FINAL
CONTRACT REPORT

EROSION PROTECTION FOR SOIL SLOPES ALONG VIRGINIA'S HIGHWAYS

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Abstract

A survey of the state of practice for designing slope erosion control measures within VDOT's nine districts has been conducted. On the basis of the survey, it is clear that there are no specific design procedures currently in use within VDOT for dealing with slope erosion. VDOT designers generally try to limit erosion by diverting runoff from adjacent areas, controlling concentrated flows on slopes, and establishing vegetation on slopes as quickly as possible. In addition, the Federal Highway Administration (FHWA) and the Departments of Transportation in states surrounding Virginia (Maryland, West Virginia, Kentucky, Tennessee, and North Carolina) were contacted. The state of practice for the FHWA and for these states appears to be similar to that used by VDOT.

A review of the literature for soil erosion was performed. The universal soil loss equation (USLE), an empirical equation developed by the U.S. Department of Agriculture, was found to provide the best available quantitative tool for evaluating factors controlling the erosion process and determining what level of protection is appropriate. The authors recommend that the USLE be used to supplement VDOT's current principle-based design practices.

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ABSTRACT

Erosion of soil slopes can undermine pavements and other structures, create safety hazards, and harm the environment. Repair of eroded soil slopes can be problematic because of difficult access and working conditions. Such difficulties can result in high costs for slope repair. Effective erosion protection measures can prevent or reduce the scope of such problems. The Virginia Department of Transportation (VDOT), through the Virginia Transportation Research Council (VTRC), requested that Virginia Tech investigate and report on guidelines for selecting appropriate erosion protection measures.

A survey of the state of practice for designing erosion control measures within VDOT's nine districts has been conducted. On the basis of the survey, it is clear that there are no specific design procedures currently in use within VDOT for dealing with slope erosion. However, slope erosion control was perceived as a very important issue, and a general design philosophy was found. Currently, VDOT designers generally try to limit erosion by diverting runoff from adjacent areas, controlling concentrated flows on slopes, and establishing vegetation on slopes as quickly as possible. In addition, the Federal Highway Administration (FHWA) and the Departments of Transportation in the states surrounding Virginia (Maryland, West Virginia, Kentucky, Tennessee, and North Carolina) were contacted. The state of practice for the FHWA and for these states appears to be similar to that used by VDOT.

A review of the literature for soil erosion was performed. Design methods for slope erosion control are not well developed. The universal soil loss equation (USLE), an empirical equation developed by the U.S. Department of Agriculture, provides the best available quantitative tool for evaluating factors controlling the erosion process and determining what level of protection is appropriate. A design example using the USLE is provided.

To the authors' knowledge, the USLE is not used as the primary tool for slope erosion design by any state department of transportation, or by the FHWA. For this reason, it is not the recommendation of this study that VDOT adopt the USLE as its primary method for slope erosion design. Instead, the authors recommend that the USLE be used to supplement VDOT's current principle based design practices. The authors also recommend that VDOT's principle based design approach be improved by development of a systematic method for documenting and communicating throughout VDOT the performance of erosion control measures.

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INTRODUCTION

The erosion of soil slopes along Virginia's highways is a serious problem. Erosion of soil slopes can create safety hazards, such as undermined pavements. Environmental quality can also be reduced by the sediments from eroded slopes. Moreover, repair of eroded slopes can be problematic due to restricted access and difficult working conditions. Such difficulties can result in high costs for slope repair. Effective erosion protection can prevent or reduce the magnitude of these problems. However, selection of appropriate erosion control protection is difficult because design methods are not well developed.

The Virginia Department of Transportation (VDOT), through the Virginia Transportation Research Council (VTRC), requested that Virginia Tech investigate erosion protection for soil slopes along Virginia's highways. There is a concurrent, but separate, VTRC sponsored research project for erosion of roadside channels and ditches; the two projects should not be confused. The objective of this research is to recommend approaches for selecting appropriate erosion protection measures for soil slopes. To accomplish this objective, a literature review for slope erosion and a survey of the state of practice were performed.

The following three sections of this report present: 1) the methods used for the research, 2) the research results and discussion, and 3) conclusions and recommendations. Because the methods used to conduct this research were limited to a literature review and interviews, the methods section is short. The results and discussion section includes the results of the literature review and the survey. Subsections based on the literature review include fundamentals of soil erosion control, principles of soil erosion control, and methods of soil erosion control. Additional subsections present the results of the state of practice survey. This includes a summary of interviews with VDOT personnel and a description of erosion control practices in surrounding states. The last subsection of the results and discussion section presents procedures for selecting soil erosion control measures. The conclusions and recommendations section includes a summary of the work accomplished, findings, and recommendations.

The report includes three appendices. Appendix A contains the questionnaire used for interviews. Appendix B contains VDOT guidance for erosion control blankets and mats. Appendix C contains a form for collecting information about slope erosion control.

METHODS

The methods used to conduct this research consisted of performing a literature review and interviewing individuals who deal with erosion control. The information collected was then synthesized to produce this report.

The interviews were conducted with personnel from VDOT and from Departments of Transportation (DOTs) in the surrounding states of Maryland, West Virginia, Kentucky, Tennessee, and North Carolina. Personnel from the Federal Highway Administration were also contacted. The interview questions are presented in Appendix A

RESULTS AND DISCUSSION

This section of the report presents and discusses the results of the literature review and the interviews. First, the fundamentals of soil erosion are discussed and the USLE is presented. Next, ten principles of soil erosion are discussed. This is followed by a discussion of available methods for soil erosion control. Next, the interviews with personnel from VDOT, the DOTs from surrounding states, and the FHWA are summarized. Finally, several approaches for selecting erosion control methods are discussed in this section of the report.

Fundamentals of Soil Erosion

Ingold and Thomson (1990) tell us that the word *erosion* is derived from the Latin, *erodere*, to gnaw, or *erosus*, to eat away. Soil erosion is the removal of soil by wind, water or ice. For the purpose of developing guidelines for selecting methods for erosion control for slopes, this report focuses on the agency of water, in particular, rainfall and runoff.

Two mechanisms are involved with soil erosion on slopes: 1) detachment and 2) transport. Rainfall erosion begins with the impact of a raindrop on the ground surface. The kinetic energy of raindrop impact can dislodge and move soil particles, beginning the process of soil erosion. After rain falls on the ground surface, it becomes runoff. The initial distributed flow of runoff across the ground is known as *sheet flow*. As soil particles are removed and transported by the flow, small channels known as *rills* form. Larger and deeper flow channels are *gullies*. The higher velocity of flow and greater depth of flow in the rills and gullies provide the energy required for transporting soil particles. Figure 1 illustrates these types of erosion on a slope.

Figure 1 also shows the erosion of stream channels and banks. While stream and ditch erosion can be significant problems in their own right, they are not the subject of this report. VTRC is sponsoring a separate, but concurrent, research project on the erosion of roadside channels and ditches.

There are five fundamental factors that influence the erosion of soil slopes under the agency of water. These are embodied in the Universal Soil Loss Equation, which is discussed next.

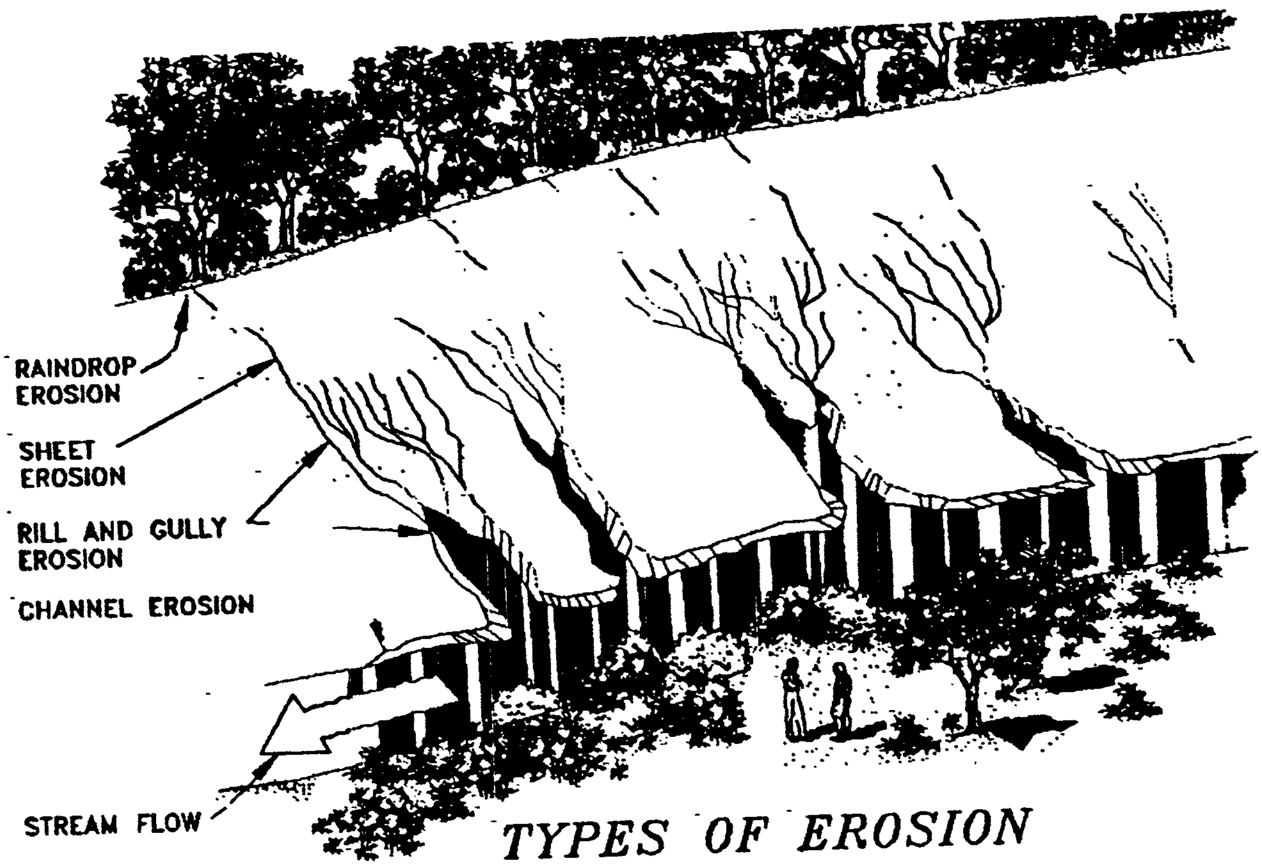

Figure 1 - Types of rainfall/runoff erosion (Virginia, 1992)

Universal Soil Loss Equation

Five factors influence soil erosion on slopes:

1) the duration and intensity of rainfall,
2) the type of soil and its erodibility,
3) the topography of the slope, its length and steepness,
4) the type and extent of vegetative cover on the slope, and
5) the type and extent of other erosion control methods and practices.

Wischmeier and Smith (1978) developed the Universal Soil Loss Equation (USLE) as an empirical tool to predict the effect of variation in the five basic factors on the amount of soil erosion. The USLE can be stated as the following:

$$A = R \times K \times L \times S \times C \times P \tag{1}$$

where A is the computed soil loss rate per unit area in tons per acre per year, R is the rainfall and runoff factor, K is the soil erodibility factor, L is slope length factor, S is the slope steepness factor, C is the cover factor, and P is the practice factor.

The USLE is an empirical equation developed in English units. When using the USLE with metric units, it is recommended that unit conversions not be performed until the result is obtained. The soil loss rate can be easily converted from tons per acre per year to kilograms per square meter per year by multiplying by 0.226 (i.e., 1 ton/acre/year = 0.226 kg/m^2/year). Hereafter, primary use of metric units will be made, the English equivalents follow in parenthesis.

Development of the USLE began in the 1940's (Wischmeier and Smith, 1978). The original version that related erosion to slope length and inclination was known as the *slope-practice* method. Subsequent modification added factors for vegetative cover and conservation practices. A similar equation, known as the *Corn Belt Equation*, contained parameters for soil type and land management practices. These two equations were combined in 1946 as the *Musgrave Equation* for estimating the gross erosion within a watershed. In the early 1950's, the methods were modified and became known as the *Universal Soil Loss Equation* (USLE). A 20-year study was undertaken to calibrate the USLE based on the erosion of standard unit plots. The standard unit plot is bare ground 22.13 meters (72.6 ft) long at a slope of 9 percent, plowed in continuous fallow (i.e., tilled up and down the slope). During the 1970's with accumulation of 10,000 plot years of data, the USLE was published in Agricultural Handbook No. 537, *Predicting Rainfall Erosion Losses, A Guide to Conservation Planning* by Wischmeier and Smith (1978). In 1997, the U.S. Department of Agriculture published Agricultural Handbook No. 703, *Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE)*. This guide uses the same empirical equation, with modification of the individual factors to reflect additional data (USDA, 1997). Since 1978, the USLE or its derivatives have remained the standard method for evaluating slope soil erosion on agricultural land.

Rainfall and runoff factor, R

The rainfall and runoff factor, R, is based on the raindrop impact effect and on the amount and rate of runoff. Average annual values of the R-factor are normally used and can be obtained from an isoerodent map, such as shown in Figure 2, which is an isoerodent map for the Commonwealth of Virginia.

For a single storm event, the R-factor is proportional to the product of the rainfall kinetic energy rate and the maximum 30-minute rainfall intensity. Table 1 is a summary of typical values of the kinetic energy rate for various rainfall intensities in a single storm. This illustration of the variation in the energy applied during rainfall events of differing intensities is important because it clearly shows that heavy rains produce the most erosion.

Table 1 - Kinetic energy and velocity of raindrops for various rainfall intensities (after *Biotechnical Slope Protection and Erosion Control*, D. H. Gray and A. T. Leiser, copyright © 1982, Van Nostrand Reinhold. Reprinted by permission of Van Nostrand Reinhold).

Rainfall	Intensity (mm/hour)	Raindrop median diameter (mm)	Velocity of fall (m/sec)	Drops per square meter per second [m^2/sec]	Kinetic energy rate (J/ m^2/hour)
Fog	0.13	0.01	3.05×10^{-3}	67,425,135	6.03×10^{-7}
Mist	0.05	0.10	0.21	27,017	1.14×10^{-3}
Drizzle	0.25	0.96	4.11	151	2.19
Light rain	1.02	1.24	4.79	280	11.8
Moderate rain	3.81	1.60	5.70	495	63.3
Heavy rain	15.24	2.05	6.71	495	185
Excessive rain	40.64	2.40	7.32	818	582
Cloudburst	101.6	2.85	7.89	1,216	1,680
Cloudburst	101.6	4.00	8.90	441	2,150
Cloudburst	101.6	6.00	9.30	129	2,320

Wischmeier and Smith (1978) provide values of R for four cites in Virginia. The R values given in Table 2 are annual values with probabilities of non-exceedance of 50, 75 and 95 percent during the 22-year observation period. Table 3 contains the expected magnitude of R for single storms with a recurrence interval of 1, 2, 5, 10 and 20 years.

Table 2 - Range of the annual rainfall factor, R (after Wischmeier and Smith, 1978).

City	Value of the rainfall factor, R			
	Observed range 22-year period	50 percent non-exceedance	75 percent non-exceedance	95 percent non-exceedance
Blacksburg	81 –245	126	168	221
Lynchburg	64 – 366	164	232	324
Richmond	102 – 373	208	275	361
Roanoke	78 – 283	129	176	237

Table 3 - Expected magnitude of single storm rainfall factor, R (after Wischmeier and Smith, 1978).

City	Value of the rainfall factor, R				
	1- year recurrence interval	2-year recurrence interval	5-year recurrence interval	10-year recurrence interval	20-year recurrence interval
Blacksburg	23	31	41	48	56
Lynchburg	31	45	66	83	103
Richmond	46	63	86	102	125
Roanoke	23	33	48	61	73

The figure shows average annual contours of the R-factor from the USLE in foot-tons per acre.

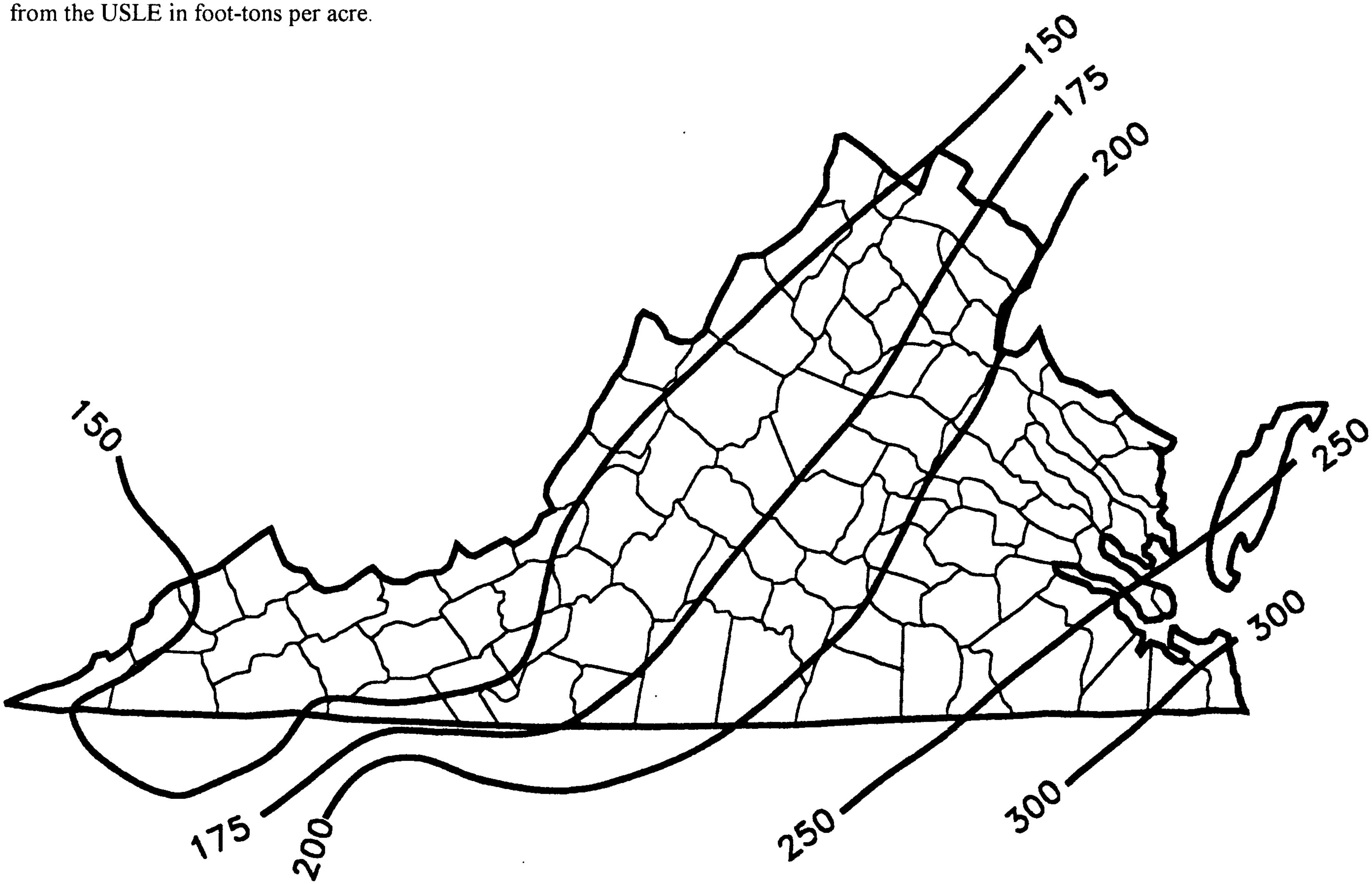

Figure 2 – Isoerodent map for Virginia (after Wischmeir and Smith, 1978)

Soil erodibility factor, K

The soil erodibility factor, K, is an empirical value. The K-factor is based on the erosion of a unit plot. The unit plot provides the reference condition for evaluating erosion in the USLE. The unit plot is bare ground 22.13 meters (72.6 ft) long at a slope of 9 percent, plowed in continuous fallow (i.e., tilled up and down the slope). The K-factor has been found experimentally to vary between 0.02 and 0.69 (Gray and Leiser, 1982).

Wischmeir and Smith (1978) developed an erodibility nomograph relating soil characteristics to the K-factor. They show five factors contributing to soil erodibility:

1) percent of silt and very fine sand (0.002 - 0.10 mm grain size),
2) percent sand (0.10 - 2.0 mm grain size),
3) percent organic matter,
4) soil structure, and
5) permeability.

Their nomograph is shown in Figure 3.

Gray and Sotir (1996) suggest this hierarchy of erodibility based on the Unified Soil Classification System:

Most erodible   Least erodible
ML > SM > SC > MH > OL >> CL > CH > GM > SW > GP > GW

where the most erodible soils are ML, silt; SM, silty sand; SC; clayey sand; MH, elastic silt; and OL, organic silt and clay. Soils with less erodibility are CL, lean clay; CH, fat clay; GM, silty gravel; SW, well-graded sand; GP, poorly graded gravel; and GW, well-graded gravel. This assessment of soil erodibility is based on the engineering characteristics of soils derived from their grain size and plasticity. However, the relationship between the K-factor, developed from agricultural classifications of soils, and the engineering properties and classifications of soils is not well defined. Gray and Sotir (1996) indicate that the following factors contribute to soil erodibility:

1) Grain size: Erodibility is low for well-graded gravels and high for uniform silts and fine sands.
2) Void ratio: Denser soils with a low void ratio are less vulnerable to erosion.
3) Organic content: Erodibility is low for soils with a high organic content due to the interconnection of organic fibers in the soil.
4) Antecedent moisture: Soils with a high antecedent moisture content are less susceptible to erosion.
5) Clay content and type: Erodibility increases with decreasing clay content. There is greater erodibility with increasing sodium adsorption ratio and decreasing ionic strength of the eroding water.

