Presented at IECA 2008, Orlando, FL

Slope Erosion Testing – Identifying "Critical" Parameters

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Biography

C. Joel Sprague is a Senior Engineer for TRI/Environmental, Inc., Austin, TX. Mr. Sprague provides technical oversight for TRI's large-scale erosion and sediment control testing facility in Anderson, SC. He is a registered professional engineer in North and South Carolina, Georgia, and Texas. He has authored numerous articles and technical papers on the development, testing, and application of erosion and sediment control materials.

Abstract

Various large-scale tests have been used to evaluate the performance of erosion control products. These tests typically are performed using boundary conditions that attempt to simulate field conditions. When evaluating slope erosion, for instance, a full-scale slope is generally eroded by rainfall impact and associated sheet runoff forces resulting from a simulated rainfall event. A certain combination of steepness, width and length of slope is selected, and the soil type, thickness, and compaction characteristics are chosen. The amount of soil loss from a protected condition is compared to that of the unprotected, or control, in order to establish product performance. In one such procedure, 6-inch thick compacted soil plots placed on a free draining tilt-table platform measuring 6 ft x 30 ft are used. Other tilting bed facilities use shorter and narrower plots, and different synthetic rainfalls. Still other facilities do the testing in-situ, out-of-doors, with even different dimensions, rainfall conditions, and soil type, preparation, and subgrade drainage. With this variety of approaches to testing, it is important to understand what mechanisms may or may not develop under modeled conditions and whether the associated mechanism depends on the type of erosion control product being tested and/or how it is installed. Specifically, some products armor the slope, encouraging efficient overland runoff, while other products encourage infiltration by absorbing the rainfall. Still other products seek to balance the two approaches to erosion control. Excess runoff may overwhelm surface "armoring", while high infiltration rates may lead to slope instability, especially for steeper slopes.

This paper uses the Revised Universal Soil Loss Equation (RUSLE) to consider the various parameters associated with large-scale slope evaluations and identifies the "critical" parameters associated with slope stability. Practical test results are also presented to support the analytical findings and demonstrate that the ASTM 6459 protocol reasonably agrees with theoretical RUSLE-based calculations. It is not clear if other (tilting bed) protocols similarly correlate.

Keywords: slope testing; slope erosion control; RUSLE, large-scale testing; mass wasting

1.0 Introduction

Evaluation of an erosion control material's ability to protect a surface soil layer from adverse effects associated with rainfall impact and infiltration, and sheet runoff forces is best done using procedures that closely simulate actual field conditions. To this end, test procedures have been developed to provide for the measurement of the amount of soil loss caused by rainfall generated by a rainfall simulator. Runoff is collected, measured, dried, and remaining sediments weighed. Soil type and conditions, slope size and geometry, and rainfall rate and duration can be controlled. The various procedures are typically used to compare the effects of rain on a protected slope versus a control, or unprotected, slope. Cabalka, et al (1998), Sutherland and Ziegler (1996), Rustom and Weggel (1993a,b), Landphair, et al (2002), and perhaps most importantly ASTM's D 6459-07 describe a variety of large-scale laboratory and field systems for testing of slope erosion. Great uncertainty exists as to the equivalence of these various procedures. Fortunately, erosion rates can be estimated based on the combined effects of rainfall, soil, topography, cover, and management practices using generally accepted soil loss calculations, allowing us to both related large-scale test results to "real world" conditions and to compare different test protocols. Additionally, surface soil layer geotechnical stability issues associated with rainfall infiltration can be addressed with well known veneer stability calculations.

2.0 Universal Soil Loss Equation, (USLE) / Revised Universal Soil Loss Equation (RUSLE)

According to Wishmeier and Smith, 1978, researchers began the development of semi-empirical equations for sheet and rill erosion in the late 1950s that have become widely known as the Universal Soil Loss Equation (USLE). The Revised Universal Soil Loss Equation (RUSLE) has largely replaced the USLE as a design tool. As with the USLE, the RUSLE is used to predict average annual soil loss rates in runoff from a site. The USLE/RUSLE calculates annual erosion rates by:

$$A = R \times K \times LS \times C \times P \qquad \textbf{Equation 1}$$

where:
A = the computed soil loss in tons (dry weight) per acre;
R = the rainfall erosion index; K = the erodibility value for a specific;
LS = the topographic factor; C = the cover factor;
P = the management practice factor.

Because of its widespread use and simplicity, the RUSLE is a useful and appropriate tool to evaluate the relative affects of various parameters on slope erosion, and thus, large-scale slope erosion testing. Following are some details on the factors comprising the RUSLE as described by Renard, et al, 1997, in Agriculture Handbook Number 703.

2.1 The R Factor - Rainfall energy and intensity

According to Renard, et al, 1997, the energy of a rainstorm is a function of the amount of rain and of all of the storm's component intensities. The median raindrop size generally increases with greater intensity, and the terminal velocities of free-falling waterdrops increase with larger drop size, but the median drop size does not continue to increase when intensities exceed 3 in/hr.

