Contract Research

GDOT PROJECT NO. 07-25
Final Report

CATEGORIZATION OF EROSION CONTROL MATTING

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May 29, 2011

Acknowledgements

The author is pleased to acknowledge the contributions of Mr. Hyunwook Choo, Mr. Ross E. Cutts, and Mr. Qian Zhao, all of whom worked as graduate research assistants on this project. In addition, thanks to Dr. Terry Sturm and Mr. Andy Udell for their help and collaboration throughout the course of this project. Finally, thanks to Mr. Bradley R. Ehrman, P.E., and Mr. Jon D. Griffith, P.G., P.E., for their continued dedication and significant contributions in the formulation of this project and throughout the course of this work.

Abstract

Erosion control is an important aspect of any Georgia Department of Transportation (GDOT) construction project, the extreme negative impacts of high sediment loads in natural waterways having been well documented. A variety of erosion control products are available for use, including geotextiles made from natural or synthetic fibers, concrete, bituminous treated roving, seed and sod, wood mulch, and soil binders. Specifically, erosion control in channels requires permanent or semi-permanent erosion control measures, with GDOT's three most commonly implemented measures being concrete channel lining, riprap channel lining, and turf reinforcement mats (TRMs). This work contains the newest guidelines for the development of a ditch protection program, including estimation of the coefficient of roughness and permissible shear stresses for a variety of lining types. Recommendations are made regarding the best selection for the critical model values.

Keywords: Channel lining, erosion, Manning's coefficient, permissible shear stress, turf reinforcement mat

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Definitions

As defined by the Erosion Control Technology Council (http://www.ectc.org/specifications.asp):

1) **Rolled Erosion Control Products** (RECP): A temporary degradable or long-term non-degradable material manufactured or fabricated into rolls designed to reduce soil erosion and assist in the growth, establishment and protection of vegetation.

   a. ***Mulch control netting or Erosion control net***: A planar woven natural fiber or extruded geosynthetic mesh used as a temporary degradable rolled erosion control product to anchor loose fiber mulches.

   b. ***Open weave textile***: A temporary degradable rolled erosion control product composed of processed natural or polymer yarns woven into a matrix, used to provide erosion control and facilitate vegetation establishment.

   c. ***Erosion control blanket:*** A temporary degradable rolled erosion control product composed of processed natural or polymer fibers mechanically, structurally or chemically bound together to form a continuous matrix to provide erosion control and facilitate vegetation establishment.

   d. ***Turf reinforcement mat***: A rolled erosion control product composed of non-degradable synthetic fibers, filaments, nets, wire mesh and/or other elements, processed into a permanent, three-dimensional matrix of sufficient thickness. TRMs, which may be supplemented with degradable components, are designed to impart immediate erosion protection, enhance vegetation establishment and provide long-term functionality by permanently reinforcing vegetation during and after maturation. Note: TRMs are typically used in hydraulic applications, such as high flow ditches and channels, steep slopes, stream banks, and shorelines, where erosive forces may exceed the limits of natural, unreinforced vegetation or in areas where limited vegetation establishment is anticipated.

Introduction

Erosion control is an important aspect of any Georgia Department of Transportation (GDOT) construction project, with the extreme negative impacts of high sediment loads in natural waterways having been well documented. A variety of erosion control products are available for use, including geotextiles made from natural or synthetic fibers, concrete, bituminous treated roving (no longer used by GDOT), seed and sod, wood mulch, and soil binders. Most specifically, erosion control in channels requires permanent or semi-permanent erosion control measures, with GDOT's three most commonly implemented measures being concrete channel lining, riprap channel lining, and turf reinforcement mats (TRMs).

TRMs are permanent, non-degradable reinforcement materials that are composed of a chemical and UV resistant synthetic matrix that facilitates growth of vegetation through the structure; over time, the plant and it roots grow through the matrix of the TRM, providing interlocking with the soil, which in turn increases resistance to high shear stresses from water flow, and reduces erosion. TRMs provide an attractive alternative to concrete because they allow infiltration of surface water, and are not subject to undercutting at edges and joints, and to riprap, which can pose safety hazards for maintenance crews, and which also has a higher cost than turf reinforcement mats. However, due to the complexity of the TRM/soil/water interaction, as well as the variety of TRMs, selection of the most appropriate product for a specific application is difficult. GDOT has a need for a consistent, standardized performance-based framework to evaluate the level of erosion control required at a given location and to select the most appropriate TRM or category of TRMs.

Research Objective

The research objective of this study is to provide designers with a methodology to assess the level of erosion protection required for a given ditch configuration and to develop a standardized test protocol that will allow categorization of turf reinforcement mats by the level of required erosion protection.

Research Significance

Soil erosion has a major detrimental impact on surface water bodies in the state of Georgia. In channels, the choice of the most appropriate TRM is complex due to the interaction between the erosion control materials, hydraulic loading, and soil types, making site-specific implementation decisions difficult. A guidance that quantitatively compares the properties of TRMs for use on GDOT projects can contribute to a significant reduction in the transport of solids into waterways in Georgia and a reduction in cost due to corrective efforts necessitated by improper erosion control products.

Research Tasks

1) A literature review on current erosion control measures used by state DOTs for channel stabilization
2) Examination of the specifications currently used for selection of channel lining by GDOT, including the HEC15R3 flexible lining computer design program, developed in 1988, and the development of updated specifications, if necessary,

including TRM resistance to hydraulic loading (peak flow, duration of flow, length of preceding dry days, etc…)

3) Update or development of a ditch protection design program that categorizes the level of erosion protection needed for a given ditch configuration
4) Development of guidelines for quantitative comparison and evaluation of TRM material properties and durability, including performance aspects like resistance to shear, interaction with a variety of Georgia soil types, stability when exposed to UV light
5) Evaluation of TRMs using ASTM test methods to quantitatively compare the performance of TRMs; these tests will allow standard categorization of a wide variety of TRMs (lab based)
6) Development of a standardized performance specification for determination of the appropriateness of TRMs in a variety of applications (i.e., dividing the TRMs into categories with varying levels of erosion protection)
7) Development of an erosion index for Georgia soils that is fundamentally based, reflects geochemical effects in addition to gravitational (particle size) effects, but that is still easily implemented on a field scale
8) Field testing of TRMs used in Georgia (Note: this task was removed due to the high quality of controlled laboratory data available, and to the complexity of controlling boundary conditions in the field. The high quality lab data yields results that are comparable across different TRM types, making field tests unnecessary.)

Task 1: Background and Literature Review

Erosion control is an area of intense research, with summary work on erosion control technologies being conducted in Iowa (Stevens, 2006) and Texas (McFalls, 2006). Work on rolled erosion control products has focused on natural and synthetic geotextiles or matting (Rickson, 2006; Gyasi-Agyei, 2004), and seed or sod. Additional studies have examined variability in the measured properties of RECPs, as determined by two different testing labs, with results demonstrating that water absorption was most distinctive for the variety of fibers tested (Smith et al., 2010).

Because so many different designs of TRMs are available commercially, it is critically important to define a standard test protocol to evaluate the relevant properties of the TRMs for a given project. Current standardized ASTM test methods include measurements of the properties of a TRM, including short term compression behavior (ASTM D6454), resiliency (ASTM D6524), mass per unit area (ASTM D6566), light penetration (ASTM D6567), geosynthetic stiffness (ASTM D6575), tensile properties (ASTM D6818), and grab breaking load and elongation of the geotextile matrix (ASTM D4632). Additionally, there is a standardized test method to quantify channel erosion protection of TRMs (ASTM D6460). In this document, primary emphasis will be on evaluating the utility of ASTM standards for classification of TRMs.

Task 2: GDOT Specifications Currently Used for Selection of Channel Lining

GDOT currently uses a flexible lining computer design program called HEC15R3, which is based on HEC 15 (1998) (revised version available 2005, (U.S. Department of Transportation, 2005)) for the selection of channel lining. Questions regarding HEC 15 that will be addressed in the following section include:

a. What are the assumptions in the model?
b. What are the model inputs?
c. What are the model outputs?
d. How is the model calibrated?
e. Does it accurately predict flow in Georgia?
f. Does it need to be updated?
g. If so, how do we categorize the level of erosion protection needed?
h. What other models are available now?
i. Do these models include provisions for TRMs?
j. Can we add new TRMs into the model?

Design Assumptions in HEC 15

Basic channel design in HEC 15 relies on two primary contributions: flow conditions, which is a function of the channel geometry, design discharge, channel roughness, channel alignment, and channel slope for given design discharge and the required level of erosion protection, which is a function of the shear stress on the channel lining.

Assumption 1: Uniform, steady flow conditions are assumed with the energy slope approximately equal to average ditch slope, with flow rate changing with time. Of additional concern is the flow condition, which can be classified as subcritical or supercritical (creating surface waves).

Basic factors for uniform, steady flow:

(1) Discharge (Q) is constant.

(2) Depth, width, discharge, channel roughness, and slope are constant.

(3) No hydraulic jump or drop occurs.

Real condition: Type of flow: Flow within a channel can be uniform or nonuniform, steady or unsteady, subcritical or supercritical.

Assumption 2: The Chezy and Manning Equations are used to calculate mean velocity (*v*) within the channel:

$$v = \frac{1.49}{n} R^{\frac{2}{3}} S_f^{\frac{1}{2}} \text{ (U.S.)}$$

$$v = \frac{1}{n} R^{\frac{2}{3}} S_f^{\frac{1}{2}} \text{ (SI)}$$

$$v = c\sqrt{RJ}$$

$$c = \frac{1}{n} R^{\frac{1}{6}}$$

And discharge:

$$Q = \frac{\alpha}{n} A R^{2/3} S_f^{1/2}$$

where, Q = discharge, m^3/s ($ft^{3/}s$), n = Manning's roughness coefficient, dimensionless, c = Chezy coefficient, $m^{1/2}/s$, ($ft^{1/2}/sec$), A = cross-sectional area, m^2 (ft^2), R = hydraulic radius, m (ft), S_f = friction gradient, which for uniform flow conditions equals the channel bed gradient (S_o), m/m (ft/ft), α = unit conversion constant 1.0 (SI) or 1.49 (U.S.).

Real condition: Heterogeneous distribution of velocity: For a Newtonian fluid, the velocity is not homogeneous in cross-section (Figure 1):

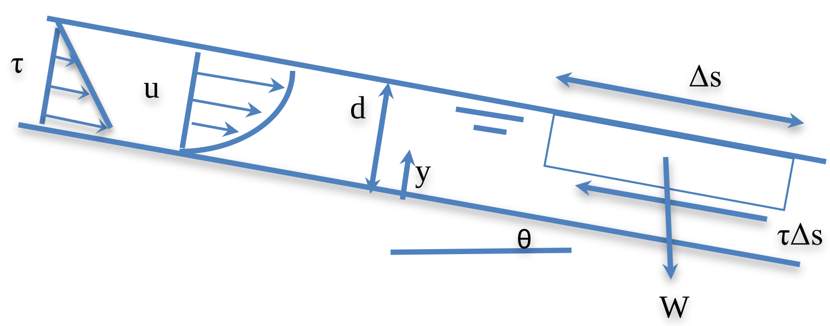


Figure 1. Velocity gradient in open, laminar channel flow (cross-sectional view).

