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SLOPE EROSION CONTROL FOR URBAN FREEWAYS IN ARID CLIMATES

Volume II - Design Manual

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16. Abstract

The purpose of this design manual is to provide a concise reference to assist in the design of slope erosion protection in arid climates. This document is based on methods developed during a two year research program conducted in the Metropolitan Phoenix area. The research report titled: Slope Erosion Control for Urban Freeways in Arid Climates, Volume I contains a detailed description of the methodology.

The use of rock fragments, resistant to weathering, and with shape factors larger than 2 to resist slope erosion is a practical technique in arid climate where the use of grasses is difficult. Slopes as steep as 26 degrees can be protected with rock fragments against design storms that deliver precipitation intensities on the order of 1.8 inches per 30 minutes.

Final Report, Volume I.

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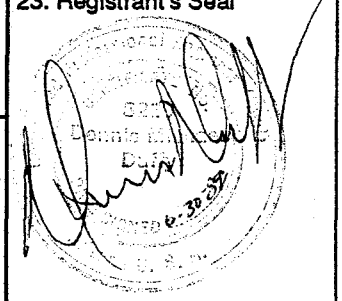

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SI (Metric) UNIT CONVERSION FACTORS

This report uses both English and SI units with the authors selecting the unit most appropriate. The following factors may be used to convert the measures used in this report to the International System of units (SI):

1 inch = 2.52 centimeters

1 foot = 0.3048 meter

1 pound force = 453.59 grams

1 centimeter per sec = 1.9685 feet per minute

1 gallon per minute = 3.785 liters per minute

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Introduction

Since freeway slopes were constructed, ADOT personnel have been attacking the slope erosion problem. As part of that effort a system of slope protection schemes has evolved. Crushed rock fragments, chemical additives, and vegetation were applied to slopes in an attempt to minimize erosion.

In 1986 ADOT contracted with the authors to review erosion costs, examine slope protection techniques tried to date, and develop a basic slope erosion research program to provide guidance for future slope protection efforts. This manual and Volume I, from which it is derived, are two products of that research.

Conclusions

The following conclusions affecting the design of slope erosion resistance were reached:

1. Any slope exposed to the environment will experience erosion. This erosion is a function of precipitation falling on a the slope. The most significant aspect of this precipitation is the accumulation of water in small channels that pass over the slope face. It is this "overland" flow that produces the greatest stress on the slope. Every slope must be designed to minimize and manage overland flow if erosion is to be held to a minimum. The use of retention basins and armored slope channels at controlled discharge

points are two ways in which overland flow can be managed (see Figure 1).

2. As slope angle increases, the erosion rate increases, the flow channel velocities increase, and the force of gravity assists in the removal of slope particles by the flow.

3. The longer the slope, the greater the collected overland flow, and the larger the erosion rate.

4. Most Arizona soils and rock masses possess a potential to develop a protective surface or "armor" when exposed to precipitation. This armor is developed by "coarser" particles that are more resistive to fluid transport. The collection of these particles at the surface provides a protective layer that insulates the underlying soil from erosion. This protective layer can be fragile or robust depending upon the particle size distribution of the soil. To maintain its effectiveness and to prevent its rupture, the armor must be exposed to as little slope traffic as possible.

A sensitive maintenance operation coupled with a few aids, such as short fences to catch debris before it blows up into the landscaped areas, would assist in reducing slope traffic.

