted experiments on highway slopes at 9.4, 16.1, 33.3, and 50.3% slopes on a silty-clay loam soil, and the calculated slope factors were 1.03, 1.40, 1.22, and 0.88, respectively. The highest S factor was at 16.1% slope. Fan (1987) recommended that an equation similar to equation 1 be used for slopes less than 14 degrees, and that a constant value of 2 be used for slopes greater than 14 degrees for highway slopes with compacted and cohesive soils. Kilinc and Richardson (1973) conducted a series of experiments on a sandy soil at six slope steepnesses ranging from 5.7 to 40%. The data were collected using a 1.5-m-wide × 4.6-m-long flume under simulated rainfall intensities of 32, 57, 92, and 117 mm/h. The authors did not attempt to provide an equation for estimating the slope factor, but the data

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Article was submitted for publication in May 1994; reviewed and approved for publication by the Soil and Water Div. of ASAE in August 1994.

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Table 1. Summary of commonly used equations which relate slope gradient to soil loss*

Author	Slope Factor	Data Source
Zingg (1940)	$(s/9)^{1.4}$	Simulated Rainfall- to 20%
Smith and Whitt (1947)	$0.025 + 0.052\ s^{4/3}$	Simulated Rainfall- to 16%
Musgrave (1947)	$(s/9)^{1.35}$	Composite of Existing Data
Smith and Wischmeier (1957)	$0.0065s^2 + 0.0453s + 0.065$	Natural Runoff Plots 3-18%
Wischmeier and Smith (1978, USLE)	$65.4\sin^2\theta + 4.56\sin\theta + 0.0654$	Natural Runoff Plots 3-18%
McCool et al. (1987a, RUSLE)	$10.8\sin\theta + 0.03\ s < 9\%$	Simulated Rainfall 0.1-3%
McCool et al. (1987a, RUSLE)	$16.8\sin\theta - 0.5\ s \geq 9\%$	Natural Runoff Plots 8-18%

* The slope factor is the soil loss normalized to a 9% slope gradient, s is the percent slope, and θ is the slope angle.

may be useful for evaluating equations for soil loss on steep slopes.

For short slopes (< 4.6 m), Singer and Blackard (1982) reported results of an experiment on interrill erosion using loam and silty clay loam soils with slopes up to 50%. They derived polynomial functions using the sine of the slope angle to relate soil loss to slope steepness for two soils. The results of that study showed that the coefficients of the best-fit equations were different for the two soils, which indicated that soil type influences the relationship between soil loss and slope gradient. The loam soil had a greater S factor than silty-clay loam soil.

Two micro-scale experiments have also been reported. Foster and Martin (1969) reported results of an experiment on 33, 50, and 100% slopes. The soil was a clay loam compacted to four different bulk densities into a very narrow flume which was 89 cm long. His data showed that there is an unique slope at which maximum soil loss occurred for a given bulk density. When slope steepness was different than that unique slope, soil loss was less. Gabriels et al. (1975) conducted an experiment on 8, 16, 24, 33, and 44% slopes using 30-cm-long soil pans. Two soil layers, the A horizon and the B horizon, of a silt loam soil were used. The slope steepness factor for the two soil horizons were quite different. These studies also indicate that soil type influences the relationship between soil loss and slope gradient.

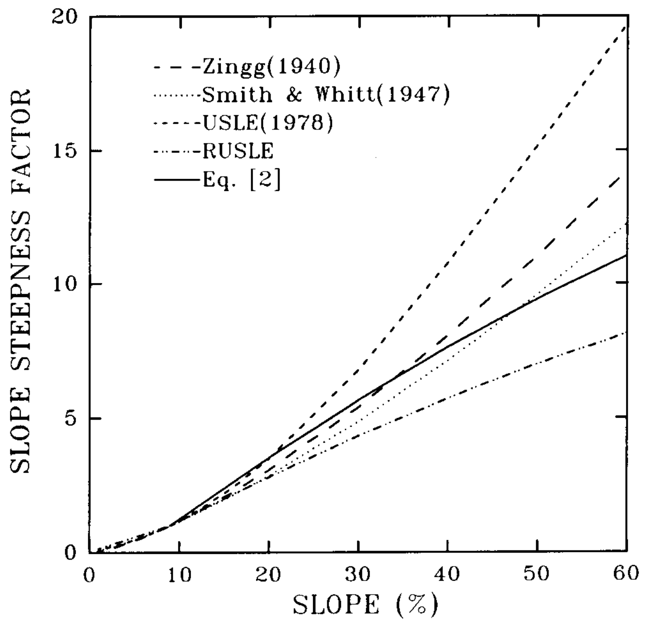

Figure 1–Slope steepness factor, normalized to 9%, for several slope steepness relationships from the scientific literature.