The velocity and shear stress distributions for channel flow in the horizontal and vertical sections have different distributions, and the shear stress between the layers of flow in a Newtonian fluid is caused by the velocity gradient:

$$\tau = \mu \frac{du}{dy}$$

Where τ = shear stress, μ = dynamic viscosity, u = velocity, and y = the perpendicular distance from the channel bottom.

In the case of uniform flow on a slope and assuming a unit width, the momentum equation can be applied to a fluid element to yield (Figure 1):

$$W \sin\theta - \tau \Delta s = 0$$

Where W = weight of element, θ = slope angle in radians, and s = distance along the flow direction. Assuming that shear stress at the liquid surface is negligible, depth is constant so pressure forces on the end sections of the element will cancel, and taking a unit width of the element, results in shear stress as a function of depth:

$$\gamma(d-y)\Delta s \sin\theta = \tau\, \Delta s$$

$$\tau = \gamma(d-y)\sin\theta$$

Where γ = unit weight of water, d = thickness of flow measured perpendicularly to the channel bottom, and y = height above the channel bottom. Substituting $\tau = \mu \frac{du}{dy}$, yields the change in velocity with respect to depth:

$$\mu \frac{du}{dy} = \gamma(d-y)\sin\theta$$

or

$$\frac{du}{dy} = \frac{\gamma(d-y)\sin\theta}{\mu}$$

After integration, the equation yields velocity as a function of depth:

$$u = \frac{\gamma \sin\theta}{\mu}\left(yd - \frac{y^2}{2}\right)$$

At the bottom of the channel, for the case where y=d, the velocity becomes:

$$u = \frac{\gamma \sin\theta}{\mu}\left(\frac{d^2}{2}\right)$$

When the slope of the channel is small, $\tan\theta \cong \sin\theta$; and the velocity at the base of the base of the channel can be expressed as:

$$u = \frac{\gamma S_o}{\mu}\left(\frac{d^2}{2}\right)$$

Taking the derivative of velocity at the base of the channel and relating back to the shear stress relation for a Newtonian fluid results in:

$$\frac{du}{dy} = 2\frac{\gamma S_o}{\mu}\left(\frac{d}{2}\right) = \frac{\gamma S_o d}{\mu}$$

$$\tau = \mu\frac{du}{dy} = \mu\frac{\gamma S_o d}{\mu} = \gamma d S_o$$

$$\tau = \gamma d S_o$$

where τ is the shear stress in the channel. When taken at the maximum depth of the channel, the shear stress corresponds to the maximum shear stress in the channel.

Analysis of the entire channel cross section typically results in a definition of the mean boundary shear stress applied across the entire wetted perimeter (HEC15, 2005):

$$\tau_o = \gamma R S_o$$

Where τ_o = mean boundary shear stress, R = hydraulic radius, and S_o = channel slope. However, because shear stress is not uniformly distributed along the wetted perimeter, the maximum shear stress in a straight channel is typically taken at the maximum depth of flow (HEC15, 2005):

$$\tau_d = \gamma d\, S_o$$

Where τ_d = shear stress at maximum channel depth and d = maximum depth of flow in the channel.

Assumption 3: The tractive force distribution is based on the stresses developed at the interface between the flowing water and the channel boundary materials. The tractive force caused by fluid flow should not be higher than the permissible of critical shear stress of the lining materials.

Defining the average tractive force:

$$\tau = \gamma RS$$

results in the mean boundary shear stress that is applied to the wetted perimeter:

$$\tau_o = \gamma RS_o$$

where, τ_o = mean boundary shear stress, N/m^2 (lb/ft^2), γ = unit weight of water, 9810 N/m^3 (62.4 lb/ft^3), R = hydraulic radius, m (ft), S_o = average bottom slope (equal to energy slope for uniform flow), m/m (ft/ft). HEC 15 assumes that the maximum channel bottom shear stress can be defined as:

$$\tau_d = \gamma dS_o$$

Where τ_d = shear stress in channel at maximum depth, N/m^2 (lb/ft^2), d = maximum depth of flow in the channel for the design discharge, m (ft).

Real condition: The actual distribution of the maximum shear stress on the sides and bottom of the channel will be a function of the channel shape.

LINING PROPERTY

Lining properties can be either rigid (static) or moveable (dynamic). Rigid channels achieve stability through the low erodibility of the materials, while moveable channels are stable as long as the net discharge remains below an acceptable value. There are two primary design methods to meet the static equilibrium condition (HEC15, 2005):

Permissible tractive force:

$$\tau_p = \gamma d S_o$$

Permissible velocity:

$$V_p = \frac{\alpha}{n\sqrt{\gamma d}} R^{1/6} \tau_p^{1/2}$$

Where V_p = permissible velocity, m/s (ft/s), τ_p = permissible shear stress, N/m^2 (lb/ft^2), α = unit conversion constant, 1.0 (SI), 1.49 (U.S.).

The tractive force method is preferred because it is a more compact approach than the permissible velocity method. In the tractive force method, the failure criteria for a particular lining are represented by a single critical shear stress value, which is applicable over a wide range of channels.

CHANNEL GEOMETRY

The cross-sectional shape of highway channels is typically trapezoidal or triangular. Due to the high water storage capacity and relatively stable side slopes, trapezoidal channels are most common. All roadway ditches should be designed to convey the 25-year peak flow such that the water surface elevation is below the bottom of the pavement structure. Typically, the channel slope parallels that of the roadway profile, and a freeboard of 0.15 m (0.5 ft) from the top of the protective lining is normally sufficient. Analysis in this document is based on the performance of trapezoidal straight channels. Whether or not the channel is trapezoidal or triangular, the cross-sectional area formula is the same. In the case of a triangular ditch, the bottom width is zero m (ft).

INPUT PARAMETERS FOR ANALYSIS OF CHANNEL PERFORMANCE

Channel lining problems can be approached in three basic ways:

(1) Lining design: For the given flow and channel conditions, the permissible shear stress is set and then the appropriate lining is chosen.

(2) Flow design: For the given lining type and channel geometry, the maximum allowable charge (velocity/ shear stress) is calculated.

(3) Geometry design: For the given lining type and flow, the geometry of the channel is determined.

In the case of lining design, the input parameters include:

Design discharge frequency Q

Channel cross-sectional geometry B, α, β

Channel slope S_f

The major steps or calculations include determination of:

Cross-sectional area (assuming equal side slopes):

$$A = Bd + cot\alpha \cdot d^2$$

Cross-sectional area (assuming unequal side slopes):

$$A = Bd + 0.5cot\alpha \cdot d^2 + 0.5cot\beta \cdot d^2$$

Hydraulic radius (assuming equal side slopes):

$$R_h = \frac{A}{L} = \frac{(b + dcot\alpha)d}{b + 2d\sqrt{1 + cot\alpha^2}}$$

Hydraulic radius (assuming unequal side slopes):

$$R_h = \frac{A}{L} = \frac{(b + dcot\alpha)dBd + 0.5cot\alpha \cdot d^2 + 0.5cot\beta \cdot d^2}{b + d\sqrt{1 + cot\alpha^2} + d\sqrt{1 + cot\beta^2}}$$

Manning's equation: $u = \frac{1}{n} R_h^{\frac{2}{3}} S_f^{\frac{1}{2}}$ and continuity equation $Q = uA$ to solve for flow depth, *d* (frequently reported in chart format). Permissible shear stress is determined as:

$$\tau_p = \gamma d S_f$$

Output will yield:

Maximum shear stress on the lining $\tau_{\max}$

Maximum velocity of the flow $u_{\max}$

The proper type of lining is then chosen to have permissible shear stress τ_p larger than $\tau_{\max}$, or permissible velocity u_p larger than $u_{\max}$.

<u>In the case of flow design, the input parameters include:</u>

Lining strength: τ_p

Channel cross section geometry B, α

Channel slope S_f

The major steps or calculations include:

Back calculate the depth of flow

$$d = \frac{\tau_p}{\gamma S_f}$$

Set permissible hydraulic radius:

$$R_h = \frac{A}{L} = \frac{(b + dcot\alpha)d}{b + 2d\sqrt{1 + cot\alpha^2}}$$

Set flow velocity when depth is at d: $u = \frac{1}{n} R_h^{\frac{2}{3}} S_f^{\frac{1}{2}}$

And:

$$Q_{max} = ud$$

Output will yield:

Maximum allowable charge: $Q_{\max}$

<u>In the case of channel geometry design of a trapezoidal channel, the input parameters include:</u>

Lining strength: τ_p

Design discharge frequency Q

Channel slope S_f

The major steps or calculations include:

Back calculate the maximum depth of flow:

$$d_{max} = \frac{\tau_p}{\gamma S_f}$$

Set the value of B, α

Set permissible hydraulic radius: $R_h = \frac{A}{L} = \frac{(B + h\cot\alpha)h}{B + 2h\sqrt{1 + \cot\alpha^2}}$

Use manning's equation: $u = \frac{1}{n} R_h^{\frac{2}{3}} S_f^{\frac{1}{2}}$ and continuity equation $Q = uA$ to solve for flow depth h (or read the numbers from chart).

If $h \le h_{\max}$ or $Q \le Q_{\max}$, B, α can be chosen as geometry parameters, or repeat until the above equation is valid.

Output will yield:

Channel cross section geometry parameters : B, α

DISCUSSION

Before additional analysis is performed, it is logical to check the validity of the assumption of uniform flow in the channels used on right-of-ways on Georgia highways. The basic equation to describe depth variation of open-channel flow can be written as (Figure 2):

$$\frac{dy}{dx} = \frac{(S_f - S_0)}{(1 - Fr^2)}$$

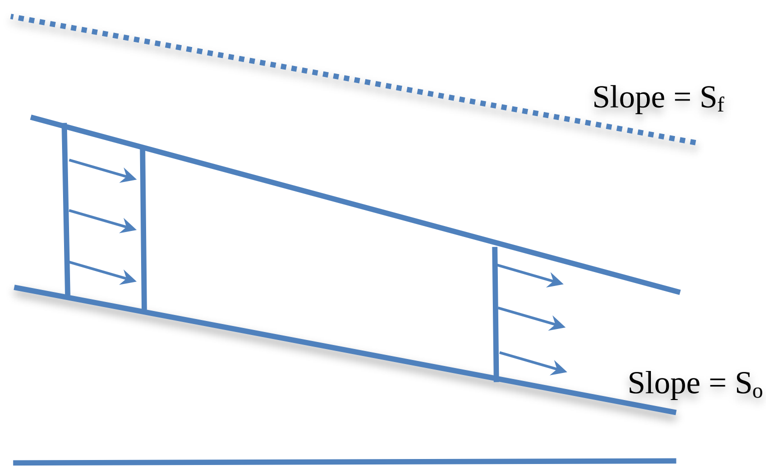


Figure 2. Depth variation of open-channel flow.