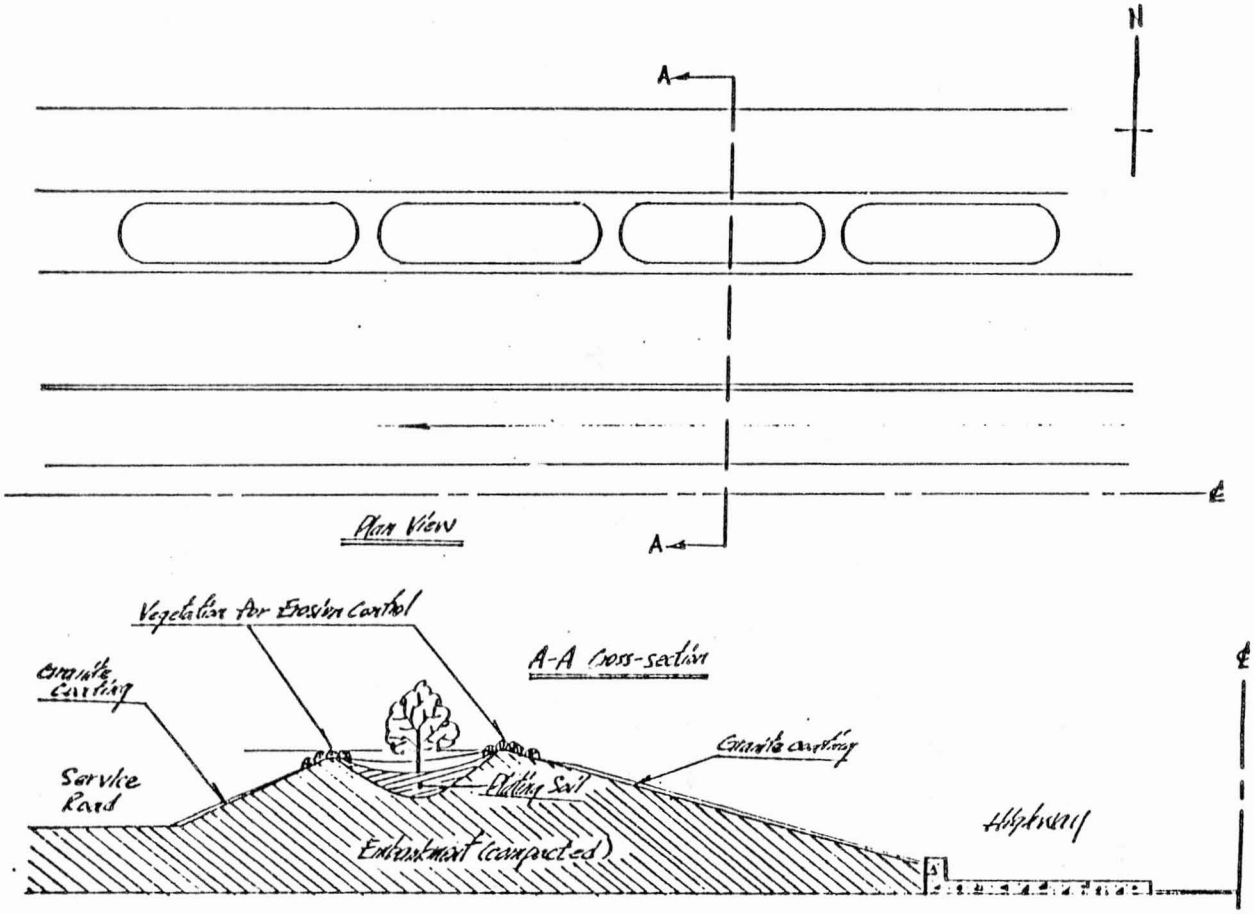

Figure 1. Suggested slope drainage and landscaping design for a wide right-of-way

5. A soil containing more than 20 percent particles larger than the No. 4 sieve is a soil with a good chance of "armoring". In general, particles larger than the No. 4 sieve size controlled the armoring process. When these particles are angular and wide relative to their thickness, the resistance is maximized. Shape factors larger than 2 are necessary to minimize rolling under flow conditions.

6. The use of crushed rock as slope protection is in effect producing "instant" armor. In arid climates, where available, rock particles used as surface protection will most likely be the long term protection of choice.

7. The granites in use as surface protection on SR 360 and I 10 were found to be resistant to laboratory weathering tests that were designed to simulate the field conditions.

General Erosion Concerns, Field Observations, and Design Concepts

The importance of slope and length of surface exposed to erosions was recognized early (Duley and Hays, 1932, Zingg, 1940, and Musgrave, 1947). Soil loss was related to slope in percent raised from the 1.35 to 1.7 power for mid-western soils (Zingg, 1940 and Musgrave, 1947, and Barnett and Rogers, 1966). A wide variety of precipitation events and several soil types were used to form conclusions about slope angle and soil erosion potential. Using

soil loss data from Texas to Wisconsin, Zingg, 1940, concluded that the average total soil loss varies as percent slope to the 1.37 power, and horizontal slope length to the 1.6 power.

As the erosion phenomena continued to be studied the role land use played in erosion became better understood. When under cultivation, Midwestern soils were reported to yield sediment at a rate equal to: 0.43 + 0.3S + 0.043S2 in tons per acre.

Consideration of erosion on slopes steeper than 2:1 was of interest as erosion concerns became part of the construction sequence. Steepness factors were developed for slopes steeper than 1.5:1, Wischmeier and Smith, 1978. Particularly on steep slopes, the importance of reducing slope length became apparent. If the slope length is reduced by half, the calculated amount of erosion decreases by 70 percent (Wischmeier and Smith, 1978).

In addition to the constraints that are appropriate for the erosion predicting techniques, it is also important to recognize that erosion is not uniform on a slope. The erodibility of a slope with uniform soil increases down the slope (Foster and Wischmeier, 1974) due to the increased probability of channel or overland flow occurring. Both rain drop impact and water flowing over the soil surface were recognized as mechanisms that contributed to erosion (Wischmeier and Mannering, 1969).

The prediction of erosion is a complex process. Not only does erosion increase as slope angle increases, but also as slope length increases. The type of land use must also be considered. The bulk of the erosion literature utilizes information gained from land under cultivation and located within the central part of the U.S. for precipitation events associated with that region. However, the problem of predicting erosion potentials for slopes in arid regions, containing coarse materials, and at angles of up to 27 degrees has received attention (Simanton and Renard, 1981, Hart, 1984).

Soil erosion predictive techniques, such as the Universal Soil Loss Equation, are not easily applied to highway slopes for several reasons. Steep slopes involve a complex flow and gravitational environment. The soil materials not subjected to cultivation develop a natural increase in their resistance to erosion if cementation or coarse particles are present in the soils. Early studies of rock particles mixed with soil showed significant increases in erosion resistance (Grant and Struchtemeyer, 1959). When rocks larger than 2 inches were removed erosion rates increased six fold (Lamb and Chapman, 1943). The coarser particles interact with each other on the surface forming an armored surface. This surface is similar to the desert pavements that are formed by wind ablation in arid regions. The affect of this resistance change is to make the actual erosion process time dependent. The USLE does not

recognize the effect of time nor of event sequence relative to previous flow.

In spite of increasing interest, much is unknown about how coarse soil fractions interact with the eroding forces. During the planning stage of the project, a fortuitous, from a research standpoint, storm hit SR 360 in October, 1987. This storm produced extensive erosion damage in an area protected with a decomposed granite (see Plate 1).

