FINAL
CONTRACT REPORT

RESEARCH ON DESIGN FOR PREVENTION OF DITCH EROSION ON VIRGINIA HIGHWAYS

P. DIPLAS, Ph.D.
J. M. DUNCAN, Ph.D.
J. K. MITCHELL, Ph.D.
J. COFFEY
C. SMITH
S. STALLINGS

Charles E. Via, Jr.
Department of Civil and Environmental Engineering
Virginia Polytechnic Institute and State University
Blacksburg, Virginia

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16. Abstract

Roadside ditch erosion has been problematic on Virginia highways. VDOT, through the Virginia Transportation Research Council, requested that roadside ditch erosion be investigated by means of a research project. Virginia Tech was selected to conduct this study. In support of this research, design guidance documents were surveyed to learn the current established policy and procedures for soil data collection and reporting, and the design practice for hydrologic and hydraulic analyses of roadside ditches. Site visits to each of Virginia's nine construction districts were made to interview district personnel about their personal experience with roadside ditch design, performance, and erosion failures. Current ditch design practices in nine other states were investigated through the collection and survey of state drainage manuals, and phone interviews with DOT personnel. Finally, an extensive review of current literature was performed with the intent of investigating current research on ditch erosion and erosion control. Results of the research indicate that three major factors are contributing to the occurrence of erosion in roadside ditches. They include, 1) insufficient soil information collected on road projects and reported in unusable formats for the hydraulic designers, 2) overuse of default values and criteria in hydraulic design, and 3) geographical and management issues not currently encompassed by current VDOT ditch design policies and procedures. Recommendations directed at these factors are provided, along with tables presenting updated correlations between site-specific conditions and hydraulic parameters for design.

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P. Diplas, Ph.D., J. M. Duncan, Ph.D., J.K. Mitchell, Ph.D.
J. Coffey, C. Smith, and S. Stallings
Charles E. Via, Jr. Department of Civil and Environmental Engineering
Virginia Polytechnic Institute and State University
Blacksburg, Virginia

Project Monitors
G. Michael Fitch, Virginia Transportation Research Council
Edward J. Hoppe, Virginia Transportation Research Council

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ABSTRACT

Roadside ditch erosion has been problematic on Virginia highways. VDOT, through the Virginia Transportation Research Council, requested that roadside ditch erosion be investigated by means of a research project. Virginia Tech was selected to conduct this study. In support of this research, design guidance documents were surveyed to learn the current established policy and procedures for soil data collection and reporting, and the design practice for hydrologic and hydraulic analyses of roadside ditches. Site visits to each of Virginia's nine construction districts were made to interview district personnel about their personal experience with roadside ditch design, performance, and erosion failures. Current ditch design practices in nine other states were investigated through the collection and survey of state drainage manuals, and phone interviews with DOT personnel. Finally, an extensive review of current literature was performed with the intent of investigating current research on ditch erosion and erosion control. Results of the research indicate that three major factors are contributing to the occurrence of erosion in roadside ditches. They include, 1) insufficient soil information collected on road projects and reported in unusable formats for the hydraulic designers, 2) overuse of default values and criteria in hydraulic design, and 3) geographical and management issues not currently encompassed by current VDOT ditch design policies and procedures. Recommendations directed at these factors are provided, along with tables presenting updated correlations between site-specific conditions and hydraulic parameters for design.

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P. Diplas, Ph.D, J. M. Duncan, Ph.D., J.K. Mitchell, Ph.D.,
J. Coffey, C. Smith, and S. Stallings
Charles E. Via, Jr. Department of Civil and Environmental Engineering
Virginia Polytechnic Institute and State University
Blacksburg, Virginia

INTRODUCTION

In some areas in Virginia, ditch erosion has caused problems on VDOT projects. It appears that some Virginia soils, notably in the area around Lynchburg, are more easily erodible than would be inferred based on grain size and plasticity. In addition, the performance of some erosion protection linings has not been good--flow beneath the linings has caused erosion. VDOT personnel, through the Virginia Transportation Research Council, have requested that these problems be investigated by means of a research project. Virginia Tech was selected to conduct this study.

PURPOSE AND SCOPE

The purpose of this research was to find improved methods of analysis and design for preventing erosion of soil in roadside ditches.

This report is a culmination of the work performed on the research project and is organized into four main sections titled, Section 1: Survey of Design Guidance, Section 2: Review of Computer Programs, Section 3: Collection and Utilization of Data for Design, and Section 4: Synthesis of Design Criteria, and followed by conclusions and recommendations.

SECTION 1: SURVEY OF DESIGN GUIDANCE

Background

The primary goal of this section is to determine the current state of practice for roadside ditch design. Presently, no comprehensive study of roadside ditch design practices has been found in published literature. This section will discuss the findings of a literature review focussing on current practice as defined by state drainage manuals, federal highway publications, and in other scientific publications. The results of this survey should serve as a general template to view notable similarities and differences among ditch design practices in various states.

Roadside ditch design is an important aspect of roadway structure and safety. Their design may be influenced by many factors, including motorists' safety, aesthetics, economy of construction and maintenance. A stable ditch should provide adequate capacity for the intended design storm and be resistant to erosion failures. Ideally, the ditch design should also provide recoverable slopes to enhance driver safety in errant vehicles. Inadequate design of ditch capacity can result in compromised driver safety conditions, including water overtopping the ditch line and flooding the intended path of travel. Also, erosion failures can result in steeper ditch sideslopes, and possibly failure of the roadway shoulder and structure. Adequate right-of-way should be acquired to accommodate the required ditch sideslopes and capacity.

The successful design of roadside ditches must satisfy two requirements: ditch capacity and stability. In general, the 10-year storm is used to determine ditch capacity, while the 2-year storm is used to check ditch stability. The logic implied in the selection of storm return period is that the initial period after ditch construction, before vegetation is developed, constitutes the most critical period regarding ditch stability. After vegetation is fully developed, the channel is considered stable and channel capacity becomes more critical. Highly traveled roads, such as interstates, may require an increase of the design storm to reduce the probability of capacity failure.

Flow depth and velocity are calculated following the basic principles of open channel flow. Manning's formula, shown below, is used to relate flow velocity to ditch slope, hydraulic radius, and a hydraulic roughness coefficient.

$$V = \frac{1}{n} r^{2/3} S^{1/2} \text{ for metric units, and } V = \frac{1.49}{n} r^{2/3} S^{1/2} \text{ for English units} \qquad (1)$$

where:
- V = velocity, m/s (ft/s)
- n = hydraulic roughness coefficient
- r = hydraulic radius, m (ft)
- S = slope, m/m (ft/ft)

Appropriate selections of Manning's roughness coefficient should be made to reflect the lining condition of the ditch under consideration. For instance, ditch capacity should be checked using the hydraulic roughness coefficient reflecting a fully vegetated ditch lining.

The Continuity Equation is used to relate discharge to flow velocity and cross-sectional area, shown below

$$Q = V A_c \tag{2}$$

where: A_c = cross-sectional area, m^2 (ft^2)

Ditch flow, based on a selected storm return period, is generally calculated using the Rational Method.

$$Q = C_f C i A \tag{3}$$

where: Q = peak discharge (flow)
C_f = correction factor for ground saturation
C = weighted runoff coefficient
i = rainfall intensity
A = drainage area

When applied correctly, the Rational Method provides a quick and easy method of approximating peak flow for small watersheds, like those typically associated with ditches.

The intricate relationship between capacity and stability must be satisfied to maintain an adequate, stable ditch. Designing ditches resistant to particle entrainment requires a good understanding of soil properties and flow behavior. When material forming the ditch boundary effectively resists erosion, stability is achieved. Ditch stability is a function of several aspects unique to each location, including soil type and plasticity, particle size and shape, etc. Presently, two theories are in practice for the design of stable, erosion resistant ditches: the Maximum Allowable Velocity Method and the Tractive Force Method.

Maximum Allowable Velocity Method

The traditional approach to ditch stability design, and the current VDOT practice, is to use a maximum allowable velocity criterion. This is an empirical approach that assigns a maximum allowable velocity to various soil types. The relationship between maximum velocity and soil type has been developed through lab experiments and from field experience.

To implement this method, the designer will initially need to determine the 10-year and 2-year storm flows. Adequate ditch dimensions are determined using the 10-year storm flow and a fully developed vegetation condition. Ditch stability is checked based on the 2-year storm flow under bare earth conditions. Using the soil type comprising the bare ditch line, the designer determines the corresponding maximum allowable velocity from a chart and compares it to the predicted 2-year storm velocity. If the predicted 2-yr storm velocity exceeds the allowable velocity for the given soil type, the ditch will be expected to have erosion failure. Consequently, the designer must make revisions in the ditch design, possibly reconsidering selection of ditch geometry, slope, or lining, until a stable configuration is found.

Computer programs have been developed which evaluate ditch design using the Maximum Allowable Velocity Method. The Virginia Department of Transportation has developed RDITCH, a DOS based program, which facilitates the design of roadside ditches. This program contains a computational routine that calculates peak flow using the Rational Method. When provided with the required hydrological data and ditch geometry, the program will calculate flow depth and velocity for both the 2-year and 10-year storms. From the output data, the user must determine if the ditch configuration is adequate, and then if the configuration is stable based on a selected ditch lining.

Anderson & Associates, a Civil Engineering consulting firm based in Blacksburg, VA, has developed an Excel spreadsheet which performs calculations for ditch design in accordance with the Drainage Manual (VDOT, 1991). The spreadsheet is programmed to evaluate capacity and stability of a given ditch configuration. User inputs of hydrological data allow the spreadsheet to calculate peak storm flow using the Rational Method. With a given ditch configuration, capacity is checked using the 10-year storm and fully developed vegetation roughness. The predicted 2-year storm velocity is compared against a maximum allowable velocity for bare earth. If the stability requirement is satisfied, the program stops. If stability is not met, the program will automatically iterate lining selection until a stable configuration is met. Upon program completion, a message is displayed indicating the stable ditch lining.

More information concerning these programs is provided in Section 2.

Tractive Force Method

The Tractive Force Method is a more recently developed design theory. The Federal Highway Administration publication on computer program HEC-15 (Chang et al., 1988) discusses the application of the Tractive Force design theory to roadside ditch design.