The most important "single" measure of the erosion-producing power of a rainstorm is called the *erosivity* and is the product of rainfall energy (E) times the maximum 30-minute rainfall intensity (I30). The relationship between detachment and storm erosivity, EI, is linear, which means that individual storm EI values can be summed to determine monthly and annual values. The EI product for storm erosivity captures the effects of the two most important rainfall variables in determining; how much it rains (rainfall amount) and how hard it rains (rainfall intensity). Total energy for a storm is computed from:

$$R_{storm} = (EI)_{storm} = E * I_{30} = (\Sigma\, e\, d)\, I_{30} \qquad \textbf{Equation 2}$$

where: e = unit energy (energy per unit of rainfall), d = rainfall amount for individual period

Unit energy is computed from:

$$e = 1099 [1 – 0.72 e^{(-1.27i)}] \quad \textbf{Equation 3}$$

where: unit energy e has units of (ft ton) / (acre in) and i = rainfall intensity (in/hr)

Time (hrs:min)	Cummulative Depth (in)	Duration of interval (minutes)	Interval Depth, d (in)	Intensity, i (in/hr)	e, Unit Energy in interval (ft ton / acre in)	Incremented Energy, e x d (ft ton /acre hr)
4:00						
4:20	0.05	20	0.05	0.15	445	22
4:27	0.12	7	0.07	0.60	730	51
4:36	0.35	9	0.23*	1.53	985	227
4:50	1.05	14	0.70*	3.00	1081	757
4:57	1.20	7	0.15*	1.29	945	142
5:05	1.25	8	0.05	0.38	611	31
5:15	1.25	20	0.00	0.00	308	0
5:30	1.30	15	0.05	0.20	485	24
Total		90	1.3			1254

* max 30 minute rainfall = 1.08 in

Table 1. Sample computation of energy for an individual storm

Table 1 illustrates computation of total energy for a storm which will be a useful basis for comparing test procedures which are done to simulate storm event rather than long-term performance. The total energy for the storm is multiplied by a constant factor of 10^{-2} to convert the storm energy to the dimensions in which EI values are typically expressed. I_{30} is two times the maximum amount of rain falling within 30 consecutive minutes. Then, erosivity for the storm is calculated as the product of storm energy and maximum 30-minute intensity as follows:

$$R_{storm} = (EI)_{storm} = (1254 \times 0.01) \times (1.08 \times 2) = 27.7 \text{ ft ton in / acre hr} \quad \textbf{Equation 4}$$

2.2 The K Factor - Soil erodibility

Soils vary in their susceptibility to erosion. Fine textured soils high in clay have low K values, about 0.05 to 0.15 tons/acre per US erosivity unit, because they are resistant to detachment. Coarse textured soils, such as sandy soils, have low K values, about 0.05 to 0.2 tons/acre per US erosivity unit, because of low runoff even though these soils are easily detached. Medium textured soils, such as the silt loam soils, have moderate K values, about 0.25 to 0.45 tons/acre per US erosivity unit, because they are moderately susceptible to detachment and they produce moderate runoff. Soils having high silt content are especially susceptible to erosion and have high K values. They are easily detached and they tend to crust, produce large amounts and rates of runoff, and produce fine sediment that is easily transported. Values of K for these soils typically exceed 0.45 tons/acre per US erosivity unit and can be as large as 0.65 tons/acre per US erosivity unit.

The RUSLE soil erodibility factor is entirely an empirical measure of erodibility and is not based on erosion processes. It is not a soil property like texture. The soil erodibility factor K is defined by the variables used to express erosivity, which is the product of storm energy and maximum 30-minute intensity. K values are unique to this definition, and values based on other measures of erosivity, such as runoff, must not be assumed for K. Values for K are not proportional to erodibility factor values for other erosivity measures and may not increase or decrease in the same sequence relative to each other. For example, the K value for a sandy soil is low whereas the value for an erodibility factor based on runoff is high. Soil organic matter reduces the K factor because it produces compounds that bind soil particles and reduce their susceptibility to detachment by raindrop impact and surface runoff. Also, organic matter increases soil aggregation to increase infiltration and reduce runoff and erosion. Permeability of the soil profile affects K because it affects runoff. Soil structure affects K because it affects detachment and infiltration. Soil structure refers to the arrangement of soil particles, including primary particles and aggregates, in the soil. Soil mineralogy has a significant effect on K for some soils, including subsoils,

soils located in the upper Midwest of the US, and volcanic soils in the Tropics. An algebraic approximation by Wishmeier and Smith, 1978, provides a straightforward calculation of K for soils where the silt fraction does not exceed 70% as shown in Equation 5.

$$K = [2.1 \times 10^{-4}(12 - OM)\, M^{1.14} + 3.25(s-2) + 2.5(p-3)] / 100 \qquad \textbf{Equation 5}$$

where: M is the product of the sand and the very fine sand + silt fractions; OM is the organic content, s is the structure class, and p is the permeability class. Some typical values for K based on Equation 5 are shown in Table 2.