For open channel flow, uniform flow can form when the energy line parallels the slope line $S_f = S_0$ (Or $\sum F = 0$). For channels in Georgia, the typical ditch has a 1.2 m (4 ft) flat bottom with 2:1 side slopes, or a 2:1 back slope with a 4:1 or 6:1 foreslope. The longitudinal slopes range from about 0.5% to 30%. Lengths are commonly up to 305 m (1000 ft); however, long ditches typically have driveways pipes every 60 m to 90 m (200 ft to 300 ft). It is also very important to note that the slopes S_0 encountered in Georgia can be large, as high as 30%, which is large enough to exceed the actual energy slope S_f. In that case, the unbalanced force along the slope would accelerate the flow and at the same time, reduce the depth of the flow. The results of a numerical simulation, performed to analyze the assumptions of uniform flow, follow in the next section. When analyzing the assumption of uniform flow, it is also important to note that the magnitude of shear stress involved in open-channel flow, is typically significantly lower than that encountered in traditional geotechnical design (Figure 3):

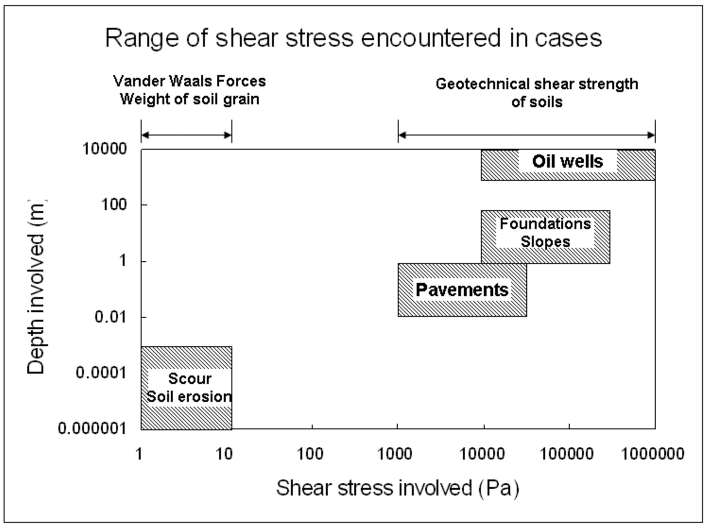


Figure 3. Magnitude of shear stress in erosion problems (Briaud, 2008).

NUMERICAL SIMULATION

Two governing equations are included to establish the relationship between quantity of flow (Q), average velocity ($\overline{u}$) and flow depth (or cross-sectional area for given geometry):

(1) Continuity equation

$$Q = \bar{u} \cdot A$$

(2) Backwater equation (Chow, 1959)

$$\frac{dy}{dx} = \frac{S_0 - S_f}{1 - F_r^{\,2}}$$

Where $Fr = \frac{u}{\sqrt{gy}}$

The following examples present numerical simulations designed to mimic those conditions typically encountered for roadside channels in Georgia. Channel configurations were modeled according to the following parameters:

Flow rate: $Q = 15\,ft^3/\sec = 0.41m^3/\sec$

Slope gradient: $\theta = 1^\circ, 2.5^\circ, 5^\circ, 10^\circ, 16.58^\circ$ deg

Manning's roughness coefficient: $n = 0.02, 0.03, 0.04\sec/m^{1/3}$

Geometry of the channel: Trapezoidal with 2:1 sides lopes, and a 4 ft bottom width

Example.

The depth of flow, flow velocity, and the influence of channel slope can be determined for a trapezoidal channel with the following initial conditions (Figure 4 and Figure 5):

Flow rate: $Q = 15\,ft^3/\sec = 0.41m^3/\sec$

Initial head $h_0 = 0.1m$

Geometry $B = 1.2m$ 4:1 back slope and 4:1 foreslope $L = 20m$ L $\theta = 16.58^\circ$

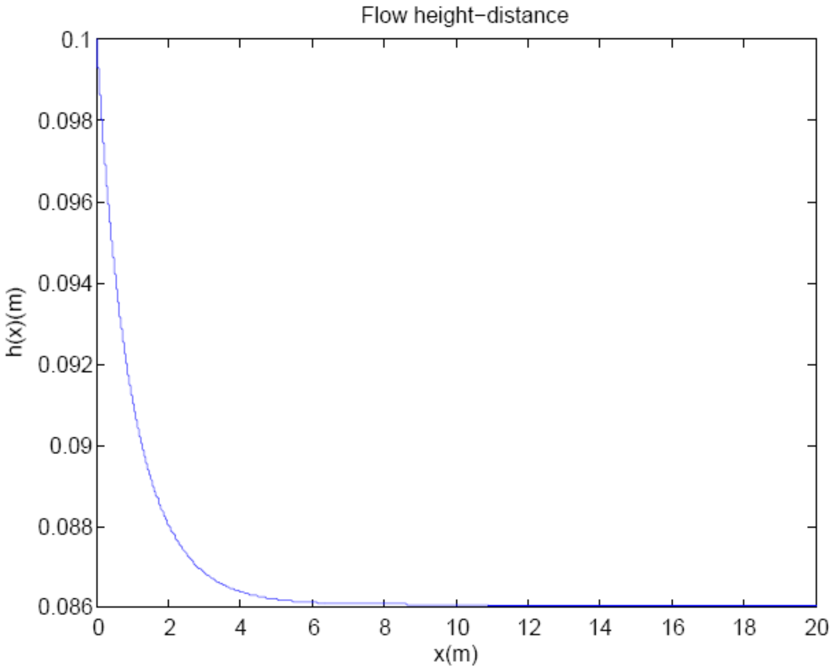


Figure 4. Flow depth-distance (along the slope).

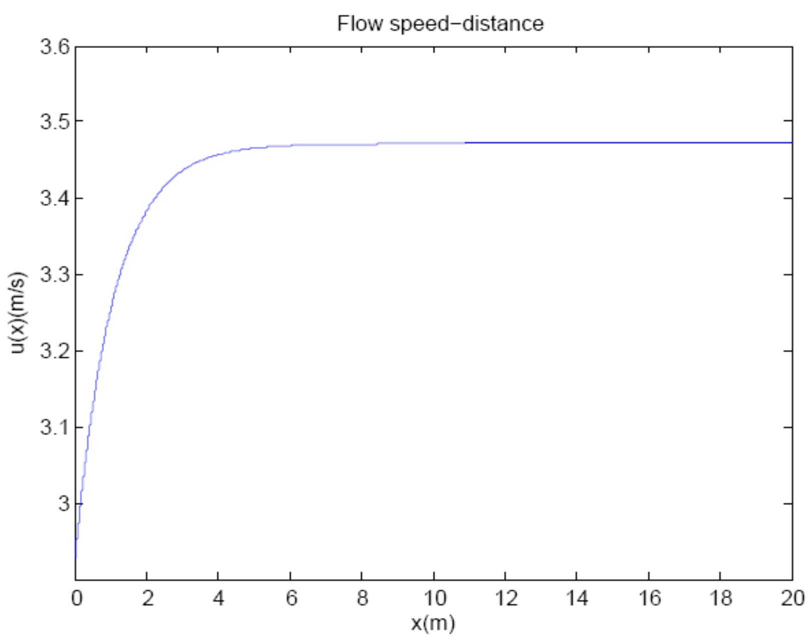


Figure 5. Flow speed-distance (along the slope).

As would be anticipated, increasing the slope resulted in more shallow flow depth and higher terminal velocity (Figure 6 and Figure 7).

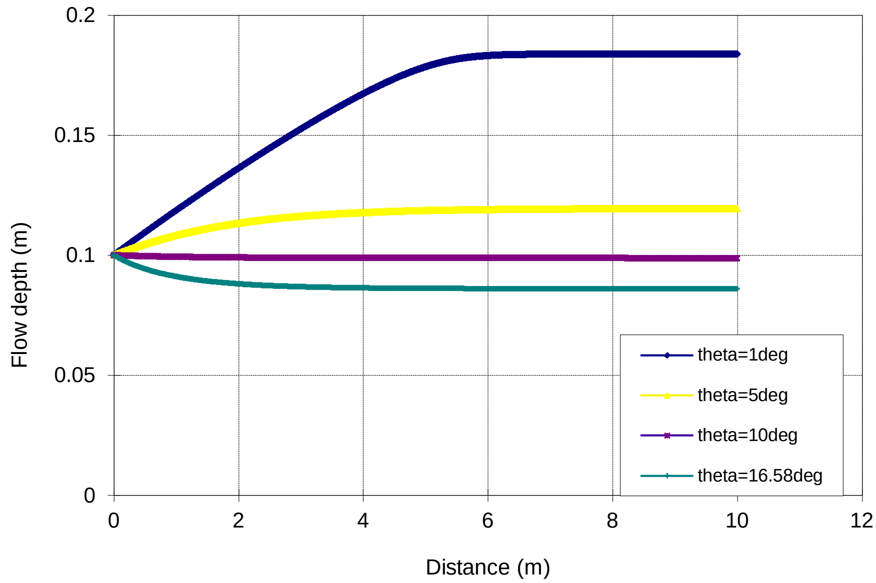


Figure 6. The influence of slope gradient on flow depth.

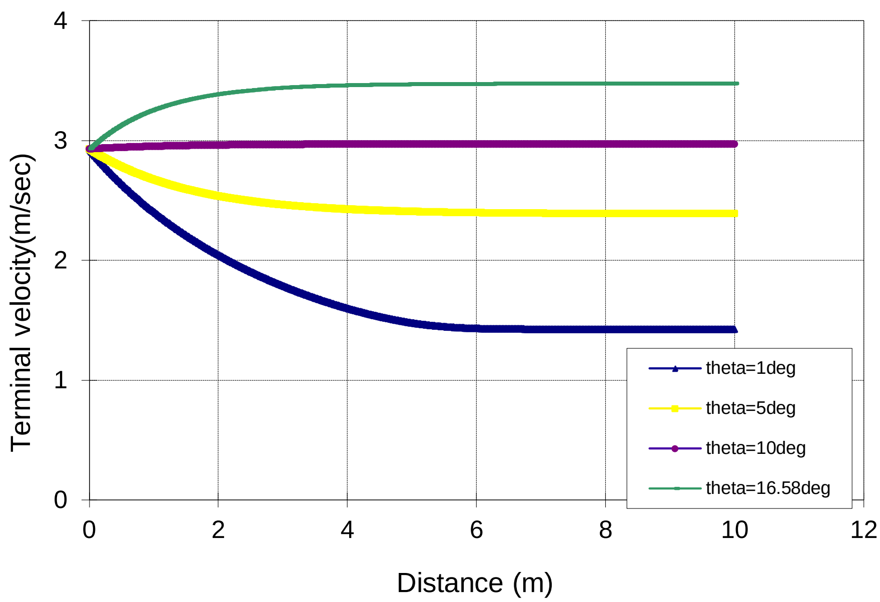


Figure 7. The influence of slope gradient on terminal velocity.

Comparison between Manning's equation and the Backwater equation resulted in relatively similar terminal velocity (Figure 8).