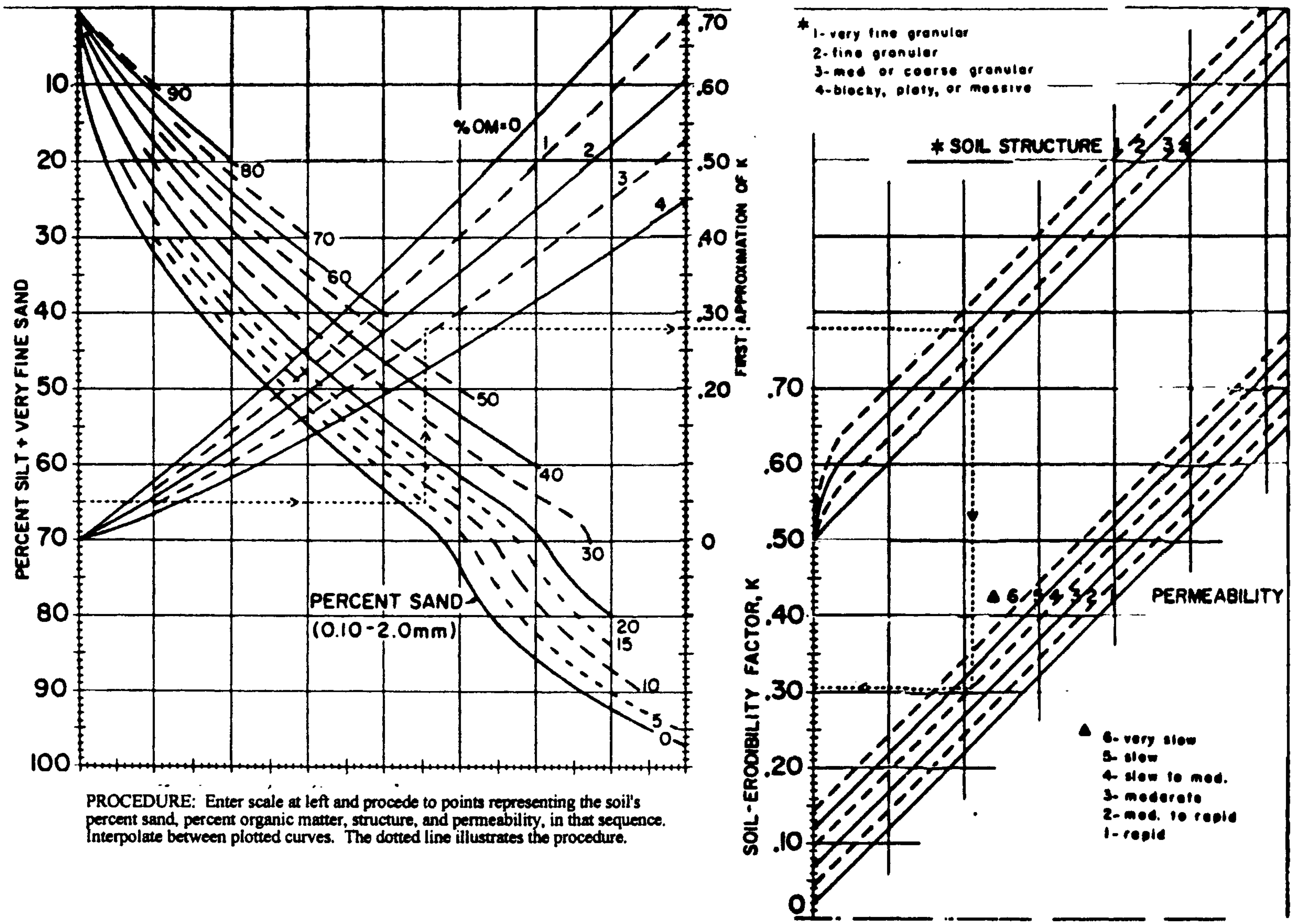

Figure 3 – Nomograph for the soil erodibility factor, K (Wischmeir and Smith, 1978)

There is substantial uncertainty regarding the last factor cited, the effects of clay content and the type of clay on erodibility. The sodium adsorption ratio has been used as an index of erodibility because sodium is an easily replaceable cation, while the ionic strength of water reflects the availability of cations for replacement. As shown above, clays are generally thought of as being less erodible. However, dispersive clays are known to be highly susceptible to erosion.

At least one experimental study highlights the difficulty in using clay type and content as a guide for assessing soil erodibility. Shaikh et al. (1987) conducted erosion testing of three clays: sodium montmorillonite, kaolinite, and calcium montmorillonite. Calcium is a cation less replaceable than sodium. Kaolinite is a type of clay noted for low susceptibility for cation replacement. It was found that sodium montmorillonite with a high sodium adsorption ratio (19.8 meq/liter) was less susceptible to erosion than a calcium montmorillonite with a low sodium adsorption ratio (0.4 meq/liter). The kaolinite tested (with a sodium absorption ratio of 0.5 meq/liter) had the same susceptibility to erosion as the sodium montmorillonite.

In addition, the shear strength of soil has been cited as a factor in reducing erodibility. Cohesion, a component of shear strength often associated with clay soils, has been cited as resisting the detachment of soil for transport. However, the experimental work of Shaikh et al. (1987) also found that the Torvane shear strength of the three clays tested did not correlate with erodibility.

The erodibility of gravels, sands, and silts is better understood. Duffy and Hatzell (1991) reported on the erodibility of gravels and sands. They found that the ground surface of sandy soils becomes armored against raindrop impact when half the soil particles are larger than a U.S. No. 4 sieve. This means that gravel size particles are able to protect sand size particles from the erosive force associated with raindrop impact. They also found that for 2H:1V slopes, larger diameter, angular soil particles can resist rill erosion. The use of very large particles, such as used for rip-rap, were not required. Particles as small as 38.1 mm (1.5 in) in diameter with a shape factor greater than 2.0 resisted rill erosion on the 2H:1V test slope. The shape factor is the ratio of the longest to shortest particle dimensions. This illustrates the resistance of gravels to the erosive force associated with the transport mechanism of slope erosion. Armstrong and Wall (1991) conducted laboratory testing on the erodibility of a sandy silt. They found excellent agreement between the test results (K=0.25 to 0.26) and the K-factor found from Wischmeier and Smith's nomograph (K = 0.26). Therefore, it seems reasonable to use the nomograph in Figure 3 for evaluating the erodibility of gravels, sands, and silts.

Topographic factor, LS

The length and inclination (or steepness) of a slope affects the amount of soil erosion. The contributions of slope length factor, L, and the slope steepness, S, were separately analyzed by Wischmeier and Smith (1978) based on the unit plot described above. Empirical equations were developed to estimate values for L and S.

Values of the length factor, L, are primarily related to the slope length, but also depend on the soil type and inclination of the slope. USDA (1997) provides an empirical equation to calculate the L-factor for slopes steeper than 9 percent (most slopes along highways have an inclination greater than 9 percent). The L-factor varies with the slope length in feet as shown by the empirical Equation 2:

$$L = (\lambda / 72.6)^m \tag{2}$$

where L is the slope factor, λ is the horizontal slope length in feet, and m is a variable exponent.

Selection of the horizontal slope length in Equation 2 requires judgement. For example, the use of terraces or other interruptions to a continuous slope face can reduce the slope length. Figure 4 illustrates the reduction in slope length produced by selected erosion control practices. Wischmeir and Smith (1978) offer additional guidance for assessing slope length.

The value of the exponent, m, varies with the soil type and inclination of the slope. The exponent, m, can found using Equations 3 and 4:

$$m = B / (1 + B) \tag{3}$$

$$B = (\sin\theta / 0.0896) / \; (3.0 (\sin\theta)^{0.8} + 0.56) \tag{4}$$

where m is the variable exponent describe above and B is a ratio based on θ, the slope inclination in degrees and the soil's susceptibility to rill erosion. For soils highly susceptible to rill erosion values of B from Equation 4 are doubled when calculating m. Conversely, for soils where rill erosion is less significant, values of B from Equation 4 are halved when calculating m. USDA (1997) contains additional information for selecting appropriate values of the variable exponent, m. Table 4 provides values of the exponent m for typical highway slopes.

Table 4 – Variation in values of the exponent, m, with susceptibility to rill erosion for typical highway slopes (after USDA, 1997)

	Values of the exponent, m		
	Susceptibility to rill erosion		
Slope inclination	**Low**	**Moderate**	**High**
5H:1V	0.44	0.61	0.76
4H:1V	0.47	0.64	0.78
3H:1V	0.50	0.67	0.80
2.5H:1V	0.52	0.68	0.81
2H:1V	0.54	0.70	0.82
1.5H:1V	0.56	0.72	0.84
1H:1V	0.58	0.74	0.85

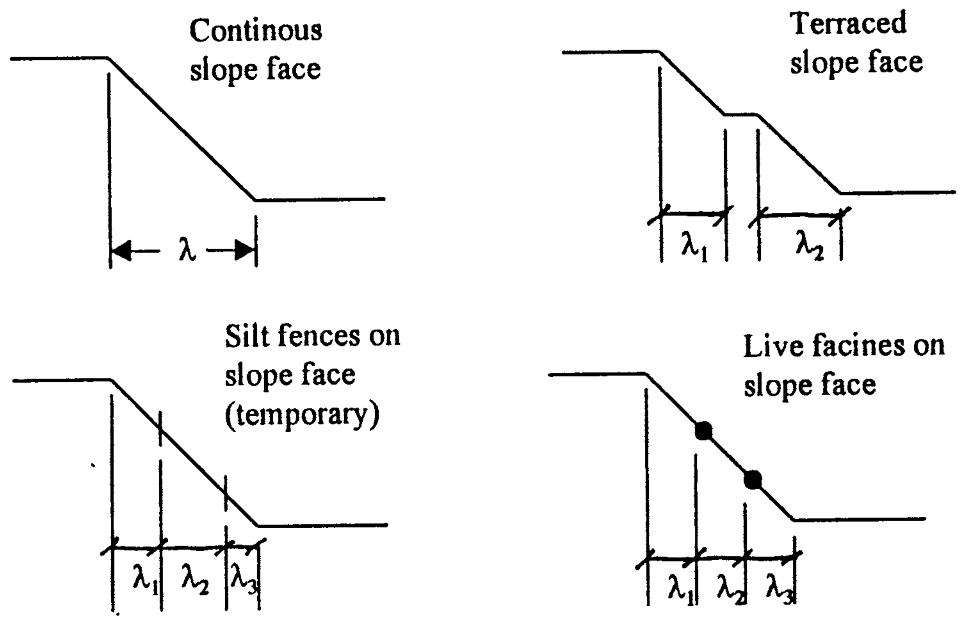

Figure 4 – Examples for the selection of horizontal slope length, λ

Soil loss due to erosion increases more quickly with slope inclination than it does with slope length (USDA, 1997). For slopes steeper than 9 percent, the slope factor, S, is given by the empirical equation:

$$S = 16.8\,(\sin\theta) - 0.5 \tag{5}$$

where S is the slope factor, and θ is the slope inclination in degrees. A similar empirical equation is provided in USDA (1997) for slopes flatter than 9 percent.

The empirical equations for L and S have been provided above, because unlike the rainfall factor, R, and the soil erodibility factor, K, that are essentially constant for a specific site, it may be appropriate to vary values of the topographic factor during design. A spreadsheet is especially useful for this. Moreover, for practical purposes, the effects of L and S are often combined. Table 5 shows typical combinations of slope length and steepness for highway slopes and the associated value of the combined LS-factor. The values in Table 5 were calculated using the empirical equations shown above with *moderate* values of the exponent, m, from Table 4.

Table 5 – Typical values for the topographic factor, LS

Slope inclination	Slope length, meters (feet)					
	7.62 (25)	**15.24 (50)**	**22.86 (75)**	**30.48 (100)**	**60.96 (200)**	**91.44 (300)**
5H:1V	1.5	2.2	2.9	3.4	5.2	6.6
4H:1V	1.8	2.8	3.6	4.4	6.8	8.9
3H:1V	2.4	3.7	4.9	6.0	9.5	12.5
2.5H:1V	2.8	4.5	5.9	7.1	11.4	15.1
2H:1V	3.3	5.4	7.2	8.8	14.3	18.9
1.5H:1V	4.1	6.7	9.0	11.1	18.3	24.5
1H:1V	5.2	8.6	11.7	14.4	24.1	32.5

Unlike the slopes along highways, which are usually uniform, natural slopes are often irregular. The shape of the slope can also affect the amount of erosion. Convex slopes, which are slopes that steepen near the toe of the slope, may have a greater amount of erosion than concave slopes, which are slopes that flatten near the toe. Wischmeier and Smith (1978) and USDA (1997) offer guidance for assessing these irregular slopes.

Cover and management factor, C

The cover and management factor, C, is defined as the ratio of soil eroded under specific vegetative cover conditions to the amount of soil eroded from bare ground (Wischmeier and Smith, 1978). Gray and Leiser (1982) describe the cover factor as "the protective effects of vegetation against erosion." Choice of the cover factor, C, is important when using the USLE for the evaluation of erosion control methods. The protective effects of any given erosion control method can be described using the cover factor.

Bare ground would have a C-factor of 1.0. Values as small as 0.001 have been reported (Ingold and Thomson, 1990). The cover factor can also have a value greater than 1. This can occur, for example, where a specific erosion control method channelizes flows, increasing erosion. Table 6 is a summary of typical values of the cover factor, C.

Ingold and Thomson (1990) pointed out that the cover factor, C, was originally intended to vary with types and densities of vegetative cover to describe long term behavior. They applied the USLE to evaluate the cover factor for erosion control methods in the short term, prior to the establishment of vegetative cover. The short-term behavior of an erosion control method is important because the erosion of an unprotected slope under moderate rainfall events, and for even a short period of time, can be much greater than the erosion of a protected slope. Sprague (1999) provides guidance on selecting C-factors to describe this short-term behavior. Table 7 contains C-factors for various slope treatments over the first year growing period. The annualized values shown from Table 7 are comparable to the values shown in Table 6.

Design values of C can be chosen based on the information in Tables 6 and 7. However, reported values of the cover factor, C, vary from source to source for the same type of protection. It is important to note that individual cover factors should not be combined. A single value of the cover factor should be chosen to most appropriately represent the cover conditions on the slope. Field testing of specific products and conditions would provide the best information for design values.

Erosion control practice factor, P

The practice factor, P, is defined as ratio of soil loss on a slope with a specific erosion control practice to the soil loss for the same slope plowed in continuous fallow, tilled up and down the slope (Wischmeier and Smith, 1978). Improved practices for highway slopes include the use of silt fences or hay bales, terracing, sediment traps, and sediment basins and ponds. Descriptions of the individual practices are provided subsequently. Table 8 is a summary of typical values of the P-factor. Erosion control practices can and should be used to complement the cover provided by an erosion control system. Cover and practice factors are represented by separate factors within the USLE and are multiplicative.

As with the cover factor, the individual values of the practice factor should not be combined. A single value of the practice factor should be chosen to most appropriately represent the practices applied to the slope. However, as has been noted previously, any reduction in slope length due to practices such as terracing should be separately reflected in the slope length factor (Wischmeier and Smith, 1978). Additional discussion of this issue is presented when terracing is discussed later in the report.

Table 6 - Cover factor, C, for varying ground cover conditions (long term behavior) (after Wischmeier and Smith, 1978).

Surface treatment	Cover factor, C
None	1.0
Temporary seedlings (90% stand) – Ryegrass (perennial)	0.05
Temporary seedlings (90% stand) – Ryegrass (annual)	0.10
Temporary seedlings (90% stand) – Small grain	0.05
Temporary seedlings (90% stand) – Millet or sudan grass	0.05
Temporary seedlings (90% stand) – Field bromegrass	0.03
Permanent seedlings (90% stand)	0.01
Sod (laid immediately)	0.01
Hay mulch at 0.11 kg/m^2 (0.5 tons/acre)	0.25
Hay mulch at 0.23 kg/m^2 (1.0 tons/acre)	0.13
Hay mulch at 0.45 kg/m^2 (2.0 tons/acre)	0.02
Hay mulch at 0.45 kg/m^2 [2.0 tons/acre] (Fitfield, 1991)	0.06 - 0.20
Small grain straw mulch	0.02
Wood chips	0.06
Wood chips at 1.58 kg/m^2 [7.0 tons/acre] (Smith and Ports, 1976)	0.08
Wood chips at 2.71 kg/m^2 [12.0 tons/acre] (Smith and Ports, 1976)	0.05
Wood chips at 5.65 kg/m^2 [25.0 tons/acre] (Smith and Ports, 1976)	0.02
Wood cellulose	0.10
Hydraulic mulch (Fitfield, 1991)	0.10
Hydraulic mulch, wood fiber slurry at 0.11 kg/m^2 [0.5 tons/acre] (Armstrong and Wall, 1991)	0.05
Hydraulic mulch, wood fiber slurry at 0.16 kg/m^2 [0.7 tons/acre] (Armstrong and Wall, 1991)	0.01 – 0.02
Hydraulic mulch, wood fiber slurry at 0.40 kg/m^2 [1.75 tons/acre] (Armstrong and Wall, 1991)	0.01
Soil sealent (Fitfield, 1991)	0.01 – 0.60
Erosion control net (Armstrong and Wall, 1991)	0.04 – 0.10
Erosion control blankets (Armstrong and Wall, 1991)	0.009 – 0.015
Erosion control blankets (Sprague, 1999)	0.02
Erosion control mats (Fitfield, 1991)	0.10
Erosion control mats (Sprague, 1999)	0.005 – 0.05
Crushed stone (rip-rap) at 30.51 kg/m^2 [135 tons/acre] (Smith and Ports, 1976)	0.05
Crushed stone (rip-rap) at 52.24 kg/m^2 [250 tons/acre] (Smith and Ports, 1976)	0.02

Table 7 – Effect of short-term behavior on the C-factor (after Sprague, 1999, with permission of the International Erosion Control Association)

Surface treatment	Dry mulch rate: kg/m² (Tons/acre)	Dry mulch rate: Slope inclination	C-factor for growing period: Less than 1.5 months	C-factor for growing period: 1.5 – 6 months	C-factor for growing period: 6 – 12 months	C-factor for growing period: Annualized*
No mulching or seeding	None	All	1.0	1.0	1.0	1.0
Seeded grass	None	All	0.70	0.10	0.05	0.15
	0.23 (1.0)	< 10 %	0.20	0.07	0.03	0.07
	0.34 (1.5)	< 10 %	0.12	0.05	0.02	0.05
	0.45 (2.0)	< 10 %	0.06	0.05	0.02	0.04
	0.45 (2.0)	11 – 15 %	0.07	0.05	0.02	0.04
	0.45 (2.0)	16 – 20 % (5H:1V)	0.11	0.05	0.02	0.04
	0.45 (2.0)	21 – 25 % (4H:1V)	0.14	0.05	0.02	0.05
	0.45 (2.0)	26 – 33 % (3H:1V)	0.17	0.05	0.02	0.05
	0.45 (2.0)	34 – 50 % (2H:1V)	0.20	0.05	0.02	0.05
2nd year grass	None	All	---	---	---	0.01
Erosion control blankets	None	All	0.07	0.01	0.005	0.02
Erosion control mats	None	All	0.14	0.02	0.005	0.05
Fully vegetated erosion control mats	None	All	---	---	---	0.005

*Annualized C-factor = (< 1.5 months value x 6/52) + (1.5 – 6 months value x 20/52) + (6 – 12 months value x 26/52)

Table 8 - Typical values of the Practice factor, P.

Type of Practice	Practice factor, P
Bare surface, compacted and smooth (Gray and Sotir, 1996)	1.3
Bare surface, trackwalked along contour (Gray and Sotir, 1996)	1.2
Bare surface, continuous fallow (Wischmeier and Smith, 1978)	1.0
Bare surface, packed and smooth (Fitfield, 1991)	1.0
Bare surface, trackwalked up and down slope (Gray and Sotir, 1996)	0.9
Bare surface, rough and irregular, tracks in all directions (Fitfield, 1991)	0.9
Punched straw (Gray and Sotir, 1996)	0.9
Rough irregular cut (Gray and Sotir, 1996)	0.9
Bare surface, Freshly disked to 0.31 m [12 in] (Fitfield, 1991)	0.9
Loose to 0.31 m [12 in] depth (Gray and Sotir, 1996)	0.8
Barriers, straw bales (Fitfield, 1991)	0.8
Barriers, gravel filters (Fitfield, 1991)	0.8
Barriers, filter fence (Fitfield, 1991)	0.5
Sediment basins (Fitfield, 1991)	0.5
Terracing (Wischmeier and Smith, 1978)	0.1 - 0.18

Limitations and accuracy of the Universal Soil Loss Equation (USLE)

The Universal Soil Loss Equation (USLE) is an empirical equation for the prediction of sheet and rill erosion rates on slopes. The USLE does not predict erosion from concentrated flows such as in gullies and stream channels. Advantages of use of the USLE include:

1) The USLE highlights important factors for evaluating slope erosion,
2) The USLE allows evaluation of a combination of factors,
3) The cover factor, C, and the practice factor, P, are useful ways to describe the performance of erosion control methods, and
4) The USLE is widely used for predicting erosion rates.

The USLE was originally developed for the conditions typically encountered in agricultural settings. Wischmeier and Smith (1978) state that the most accurate estimates are provided for medium-textured soils, slope lengths of less than 121.92 m (400 ft), gradients of 3 to 18 percent, and consistent cropping and management systems that have been represented in the erosion plot studies. These conditions are not always typical of highway slopes. For example, slope gradients along highways are often greater than 18 percent.