Water flowing over a boundary creates a shear stress. The boundary (bare soil, synthetic, or vegetated) can withstand a certain permissible (maximum) tractive force before erosion occurs. Based on the Tractive Force theory, for a ditch to remain stable, the shear stress applied by flowing water should not exceed the permissible stress of the boundary soil or lining.

In uniform flow, the tractive force is equal to the gravitational component of the force acting on the water parallel to the ditch bottom (Chang et al., 1988). The average tractive force applied on the channel boundary is equal to:

$$\tau_o = \gamma \, r \, S \qquad (4)$$

where: τ_o = average boundary shear stress, Pa (lb/ft^2)
γ = specific weight of water
r = hydraulic radius, m (ft)
S = slope, m/m (ft/ft)

When a channel is sufficiently wide (with aspect ratio of at least 20), the hydraulic radius can be approximated using the flow depth, H. However, this condition is rather unlikely to be satisfied for the typical roadside ditch.

Shear stress is not uniformly distributed along the ditch boundary. The maximum shear stress for a straight channel occurs along the ditch line at maximum depth (Chang et al., 1988). The maximum boundary shear stress, τ_{max}, can be calculated as:

$$\tau_{max} = \gamma \, H_{max} \, S \qquad (5)$$

where: H_{max} = maximum flow depth

The ditch boundary has the ability to resist the tractive force created by flowing water up to a maximum value before erosion occurs. The maximum tractive force that the boundary can withstand is related to the type of boundary lining. Research has been done to measure the maximum tractive forces that temporary linings, such as bare earth and synthetic linings, can withstand. When evaluating the maximum permissible tractive force bare earth can withstand, it is important to distinguish the soil comprising the lining as cohesive, or noncohesive. Maximum allowable tractive forces for synthetic linings are published by product manufacturers. The ditch is considered stable when vegetation is fully established.

Typically, cohesive soils tend to be more resistant to erosion. Relatively large forces are necessary to break the aggregates within the bed while relatively small forces are necessary to transport the material (Hoffman and Verheij, 1997). However, quantifying the amount of influence the cohesive property has on erosion resistance of bare soil is difficult because of limited research in this area. The publication on HEC-15 has related the permissible tractive force for cohesive soils as a function of soil plasticity index and compactness of the soil.

Extensive research has been done on particle entrainment of noncohesive soils. Shields' (Vanoni, 1977) published a criterion for the initiation of movement of uniform granular material on a flat bed. This classic work relates the Shields' parameter, τ^*, and particle Reynold's number, R, to determine if flow conditions support particle entrainment. The dimensionless shear stress parameter can be calculated as:

$$\tau^* = \frac{\tau_o}{(\gamma_s - \gamma) D_s} \qquad (6)$$

where: τ_o = average boundary shear,
γ and γ_s = specific weights of water and sediment respectively, and
D_s = representative soil particle diameter.

and particle Reynolds number can be calculated as:

$$R = \frac{u^* D_s}{\nu} \qquad (7)$$

Where: $u^* = \sqrt{\frac{\tau_o}{\rho}}$ = shear velocity
ν = kinematic viscosity

When particle motion is incipient, the Shields' parameter is said to be critical, τ_c^*. The dimensionless critical shear stress becomes independent of Reynold's number when Reynold's number exceeds 500. The flow in this Reynold's range is said to be fully rough. Extensive research has shown that critical Shields' parameter is in the range of 0.033 to 0.06 for fully rough flow (Vanoni, 1977). Typically, this region describes a coarser boundary, beginning in the range of fine gravel.

Currently, two programs have been developed by the Federal Highway Administration that facilitate the design of roadside channels using the Tractive Force Theory. The program *Stable Channel Linings* (Chang et al., 1988) checks the stability of simple, straight ditches with lining, excluding the bare earth condition. A more complex model, *HYDRAIN* (Young et al., 1996), is an integrated drainage design computer software. Within *HYDRAIN*, the submenu HYCHL is intended for use in the design of roadside channels using the tractive force theory presented in HEC-15. This program has the capability of determining stability of ditches with rigid, vegetative, gabion, and temporary linings including the bare earth condition for both the cohesive and noncohesive soil conditions. Stability analysis can include side shear and ditches designed with bends. More information concerning these programs is provided in Section 2.

Methods

To determine current design practices for roadside ditches, various state drainage manuals were reviewed. Some criteria used in selecting states for the survey include geomorphological features similar to those found in Virginia, and densely populated states. Information from nine states' Drainage Manuals and telephone interviews with hydraulic engineers was collected and evaluated. The states included in this review are: California, Kentucky, Maryland, New York, North Carolina, Ohio, Pennsylvania, South Carolina, and West Virginia.

Contacts from each state were established by use of available information on the web. Because of the diversity in responses concerning methods of roadside ditch design received when interviewing Virginia engineers, it should be noted that, at most, two engineers from each state were interviewed concerning their respective state's ditch design practice. Therefore, information obtained from telephone interviews may not reflect design practices across the entire state. However, relevant portions of Drainage Manuals were obtained and should provide a template that accurately describes the general approach to roadside ditch design practice in each state surveyed.

Other publications, such as those published by the Federal Highway Administration (FHWA) and journal articles, have been consulted and included in this review.

Results

The Federal Highway Administration has made a considerable effort to improve the methods used for the design of roadside ditches. In 1988, the publication HEC-15 (Chang et al., 1988), intended for the design of roadside channels with flexible linings, was released. This publication promotes the use of the tractive force method for roadside channels. Information necessary for the complete design of roadside channels is available in HEC-15 through charts and graphs.

Drainage manuals from various states surveyed were reviewed and summarized below by notable design specifications. These specifications have been generalized and listed below as topics. Because each state uniquely specifies design criteria, not all states will be listed under each topic. The topic areas should serve as an overview to show general trends in engineering practice.

Design Method for Channel Stability

Tractive Force Method

- *Kentucky* – The tractive force theory is prescribed with a descriptive design procedure following FHWA HEC-15.
- *Pennsylvania* – FHWA HEC-15 procedures should be used to design stable ditches and to select appropriate erosion control measures.
- *South Carolina* – FHWA HEC-15 procedures should be used to design a stable channel. The HYCHL routine in *HYDRAIN* is suggested to aid design. These methods are not recommended when the discharge under consideration exceeds 1.4 m^3/s (49.4 ft^3/s). When flow exceeds 1.4 m^3/s (49.4 ft^3/s), then riprap lining is to be used following FHWA HEC-11 (FHWA, 1987). HEC-11 should be used for the design of some types of lining.

Maximum Velocity Approach

- *California*
- *Maryland*
- *North Carolina*
- *Ohio*
- *Virginia*

Either Design Theory Recognized

- *New York* – The designer can choose which design theory to use. When following the maximum permissible velocity approach, the designer is referred to Hydraulic Design Series No. 3 (FHWA, 1961), Hydraulic Design Series No. 4 (FHWA, 1965), and New York Geotechnical Design Procedures No. 10 (NYSDOT, 1995). When following the permissible tractive force approach, the designer is referred to the FHWA publication HEC-15 (Chang et al., 1988) and the *HYDRAIN* modeling program (Young et al., 1996).
- *West Virginia* – The published Drainage Manual (VDOT, 1991), last updated 1984, indicates that a maximum velocity approach should be used. However, *HYDRAIN* is the computer program recommended and given to consultants for design by the state, which employs the tractive force design approach.

Specified Freeboard Requirements

- *Maryland* – A freeboard of 9 inches measured below the edge of the shoulder is specified.
- *Ohio* – A freeboard of 12 inches should be observed.
- *Pennsylvania* – Freeboard should be either 2 feet or 6 inches below the sub-base, whichever governs.

- *Virginia* – A freeboard of 12 inches should be observed.
- *West Virginia* – A freeboard of 18 inches below the edge of the shoulder is specified. Flow depth should not exceed one foot in ditches for all roads. An exception to this rule can be applied to low volume roads where economic design warrants deviation from this standard.

Minimum Ditch Grades

- *California* – The lowest recommended grade for ditch design should be 0.25% for earth ditches and 0.12% for paved ditches.
- *Kentucky* – A minimum grade of 0.5% should be observed to minimize ponding and sediment accumulation.
- *New York* – The minimum slope for turf lined roadside channels should be 0.5% to prevent sediment deposition. The grade of channels fully lined with grass should not be less that 0.5%.
- *Ohio* – As a general rule, the desirable minimum ditch grade should be 0.48% with an absolute minimum of 0.24%.
- *South Carolina* – Minimum grade on ditches should be 0.3% where possible.

Determining Ditch Capacity and Protective Lining

- *Maryland* – Capacity and lining requirements should accommodate a 10-year frequency storm.
- *Ohio* – For roadways with design traffic of 2000 ADT or less, it is recommended that a 5-yr frequency storm be used to determine the flow depth. For roadways with design traffic exceeding 2000 ADT, it is recommended that a 10-year frequency storm be used to determine the flow depth, and a 5-year frequency flow depth and velocity be used to determine erosion control linings, where needed.
- *Pennsylvania* – In general, a 10-year storm frequency should be used for design of ditches.
- *South Carolina* – The design storm for roadside ditches is the 10-year storm for drainage areas from 0-40 acres, the 25-year storm for drainage areas from 40-500 acres and the 50-year storm for drainage areas greater than 500 acres.
- *Virginia* – The 2-year storm is used to determine lining requirements, and the 10-year storm is used to determine capacity requirements.
- *West Virginia* – Capacity should be determined based on a 10-year storm frequency. If grass is adequate as a ditch lining, the earth ditch as originally constructed is checked to see if matting is required for a 2-year frequency during the establishment of vegetation.

Ditch Geometry Specifications

- *Maryland* – Flat bottom (trapezoidal) ditches are used in fill sections.
- *New York* – Roadway ditches should be trapezoidal or V-shaped. Toe-of-slope ditches should be trapezoidal. Intercepting ditches should be semi-circular or trapezoidal.
- *Ohio* – Special ditches, such as toe of fill ditches and steep ditches used to carry flow from a cut section to valley floor, are usually trapezoidal in shape

Specifications for Protective Linings, Including Concrete

- *Kentucky* – Due to the high failure rate of paved lining channels, paved linings will be used only in extreme cases under the approval of the Division of Design.