There were no rain gauges along the alignment; however, adjacent stations recorded a maximum precipitation rate of 0.55 inches per hour for the storm (Klenner, 1987). A view of the slope from the side provides another perspective of the damage (see Plate 2). The damage produced by this storm was striking. The rills were not only uniformly spaced, 3 to 8 feet, but they also started at the same location. The rills started at a break in slope that separates the upper and lower slope segments. The upper slope segment had a slope of from 6 to 14 degrees. The lower segment angle varied from 8 to 24 degrees. The observed erosion was widespread, occurring wherever the granite protection was used, within the storm limits. The granite, designated as SRG8, had 100 percent passing the 1 inch sieve size and 72 and 0 percent passing the numbers 4 and 200 sieves sizes respectively. The thickness of the granite on the slopes had a nominal thickness of less than 1 inch.

Plate 1. Rock slope protection damage on SR 360 by storm of October, 1987

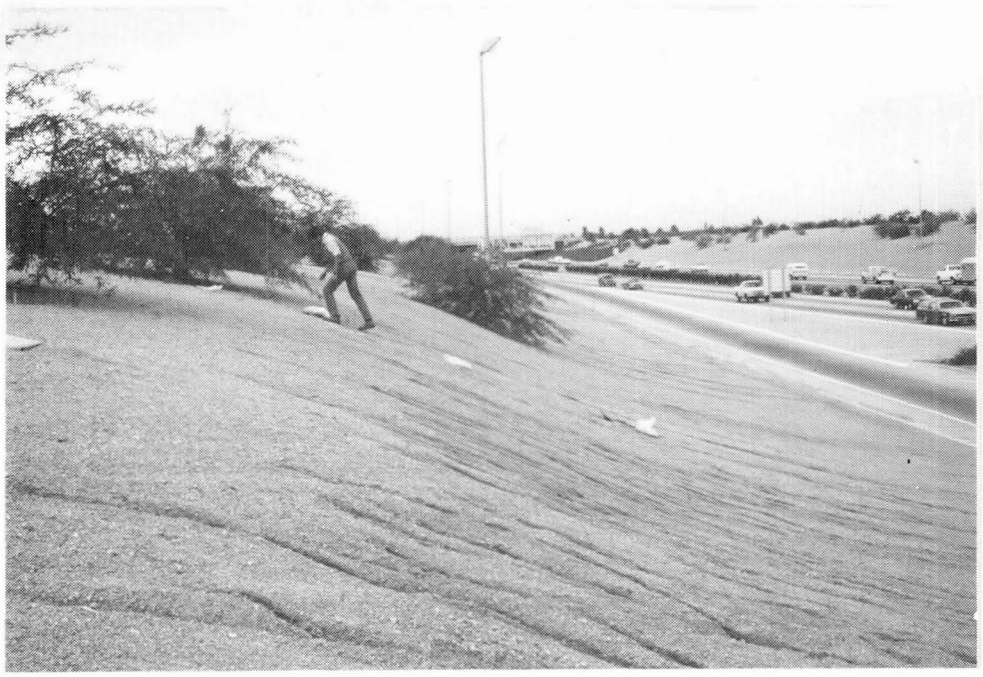

Plate 2. Elevation view of SR 360 rock slope protection damage

The rills, when examined closely, had an average width of approximately 3 inches and were incised through the granite and into the underlying soil an additional 0.5 to 1.5 inches. The bottom of the rill channel was irregular and displayed an armored surface almost always free of granite particles.

The length of upper slope necessary to produce the rill cutting, for the October 1987 storm, appears to be approximately 15 feet. When less than 15 feet of upper slope existed, rills did not form. The slope areas that had an uppe segment greater than 15 feet always had rilling in the granite.

The slope erosion from the October, 1987, storm refined the understanding of the slope erosion process. The rills on the slope were formed by the delivery of water from the upper slope segment to the lower. The precipitation falling on the slope was accumulated on the upper segment by microdrainages that had a period of 3 to 8 feet. Precipitation, also falling on the lower segment, was added to the flow arriving from the upper segment. Channel cutting then progressed from the point where the combined effect of quantity of water, Q, and the flow velocity, V, overcame the granite erosion resistance.

Design Procedure

The erosion design process is broken into two sections that address specific aspects of it. The first involves tasks that precede the slope protection design phase and will have generic erosion impacts on overall design. The most important tasks are:

1. The review of right-of-way considerations, including:

   a. Consideration of aesthetics, low water consumption landscaping, and vehicle safety by determining: 1) whether or not vegetation is required, and if so what kinds; 2) slope material colors and limits; 3) vehicle safety in terms of slope angle, rolling resistance of slope materials, sight distance, animal attraction potential, and dust hazards, for example.

   b. Selection of maximum/minimum slope limits

   c. Determination of slope segment angles and top of slope drainage options. The area segment is that slope area that functions as a microdrainage basin collecting and concentrating runoff down the slope. This microdrainage area is determined by multiplying the microdrainage basin width by slope segment length.

The designer must then consider the slope lengths and the respective flows to be delivered by each. Within the study area, the typical slope examined can be characterized by two segments (see Figure 2).