Since its development, the USLE has been used as an engineering tool, although this aspect has not been recognized by the USDA with the publication of the RUSLE in 1997. The accuracy of the predicted soil erosion losses depends on how well the conditions at a specific site are represented by individual parameters. Large scale averaging of parameters for mixed conditions generally reduces accuracy. For example, areas with different soil types, slopes, or surface covers should be broken down into smaller areas for analysis. An exception to this rule applies to the rainfall factor. The USLE is best used as a predictor of annual average values, rather than for specific storm events. Gray and Sotir (1996) state that considerable judgement is required in selecting factor values.

Other Criteria for Evaluating Erosion

The suitability of a particular erosion control product or method is often described in terms of a limiting/permissible velocity or a tractive stress. These two criteria have been developed for the evaluation of erosion in channels with concentrated flow. While the flow in ditches, gullies, and stream channels is not the subject of this report, a familiarity with these criteria is useful when reviewing manufactures' brochures describing erosion control products.

Limiting or permissible velocity criteria

Many guidelines for erosion control products describe the effectiveness of a product in terms of a permissible velocity and duration of flow. The velocity of flowing water is a measure of its erosive capacity. The duration of flow is also important. Large storms can develop periods of flow lasting several days. Over longer periods of flow, lower flow velocities can cause erosive damage equivalent to higher flow velocities with shorter durations. Accordingly, a flow of long duration may have a much lower permissible velocity than a short duration flow would have. Permissible velocities and durations are determined for specific products and conditions, such as channel slope, geometry, and soil type. Permissible velocities are often determined based on the results of laboratory flume testing.

The permissible velocity of flow is compared to the expected velocity to determine the suitability of a potential channel lining. The permissible velocity for a channel lining should be greater than the expected velocity of flow in the channel. The expected velocity for a given flow channel is often evaluated based on the peak runoff. Iteration using the empirical Manning's equation links the velocity of flow with the channel geometry (i.e., hydraulic radius), the slope of the channel, and the roughness of the channel. Manning's equation is given as:

$$V = \frac{1.003R^{\frac{2}{3}}S^{\frac{1}{2}}}{n} \quad \text{or} \quad V = \frac{1.49R^{\frac{2}{3}}S^{\frac{1}{2}}}{n} \tag{6}$$

Metric English

where V is the velocity of flow in meters per second (ft/sec), R is the hydraulic radius in meters (feet) [the hydraulic radius is the ratio of cross-sectional area of flow to the length of the wetted perimeter], S is the slope of the channel, and n is Manning's roughness coefficient. Manning's roughness coefficient is an empirical term used to measure the resistance to flow along the sides of the flow channel. *Hydraulic Engineering Circular No. 15, Design of Roadside Channels with Flexible Linings*, published by the FHWA, describes the use of Manning's equation and provides typical values of the roughness coefficient, n (Chen and Cotton, 1988).

Tractive stress criteria

In 1988, the Federal Highway Administration published procedures for evaluating flexible channel linings using the criteria of tractive stress (Chen and Cotton, 1988). The principal practical advantage of the tractive stress criteria is that only a single parameter is used as a failure criterion, the permissible tractive stress. In addition, use of the tractive stress method is thought to provide a more realistic model of erosion within channels than the permissible velocity approach described above (Chen and Cotton, 1988).

While the tractive stress varies along the sides of a channel, the average tractive stress is given by Equation 7 as:

$$\tau = \gamma_w RS \tag{7}$$

where τ is the average shear or tractive stress in kPa (pounds per square foot, psf), γ_w is the unit weight of water in kN/m^3 (pounds per cubic foot, pcf), R is the hydraulic radius in meters (feet), and S is the average bed slope. It is worth noting that the tractive stress equation does not contain a term describing the roughness of the channel.

The tractive stress method is applied in a manner similar to that of permissible velocities. A comparison of the permissible value for a particular lining to the expected value provides a basis for channel lining selection. Chen and Cotton (1988) provide examples for flexible channel lining design using the tractive stress method.

Principles Of Soil Erosion Control

Erosion is unavoidable during construction. However, the severity of erosion can be mitigated by the consistent application of the principles of soil erosion control. The origin of the principles can be surmised from an evaluation of the terms in the USLE. Principles of erosion control are presented in many sources and their number is not fixed (Goldman et al., 1986; Carroll et al., 1992; Virginia, 1992; Wang and Grubbs, 1992; Gray and Sotir, 1996). Goldman et al. (1986) contains the earliest listing of these principles found, with 10 principles described. The Virginia Sediment and Erosion Control Handbook (Virginia, 1992) lists and describes seven principles of erosion control. The listing from Goldman et al. (1986) has been adapted for use in this section without further attribution.

Fit Development to the Terrain

The natural characteristics of a site should be analyzed during the design of a project. Fitting a project to a site can include aligning roads along contours and locating building pads on the flatter portions of the site. Roads running straight up and down a hill have a long slope length and very high flow velocities, both of which greatly increase the potential for erosion. Building on flatter sites reduces the amount of grading required and hence reduces the area stripped of vegetation.

Time Construction Activities to Reduce Soil Exposure

Construction activities should be timed to reduce the exposure of soil to erosion. This can be accomplished in two ways. First, construction should be staged so that the size of exposed areas is reduced. This includes the prompt installation of erosion control measures in disturbed areas. Second, if possible, construction should be performed during times of the year when the erosion potential is least. Rainfall intensity is a key component affecting the R-factor in the USLE. In Virginia, 70 to 80 percent of the annual rainfall energy occurs between May and September.

Retain Existing Vegetation

Very little erosion occurs on soil covered with undisturbed vegetation. Reestablishing vegetation can be a difficult and costly process, and even after stabilization, disturbed soils erode at a rate greater than undisturbed soils. It has been suggested that it takes at least five years for the rate of erosion at construction sites to approximate the preconstruction rate. Therefore, the area of construction disturbance should be kept as small as possible.

Use Erosion Control Methods and Practices

Erosion control methods and practices protect the ground surface from erosion and restrain the movement of eroded soil. The erosion of an unprotected slope under moderate rainfall events, and for even a short period of time, can be much greater than the erosion of a protected slope. Inspection of the variation in the cover and practice factors for the USLE, as shown in Tables 6, 7, and 8 of this report, clearly shows that the use of erosion control methods and practices can greatly reduce erosion. Prompt application of these methods and practices can significantly reduce erosion on unprotected slopes.

Divert Runoff Away From Denuded Areas

Runoff from areas up gradient should not be allowed to cross construction sites, especially a site stripped of vegetation. Diversion ditches or dikes can be used to divert upland runoff away from disturbed areas.

Minimize Length and Steepness of Slopes

Slope length and steepness are important factors influencing the amount of erosion. Long slopes should be broken up; terraces can be used to slow down runoff and allow some sediment to settle out. Including a ditch on the terrace or slope bench allows for controlled conveyance of water to a stable outlet. Cross-slope ditches should have a gentle slope and should be protected with an erosion resistant lining if erosion potential exceeds the tolerance of the soil.

Keep Runoff Velocities Low

The energy of flowing water increases with the square of velocity. The use of check dams or broad, shallow and flat areas at intervals along a ditch will reduce the velocity of flow and allow settlement of sediments. Runoff velocities in ditches can be kept low by using rough surfaces such as vegetation or rip-rap. Smooth surfaces, such as concrete, remove runoff quickly and may cause flooding downstream. Vegetated surfaces or the use of rip-rap more nearly duplicate channel banks in natural streams and are less likely to contribute to downstream problems.

Manage Concentrated Flows

Construction and development can cause runoff that was once diffuse to become concentrated. Concentrated flow has more erosive potential. The increased erosion from concentrated flows can be mitigated by designing waterway capacity to withstand peak flows, selecting channel linings to match the expected flows, and using energy dissipaters at critical points in the channel.

Trap Sediment on Site

Eroded soil becomes sediment. Sediment control is the trapping of suspended soil particles. It is often desirable or required to trap sediments before they leave a construction site. Common sediment barriers include silt fences, sediment ponds, basins, and traps. Erosion prevention is more efficient than attempting to trap soil particles already in suspension.

Inspect and Maintain Erosion Control Measures

Erosion control measures require maintenance to retain their effectiveness. A single storm event can cause damage that degrades or eliminates the effectiveness of an erosion control method. Examples of this include a breach in a sediment basin, displacement of hay or straw bales, or the loss of anchorage for rolled erosion control products. Inspection and maintenance of control measures can determine the success or failure of an erosion control program.

Significance of the Principles

Design methods for slope erosion control are not well developed. In the absence of design procedures, the principles of erosion control are very important. They provide the designer with rules of thumb for making design decisions. As will be shown in subsequent sections, the current state of practice within VDOT is based around a design philosophy of diverting and controlling runoff, managing concentrated flows, and establishing vegetation on slopes. VDOT's current practices can be described as principle based design.

Methods For Soil Erosion Control

Erosion control consists of reducing the effects of the fundamental erosive mechanisms of detachment and transport. The detachment of soil particles can be reduced by protecting or reinforcing the ground surface with a suitable cover. The movement of soil particles can be limited by reducing the tractive forces of flowing water, by curtailing the amount of flow, or by lowering the velocity of flow. The best erosion control methods address both surface protection from raindrop impact and resistance to the transport of soil. However, there are also niche erosion control methods or products that have been developed to solve specific problems.

Many erosion control measures focus on assisting in the establishment or maintenance of vegetative cover. These types of measures are known collectively as biotechnical methods of erosion control. However, as erosive forces increase, vegetative cover alone may not be sufficient. Armoring of the ground surface may be required to resist erosion. Both biotechnical methods and armoring prevent erosion by protecting the ground surface. Their effectiveness is represented by the cover factor, C, in the USLE. The practice factor, P, represents the contribution of improved land management practices in reducing erosion. Descriptions of specific methods and practices of erosion control are provided below.

Vegetation (Biotechnical Methods)

Any method that uses live vegetation is a biotechnical method of erosion control. The establishment of vegetative cover is traditionally one of the easiest and most efficient methods used to control erosion, with a dense stand of grass cover being one of the best vegetative covers. Grass resists erosion by increasing interception, restraint, retardation, and infiltration of water. The interception of raindrops prior to their impact on the ground surface reduces the potential for soil particle detachment. The grass root system provides reinforcement to restrain soil particles and allows increased moisture infiltration. The presence of grass also retards the velocity of flow across the ground surface, although this effect is more pronounced on flatter slopes (Gray and Sotir, 1996).

Gray and Leiser (1982) and Gray and Sotir (1996) provide a good overview of the uses of vegetation for erosion control. Russ (1993) provides recommendations for site preparation to facilitate grass growth. Rodencal (1995) discusses the lifecycle of grasses and the effect of lifecycle on the selection of an erosion control method. Hunt et al. (1998) provide guidelines for vegetation selection and a guide to types of grasses. Sotir et al. (1998) provide suggestions for partnering geosynthetics and vegetation.

The following subsections contain descriptions of specific biotechnical methods that have been used to foster and sustain vegetation on slopes for the purpose of controlling erosion. These methods involve the use of manmade and natural materials to protect the ground surface against erosion until vegetation can be established. The methods include the following:

1) Loose mulches, tackifiers, and hydraulic mulches,
2) Geosynthetic, rolled erosion control products (RECP) such as nets, meshes, blankets, and mattings,
3) Geocellular containment systems,
4) Fiber roving systems, and
5) Live staking, live facines and brush-layering.

Each is described below. Sample specifications for the installation of erosion control blankets and mats are available in Berg (1993).

Mulches, Tackifiers, and Hydraulic Mulches

Mulches, a traditional method of erosion control, aid the establishment of vegetation. The use of mulches is well accepted. Gray and Sotir (1996) cite three principal benefits of mulches: 1) aiding in the retention of soil moisture by moderating soil temperature and reducing evaporative losses, 2) protecting the ground surface against raindrop impact, and 3) contributing organic matter to the soil by decomposition of the mulch.

Straw and hay are two common types of mulch that are applied to the slope by hand or by mechanical means. Typical application rates range up to 0.45 kg/m^2 (2 tons/acre). Cover factors in the USLE for application rates from 0.11 to 0.45 kg/m^2 (0.5 to 2 tons/acre) are shown in Tables 6 and 7. Fiber lengths of 100 to 200 mm (4 to 8 inches) are suggested as most effective. Loose application of mulches is often used on relatively flat slopes. However, loose mulches are susceptible to blowing and washout. On steeper slopes, some means of anchoring the mulch to the ground surface must be used. Table 9 provides a summary of the advantages and disadvantages of mulches in erosion control.

Table 9 - Advantages and disadvantages of mulches (after CE News, 1998).

Advantages	Disadvantages
• Lowest cost erosion control method • Well accepted • High installation rate, can be placed rapidly • Moderate sediment yield • Promotes vegetative density	• Very temporary (less than 1 year) • Should not be used under severe conditions • Dusty • May require tackifier

Tackifiers consisting of asphaltic emulsions, acrylic polymers, or vegetable gums are often used to hold mulches in place. Miller et al. (1996) describe a testing program for two tackifiers and note that no standard test method is available for evaluating the effectiveness of tackifiers. The tests conducted by Miller et al. (1996) were performed on slopes at a 25 degree inclination, nearly 2H:1V. Using a tackfier provides erosion protection for only a very short time, during which vegetation must become firmly started. The tackifiers tested by Miller et al. (1996) degraded and broke down over an 8 week period after placement.

Lentz and Sojka (1996) describe a method similar to the use of a tackifier. They used a floculant, polyacrylamide (PAM), in irrigation water to reduce the effect of erosion. They found the use of PAM to be most effective on slopes with an inclination of less than 7 percent.

Hydraulic mulches include the use of wood cellulose, paper pulp, or cardboard fiber sprayed on a slope in combination with seed, fertilizer, or other soil amendments such as a tackifier. Remote application in one step (i.e., spraying) is a particular advantage for hydraulic mulches. A principal disadvantage of hydraulic mulches is the relatively short fiber length that must be used. A maximum fiber length of about 5 mm (0.2 inches) is necessary so that the mulch can be pumped and sprayed. Table 10 provides a brief summary of the advantages and disadvantages of hydraulic mulches.

Table 10 - Advantages and disadvantages of hydraulic mulches (after CE News, 1998).

Advantages	Disadvantages
• Low cost erosion control method • Well accepted • High installation rate, can be placed rapidly • Moderate sediment yield • Promotes vegetative density	• Very temporary (less than 1 year) • Should not be used under severe conditions

Erosion Control Nets

Erosion control nets are used to hold down and anchor loose fiber mulches such as straw and hay. Gray and Sotir (1996) provide a physical description of erosion control nets as "relatively thin, two-dimensional woven natural fibers or geosynthetic biaxially oriented process (BOP) nettings." Stakes, staples or pins are used to anchor the netting to the ground surface. The netting itself does not provide any appreciable protection for the ground surface. The anchored mulch serves this role. However, natural fiber nets can absorb moisture and aid in moisture retention. Theisen (1992) states that geosynthetic nets do not absorb moisture, and do not shrink and swell as natural fiber nets do, but are easier to place and may be more durable during installation. Erosion control nets are suitable for moderate site conditions where more costly measures are not required. Table 11 provides a summary of the advantages and disadvantages of the use of erosion control nets.

Table 11 - Advantages and disadvantages of erosion control nets (after CE News, 1998).

Advantages	Disadvantages
• More effective than tackifier	• Temporary (1-2 years) • More costly than tackifier • May interfere with maintenance

Erosion Control Meshes

Erosion control meshes are similar to nettings, but differ in the greater amount of surface cover and protection provided. As with nettings, meshes are intended to work in conjunction with loose fiber mulches. Theisen (1992) notes that meshes may also be used alone or as an underlayer for sod reinforcement. Erosion control meshes are woven using either natural or geosynthetic yarns. Natural fibers include either jute or coir (coconut fiber), while polypropylene geotextiles are used in common geosynthetic meshes. Gray and Sotir (1996) describe coir meshes as being particularly durable (a useful life of 5 to 10 years) with high tensile strength (1790 kg/m to 2684 kg/m [100 to 150 pounds per inch]) and high moisture retention. Jute meshes are noted for their moisture retention, with a water absorption capacity of 450 percent of the dry fabric weight (Gray and Sotir, 1996). An advantage of natural fibers is that they add organic matter to the soil when they degrade. Geosynthetic meshes have high tensile strength to unit weight ratios, but do not significantly retain moisture. Geosynthetic meshes are generally biodegradable. Table 12 summarizes the advantages and disadvantages of erosion control meshes.

Table 12 - Advantages and disadvantages of erosion control meshes (after CE News, 1998).

Advantages	Disadvantages
• Low to moderate cost	• Temporary (1-2 years)
• Moderate sediment yield	• Low flows only
• Good vegetative density	• Not complete ground cover
• Good moisture absorption	

Erosion Control Blankets

Erosion control blankets (ECBs) combine the protective function of mulches with the structure of nettings and meshes. Erosion control blankets are constructed from a blanket of synthetic or natural fibers constrained by woven, glued, or bound geosynthetic biaxially oriented process (BOP) netting or woven natural netting. Fibers consist of some combination of straw, wood, excelsior (a processed wood fiber), coconut, or polypropylene. A wide variety of ECBs are available. Their properties, such as strength and durability, are diverse. Erosion control blankets should be installed in very close contact with the ground surface. Erosion rills can form beneath improperly installed ECBs. As with nettings and meshes, ECBs are held in place with stakes, staples, or pins. VDOT's list of approved products includes erosion control blankets as EC-2 type products. Appendix B contains this listing.

Erosion control blankets are for use under more difficult site conditions than are advisable for nettings or meshes. According to Gray and Sotir (1996), ECBs can be applied on slopes with inclinations up to 1H:1V when flow velocities are under 2.74 meters per second (9 feet per second) for flows with a duration of less than 2 hours. They also can be used on low-impact shorelines. Koerner and Carson (1998) evaluated the field performance of ECBs, and their recommendations for usage are more conservative. While they did not test resistance to flow or shoreline application, Koerner and Carson (1998) recommend the use of ECBs for slopes up to 2H:1V. Additional descriptions of ECB performance can be found in Armstrong and Wall (1991), Fitfield (1992), and Northcutt (1993). Because erosion control blankets degrade with time, their use is limited to areas where permanent, natural vegetation will eventually provide long-term erosion protection. Table 13 is a summary of the advantages and disadvantages for the use of ECBs for erosion control.

Table 13 - Advantages and disadvantages of erosion control blankets (after CE News, 1998).

Advantages	Disadvantages
• Low cost • Easy to install • Very good vegetative density • Very low sediment yield • Good moisture absorption	• Temporary (1-2 years) • Low to moderate flows • May interfere with maintenance

Erosion Control Mats

Unlike mulches, nettings, meshes, and ECBs, erosion control mats provide long-term erosion protection. Erosion control mats are constructed from geosynthetics stabilized against degradation under ultraviolet (UV) light. The matting consists of a matrix of interconnected fibers, which become fully penetrated by plant roots and soil. Erosion control mats provide reinforcement to restrain the movement of soil and vegetation. Erosion control mats should be installed in very close contact with the ground surface. As with nettings, meshes, and blankets, erosion control mats are held in place with stakes, staples, or pins.

There are two classes of erosion control mats available: 1) turf reinforcement mats (TRMs), and 2) erosion control revegetation mats (ECRMs). Figure 5 shows a cross-section illustrating the near surface reinforcement provided by a TRM. Gray and Sotir (1996) highlight the differences between TRMs and ECRMs. Turf reinforcement mats have a thicker cross-section than ECRMs. Perhaps the most significant differences between TRMs and ECRMs are in their methods of installation. The ground surface is not seeded prior to placement of a TRM. The mat is covered with soil and seeds after installation. In contrast, the ground surface is seeded prior to placement of an ECRM. No soil or seeds are used after installation. This order of application can be a disadvantage, because vegetation is established more slowly as the ECRM is gradually filled with sediments. However, erosion control revegetation mats are denser and provide better short-term erosion protection. Table 14 highlights the advantages and disadvantages of erosion control mats.

Erosion control mats should be used for difficult site conditions. Koerner and Carson (1998) recommend the use of turf reinforcement mats for slopes steeper than 2H:1V. The use of erosion control mats as *soft-armor* is described by Carroll and Theisen (1990), Carroll et al. (1991), Cazzuffi et al. (1991), and Theisen and Carroll (1990). VDOT's list of approved products includes erosion control mats as EC-3 type products. Appendix B contains this listing.

Table 14 - Advantages and disadvantages of erosion control mats (after CE News, 1998).