- *Maryland* – Soil stabilization matting is to be used for all ditches with flow velocity less than 5.0 ft/s. Ditches with flow velocities exceeding 5 ft/s should be designed with riprap.
- *New York* – Roadway channels should be lined to minimize or prevent erosion. Turf, and then stone filling, are preferred, in order of preference, when linings need to be applied for stability. An apron of stone filling will be specified at the end of a paved channel to minimize erosion. A 0.5-meter wide strip of sod is to be specified on each side adjacent to the paved lining.
- *South Carolina* – Preferred channel lining materials in order of preference for the hydraulic design stand point are: 1) Grass lining, 2) Temporary biodegradable lining with grass, 3) Permanent synthetic lining with grass riprap, 4) Wire enclosed rock, called gabions, and mattresses, 5) Asphalt paving, 6) Articulated precast blocks.
  Resident Maintenance Engineers usually prefer asphalt paving to riprap because of problems encountered when mowing. The designer should work with them to arrive at an acceptable design. The use of silt fences is limited to areas of sheet flow and areas of concentrated flow of less than 1.0 cfs. The sheet flow should have no more than ¼ cfs per 100 feet of silt fence and the maximum fill slope protected by the fence must not exceed 2:1.

Minimum Velocity Specification

- *Maryland* – Minimum velocity in a paved ditch or gutter shall be 3.0 ft/s when flowing full.

Use of Soil Information

- *Kentucky* – The gradation of the aggregate lining and the underlying soil must be obtained. A plasticity index is used to determine stability of cohesive soils.
- States recommending the maximum velocity design approach require designers to have knowledge of soil types located within the ditch line in order to apply a maximum permissible velocity.

Regulation on Vegetation

- *North Carolina* – NCDOT has 7 different seed mixes to be applied over various regions of the state. In addition, seasonal seed mixes for each county are provided to better accommodate seed germination. The resident engineer can adjust the mix, if needed. NCDOT has incentives built into their contracts for completing erosion control, particularly for establishment of all permanent seeding and mulching, within certain times of the contract lifetime. A program promoted by NCDOT, called "Response for Erosion Control", has incentives for contractors to come back to the project to complete different phases of the erosion control measures. NCDOT uses phased construction on their projects. By law, a maximum of 17 acres can be open (bare earth) to the weather at any time without erosion control measures.
- *South Carolina* – The recommended best means of sediment and erosion control is to stabilize disturbed areas as soon as possible by planting grass when work temporarily stops on an area. Regulations require that temporary stabilization must be in place within 7 days after work stops on an area unless work will start back in less than 21 days.

Discussion

The results of the literature review show two significant findings. First, channel dimensions are determined to satisfy the requirement for the ditch to convey a design discharge, which typically represents the 10-year storm peak. Second, two methods of stability criteria are accepted and used in current practice to evaluate ditch stability based on the 2-year storm. Though most states recognize and accept the newly developed Tractive Force Method, the majority of states surveyed still recommend the traditional Maximum Allowable Velocity Approach for design of roadside ditches. Only three of the states surveyed have completely adopted the Tractive Force Theory published by the FHWA (Chang et al., 1988).

In general, states that practice the Maximum Allowable Velocity Approach, essentially employ the same design procedure. Typically the 10-year storm or larger is used to determine ditch capacity, while the 2-year storm is typically used to determine stability. Many states practice pro-active measures to protect against erosion. For example, some states are more rigorous in defining detailed specifications, such as minimum/maximum slopes, channel shapes, and velocities. Other states make special recommendations for the use of erosion control matting.

A distinguishing feature of states employing the Maximum Allowable Velocity Approach is the recommended relationship between soil type and maximum velocity. The method of how each state surveyed developed the relationship between soil type and maximum velocity is unknown. Attempts to relate soil type and maximum velocity have been published, such as the survey by Fortier and Scobey (1926). Fortier and Scobey developed the relationship of soil type and maximum permissible velocity using agricultural soil description. Some states continue to relate agricultural soil classification to maximum velocities, while others have chosen to adopt the more recent AASHTO classifications. The method used by states to relate AASHTO classification to a maximum velocity is unknown.

States adopting the FHWA HEC-15 (Chang et al., 1988) design approach using the Tractive Force Method appear to apply the procedure as described in the publication, without modification. Permissible tractive force values are published for the bare earth condition, and, temporary and permanent linings. For bare earth, permissible tractive force is related to soil properties, such as soil plasticity for cohesive soils, and particle size for noncohesive soils. Some values of permissible tractive force for various types of temporary linings are listed. However, the best approximations for hydraulic roughness and permissible shear stress will be given by manufacturers of temporary linings. Manning's roughness coefficients for all lining conditions are given as a function of flow depth. Vegetal stiffness, height, and flow depth are used to characterize hydraulic roughness for vegetated linings.

No distinguishing recommendations were made by any state on the method to be used for determining the peak flow to the ditch. Generally, the Rational Method is suitable for the usually small watersheds of roadside ditches. The designer should ensure that the properties of the watershed associated with the roadside ditch under consideration are suitable for the use of the Rational Method. A rigorous application of this method should result in reasonable estimates of peak flow for a desirable return period for small watersheds.

SECTION 2: REVIEW OF COMPUTER PROGRAMS

Background

Computer software can be a useful tool for the design of roadside ditches. An effective program will be user intuitive, minimizing the need for personal instruction. Because different theories exist in the design of roadside ditches, users of ditch design software need to be knowledgeable of the theories and assumptions applied in the development of the software. Improper use of software can lead to inaccurate designs, especially when software is applied outside its range of validity.

Methods

In an attempt to establish the state of practice of roadside ditch design in Virginia, engineers across Virginia were interviewed during visits to each VDOT construction district. During these visits, engineers were asked which computer programs, if any, are used regularly for ditch design.

To determine the state of practice in surrounding states, contacts were established with design engineers in the states surveyed, as described in Section 1- Survey of Design Guidance. Contacts were initiated based on information available on the Internet. Each engineer contacted was asked which programs, if any, are widely used in their state for the design of roadside ditches. Because at most two designers were questioned from each state, responses obtained reflect the experience of the individual(s) and may not be representative of the practice for the entire state. When available, information concerning recommended computer programs was taken directly from state drainage manuals.

All programs noted by the engineers in the survey were obtained for testing. Each program was evaluated based on theory of design, ease of use, and reliability of results. A variety of design scenarios were tried on each program with the intent of gaining a general idea of how each program responds to changing parameters.

Results

Because calculations associated with roadside ditch design are not complicated, few programs have been developed with the specific intent for use in designing roadside ditches. Collectively, only four programs were found to be used for ditch design in Virginia and in the various states surveyed. Of these four programs, two were developed based on the Maximum Allowable Velocity Method. The other two programs were based on the Tractive Force Method presented in FHWA HEC-15 (Chang et al., 1988). Each program and User's Manual, where available, were obtained for evaluation. The results are categorized by the design theory employed by the software packages.

The two programs that employ the maximum allowable velocity stability criterion are VDOT's RDITCH and an *Excel* spreadsheet developed by Anderson and Associates, a Civil Engineering consulting firm based in Blacksburg, VA. RDITCH was developed by the Virginia Department of Transportation specifically for use to design roadside ditches in Virginia. This is a DOS-based program capable of computing peak storm flows and calculating ditch flow depth and velocity for three lining types: bare earth, lined (synthetic or vegetated), and paved. The Anderson and Associates' *Excel* spreadsheet, also intended for roadside ditch design on Virginia highways, provides a more efficient interfacing tool. The spreadsheet is based on guidelines set forth in the Drainage Manual (VDOT, 1991) and is capable of computing peak design flow and determining ditch stability based on calculated flow depth and velocity.

The Tractive Force Method, developed in HEC-15, has been programmed into two software packages by the FHWA. The program called HY-15 *Stable Channel Linings* was the first software package developed for the design of roadside channels using the Tractive Force Method. This program can only evaluate stability of simple, straight, lined channels. A more complex model, *HYDRAIN* (Young et al, 1996), was developed more recently by FHWA. The total *HYDRAIN* package is an integrated drainage design computer system. Within *HYDRAIN*, the HYCHL interface can be used for roadside ditch design on more complex ditches, and is capable of computing stability of both bare earth and lined ditches.

Below are brief summaries listing background information about design theory and methods applied in each software package, followed by perceived advantages and disadvantages for each program. The information presented below is also summarized in Table 1. Comments listed reflect the opinions of the evaluator on the research team.

RDITCH developed by VDOT (1989)

Methods and theories used in the program

- The Rational Method is used to determine runoff flow for a given rainfall event.
- The width-of-strip method of approximating watershed area is utilized by the program for peak flow calculation of the desired storm.
- Using the Rational Method, design reach subarea information must be entered by the user.
- Manning's equation is used to determine flow velocity and depth based on design flow.
- Values of Manning's n are standard values recommended by VDOT. Bare earth, n = 0.03; temporary protective lining and vegetated linings, n = 0.05; permanent (paved) lining, n = 0.015. The user can not change these values nor add new values.
- The maximum allowable velocity criterion is used to determine the stability of the ditch. The program computes a depth and velocity for both the 2- and 10- year storms for each value of Manning's "n". From the output, the user will need to determine if the 10-year storm depth is adequately contained by the given ditch geometry. Then, the user must compare the computed 2-year storm velocity to an accepted maximum allowable velocity for the soil type/temporary lining of the ditch.

Advantages

1. The program was developed by VDOT specifically for the purpose of roadside ditch design and encompasses a computational routine calculating peak flow using the Rational Method.
2. The user can design continuous reaches of roadside ditch with a single run of the program.

3. IDF (Intensity-Duration-Frequency) curves for each county in Virginia are conveniently incorporated into the program. To use this feature, the user must enter the time of concentration for the initial design reach. Or, the user has the option of reading the IDF curves, independent from the program, and entering rainfall intensity values manually. In either case, intensity for each subsequent reach is incremented from the initial intensity.
4. It has been used extensively for ditch design on Virginia highways.

Disadvantages

1. The program is DOS-based, and not *Windows* interactive. A series of prompts are initiated which require inputs in the form of numbers, even when phrased responses may be more appropriate.
2. The user cannot see or modify data inputs on a continuous basis. Instead, all data inputs must be entered before the opportunity to edit the entries becomes an option.
3. For each design reach, all data concerning ditch geometry and subarea information must be re-entered. This may become repetitive when design parameters are the same.
4. The program does not allow the user to experiment with ditch geometry for a given reach of design with a single run of the program. The user must re-enter all data and run the program again.
5. Each ditch design segment has to be viewed on separate screens. The user cannot see, on a single screen, a continuous ditch design for a given project. The results must be printed to do this, or otherwise viewed by a different application, such as Notepad.
6. Some units used in the program can be awkward. The user must use the default units and cannot change them. Example: side-slopes are given in (in/ft).