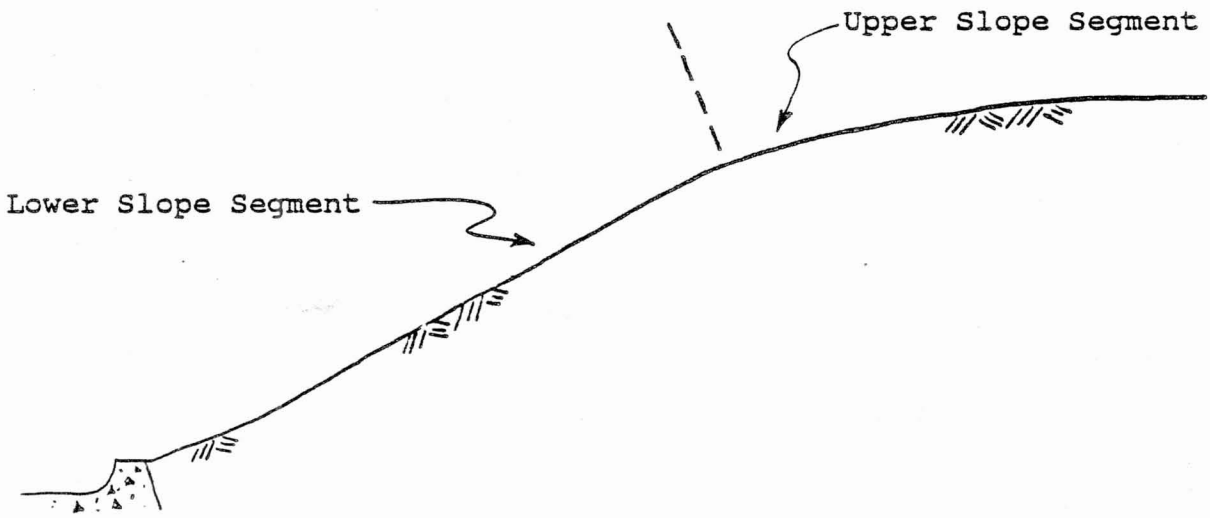

Figure 2. Typical two segment freeway slope such as found on SR 360

The runoff or overland flow from the upper segment is critical to the slope erosion design because the flow from the upper segment is generally concentrated into a drainage channel by the time the slope hinge point is reached. The erosion protection must be able to resist that flow starting at the hinge point.

2. The selection of design storm runoff characteristics including:

Determination of design storm. The design storm that is selected by ADOT should represent a significant event that has a long reoccurrence interval. The storm should also be of the cyclonic type that occurs during a typical summer thunderstorm. Once the storm has been selected, the surface runoff over the slope must be calculated using slope angle, width , and length for each slope area segment.

The 50 year, 30 minute intensity storm is suggested for the Phoenix Area slopes. This storm produces a precipitation intensity of 0.0052 ft/min.

3. The length of time the slope will be exposed to the elements prior to the development of final landscaping. If:

   a. The "stand time" is on the order of six months, permanent protection is recommended. This research showed that an aggregate protection scheme was the potentially most attractive one for arid climates.

   b. Time of exposure is less than six months, the designer will have to consider time of year and slope repair costs as the decision is made. The research at ASU indicates that considerable short term erosion control

benefit may be realized when commercially available chemicals are applied to slopes. Silty slopes with less than 30 percent coarse fragments are especially susceptible to erosion. Similar soils, when treated with resins and copolymers, developed significantly increased erosion resistance in laboratory testing.

To evaluate a potential chemical additive as an erosion retarding agent, the following steps are recommended:

1) An erosion test program should be established that evaluates chemical agent and soil placed as per the manufacturers recommendations and at design slope configuration; 2) ADOT should modify agent soil interaction if ease of placement appears to warrant such change. Then erosion testing can determine the impact of such modification in procedure; 3) The short term benefit in erosion resistance for each chemical can then be indexed to the erosion resistance of the untreated soil. This comparison will enable the slope designer to determine if sufficient benefit results to warrant the use.

The <u>second</u> section of the design involves determining the properties of an aggregate protection layer. The design of this slope protection system proceeds as follows:

1. Determine the hydraulic stress on the slope due to the amount of runoff or overland flow moving over the slope. In addition to the quantities of water moving over the slope, the designer must consider the velocity of this flow. The velocity of the flows on real slopes is difficult to assess. Table 1 provides a reasonable estimate of flow velocity on unprotected slope rough channels as a function of slope and flow rate.

   The erosion channels formed in the laboratory were essentially identical in cross-section to those observed on SR 360 slopes. If upper slope segments are steeper than 16 degrees, the designer will have to incorporate the steeper slope in the following erosion testing to evaluate the effect of higher velocity flow.

2. Establish slope soil conditions along alignment and determine erosion resistance via erosion testing. Erosion resistance testing is an important part of design due to the lack of sufficient erosion resistance data under combined precipitation and overland flow stress.

Table 1

Flow velocities for channel flow with Mirafi 6000 roughened channels used to simulate "rough" soil channels

Flow Rate, gpm	Slope Ratio, Degrees	Velocity, Ft/Min
1.2	2	78
1.2	9	127
1.2	16	141
2.4	2	104
2.4	9	132
2.4	16	167

It is important that the overland flow component of erosion be applied to the material being evaluated. The material should be placed as close as possible to the actual slope conditions (density and slope angle). The slope of the upper slope segment, if one exists, should also be used in the overland flow simulation to insure similar velocity of flow.

To accomplish these objectives, the recommended method of testing is the ASU Slope Erosion Test System described in Volume I, Slope Erosion Control for Urban Freeways in Arid Climates report. The apparatus is shown on Plate 3.

At the completion of the testing, the designer would be able to assess the need for slope protection. If the erosion test results resemble curve number 1 on Figure 3, the soil possesses sufficient natural armoring potential so as not to require protection. This assumes, of course, that the

designer and the system can tolerate the initial removal of "fines" as the armored surface develops.