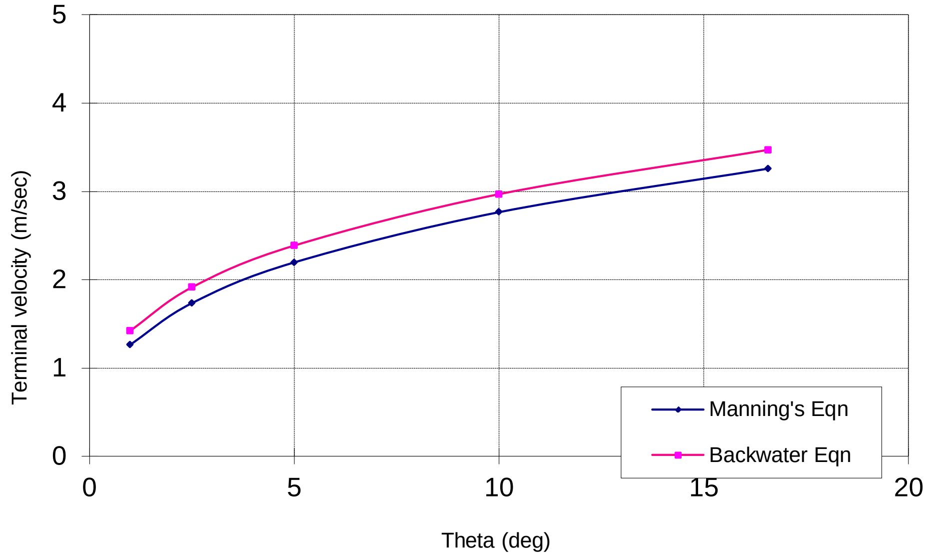


Figure 8. Comparison between Manning's equation and the backwater equation.

MANNING'S ROUGHNESS COEFFICIENT

Manning's coefficient *n* is related to the roughness of the surface of the channel; as roughness of the bottom of the channel increases, head loss increases. However, for the case of side slopes, which are erodible, it is favorable to keep *n* large in order to reduce the flow speed. Manning's coefficient is especially important for steep slopes because it influences how much tractive force the channel can provide to slow the rapid flow against the slope gradient.

For linings, the value of Manning's coefficient can vary in a wide range. Simulations were performed in order to demonstrate the relationship between Manning's coefficient and terminal velocity of flow. Different values of *n* were simulated with the same fixed conditions as introduced before. Increasing the value of Manning's roughness resulted in a decrease in the terminal flow velocity (Figure 9).

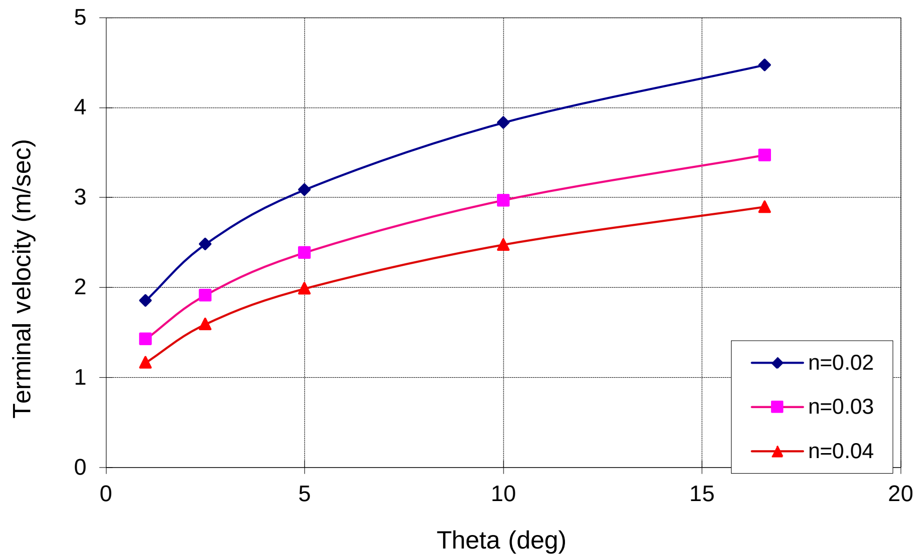


Figure 9. Terminal velocity as a function of slope and roughness.

SUMMARY: TASK 2

1. Manning's equation is applicable for uniform flow condition, but it is important to note that before the fluid reaches a steady, uniform state, it can develop high velocity, with large shear stresses acting on the soil or lining.
2. Slope gradient is important for terminal velocity of flow.
3. Manning's roughness of the interface (or lining) is also important for flow velocity. For a given slope gradient, increasing the roughness of the interface can reduce the terminal velocity and raise the flow depth, reducing the applied shear stress on the interface (or lining).

Task 3: Update to the GDOT Ditch Protection Program

This section details the program logic required for update of the GDOT Ditch Protection Program. Design is based on the assumption of uniform and steady flow conditions, with stability in the banks and beds. HEC15 relies on the concept that the "flow induced tractive force should not exceed the permissible or critical shear stress of the lining materials" (HEC15, 2005).

As detailed in the previous section, the recommended design also assumes the maximum channel bottom shear stress is equivalent to:

$$\tau_d = \gamma d S_o$$

Channel lining types will be selected from one of the following:

- Types 1-6: TRM 1, 2, 3, 4, 5, or 6 (Alternatively, Type 1A, grass with a biodegradable RECP, may be specified for shear stresses of 0-3 psf when suitable site conditions exist.)
- Types 7 and 7A: Riprap
- Type 8: Concrete

Design logic, as detailed in HEC15, is given in Figure 10.

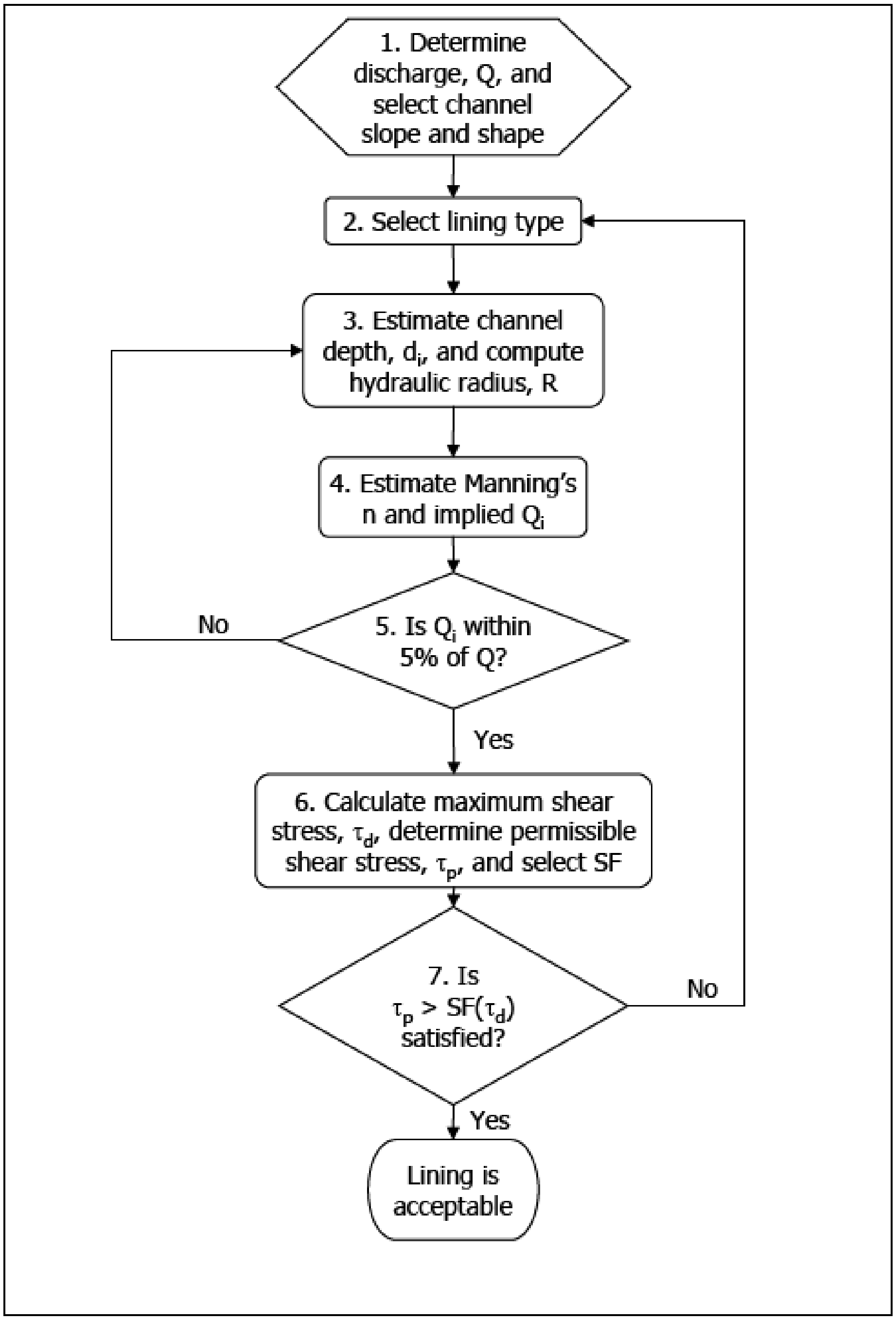


Figure 3.1. Flexible Channel Lining Design Flow Chart

Figure 10. Design logic: From HEC15, 2005.

PROGRAM INPUT

General Project Information

Project Number:

Select County:

Design Return Period (years):

Lower Station Limit:

Upper Station Limit:

Project Description:

Channel Design Criteria

Segment starting from: Segment ending at:

Basin Area (acres): A_b

Discharge (cfs): Q

Discharge cross-sectional area (ft^2): A

Longitudinal slope (ft/ft): S

Erosion Index (dimensionless):

Bottom Width (ft): B

Foreslope: S_1 (inverse = Z_1)

Backslope: S_2 (inverse = Z_2)

Select channel shape (Trapezoidal):

Channel Location (right, left, or median):

Select roughness coefficient (see Table 3):

Input Factor of Safety (=1.0 for default).

DETERMINATION OF MANNING'S ROUGHNESS COEFFICIENT

Manning's roughness coefficient is a critical parameter that will influence the depth and velocity of flow for a given channel slope. However, roughness is dependent on multiple factors, including grain size.

Calculation of Manning's roughness for grass linings

Determination of a roughness coefficient for grass is especially difficult because the roughness changes as flow depth and velocity increase. The change in roughness is attributable to the fact that stems bend as the shear stress is increased, and the bend results in a reduction in roughness. Manning's roughness coefficient for grass linings can be determined according to (HEC15, 2005):

$$n = \alpha C_n \tau_o^{-0.4}$$

Where n = Manning's roughness, $\tau_o = mean\ boundary\ shear\ stress\ (\frac{lb}{ft^2})$, α = unit

conversion = 1.0 (SI) 0.213 for (U.S.). The grass roughness coefficient, C_n is defined as (HEC15, 2005):

$$C_n = \alpha C_s^{0.10} h^{0.5}$$

Where C_n = grass roughness coefficient, C_s = density-stiffness coefficient, h = stem height, and α = unit conversion = 0.35 (SI) = 0.237 (U.S.).