Textural Class[1]	% Sand[1] (0.1–2mm)	% Silt & Very Fine Sand[1] (0.002–0.1mm)	% Clay[1] (<0.002mm)	OM (%)	Soil Structure	Perm Class[2]	K-Factor
Loam	41	41	18	1	2	3	0.11
Clay	20	20	60	1	4	6	0.16
Sand	90	6	4	1	3	1	0.01
Silt Loam	20	65	15	2	4	3	0.14
Sandy Loam	65	25	10	1	2	2	0.08

1. based on Foster, 2003; 2. based on Renard, et al, 1997

Table 2. K-Factor Calculations for Various "Typical" Soils (based on Eqn. 5)

2.3 The LS Factor - Slope Geometry (i.e. topography).

The magnitude of sheet and rill erosion on a given slope is partially affected by slope geometry, i.e. flow path length and slope. The effect of flow path length is not as great as the effect of slope angle. Steep, freshly prepared construction slopes are typically highly susceptible to rill erosion. It should be noted that runoff is generally not a function of slope steepness and that any slope effects on runoff and erosion resulting from mechanical disturbance of slopes is considered in the RUSLE's support practices factor, P. RUSLE users are provided with a table (Table 3) of LS factors that should be used for construction sites where the ratio of rill to interrill erosion is high and the soil has a strong tendency to rill.

Values for topographic factor, LS, for high ratio of rill to interrill erosion.[1]

Slope (%)	Horizontal slope length (ft) <3	6	9	12	15	25	50	75	100	150	200	250	300	400	600	800	1000
0.2	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.06	0.06	0.06
0.5	0.07	0.07	0.07	0.07	0.07	0.07	0.08	0.08	0.09	0.09	0.10	0.10	0.10	0.11	0.12	0.12	0.13
1.0	0.09	0.09	0.09	0.09	0.09	0.10	0.13	0.14	0.15	0.17	0.18	0.19	0.20	0.22	0.24	0.26	0.27
2.0	0.13	0.13	0.13	0.13	0.13	0.16	0.21	0.25	0.28	0.33	0.37	0.40	0.43	0.48	0.56	0.63	0.69
3.0	0.17	0.17	0.17	0.17	0.17	0.21	0.30	0.36	0.41	0.50	0.57	0.64	0.69	0.80	0.96	1.10	1.23
4.0	0.20	0.20	0.20	0.20	0.20	0.26	0.38	0.47	0.55	0.68	0.79	0.89	0.98	1.14	1.42	1.65	1.86
5.0	0.23	0.23	0.23	0.23	0.23	0.31	0.46	0.58	0.68	0.86	1.02	1.16	1.28	1.51	1.91	2.25	2.55
6.0	0.26	0.26	0.26	0.26	0.26	0.36	0.54	0.69	0.82	1.05	1.25	1.43	1.60	1.90	2.43	2.89	3.30
8.0	0.32	0.32	0.32	0.32	0.32	0.45	0.70	0.91	1.10	1.43	1.72	1.99	2.24	2.70	3.52	4.24	4.91
10.0	0.35	0.37	0.38	0.39	0.40	0.57	0.91	1.20	1.46	1.92	2.34	2.72	3.09	3.75	4.95	6.03	7.02
12.0	0.36	0.41	0.45	0.47	0.49	0.71	1.15	1.54	1.88	2.51	3.07	3.60	4.09	5.01	6.67	8.17	9.57
14.0	0.38	0.45	0.51	0.55	0.58	0.85	1.40	1.87	2.31	3.09	3.81	4.48	5.11	6.30	8.45	10.40	12.23
16.0	0.39	0.49	0.56	0.62	0.67	0.98	1.64	2.21	2.73	3.68	4.56	5.37	6.15	7.60	10.26	12.69	14.96
20.0	0.41	0.56	0.67	0.76	0.84	1.24	2.10	2.86	3.57	4.85	6.04	7.16	8.23	10.24	13.94	17.35	20.57
25.0	0.45	0.64	0.80	0.93	1.04	1.56	2.67	3.67	4.59	6.30	7.88	9.38	10.81	13.53	18.57	23.24	27.66
30.0	0.48	0.72	0.91	1.08	1.24	1.86	3.22	4.44	5.58	7.70	9.67	11.55	13.35	16.77	23.14	29.07	34.71
40.0	0.53	0.85	1.13	1.37	1.59	2.41	4.24	5.89	7.44	10.35	13.07	15.67	18.17	22.95	31.89	40.29	48.29
50.0	0.58	0.97	1.31	1.62	1.91	2.91	5.16	7.20	9.13	12.75	16.16	19.42	22.57	28.60	39.95	50.63	60.84
60.0	0.63	1.07	1.47	1.84	2.19	3.36	5.97	8.37	10.63	14.89	18.92	22.78	26.51	33.67	47.18	59.93	72.15

[1]Such as for freshly prepared construction and other highly disturbed soil conditions with little or no cover (not applicable to thawing soil)

Table 3. Values for topographic factor, LS, for high ratio of rill to interill erosion

2.4 The C Factor - The type and density of cover.

The C-Factor represents a combined effect of interrelated cover and management variables. The rate of erosion is directly proportional to the type and density of permanent or temporary cover. For construction sites, some typical values for erosion reduction for common erosion control approaches are given in Table 4.