Erosion Control and Revegetation Mats	
Advantages	**Disadvantages**
• Long term protection • Low sediment yields • High vegetative density	• Use for moderate water flows only • Moderate costs • Gradual vegetative growth
Turf Reinforcement Mats	
Advantages	**Disadvantages**
• Long term protection • Use for difficult slope conditions • Protects against moderate to high water flows • Moderate to high vegetative density	• Moderate costs • Low to moderate sediment yields

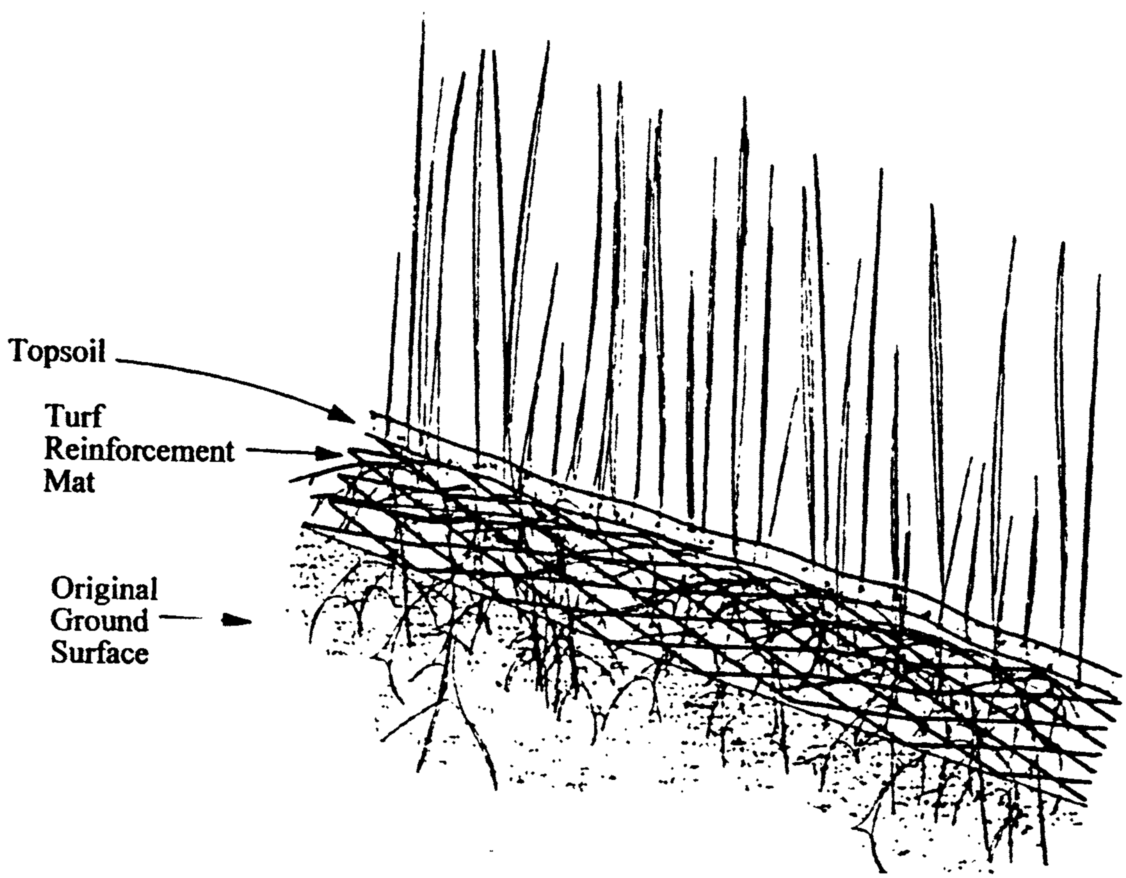

Figure 5 - Cross-section illustrating the interpenetration of roots and soil into the matrix of a turf reinforcement mat (*Biotechnical and Soil Bioengineering Slope Stabilization – A Practical Guide for Erosion Control*, D. H. Gray and R. B. Sotir, copyright © 1996, John Wiley and Sons. Reprinted by permission of John Wiley and Sons, Inc.)

Geocellular Containment Systems

Geocellular containment systems (GCSs) consist of a web of polymeric strips. Polyethylene or polyester strips are typically used. When expanded, GCSs provide an areal, honeycomb pattern of individual cells. Figure 6 illustrates the expansion of a GCS. The GCS cell depth is generally up to 200 mm (8 in). Once expanded and placed on a slope, the cells are filled with soil, gravel, or concrete. If filled with soil and seeded, the upper surface is often covered with an erosion control net or mesh to aid vegetative growth. If used as a channel lining, GCSs filled with stone or concrete can offer significant surface protection.

Cancelli et al. (1990) suggest using zoned protection for slopes with the lower portion of the slope protected with a GCS and the upper portions of the slope protected with an erosion control mat or other appropriate method. Wu and Austin (1992) provide an excellent discussion of design methods and parameters values for GCSs. Table 15 is a listing of the suggested design values for GCSs used as channel linings provided by Wu and Austin (1992). Table 16 lists the advantages and disadvantages of the use of a GCS for erosion control.

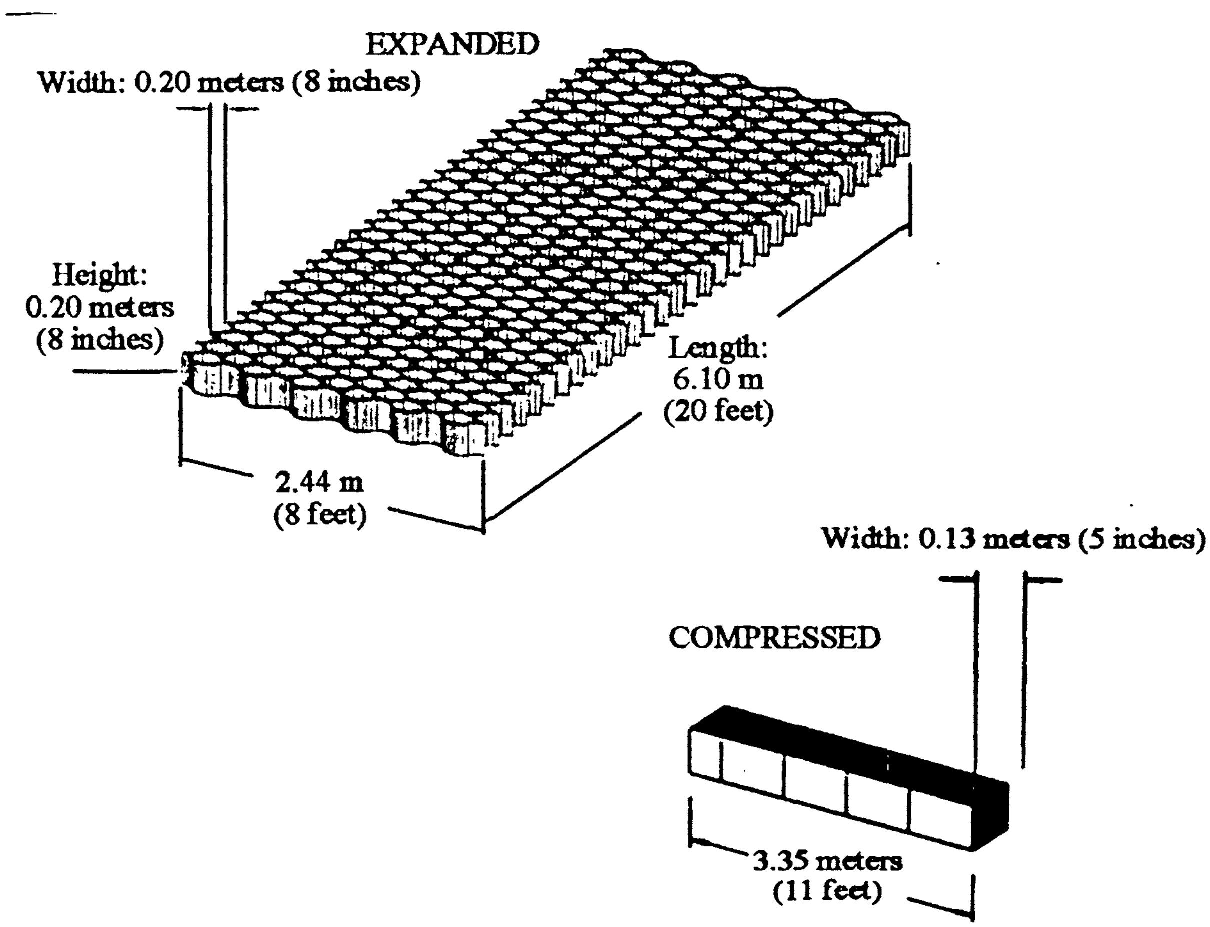

Figure 6 - Schematic illustration of geocellular containment system (*Biotechnical and Soil Bioengineering Slope Stabilization – A Practical Guide for Erosion Control*, D. H. Gray and R. B. Sotir, copyright © 1996, John Wiley and Sons. Reprinted by permission of John Wiley and Sons, Inc.)

Table 15 - Geocellular design values for channel linings (after Three-dimensional Polyethlene Geocells for Erosion Control and Channel Linings. *Geotextiles and Geomembranes*, K. J. Wu and D. D. Austin, copyright © 1992, International Geotextile Society, Vol. 11, pp. 611-620. Reprinted with permission from Elsevier Science.)

Infill material	Geocell diameter mm (inches)	Roughness coefficient, n	Limiting velocity m/s (fps)
Unvegetated topsoil	75 – 125 (3-5)	0.017	0.91 (3)
Vegetated topsoil	75 – 200 (3-8)	0.024	1.52 (5)
Coarse sand	100 – 200 (4-8)	0.020	1.83 (6)
Gravel	150 – 300 (6–12)	0.022	2.44 (8)
Concrete	150 – 300 (6–12)	0.013	4.57 (15)

Table 16 - Advantages and disadvantages of geocellular containment systems (after CE News, 1998).

Advantages	Disadvantages
• Provides long term protection • Protects against moderate to high water flows • Encourages infiltration • Low to moderate sediment yields • Can accommodate various fill materials and plantings	• Moderate costs • Delayed vegetative establishment • Special installation requirements • Low vegetative density

Fiber Roving Systems

Fiber roving systems are significantly different from the erosion control methods described previously. Fiber roving systems are installed by applying a continuous strand of either fiberglass or polypropylene fiber to a pre-seeded ground surface (Theisen, 1992). The roving is then anchored in place using a tackifier. Fiber roving systems are often described as providing only temporary erosion protection. However, UV stabilizers can be added to polypropylene roving to extend its useful life. The method of application ensures that the applied material is in close contact with the ground surface. In addition, the width and thickness of the applied roving can be easily controlled and tailored to provide the desired erosion protection. A summary of the advantages and disadvantages of fiber roving for erosion protection is in Table 17.

Table 17 - Advantages and disadvantages of fiber roving systems (after CE News, 1998).

Advantages	Disadvantages
• Low to moderate costs • High subgrade conformance • Very low sediment yield • Very good vegetative density	• Temporary (1-2 years) • Protects against low to moderate water flows • Special equipment required for installation

Live Planting Methods

Live planting methods such as live staking, live facines, and brush-layering are often thought of as quintessential biotechnical methods. However, as mentioned above, biotechnical methods are more broadly defined as the use of vegetation, often in conjunction with a structural element, to provide surface protection and erosion control. The structural element may consist of erosion control nets, meshes, blankets, or mats, for example.

Live planting methods install live vegetation into a prepared ground surface. Live staking is the insertion of live, rootable vegetation directly into the slope surface. In contrast, the live facine method uses tied bundles of plant material placed in shallow trenches on the surface of the slope. An advantage for the use of live facines is that the slope length used in the USLE can be significantly reduced (USDA, 1997). Brush-layering is similar to the use of live facines. With brush-layering, live, cut branches are placed in an overlapping pattern and partially covered with soil. The goal of all three techniques is rapid plant growth and improved aesthetic appeal. The selection of suitable vegetation for the particular application is a critical component for the use of live planting methods. To aid in plant selection, consultation with a landscape architect may be advisable where experience with specific species or conditions are not available. An advantage of live plantings is the rapid establishment of vegetation. However, the installation of live plantings is often labor intensive.

Armoring

The use of vegetation, as described above, is a common and effective method for providing erosion protection. However, for more challenging site conditions, slope armoring can be used. Armoring consists of protecting the ground surface with particles too large to be displaced by erosive forces or by providing a ground cover strong enough to resist displacement by flowing water. Armoring provides a great deal of erosion protection; however, the cost is relatively high. Rip-rap and gabions are traditional methods for protecting the ground surface from erosion under severe conditions. More recently, fabric formed revetments and articulated concrete blocks have been added to the category of erosion control methods that can be used to armor a slope. Each method is described in the following subsections.

Rip-rap

The most common method of armoring is the use of rip-rap. Rip-rap is the placement of large stones (i.e., gravel, cobbles, or boulders) on the ground surface to provide long-term erosion protection. The effectiveness of rip-rap depends on the size of the stones to resist detachment and transport by water. Stone used for rip-rap should be hard, dense, angular in shape, and should resist weathering and water action. Duffy and Hatzell (1991) found that particles at least 38 mm (1.5 in) in diameter were required to prevent erosion on a 2H:1V slope.

A filter layer is recommended between the ground surface and the rip-rap to prevent soil erosion through the voids between large stones. Holtz et al. (1997) provide a description, criteria, and sample specifications for the use of geotextiles as the filter base for rip-rap.

Disadvantages for the use of rip-rap are labor intensive installation, high costs, and relatively poor visual aesthetics. Gray and Sotir (1996) suggest the use of live cuttings with rip-rap to increase its visual appeal.

Gabions

Gabions originally had a military use; baskets of soil were used to provide protection for the attackers during a siege. Today, gabions are baskets filled with stones used as a stabilizing measure for slopes or to provide long-term erosion protection. The baskets hold the stones in place and allow the use of relatively smaller individual stones than would be used for rip-rap. The baskets are often constructed using wire or using geogrids with a high tensile strength and resistance to abrasion. Wire baskets in a corrosive environment may use a PVC coating on galvanized wire. An advantage of gabions is that they can be stacked in a variety of ways to act as structural building blocks. The advantages and disadvantages of using gabions for erosion control are very similar to those for rip-rap and are listed in Table 18.

Table 18 - Advantages and disadvantages of gabions (after CE News, 1998).

Advantages	Disadvantages
• Provides long term (indefinite) protection	• Moderate costs
• Use for severe conditions	• Delayed vegetative establishment
• Encourages infiltration	• Labor intensive installation
• Low sediment yields	• Low vegetative density

Fabric-Formed Revetments

Fabric-formed revetment systems (FFRs) are formed from two layers of geotextiles filled by pumpable concrete or cement grout. The resulting mat conforms closely to the subgrade. Articulating block mats may use two layers of woven geotextile joined in a quilt-like pattern, or high strength reinforcing strands can be used to connect segments and allow articulation of the resulting mat. Weep tubes can be used between segments to relieve uplift pressures. As with other armoring systems, the use of a filter layer beneath the FFR is recommended. Table 19 summarizes the advantages and disadvantages of FFRs.

Table 19 - Advantages and disadvantages of fabric-formed revetments (after CE News, 1998).

Advantages	Disadvantages
• Provides long term (indefinite) protection	• Moderate costs
• Use for severe conditions	• No vegetation
• Very low sediment yields	• Does not encourage infiltration
• Smooth durable lining	• Special equipment required for installation
• Accurate underwater placement	

Articulated Blocks

Articulated block systems are formed from prefabricated concrete blocks placed as mats or as individually interlocked blocks. The blocks are laid on a smooth prepared subgrade that has been covered with a geotextile filter fabric. To provide additional strength, cables may be used to connect individual blocks. Openings between blocks allow for equalization of uplift pressure and the introduction of vegetation. Articulated block systems provide a relatively smooth surface that can be aesthetically pleasing. Table 20 provides a summary of the advantages and disadvantages of articulating concrete blocks as an erosion control system.

Table 20 - Advantages and disadvantages of articulating concrete blocks (after CE News, 1998).

Advantages	Disadvantages
• Provides long term (indefinite) protection	• High cost
• Use for severe conditions	• Delayed vegetative establishment
• Encourages infiltration	• Special installation requirements
• Very low sediment yields	• Low vegetative density
• Can accommodate vegetation	
• Can be prefabricated into mats	

Improved Practices

Improved practices affect erosion by modifying the flow pattern of runoff, by reducing the rate of runoff, and by trapping sediment to reduce the amount of soil leaving the site. The effectiveness of improved practices in trapping sediments is reflected in the practice factor, P, in the universal soil loss equation. As implied by the use of separate factors in the USLE, improved practices may be combined with other erosion control methods that reduce the amount of erosion, either through vegetation or by armoring the slope. The use of silt fences, hay bales, terracing of the site, check dams, and sediment basins are all examples of improved erosion control practices. These are described in the following subsections.

Silt Fences, Hay Bales, and Brush Layers

Silt fences, hay bales, and brush layers are temporary barriers used to intercept and restrain the movement of sediments. These measures are often used as a perimeter control around a construction site. The use of these controls does not imply that other measures to prevent erosion are not required. Silt fences, hay bales, and brush layers can be though of as the last line of defense.

Silt fences typically consist of geotextile filter fabric stretched between driven stakes. An anchor trench should be used at the base of the fence to prevent flow beneath the barrier. Properly installed silt fences can have sediment trapping efficiencies as high as 97 percent, although poor installation and maintenance can greatly reduce their effectiveness (Virginia, 1992). Many installed silt fences are too short, less than 0.41 m (16 in) high; silt fences should be 0.61 to 0.86 m (24 –34 in) high to prevent breaching and should be properly supported. Good support for silt fences includes the use of stout staking with stakes at least 1.52 m (5 ft) long or the use of a wire supported fence. A sample specification for silt fences is provided in Holtz et al. (1998).

Straw bale barriers are widely used as an erosion control practice because of their low cost and ease of installation. Straw bale barriers, however, may not be the most effective form of temporary barrier because careful installation is required for effective use. Poor installation occurs, for example, where flow depths and velocities are too great or where a poor bale-ground interface allows flow to pass under the barrier. The maintenance of bale barriers is critical; the Virginia Erosion and Sediment Control Handbook (Virginia, 1992) notes that trapping efficiencies may drop from 57 percent to 16 percent in a single month due to lack of maintenance.

Brush layers use the organic litter from site clearing operations, placed in windrows, as a temporary sediment barrier. The use of tree stumps and other large diameter (i.e., over 150 mm [6 in] in diameter) objects cause large voids in the barrier, reducing its effectiveness. Geotextiles can be used to cover brush barriers to increase their effectiveness in trapping sediment. An anchor trench and tie downs should be used with the geotextile to hold it in place. Brush layers are not used as commonly as are silt fences and straw bales, but they offer the advantage of using a waste material constructively.

The Virginia Erosion and Sediment Control Handbook (Virginia, 1992) recommends the use of these temporary barriers where the watershed above the barrier is less than 1011.7 m^2 ($^1/_4$ of an acre) per 30.48 meters (100 ft) of barrier length, which means the maximum slope length above the barrier is 30.48 meters (100 feet), and the maximum slope inclination above the barrier is 2H:1V.

Terracing

Terraces or benches are one of the most effective long-term practices used to control erosion on slopes. Terraces have two principal benefits; they act to reduce sheet and rill erosion by reducing the slope length, and trap eroded sediment on the slope.

Figure 4 shows the reduced horizontal slope length used with terraces. The effect of reduced length is represented in the L-factor in the USLE as shown in Equation 2 (Wischmeier and Smith, 1978).

The low velocity flows along terraces have low erosive potential, and they allow eroded soil to settle out. The use of low cross slope grades increases trapping efficiency. The practice factor, P, assigned for terracing represents this secondary effect of reduced erosion and the trapping of sediment (Wischmeier and Smith, 1978). The value of the practice factor is also based on the length of the slope using one of three cases:

1) For smaller slopes, i.e., slopes with a length less than 33.53 meters (110 feet), use the practice factor from Table 8. Terraces are most effective when they reduce the horizontal slope length to less than 33.53 meters [110 feet] (USDA, 1997).
2) For large slopes, slopes with a length greater than 94.44 meters (300 feet), use a P-value of 1.0. No benefit is provided for long distances between terraces.
3) For intermediate slopes, i.e., slopes with a length between 33.53 and 94.44 meters (110 to 300 feet), interpolate the P-value based on the slope length. The benefits of terracing decrease gradually until no benefit is assigned using the USLE practice factor, P, for spacings greater than 94.44 meters (300 ft).

The principal disadvantage for the use of terraces is that maintenance is required. The eroded soil trapped over time must be removed to maintain the efficiency of the terrace.

Sediment Traps and Rock Check Dams

Sediment traps and rock check dams are relatively small structures used to reduce flow velocities so that sediments can settle out. The sizing of sediment traps and rock check dams is often based on judgement and experience; relatively little engineering design effort is applied to these structures.

A sediment trap is a temporary ponding area used for drainage areas less than 12,140 m^2 [3 acres] (Virginia, 1992). The efficiency of sediment traps is on the order of 40 to 60 percent.

Rock check dams are installed along ditches or other flow channels to reduce the velocity of flow. Check dams should be less than 0.91 meters (3 ft) high and should be used for drainage areas less than 40,470 m^2 [10 acres] (Virginia, 1992). To be most effective, check dams should be spaced so the crest of a lower check dam is at the same elevation as the toe of an upper check dam.

Sediment Basins and Ponds

Sediment basins and ponds are larger structures used to control the movement of sediments. As opposed to check dams and sediment traps, sediment basins and ponds can require significant engineering design effort. The trapping efficiencies of well designed sediment ponds can be quite high. Sediment basins and ponds offer the last opportunity to capture eroded soil before it leaves a site.

Summary Of VDOT Interviews

As part of this project, interviews with VDOT personnel were conducted. The purpose of the interviews was to gain an understanding of the ways that VDOT designs, constructs, and maintains erosion control measures for slopes. Materials, drainage, and environmental personnel were interviewed in each of the nine VDOT districts between March 26 and May 3, 1999. The interviews were conducted by Mr. Jessee A. Scarborough of Virginia Tech.

Prior to these interviews, a series of questions were developed during February and early March. The questions were assembled in the form of a *Request for Information about Slope Erosion Control.* Appendix A contains the questionnaire. The survey included 32 questions dealing with the perceived importance of slope erosion control, factors affecting erosion, factors governing the selection of an erosion control method, construction inspection and maintenance, post-construction inspection and maintenance, and the conditions under which erosion control measures fail. Before the interviews, the questions were sent to each respondent to allow familiarity and preparation for the meetings. The questionnaire provided the agenda at meetings in each of the nine districts.

On the basis of these meetings, it is clear that there are no specific, formal procedures currently in use within VDOT for dealing with slope erosion. However, slope erosion control was generally perceived as a very important issue, and a general design philosophy was found. . Currently, designers generally try to limit erosion by 1) diverting runoff, 2) controlling concentrated flows and 3) establishing vegetation on slopes as quickly as possible.