Table 1. Density-Stiffness Coefficient, C_s (HEC 15, 2005)

Condition	Excellent	Very Good	Good	Fair	Poor
C_s (SI)	580	290	106	24	8.6
C_s (U.S.)	49	25	9.0	2.0	0.73

Calculation of Manning's roughness for TRM linings

Because the roughness of TRMs is also a function of applied shear stress, the *n* value must be determined from full-scale laboratory flume testing. TRM manufacturers supply three n values, measured as a function of applied shear stress. HEC15 specifies that the roughness should be measured at the values of applied shear stress, as given in Table 2, with the value of the upper shear stress equal to the strength of the liner.

Table 2. Standard n Value Versus Applied Shear (Manufacturer Supplied Data) (HEC15, 2005)

Applied shear stress (lb/ft2)	n value
$\tau_{lower} = \frac{\tau_{mid}}{2}$	n_{lower}
τ_{mid}	n_{mid}
$\tau_{uppwe} = 2\tau_{mid}$	n_{upper}

Using the manufacturer reported values for roughness as a function of shear stress, the *n* value can then be determined according to:

$$n = \alpha \tau_o^b$$

Where n = Manning's roughness for chosen TRM, τ_o = mean boundary shear stress (lb/ft^2) and *a* and *b* are coefficients calculated according to:

,

$$a = \frac{n_{mid}}{\tau_{mid}^b}$$

$$b = -\frac{\sqrt{\ln\left(\frac{n_{mid}}{n_{lower}}\right)\ln\left(\frac{n_{upper}}{n_{mid}}\right)}}{0.693}$$

Calculation of Manning's roughness for riprap linings

For the case where $1.5 \leq {}^{d_a}\!/_{D_{50}} \leq 185$ (where d_a = average flow depth in channel, and D_{50} = median riprap size), roughness can be calculated according to:

$$n = \frac{\alpha d_a^{1/6}}{2.25 + 5.23\log\left(\frac{d_a}{D_{50}}\right)}$$

Where α = unit conversion, 0.319 (SI), and 0.262 (U.S.). In cases where the depth of flow is low relative to the size of the riprap ${}^{d_a}\!/_{D_{50}} \leq 1.5$, the semi-empirical Bathurst equation is recommended (HEC15, 2005).

Table 3. Manning's Roughness Coefficient (HEC15, 2005)

Boundary	**Manning's n**
Smooth concrete	0.011
Ordinary concrete	0.013
Rough concrete	0.015
Riprap	0.033
Grass	Function of shear stress
TRM	Function of shear stress

PERMISSIBLE SHEAR STRESS

Determination of permissible shear stress for grass linings

The permissible shear stress that can be tolerated by a lining represents the limit of applied shear stress to prevent the initiation of erosion. Permissible shear stresses for vegetative linings include contributions from both the underlying soil and the vegetative covering.

Permissible shear stress for vegetation/soil lining can be determined according to (HEC15, 2005):

$$\tau_p = \frac{\tau_{p,soil}}{(1-C_f)}\left(\frac{n}{n_s}\right)^2$$

Where τ_p = permissible shear stress on vegetative lining (lb/ft^2), $\tau_{p,soil}$ = permissible soil shear stress (lb/ft^2), C_f = grass cover factor (Table 4), n_s = soil grain roughness, n = overall roughness:

n_s = 0.016, when D_{75}<1.3mm,

Otherwise: $n_s = \alpha(D_{75})^{1/6}$

Where D_{75} = grain size at which 75% of soil is finer, mm (in), and n = Manning's roughness coefficient as determined for grass.

Table 4. Cover Factor Values for Uniform Stands of Grass (HEC15, 2005)

Growth Form	Cover Factor, C_f				
	Excellent	Very Good	Good	Fair	Poor
Sod	0.98	0.95	0.90	0.84	0.75
Bunch	0.55	0.53	0.50	0.47	0.41
Mixed	0.82	0.79	0.75	0.70	0.62

Determination of permissible shear stress for TRM linings

Like grass linings, permissible shear stress for TRM linings also combine the properties of the underlying soil and vegetation, as well as the TRM. The presence of the TRM modifies the cover factor in the permissible shear stress relationship. Consequently, the permissible shear stress is determined according to:

$$\tau_p = \frac{\tau_{p,soil}}{(1 - C_{f,TRM})}\left(\frac{n}{n_s}\right)^2$$

And

$$C_{f,TRM} = 1 - \left(\frac{\tau_{p,VEG-test}}{\tau_{p,TRM-test}}\right)(1 - C_{f,VEG})$$

Where τ_p = permissible shear stress on vegetative/TRM lining (lb/ft^2), $\tau_{p,soil}$ = permissible soil shear stress (lb/ft^2)$C_{f,TRM}$ = TRM cover factor, $C_{f,VEG}$ = grass cover factor, $\tau_{p,VEG\text{-}test}$ = permissible shear stress on the vegetative lining, as reported by manufacturer's test data, and $\tau_{p,TRM\text{-}test}$ = permissible shear stress on the TRM reinforced lining, as reported by manufacturer's test data, n_s = soil grain roughness, n = overall roughness:

n_s = 0.016, when D_{75}<1.3mm,

Otherwise: $n_s = \alpha(D_{75})^{1/6}$

Where D_{75} = grain size at which 75% of soil is finer, mm (in), and n = Manning's roughness coefficient as determined for grass.

Determination of permissible shear stress for riprap linings

Permissible shear stress for riprap linings is given in HEC 15 (2005):

$$\tau_p = F*(\gamma_s - \gamma)D_{50}$$

Where $F*$ = Shields parameter, γ_s = specific weight of stone, γ = specific weight of water, and D_{50} = median riprap size. Combining with shear stress relationships, allows sizing of riprap according to (HEC15, 2005):

$$D_{50} \geq \frac{SFdS_o}{F*(SG-1)}$$

Where SF = safety factor, d = maximum channel depth, S_o = channel slope, SG = specific gravity of rock, commonly 2.7 for continental crustal rocks.

Ranges of permissible shear stresses are given in Table 5.

Table 5. Permissible Shear Stresses

Lining Type	**Permissible Shear Stress (lb/ft^2)**
Type 1: TRM 1	0-2
Type 1A: Grass with temporary RECP	0-3
Type 2: TRM 2	0-4
Type 3: TRM 3	0-6
Type 4: TRM 4	0-8
Type 5: TRM 5	0-10
Type 6: TRM 6	0-12
Type 7: Riprap $D_{50} \leq 0.573$ ft (Type 3) [1]	$\tau_p = F_*(\gamma_s - \gamma)D_{50}$ (HEC 15)
Type 7A: Riprap 0.573< $D_{50} \leq 1.078$ ft (Type 1) [2]	$\tau_p = F_*(\gamma_s - \gamma)D_{50}$ (HEC 15)
Type 8: Concrete D_{50} >1.078 ft	D_{50} sizing > Type 1

[1]GDOT Type 3 riprap D_{50} = 0.66 ft.

[2]GDOT Type 1 riprap D_{50} = 1.20 ft.

Historically, design for riprap and concrete channels has been performed not on the basis of a permissible shear stress, but on a sizing criteria for riprap D_{50}. Riprap D50 is determined according to (HEC 15, 2005):

$$D_{50} \geq \frac{SFdS_o}{F_*(SG-1)}$$

where SF = safety factor, d = maximum channel depth, F_* = Shields parameter, and SG = specific gravity. Values for Shields parameter and safety factor are given as follows:

Reynolds Number	F*	SF
$\leq 4x10^4$	0.047	1.0
$4x10^4 < Re < 2x10^5$	Linear interpolation	Linear interpolation
$\geq 2x10^5$	0.15	1.5

PROGRAM CALCULATIONS

Estimate initial depth of flow derived from Manning's discharge equation assuming normal depth:

$$D_i = \left(\frac{0.033Q}{BS^{0.5}}\right)^{0.6}$$

Calculate the hydraulic radius, R:

$$A = BD + 0.5D^2(Z_1 + Z_2)$$

$$P = B + D\left[\left(Z_1^2 + 1\right)^{0.5} + \left(Z_2^2 + 1\right)^{0.5}\right]$$

$$R = {A}/{P}$$

Calculate new discharge Q_i using depth of flow determined previously.

$$Q = \frac{\alpha}{n} AR^{2/3}$$

If Qi > 1.05 Q or Qi < 0.95 Q, then, estimate new flow depth:

$$d_{i+1} = d_i \left(\frac{Q}{Q_i} \right)^{0.4}$$

Recalculate hydraulic radius, and recheck flow condition.

If: 0.95 Q $\leq$ Qi $\leq$ 1.05 Q then calculate shear stress at maximum depth

Calculate the shear stress at maximum depth

$$\tau_d = \gamma d S_o$$

Compare to permissible shear stress.

If permissible shear stress is adequate, then the lining is acceptable.

If permissible shear stress is not adequate, then select another lining and redesign.

Determination of roughness is performed as previously discussed.

Tasks 4, 5, and 6: Categorization of Turf Reinforcement Mats and Recommended Guidelines

Turf reinforcement mats (TRMs) can be categorized according to two primary methods: testing of material properties (index testing) and large-scale performance testing in the field.

Index testing provides classification of TRMs based on properties of the materials that are easily quantified within a laboratory setting, e.g., mass per unit area. The ease and relative inexpense of index testing makes it appealing for testing a large number of samples; however, index testing does not provide quantitative data that can be used for design on the basis of conditions in the field.

Sample ASTM standards governing index tests performed on TRMs include:

D 4354 Practice for Sampling of Geosynthetics for Testing

D 5199 Test Method for Measuring the Nominal Thickness of Geosynthetics

D 6475 Test Method for Measuring Mass per Unit Area of Erosion Control Blankets

D 6525 Standard Test Method for Measuring Nominal Thickness of Permanent Rolled Erosion Control Products

D 6566 Test Method for Measuring Mass per Unit Area of Turf Reinforcement Mats

D 6567 Test Method for Measuring the Light Penetration of a Turf Reinforcement Mat (TRM)

D 6818 Test Method for Ultimate Tensile Properties of Turf Reinforcement Mats

In contrast, large-scale field testing does provide a performance measurement that can be used for design by subjecting the TRMs to actual flow conditions observed in the field. The disadvantage of field testing is the high cost and labor involved. Standards governing large scale tests include:

D 6459 – 07 Standard Test Method for Determination of Rolled Erosion Control Product (RECP) Performance in Protecting Hillslopes from Rainfall-Induced Erosion

D 6460 – 07 Standard Test Method for Determination of Rolled Erosion Control Product (RECP) Performance in Protecting Earthen Channels from Stormwater-Induced Erosion

Bench-scale testing does exist as an alternative to both the relatively simple index testing and the relatively expensive field testing. While bench-scale methods do not provide design numbers, they do result in semi-quantitative comparisons between different TRMs. Bench-scale ASTM standards include:

D 7101 – 08 Standard Index Test Method for Determination of Unvegetated Rolled Erosion Control Product (RECP) Ability to Protect Soil from Rain Splash and Associated Runoff under Bench-Scale Conditions

D 7207 – 05 Standard Test Method for Determination of Unvegetated Rolled Erosion Control Product (RECP) Ability to Protect Sand from Hydraulically-Induced Shear Stresses under Bench-Scale Conditions

D 7322 – 07 Standard Test Method for Determination of Rolled Erosion Control Product (RECP) Ability to Encourage Seed Germination and Plant Growth under Bench-Scale Conditions

The Texas Transportation Institute (TTI) and Texas DOT (TxDOT) have conducted a series of large-scale channel tests to categorize TRMs for use as channel linings. On the basis of the test results, TTI grouped TRM performance into six categories of shear stress ranges. These six categories are shown below along with riprap and concrete channel linings. GDOT designates these eight channel linings as Types 1 through 8.