Cover Type	Cover Condition	Erosion Reduction, %
Mulch - hay or straw	0.5 tons/acre	75
	1.0 tons/acre	87
	2.0 tons/acre	98
Grass - seeding & sod (no canopy)	90+% cover	99
	60% cover	96
	40% cover	90
Bushes	25% cover	60
	75% cover	72
Trees	25% cover	58
	75% cover	64
Rolled Erosion Control Products (a.k.a. blankets, mats)	100% cover	95-99

Table 4. Typical Slope Cover Erosion Reduction (Fifield, 1995)

2.5 The P Factor - Management practices

The P-Factor represents a combined effect of support practices and management variables. The values used in RUSLE for construction sites refer to structural methods for controlling sediment. For construction sites, some typical values for erosion reduction for common erosion control approaches are given in Table 5.

Surface Condition	Impact on Erosion
Compacted and smooth	+ 30%
Trackwalked along contour	+ 20%
Trackwalked up and down slope	10%
Punched straw	10%
Rough, irregular cut	10%
Loose to 30 cm depth	20%
Sediment control structures	*50% to 99%*

Table 5. Typical Slope Management Erosion Reduction (Fifield, 1995)

3.0 Test Slope Stability Related to Mass Wasting

The primary drawback to relying exclusively on the RUSLE for comparing various slope testing scenarios is that it examines only the effects of runoff and cannot address the potential for mass wasting, either localized or on a large scale, resulting from infiltration. Mass wasting occurs when the moisture content of the soil increases to the point where it disrupts the particle-to-particle interactions that enable the soil to support its own weight and the weight of the water in the soil. If rainfall is not allowed to run off the slope, it by necessity must infiltrate the slope. While this is an effective way to prevent surface erosion, it can lead to excess water in the slope leading to mass wasting.

Richardson, 2007, recently reported concerns that 3:1 soil veneers over geomembranes in landfill caps are failing (mass wasting) with alarming frequency because of surface water seepage/infiltration exceeding the drainage capacity of underlying drainage layers. This phenomenon leads to buoyancy in the soil veneer and loss of frictional stability along the geomembrane boundary. A similar occurrence has been found in in-situ slope erosion testing (without a geomembrane layer) when an erosion control material is highly effective in encouraging infiltration. If no artificial drainage of the soil is provided, the high infiltration rate can lead to soil saturation, slippage at the subgrade interface, and mass wasting.

Figure 1 shows an analysis that can explain the instability called mass wasting, or veneer instability. In the model the lower boundary layer – either geomembrane or subsoil – is defined with appropriate strength/friction properties. A parametric study based on the stability model shown in Figure 1 was performed. As shown in Figure 2, numerous parameters were varied to assess model sensitivity to differences that would be expected to be found between testing protocols. This enabled specific "critical" testing parameters to be identified that control whether mass wasting is a possible outcome of the chosen protocol. Soil permeability, strength and friction values were based on soil type (sandy loam). The parametric study produced the observations detailed in Figure 3.