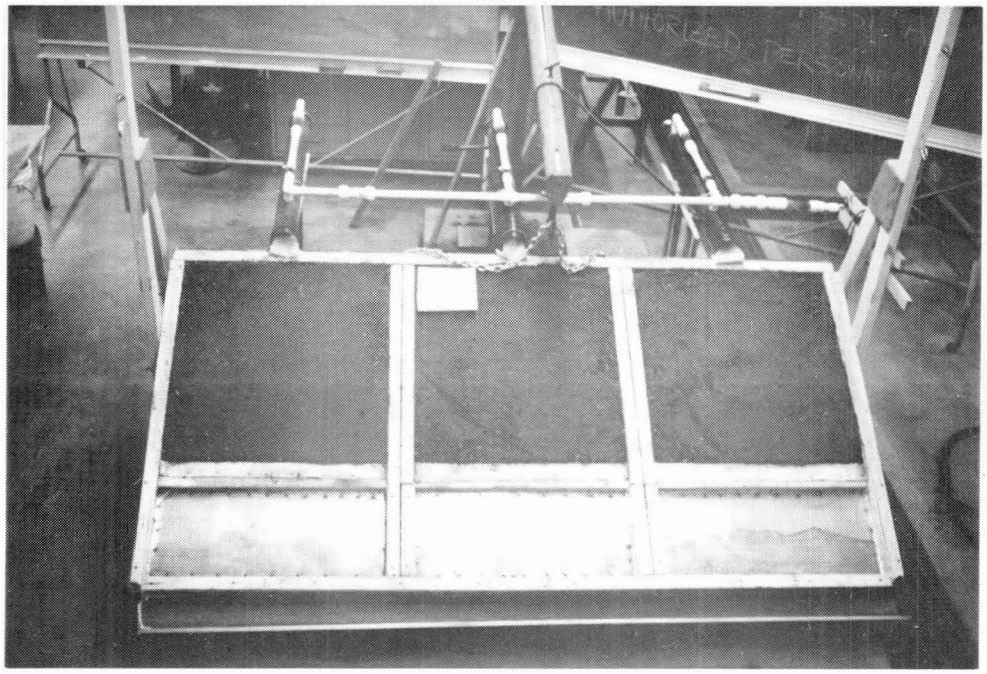

Plate 3. Erosion cell test apparatus

If the erosion testing, however, produces a curve similar to number 2, then protection will be required. The subsequent testing of protection materials placed over this soil will enable the designer to check the appropriateness of the design. The final protection system should be verified by erosion test before acceptance.

3. If erosion resistance is required, determine if coarse particles can be added to the slope soils or if a protective layer should be utilized. Figure 4 presents the relative

rate of return realized when coarse particles are added to silty soils.

As the plasticity of the soil increases, there is an improvement in the relative benefit of the addition of coarse particles. The designer should not rely on this benefit, however, since there is insufficient information available to allow a quantitative adjustment in the predictive erosion resistance relationship. The erosion testing conducted will depict the actual benefit to be realized by the addition of coarse particles.

If the protection selected takes the form of a coarse or rock protective layer, then two basic questions must be addressed. These questions are: What is the maximum size of the particles and how thick must this layer be? When the permeability is low enough so as to develop surface flow, and when the aggregate has a shape factor of at least 2, the following limiting conditions exist (see Table 2).

As the angle of the slope decreases an increase in erosion resistance occurs (see Figure 5).

The relative erosion rate versus slope angle depicted on Figure 5 represent four soil/aggregate gradations. As can be seen, the response to slope change can be appreciable. As the percentage of coarse particles increases, the difference in erosion rate decreases. The state-of-the-art is such that the research team

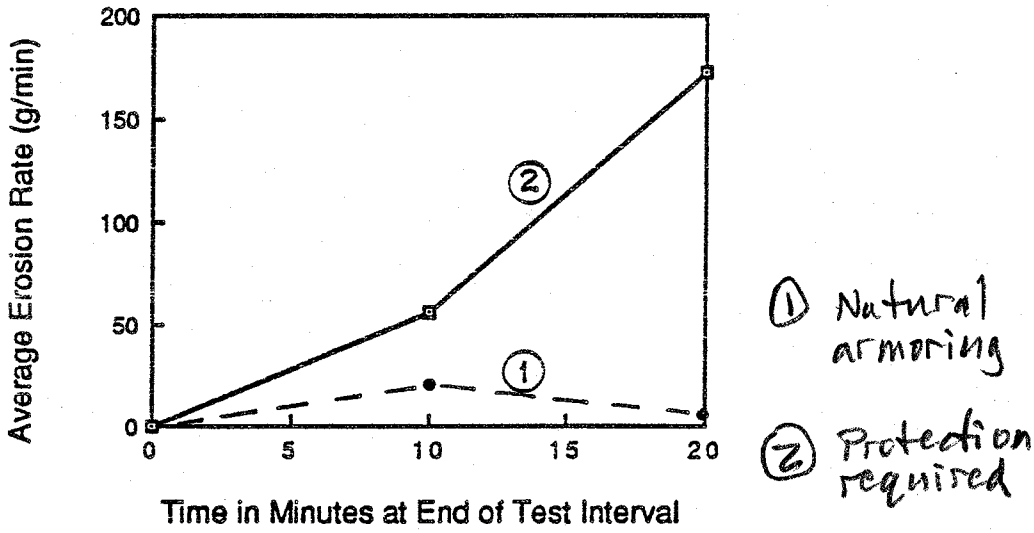

Figure 3. Average erosion rate vs time for design combined precipitation and overland flow conditions