Table 6. Channel-lining Material Classification by Allowable Shear Stress

Classification	Allowable Shear Stress
Type 1 TRM*	0-2 psf
Type 2 TRM	0-4 psf
Type 3 TRM	0-6 psf
Type 4 TRM	0-8 psf
Type 5 TRM	0-10 psf
Type 6 TRM	0-12 psf
Type 7A: Riprap D_{50} = 0.66 ft (GDOT Type 3)	$\tau_p = F_*(\gamma_s - \gamma)D_{50}$ (HEC 15, 2005)
Type 7B: Riprap D_{50} = 1.2 ft (GDOT Type 1)	$\tau_p = F_*(\gamma_s - \gamma)D_{50}$ (HEC 15, 2005)
Type 8: Concrete	For D_{50} sizing > Type 1

* Alternatively, Type 1A, grass with a biodegradable RECP, may be specified for shear stresses of 0-3 psf when suitable site conditions exist.

All products are classified into groups of acceptable performance, so the list of acceptable products is largest at 0-2 psf, and becomes smaller as the performance requirements increase (i.e., products drop off the list as the requirements become more stringent). If channel conditions exceed 12 psf of shear stress, then riprap, concrete, or other suitable channel lining is specified for application.

In addition to the Texas testing, rating, and approval process, the Erosion Control Technology Council (ECTC) manages a program for review and certification known as the Quality Data Oversight and Review (QDOR™) program. This program is an industry-derived certification procedure designed to review material performance data and index property test results, and to identify unique products. The program verifies TRM performance by issuing a QDOR™ certification for TRM meeting the QDOR™ testing protocol described in the QDOR™ Guidance Manual. For a TRM product to receive QDOR™ certification, the QDOR™ program requires that the TRM be tested under the guidance of the AASHTO-NTPEP program for index testing and large-scale testing by the ASTM D 6459 and 6460 procedures. Currently approved GDOT products and their status in terms of TTI and TxDOT approval, QDOR™ certification, and NTPEP bench tests are given in Table 7 through Table 9. NTPEP Status of Materials on the Qualified Products List.

It is recommended that manufacturers who wish to add new TRMs to the Georgia Department of Transportation Qualified Products List submit their products to the AASHTO-NTPEP program and QDOR™ certification. Ideally, products would also the tested according to the Texas Transportation Institute guidelines as well; however, it is important to note that recent backlog in that testing system have made obtaining the TTI certification more difficult.

Table 7. Turf Reinforcement Mats on GDOT Qualified Product List (as of 11/9/2009)

Manufacturer	Product	Material Type
American Excelsior Company	Recyclex TRM	Polyester Fibers Polypropylene Netting
Colbond Geosynthetics Incorporated	ENKAMAT 7020	Nylon
Contech Construction Products, Incorporated	Contech TRM C-45	Polypropylene
East Coast Erosion Control Blankets	ECP-2	Polypropylene
Erosion Tech	[1]ET-PM-10	Polypropylene
Greenfix America	[2]CF 072 RP	
L and M Supply	EG-2P10	Polypropylene
North America Green	[3]P300	Polypropylene
North America Green	C350	Polypropylene Coconut Fibers
North America Green	P550	Polypropylene
Propex	Landlok® 450	Polypropylene
Propex	PYRAMAT® Tan/Green	Polypropylene
Robex	Robexshield RSP5-10	
Rolanka	3DTRM-PP	Polypropylene
Southern Environmental Conservation	SEC-P2	Polypropylene
Tensar	[2,4]TB1000	
Tensar	[2,4]TB3000	
Webtec	Terra Guard 45P	Polypropylene
Western Excelsior	PP5-10	Polypropylene
Western Excelsior	PP5-12	Polypropylene

[1]Manufacturer new name ETPP-10
[2]No longer produced
[3]First generation design, lower performance standard per manufacturer
[4]North American Green merged with Tensar 4-5 yrs ago

Table 8. Turf Reinforcement Mats on GDOT QPL: TTI and QDOR Status

Product	Texas Transportation Institute Results						QDOR Certified for Channel
	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	
	0-2 (psf)	0-4 (psf)	0-6 (psf)	0-8 (psf)	0-10 (psf)	0-12 (psf)	
Recyclex TRM	x	x	x	x	x	x	Yes
ENKAMAT 7020	x						Yes
Contech TRM C-45	x	x	x	x			No (6/15/10)
ECP-2	Testing in Progress						To be submitted 2010
[1]ET-PM-10	Not Tested						No (6/15/10)
[2]CF 072 RP	No Longer Produced						
EG-2P10	Not Tested						
[3]P300	Not Tested						Yes
C350	x	x	x	x	x		Yes
P550	x	x	x	x	x	x	Yes
Landlok® 450	x	x	x	x	x	x	
PYRAMAT® Tan/Green	x	x	x	x			
Robexshield RSP5-10	Out of Production						No (3/15/10)
3DTRM-PP	Not Tested						No (3/15/10)
SEC-P2	x	x	x	x			No (3/15/10)
[2,4]TB1000	No Longer Produced						
[2,4]TB3000	No Longer Produced						
Terra Guard 45P	x	x	x	x			No (3/15/10)
PP5-10	x	x	x	x	x		Yes
PP5-12	x	x	x	x	x	x	Slope only

Table 9. NTPEP Status of Materials on the Qualified Products List

Manufacturer	Product	Material Type	NTPEP Bench[5]
American Excelsior Company	Recyclex TRM	Polyester Fibers Polypropylene Netting	Yes
Colbond Geosynthetics Incorporated	ENKAMAT 7020	Nylon	Yes
Contech Construction Products, Incorporated	Contech TRM C-45	Polypropylene	--
East Coast Erosion Control Blankets	ECP-2	Polypropylene	Yes
Erosion Tech	[1]ET-PM-10	Polypropylene	Yes
Greenfix America	[2]CF 072 RP		
L and M Supply	EG-2P10	Polypropylene	--
North America Green	[3]P300	Polypropylene	Yes
North America Green	C350	Polypropylene Coconut Fibers	Yes
North America Green	P550	Polypropylene	Yes
Propex	Landlok® 450	Polypropylene	Yes
Propex	PYRAMAT® Tan/Green	Polypropylene	Yes
Robex	Robexshield RSP5-10		Yes
Rolanka	3DTRM-PP	Polypropylene	--
Southern Environmental Conservation	SEC-P2	Polypropylene	Yes
Tensar	[2,4]TB1000		
Tensar	[2,4]TB3000		
Webtec	Terra Guard 45P	Polypropylene	
Western Excelsior	PP5-10	Polypropylene	Yes
Western Excelsior	PP5-12	Polypropylene	Yes

[1]Manufacturer new name ETPP-10
[2]No longer produced
[3]First generation design, lower performance standard per manufacturer
[4]North American Green merged with Tensar 4-5 yrs ago
[5]Test methods listed below:

D 6525 Standard Test Method for Measuring Nominal Thickness of Permanent Rolled Erosion Control Products

D 6566 Test Method for Measuring Mass per Unit Area of Turf Reinforcement Mats

D 6567 Test Method for Measuring the Light Penetration of a Turf Reinforcement Mat (TRM)

D 6818 Test Method for Ultimate Tensile Properties of Turf Reinforcement Mats

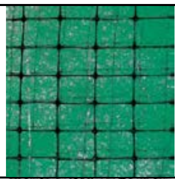
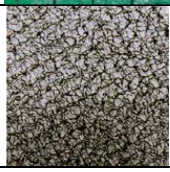
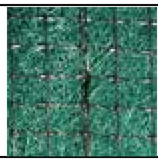
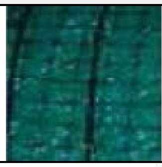
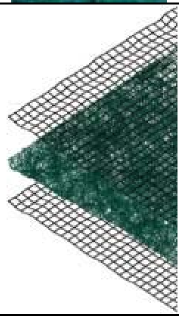
D 792 Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement (Net only)

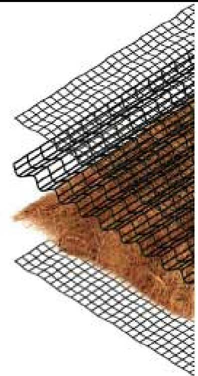
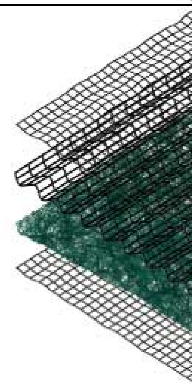
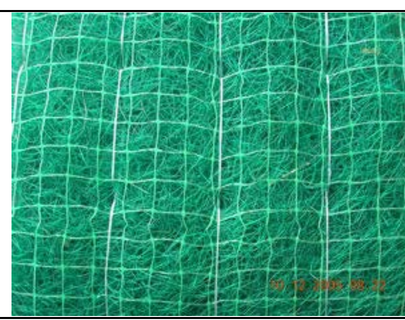
D 7101 – 08 Standard Index Test Method for Determination of Unvegetated Rolled Erosion Control Product (RECP) Ability to Protect Soil from Rain Splash and Associated Runoff under Bench-Scale Conditions (ECTC Test Method 2)

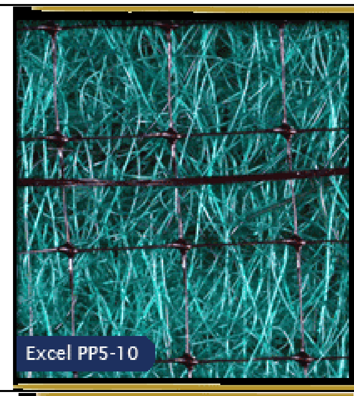
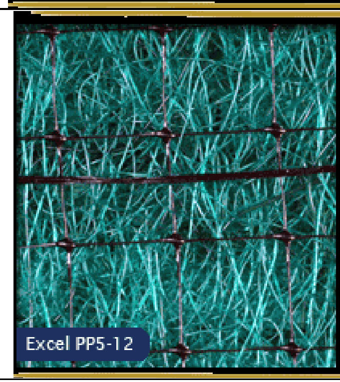
D 7207 – 05 Standard Test Method for Determination of Unvegetated Rolled Erosion Control Product (RECP) Ability to Protect Sand from Hydraulically-Induced Shear Stresses under Bench-Scale Conditions (ECTC Test Method 3)

D 7322 – 07 Standard Test Method for Determination of Rolled Erosion Control Product (RECP) Ability to Encourage Seed Germination and Plant Growth under Bench-Scale Conditions (ECTC Test Method 4)

Table 10. Manufacturers Photgraphs of Materials on GDOT's Qualified Products List

Manufacturer	Product	Photo
American Excelsior Company	Recyclex TRM	
Colbond Geosynthetics Incorporated	ENKAMAT 7020	
Contech Construction Products, Incorporated	Contech TRM C-45	-
East Coast Erosion Control Blankets	ECP-2	
Erosion Tech	[1]ET-PM-10	-
Greenfix America	[2]CF 072 RP	
L and M Supply	EG-2P10	
North America Green	[3]P300	

North America Green	C350	
North America Green	P550	
Propex	Landlok® 450	
Propex	PYRAMAT® Tan/Green	
Robex	Robexshield RSP5-10	
Rolanka	3DTRM-PP	
Southern Environmental Conservation	SEC-P2	

Tensar	[2,4]TB1000	
Tensar	[2,4]TB3000	
Webtec	Terra Guard 45P	
Western Excelsior	PP5-10	
Western Excelsior	PP5-12	

Task 7: Erosion index for use in Georgia

The potential for a soil to erode is a function of soil characteristics such as grain size, plasticity, and soil density, as well as flow characteristics, which makes it exceedingly difficult to quantify erosion susceptibility in a simple form. A review of the factors important in the erodibility of soils follows. Currently, GDOT uses the Erosion Index (EI) as an empirical measure of the erodibility of a soil. The EI is a dimensionless number ranging from 0-10, with 0 representing highly erosion-resistant soils, and 10 representing highly erodible soils. The EI is based on the percentage of fines that compose the soil. As the percent of fine-grained soils increases, the EI decreases (Table 11). Although EI is an easily measured parameter, it does not account for the physic-chemical forces that contribute substantially to erosion potential, which significantly reduces its ability to predict erosion potential.