The survey revealed that vegetation was used for long-term erosion control on virtually all projects. Rip-rap was used on about 30 percent of the projects, generally for repairs. Geosynthetic erosion control products were used on about 20 percent of projects. The use of other methods for long-term erosion control was sporadic.

Silt fences were found to be the most frequent practice used for temporary sediment control. The use of hay bales and brush layers was much lower, at average use rates of about 10 percent and 20 percent, respectively.

Construction inspection of erosion control was perceived as adequate in five of the nine districts. A lack of personnel to perform inspections was generally cited as the reason for inadequate inspection. Modification of the erosion control measures designed and specified in the plans was generally not required during construction. Fitting the design to actual conditions was the reason most often given for the relatively rare changes that were made. However, most districts stated that the timing of installation for erosion control measures usually exceeded that allowed by current regulation, specification, or policy.

As with construction inspection, similar perceptions of post-construction inspection and maintenance were found in the survey. Personnel in five of the nine districts believed post-construction efforts to be adequate. Visibility of an area to the public and to drive-by inspections was often given as a controlling factor for maintenance performed.

The following subsections describe information obtained from VDOT during the survey. This information includes factors contributing to erosion; selection of erosion control methods; and construction, maintenance, and performance of slope erosion controls. Finally, the district responses to a request for other comments about slope erosion are presented.

Factors Contributing to Erosion

One purpose of the survey was to determine what factors were perceived by VDOT personnel as contributing to slope erosion. Inquiry was made into the effect of rainfall duration and intensity, soil type, slope length and inclination, and differences between cut and fill slopes on slope erosion.

Rainfall duration and intensity were not factors considered by VDOT personnel in relation to slope erosion. Six out of nine districts cited the use of rainfall duration and intensity in sizing ditches and curbing, but not for evaluating slope erosion.

Soil type was generally perceived as a factor contributing to slope erosion by VDOT personnel. Problem soils were often identified by the respondents. Table 21 is a summary of the comments made about soil type and its influence on the erodibility of slopes. Soils were classified as problematic by either being highly erodible or by inhibiting the establishment of vegetation. The two most frequently mentioned cases of problematic soil conditions were: 1) micaeous soils were identified as being highly erodible, and 2) residuals soils with a low pH (acidic) were cited as being difficult for establishing vegetation.

Table 21 – Perceived influence of soil type or condition on slope erosion

Soil condition	Frequency (cited in x of 9 districts)	Comment
Micaeous silts	6	High erodibility
Low pH residual soils	4	Establishing vegetation difficult
Sandy soils more erodible than clayey soils	2	Relative erodibility
Placement of topsoil	2	Promotes vegetative growth
Clays with low strength	1	Poor surficial stability
Soils with low plasticity	1	High erodibility
Silty clays and sandy, silty clays	1	High erodibility
Rock fragments in soil	1	Reduces erodibility

Flattening the slope was cited as a potential solution for sites with highly erodible soils. However, increasing the amount of erosion protection on the surface of the slope was not mentioned in the context of designing slopes to reduce erosion. Increasing erosion protection was cited as a remedial measure after an erosion problem was discovered.

The use of topsoil was cited as a potential solution for sites where it was difficult to get vegetation growing. One district reported a need for VDOT guidelines concerning when topsoil should be placed on slopes.

Slope length and inclination were perceived as factors contributing to slope erosion by VDOT personnel. Mass stability and right-of-way constraints were found to be the most significant factors controlling slope length and inclination in the survey. Concerns about erosion on slopes were rarely given as a factor that changed slope design. Slopes steeper than 2H:1V were generally perceived as being more susceptible to erosion. For longer slopes, collection and conveyance of water in ditches, flumes, and pipes were cited as measures for reducing erosion on the slopes. Incremental seeding of slopes was also cited as a factor in reducing erosion on slopes during construction.

Fill slopes were perceived as being more erodible than cut slopes in all nine districts. The reason most often given for this was the likelihood of reduced compaction at the edges of a fill. Increasing compaction at the edges of a fill may reduce the potential for erosion. Moreover, cut slopes in residual soils were generally perceived as being more stable than other cut soil slopes. One district stated that most cut slopes were in rock with limited potential for erosion.

VDOT personnel were also asked, "What other characteristics of a site are taken into account when designing erosion control measures for a slope, and how are they taken into account?" Table 22 is a summary of the replies.

Table 22 – Other factors cited as contributing to slope erosion

Factor	**Frequency (cited in x of 9 districts)**	**Comment**
Size of drainage area or watershed above slope	4	Concentrated flows across the slope face increases erosion
Seeps or springs on slope face	3	Discovered during construction, often unknown during design
Slope location	2	Location relative to streams, wetlands, or private property
Slope facing direction	1	Contributes to the ease with which vegetation grows
Contouring of slope	1	Grooving across face reduces erosion
Discontinuities in rock slopes	1	Can provide conduits for flow and may contain erodible material
Uncontrolled zonation within fills	1	Different fill soils used in the same embankment

Factors in the Selection of Erosion Control Products or Methods

A second purpose of the survey was to determine what factors were perceived by VDOT personnel as significant when selecting an erosion control product or method. Queries included how effectiveness in reducing erosion, promoting vegetation, stability under water flow, durability, and cost were considered when designing for erosion control.

Based on the survey, the effectiveness of an erosion control product or method was only known based on prior experience. Experience with methods proven effective in the past was generally considered to be the most important factor in selecting products or methods for future use. The importance of experience was cited in six of the nine districts. Only one district stated that the current procedures for selecting erosion protection were adequate.

Seven out of nine districts indicated that vegetation was the best erosion control measure. The prevailing view seemed to be that most erosion control measures were temporary until vegetation could be established. Permanent measures, such as geosynthetic mattings and rip-rap, were generally used as a remedial measure for erosion problems. A notable exception to this practice was the use of rip-rap under bridges. Rip-rap is often used for this application because it is difficult to establish vegetation under bridges.

VDOT personnel stated that the stability of erosion control products or methods under water flow was not an important factor for design against erosion on slopes. However, the control of water flow from watersheds above slopes was cited as a very important factor in controlling slope erosion. Flumes and pipes were used to convey storm water down a slope. Stability under water flow was identified as a significant criteria for erosion protection within flumes and ditches.

The durability of erosion control products or methods was generally not considered a significant factor for design. Three districts indicated that erosion control measures must last long enough for vegetation to be established, but that longer lasting measures may provide a maintenance problem by interfering with mowing. There was recognition within the districts that there was a difference in durability between products on VDOT's approved lists. Erosion control blankets (i.e., EC-2 type products) were perceived as less durable than erosion control matting (i.e., EC-3 type products).

The costs for erosion control were not considered in a systematic fashion within the VDOT districts. Engineering concerns, design factors, and compliance with applicable regulations were all of more concern than costs. However, there was a perception that doing it right the first time is less expensive than dealing with continuing maintenance problems. Costs for erosion control were suggested to be of more concern to the residencies than to the districts. VDOT residencies are administrative divisions within a district with jurisdiction for maintenance and small construction efforts.

VDOT personnel were also asked, "What other factors are taken into account when selecting slope erosion control products or methods, and how are they taken into account?" Table 23 is a summary of the responses.

Table 23 – Other factors important in selecting erosion control products or methods

Factor	Frequency (cited in x of 9 districts)	Comment
Environmental or water quality issues	4	Sites near streams or wetlands may require stronger controls
Size of drainage area or watershed above slope	3	Concentrated flows across the slope face increases erosion
Aesthetics	2	How the slope face looks to the driving public
Constructability	2	Site access can be a problem
Contouring	1	Roughening the face of the slope aids vegetative establishment
Freeze thaw	1	Affects surficial stability
Season/time of year	1	Time of year affects vegetative growth
Reducing time of exposure	1	Bare ground is much more susceptible to erosion
VDOT guidelines	1	See Appendix D

The survey respondents were asked what other information and design aids would be helpful in designing slope erosion control measures. A wide variety of responses were received. Table 24 is a listing by district.

Construction, Maintenance, and Performance of Slope Erosion Controls

Another major purpose of the survey was to inquire how measures to prevent slope erosion have performed in the field. VDOT personnel were asked about construction, maintenance, and performance of erosion control measures on slopes. Inspection and maintenance during and after construction were examined, as were the reasons that slope erosion controls failed.

Construction inspection of erosion control was perceived as adequate in five of the nine districts. Conversely, construction inspection was not thought to be adequate in the other four districts. Most of the erosion controls specified in the plans were built without modification. In the cases where changes were made, field engineering to fit the design to the actual conditions was a primary reason for changes.

The time required for installation of slope erosion control measures generally exceeded that required by regulation, specification, or policy. Perimeter controls, such as silt fencing, were described as being installed prior to the start of work in most cases. However, the timing of subsequent seeding during construction was found to vary widely. This variation was reported by one district as being from hours to months after the slope was cut or placed.

Table 24 – Design aids or other needed help

District	What information and/or design aids would be most helpful for use in designing slope erosion control measures?
Bristol	None required
Culpepper	1) We would like to have a computer program, "Windows" based, to consider sheet flow on slopes. The program should allow for incremental consideration of the slope. 2) A responsible party for erosion control in VDOT should be designated.
Fredericksburg	1) Flexibility in design, the ability to tailor the design to the project. 2) We need training for the installation and use of geosynthetics and other similar products.
Lynchburg	Simple charts that provide guidance for selecting methods and provide guidance about where specific methods should be used.
Northern Virginia	Need guidelines for the use of asphalt curbing and slope drains, to help size outlets. The guidelines should be in the form of: For "X" height and with "Y" lanes use "Z."
Richmond	We should obtain more right-of-way, so we can have flatter slopes.
Salem	1) Experience, knowing what works in a given area. We need to make all designers aware of what other designers are doing. 2) We need a training course for erosion control.
Staunton	1) We need funding to be able to provide more focus on smaller jobs. 2) We need more site specific data on what works and what doesn't work.
Suffolk	We need VDOT to commit to evaluating erosion and sediment control issues on slopes.

Incremental seeding of slopes was used to limit the amount of bare ground during construction. Five foot increments of slope height are required in several districts. In addition, work areas greater than 929 square meters (10,000 feet^2) are required to have an erosion and sediment control plan.

The time of year for construction was perceived by VDOT personnel as an important factor influencing the amount of slope erosion that occurs. Table 25 summarizes the relationship between slope erosion and time of year expressed by the respondents. Winter, summer, and spring were perceived as the times of year when most erosion occurs.

Table 25 – Seasonal variation in slope erosion

Season	Frequency (cited in x of 9 districts)	Comments (i.e., causes of erosion)
Spring	5	Heavy rains, continuously wet weather, and freeze-thaw
Summer	6	Heavy rains such as from thunder storms
Fall	1	Many jobs finishing up, so a lot of bare ground
Winter	7	Wettest time of the year, can't grow vegetation

Post-construction inspection and maintenance were perceived as adequate in five of the nine districts. However, inspections were often limited to drive-by inspections. In addition, the visibility of an area to the driving public was cited as a controlling factor for maintenance performed. Based on responses to the survey, there is no VDOT program for regular inspection of slopes. Therefore, slopes not seen easily from the roadway may not be inspected for erosion and may not receive maintenance.

Table 26 is a summary of the reasons given for the failure of slope erosion control measures. Heavy rains and poor installation were the most prevalent conditions identified for failure. Other significant factors identified included difficulty in establishing vegetation and a lack of maintenance.

Table 26 – Perceived causes of failure for slope erosion control measures

Cause of failure	Frequency (cited in x of 9 districts)
Heavy rains	9
Poor installation	5
Can't establish vegetation	3
Lack of maintenance	3
Concentrated storm water flow	2
Differential settlement	1
Erodible soils	1
Poor seed mixtures used	1
Seeps in cut slopes	1
Slopes too steep	1

Other Comments About Slope Erosion

The final question of the survey was, "Please provide any other comments you would like to make about slope erosion." The responses to this question varied, as shown in Table 27.

Table 27 – Responses to the concluding question

District	Please provide any other comments you would like to make about slope erosion.
Bristol	None.
Culpepper	We need guidance on seed/fertilizer criteria for different soils. Right-of-way constraints are a significant influence on what's done for erosion control.
Fredericksburg	The combined efforts of maintenance, construction, and design personnel are needed to prevent slope erosion.
Lynchburg	None.
Northern Virginia	We need to allow limited use of sod in urban areas.
Richmond	The standard seeding rate (i.e., pounds of seed and additive per acre) should be increased.
Salem	Leave room for engineering judgement.
Staunton	Need to balance spending versus the end achieved, and balance cost versus aesthetics and public acceptance. Public perception is very important. Safety: Check dams in ditches may be a safety hazard to the driving public.
Suffolk	VDOT should develop a method to prevent accepting projects from contractors when vegetation is not established.

Erosion Control Practices in Surrounding States

In addition to evaluating the standard of practice for slope erosion control within VDOT, the Departments of Transportation for the states surrounding Virginia were also contacted. DOT personnel in Maryland, West Virginia, Kentucky, Tennessee, and North Carolina were asked to provide feedback. The Federal Highway Administration was also contacted. The following subsections provide a summary of the responses.

Maryland

Maryland has a progressive reputation for erosion control. Montgomery County in Maryland adopted the first sediment control program in the United States in 1965. In 1969, the Maryland legislature required the use of sediment control measures in the Patuxent River watershed, and in 1970 adopted a comprehensive sediment control program. (Smith and Ports, 1976). Mr. Ed Obrec from the Maryland State Highway Administration filled out the survey. The state of practice for Maryland appears to be very similar to that of Virginia. A summary of significant points from the Maryland response is provided below.

Erosion control was perceived to be very important. However, as in VDOT, no specific design procedures were used. The experience of the design engineer with the effectiveness of a specific method was cited as one of the most important factors relied upon during the design process. Maryland has a centralized design bureau. Vegetation was identified as the single most important method of erosion protection. Mulches were almost always used as an aid to establishing vegetation. Other methods of erosion protection such as geosynthetic rolled erosion control products and rip-rap were used less than 10 percent of the time. Silt fences were the erosion control practice of choice, with hay bales, brush layers, sediment traps, and sediment ponds used to a lesser extent.

While Maryland uses a central design bureau, districts throughout the state perform inspection and maintenance. The inspection of erosion controls during construction and post-construction was not believed to be adequate. Some problems were noted to have been found only after they became serious. The failure of erosion control measures was attributed to: 1) inadequate design, 2) poor establishment of vegetation, 3) erodible soils, 4) excessive rains, or 5) subsequent development of adjacent areas. Post-construction maintenance, however, was believed to be adequate.

West Virginia

Mr. Glenn Sherman, the Geotechnical Group Leader for the West Virginia Department of Transportation (WVDOT), provided a summary of the erosion control practices used along West Virginia highways. No design procedures were used for erosion control measures, and erosion was perceived as a construction problem, not generally considered during design. Erosion was noted as more of a problem in cuts in soft shale material and on high embankment fills. During construction, seeding and mulching were the predominant erosion controls used. Moreover, geosynthetic rolled erosion control products were not used for large areas, but were used in ditches at the interface of cut and fill sections. Rip-rap was used to construct repairs in areas where erosion occurred.

West Virginia has an approved listing for erosion control products. Selection of products for the list is made by committee. Field testing has not generally been conducted in the past, although a testbed for some of the newer erosion control methods is proposed along *Corridor H*, an 128.7 km (80 mile) stretch from Elkins, West Virginia, toward Strasburg, Virginia.

Kentucky

Kentucky provided the largest response to the survey outside of Virginia. Five responses were returned. Mr. Gary Poole, chief drainage engineer for the Kentucky Transportation Cabinet (KYTC) coordinated the Kentucky response. The design for slope erosion control was addressed in one of the five returned surveys, while the other four responses provided information on construction, maintenance, and performance of erosion control measures.

The Kentucky Department of Transportation (KYDOT) recently started incorporating erosion control plans into project plans. KYDOT's guidance for design can be found on the internet at www.kytc.state.ky.us/design as design memorandum number 8-98. The design memorandum contains information on Best Management Practices (BMPs) similar to Virginia (1992). District offices and consultants perform slope erosion protection design, with design review provided by the drainage section in the central office. While slope erosion control was perceived as very important, no specific design procedures were reported.

A wide variety of erosion control measures are used in Kentucky. The usage rate for vegetation and loose mulches was 100 percent, and erosion control nettings and meshes had a usage rate of 70 percent. Erosion control blankets and mattings were used at rates of 30 and 50 percent, respectively. The reported frequency of use for rip-rap was 80 percent. Limited use of geocellular containment systems, fiber roving systems, and articulated blocks was also reported. Silt fences and hay bales had a reported usage rate of 100 percent, while no use of brush layers was reported. KYDOT makes extensive use of terraces. Sediment traps, check dams, and sediment basins or ponds had a usage rate of 60 percent.

All respondents reported adequate construction inspection of slope erosion control measures. The time required for inspection, however, was reported as varying from 1 minute per acre to as much time as needed. Opinions about post-construction inspection and maintenance were mixed; responses varied from not adequate to adequate. One response provided a specific description: inspection and maintenance occurred every 2 months for the first 6 months after construction, with no inspection or maintenance performed after 6 months.

Tennessee

Mr. Bill Trolinger, the Assistant State Materials Engineer for the Tennessee Department of Transportation (TDOT) filled out and returned the survey. Slope erosion control was perceived as important and concerns about erosion were noted as sometimes affecting the length and steepness of cuts and fills. However, material types were perceived as having a greater impact on allowable slope height and inclination. Flattening slopes and providing erosion protection were cited as design procedures to prevent erosion. The effect of slope length on erosion was highlighted. Maximum slope lengths in the context of slope erosion control are 7.62 meters (25 ft). Techniques used to reduce slope length for erosion control included benches or a line of straw bales.

Tennessee reported the lowest use of vegetation, at a rate of 80 percent. The use of geosynthetic rolled erosion control products was one of the highest found from the survey, with a usage rate of 50 percent (Kentucky had the highest reported rate of 70 percent). Silt fences, terracing, sediment traps, and sediment ponds were practices always used for erosion control. The 100 percent usage rate for terracing, sediment traps, and ponds was the highest in the survey.

Construction inspection of erosion control was reported as probably not adequate. No response was made regarding post-construction inspection and maintenance. However, improper installation, use of improper methods for the conditions, or extreme rainfall events were cited as common reasons for the failure of erosion control.

North Carolina

North Carolina has apparently unified design and construction inspection for erosion control within a single section/division. Mr. Randy Wise, the Soil and Water Engineering Supervisor for the North Carolina Department of Transportation (NCDOT) completed the survey for NCDOT. Slope erosion control was perceived as very important. Design procedures to reduce slope erosion were very similar to those in Virginia. Priorities for design to control slope erosion included minimizing flows from adjacent watersheds by diversion, the use of slope drains to control concentrated flows, and establishing vegetation. A design storm with a 10-year recurrence interval was used to size slope drains and ditches. Mass stability was noted as the primary factor controlling slope geometry, although terraces were used to reduce the slope length as an erosion control measure.

Stable vegetative cover was noted as a principal design goal and a usage rate of 100 percent were reported. Erosion control blankets and mats, fiber roving systems, and rip-rap were used on 50 percent of the projects. Rip-rap was specifically mentioned as a design alternative to vegetative cover. The rate of 50 percent was the highest rate reported for erosion control blankets and mats. In addition, North Carolina was the only state to report significant use of fiber roving systems. Records of the effectiveness of a product or practice are kept so that design practices can be adjusted based on actual field performance.

An exposed area limit of 4050 to 6070 square meters (1 to 1.5 acres) and staged seeding for slopes in 6.10 to 9.14 meter (20 to 30 ft) vertical increments were reported. Construction inspection of erosion control is centralized in North Carolina. Seven engineers and seven technicians work with the goal of inspecting each project every two weeks during construction. The criteria for post-construction inspection were not reported, and the respondent was unsure if post-construction maintenance was adequate. Poor vegetation, large storm events (storms with a recurrence interval of 25 years or more), and improper construction techniques were mentioned as reasons that slope erosion control measures fail.

Federal Highway Administration

Federal Highway Administration (FHWA) personnel were contacted about slope erosion control practices. Four individuals were interviewed. Mr. Jerry DiMaggio and Dr. Chris Dumas, technical experts for geotechnical engineering within the FHWA, provided a list of contacts in the FHWA and state DOT's. Mr. Jorge Pagan and Mr. Philip Thompson were also interviewed. Mr. Pagan is a FHWA technical expert for erosion along stream channels and for bridge scour, and Mr. Thompson is the senior hydraulics engineer for the FHWA.

Based on a phone conversation with Mr. Pagan on May 12, 1999, there are apparently no design procedures promoted by the FHWA for selecting slope erosion control measures. However, the FHWA does have recommended procedures and specifications for the use of geosynthetic rolled erosion control products, silt fences, and rip-rap, as well as recommended Best Management Practices (BMPs) for sediment and erosion control. Sample specifications from the FHWA work can be found in Berg (1993), Holtz et al. (1997), and Holtz et al. (1998). Mr. Pagan also recommended the use of Chen and Cotton (1988) for the design of channel linings. Mr. Pagan suggested contact with Mr. Philip Thompson, senior hydraulic engineer with the FHWA. Mr. Thompson was interviewed by phone on May 26, 1999. He confirmed Mr. Pagan's assertion that no specific procedures are used by the FHWA for the design of slope erosion control.

Both the FHWA and the American Association of State Highway and Transportation Officials (AASHTO) do provide guidance on drainage and sediment and erosion control (AASHTO, 1999 and FHWA, 1995). The Best Management Practices (BMPs) described in these documents are similar to the information found in the Virginia Sediment and Erosion Control Handbook (Virginia, 1992).