Test Slope Stability Evaluation Model

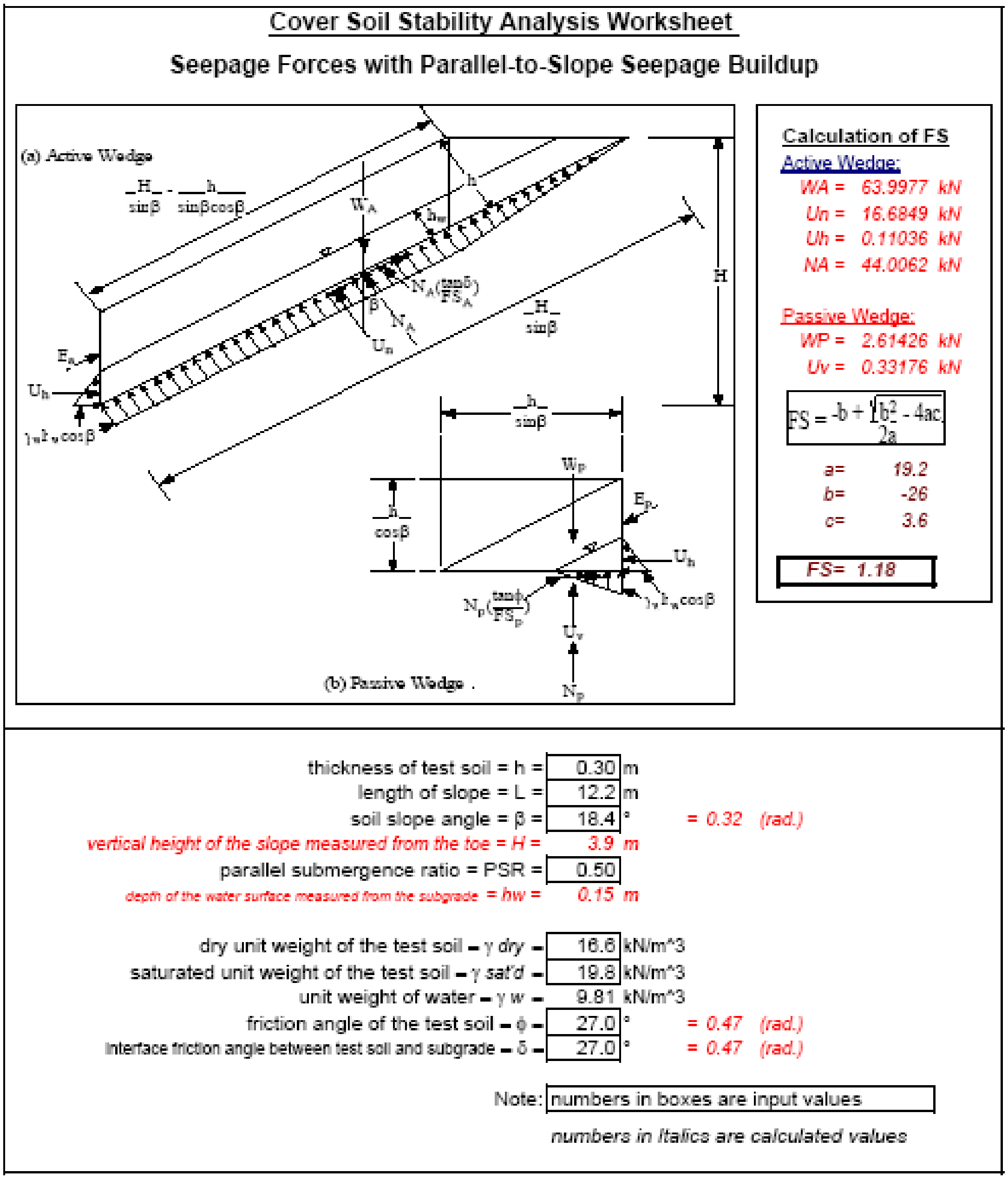

Figure 1. Slope Stability Model (Geosynthetic Research Institute, 1996)

Test Slope Stability Evaluation - Parameter Sensitivity

Input Parameter	units	TRI Loam (silty clayey sand)																	
Soil Thickness	in	12	12	12	12	12	12	18	18	18	18	18	18	12	12	12	12	12	12
	m	0.30	0.30	0.30	0.30	0.30	0.30	0.46	0.46	0.46	0.46	0.46	0.46	0.30	0.30	0.30	0.30	0.30	0.30
Slope Length	ft	40	30	20	40	30	20	40	30	20	40	30	20	40	30	20	40	30	20
	m	12.2	9.1	6.1	12.2	9.1	6.1	12.2	9.1	6.1	12.2	9.1	6.1	12.2	9.1	6.1	12.2	9.1	6.1
Slope Angle	H:V	3:1	3:1	3:1	3:1	3:1	3:1	3:1	3:1	3:1	3:1	3:1	3:1	2:1	2:1	2:1	4:1	4:1	4:1
	deg	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	26.6	26.6	26.6	14.0	14.0	14.0
Test Soil Dry Unit Wt	lb/ft^3	106	106	106	106	106	106	106	106	106	106	106	106	106	106	106	106	106	106
	kN/m^3	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6
Test Soil Sat. Unit Wt	lb/ft^3	126	126	126	126	126	126	126	126	126	126	126	126	126	126	126	126	126	126
	kN/m^3	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8
Unit Weight of Water	lb/ft^3	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4
	kN/m^3	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8
Test Soil Friction Angle	deg	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27
Test Soil Subgrade Friction Angle	deg	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27
Depth of Saturation in Test Soil	% of thickness	50%	50%	50%	100%	100%	100%	50%	50%	50%	100%	100%	100%	50%	50%	50%	50%	50%	50%
Factor of Safety		**1.18**	**1.20**	**1.24**	**0.81**	**0.83**	**0.86**	**1.21**	**1.25**	**1.32**	**0.84**	**0.86**	**0.91**	**0.79**	**0.80**	**0.83**	**1.58**	**1.62**	**1.68**