Table 11. Erosion Index (EI) Description Chart (From GDOT, 1988)

Erosion Index (EI)	-200 Range	Soil Description
0-2	80% to 76%	A highly impervious and cohesive soil.
2-4	76% to 50%	An impervious soil that is cohesive to moderately friable.
4-6	50% to 34%	Moderately cohesive to friable soil.
6-8	34% to 17%	Slightly cohesive to non-cohesive, highly friable soil.
8-10	17% to 0%	Non-cohesive coarse to fine sand. Highly friable, highly porous soil.

MEDIAN GRAIN SIZE D_{50}

The median grain size is frequently used as an indicator of a soil's erosion potential because as the grain size of soil increases, the larger weight of the particle contributes to an increase resistance to erosion (i.e., erosion is controlled by gravitational forces). For fine-grained soils, such as clays and silts, electrostatic forces become significant and help bond particles against erosion. While there are many factors that should be taken into account for a complete description of erosion resistance, in general, the greatest susceptibility to erosion comes from particles in the intermediate size range (e.g., silty fine sand) (Figure 11).

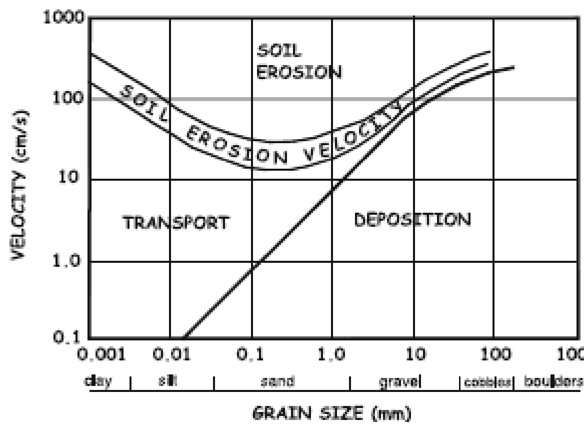


Figure 11. Erodibility of soils as a function of grain size (Figure from Hjulstrom 1935 ; Infanti and Fornasari Filho 1998).

Tests using the Erosion Function Apparatus (EFA) to identify the critical shear stress (or critical velocity) at which the soil erodes demonstrate similar trends, as plotted on the Shields diagram (Briaud, course notes, 2008) (Figure 12). When the shear stress is below the critical value, the soil loss is not very significant; however, when the shear stress exceeds the threshold, the rate of erosion increases and the loss increases as a function of shear stress (Shields, 1936):

$$\tau_c = \tau_{*c}(\gamma_s - \gamma_w) \cdot D_{50}$$

where, τ_{*c} : dimensionless critical shear stress or Shields parameter.

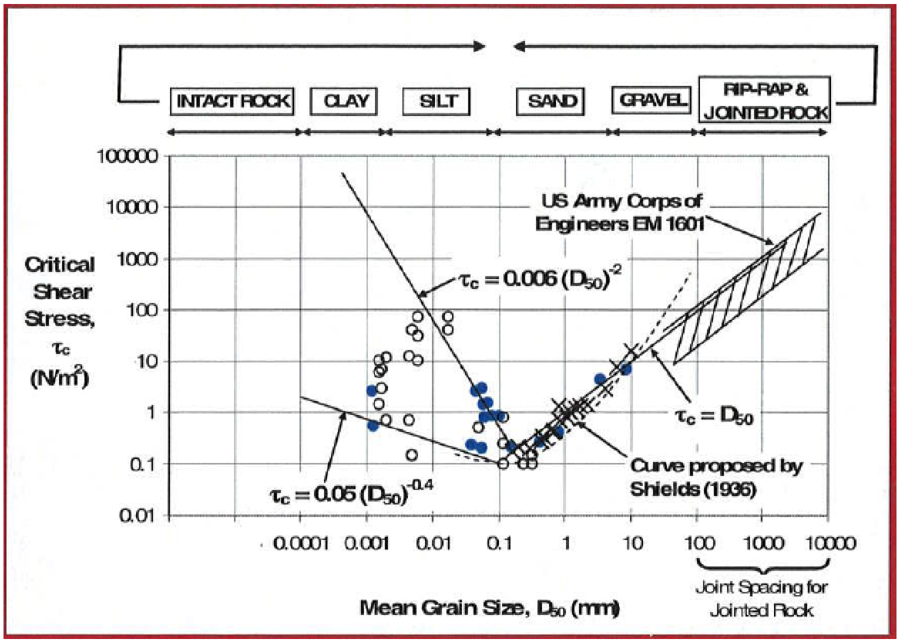


Figure 12. Critical shear stress as a function of mean grain size (Briaud, 2008).
From: Erosion short course notes, Texas A&M University

SURFACE SOIL DENSITY

Fine-grained dense soils are more resistant to the erosive forces of water, and the degree of compaction, especially at the soil-water interface, is critical for limiting soil loss behavior. When $d_{50} \geq 1.5mm$ (0.06 in), the density has negligible effect on erodibility of soils. When $d_{50} < 1.5mm$ (0.06 in) the erosion potential has a very strong logarithm correlation with the bulk density of the soil, even under different bed shear stresses (Roberts, 1998).

INFLUENCE OF CLAY MINERALS

Increasing the percentage of clay minerals within a soil yields a less erodable soil, primarily due to van der Waals forces which represent the dominant bonding mechanism between fine grained soil particles (Grissinger, 1966; Kemper and Koch, 1966; Panagiotopoulos et al. 1997). In terms of the mineralogy of the clay, the predominant mineral type also exhibits a significant influence on the soil's susceptibility to erosion. Consider the typical geometry of the kaolinite and montmorillonite particles: because they both have a close electrical potential at the surface, the repulsion between the two types of clays is of the same magnitude. However, because van der Waals attraction is largely dependent on the particle size, the attractive force tends to be much larger between kaolinite particles than montmorillonite particles. As the result, the net force between those particles varies greatly. Assuming the pore fluid has an ionic concentration of $1x\ 10^{-4}$ mol/L and a pH value = 7, the attractive/repulsive forces between the particles can be determined, and is a net force of repulsion that is much stronger in montmorillonite than in kaolinite (Figure 13). Because of the above mechanisms, soil mineralogy has a substantial effect on aggregate stability and dispersion. The microscopic forces are dominated by electrostatic and van der Waals attractions and aggregate destruction can result from slaking (macro-scale) or dispersion (micro-scale) forces, or from the combined effects of both (Abu-Sharar et al, 1987). It should be noted that clay minerals can also develop substantial surface charge due to isomorphic substitution, pH dependent surface dissociation, and broken edge charges. When particles have like charges (either positive/positive or negative/negative), the tendency is toward dispersion in aqueous systems.

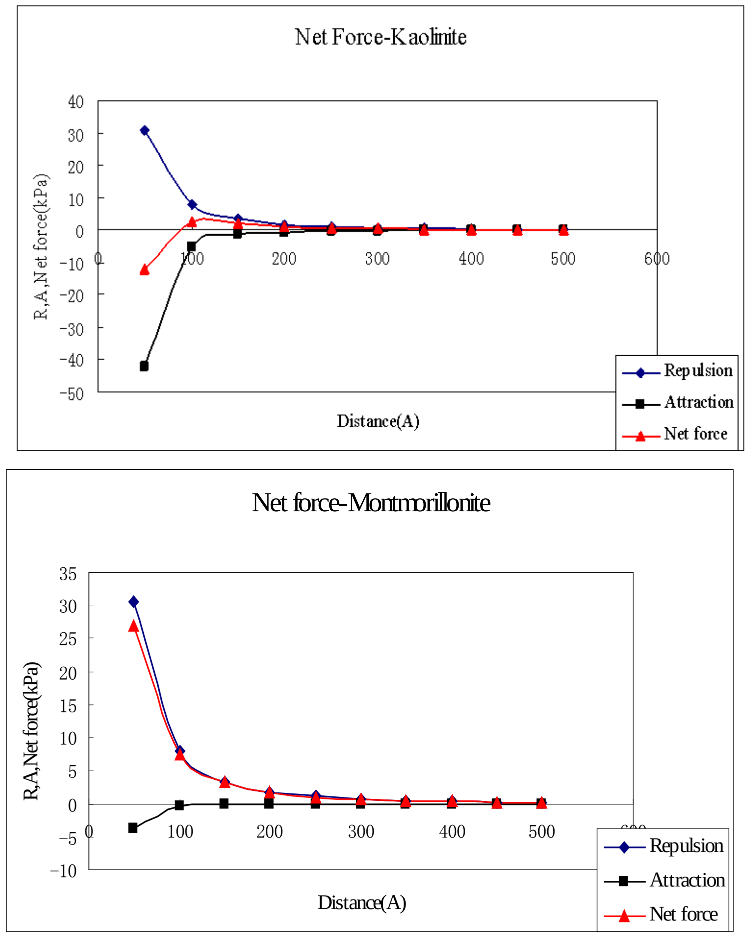


Figure 13. Net force as a function of clay particle separation.

Singer (1994) reviewed the effects of clay mineralogy on soil dispersion and concluded that kaolinitic soils have the greatest aggregate stability and the montmorillonitic soils the lowest. The illitic soils have medium resistance to dispersion; however, they may sometimes exceed that of montmorillonitic soils. Soil loss through erosion is significantly lowest in the kaolinitic, highest in the montmorillonitic, and intermediate in the non-phyllosilicate soils. Kaolinitic soils, with the lowest soil loss, high aggregate stability, and low soil detachment and runoff transport capacity, are in contrast to montmorillonitic soils, which are highly susceptible to erosion (Wakindiki and Ben-Hur, 2002).