Anderson and Associates Excel Spreadsheet for Ditch Design Computations

Methods and theories used in the program

- Anderson & Associates developed an Excel spreadsheet to aid computations associated with ditch design calculations. The program is developed using the Maximum Allowable Velocity Approach and design criteria specified in the Drainage Manual (VDOT, 1991).
- The Rational Method is used in determining peak flow to the ditch. Drainage area parameters (Area, rainfall intensity, and runoff coefficients) must be entered to compute flow using the Rational Method. An initial time of concentration is entered by the user. Rainfall intensity from both the 2- and 10- year storms is read by the designer from the appropriate IDF curve and then entered into its respective column. The intensity is decreased by 0.1 in/hr for each subsequent design reach until the ditch is emptied.
- On a separate worksheet within the file, the designer can define and name ditch cross-sections to be used on a given project. This feature allows the user to enter ditch geometry specifications once. From this list, the user can enter the "name" of the ditch into the column "DITCH TYPE" and the cell then references the correct ditch geometry. When ditch geometry is named, the corresponding description must include intended side-slopes, bottom width, and maximum permissible depth.
- Given all necessary data, the spreadsheet computes both depth and velocity for the 2- and 10-year storms using Manning's equation. The program will first determine if the capacity is adequate for the 10-year storm depth. A message will be sent to the "Comment" column if

this requirement is not satisfied. Then, the spreadsheet is programmed to compare the predicted 2-year storm velocity against the maximum allowable velocity for bare earth, currently entered as 3 ft/s. If the predicted velocity exceeds 3 ft/s, the spreadsheet will automatically iterate lining type, using stored data concerning lining stability, until the stability requirement is met. Lining types can be easily added to or deleted from the spreadsheet.

- When the program has found a stable lining, a message will be displayed in a column indicating the name of the stable lining.
- The file uses color-coded fonts to distinguish user inputs from programs generated outputs. All user inputs are displayed in blue while program calculated outputs are seen in black.

Advantages

1. An entire project can be designed and displayed on the same file. The designer can view changes in ditch lining requirements along a design reach and on both sides of the road alignment.
2. Ditch "Types" can be added to or deleted from the spreadsheet. Ditch "Types" can be either trapezoidal or V-shaped. Also, lining types can be added to or deleted from the spreadsheet. All parameters, for ditch types and lining types, can be adjusted as needed. For example, stability parameters for various linings can be updated.
3. The spreadsheet can be customized to the individual user's needs. Additional rows can be inserted, automatically formatted as the previous row, or extra rows can be deleted for more economical screen display.
4. All data within the spreadsheet can be updated by the user as needed to accommodate changes in design guidelines and/or synthetic lining criteria.
5. The spreadsheet is intuitive for the experienced *Excel* user.

Disadvantages

1. The spreadsheet has all calculations performed in English units. The programs would have to be modified to convert to metric units.
2. When deleting inputs, the user has to be careful not to delete black font cells, which hold programmed expressions for calculations. This may be a concern for color-blind users.
3. The current spreadsheet uses a default maximum allowable velocity of 3 ft/s for all bare earth conditions.
4. The spreadsheet is a more recently developed program and has not been used extensively for design on Virginia highways.

Stable Channel Linings (Chang et al., 1988)

Methods and theories used in the program

- The program employs the Tractive Force Method as described in FHWA HEC-15 (Chang et al., 1988).
- Stability for a given lining type can be evaluated for an entered discharge.
- Manning's n is calculated as a function of flow depth.

- For given ditch parameters and lining types, the program calculates the tractive force generated by the flow, and compares it against a maximum permissible tractive force for the same lining. The maximum permissible tractive force is based on information published in FHWA HEC-15 (Chang et al., 1988).

Advantages

1. The program is one of two software packages based on the tractive force method presented in FHWA HEC-15 (Chang et al., 1988) and is capable of analyzing both rigid and flexible linings.
2. The program will compare calculated shear stress with maximum permissible shear and indicate the stability of the selected lining.
3. Data entries are easily entered and edited. Overall, the program is self explanatory and easy to use.

Disadvantages

1. The program is DOS-based and not *Windows* compatible.
2. The program does not compute peak ditch discharge. The user must calculate this information outside the application of this program.
3. Only one ditch flow can be entered per execution of the program. The 2- and 10- year storms cannot be analyzed and viewed together.
4. The bare earth condition cannot be analyzed using this program. This program allows the user to analyze the stability of temporary and permanent linings, only.

HYDRAIN **using the HYCHL submenu for ditch design (Young et al., 1996)**

Methods and theories used in the program

- The program uses the tractive force method of analysis as described in FHWA HEC-15 (Chang et al., 1988).
- Manning's formula is used to compute ditch flow and velocity.
- Manning's roughness, for the bare earth and vegetation cases, is determined as a function of flow depth. For vegetative linings, the average grass height and stiffness are considered in the determination of hydraulic roughness. Vegetal classification must be entered by the user. Hydraulic roughness of bare soil (considered a temporary lining) is independent of soil type and based as a function of flow depth, H. For unlined bare soil with $H < 0.15$m, $n = 0.023$ and $H > 0.2$ m, $n = 0.02$. Linear interpolation is used for $0.15 \text{ m} < H < 0.2$ m.
- When given design flow and channel parameters (slope, shape, and lining type), the program calculates: flow depth, velocity, applied shear stress, permissible shear stress, and maximum ditch discharge.
- The program can evaluate a constant flow for the entire ditch length or a variable flow over the ditch length. Variable flow is typical of ditch flow, with increasing discharge occurring along a ditch length due to inflow from the watershed.
- Normal depth is calculated using an iterative process beginning with an initial estimate for depth. The iteration continues until the estimated flow calculated from an assumed depth is within 0.1 percent of the given design flow.

- Once depth has been calculated, shear stress for the channel bottom is obtained from Equation (5).
- For noncohesive soil linings, the maximum permissible shear stress, τ_p, is determined from the expression:

$$\tau_p = 800.93\ D_{50}. \tag{8}$$

where units are: $[\tau_p] = N/m^2$ and $[D_{50}] = m$.
(Note: A misprint in the *HYDRAIN* User's Manual incorrectly applied the conversion constant of 800.93 as 244.2.)

- For cohesive linings, the maximum permissible shear stress is dependent on soil type, plasticity index (PI), and compactness of the soil. The equations are:

Loose $\quad \tau_p = 0.1628\ PI^{0.84}$ (9)

Medium $\quad \tau_p = 0.2011\ PI^{1.071}$ (10)

Compact $\quad \tau_p = 0.2729\ PI^{1.26}$ (11)

- The user may override the permissible shear stress for a lining dictated by the program by entering a different value.
- Rigid linings in HYCHL include concrete, grouted riprap, stone masonry, soil cement and asphalt. Flexible linings include those which may be considered permanent and those considered temporary. Permanent flexible linings include vegetation, riprap, and gabions. Temporary linings include woven paper, jute mesh, fiberglass roving, straw with net, curled wood mat, synthetic mats, and bare soil.
- The analysis of rigid, vegetative, gabion, and temporary linings in HYCHL is applicable to channels of uniform cross section and constant bottom slope.
- The procedure used to analyze temporary linings is identical to that applied for permanent linings. However, since temporary linings are intended to have a shorter service life, the design flow may be lower.
- Roadside channels are considered stable when the stability factor (ratio of permissible to calculated shear stress) is greater than one.
- Channel side slope shear is analyzed using the parameter of K_{side} (the ratio of maximum channel side shear to channel bottom shear). It is a function solely of channel shape and is dependent of channel geometry and channel sideslopes. The maximum shear stress on the side slope will always be less than or equal to that on the bottom. Parabolic and V-shaped ditches are assumed to require a $K_{side} = 1$ as a conservative estimate. Because K_{side} is always equal or less than 1, side shear does not limit the design of ditches. It may affect the design of composite linings.
- A maximum discharge can be calculated by setting the applied shear equal to the maximum permissible. The maximum allowable flow depth takes the form of:

$$H_{max} = \frac{\tau_p}{\gamma S}$$

This depth can be used in Manning's formula to compute the maximum discharge.

Advantages

1. Allows analysis of both rigid and flexible linings.
2. Allows analysis of both straight and curved channel segments.
3. HYCHL can analyze all linings with a known permissible shear for both stability and maximum conveyance.
4. The channel shape can consist of regular and irregular profiles.
5. HYCHL provides for the analysis of all the lining types collectively (temporary and permanent), individual liner analysis, or analysis when two linings are specified together as a composite lining. Composite linings are used when lining side slopes with the same material applied to the bottom is undesirable for reasons of economics aesthetics, or safety. (VOLUME VI, HYCHL)
6. The program considers differences in maximum permissible shear for cohesive and noncohesive soils.
7. Visual representations of the ditch geometry and flow depth are shown on the screen.
8. Once in the CHSHL interface, user inputs are guided to provide an intuitive process.
9. The user can modify any default calculations made by the program with their own values.
10. Several choices of ditch shape (triangular, trapezoidal, parabolic, and V-shaped with rounded bottom, and irregular) can be analyzed.

Disadvantages

1. The equations used in *HYDRAIN* to calculate maximum permissible shear stress are applicable <u>only</u> for the larger particle diameters. This constraint on validity occurs because the equations are developed based on Shields' criteria, where the Shields' parameter is considered constant and independent of Reynold's number. This region corresponds to larger particle sizes. The Shield's parameter used in programming *HYDRAIN* for metric units is 0.047, and 0.049 for English units. Because the equation for calculating permissible shear stress is based on the fully rough portion of the Shield's diagram, there are large inaccuracies in the calculation of permissible shear stress for fine grain sizes, like those typically found in roadside ditches. Based on trial and error runs of *HYDRAIN*, the program appears to become more accurate for particles beginning in the range of 5-50 mm, with closer accuracy for larger particles. Extensive testing would have to be performed to better quantify the validity range for particle sizes.
2. The user most likely will need instruction before using this program for designing roadside ditches. Difficulties may be encountered in the proper setup and execution of the program when using modern software because of the dated nature of the program.
3. The program does not directly compute expected storm flows to the ditch. The user must determine this outside the HYCHL interface using a different *HYDRAIN* interface, called HYDRO.
4. Only one ditch flow can be entered per execution of the program. The 2- and 10- year storms cannot be analyzed together. Results obtained using *HYDRAIN* must be stored in separate files. Therefore, multiple files will be stored for a single project.