Input Parameter	units	TRI Loam (silty clayey sand)																	
Soil Thickness	in	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	6	6	6
	m	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.15	0.15	0.15
Slope Length	ft	40	30	20	40	30	20	40	30	20	40	30	20	40	30	20	40	30	20
	m	12.2	9.1	6.1	12.2	9.1	6.1	12.2	9.1	6.1	12.2	9.1	6.1	12.2	9.1	6.1	12.2	9.1	6.1
Slope Angle	H:V	3:1	3:1	3:1	3:1	3:1	3:1	3:1	3:1	3:1	3:1	3:1	3:1	3:1	3:1	3:1	3:1	3:1	3:1
	deg	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4
Test Soil Dry Unit Wt	lb/ft^3	96	96	96	96	96	96	116	116	116	116	116	116	106	106	106	106	106	106
	kN/m^3	15.1	15.1	15.1	15.1	15.1	15.1	18.2	18.2	18.2	18.2	18.2	18.2	16.6	16.6	16.6	16.6	16.6	16.6
Test Soil Sat. Unit Wt	lb/ft^3	120	120	120	120	120	120	132	132	132	132	132	132	126	126	126	126	126	126
	kN/m^3	18.8	18.8	18.8	18.8	18.8	18.8	20.7	20.7	20.7	20.7	20.7	20.7	19.8	19.8	19.8	19.8	19.8	19.8
Unit Weight of Water	lb/ft^3	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4
	kN/m^3	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8
Test Soil Friction Angle	deg	25	25	25	25	25	25	29	29	29	29	29	29	27	27	27	27	27	27
Test Soil Subgrade Friction Angle	deg	25	25	25	25	25	25	29	29	29	29	29	29	27	27	27	27	27	27
Depth of Saturation in Test Soil	% of thickness	50%	50%	50%	100%	100%	100%	50%	50%	50%	100%	100%	100%	0%	0%	0%	100%	100%	100%
Factor of Safety		**1.05**	**1.07**	**1.11**	**0.71**	**0.72**	**0.74**	**1.31**	**1.34**	**1.39**	**0.92**	**0.94**	**0.97**	**1.61**	**1.64**	**1.70**	**0.79**	**0.80**	**0.81**

Figure 2. Results of Parametric Study

Observations from Test Slope Stability Sensitivity Evaluation

Common Parameters	Changing Parameter	Effect of Changing Parameter
3:1 Slopes; 12" thick test soil	Test Soil Dry	All slopes should be very stable.
	Test Soil 50% Saturated	All slopes should be stable.
	Test Soil 100% Saturated	All slopes should be unstable.
	Slope Length	Shorter slopes are nominally more stable.
	Friction Angles	Test soil friction angle and test soil / subgrade friction angles are directly related to stability.
3:1 Slopes; Any Depth of Saturation; Any Slope Length	Test Soil Thickness	Stability increases nominally with increasing thickness and decreases nominally with decreasing thickness.
	Test Soil Density / Strength	Stability increases with increasing density / strength and decreases with decreasing density / strength.
	Test Slope Steepness	Stability decreases with increasing slope steepness and increases with decreasing slope steepness.
	Test Soil Saturation	Stability decreases with increasing saturation and increases with decreasing saturation.

Observations Concerning Test Parameters

Common Parameters	Critical Parameter	"Real World" Field vs. "Simulated" Lab
Insitu Field Tests vs. Elevated Platform Laboratory Tests	Test Soil & Test Soil / Subgrade Friction Angles	Similarity to field determined by lab platform floor.
	Test Soil Density / Strength	Density harder to achieve on field slope vs. on horizontal platform raised after compaction.
	Test Slope Geometry	Field includes "unknowns" associated with full-scale trials.
	Test Soil Saturation	Platform drainage will affect saturation differently than in the field where subgrade drainage is present.

Figure 3. Observations from Parametric Study

4.0 Large-scale Slope Testing Protocols

As described in the introduction, there are several different large-scale slope testing protocols in current use. Table 6 summarizes the different parameters of representative ASTM D 6459 (Labs #1 and #3) and in-door tilting bed (Lab #2) protocols.

Test Slope Parameter	Lab #1 (Early, et al, 2003)	Lab #2 (Landphair, et al, 2002)	Lab #3
Dimensions (W x L)	8 ft x 40 ft	6 ft x 30 ft	8 ft x 40 ft
Steepness ((H:V)	3:1	2:1 and 3:1	3:1
Soil Type Tested	Loam	Sand and Clay	Sandy Loam
Soil Moisture Conditions	± 4% optimum	n/a	± 4% optimum
Soil Compaction	“light”	“light”	“light”
Soil Depth	12 - 18 in	9 in	12 – 18 in
Test Bed Condition	90% Std Proctor	Permeable steel grating + cross-members @ 2ft	90% Std Proctor
Rainfall Scenario	2, 4, 6 in/hr @ 20 minutes	(3.5, 3.5, 3.5 in/hr @ 30 mins) x 3	2, 4, 6 in/hr @ 20 minutes
Raindrop Drop Height	14 ft	14 ft	14 ft
Soil Compactor	Steel roller (70± lbs)	Steel roller (125± lbs)	Steel roller (70± lbs)
# of Replicate Slopes	3	3	3
Facility	Outdoor	Indoor	Outdoor within Windscreen
Test QC	Periodic Calibration + Rain gauges deployed during testing	Periodic Calibration	Periodic Calibration + Rain gauges deployed during testing