see pg. 15

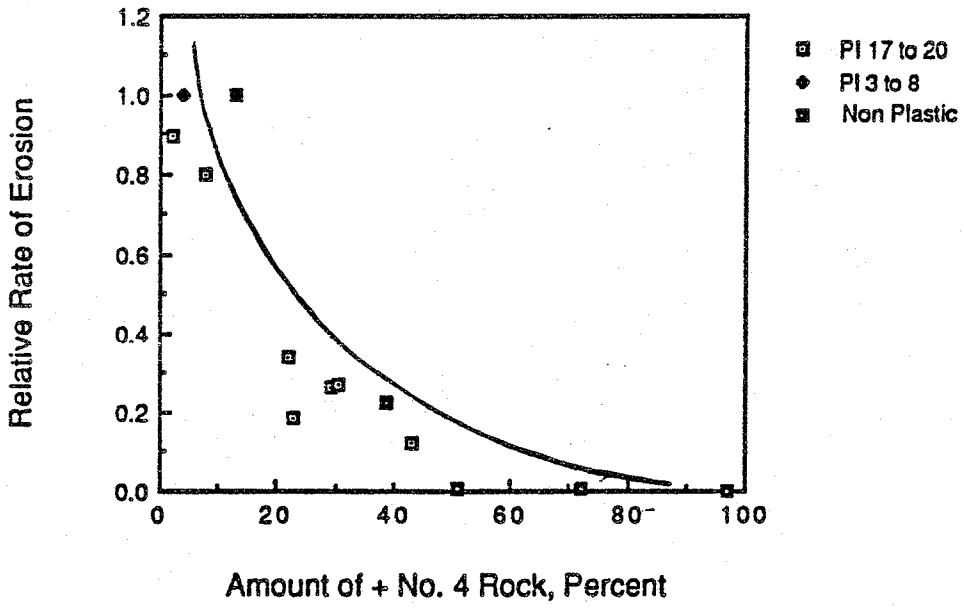

Figure 4. The effect of particles larger than the Number 4 sieve size on silty soil erosion when mixed to an initial depth of 2.5 inches

Table 2

Limiting or failure conditions when the aggregate shape factor is at least 2 and surface flow occurs for slopes less than 16 degrees.

Maximum Particle Size, inches	Maximum Channel Flow, gpm
11/2	8
1	6
1/2	1

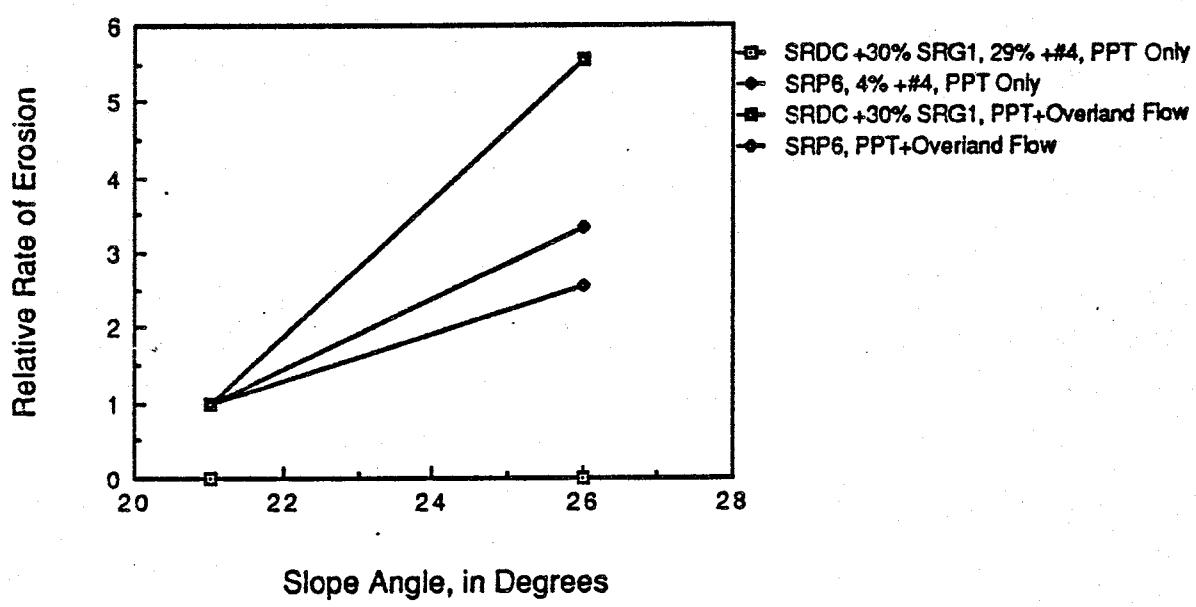

Figure 5. The effect of slope angle on erosion resistance

suggests that the slope protection either be maximum particle sized from Table 2, or that specific erosion testing at the desired slope be conducted to establish the required maximum size.

In addition to the hydraulic aspects of the problem, the larger particle sizes that would be required for flatter than 2:1 slopes

will be more resistant to weathering and will be more effective in discouraging slope traffic.

The minimum shape factor of the particles larger than the number 4 sieve size should be 2. There is a continued benefit in erosion resistance up to a shape factor of 8. However, the benefit falls off rapidly after a value of 2 (see Figure 6).

A suggested form of working through the slope protection process is as follows by the following procedure sheets.