Data from the loess plateau of north-central China provides a unique opportunity to evaluate the relationship between slope gradient and soil loss for steep slopes under agricultural management. Much of the cultivated farmland in this area of China lies on slopes ranging from 20 to 40%, with some up to 50%. Because of the homogeneity of the deep loessial parent material, the soil materials are relatively uniform in character for different slope gradients in a particular location under similar management practices. The primary objective of this study was to quantify the relationship between soil loss and slope gradient on steep slopes. This was accomplished using natural rainfall data from three locations in the loess plateau of China and existing data from the literature. The resulting relationships were then compared to the relationships which others have proposed.

MATERIALS AND METHODS

Natural rainfall soil loss data from three locations on the loess plateau of China were used: Tianshui, Ansai, and Suide experiment stations. Soil texture in the loess plateau region changes from south to north (Liu, 1966). The plateau is divided into three zones; clayey loess, loess, and sandy loess. Each of the erosion stations used in this study was located in one of the three zones. The region is semi-arid with annual rainfall ranging from 400 to 600 mm (Li et al., 1985). Greater than 60% of the precipitation occurs from June through September. Average annual rainfall was about 600, 541, and 485 mm for the Tianshui, Ansai, and Suide locations, respectively. Most of the soil loss were caused by the storms with maximum intensities ranging from 18 to 150 mm/h. At the Ansai site, for instance, more than 90% of the soil loss occurred in July and August. On the average only eight erosion events occur in a year. The largest event was 137.6 mm rainfall on 4 August 1988 and produced 192.6 t/ha of soil loss. This accounted for 80% of the total soil loss in that year. Two of the soils were silt loams, and the soil at Tianshui was a silty-clay loam soil (table 2). Rill erosion on all of these three locations was obvious. Some scientists estimate that half or more of the soil loss from these plots is caused by rill erosion. All of the data were collected under natural rainfall conditions from plots which were 5 m wide and 20 m long measured horizontally. Runoff was collected using natural runoff

Table 2. Soil properties of the three sites

Location	Sand (%)	Silt (%)	Clay (%)	Cation Exchange Capacity (meq/100g)	Organic Matter (%)	Field Capacity (mm/mm)	Wilting Point (mm/mm)
Suide	32.1	56.2	11.8	9.23	0.47	15.8	3.7
Ansai	19.0	65.2	15.8	11.63	0.63	21.7	4.5
Tianshui	9.0	62.0	29.0	19.55	0.99	23.3	10.7

plots. Soil loss was measured by sampling the sediment concentration of the runoff which was collected in non-permeable reservoirs.

The data set used in this study were selected from a larger database using cropping and tillage factors as selection criteria. Two sites were cropped plots and one was fallow. Cropping on these plots was very sparse due to the slope steepness and the low amounts of available moisture. Plots were usually tilled by hand before planting for cropped plots or tilled in spring for fallow plots and then cultivated by hoe several times during the growing season. The data from Tianshui consisted of nine years of observations collected from 1945 through 1953. These plots were cropped in a three-year four-crop rotation of winter wheat, buckwheat, corn, and beans, on slopes of 9, 25, 31, and 44%. Data from Ansai site (Jiang et al., 1991) was for five years of fallow conditions on slopes of 9, 18, 27, 36, 47, and 53%. Four years of data were used from the Suide site. It was cropped in a four-year rotation of sorghum, bean, millet, and potatoes on slopes of 15, 26, and 55%.