Table 6. Large-scale Testing Protocol Parameters

5.0 Using The RUSLE To Compare Test Protocols

As noted in the introduction, erosion rates can be estimated based on the combined effects of rainfall, soil, topography, cover, and management practices using generally accepted soil loss calculations. The RUSLE provides generally accepted soil loss calculations that facilitate the comparison of different test protocols. Referring to Table 6, a Factor-by-Factor comparison of labs #1, #2 and #3 can be made as follows:

5.1 The R Factor

It was shown earlier how the computation of total energy for a storm provides a useful basis for comparing test procedures which are done to simulate storm event rather than long-term performance. Tables 7a and 7b and the equation that follows each show the calculation of total energy produced by the storm events simulated by labs #1, #2 and #3 shown in Table 6.

Time (hrs:min)	Cummulative Depth (in)	Duration of interval (minutes)	Interval Depth, d (in)	Intensity, i (in/hr)	e, Unit Energy in interval (ft ton / acre in)	Incremented Energy, e x d (ft ton / acre hr)
0:00						
0:20	.67	20	0.67	2.00	1037	695
0:40	2.00	20	1.33	4.00	1081	1438
1:00	4.00	20	2.00	6.00	1081	2162
Total		60	1.3			4295

- max 30 minute rainfall = (2.00 + (0.5 * 1.33)) = 2.67 in

Lab #1 & #3 $R_{storm} = EI_{storm}$ = (4295 x 0.01) x (2.67 x 2) = 229.4 ft ton in / acre hr

Table 7a. Lab #1 & #3 Energy for an Individual Storm

Time (hrs:min)	Cummulative Depth (in)	Duration of interval (minutes)	Interval Depth, d (in)	Intensity, i (in/hr)	e, Unit Energy in interval (ft ton / acre in)	Incremented Energy, e x d (ft ton / acre hr)
0:00	Day 1					
0:10	0.58	10	0.58	3.48	1081	627
0:20	1.16	10	0.58	3.48	1081	627
0:30	1.74	10	0.58	3.48	1081	627
0:00	Day 2 (after 24 hour wait & drainage)					
0:10	0.58	10	0.58	3.48	1081	627
0:20	1.16	10	0.58	3.48	1081	627
0:30	1.74	10	0.58	3.48	1081	627
0:00	Day 3 (after 24 hour wait & drainage)					
0:10	0.58	10	0.58	3.48	1081	627
0:20	1.16	10	0.58	3.48	1081	627
0:30	1.74	10	0.58	3.48	1081	627
Total		90	1.3			5643

Note: max 30 minute rainfall = 3 x 0.58 = 1.74 in

Lab #2 $R_{storm} = EI_{storm}$ = (5643 x 0.01) x (1.74 x 2) = 196.4 ft ton in / acre hr

Table 7b. Lab #2 Energy for an Individual Storm

5.2 The K Factor

As detailed earlier, soils vary in their susceptibility to erosion. Fine and coarse textured soils typically have low K values, while medium textured soils, such as the silt loam soils, have moderate K values. Soils having high silt content are especially susceptible to erosion and have high K values. They are easily detached and they tend to crust, produce large amounts and rates of runoff, and produce fine sediment that is easily transported. Table 8 presents representative percentages of sand, silt and clay for the soils used in Labs #1, #2 and #3 detailed in Table 6, as well as, other textural characteristics. These typical characteristics allow Equation 5 to be used to compare the K-Factors for the soils used in testing.

Textural Class	Lab #	Sand (0.1–2mm) (%)	Silt & Very Fine Sand (0.002–0.1mm) (%)	Clay (<0.002mm) (%)	OM (%)	Soil Structure	Perm Class	K-Factor
Loam	1	46	42	12	1	2	3	0.13
Clay	2	20	20	60	1	4	6	0.16
Sand	2	90	8	2	1	3	1	0.03
Sandy Loam	3	65	25	10	5	2	2	0.04

Table 8. Erodibility of Various Laboratory Soils (based on Eqn. 1)

5.3 The LS Factor

As detailed earlier, the magnitude of sheet and rill erosion on a given slope is partially affected by slope geometry, i.e. flow path length and slope, though the effect of flow path length is not as great as the effect of slope angle. Using Table 4 of LS factors that should be used for construction sites it is possible to look at the effects of slope length and steepness together for the purpose of comparing testing protocols, as shown in Table 9. The LS Factor is determined by interpolation between values in the table.

Lab #	Slope Length, ft	Slope Steepness, H:V	Slope Steepness, %	LS Factor
1 & 3	40	3:1	33	2.926
2	30	3:1	33	2.325
2	30	2:1	50	3.360

Table 9. LS for Various Test Slopes

5.4 The C and P Factors

It is reasonable to assume that the same surface condition exists (i.e. bare or protected) and the same surface management exists (i.e. smooth, compacted) in laboratories being compared. Thus, the C and P factors can be assumed to be 1.0 for the comparative analysis.