Table 1. Summary of input/output from computer programs used in roadside ditch design

	Design Theory	*Input*	*Output*	*Comments*
RDITCH	Maximum Velocity	# subareas, C-values, rainfall intensity, drainage area, time of concentration, ditch grade, front/back slopes, width of ditch bottom	Velocity and depth are computed for both the 2- and 10-yr storms for three Manning's "n" values: 0.03 (bare earth), 0.05 (lining), and 0.015 (paved ditch).	* RDITCH is a DOS-based program with straightforward inputs, and well organized output. * Some data entry units are awkward, and cannot be adjusted. * Continuous reaches of ditch designed can be done with a single execution of the program.
Anderson & Associates spreadsheet	Maximum Velocity	C-value, drainage area, time of concentration, rainfall intensity, ditch type as defined on attached worksheet, ditch grade	The program calculates a predicted velocity and compares it to the maximum permissible velocity for each lining type until the predicted velocity satisfies the stability requirement.	* An entire project can be designed and saved on a single file. Complete design segments can be saved on a worksheet within the file. * Currently, stability analysis of bare earth lining does not include soil type. A single value of 3ft/s is used as the maximum permissible velocity for bare earth. * The spreadsheet allows flexibility to update all design criteria
HY-15	Tractive Force	ditch bottom width, left and right side-slopes, ditch grade, lining type (not bare earth), discharge	Hydraulic radius, Manning's "n", normal depth, velocity, and applied and maximum permissible shear stress are calculated. Stability analysis computed.	* Data inputs are straightforward and easily edited. Units are clearly stated. * Stability of temporary and permanent linings can be analyzed, excluding the bare earth condition. * The program is not *Windows* interactive
HYDRAIN	Tractive Force	ditch shape, side-slopes, bottom width, lining type [including option of bare earth condition -- cohesive (PI) and noncohesive (D_{50})], ditch grade, discharge	Permissible shear, bottom shear stress, Manning's roughness, flow depth and velocity, stability factor, and a maximum flow is calculated. Stability is analyzed.	* Validity range of stability analysis for bare earth lining limits the particle size range that can be analyzed. * *HYDRAIN* allows for analysis of bends and various lining options, including bare earth. * The program does not compute peak ditch flow within the HYCHL editor.

Discussion

The present review shows that few software packages have been developed and widely used for the design of roadside ditches. Of the programs reviewed, three have the ability to perform all calculations necessary for roadside ditch design, including the ability to calculate peak storm flow. Of these programs, two (RDITCH and the Anderson and Associates' spreadsheet) are capable of determining the peak design storm flow and perform stability analysis within a single execution of the program.

Of the programs evaluated based on the Maximum Allowable Velocity Approach, the spreadsheet developed by Anderson & Associates is better equipped to aid the designer. The spreadsheet is user intuitive, compact, and compatible with current *Microsoft Windows*' operating systems. The program calculates peak storm flow, flow depth and velocity for both the 2- and 10-year storms. The spreadsheet is programmed to compare calculated velocity values against a maximum allowable velocity to determine stability. An entire project can be designed and saved on a single file. Multiple design segments, including dual highways, can be saved on separate worksheets within the file. Because the program is *Windows* interactive, the user has the ability to copy, paste, and modify data entries as needed on a continuous basis. Rows and columns can be inserted or deleted as needed. The designer can personalize the interface to best suit her/his needs.

Though the current operation of the Anderson and Associates spreadsheet uses a single value for the maximum allowable velocity of bare earth, the capability exists to add multiple lining types, including soil types. Three values of Manning's n are stored in the spreadsheet corresponding to bare earth, lined, and paved conditions. Again, additional values of Manning's n can be named and inserted to fit the needs of the designer. Some commonly used ditch cross-sections are stored on a separate page of the file, and can be modified, added or deleted as necessary. The flexibility of the spreadsheet to be adjusted to fit the needs of the designer makes this spreadsheet a valuable design tool.

The software developed by the Virginia Department of Transportation called RDITCH is also a valuable design tool equipped to calculate all values necessary for ditch design. This is a user intuitive program capable of calculating peak storm flow, and flow depth and velocity for the 2- and 10-year storms. However, RDITCH is executed through DOS and does not allow the user to modify data entries on a continuous basis. Because the program does not allow the user to edit and copy data, data entry may become repetitive as multiple reaches are designed. Also, units used in the program may be awkward, and cannot be changed by the user. Though the program is easy to use and performs calculations necessary for ditch design, it lacks efficiency and the flexibility to be modified for changing design conditions.

The initial program developed by FHWA (Change et al., 1988), called HY-15, employs the tractive force method for stability analysis of flexible and concrete ditch linings. The program, based in DOS, is user intuitive and has the capability for the user to modify most data entries on a continuous basis. The program is useful in checking stability using maximum allowable tractive force for simple, lined roadside ditches. However, storm discharges cannot be calculated within the program and stability of bare earth ditches cannot be evaluated. Overall, the program is a useful design tool, but limited in applications.

The *HYDRAIN* Integrated Drainage Design Computer System (Young et al., 1996) is a powerful design tool developed by the FHWA. Various aspects of drainage design can be accomplished using the *HYDRAIN* package, including hydrological analysis, storm drainage design, step backwater, bridge hydraulics, culvert design, and roadside channel design. The roadside channel design submenu, HYCHL, can calculate flow depth, velocity and stability for a given channel and design flow rate. This DOS-based software package is programmed to check channel stability using the Maximum Permissible Tractive Force Theory presented in HEC-15 (Chang et al., 1988). Complex channel shapes, and temporary and permanent linings (including riprap design) can be analyzed in *HYDRAIN.* Unlike HY-15, the bare earth lining condition can be analyzed in *HYDRAIN.* When applied correctly, this program can be a useful design tool using the tractive force method.

Unfortunately, *HYDRAIN* uses equations to calculate maximum permissible shear stress for the noncohesive bare earth condition that are valid only for larger particle sizes, at least 30 mm (1.18 in.) in size. Using the soil descriptions listed in the current VDOT maximum velocity chart, the particle sizes for most soils described are outside the range of validity for these equations. Large inaccuracies in design can occur with improper use of the equations programmed in *HYDRAIN*, especially when designing with small particle sizes. Through trial, it was found that the Maximum Allowable Velocity Approach and the Tractive Force Method begin converging for characteristic particle sizes greater than 5 mm in diameter. Information concerning validity ranges between particle size and maximum permissible tractive stress for finer grained particles needs to be included in the program.

SECTION 3 - COLLECTION AND UTILIZATION OF DATA FOR DESIGN

Background

Effective design of roadside ditches requires an accurate estimate of the amount of water that will flow in the ditch for the design storm, evaluation of the ability of the ditch to convey the flow, evaluation of the ability of the soils and rocks in which the ditch will be constructed to resist erosion, and, in the case of lined ditches, evaluation of the ability of the lining to resist erosion. In addition, to perform as intended, the ditch must be constructed as designed.

If the data needed for design is not available, the design must necessarily be based on assumed conditions and default values of the parameters involved in the design analyses, which can result in ditches that are more costly to construct than necessary, and/or that are damaged by erosion during service and require costly repair. Both of these consequences result in costs related to roadside ditches that are higher than necessary, and are therefore undesirable.

Methods

To investigate the potential for improvements in the way that data is collected and used in ditch design within VDOT, each of the nine VDOT districts was visited to survey current design practices, and to discuss district personnel's experiences and opinions. Participation at each district meeting included VDOT personnel from the Construction, Environmental, Location & Design (Hydraulics), Maintenance, and Materials Divisions.

Reference documents mandated by VDOT for roadway design were reviewed to learn established procedures and policies for soil data collection and reporting, hydrologic analysis, and hydraulic analysis. The references reviewed include the Drainage Manual (VDOT, 1991), Manual of Instructions (VDOT, 1995), Road Design Manual (VDOT, 1998), and Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part II Tests (AASHTO, 1990).

Results

Collection and Reporting of Soil/Rock Data

Field practices for collecting soil/rock data vary widely among the VDOT districts, and in many instances consist of the minimum recommended practice, outlined in the Manual of Instructions (VDOT, 1995), or less. The content and format of a typical Materials division soil survey report are tailored to roadway topics other than ditch design, as a matter of policy (AASHTO, 1990a and VDOT, 1995) and district-level adaptation. It is common for the soil survey report to arrive at the ditch designer's desk after the design has been substantially completed, or not at all.

Hydrologic and Hydraulic Analyses

Hydrologic and hydraulic design computations, at the district level, are primarily based on default values that are consistently and uniformly applied to projects within the district. This approach does not take into consideration site specific factors in roadway ditch design.

Geographical and Management Factors
The survey of district personnel revealed that geographical and management factors contribute to design and construction inaccuracies, potentially leading to ditch erosion. These factors include regional site factors not currently included in ditch design, enforcement of state stormwater regulations on adjacent private land, acquisition of roadway right-of-way, construction contract provisions, and District participation in Central Office and consultant project designs.

Discussion

Collection and Reporting of Soil/Rock Data
Many aspects of roadway design involve adapting the roadway to field conditions along the planned route. Whether selecting route alignments to take advantage of existing topography, adapting cut and fill slopes to in place subsurface conditions, or adjusting pavement layer thicknesses to accommodate changes in soil subgrade support, complete and accurate knowledge of field conditions are essential to reliable and economical roadway design.

Ditch design similarly relies on complete and accurate knowledge of field conditions. The designer must anticipate soil/rock conditions at the final ditch line to assess whether a lining is required for the initial period after ditch construction (i.e., prior to establishment of vegetation). If the prediction of soil/rock condition is inaccurate one of two undesirable outcomes will result; installation of a lining when the native soil or rock is capable of withstanding the design flow (conservative), or erosion by overestimating the native soil's ability to remain stable under the design flow (unconservative). Established VDOT hydraulic design procedures subdivide each ditch into 30 m (100 ft) segments and successively analyze each segment to identify where a lining is required (VDOT, 1991). Using this procedure, the designer should have complete and accurate knowledge of field conditions within each 30 m (100 ft) segment, to ensure a reliable and economical ditch design.