Procedures for Selecting Erosion Control Methods

VDOT designers typically select and specify a level of protection based on experience with locally varying conditions and principles of erosion control. Once a design has been developed, contractors then have responsibility for providing the specified cover type. Contractors can choose from a list of VDOT approved products to provide the needed erosion protection. The contractor is accountable for installation and short-term maintenance, while the responsibility for construction observation and long-term maintenance remains with VDOT. For VDOT, the problems associated with this process include identifying problematic site conditions, selecting an appropriate level of erosion protection, maintaining a suitable list of approved products, and performing adequate inspection and maintenance.

The selection of appropriate and cost-effective erosion control methods is a real problem for design engineers. In most other situations, engineering designs are based on rational procedures, reference to previous work, published standards, or the testing of alternatives. However, the state of practice for erosion control design is not well developed. For example, the American Society of Testing and Materials (ASTM) is in the process of developing standards for erosion and sediment control, but this work is not yet complete.

Currently, information about erosion control methods is based on data from manufacturers or from field tests. The Texas Department of Transportation (TxDOT) uses a test program to select geosynthetic rolled erosion control products for addition to their list of approved products. While data from the TxDOT program is primarily applicable to local conditions, the Texas program is a model for selection of products based on performance observations.

In addition to the use of published standards or test programs, the selection of a specific product can also be based on decision analysis techniques. Decision analysis techniques employ weighting of product characteristics that provides a ranking of expected performance. The ranking can be used for product selection. A disadvantage of these techniques is the lack of case histories and experience using decision analysis for selecting erosion control methods.

The universal soil loss equation (USLE) can be used as a design tool for selecting erosion control methods. Advantages of use of the USLE are that it provides a rational basis for evaluating site condition and is well accepted for predicting erosion rates. It must be recognized, however, that the USLE was developed for agricultural use and that its application to highway slopes represents an extension. To the authors' knowledge, the USLE is not routinely used for slope erosion design by any state department of transportation or by the FHWA. Neither has the reliability of the USLE for slope erosion design been comprehensively evaluated by research studies.

The following subsections contain descriptions of principle based design, use of the USLE, field testing programs such as the TxDOT program, decision analysis techniques, and the ongoing ASTM effort. Design examples are provided for the USLE and decision analysis.

Regardless of what methods are used for selection, cost will be a factor. Methods that provide a high level of protection often have higher costs. Examples of high cost/high protection methods are rip-rap, gabions, and articulated block systems. Table 28 contains a summary of costs that may prove helpful during preliminary design. The costs shown include installation and have been rounded to the nearest dollar.

Table 28 – Cost comparison for common erosion control methods and practices

Erosion control method or practice	Installed Cost
Seed (after Virginia, 1992)	< $ 1 / SY
Loose mulches (after Virginia, 1992)	< $ 1 / SY
Tackifiers (after Virginia, 1992)	< $ 1 / SY
Hydraulic mulches (Means, 1993)	< $ 1 / SY
Erosion control nets (Means, 1993)	$ 1 / SY
Erosion control meshes (Means, 1993)	$ 2 / SY
Erosion control blankets (Means, 1993)	$ 4 / SY
Erosion control mats (Theisen and Richardson, 1998)	$ 6 to 15 / SY
Geocellular containment systems, vegetated (Theisen and Richardson, 1998)	$ 20 to 40 / SY
Geocellular containment systems, concrete filled (Theisen and Richardson, 1998)	$ 30 to 60 / SY
Fiber roving systems, UV stabilized (Theisen and Richardson, 1998)	$ 1 to 2 / SY
Rip-rap (Theisen and Richardson, 1998)	$ 15 to 80 / SY
Rip-rap (Means, 1993)	$ 50 to 60 / SY
Gabions (Theisen and Richardson, 1998)	$ 45 to 75 / SY
Gabions (Means, 1993)	$ 33 to 80 / SY
Fabric formed revetments (Theisen and Richardson, 1998)	$ 15 to 30 / SY
Articulated blocks (Theisen and Richardson, 1998)	$ 40 to 60 / SY
Silt fences (Means, 1993)	$ 1 to 2 / LF
Silt fences (Virginia, 1992)	$ 2 to 5 / LF
Straw or hay bales (Virginia, 1992)	$ 3 to 6 / LF
Brush barrier (Virginia, 1992)	$ 2 to 5 / LF
Cut drainage ditch (Means, 1993)	< $ 1 / LF
Diversion ditch (Virginia, 1992)	$ 3 to 12 / LF
Clean out of ditch (Means, 1993)	< $ 1 / LF
Rock check dams (Virginia, 1992)	$ 13 to 20 / ton
Sediment traps (Virginia, 1992)	$ 500 to 2,100/ unit
Sediment basins (Virginia, 1992)	> $ 15,000 / unit
Sediment removal (Virginia, 1992)	$ 5 to 10 / CY
Notes on units: SY – square yard (1 SY = 0.8361 m^2), LF – linear foot (1 LF = 0.3048 m), and CY – cubic yard (1 CY = 0.7646 m^3)	

Principle Based Design

As described above, VDOT currently uses a design philosophy of slope erosion control by diverting and controlling runoff, managing concentrated flows, and establishing vegetation on slopes. This is principle based design. Principle based design is widespread, based on our survey of surrounding states and the FHWA, and has been successfully used for the design for slope erosion control. According to Goldman et al. (1986), the principles for erosion control are:

1) fit development to the terrain,
2) time construction activities to reduce soil exposure,
3) retain existing vegetation,
4) use erosion control methods and practices,
5) divert runoff away from denuded areas,
6) minimize the length and steepness of slopes,
7) keep runoff velocites low,
8) manage concentrated flows,
9) trap sediement on site, and
10) inspect and maintain erosion control measures.

Tables 29, 30, and 31 provide guidelines for the use of erosion control methods and practices (item 4 in the above list) in principle based design.

Success of principle based design depends on the knowledge, judgement, and experience of the designers. In a large organization like VDOT, designers' knowledge can be expanded by good record keeping and sharing experience across districts. A proposed format for record keeping is included in Appendix C. Compilation and distribution of this information from VDOT projects across the Commonwealth would provide a good basis for improving VDOT's principle based design strategy.

Using the USLE as a Design Tool

Rational selection of a method for erosion control is difficult because of the variety of factors that must be considered. These factors include the physical characteristics of the site, characteristics of an erosion control method, costs, and construction and maintenance practices. The physical factors for the site environment, topography, and surface cover can be assessed using the universal soil loss equation (USLE), as described previously in this report. Figure 7 is a flowchart for the general use of the USLE. To highlight the use of the USLE as a design tool, the U.S. 29 bypass embankments near Madison Heights, northeast of Lynchburg, Virginia will be used as a design example. While construction of this project is ongoing, work on the proposed embankment has not begun. The embankments will be constructed using micaeous residual soil fill, which is known for high erodibility.

Table 29 – Summary of vegetative methods for erosion protection on soil slopes

Method	Guidelines for use
Loose mulches	• Used to protect seeds and ground surface • Long fiber length is primary advantage, more effective than hydraulic mulches • Must be held in place
Hydraulic mulches	• Used to protect seeds and ground surface • Easy application is primary advantage • Must be held in place
Tackifiers	• Used to hold seed and mulches in place • Use for slopes at 2H:1V or flatter [1] • Should not use on long slopes
Erosion control nettings and meshes	• Used to hold seed and mulches in place • Use for slopes at 3H:1V or flatter [2] • Good installation required
Erosion control blankets	• Provides temporary erosion protection • Use for slopes at 2H:1V or flatter [2] • Good installation required • Generally correlates to VDOT's EC-2
Erosion control mattings	• Provides long-term erosion protection • Use for steep slopes • Good installation required • Generally correlates to VDOT's EC-3
Geocellular containment systems	• Provides long-term erosion protection • Can be combined with other methods • Use for steep slopes • Good installation required
Fiber roving systems	• Can provide long-term protection • Amount of protection can be tailored • Use for slopes at 2H:1V or flatter [3]
Live planting methods	• Provides rapid establishment of vegetation • Can be combined with other methods

[1] Based on information from Miller et al. (1996) and interviews with state DOTs.
[2] According to Koerner and Carson (1998).
[3] Based on information from Theisen (1992).

Table 30 – Summary of armoring methods for erosion protection on soil slopes

Method	Guidelines for use
Rip-rap	• Provides long-term protection • Use for severe conditions • Can be combined with live plantings • Use filter layer below rip-rap
Gabions	• Provides long-term protection • Use for severe conditions • Can be combined with live plantings • Can act as structural building blocks • Use filter layer below gabions
Fabric formed revetments	• Provides long-term protection • Use for severe conditions • Use a filter layer below FFRs
Articulated blocks	• Provides long-term protection • Use for severe conditions • Can be combined with live plantings • Use filter layer below articulated blocks

Table 31 – Summary of improved practices for sediment and erosion control

Method	Guidelines for use
Silt fences	• Use for sediment control around perimeter of site • Limit areas upstream of silt fences • Not intended for use in ditches and swales • Good installation required
Hay bales	• Use for sediment control around perimeter of site • Limit areas upstream of hay bales • Short-term use only • Not intended for use in ditches and swales • Good installation required
Brush layers	• Use for sediment control around perimeter of site • Limit areas upstream of brush layers • Allows use of waste material constructively • Not intended for use in ditches and swales • Good installation required
Terracing (Benching)	• Used to break up the slope face and capture sediment • USLE considers the effect of reduced slope length separately • Must provide for conveyance along the bench • Provides long-term protection
Sediment traps	• Used to capture sediment • Limited design effort required, field engineering often adequate • Use to provide short-term sediment control • Use with a limited drainage area (i.e., less than 20,234.3 m^2 [5 acres]) • Provide stable outlet
Check dams	• Used to reduce flow velocity in ditches and swales • Limited design effort required, field engineering often adequate • Short-term use only
Sediment basins and ponds	• Used to capture sediment • Detailed design usually required • Use to provide long-term sediment control

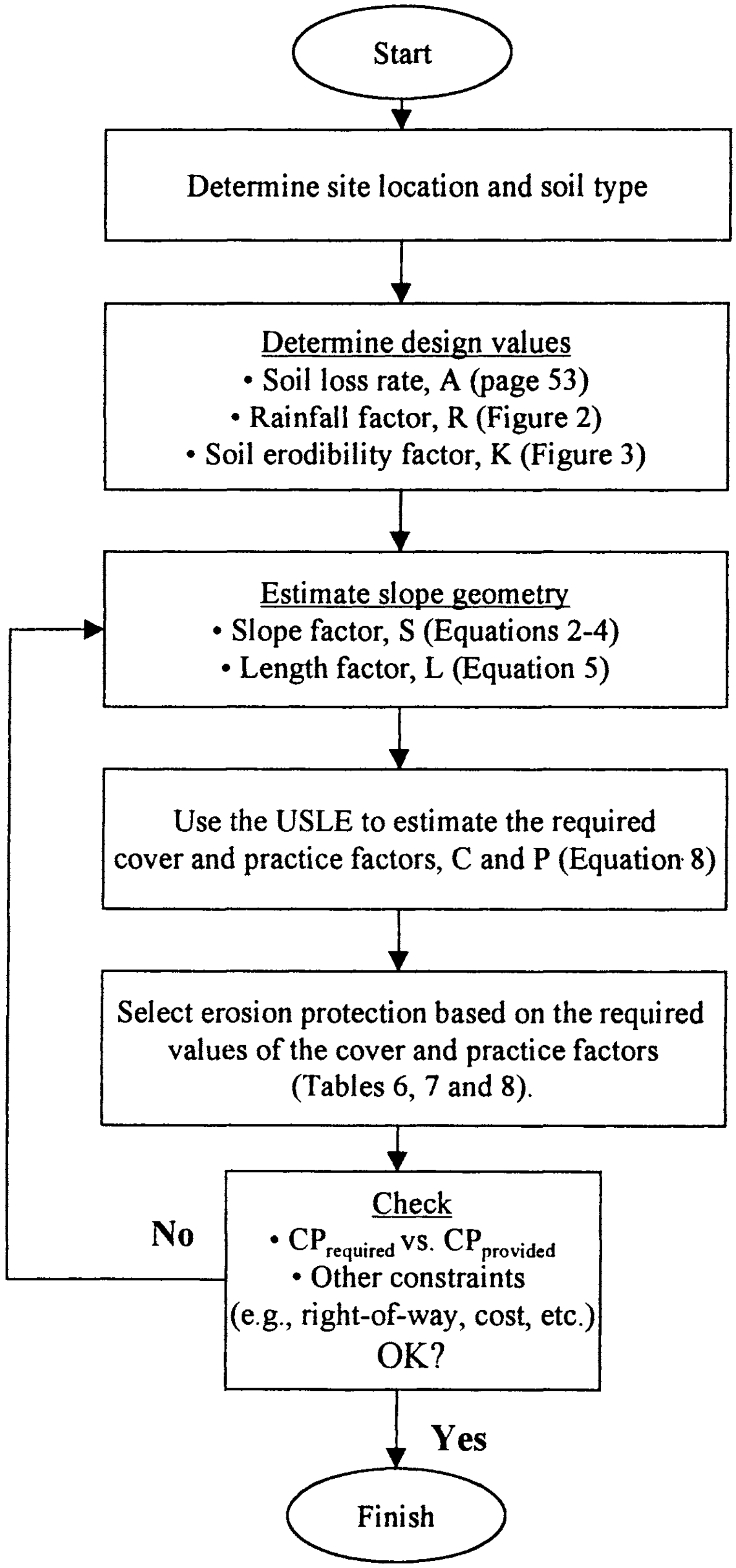

Figure 7 – Flowchart for erosion control design using the USLE

Selection of Design Values

A critical decision when using the USLE as a design tool is the amount of acceptable erosion. Smith and Ports (1976) describe natural erosion rates as being on the order of 0.045 $kg/m^2/year$ (0.2 tons per acre per year) for forest land and 0.023 to 0.226 $kg/m^2/year$ (0.1 to 1.0 tons per acre per year) for a stable, protected watershed. Typical rates for agricultural erosion range from 0.068 to 1.36 $kg/m^2/year$ (0.3 to 6.0 tons per year per acre). Theisen and Richardson (1998) state that for landfill final cover the maximum allowable erosion rate is 0.45 $kg/m^2/year$ (2 tons per acre per year). In addition to describing natural erosion rates, Smith and Ports (1976) also recommend acceptable erosion rate values for application along highways. They recommend design values of 3.39 $kg/m^2/year$ (15 tons per acre per year) during construction and 1.13 $kg/m^2/year$ (5 tons per acre per year) for post-construction sites. For construction projects with a duration of more than 2 years, the lower rate of 1.13 $kg/m^2/year$ (5 tons per acre per year) is recommended. Wischmeier and Smith (1978) also recommended a rate of 1.13 $kg/m^2/year$ (5 tons per acre per year) for construction projects. A value of 1.13 $kg/m^2/year$ (5 tons per acre per year) will be used for the Madison Heights design example in accordance with the recommendations of Smith and Ports (1976).

As described previously, the rainfall factor, R, can be selected based on isoerodent maps as shown in Figure 2. Using Figure 2, a R-value of 175 can be found for the Madison Heights area. In addition, Table 2 provides a range of annual values for the rainfall factor, R for Lynchburg, Virginia. The observed range for the 22 year observation period varied between 64 and 366. Annual values with a probability of non-exceedance of 50, 75 and 95 percent are 164, 232, and 324, respectively. Because most sites do not have such detailed information, and to generalize the design example, the value of 175 from Figure 2 will be used.

The soil erodibility factor, K, has also been described previously. Residual soils for the Madison Heights project are described by Scarborough et al. (1998). Two micaeous residual soils were found: a reddish, sandy elastic silt and a brown, silty sand. In the following discussion these soils are referred to as the red and brown soils. Values for the K-factor can be found using the nomograph in Figure 3. Table 32 shows the soil characteristics used with Figure 3 to select the K-factor. The soil erodibility factors found were 0.47 and 0.29 for the red and brown soils, respectively. The higher proportion of fine grained material in the red soil is the most significant factor in the difference for the estimated soil erodibility factors

Table 32 – Information used to determine the K-factor for the red and brown soils

Characteristic	Red soil	Brown soil
Percent silt & very fine sand	50	30
Percent sand	50	70
Percent organic content	0	0
Soil structure	Very fine granular	Fine granular
Permeability	Slow	Slow to moderate
Soil erodibility factor, K	0.47	0.29

Since the red and brown soils are not expected to be separated during construction of embankments, the higher value for erodibility of the red soil (K = 0.47) will be used for this design example.

Scarborough et al. (1998) found that at Madison Heights, for a 27.43 meter (90 ft) high slope constructed using either the red or brown soil, an inclination of 2.25H:1V was required to provide a long-term factor of safety of 1.3 against mass instability. Steeper slopes would require reinforcement to be stable. We understand that VDOT intends to construct the Madison Heights project with slopes of 2.5H:1V.

A range of slope inclinations from 3H:1V to 1.5H:1V are used in the calculations that follow. The empirical equations (Equations 2 to 5) for the topographic factors shown previously were used to calculate values of L and S. Tables 33 and 34 show the resulting combined values for the topographic factor, LS. Table 33 is based on moderate susceptibility to rill erosion, while the results in Table 34 are based on an assumption of high susceptibility for rill erosion. In Tables 33 and 34, values of LS are provided for slope lengths less than those corresponding to the full 27.43 meter (90 ft) embankment height. The shorter slope lengths are provided so that the impact of terracing can be evaluated.

Table 33 – Calculated values for the topographic factor, LS, assuming moderate rill erosion for the Madison Heights embankments

		Value of the topographic factor, LS					
		Horizontal slope length, meters (feet)					
Slope inclination	**Maximum slope length [1] meters (feet)**	13.72 (45)	27.43 (90)	41.15 (135)	54.86 (180)	68.58 (225)	82.30 (270)
3H:1V	82.30 (270)	3.5	5.6	7.3	8.8	10.3	11.6
2.5H:1V	68.58 (225)	4.1	6.6	8.8	10.6	12.4	---
2H:1V	54.86 (180)	5.0	8.2	10.8	13.2	---	---
1.5H:1V	41.15 (135)	6.2	10.3	13.8	---	---	---

[1] Maximum horizontal slope length for a 27.43 meter (90 ft) high embankment

Table 34 – Calculated values for the topographic factor, LS, assuming high rill erosion for the Madison Heights embankments

		Value of the topographic factor, LS					
		Horizontal slope length, meters (feet)					
Slope inclination	**Maximum slope length [1] meters (feet)**	13.72 (45)	27.43 (90)	41.15 (135)	54.86 (180)	68.58 (225)	82.30 (270)
3H:1V	82.30 (270)	3.3	5.7	7.9	10.0	11.9	13.3
2.5H:1V	68.58 (225)	3.9	6.8	9.5	12.0	14.3	---
2H:1V	54.86 (180)	4.7	8.4	11.7	14.8	---	---
1.5H:1V	41.15 (135)	5.9	10.6	14.8	---	---	---

[1] Maximum horizontal slope length for a 27.43 meter (90 ft) high embankment

Both the red and brown soils are micaeous. Micaeous soils were specifically identified as highly erodible in our VDOT erosion survey. To account for high erodibility, the slopes constructed with these micaeous soil are judged to have a high susceptibility to rill erosion. Therefore, the values for the topographic factor, LS, shown in Table 34 will be used.

Required Cover and Practices to Control Erosion

The USLE can be used to select the cover and practice factors required to limit the rate of erosion to an acceptable value (Wischmeier and Smith, 1978). Rearranging the terms of the USLE, Equation 8 shows how the required cover, C, and practice, P, factors can be found:

$$C \times P = A / (R \times K \times L \times S) \tag{8}$$

where A is the acceptable erosion rate of 1.13 kg/m^2/year (5 tons per acre per year), R is the rainfall factor with a design value of 175 for the Madison Heights U.S. 29 bypass project area, K is the soil erodibility factor with design value of 0.47, and LS is the topographic factor with design values shown in Table 34. Using a spreadsheet, required values of the cover and practice factors can be easily found using Equation 8. Table 35 contains acceptable values of the cover and practice factor product for the slopes at Madison Heights.

Table 35 – Maximum allowable values of the cover and practice factor product for the Madison Heights embankments

	Value of C P					
	Horizontal slope length in meters (feet)					
Slope inclination	13.72 (45)	27.43 (90)	41.15 (135)	54.86 (180)	68.58 (225)	82.30 (270)
3H:1V	0.019	0.011	0.008	0.006	0.005	0.004
2.5H:1V	0.016	0.009	0.006	0.005	0.004	---
2H:1V	0.013	0.007	0.005	0.004	---	---
1.5H:1V	0.010	0.006	0.004	---	---	---

An example calculation to produce one of the entries in Table 35 is shown below. This example is for a 27.43 meter (90 ft) high slope with an inclination of 2.5H:1V and horizontal slope length of 68.58 meters (225 ft). The calculation using Equation 8 is shown below. Note that using the metric value of A (1.13 kg/m^2/year) will yield incorrect values for the cover and practice factor product.

$$C \times P = \frac{A}{R \times K \times LS} = \frac{5.0}{175 \times 0.47 \times 14.3} = 0.004$$

Selected values for C and P from Tables 6, 7, and 8 are reproduced in Table 36. Table 36 also contains expected installation costs for the method or practice from Table 28.

The maximum allowable CP product of 0.004 is not provided by any single control listed in Table 36. Therefore, a combination of controls must be applied to produce an acceptable value of CP.