SUMMARY

Although multiple factors influence the erodibility of soils, it remains important that soils can be, at least initially, classified on the basis of the data available from currently existing soil investigations performed by GDOT's Office of Materials and Research. Consequently, to balance a measurement that is fundamentally based, while maintaining reasonable practices for collection of data, the following classifications are recommended (after HEC15, 2005):

Table 12. Erosion Susceptibility by Soil Type

Grain Size	Soil	Plasticity Index	Erosion Susceptibility
Coarse grain	Medium to fine sand	< 10	High
Coarse grain	Clayey sands Silty sands	= 10	High
Fine grain	Inorganic silt	= 10	High
Coarse grain	Fine gravel	< 10	Medium
Coarse grain	Clayey sands Silty sands	≥ 20	Medium
Fine grain	Inorganic silt Inorganic clay	≥ 20	Medium
Coarse grain	Gravel Coarse gravel Very coarse gravel	< 10	Low

Conclusions

This work examined current transportation applications using turf reinforcement matting. Most specifically, the design assumptions inherent in the use of HEC15 were discussed, and were modeled with conditions commonly encountered on Georgia DOT roadways, in order to verify the logic and assumptions currently used for design in Georgia. Design logic for the currently used Georgia ditch protection program was also examined and updated to include new categories of turf reinforcement matting. A new categorization framework was developed for turf reinforcement matting applications in Georgia, along with recommendations for approval and incorporation in the Qualified Products List. Finally, recommendations were made for a new, easily measured, erosion index to be used on GDOT sites.

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Appendix A

Original program requested the following input information:

Input Information:

Design return period

Project Number

County

Lower Station Limit

Upper Station Limit

Sta:

Design shear stress

Side

Drainage area

Discharge

Slope

Width

Side slope left

Side slope right

Erosion index

Roughness coefficient

Velocity

For each channel section:

Enter station limits of this channel

Channel location: right, left, or median

Input discharge area (acres) = DA

Input discharge (cfs) = Q

Input slope (ft/ft) = S

Input Erosion Index = EI

Select channel geometry (1) trapezoidal, (2) triangular, (3) parabolic

For trapezoidal:

Input bottom width (ft) = B

Input left side slope = Z1

Input right side slope = Z2

Select Lining Type

Grass

BTGFM (Bituminous Treated Glass Fiber Mulch)

PSRM (Permanent Soil Reinforcing Mat)

Riprap

Concrete

Variables

DA = Drainage Area

Q = Discharge

S = Slope

EI = Erosion Index

B = Channel Bottom Width

Z1 = Left Side Slope

Z2 = Right Side Slope

J = Counter

K = Tractive Force

D = Depth

DP = Depth of Protection

ZZ (?) = Counter

A = Cross sectional Area

P = Wetted Perimeter

R = Hydraulic Radius

N = Roughness Coefficient

V = Velocity

TD = Design Shear Stress

TP = Permissible Shear Stress

Appendix B

The ditch protection program currently in use by the Georgia Department of Transportation uses the following parameters for determination of roughness and permissible shear stress:

Roughness coefficients for current program

Grass

$$RS = (R^{1.4})S^{0.4}$$

$$LG = LOG(RS)0.4342945$$

$$N = \frac{R^{.1667}}{K * (19.97 * LG)}$$

Permanent Soil Reinforcing Mat

$$RR = \left(\frac{R}{KS}\right)$$

$$LG = LOG(RR) * .4342945$$

$$N = \frac{R^{.1667} * KS\text{^}.167}{(3.82 * (KA * (KB * LGR)))}$$

Riprap

$$D50 = (D * 62.4 * S)/5$$

$$KS = D50/12$$

$$RR = \left(\frac{R}{KS}\right)$$

$$LGR = LOG(RR) * .4342945$$

$$N = (RR)^{.167} * (KS)\text{^}.167)/(3.82 * (KA + (KB * LGR)))$$

Concrete

For 0<D<0.5 N = 0.015

For D>2, N = 0.013

Permissible shear stresses

Grass

$$TP = 3.638531 - .169382EI - 0.082564EI^2 + 0.007471EI^3$$

Permanent Soil Reinforcing Mat

$$TP = 5.141841 - .1673639 * EI$$

Riprap

Concrete

Appendix C

July 15, 2010

GEORGIA DEPARTMENT OF TRANSPORTATION

STATE OF GEORGIA

SPECIAL PROVISION

Section 710—Turf Reinforcement Matting

Delete Section 710 and substitute the following:

710.1 General Description

This section includes the requirements for furnishing and placing turf reinforcement matting (TRM) over prepared areas according to the Plans or as directed by the Engineer. This section replaces the former Section 710 entitled "Permanent Soil Reinforcement Mat".

710. 1.01 Definitions

General Provisions 101 through 150.

710.02 Related References

A. Standard Specifications

Section 700—Grassing

B. Referenced Documents

OPL 49

710.02 Submittals

General Provisions 101 through 150.

710.2 Materials

Use materials listed on QPL 49 . TRM is designated Types 1, 2, 3, 4, 5, and 6 for use on GDOT projects and range in shear strength from Type 1 to Type 6, Type 6 being the strongest. The contractor shall use a TRM type that is equal to or stronger than the TRM type specified by the designer. All cases require that permanent grass be sown.

Alternatively, in special cases dependent upon the vegetative-support quality of the soil and the growing season, the designer may specify only grass and mulch or grass and a biodegradable rolled erosion control product for 0-3 psf shear stress conditions.

Allowable Shear Stress Ranges Without Vegetation

Type 1	Type 2	Type 3	Type 4	Type 5	Type 6
0-2 psf	**0-4 psf**	**0-6 psf**	0-8 psf	**0-10 psf**	**0-12 psf**

Determine the shear strength of the TRM by using either of the independent laboratories of the Texas Transportation Institute (TTI) or of the National Transportation Product Evaluation Program (NTPEP). Use the following large-scale test methods:

ASTM D 6459 – 07 Standard Test Method for Determination of Rolled Erosion Control Product (RECP) Performance in Protecting Hillslopes from Rainfall-Induced Erosion

ASTM D 6460 – 07 Standard Test Method for Determination of Rolled Erosion Control Product (RECP) Performance in Protecting Earthen Channels from Stormwater-Induced Erosion

Ensure that materials meet the following requirements.

A. Preformed TRM

Use TRM with a web of mechanical or melt-bonded polymer nettings, monofilaments, or entangled fibers to form a dimensionally stable matrix. Bond the TRM with one of the following:

- Polymer welding
- Thermal fusion
- Polymer fusion
- Fibers placed between two high-strength, biaxially oriented nets bound by parallel-lock stitching with polyolefin, nylon, or polyester threads

Use TRM with enough strength and elongation to limit stretching and maintain its shape before, during, and after installation under dry or wet conditions. Provide TRM with stabilized components that avoid ultraviolet degradation and are inert to chemicals normally encountered in a natural soil environment. Ensure that the TRM conforms to the following physical properties:

Property	Minimum Value	Test Method
Tensile strength (grab)	Varies*	ASTM D 6818
Ultraviolet stability	80%	ASTM D 4355
1,000 hours in an Atlas ARC Weatherometer (ASTM G 23, Type D)		ASTM D 822
* 300 lb/ft x 300 lb/ ft for Types 1 &2; 2000 lb/ft x 2000 lb/ft for Types 3 and 4; 3000 lb/ft x 3000 lb/ft for Types 5 and 6		

B. Stakes or Staples

Use 1 in. by 3 in. (25 mm by 75 mm) wooden stakes made from sound stock cut in a triangular shape. Cut stakes 12 in. to 18 in. (300 mm to 450 mm) long depending on soil compaction. Use metal staples with the following characteristics:

- 11 gauge steel

- U shape
- Legs at least 8 in. (200 mm) long
- Crown 2 in. (50 mm) across

The construction plans may specify that deep harpoon-style anchors be used instead of stakes or staples for zones of shear stress greater than 12 psf as an alternative to using riprap. When anchors are specified, follow the TRM manufacturer's guidelines for anchor selection and installation procedures and provide the Engineer with the details of the recommended procedure. Use anchors that are listed on the QPL 49.

710.2.01 Delivery, Storage, and Handling

General Provisions 101 through 150.

710.3 Construction Requirements

710.3.01 Personnel

General Provisions 101 through 150.

710.3.02 Equipment

General Provisions 101 through 150.

710.3.03 Preparation

A. Site Preparation

Before protecting areas with TRM, prepare the area according to Section 700 with the following steps:

1. Bring the area to final grade.
2. Plow the area.
3. Lime the area.
4. Fertilize the area.
5. Grass the area.

Provide a smooth, firm, and stable surface free of rocks, clods, roots, or other obstructions that would prevent the TRM from fully contacting the soil.

710.3.04 Fabrication

General Provisions 101 through 150.

710.3.05 Construction

A. Installing TRM

Do not use TRM in areas where rock crops out or over large rocks. Install the TRM either in ditches or on slopes according to the following manufacturer's instructions and provide the Engineer with the details of the recommended procedure. In the absence of specific instructions from the manufacturer, install the TRM according to the following requirements:

1. Ditches

   To install the TRM in ditches:

   a. Cut a transverse trench 6 in. wide by 9 in. deep (150 mm wide by 225 mm deep) at the ends of the TRM and at 25 ft (7.5 m) intervals along the ditch.
   b. Cut longitudinal, 4 in. (100 mm) deep anchor slots along each side of the TRM along the full length of the ditch, and bury the TRM edges. The Engineer will require additional or deeper anchor slots or deep harpoon-style anchors for large volumes of water that cause high shear stress.
   c. Roll out the center strip of TRM, starting at the lower end of the ditch.
   d. Roll out each adjacent strip of TRM to overlap the preceding strip at least 3 in. (75 mm).

e. Overlap the ends of each TRM roll 3 ft (1 m) with the upslope mat on top. Stretch the TRM to the bottom of the slot, folding it back and staking through two layers of material.

f. Stake each strip of TRM at 1 ft (300mm) intervals in each anchor slot, with one stake serving the overlapped edges of adjoining strips.

g. Backfill and compact the slot.

h. Fold the TRM back over the slot and continue in the upstream direction (closed anchor slot).

i. Stake the TRM snugly in the longitudinal slots and at intervals a maximum of 5 ft (1.5 m) along the ditch (open anchor slot).

j. Backfill and dress the longitudinal anchor slots.

B. Grassing

Grass the entire area where the TRM will be placed and any adjacent disturbed soil area according to Section 700.

710.3.06 Quality Acceptance

General Provisions 101 through 150.

710.3.07 Contractor Warranty and Maintenance

General Provisions 101 through 150.

710.4 Measurement

TRM completed and accepted is measured for payment by the square yard (meter) of surface measured.

710.4.01 Limits

Overlaps and anchor slots are incidental to the work and are not measured for payment.

710.5 Payment

This work will be paid for at the Contract Price per square yard (meter) for TRM completed, in place, and accepted. Payment is full compensation for furnishing and installing the TRM according to this Specification, including filter fabric and maintenance.

Preparation of the area and grassing will be paid for according to Section 700.

Payment will be made under:

Item No. 710	Turf reinforcement matting	Per square yard (meter)

710.5.01 Adjustments

General Provisions 101 through 150.