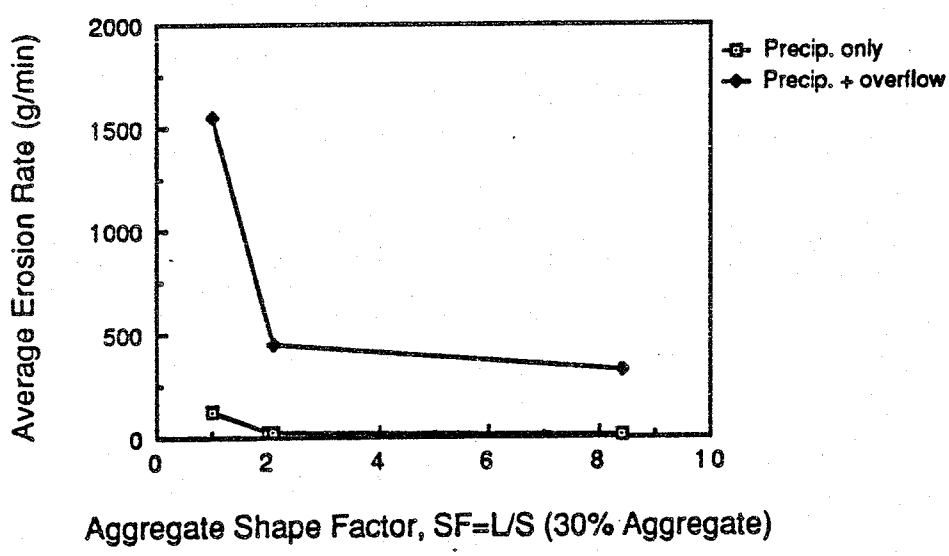

Figure 6. Shape factor vs relative erosion under constant overland flow conditions

Design Procedure Sheets

Slope design procedures are as follows:

1. Establish overview slope configuration characteristics. This effort should result in minimized slope runoff, maximum retention of precipitation at potential vegetation locations, establish slope channel discharge locations to handle "overflow" conditions, and minimize slope disturbance during the slope design life.

2. Establish geometrical constraints. The most important of which is maximum slope length for each segment of alignment.

Slope Segment ID _____

Maximum Slope Angle _____

Maximum Slope Length

Upper Segment (USL)_____(ft)

Lower Segment (LSL)_____(ft)

3. Select the design storm. Needed input from the design storm is maximum intensity.

Precipitation Intensity (I)_____(ft/min)

4. Determine microchannel width and subsequent slope drainage basin area. Note that this area is the horizontal projected area.

Microbasin Width (W)_____(ft)

5. Determine maximum overland flow rate delivered across the slope segment. Assume that infiltration is zero and that all microbasin flow is in a channel by the time it reaches the slope toe.

Slope Flow (Q) in gpm = I x (USL + LSL) x W x 7.48 =____(gpm)

6. Select appropriate maximum fluid velocity as fluid leaves the upper slope segment.

Maximum Upper Slope Flow Velocity (V) _____(ft/min)

7. Conduct erosion tests to establish natural slope erosion sensitivity. Conduct testing using Q and V determined from proceeding steps.

Estimated Rate of Erosion in g/min _____

Protection Required? _____Yes _____No

If answer is Yes, go to next step. If answer is No, then stop for no further design of slope protection systems is required.

8. Determine the characteristics of the slope protection material required.

a. Select maximum particle size (S) in inches. Use Table 2, noting that minimum recommended size for any slope between 2:1 and 2 1/2:1 is 1.0 inches maximum dimension.

Maximum Particle Size (S) _____

b. Percentage of particles larger than the number 4 sieve size (S%). Note that this percentage should fall between 20 and 40 percent of the particles by weight.

Percentage of Coarse Particles (S%) _____

c. Percentage of particles smaller than the number 10 sieve size (Smin) is controlled by the grain size distribution of the soil being protected. In general the percentage of particles smaller than the number 10 sieve size should be on the order of 10 percent of smaller. This is suggested to minimize initial sediment transport with the first storm.

Percentage Number 10 Size Particles (Smin) _____

d. Protective layer thickness (LT) determination is based on preventing piping of underlying soil. Thickness should be approximately 1.5 times the maximum particle size of the protective material andnot less than 1 1/2 inches.

Layer Thickness (LT) in inches _____

9. Conduct confirmation laboratory erosion testing using the design material, placed at design thickness, over the natural soil. This "proof" testing of the material proposed for use should be conducted with the same conditions used in Step 7. Test duration should be sufficiently long to establish whether or not long term armoring will be established.

Confirmation Test Satisfactory? _____Yes _____No

If the answer is yes, move to step 9; if no, go back to Step 7 and modify the protective layer characteristics. If armoring did not develop under the design flow, check increasing maximum particle size, increasing the percentage of coarse particles, increasing layer thickness, or increasing shape factors. If the protective layer was undermined due to soil piping, increase the percentage of minus number 10 sieve size particles in the protective layer.

With the modified design, reconduct the Confirmation testing until a satisfactory test is realized and the answer to Step 8 is Yes.

10. Conduct weathering testing if the materials selected were not studied during the research program, Volume I. The weathering test program that is recommended is the same as described in Volume I. The objective of this step is to insure that the "Coarse" fraction of the protective layer will remain coarse during the design life of the slope.

11. If short term protection is required and prior to final landscaping, chemical protection may be an option. If chemical stabilization is under consideration the designer is referred to page 13 of this manual for guidance in selecting the agent of choice.

Once a stabilizing agent is selected for possible use, confirmation testing as in Step 8 should be conducted.