Since the amount of soil loss was different from site to site, it was normalized so that the data could be pooled and comparisons between the sites could be made. This also made it possible to fit a single equation to the soil loss data from each location. A slope of 25% was selected for the normalization because each location had plots with slopes very nearly equal to 25%, and because this value was in the mid-range of the measured data. Linear regression was performed between soil loss and slope percent for the data at each of the sites for the three slopes nearest to 25%. Note that for the Tianshui site, three slope level were triplicated, thus data from nine plots at that site were used in the normalization to 25%. This line fit the data very well as indicated by the correlation coefficients of 0.97, 0.99, and 0.94 for the Suide, Ansai, and Tianshui sites, respectively. The regression was then used to determine an estimated value of soil loss for a slope of exactly 25% for each of the three sites. The 25% values were 17.25, 68.93, and 25.37 t/ha for the Suide, Ansia, and Tianshui sites, respectively.

Regression analysis was then used to evaluate the fit of the measured erosion data, normalized to 25%, using both sine of slope angle and percent slope as the independent variable. The best fit equation was selected, and then the equation was mathematically transformed so that the S factor calculated was normalized to the usual 9% value used in the USLE and RUSLE to describe slope gradient effects on soil loss.

RESULTS AND DISCUSSION

Average annual soil loss measured from each of the plots are presented in table 3. When the normalized values of soil loss were plotted for all of the locations, it was apparent that a single equation could be used to fit all of the data (fig. 2). There is some question in the scientific literature as to whether percent slope or the sine of the slope angle is more appropriate for characterizing slope gradient effects on soil loss (McIsaac et al., 1987; McCool et al., 1987a). McCool et al. (1987a) presented conceptual reasoning for why the sine of the slope angle is preferable to use in place of slope percent. The sine term is consistent with the relationship for calculating average flow shear stress of runoff water, and thus it was suggested that the sine of the slope angle should be more physically representative of erosion processes on slopes. McIsaac et al. (1987), however, analyzed several data sets and found that percent slope as an independent variable tended to have a better fit to the data, but that the differences were not significant. Table 4 shows a comparison of regressions between the soil loss data from this study and both the percent slope and the sine of the slope angle. For two of the three locations the sine of the slope angle produced greater coefficients of determination than did use of the slope percent term. Because of the better fit at two of the three sites, the sine of the slope angle was used to describe the slope gradient relationship.

The relationship between soil loss and slope angle derived from this data is:

$$S = 21.91 \sin\theta - 0.96 \tag{2}$$

Table 3. Average annual soil loss in t/ha and normalized to 25% slope

Plot Number	Slope (degree)	Slope (%)	Annual Runoff (mm)	Annual Soil Loss (t/ha)	Annual Soil Loss (Normalized to 25%)
			Suide Site		
32	8.6	15.1	20.8	5.80	0.336
18	14.7	26.2	20.0	21 93	1.271
11	28.7	54.7	17.8	42.71	2.476
			Ansai Site		
1	5	8.7	45.1	15.32	0.222
2	10	17.6	52.0	44 21	0.641
3	15	26.8	52.8	77.52	1.124
4	20	36.4	55.3	103.26	1.497
5	25	46.6	55.2	139.87	2.027
6	28	53.2	55.5	140.70	2.039
			Tianshui Site		
15	5.4	9.4	9.3	8.01	0.316
16	5.1	8.9	16.8	7.80	0.307
17	4.7	8.3	13.4	13.51	0.533
7	14.2	25.3	10.7	24.45	0.964
8	14.1	25.2	14.0	25.28	0.996
9	13.9	24.8	12 5	23.95	0.944
12	17.4	31.3	12.3	30.87	1.217
13	17.7	31.8	15.7	36.25	1.429
14	17.5	31.4	9.9	30.23	1.192
18	23.7	43.9	16.1	65.19	2.570