The Materials division is responsible for collecting and reporting subsurface information, and for providing preliminary engineering assistance to design units in the form of a final soil survey report (VDOT, 1995). The purpose, in part, of a final soil survey is to locate and identify the various soil/rock types within the project limits, provide representative samples of each soil type for testing, and identify any geologic conditions that may have an adverse effect on the project. The final soil survey is to be conducted in general accordance with AASHTO T86 - *"Recommended Practice for Investigating and Sampling Soils and Rock for Engineering Purposes"* (VDOT, 1995).

The Materials Division's *Manual of Instructions* (VDOT, 1995) specifies the *minimum* exploration program for a final soil survey; which varies with the presence of rock or unsuitable soil, and whether or not the lanes of a divided highway will be graded independent of one another. The *minimum* distribution of borings varies from 2 per cross-section, repeated at 60 m (200 ft) intervals along the mainline (for soil conditions with independent grading) up to 8 borings per cross-section, repeated at 30 m (100 ft) intervals along the mainline (for rock conditions with independent grading). A greater number of borings is permissible, and justified, for complex subsurface conditions or where subsurface information is important to the roadway design. Boring placement across a single cross-section (i.e., outside ditch line, halfway up cut slope, project centerline, etc.) is also determined by subsurface conditions and grading. As the borings are drilled, 100 gm samples are to be recovered at 1.5 m (5 ft) intervals for determination of field moisture content (VDOT, 1995). Immediately upon completing the field exploration program, the geologist is to report field conditions and any recommendations in the form of a final soil survey report, which is delivered to the division that requested the investigation (VDOT, 1995).

Despite VDOT's established procedures, the surveyed hydraulics personnel indicated that they seldom use actual field conditions (soil/rock) in ditch design. Stated reasons for this include incomplete reporting of soil/rock conditions in the final soil survey report and late distribution of the final soil survey report, arriving after substantial completion of the ditch design or not at all.

The district surveys revealed that soil survey exploration programs routinely consist of the minimum recommended practice as outlined in the Manual of Instructions (VDOT, 1995), or less than the minimum (with the exception of the Staunton District). Boring spacing and method of representative sampling appear as the two most common deficiencies, reducing the completeness and accuracy of reported field conditions.

The current *minimum* recommended practice of 2 borings per cross-section, spaced at 60 m (200 ft) along the roadway (a common scenario), which is twice the standard ditch segment length analyzed by a designer. Any additional reduction in boring frequency (i.e., an exploration program not meeting the *minimum* recommended practice) produces even farther spaced data points, leaving the designer with little actual field information to reliably predict soil/rock conditions within a single 30 m ditch segment. The surveyed district personnel reported that they routinely space borings up to 106.7 m (350 ft) apart, and on divided highways, alternate borings between the centerlines of both lanes.

Borings are performed to document soil and rock conditions at distinct points along the roadway. Between boring locations, the subsurface conditions are approximated by interpolating conditions encountered in nearby borings. Reliability of the interpolation depends, in part, on the accuracy of recorded conditions in each boring. It is the field geologist's responsibility to record conditions encountered in the borings. This requires considerable experience in field classification of soil and rock to distinguish changes that identify distinct formations with depth in a single boring, and lateral changes between adjacent borings. AASHTO T 86 states that a complete soil investigation should identify soil types with the depth of their occurrence and recover representative disturbed samples of each subsurface material for laboratory classification tests (AASHTO, 1990a).

Our surveys of the districts revealed that most districts recover non-representative soil samples during field exploration, which are typically unsuitable for field and laboratory classification purposes. The common sampling practice is to collect soil specimens using auger flight of a drill rig, either as the rotating augers lift and deposit formation soils at the ground surface, or by grab sampling soil directly from auger flight that have been lifted out of the ground without rotation. Both sampling methods produce soil specimens that differ in material composition from the in-place formations, due to mixing of adjacent formation materials by the rotating augers. This has the effect of obscuring individual formations and their boundaries with depth in a boring, reducing the accuracy of conditions recorded on the boring log.

The disparity between ditch design needs and current practice related to conducting a final soil survey may arise from VDOT policy. The Manual of Instructions (VDOT, 1995) states, "the main objective of the geotechnical investigations is to acquire data needed for the design of *roadway foundations*, *cut and fill slopes*, *soil stabilization and retaining systems*, and *structure foundations*." Similarly, Section 3 of AASHTO T86 discusses that an adequate field investigation provides pertinent information for decision-making on one or more specific topics, none of which explicitly relates to ditch design (AASHTO, 1990a). As a result, the current focus of a final soil survey is not directly influenced by ditch design needs as a matter of policy.

The district personnel surveyed indicated that the final soil survey report is typically formatted to present data on issues other than ditch design, such as laboratory test results (e.g., moisture-dry density relationships, natural moisture content determinations, and California Bearing Ratio), and less on soil stratigraphy along the roadway. Recommendations in the report focus on pavement design, areas of anticipated undercut of unsuitable soils at and below planned road subgrade, and cut slope ratios, all topics that correspond with current VDOT policy on the objective of a final soil survey. Only the Lynchburg, Northern Virginia, and Staunton districts present soil stratigraphy, station by station along the roadway, in the final soil survey report. Despite the valuable soil/rock information in the reports of these districts, the use of actual field conditions in ditch design is still very limited.

In general, the district hydraulics personnel feel that the timing and distribution of the final soil survey report are the primary reasons for limited use of this information in ditch design. Currently, the report reaches the designer's desk after design of the ditch is complete, or not at all. In many instances, the Materials Division was unaware of the Hydraulics Division's need for the information and has not been distributing a copy of the report to the ditch designer. It is common for the report to be delayed or to remain on the road designer's desk, leaving the ditch designer without useful information during design.

VDOT's current policy on when to authorize a final soil survey contributes to the timing problem. The Manual of Instructions (VDOT, 1995) states that "the final detailed soil survey will be requested only after the line has been approved by the Location and Design Division." Within the context of VDOT's typical project development flow chart, the final soil survey is requested as part of the "request for supplemental data" of the Field Inspection stage, which is simultaneous with the drainage design (VDOT, 1991), and thus provides the information too late for use in ditch design.

Hydrologic and Hydraulic Analyses
Roadside ditch design fundamentally focuses on two issues, ditch capacity and ditch stability. In general, the 10-year storm is used to determine ditch capacity, while the 2-year storm is used to check ditch stability. The computations for evaluating both ditch capacity and stability depend on site-specific information.

Ditch Capacity

Ditch capacity, for a selected storm return period, is generally calculated using the Rational Method (Eqn. 3, Section 1). The designer adapts the model to each ditch segment using the weighted runoff coefficient (C) and drainage area (A) applicable to the segment. The drainage area (A) is commonly divided into three distinct zones; the road surface, the road shoulder, and the area outside of the right-of-way (the part that drains toward the ditch segment). The weighted runoff coefficient (C) is obtained by applying individual coefficient values to each land use within the tributary drainage area (i.e., business, residential, pasture, forest, etc.), and dividing by the total drainage area. These site-specific variables enable the designer to improve reliability of the computed flow.

The survey of district personnel revealed that the hydraulic designers routinely use a weighted average runoff coefficient (C) to reflect site specific conditions in the drainage area, but often use a very rough estimate of the drainage area outside the right-of-way (i.e., "width of strip"). It is common practice for the hydraulic designers to review topographic maps for identifying the drainage break that delineates the drainage area outside the right-of-way. When using this method, it is important that the maps are sufficiently accurate for the intended purpose. In other cases, designers rely solely on field inspection to delineate the drainage area. Several districts limit the maximum width of strip to an arbitrary value, typically 30 m (100 ft), if the actual drainage break lies beyond this distance. Since the computed flow is directly proportional to the drainage area, inaccurate representation of the actual drainage area has a corresponding influence on the computed flow. Using a drainage area less than actual, either intentionally by using an arbitrary width of strip, or unintentionally by inaccurate identification of the drainage break, under-predicts the actual flow in the ditch. This leads to an actual flow and velocity exceeding those computed in design, potentially initiating erosion within the ditch for the 2-year storm and overflowing the ditch banks for the 10-year storm.

Ditch Stability

Current VDOT practice for evaluating ditch stability is to use the maximum allowable velocity criterion presented in Section 1. The designer compares the predicted 2-year storm velocity (Eqn. 1) to the recommended maximum allowable velocity for the bare earth lining present in the analyzed ditch. If the predicted storm velocity exceeds the recommended allowable velocity for the soil type, ditch erosion is expected. Consequently, the designer must make revisions in the ditch design until a stable configuration is found.

The designer adapts the velocity computation (Eqn. 1) to each ditch segment using the hydraulic roughness coefficient (or Manning's n) to represent soil lining conditions. The smoother the wetted perimeter conditions the lower the coefficient, generating more efficient water conveyance, lower flow depth, and a faster average discharge velocity. Site specific information regarding soil type enables the designer to improve reliability of the computed velocity. Suggested roughness coefficient values for a variety of ditch lining conditions are provided in Table 2.8.2 of the Drainage Manual (VDOT, 1991).

The survey of hydraulics personnel revealed that the designers consistently and uniformly apply default coefficient values, which may be irrespective of actual soil or lining present on the wetted perimeter. The default values used are 0.015, 0.03, and 0.05 representing rigid (paved) lining, "bare earth", and non-rigid lining, respectively. Table 2.8.2 lists several "natural lining" or bare earth categories with recommended roughness coefficients ranging from 0.016 to 0.025, which are lower than VDOT's "bare earth" default value of 0.03. Categories in Table 2.8.2 corresponding to a value of 0.03, have descriptions such as "grass, some weeds", "dense weeds in deep channels", and "gravel or cobble bottom".

Since the computed discharge velocity is inversely proportional to the roughness coefficient, inaccurate representation of roughness has a significant effect on the computed discharge velocity. Using a higher roughness than actual, either intentionally by using default values, or unintentionally, by limited knowledge of conditions, under-predicts the actual discharge velocity in the ditch. This leads to an actual discharge velocity exceeding the value computed for design, potentially initiating instability of the ditch. At the same time, this results in larger ditch dimensions and therefore higher construction cost.