Table 36 – Selected values of cover factor, practice factor, and cost

Method	Cover Factor, C	Practice factor, P	Cost	Comment
Second year grass	0.01	---	< \$1 / SY	---
Hay mulch 0.45 kg/m^2 (2 tons/acre)	0.05	---	< \$1 / SY	Should not be used for slopes steeper than 2H:1V
Hydraulic mulch 0.40 kg/m^2 (1.75 tons/acre)	0.10	---	< \$1 / SY	Should not be used for slopes steeper than 2H:1V
Geosynthetic erosion control blanket	0.02	---	\$4 / SY	Should not be used for slopes steeper than 2H:1V
Geosynthetic erosion control mat	0.05	---	\$6-15 / SY	No published limitation on slope steepness
Fully vegetated erosion control mat	0.005	---	\$6-15 / SY	No published limitation on slope steepness
Rip-rap, crushed stone, 54.24 kg/m^2 (240 tons/acre)	0.02	---	\$15-80 / SY	C-factor based on 2H:1V slope inclination
Bare slope surface, trackwalked up and down slope	---	0.9	---	---
Terracing, slope length less than 33.53 meters (110 ft)	---	0.1 – 0.18	---	Also reduces slope length (Wischmeier and Smith, 1978)
Terracing, intermediate slope length	---	Interpolated	---	
Terracing, slope length greater than 91.44 meters (300 ft)	---	1.0	---	
Note on units: SY – square yard (1 SY = 0.8361 m^2)				

One possible approach to erosion control for this example would be to construct the embankment with a terrace at mid-height on the slope so that the slope height becomes 13.7 meters (45 ft) for purposes of erosion control design. At this height, the horizontal slope length becomes 34.2 meters (112.5 ft) for a 2.5H:1V slope inclination. Applying Equations 2 to 5 and 8, the maximum allowable value of CP is 0.0074, which can also be obtained by interpolating the values in Table 35. The practice factor for this bench configuration can be obtained by interpolating between the values listed in Table 36. Conservative interpolation yields a practice factor of 0.19. Applying a practice factor of 0.19 to the maximum allowable CP value of 0.0074 yields a maximum allowable C-factor of 0.039. From Table 36, it can be seen that a geosynthetic erosion control blanket with a C value of 0.02 is appropriate. Once vegetation becomes established, erosion should be further reduced, because second year grass has a C value of 0.01, as shown in Table 36.

In summary, this example slope erosion control design for a 27.43 meter (90 ft) high embankment at Madison Heights with 2.5H:1V side slopes consists of providing one bench at mid-height of the slope combined with an erosion control blanket on the slopes above and below the bench. According to the USLE, these control measures should result in an erosion rate less than 1.13 kg/m^2/year (5 tons/acre/year).

Terracing the slope to reduce the slope length for the purpose of erosion control design increases the overall horizontal length of the entire slope by the width of the terrace. Thus, terraces may conflict with other design constraints such as limited right-of-way, and these potential conflicts should be checked. Moreover, benches must slope along the length of the embankment to provide an outlet for drainage. On very long embankments, multiple benches may be required to maintain consistent slope lengths for erosion control.

Only one possible design for slope erosion control was evaluated for the example of the Madison Heights embankments. Other combinations of surface protection and improved practices are available and could also provide adequate protection.

Field Testing Programs for Specific Products and Conditions

Field test programs have been implemented by the Texas Department of Transportation and the Colorado Department of Transportation. These programs, along with two other test programs in Ohio and Wisconsin are described below.

The Texas Department of Transportation (TxDOT) developed a protocol and test facility for selecting geosynthetic rolled erosion control products for addition to a list of approved products. The TxDOT program is described by Godfrey and McFalls (1992) and Northcutt (1993). Northcutt (1993) also provides a description of the program's first year results. This information has been incorporated into the descriptions of erosion control blankets and mats provided previously.

In 1982, TxDOT's standard specifications described erosion control blankets in terms of their physical properties such as unit weight, thickness, tensile strength, and elongation. These requirements were very specific and limited the number of available products. In the early 1990's, TxDOT rewrote their standard specifications to include the following statement: "All soil retention blankets must be prequalified by the Director, Division of Maintenance and Operations prior to use." To satisfy the prequalification requirement, TxDOT established an ongoing formal testing program to evaluate erosion control products. Manufacturers desiring to have products approved pay a testing fee and must submit materials for testing. One test cycle lasts 9 months, beginning in May and lasting until February. A product's ability to provide both slope protection and channel lining protection is tested by TxDOT.

The TxDOT test facility evaluates the slope protection provided by candidate products in the field on an actual embankment. The test embankment is *ell*-shaped, is 6.71 meter (22 ft) high, and has a total length of 267 meters (876 ft). The test embankment's side slopes were constructed at inclinations of 2H:1V and 3H:1V using two soils, a sandy soil and a clay soil. The soils were selected to be typical of conditions found in Texas. Rainfall simulators are used to apply controlled storm intensities and durations. TxDOT evaluates the slope protection provided in terms of two criteria: 1) the ability to prevent the loss of sediment, and 2) the ability to establish permanent vegetative cover.

The TxDOT facility also has the capability to test the performance of flexible channel liners. Ten channels, four with slopes of 3 percent and six with slopes of 7 percent, are used for the liner testing. Each channel has a uniform cross-section with side slopes of 3H:1V. Flexible channel liners are evaluated using the tractive stress criteria (Equation 7).

The methodology used by TxDOT for the selection of approved products is based on the measured performance of installed products over a 9-month period. It includes evaluation of short-term performance, prior to the establishment of vegetation, as well as performance evaluations for long-term behavior with vegetation established.

The Colorado DOT is conducting a three year study of slope erosion control methods. The test location is along U.S. 40 over Berthod Pass. The highway was first built in the early 1960's. Slopes consist of highly erodible soils with variable sized rocks. Erosion of the slopes has apparently contributed to a long standing rockfall hazard for the highway. Methods used for rehabilitation of the slopes along the highway include: small retaining walls, concrete paved ditches, five different tackifiers, five different erosion control mats, two fertilizers, and two types of mulch. Results of the three year project will become available sometime after the year 2000 (FHWA, 1997).

Koerner and Carson (1998) and Cabalka and Clopper (1998) describe two other examples of ongoing field test programs. Results from these studies are included in the sections on erosion control blankets and mats. Koerner and Carson (1998) describe a program evaluating the long-term stability of geosynthetic clay liners for use in solid waste landfills. The study was conducted near Cincinnati, Ohio, and is sponsored by the USEPA. The liners were installed on 2H:1V and 3:H:1V slopes. The surface of the test plots were protected with a variety of geosynthetic erosion control products. Over the last 4 years, 15 erosion control blankets and turf reinforcement mats have been tested in a on-going study. Cabalka and Clopper (1998) describe an erosion test facility in Rice Lake, Wisconsin, operated by the American Excelsior Company. This test facility can evaluate both slope protection and channel protection provided by erosion control products. Slope erosion plots were constructed with slopes at an inclination of 3H:1V using an 0.46 meter (18 in) thick veneer of 3 different soils. The trapezoidal channels were built with side slopes at 2H:1V and longitudinal slopes of 5 and 10 percent. The test procedures described by Cabalka and Clopper (1998) have been submitted to ASTM committee *D-18.25, Erosion and Sediment Control Technology,* for possible inclusion in a final standard.

In addition to qualifying products for an approved list of materials, such as done by TxDOT, field tests provide excellent data for use by designers to evaluate the expected performance of potential erosion control methods. The applicability of this information can be limited by local conditions of the test. For example, data from climatic and physiographic conditions in Texas may not be representative of erosive conditions in Virginia. However, general trends of effectiveness for specific conditions are applicable. The data used to develop the USLE came from a systematic evaluation of similar tests on agricultural plots.

VDOT may wish to consider use of a test program as a tool to evaluate current and potential erosion control products for the approved list of products. Appendix B contains the current VDOT approved listing of erosion control blankets and mats.

Decision Analysis

Williams and Luna (1987) developed a decision analysis technique for the selection of geotextile drainage products. Their procedure was based on a weighting of product characteristics to provide a ranking of expected performance as a basis for product selection. Sprague and Paulson (1996) applied this methodology to the selection of erosion control geosynthetics.

The first step in applying the decision analysis procedure is to select performance criteria. Sprague and Paulson (1996) selected five parameters to act as a yardstick for evaluating erosion control products:

1) sediment yield,
2) vegetative enhancement,
3) stability under flow,
4) durability, and
5) cost.

The five parameters are then ranked, with a *performance number* assigned to each of the five. Since five aspects of behavior were evaluated, the highest value assigned as a performance number is 5; the lowest value is 1. Table 37 contains an example of this initial ranking.

Table 37 – Example of assigning performance numbers (after Sprague and Paulson, 1996, with permission of the International Erosion Control Association)

	Proposed use of the erosion control method	
Performance criteria	**Case 1 Urban drainage channel**	**Case 2 Rural highway slope**
Sediment yield	4	5
Vegetative enhancement	5	3
Stability under flow	4	1
Durability	2	2
Cost	1	4

For Case 1, the criteria of sediment yield and stability under flow are assumed to have equal importance for selection. Therefore, they are assigned performance numbers with equal value.

The second step of the decision analysis procedure is to rank each product's performance in each of the performance categories. These assigned rankings are called the *erosion control indices*. Again, just as with the performance number, the best performing product is assigned the highest value of the erosion control index. In this step, the ranking may be broken down to compare index properties, field test results, or other important factors such as ease of installation.

An example of assigning an erosion control index to four products in the performance category of sediment yield is shown in Table 38. The assessment is made by evaluating and ranking the specific properties for each product, as described previously. The values are then totaled, and the erosion control index is based on the totals. Higher totals indicate better performance.

Table 38 – Example of ranking specific products and assigning the erosion control index

	Performance criteria – Sediment yield					
Product ID	**Flexibility**	**Ground Cover**	**Short-term Behavior**	**Long-term behavior**	**Total**	**Erosion Control Index**
Product A	1	2	1	1	4	1
Product B	2	4	3	1	10	3
Product C	3	3	3	1	9	2
Product D	4	2	4	1	11	4

While not shown here, a similar ranking procedure would be repeated for each of the major performance categories. Sprague and Paulson (1996) provide examples of this. An evaluation of *vegetative enhancement* might be performed by evaluating color, moisture absorption, porosity, and thickness of the candidate products. *Stability under flow* might be evaluated based on the products' permissible tractive stress or velocity. An evaluation of *durability* could be based on the tensile strength, susceptibility to creep, or resistance to ultraviolet degradation. The evaluation of *cost* could be based on installation costs and anticipated maintenance costs. Erosion control indices would be assigned to each product in each performance category.

The third and final step of the selection process is to calculate the *suitability number*, as shown by Equation 9. Product selection can be based on high values of the suitability number.

$$\textit{Suitability number} = \Sigma\,[1 + 0.5\,(\textit{Performance number})]\,[\textit{Erosion control index}] \qquad (9)$$

Table 39 shows an example of applying Equation 9 for the calculation of suitability numbers. This example uses the performance numbers assigned from Case 2 in Table 37, and the erosion control indices for sediment yield from Table 38. Values of erosion control indices for the other performance criteria were obtained in manner similar to that shown in Table 38.

Table 39 – Example for calculating the suitability number

Product ID	Sediment Yield	Vegetative Enhancement	Stability under flow	Durability	Cost	Calculated suitability number
	Performance number					
	5	3	1	2	4	
	Assigned erosion control indices					
Product A	1	2	1	4	4	30
Product B	3	4	2	1	1	29.5
Product C	2	3	3	1	1	24
Product D	4	2	4	4	2	39

Based on the example shown in Table 39, Product D would be the most appropriate product selection with a suitability number of 39. Products A, B, and C follow with suitability numbers of 30, 29.5, and 24, respectively.

The decision analysis technique developed by Williams and Luna (1987) and adapted by Sprague and Paulson (1996) to erosion control applications can provide a basis for the selection of erosion control products. Justification for assigned values should be presented with the results of the analysis so that any partiality in weighting characteristics can be reasonably judged. The outcome of decision analysis techniques should be examined to see if the result is reasonable.

To the author's knowledge, the decision analysis approach has not been assessed by research studies, nor is it routinely used by state departments of transportation or the FHWA.

Proposed ASTM Standard for Erosion Control Products

In 1996, the American Society of Testing and Materials (ASTM) established committee *D-18.25, Erosion and Sediment Control Technology,* to develop standards for erosion and sediment control best management practices (BMPs). The committee plans to address material characteristics, installation requirements, performance capabilities, and application guidelines. Cabalka (1999) reports that the proposed standard will be developed with ten sections. The ten sections consist of the following:

1) Mulches and tackifiers,
2) Erosion control blankets,
3) Turf reinforcement matting,
4) Articulating concrete block revetments,
5) Gabions,
6) Geocellular confinement materials,
7) Fabric-formed concrete revetments,
8) Sediment control,
9) Terminology, and
10) Soil bioengineering.

About 150 personnel are reported to be participating in committee D-18.25. These personnel represent government officials (including several DOT representatives), owners, designers, contractors, manufacturers, testing laboratories, colleges/universities, and industry associations (Cabalka, 1999). A schedule for publication of the proposed standard has not been developed.

Standard terminology, classifications, characteristics, and test methods are expected benefits of the new ASTM standard. The proposed standard should make it easier to evaluate the performance claims made by manufacturers. However, the new standard is not likely to provide a design method for slope erosion control.

CONCLUSIONS AND RECOMMENDATIONS

The erosion of soil slopes is a problem along Virginia's highways. Erosion of soil slopes can create safety hazards, such as undermined pavements. Environmental quality can also be reduced by the sediments from eroded slopes. Moreover, repair of eroded slopes can be problematic due to restricted access and difficult working conditions. Such difficulties can result in high costs for slope repair. Effective erosion protection can prevent or reduce the magnitude of these problems.

A research study was completed to assess the state of erosion control practice and to develop recommendations for improving erosion control activities in VDOT. The following subsections present a summary of the work accomplished to achieve these objectives, the findings of the research, and our recommendations.

Summary of Work Accomplished

An extensive literature review was conducted. In addition, a survey of the state of practice within VDOT was conducted by visiting each of the nine VDOT districts. The purpose of the survey was to gain an understanding of how VDOT designs, constructs, and maintains erosion control measures for slopes. The state of practice within surrounding states and the FHWA was also assessed. The information from these sources was synthesized to produce this report, which include descriptions of erosion fundamentals, erosion control principles, erosion control methods, and procedures for selecting erosion control methods. Design examples are also included.

Findings

The state of the art for design of slope erosion controls is not well developed. Moreover, based on our visits to each of the nine districts, it is clear that there are no specific quantitative design procedures currently in use within VDOT for slope erosion. However, slope erosion was perceived as an important issue and a general design strategy was found. Designers generally try to limit erosion by diverting runoff, controlling concentrated flows on slopes, and establishing vegetation. This is a practice of design by principle, a qualitative process that is heavily dependent on the experience of the designer.

We found that the design practices for the Departments of Transportation in the surrounding states of Maryland, West Virginia, Kentucky, Tennessee, and North Carolina, and for the FHWA, are similar to those used in Virginia. All agencies currently use a principle and experience based strategy for the design of slope erosion control.

We found that an alternative to principle based design of erosion control measures does exist. This alternative employs the Universal Soil Loss Equation (USLE). The USLE is an empirical equation developed to predict erosion losses on slopes. The USLE was developed to quantitatively evaluate the impact that variation in five basic factors have on the rate of soil erosion. These five factors include:

1) the duration and intensity of rainfall,
2) the type and erodibility of soil,
3) the length and steepness of the slope,
4) the type and extent of cover on the slope, and
5) the type and extent of erosion control practices on the slope.

The USLE can be used as a tool for the design of erosion protection. A design example is presented in this report.

Product specific values for the cover factors in the USLE are not generally available. Generic values are available, however, as shown in Tables 6 and 7. Field tests provide the best information about product performance.

Although it shows promise as a design tool, it must be recognized that the USLE is not currently used by VDOT, the Departments of Transportation in surrounding states, or the FHWA for slope erosion control design.

Regardless of the erosion control method selected, construction and maintenance practices will significantly affect field performance. Poor installation is a common problem during construction. Moreover, a single storm event can degrade system performance. Thus, on-going maintenance is required. Lack of maintenance for installed erosion control methods has often been cited as a significant factor in reported failures. Personnel in 4 of 9 districts believed VDOT's current inspection and maintenance practices are not adequate.

We also found, based on our review of the state of practice, that VDOT personnel indicated a need for guidelines to address:

- The use of asphalt curbing and slope drains (from the Northern Virginia district).
- Seed/fertilizer mixes and associated criteria for different soils (from the Richmond and Culpepper districts).

- The use of sod for establishing vegetation in urban areas (from the Northern Virginia district).
- Acceptance of projects from contractors when vegetation has not been established (from the Suffolk district).

Recommendations

We recommend that VDOT continue to use its principle and experience based design practices across the Commonwealth. We also recommend that a system of documentation and communication be established within VDOT to enhance its principle based design. Appendix C contains a listing of elements that can be used to document slope erosion performance. Compilation and distribution of this information has the potential to improve the experience base necessary for successful principle based design.

We also recommend that the USLE be used to complement VDOT's current design practices. The USLE should be used because it is the best available tool, in our opinion, for the quantitative evaluation of slope erosion. VDOT should adopt guidelines for an acceptable soil loss rate for use with the USLE. Based on Smith and Ports (1976) and Wischmeier and Smith (1978), the following acceptable soil loss rates along highways are recommended:

- 3.39 kg/m^2/year (15 tons per acre per year) for most construction,
- 1.13 kg/m^2/year (5 tons per acre per year) for construction projects with a duration of more than 2 years, and
- 1.13 kg/m^2/year (5 tons per acre per year) for post-construction sites.

We recommend that VDOT consider field testing of erosion control products and methods to collect performance data in addition to that generated by the documentation described above for existing and future slope erosion control projects. The test results would be distributed within VDOT to expand designers' experience base. One method for generating performance data is the use of a field testbed, similar to that used by the Texas Department of Transportation, to pre-qualify erosion control products and to generate parameters for design. An alternative method for generating performance data is to incorporate erosion test sections on embankment construction projects. Two levels of performance tests could be performed. The most detailed level of testing would allow assessment of the cover and practice factors for use with the USLE. The bibliography from Wischmeier and Smith (1978) provides sources for guidance in performing this level of testing. Less rigorous testing would be similar to the pre-qualification testing performed by Texas. Godfrey and McFalls (1992), Northcutt (1993), Koerner and Carson (1998), and Cabalka and Clopper (1998) describe this type of *yes/no* testing.

VDOT should review and update their policies on slope erosion inspection and maintenance. Personnel in 4 of the 9 VDOT districts believed the current inspection and maintenance practices to be inadequate. Such a review and update could include a short course on slope erosion control for project inspectors and establishing recommended frequencies for inspection during and after construction.

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Appendix A

Questionnaire: Request for Information about Slope Erosion Control

Erosion Protection for Soil Slopes
along Virginia's Highways

Request for Information about Slope Erosion Control

Section 1 - General

1. What is your job title? ____

2. How long have you worked for VDOT? ____________________ years

3. How important is slope erosion control?

   Very important Important Somewhat important Not important

4. What percentage of your time is spent on slope erosion control issues? ______ %

Section 2 - Design

5. The length and steepness of cut and fill slopes are often determined by requirements related to road alignment, slope stability, and maintenance. Is slope erosion ever taken into account when establishing the length and steepness of soil cut slopes or soil fill slopes?

   Always Sometimes Never Don't Know

   If you answered "always" or "sometimes," how do considerations of slope erosion influence decisions about the length and steepness of soil cut slopes or soil fill slopes?

   ____

   ____

   ____

   ____

6. What personnel are responsible for design of slope erosion protection measures?

   ____

   ____

   ____

7. What design procedures are normally employed for slope erosion protection measures?

____

____

____

8. When designing erosion control measures for a slope, is duration and intensity of rainfall taken into account?

   Always Sometimes Never Don't Know

   If you answered "always" or "sometimes," how is duration and intensity of rainfall taken into account?

____

____

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____

9. When designing erosion control measures for a slope, is soil type taken into account?

   Always Sometimes Never Don't Know

   If you answered "always" or "sometimes," how is soil type taken into account? We are especially interested in knowing how you identify erodible soils.

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____

____

____

10. When designing erosion control measures for a slope, is slope length taken into account?

Always Sometimes Never Don't Know

If you answered "always" or "sometimes," how is slope length taken into account?

____

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____

____

11. When designing erosion control measures for a slope, is slope steepness taken into account?

Always Sometimes Never Don't Know

If you answered "always" or "sometimes," how is slope steepness taken into account? We are especially interested in learning your experience about the relationship between slope inclination and erosion severity.

____

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____

____

____

12. When designing erosion control measures for a slope, are soil cut slopes and soil fill slopes treated differently?

Always Sometimes Never Don't Know

If you answered "always" or "sometimes," how are soil cut slopes and soil fill slopes treated differently when designing slope erosion control measures?

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____

13. What other characteristics of a site are taken into account when designing erosion control measures for a slope? How are they taken into account?

____

____

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____

____

14. When selecting slope erosion control products or methods, is effectiveness in reducing erosion taken into account?

Always Sometimes Never Don't Know

If you answered "always" or "sometimes," how is effectiveness in reducing erosion taken into account?

____

____

____

15. When selecting slope erosion control products or methods, is effectiveness in promoting vegetative growth taken into account?

Always Sometimes Never Don't Know

If you answered "always" or "sometimes," how is effectiveness in promoting vegetative growth taken into account?

16. When selecting slope erosion control products or methods, is stability under water flow taken into account?

Always Sometimes Never Don't Know

If you answered "always" or "sometimes," how is stability under water flow taken into account?

17. When selecting slope erosion control products or methods, is durability taken into account?

Always Sometimes Never Don't Know

If you answered "always" or "sometimes," how is durability taken into account?

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18. When selecting slope erosion control products or methods, is cost taken into account?

Always Sometimes Never Don't Know

If you answered "always" or "sometimes," how is cost taken into account?

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____

19. What other factors are taken into account when selecting slope erosion control products or methods? How are they taken into account?