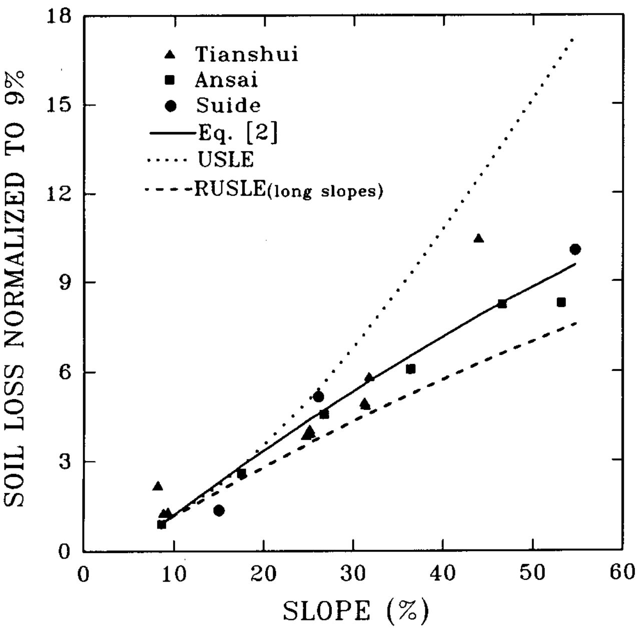

Figure 2–Soil loss, normalized to 9% slope, from the natural rainfall plot data used in this study.

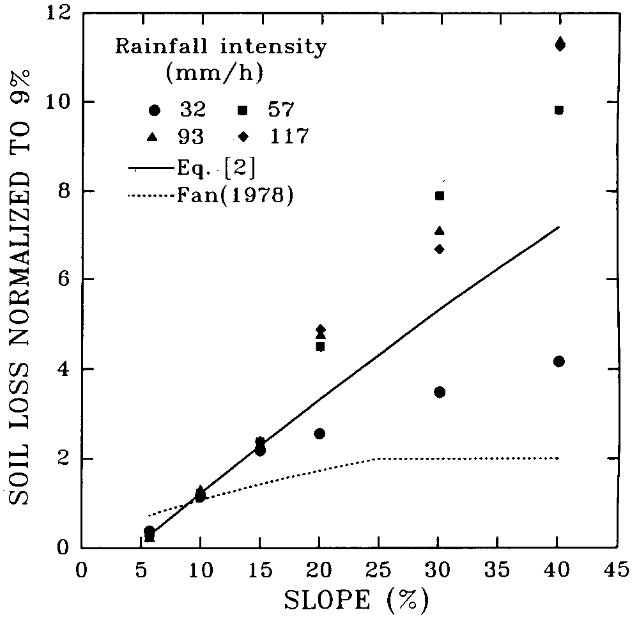

Figure 3–Data from the study of Kilinc and Richardson (1973), measured in the laboratory of 4.6-m-long beds using a rainfall simulator and normalized to a 9% slope. Equation 2 was derived from the natural rainfall data presented in this study.

where S is the average annual soil loss relative to a 9% slope. An analysis of variance showed that the regression coefficient in equation 2 was significantly ($\theta = 0.01$) greater than zero indicating a linear relationship. Since this equation was derived from data using slope lengths of 20 m under conditions similar to those under which USLE parameters were developed, it can be considered applicable to hillslope scale erosion on steep slopes. The coefficient in this equation is greater than the one used in RUSLE (McCool et al., 1987a, equation, table 1), and thus gives greater values for the slope factor. On the other hand, equation 2 gives a lower slope factor at high slopes than the one which was used in the USLE (fig. 1).

Equation 2 predicted lower S factor than were indicated from Kilinc and Richardson's (1973) soil loss data from three higher rainfall intensities, but higher than the soil loss data from one low rainfall intensity (fig. 3). However, it produced higher S factors than those suggested by the soil loss data of Fan (1987). The Kilinc and Richardson study was conducted using a noncohesive sandy soil while Fan's study was conducted on a cohesive silty-clay loam soil on which very little rill erosion occurred. It is interesting to note that for the three higher rainfall intensities in Kilinc and Richardson's study (1973), there was a greater increase in soil loss with slope gradient than for the lowest intensity, which appeared to approach a constant value. Fan's study also appeared to approach a constant value. The fact that some data indicates that the S factor approaches a constant value may be related to transport processes for lower rainfall intensities or areas dominated by interrill erosion. If the transport capacity of flow is limited due to lower rainfall intensities, a lack of rills, or a very cohesive soil which limits sediment supply, then total soil loss would approach a constant maximum value. Both the formation of rills and the use of noncohesive soils would tend to increase the S factors. While the data displayed considerable variability, the slope factors produced by equation 2 fell within the range of measured values for these two studies.