Ditch charts included in the Drainage Manual (VDOT, 1991) promote the use of default values. The charts allow rapid, graphical determination of discharge velocity based on values of ditch slope, water discharge, depth of flow and ditch geometry. Each chart includes three sets of axis scales, one for each of the three default roughness coefficient values. Solutions for other coefficient values require hand calculations or the use of a nomograph.

Questions have been raised regarding the appropriate roughness coefficient for flexible synthetic lining products currently in use. VDOT categorizes these products into three groups (EC-2, EC-3A, EC-3B) based on their performance properties. Industry-wide specifications for categorizing flexible synthetic lining products, similar to VDOT's groupings, currently do not exist. Since each category is designed to withstand different discharge velocities, their construction and related hydraulic roughness must vary as well. Product manufacturers provide the only available data for design.

The final step in evaluating ditch stability is to compare the predicted 2-year storm velocity to the recommended maximum allowable velocity for the bare earth lining present in the analyzed ditch. Current recommended maximum allowable water velocities for earth linings are presented in Table 2.8.1 of the Drainage Manual (VDOT, 1991), and presented in Section 4 as Table 1. To determine whether the predicted storm velocity is acceptable, the hydraulic designer must accurately determine soil/rock conditions at the ditch line.

The survey of district personnel revealed that soil type is often not differentiated in this step. Instead, most hydraulic designers use a single default maximum allowable velocity value for all earth linings. The default value varies by District, ranging from 1.5 ft/sec to 6 ft/sec, and is consistently applied within each District. The surveyed hydraulic designers indicated that this procedure is necessary to compensate for incomplete reporting of soil/rock conditions in the final soil survey report, an absence of recommendations from the Materials division (except in the Lynchburg District) on maximum allowable water velocities (V_{max}) for anticipated soil types, and late distribution of the final soil survey report, arriving after substantial completion of the ditch design or not at all.

If the soil/rock condition is not represented appropriately, the result can be one of two undesirable outcomes -- installation of a lining when the native soil or rock is capable of withstanding the design flow (excessively conservative), or erosion due to overestimating the native soil's ability to remain stable under the design flow (unconservative).

Similar to the question of selecting an appropriate roughness coefficient for flexible synthetic lining products, there are questions regarding selection of the appropriate maximum allowable velocity for flexible synthetic lining products in use today. Product manufacturers provide the only available data for design. There is little consistency between districts on maximum allowable velocities used for flexible synthetic linings.

Geographical and Management Factors

The survey of district personnel revealed that unexpected factors contribute to the occurrence of roadside ditch erosion. These factors include geographical and management issues not encompassed by current VDOT policies and procedures.

Geographical factors represent regional topographic, geologic and environmental issues unique to different areas within the state. In the eastern districts, the influence of tidal fluctuations on ditch capacity and stability is not specifically incorporated in ditch design and construction. In the central districts, the behavior of micaceous soils and the degradation of exposed rock subgrades are not specifically incorporated in ditch design and construction. In the western districts, the influence of acidic soils and long steep grades are not specifically incorporated in ditch design and construction. (Acidic soils also occur in the Fredericksburg District.) Improved understanding of these factors and their influence on ditch performance would enhance current design procedures.

Management factors also impact ditch design. In contrast to the geographical factors, the management factors appear to impact all districts about evenly. They include enforcement of state stormwater regulations on adjacent private land, acquisition of sufficient roadway right-of-way, construction contract provisions, and district participation in Central Office and consultant project designs.

The district personnel surveyed expressed serious concern over poor enforcement by local and state agencies of state erosion and sediment control regulations on adjacent private land development. It is common for unchecked runoff from adjacent private developments to enter VDOT right-of-way, causing actual discharge flows to exceed ditch design flows. Ditch erosion and sedimentation have been linked to this problem.

Whether for political or economic reasons, the purchase of right-of-way for new roads and existing road improvements will from time to time be barely sufficient to pass the travel lanes. Incidentals such as roadside ditches, buried utilities, and light poles or signs get crowded into any remaining available right-of-way. This space limitation imposes restrictions on ditch geometry, and can result in buried utilities along the ditch line and light or sign pedestals within the conveyance area of the ditch. Ditch erosion has been linked to this problem, particularly in urban settings.

Current VDOT contract language treats erosion control measures as task-based activities. Once the contractor has performed the task, they have fulfilled the intent of the contract item. The district personnel indicated that this approach transfers erosion control problems and costs from the contractor to the district's Construction and Maintenance Divisions. Often the contractor will place seed and mulch near the end of the project, and VDOT accepts the project before knowing whether vegetation will become established. Any necessary repairs then become the responsibility of the district. This drains labor and economic resources from the districts. The district personnel expressed interest in using performance-based contract language for erosion control measures to avoid problems of this type.

During this study we visited with North Carolina Department of Transportation (NCDOT) to learn how they handle similar issues. To entice the contractor to place seed and mulch at regular intervals during a project, not as a single task at the end of the project, North Carolina construction contracts include a "seeding incentive" clause. The clause provides a percentage additive to seeding and mulching unit prices based on satisfactorily completing the task early in the contract period. If completed within 0 to 30 percent of the contract time, a 30 percent additive is awarded. If the work is completed during 30.01 to 50 percent of the contract time, the additive awarded drops to 15 percent. No additive is awarded for work beyond 50 percent of the contract time. This incentive is used to establish vegetation prior to NCDOT accepting the project and the contractor pulling off the site.

To minimize damage to ditches during construction, North Carolina construction contracts include a "response for erosion control" clause. The clause provides an additional payment to the contractor for the number of times the erosion control contractor moves onto the project, at the engineer's request, to repair temporary or permanent erosion control works. Under conventional contract agreements, the contractor includes a limited number of mobilization costs items in their bid. It is unlikely that the erosion control subcontractor will move onto the site as needed for repair work after the estimated number of mobilizations have been reached. The "response for erosion control" provides incentive to the contractor, by assuring payment for their work. This places greater control over effective erosion control measures and maintenance in the hands of NCDOT.

The final management factor involves the lack of provisions for district involvement in Central Office and Consultant designs. The surveyed district personnel feel that their experience with ditch design and erosion control measures for conditions unique to their district is not realized in projects designed by Central Office or Consultants. When these designs go to construction, district personnel must address field modifications of designs they view as inadequate. This places a considerable demand on the district's staff, for problems that could have been averted had district personnel been involved in the original design.

SECTION 4: SYNTHESIS OF DESIGN CRITERIA

Background

Understanding the interaction between flowing water and its boundary is critical to the appropriate design of earthen hydraulic structures, such as erosion-resistant roadside ditches. In the design of roadside ditches, this interaction becomes visible through two primary features: the selection of a hydraulic roughness coefficient and the application of stability criteria for a given soil type/lining.

Hydraulic Roughness Coefficients

In the application of Manning's formula, the hydraulic roughness coefficient is a measure of the resistance the boundary offers to flow. Hydraulic roughness is a function of many ditch properties; consequently, the relationship between flowing water and the roughness of its boundary is not easily defined. Research to better quantify this relationship has been in progress for many years. As early as 1923, Strickler attempted to characterize Manning's roughness using sediment diameter. Reports and technical papers suggest that the roughness coefficient, n, may be a function of 8 – 10 parameters (Yen, 1992). Six primary factors used in estimating Manning's n value are grain roughness, irregularity of the surfaces of the channel sides and bottom; variation in shape and size of cross sections; obstructions; vegetation; meandering (Cowan, 1956). Because any one of these features may influence flow more significantly than others, each ditch possesses a unique roughness characteristic. Hydraulically, it is important to distinguish flow boundaries as being natural (earthen), flexible, or rigid. Boundary flexibility and porosity will modify the flow velocity distribution near the boundary and, consequently, the resistance.

For earthen channels, properties of the soil lining (including particle size, shape, orientation to flow, compaction, etc.) greatly influence hydraulic roughness. Because many parameters can affect hydraulic roughness, many methods have been used to characterize Manning's n. Particle size has the most influence on hydraulic grain roughness and has been widely used to characterize hydraulic roughness for bare soil conditions. Typically D_{50} (diameter for which 50 percent of the particles are finer in a given sample) is a statistical property of a soil grain size distribution which has been used to predict hydraulic roughness (Strickler, 1923). However, because larger particles project further into the flow field, it seems that larger particle diameters are better suited for characterizing Manning's n. For example, Meyer-Peter and Muller (1948) recommend D_{90} as a more appropriate size for characterizing grain roughness. Another method uses a base roughness coefficient to account for grain roughness and then adds modifiers to account for other roughness elements based on visual inspection (Cowan, 1956). Also, flow depth has been found to have an effect hydraulic roughness for the case of relatively shallow flows (Chang et al., 1988). As flow becomes shallower, roughness elements can provide increased resistance to flow.

When needed, synthetic linings can be placed onto the ditch boundary to increase a ditch's resistance to erosion. While erosion resistance is increased, the selected temporary synthetic lining also typically increases the hydraulic roughness of the ditch. Hydraulic roughness can be significantly affected by the class of lining, both temporary and permanent, selected by the designer. Manufacturers of temporary linings (example: jute mesh) publish Manning's n values for each of their products. Because such products are continuously being created and revised by manufacturers, care must be taken to ensure that the most current value of Manning's n for a particular product is used for design. Inaccurate approximations of Manning's n can greatly affect the predicted design velocity of a ditch, and may result in erosion failure.

Vegetation (typically grass) is the preferred permanent lining for roadside ditches. Vegetated linings provide an economical and low maintenance lining option, since they tend to retard the flow near the boundary and strengthen the soil stability through their root system. Hydraulic resistance of vegetated linings is related to blade stiffness, growth height, and plant density. Ideally, Manning's n should be calculated as a function of all these properties.

When bare earth and temporary linings are predicted to be unstable (prone to erosion), rigid linings may be necessary. Rigid linings (permanent) are concrete/paved linings that characteristically generate high flow velocities. Because the boundary roughness of the concrete/paved lining is not extremely variable from site to site, approximating hydraulic roughness for these structures is less difficult.