Chemical Testing Satisfactory? _____Yes ____No

If the answer is yes, stop. If no, review the selection of chemical agents and select another product for confirmation testing and repeat Step 11 until satisfactory performance is realized.

Example of Slope Erosion Design

The first example is for a slope segment of a freeway havinga slope graded similar to SR 360. This slope has an upper slope segment length (USL) of 10 ft and a lower slope segment length (LSL) of 20 ft. The upper slope segment angle is 10 degrees and the lower segment angle is 21 degrees.

An observation of this slope that has been graded for 3 months shows rills with a maximum rill spacing of 6 feet. Use this value to establish slope flow.

The soil is a silty sand with only 5 percent of the particles, by weight, larger than the number 4 sieve size. A test panel is prepared and this sample armors poorly. The shape of the erosion rate versus time of precipitation curve is a type 2 curve, Figure 3. Erosion protection is, therefore, required.

The design proceeds as follows using the suggested format:

1. Establish overview slope configuration characteristics. This effort should result in minimized slope runoff, maximum retention of precipitation at potential vegetation locations, establish slope channel discharge locations to handle "overflow" conditions, and minimize slope disturbance during the slope design life.

2. Establish geometrical constraints. The most important of which is maximum slope length for each segment of alignment.

Slope Segment ID Sample design 1

Maximum Slope Angle 21 degrees

Maximum Slope Length

Upper Segment (USL) 10 ft

Lower Segment (LSL) 20 ft

3. Select the design storm. Needed input from the design storm is maximum intensity.

Precipitation Intensity (I) 0.0052 ft/ min

4. Determine microchannel width and subsequent slope drainage basin area. Note that this area is the horizontal projected area.

Microbasin Width (W) 6 ft

5. Determine maximum overland flow rate delivered across the slope segment. Assume that infiltration is zero and that all microbasin flow is in a channel by the time it reaches the slope toe.

Slope Flow (Q) in gpm = I x (USL + LSL) x W x 7.48 = 7.0 gpm

6. Select appropriate maximum fluid velocity as fluid leaves the upper slope segment (see Table 1).

Maximum Upper Slope Flow Velocity (V) = 130 ft/min

7. Conduct erosion tests to establish natural slope erosion sensitivity. Conduct testing using Q and V determined from proceeding steps.

Estimated Rate of Erosion in g/min = 4600 g/min

Protection Required? x Yes _____ No

If answer is Yes, go to next step. If answer is No, then stop for no further design of slope protection systems is required.

8. Determine the characteristics of the slope protection material required.

a. Select maximum particle size (S) in inches. Use Table 2, noting that minimum recommended size for any slope between 2:1 and 2 1/2:1 is 1.0 inches maximum dimension.

Maximum Particle Size (S) = 1½ inches

b. Percentage of particles larger than the number 4 sieve size (S%). Note that this percentage should fall between 20 and 40 percent of the particles by weight.

Percentage of Coarse Particles (S%) = 38

c. Percentage of particles smaller than the number 10 sieve size (Smin) is controlled by the grain size distribution of the soil being protected. In general the percentage of particles smaller than the number 10 sieve size should be on the order of 10 percent of smaller. This is suggested to minimize initial sediment transport with the first storm.

Percentage Number 10 Size Particles (Smin) = 15

d. Protective layer thickness (LT) determination is based on preventing piping of underlying soil. Thickness should be approximately 1.5 times the maximum particle size of the protective material and not less than 1 1/2 inches.

Layer Thickness (LT) in inches = 2 to 2½

9. Conduct confirmation laboratory erosion testing using the design material, placed at design thickness, over the natural soil. This "proof" testing of the material proposed for use

should be conducted with the same conditions used in Step 7. Test duration should be sufficiently long to establish whether or not long term armoring will be established.

Confirmation Test Satisfactory? __x__Yes _____No

The proposed protective material would then be subjected to the weathering test cycle to assess long term stability.

Additional design recommendations that are generic to both new and rehabilitated slopes and thus applicable to this example are:

a. Keep the slope traffic to a minimum. Consider using fences to restrict trash on the slopes thereby reducing maintenance activities. Place signs advising motorists and pedestrians to keep off the slopes.

b. If vegetation is to be incorporated into the landscaping try to keep the vegetation on the upper slope segments. On lower slope faces low density areas associated with groundcover for example, should be protected with a geotextile. This geotextile would be placed beneath the slope protection to protect it from ultraviolet radiation. The fabric most suitable would be similar to geotextiles used to control piping in soils.

c. If vegetation is incorporated in upper segments graded to contain precipitation, slope spillways should be constructed to handle the overfill flow. These spillways should be constructed using cobbles over geotextiles to insure scour resistance.

Recommendations for Future Research

To expand the design flexibility of slope protection systems, the authors recommend research be conducted in the following topics:

1. Additional erosion testing to incorporate a wider spectrum of soils to reduce the need for erosion testing as part of the design sequence.

2. Conduct an extensive field study of slope rill forming processes. A better understanding of what slope characteristics affect rill formation will enable a less conservative protection scheme to be applied.

3. Examine methods of applying chemical stabilizers to maximize cost effectiveness. Combine real world restraints on application processes with manufactures recommendations to develop a practical method of using chemical stabilizers. In addition to exploring constraints on use, the length of effectiveness of prospective chemical agents should be explored. At this point there is no way to evaluate the slope life of chemical agents. This proposed effort would enable the most efficient and durable chemical stabilization program to be developed.

4. The construction and observation of a test or test sections would enable the current design precision to be evaluated. Additional information concerning maintenance impacts on slope erosion would also be a product of this research.

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