5.5 Combined Effects of Rainfall, Soil, Topography, Cover, and Management Practices

Table 10 uses the RUSLE equation to assess the combined effects of the various test parameters.

Lab #	Slope	Soil	R	K	LS	C	P	Soil Loss (tons/acre)
1	3:1	Loam	229	0.13	2.926	1.0	1.0	87
2	3:1	Clay	196	0.16	2.325	1.0	1.0	73
	2:1	Clay	196	0.16	3.360	1.0	1.0	105
	3:1	Sand	196	0.03	2.325	1.0	1.0	14
	2:1	Sand	196	0.03	3.360	1.0	1.0	20
3	3:1	Sandy Loam	229	0.04	2.926	1.0	1.0	27

Table 10. Combined Effects of Test Parameters

6.0 Mass Wasting Potential

As noted earlier, RUSLE cannot address slope stability associated with excess infiltration should it occur. Such would likely only occur if the soil was very loosely placed or an erosion control material dramatically inhibited runoff during a very substantial rainfall event such as is called for in the ASTM protocol. This potential for mass wasting can only be addressed by accurately simulating the soil/subsoil conditions and associated effects of infiltration. This requires that the test soil layer be an appropriate thickness and be supported by either soil or structure able to provide "real world" friction and permeability (drainage) conditions, especially if and when a saturated condition in the test soil is achieved. While it can be argued that "real world" conditions are inherent in the ASTM – insitu – protocol, the tilt-bed protocol(s) appear to reduce or eliminate the potential for infiltration-induced instability to occur by providing artificial roughness and drainage at the test soil / test bed interface.

7.0 Actual Test Results

Table 11 presents representative actual bare soil test results from Labs #1 and #3, enabling an assessment of how well the ASTM protocol compares to RUSLE and, by extension, to generally expected field performance. Not only do these results compare quite favorably with the theoretical results shown for Labs #1 and #3 in Table 10, but, along with the intermediate data from these tests, produces a plot of R vs Soil Loss that was used to calculate a K factor of 0.15 and 0.035 for Labs #1 and #3, respectively, which also compares favorably with theoretical values from Table 10. Bare soil results for Lab #2 have not been made public.

Cummulative Test Result	Lab #1[1]			Lab #3			
R_{storm} (ft ton in / acre hr)	213	232	370	220	273	290	190
R_{storm} fom RUSLE	229			229			
Soil Loss (T/acre)	118	97	126	25	25	22	28
Soil Loss from RUSLE	87			27			

1. Early, et al, 2003

Table 11. Representative Actual Bare Soil Test Results from Lab #3

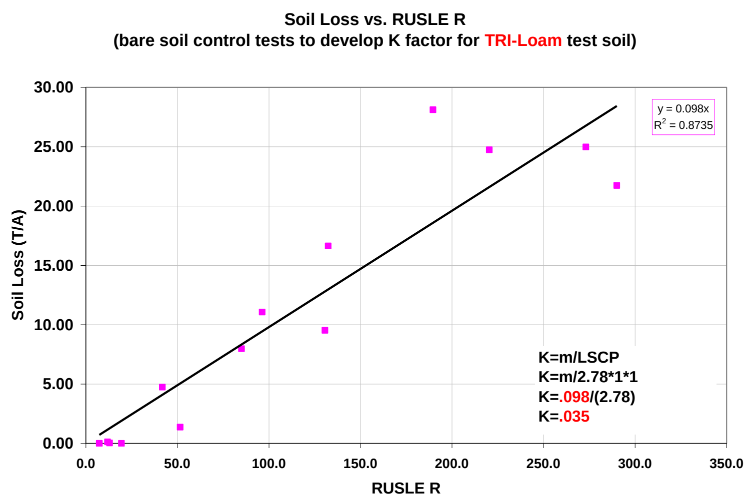

Figure 4. Lab #3 – K Calculation from Bare Soil Data

8.0 Conclusions

Large-scale slope erosion testing is important for assessing the relative performance of various erosion control materials. Yet, currently used testing protocols vary widely. Using the RUSLE it has been shown that there are significant differences in the erosivity (R), erodibility (K), and topographic (LS) factors associated with the indoor and outdoor (ASTM) testing protocols examined. Additionally, a parametric stability analysis identified critical parameters related to stability as test soil unit weight and strength, test soil / subsoil (or test bed) friction and drainage, slope steepness, and degree of test soil saturation. All of these parameters vary significantly between the indoor and outdoor (ASTM) testing protocols examined, suggesting that very different stability conditions exist between insitu and tilting bed protocols. Finally, comparison of the calculated and actual soil loss test results shown in Tables 10 and 11, respectively, indicate that there is reasonable consistency between the ASTM protocol (Labs #1 and #3) and RUSLE-based theoretical performance. Actual test results from other labs/protocols should be similarly compared to RUSLE to assess whether measured laboratory performance in those protocols satisfactorily correlates to expected field performance.

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