Table 4. Coeffcients of determination of linear regressions in slope steepnees-soil loss relationships

Data Source	% Slope	sin (θ)
Suide	0.97	0.98
Ansai	0.98	0.99
Tianshu	0.87	0.85

On short slopes there is less opportunity for rill erosion to occur and the slope steepness factor relationships of the USLE, which are based on unit plot scale data, are not reliable (Foster et al., 1981). Foster (1982) developed a different relationship for short slopes which was based on the study by Lattanzi et al. (1974). This relationship was subsequently used in RUSLE (Renard et al., 1993, McCool et al., 1987a). As for the case of long slopes, the slope steepness relationship for steep slopes may be different than the ones derived with data from slopes under 20%. Singer and Blackard's (1982) data were useful for deriving a relationship for steep slopes with short lengths. A power function normalized to 9% of the form:

$$S = 12.14(\sin\theta)^{0.97} - 0.81 \tag{3a}$$

$$S = 4.87(\sin\theta)^{0.69} + 0.08 \tag{3b}$$

fit the Singer and Blackard data quite well (fig. 4) for the loam and silty-clay loam soils, respectively. Comparison of equations 3a and 3b with the corresponding equation used in RUSLE shows that, as is true for the case of long slopes,

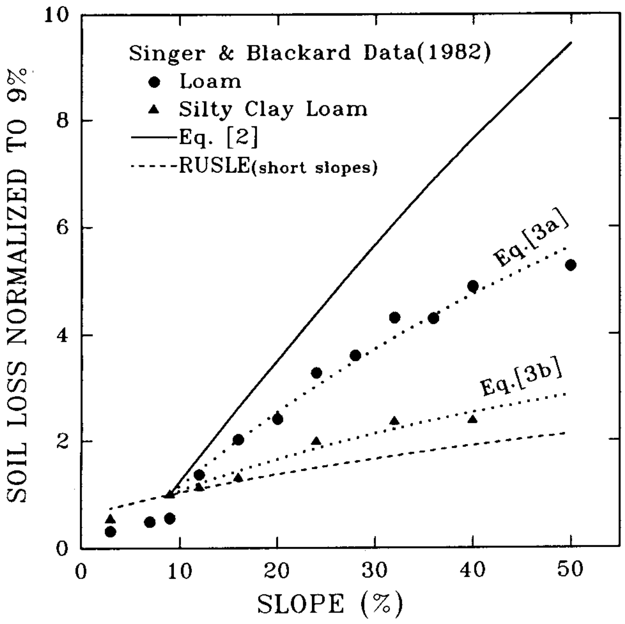

Figure 4–Interrill erosion data from the study of Singer and Blackard (1982) compared to the results of this study for 20-m-long plots and the RUSLE relationship for short slopes.

the RUSLE relationships may be underpredicting the effects of slope gradient on erosion for steep slopes (fig. 4), particularly relative to the loam soil data. Studies conducted by both Gabriels et al. (1975) and Foster and Martin (1969) have also indicated the importance of soil properties in defining the relationship between slope steepness and soil loss on short slopes. Foster and Martin found that there was a unique slope from which maximum erosion would occur for soils with varying bulk densities while Gabriels et al. (1975) found that soils with different aggregate sizes displayed different relationships between soil loss and slope steepness. However, most of the data from these studies also indicate that the RUSLE equation may underestimate the S factor on short steep slopes. Comparing the case of short slopes to long slopes, i.e., in comparing the Singer and Blackard data to equation 2 as shown in figure 4, we find that the slope gradient effect is greater for the long slopes (i.e., for equation 2). This is consistent with what we would expect in terms of the relative amounts of rill versus interrill erosion which occurs on the short and long slopes.

CONCLUSIONS

- This study reports some of the few existing soil loss data from natural runoff plots at slopes up to 50%. The data from 20-m-long natural runoff plots from three sites on the loess plateau of China showed that for slopes between 9 and approximately 50%, soil loss was linearly related to the sine of the slope angle according to the relationship given in equation 2. The form of equation 2 is similar to the one used in RUSLE, but produces greater slope steepness factors than does RUSLE, particularly at slopes greater than 25% where measured data are extremely rare.
- The data in the scientific literature for assessing the effect of slope gradient at slopes greater than 25% is limited, however, for the data which do exist for longer slopes (4.6 m), equation 2 falls within the range of the measured data. The existing data for shorter slopes would indicate a lesser slope gradient effect for short-steep slopes than for long-steep slopes.

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