____

____

____

20. How frequently are the following slope erosion control methods used? Sometimes erosion control methods are used in combination, so the sum of your responses may exceed 100%

Erosion control method	**Frequency of use as percentage**										
Vegetation	100	90	80	70	60	50	40	30	20	10	0
Loose straw or hay mulch	100	90	80	70	60	50	40	30	20	10	0
Hydro-seeding	100	90	80	70	60	50	40	30	20	10	0
Tackifier	100	90	80	70	60	50	40	30	20	10	0
Geosynthetic erosion control netting	100	90	80	70	60	50	40	30	20	10	0
Geosynthetic erosion control meshes	100	90	80	70	60	50	40	30	20	10	0
Geosynthetic erosion control blanket	100	90	80	70	60	50	40	30	20	10	0
Geosynthetic erosion control matting	100	90	80	70	60	50	40	30	20	10	0
Geocellular containment system	100	90	80	70	60	50	40	30	20	10	0
Fiber roving systems	100	90	80	70	60	50	40	30	20	10	0
Rip-rap	100	90	80	70	60	50	40	30	20	10	0
Gabions	100	90	80	70	60	50	40	30	20	10	0
Fabric formed revetments	100	90	80	70	60	50	40	30	20	10	0
Articulated blocks	100	90	80	70	60	50	40	30	20	10	0
Silt fences	100	90	80	70	60	50	40	30	20	10	0
Hay or Straw bales	100	90	80	70	60	50	40	30	20	10	0
Brush layers	100	90	80	70	60	50	40	30	20	10	0
Terracing or benches on the slope	100	90	80	70	60	50	40	30	20	10	0
Sediment traps or check dams	100	90	80	70	60	50	40	30	20	10	0
Sediment basins or ponds	100	90	80	70	60	50	40	30	20	10	0

Selected definitions of these erosion control products and methods are provided on the next page.

Erosion control product definitions for question No. 20:

Tackifier – The use of an asphaltic emulsion, acrylic polymer or vegetable gum to hold mulchesin place.

Geosynthetic erosion control netting – Erosion control nettings provide temporary protection. Erosion control nets are relatively thin and two-dimensional; they are used to hold down and anchor loose mulches.

Geosynthetic erosion control meshes - Similar to erosion control nettings, meshes are used to hold down loose mulches and provide only temporary protection. Physically they have a woven structure of either natural or geosynthetic fibers.

Geosynthetic erosion control blanket – Erosion control blankets (ECBs) provide temporary protection. Erosion control blankets combine the function of nettings and meshes, and contain a mesh or blanket of synthetic or natural fibers constrained by netting.

Geosynthetic erosion control matting - Erosion control mats provide permanent erosion proctection. Two types are commonly used: Turf reinforcment mats (TRMs) of Erosion control revegetation mats (ECRMs). Erosion control mats are noted for their relatively thick cross-section.

Geocellular containment systems – Geocellular containment systems (GCSs) consist of a web of polymeric strips. When expanded GCSs provide an areal honeycomb pattern of individual cells. They cells are typically filled with soil, stone, or concrete.

Fiber roving systems – Fiber roving systems are significantly different than the erosion control methods described above. Fiber roving systems are installed by applying a continuous strand of polymeric fiber to a pre-seeded ground surface.

Fabric formed revetments – Fabric formed revetments (FFRs) are formed from two layers of geotextiles filled with pumpable concrete or cement grout and are used to armor the ground surface in a manner similar to rip-rap.

Articulated blocks – Articulated block systems are formed from prefabricated concrete blocks placed as either mats or as individually interlocked blocks; they are used to armor the ground surface in a manner similar to rip-rap.

Brush layers – Windows of vegetative debris; they restrict the movement of sediment in a manner similar to silt fences.

21. What information and/or design aids would be most helpful for use in designing slope erosion control measures?

____

____

____

Section 3 – Construction, Maintenance, and Performance

22. How soon after cut slope excavation or fill slope placement are erosion control measures usually implemented? Please tell us the typical amount of time.

____

____

____

23. Is there a limit on the amount of exposed ground before slope erosion control measures are implemented? If yes, what is the limit?

____

____

____

24. How important is the influence of the time of year in the amount of slope erosion that occurs?

Very important Important Somewhat important Not important

If you answered "Very important" or "Important," in which season does the most slope erosion occur and why?

Spring Summer Fall Winter

____

____

____

25. What personnel are involved in construction inspection for slope erosion control measures?

____

____

____

26. Is the effort expended on construction inspection for slope erosion control measures adequate? How much time should be allotted per acre for construction inspection of erosion control measures?

____

____

____

27. Are all of the slope erosion control measures specified in the contract documents always constructed?

____

____

____

28. Are certain specified slope erosion measures routinely altered or deleted during construction? If yes, which ones?

29. Is post-construction inspection of erosion control measures adequate? How often should erosion control measures be inspected after construction? How much time (hours/acre/year) should be allotted for post-construction inspection of erosion control measures?

30. Is post-construction maintenance of erosion control measures adequate? How much money ($/year/acre) should be allotted for post-construction maintenance of erosion control measures?

31. Under what conditions do slope erosion control measures fail?

Section 4 – Concluding Question

32. Please provide any other comments you would like to make about slope erosion:

Thank you very much for your cooperation!

Appendix B

VDOT Guidance for Erosion Control Blankets and Mats

Erosion Protection for Soil Slopes
along Virginia's Highways

Appendix B.1

Listing of Approved Products: EC-2 and EC-3

Erosion Protection for Soil Slopes
along Virginia's Highways

VIRGINIA DEPARTMENT OF TRANSPORTATION
STD. EC-2 EROSION CONTROL BLANKETS
APPROVED LIST (REV. 3/7/97)

(VELOCITY 2.5 - 4.0 f.p.s.)

Curlex
Americam Excelsior Company
P.O.Box 5067
Arlington, Tx.76011

Dekowe 700
Dekowe 900
Belton Industries
Hambry Road
Belton, South Carolina 29627

Poplar Excelsior Stitched Blanket
Winters St'd. & H. V. Straw Blankets
Winters Excelsior Company, Inc.
P. O. Box 39, Hwy 21
McWilliams, Alabama 36753

Jute Mesh
Ludlow Manufacturing & Sales Co.
Needham Heights 94, Ma.

Ridgegrow Excel. Eros. Cont. Blanket
Ridgegrow Wood Products
P.O.Box 812
Somerset, Ky. 42501

North American Green S-75
North American Green SC-150
North American Green C-125
North American Green, Inc.
Evansville, Indiana 47711

Soil Saver Heavy Jute Mesh
Jim Walls Company
Commerce Plaza, Suite 109
12820 Hillcrest Road
Dallas, Texas 75230

Jute Mesh
B & M Packaging Co., Inc.
11515 Granite Street 28273
P.O.Box 411007
Charlotte, N. C. 28241-1007

Anti-Wash/Geojute
Belton Industries
8613 Roswell Road, Suite 200
Atlanta, Ga. 30350

X-Cel Permamat 100,
X-Cel Regular, and X-Cel Superior
PPS Packaging Co.
P.O.Box 427
Fowler, CA. 93625-0427

Jute Mesh
Bemis Brothers Bag Company
St. Louis, Mo.

Jute Mesh
Belting Bagging Company
Belton, South Carolina

JMD Jute Mesh
JMD Manufacturing
5401 Progress Blvd.
Bethel Park, PA. 15102

Verdyol Standard ERO-MAT
Verdyol High Vel. ERO-MAT
Verdyol Excelsior Standard
Verdyol Excelsior High Vel.
Verdyol Xtra Standard
Verdyol Xtra High Velocity
Verdyol Alabama, Inc.
P.O.Box 605
105 Miles Pkwy.
Pell City, AL. 35125

BonTerra S-1, S-2, CS-2, & C-2
BonTerra America
P. O. Box 9485
Moscow, ~~Ø~~daho 83843
I

Earthlock
ECS Products, Inc.
9015 Energy Lane
Northport, Alabama 35406

Standard Excelsior Blanket
Standard Straw Mat
High Velocity Excelsior Blanket
High Velocity Straw Mat
Erosion Control Systems, Inc.
9015 Energy Lane
Northport, Alabama 35476
(205)333-3080

BioD-Mat 70 & BioD Mat 90
Rolanka International, Inc.
6476 Mill Court
Morrows, Georgia 30260
(404)961-0331

Greenfix WS052 Straw Mat
Greenfix America
P. O. Box 23310
Santa barbara, California 93121
(619)344-6700

§244.02 (k)(2) Soil retention mats shall consist of a machine-produced mat of wood fibers, wood excelsior, or manmade fiber that shall intertwine or interlock. Matting shall be nontoxic to vegetation and germination of seed and shall not be injurious to the unprotected skin of the human body.

Mats shall be of consistent thickness, with fiber evenly distributed over its entire area, and covered on the top and bottom side with netting having a high web strength or covered on the top side with netting having a high web strength and machine sown on maximum 5.08 cm centers along the longitudinal axis of the material. Netting shall be entwined with the mat for maximum strength and ease of handling.

STD. EC-3 TYPE A AND TYPE B SOIL STABILIZATION MATS
APPROVED LIST (REV. 7/20/98)

TYPE A MATS
(Velocity 4.0 - 7.0 f.p.s.)

Enkamat Earthlock, 7005, and 7010
Erosion Control Systems
9015 Energy Lane
Northport, Al. 35476
(800)942-1986 FAX (205)333-3090

Miramat Regular (18 oz./sq.yd.)
TC Mirafi
365 S. Holland Drive
Pendergrass, Georgia 30567
(800)685-9990 e589 FAX (706)693-4400

Landlok 1050
Synthetic Industries
4019 Industry Drive
Chattanooga, Tennessee 37416
(800)621-0444 FAX (423)499-0753

North American Green C350
North American Green
14649 Highway 41 North
Evansville, Indiana 47711
(812)867-6632

Type B
(Velocity 7.0 - 10.0 f.p.s.)

Bon Terra America SFB
Bon Terra America Inc.
P.O.Box 9485
Moscow, Idaho 83843
(208)882-2512

TerraGuard 44P & 45P
WEBTEC, Inc.
P. O. Box 240302
Charoltte, NC 28224-0302
(800)438-0027, FAX (704)394-7946

Enkamat 7012, 7020, 7210, & 7220
Erosion Control Systems
9015 Energy Lane
Northport, AL 35476
(800)942-1986, FAX (205)333-3090

Tensar TB1000 & TM3000
Tensar Earth Technologies
5775-B Glenridge Drive
Lakeside Center, Suite 450
Atlanta, Georiga 30328-5363
(800)292-4459, FAX (404)705-9650

Miramat Heavyweight (24 oz./sq.yd.)
Mirafi TM 8
TC Mirafi
365 S. Holland Drive
Pendergrass, Georgia 30567
(800)685-9990 e589 FAX (706)693-4400

Landlok 435, 450, 460, & 1060
Synthetic Industries
4019 Industry Drive
Chattanooga, Tennessee 37416
(800)621-0444, FAX (423)499-0753

North American Green P-300, P300P
North American Green
14649 Highway 41 North
Evansville, Indiana 47711
(812)867-6632

PEC-MAT
Greenstreak, Inc.
3400 Tree Court Ind. Blvd.
St. Louis, Missouri 63122
(800)325-9504, FAX (314)225-9854

* Mats listed in the Type B category may be substituted for the Type A material at no additional cost the VDOT.

STD. EC-3 TYPE C SOIL STABILIZATION MATS
APPROVED LIST (REV. 7/20/98)
(Slopes 3:1 and flatter)

Enkamat Earthlock, 7005, and 7010
Erosion Control Systems
9015 Energy Lane
Northport, AL 35476
(800)942-1986, FAX (205)333-3090

Landlok 1050
Synthetic Industries
4019 Industry Drive
Chattanooga, Tennessee 37416
(800)621-0444, FAX (423)499-0753

Miramat Regular (18 oz./sq.yd.)
TC Mirafi
365 S. Holland Drive
Pendergrass, Georgia 30567
(800)685-9990 e589, FAX (706)693-4400

North American Green C350
North American Green
14649 Highway 41 North
Evansville, Indiana 47711
(812)867-6632

* Mats listed in the Type B category may be substituted for the Type A material at no additional cost the VDOT.

TYPE C MATS
(Slopes steeper than 3:1)

Enkamat S
Erosion Control Systems
9015 Energy Lane
Northport, AL 35476
(800)942-1986, FAX (205)333-3090

Pyramat 4700
Synthetic Industries
4019 Industry Drive
Chattanooga, Tennessee 37416
(800)621-0444, FAX (423)499-0753

Appendix B.2

Instructional and Informational Memorandum
for the use of EC-3

Erosion Protection for Soil Slopes
along Virginia's Highways

VIRGINIA DEPARTMENT OF TRANSPORTATION

LOCATION AND DESIGN DIVISION

INSTRUCTIONAL & INFORMATIONAL MEMORANDUM

GENERAL SUBJECT: SOIL STABILIZATION MAT	NUMBER: LD-96 (D) 166.3
SPECIFIC SUBJECT: STANDARD EC-3	DATE: March 22, 1996
	SUPERSEDES: LD-94 (D) 166.2
SIGNATURE:	

Changes are shaded.

CURRENT REVISION

- Standard EC-3 Soil Stabilization Mat Slope Installation **Sheet 2 of 2** in the 1994 Metric Road and Bridge Standards and the 1993 Imperial Road and Bridge Standards is void.
- Standard EC-3, **Sheet 2 of 2**, is replaced by an Insertable Sheet for Standard EC-3, **Type C**, Soil Stabilization Mat for use in slope stabilization.
- A Pay Item has been added for Standard EC-3, **Type C**, Soil Stabilization Mat.

EFFECTIVE DATE

- These instructions are effective on all projects scheduled for the August 1996 advertisement and all subsequent projects.

POLICY

Ditches

- Geotextile materials designated as Standard EC-3 (Type A and B) Soil Stabilization Mat are used for protective linings in ditches.

- Standard EC-3 Soil Stabilization Mat is intended to be used as a protective ditch lining material to be applied when the design velocity exceeds the allowable velocity for Standard EC-2 (i.e., jute mesh).

- When the design velocity exceeds the allowable velocity for Standard EC-3, a paved (or riprap) lining will be required.

Slopes

- The Standard EC-3 (Type C) Soil Stabilization Mat may be used as a protective slope lining for dry cut or fill slopes and wet cut slopes to stabilize the slope on which vegetation is being established. (See <u>Road and Bridge Standards</u>)

TYPES AND APPLICATION

Ditches

- Type A is to be employed where the design (2 year) velocity in the ditch is within the range of 1.2 to 2.1 meters per second (m.p.s.) (4 to 7 f.p.s.)

- Type B is to be employed where the design velocity is within the range of 2.1 to 3.0 m.p.s. (7 to 10 f.p.s.)

- A Manning's "n" value of 0.05 should be used with Standard EC-3.

- Typically, the use of Standard EC-3 Type A should begin at the point where flow velocity exceeds 1.2 m.p.s. (4 f.p.s.) (velocity is assumed to be for flow in an EC-2 lined channel) and continue changing to EC-3, Type B at the appropriate point, until the design velocity exceeds 3.0 m.p.s. (10 f.p.s.) or until such point as the use of a ditch lining can be discontinued.

- Experience has shown that the installation of this material is particularly critical. <u>It must be installed in strict accordance with the standard drawings and manufacturer's specifications.</u>

- It is requested that Standard EC-3 (Type A and B) installations be monitored very closely to determine the validity of the present design criteria. It is recommended that the District Drainage Engineer, in cooperation with appropriate District Environmental and/or Maintenance personnel, visit these installations, particularly after significant or intense rainfall events, and prepare a report of their observations which would then be submitted to the Central Office Hydraulics Section on a regular basis until further notice.

Slopes

- Locations are to be recommended by the District Environmental and/or Materials sections during plan development.
- Standard EC-3 Type C is to be installed in accordance with the standard drawing and the manufacturer's specifications.

PAY ITEMS AND SUMMARIZATION

The following items are to be summarized, when applicable, in the Erosion & Sediment Control Summary on the Roadside Development Sheet:

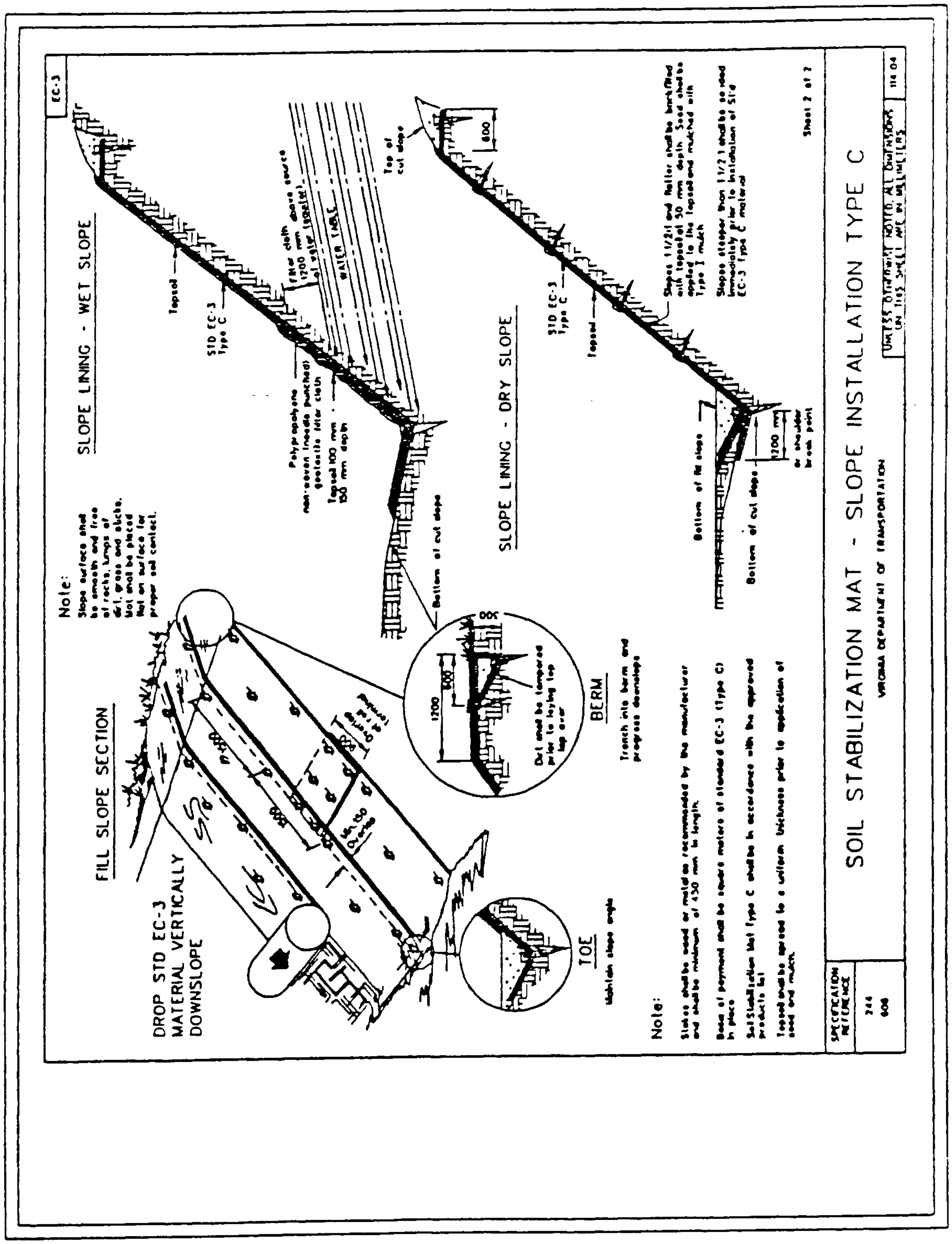
ITEM	UNIT	ITEM CODE
Soil Stabilization Mat EC-3, Type A	m^2 (S.Y.)	27325
Soil Stabilization Mat EC-3, Type B	m^2 (S.Y.)	27326
Soil Stabilization Mat EC-3, Type C	m^2 (S.Y.)	27327

INSERTABLE SHEET

The following Insertable Sheet (Metric and Imperial) will be available in the CADD Insertable Sheet Directory after March 25, 1996.

- Soil Stabilization Mat - Slope Installation Type C, Drawing No. A 107.

NOTE: THIS IS A SAMPLE INSERTABLE SHEET. FOR A MORE LEGIBLE AND CURRENT VERSION, ACCESS THE CADD INSERTABLE SHEET DIRECTORY.



Appendix C

Form for Collecting Information about Slope Erosion Control

Erosion Protection for Soil Slopes along Virginia's Highways

Project designation:		District:	
Location:		Type of slope:	Cut / Fill

Design data

Method used:	principle based	USLE	decision analysis	field engineering
	other (describe):			
Protection required or other data :				

Slope description

Slope height:		Slope length(s):			
Slope inclination (H:V or degrees):			Shade or sun:		
Soil type(s):					
Geologic origin:					
Slope strike direction:			Slope dip direction:		
Drainage structures on slope:					
Type(s) of existing vegetation:					
Evidence of existing erosion:	bare ground	rills	gullies	sediment at toe	
Other (describe):					

Erosion protection provided

Temporary or permanent:			
Type(s) of protection provided: Additional description(s):	Biotechnical mulches tackifiers nettings meshes blankets (EC-2) mats (EC-3) geocelluar system fiber roving system live plantings	Armoring rip-rap gabions articulated blocks fabric revetments If used is there a filter layer beneath: yes no	Improved practices silt fences hay bales brush layers benches sediment traps check dams sediment basins sediment ponds
List manufacturers and brands:			
Type(s) of vegetation:			

Performance

Contractor name:			Date constructed:			
Construction quality:	outstanding	excellent	good	poor	other	
Significant rainfall:						
Describe performance: (use back of form if additional space is required)						