Stability Criteria

Historically, maximum allowable velocity criteria for unlined and lined irrigation canals were developed in the 1920's from a survey of Irrigation Engineers (Fortier and Scobey, 1926). "The pioneering work of Fortier and Scobey was the basis of channel design for many years; however, it is a design methodology based primarily on experience and observation rather than physical principles" (French, 1985). The results of Fortier and Scobey's research were distilled into a table that lists maximum allowable water velocities for different types of soils in which irrigation canals were constructed. It was compiled on the basis of information from many Irrigation Engineers in the West and Southwest regions of the United States and relied on the USDA Textural system for descriptions of soils. A ditch is considered stable against erosion if the predicted water velocity is less than the recommended maximum allowable water velocity of the boundary soil.

The maximum allowable velocity criteria developed by Fortier and Scobey have been used to design irrigation channels and other earthen hydraulic structures for decades. However, many differences exist between the basis and intended use of the Fortier and Scobey table and the application of this table to roadway drainage ditch design in Virginia. AASHTO soil classification, mandated by VDOT for use in Virginia, provides more precise soil classifications than USDA soil descriptions. Data used in compiling the Fortier and Scobey table was collected in the western regions of the U.S., where soil conditions can differ considerably from soil conditions in Virginia. The USDA Textural soil descriptions used by Fortier and Scobey are vague, making conversion to AASHTO soil classifications difficult. Irrigation channels tend to be larger, and consequently may be constructed differently. Also, they usually have sustained flows while roadside ditches have intermittent flows. For these reasons, caution must be used in extrapolating the results of Fortier and Scobey's survey to roadside drainage ditch applications in Virginia.

The current state of practice in Virginia of relating soil type and maximum allowable velocity for roadside ditch design is to refer to a table adapted from the 1926 Fortier and Scobey survey (Table 2. – Table 2.8.1 in the Drainage Manual (VDOT, 1991)). It was adapted from the original Fortier and Scobey table with few modifications, such as equating a few of the USDA Textural soil descriptions with AASHTO soil classifications.

The State of Virginia contains five geological regions within its borders – the Coastal, Piedmont Blue Ridge, Valley and Ridge, and Appalachian Plateau. Within each region a variety of soils and soil conditions exist. Individual VDOT Construction Districts have, in some instances, modified the maximum allowable velocities listed in Table 2 to reflect the local soil conditions within their District.

The Tractive Force Method, based on scientific principles and presented in the FHWA HEC-15 (Chang et al., 1988), is used mainly for design of rip rap lined ditches in Virginia. This is a more recently developed design theory, and represents the interaction between flowing water and its boundary more closely. For a ditch to remain stable against erosion, the shear stress exerted by flowing water should not exceed the predicted maximum permissible stress of the soil boundary or lining.

Methods

As part of a literature review, various states' drainage manuals were surveyed with the intent of gaining a general understanding of the current use of Manning's n values for roadside ditch design. Also, a literature review of journal articles and various publications was performed to learn the most recent findings regarding the determination of Manning's n.

The current state of practice for stability design criteria of roadside drainage ditches has also been investigated. Three approaches have been used to accomplish this task.

First, a literature search was performed to locate information on ditch design and erosion.

Next, on-site interviews were conducted with Drainage Engineers, Materials Engineers, Environmental Managers and technicians from all nine VDOT Construction Districts. Because North Carolina has similar soil types and conditions, a meeting was held with personnel of similar backgrounds from the Mount Airy District of the North Carolina Department of Transportation. The objective of the meetings in Virginia and North Carolina was to ascertain how aspects of roadside ditch design, construction and maintenance are inter-related to ensure ditch stability. These meetings were extremely helpful in determining the state of practice in Virginia.

Lastly, a review of drainage manuals from Virginia and other states was conducted. States surrounding Virginia were especially targeted for this information. Drainage manuals from various states were procured, where possible. Hydraulics personnel from other state DOTs were also contacted directly to obtain information on erosion and design methodology.

Table 2*. Current VDOT Table of Maximum Allowable Velocities for Erodible Linings

Soil Type	Maximum Allowable Velocities: Clear Water (fps)	Water Carrying Fine Silts (Colloidal) (fps)	Water Carrying Sand & Gravel (fps)	Materials Division Classification
a. Fine Sand (noncolloidal)	1.2	2.5	1.5	Beach Sand or A-3 Soils
b. Sandy Loam (noncolloidal)	1.75	2.5	2.0	Highly micaceous soils. Non-plastic A-2-4(0) soils.
c. Silt Loam (noncolloidal)	2.0	3.0	2.0	Low to medium micaceous soils. Non-plastic A-4 soils.
d. Ordinary firm loam	2.5	3.5	2.25	Silty clays. Plastic A-4 and A-7-5 soils.
e. Fine gravel	2.5	5.0	3.75	Sandy Granuals (Fine)
f. Stiff clay (very colloidal)	3.75	5.0	3.0	Clay soils (such as pipe clay). A-7-6 soils.
g. Graded, loam to cobbles (noncolloidal)	3.75	5.0	5.0	Soil and rock. Non-plastic. (Disintegrated stone)
h. Graded, silt to cobbles (colloidal)	4.0	5.5	5.0	Soil and rock – plastic.
i. Alluvial silts (noncolloidal)	2.0	3.5	2.0	Top soil – non-plastic.
j. Alluvial silts (colloidal)	3.75	5.0	3.0	Top soil – plastic.
k. Coarse gravel (noncolloidal)	4.0	6.0	6.5	Creek Gravel.
l. Cobbles and shingles	5.0	5.5	6.5	Soft rock (can be loosened with a rooter).

* Table 2.8.1 of the Drainage Manual (VDOT, 1989).

Results

Hydraulic Roughness Coefficients

Accurate approximations of hydraulic roughness are important for determining the velocity of flow and capacity of roadside ditches. The selection of the hydraulic roughness coefficient has a significant influence on the predicted design velocity. When Manning's n is under-estimated, the predicted velocity will be larger than the actual velocity in the channel. When Manning's n is over-estimated, a smaller predicted velocity will result. When analyzing erosion resistance of a roadside ditch, the higher the predicted velocity, the more conservative the estimate of stability. Following this logic, it is more conservative to under-estimate hydraulic roughness. Typically, stability analysis involves the need to approximate hydraulic roughness of the earthen lining, and possibly synthetic temporary linings when needed. Because hydraulic roughness of temporary synthetic lining products can be obtained from the manufacturer, approximating Manning's n for a bare earth soil lining can be critical.

Analysis of predicted design capacity is also influenced by deviations in hydraulic roughness coefficients. Typically, analysis of design capacity is influenced by the selection of roughness coefficient for the fully vegetated, or paved, lining condition. The smaller the selection of hydraulic roughness coefficient for this lining condition, the faster the predicted velocity, and consequently the smaller the required cross-sectional area. Therefore, the more conservative (larger) capacity design would use a larger approximation of hydraulic roughness.

Manning's n is an empirically derived value for channel cross sections developed without clearly accounting for either wall roughness or movable alluvial bed (Yen, 1992). Various techniques have been used in attempts to better quantify Manning's n, especially for earthen and vegetated channel linings. This section contains a literature review of some methods of characterizing hydraulic roughness which are presented below by lining type.

Soil lined channels

Estimating hydraulic roughness for an earthen (unlined) channel can be difficult. Many parameters, including particle size and shape, compaction, channel shape or geometry, meandering etc., can all influence hydraulic roughness. Some researchers have chosen to characterize Manning's n by soil roughness, flow depth variation, or by choosing a base value with modifiers to account for channel variance.

For non-cohesive soils, particle size has widely been used to characterize hydraulic roughness. Because soils are rarely uniform in nature, a representative particle size has to be selected to characterize roughness. Several sediment sizes have been proposed in literature for this purpose. Statistically, D_{50} (particle diameter representing 50 percent finer particles in the given sample) is readily available and meaningful. Physically, larger particles have a more pronounced effect on flow resistance because they tend to project further into the flow field. For this reason, many researchers have chosen to use a particle size greater than D_{50} to approximate hydraulic roughness (Yen, 1992). A summary of various techniques to characterize Manning's n for unvegetated channels can be found in Table 3.

Table 3. Techniques for estimating Manning's n, or base roughness (n_o).[*, **, +]

Source	Equation of Method	Limitations
Techniques requiring measurement:		
Strickler, 1923[1]	n or $n_o = 0.047\ D_{50}{}^{1/6}$	Do not use where n changes with depth
Meyer-Peter Muller, 1948[1]	n or $n_o = 0.038\ D_{90}{}^{1/6}$	Do not use where n changes with depth.
Limerinos, 1970	n or $n_o = \dfrac{0.1129r^{1/6}}{1.16 + 2.0\log(r/D_{84})}$	Based on data from reaches where sediment is primary source of roughness.
Jarrett, 1984	n or $n_o = 0.032\ S^{0.38}\ r^{-0.16}$	Tested for r from 0.15 to 2.1 m, slope from 0.002 to 0.04. Avoid backwater effects.
Bathurst, 1985[2]	$n = \dfrac{0.3194r^{1/6}}{4.0 + 5.62\log(r/D_{84})}$	Based on data for slope > 0.004. Not intended for use in plunge pool and chute reaches.
Techniques requiring visual estimates:		
Cowan, 1956[3]	$n = (n_o + n_1 + n_2 + n_3 + n_4)m_5$	Only for r < 4.6 m, streams with stable beds.
Chow, 1959	Table of n values based on channel characteristics[3]	
Benson and Dalrymple, 1967	Table of n_o values based on sediment size[4]	

* Adapted from Marcus et al. (1992).

** S is slope, r is hydraulic radius in m, D is sediment size in m.

\+ Total roughness is n, base roughness is n_o; S_f is friction slope, r is hydraulic radius in meters, d is sediment size in meters.

[1] As reported in Simons and Senturk, 1977, p.309

[2] Conversion based on $n = (f/8g)^{0.5}\ r^{1/6}$ where f is the Darcy-Weisbach friction factor and g is the acceleration due to gravity (Chow et al., 1988) and on assumption that average depth used in Bathurst equation approximately equals hydraulic radius.

[3] See respective publication for explanation and summary of the component n values.

[4] See respective publication for summary of n values for Chow (1959), and Benson and Dalrymple (1967).

[5] Cowan's approach was to break the roughness estimate into six factors: sediment size (n_0); degree of surface irregularity (n_1); variation of channel cross-section (n_2); effect of obstructions (n_3); vegetation (n_4); and degree of meandering (m_5).

The earliest attempt to relate a roughness coefficient to a sediment property was made by Strickler in 1923 (Yen, 1992). Strickler's formula relates Manning's n to the mean particle diameter (D_{50}) raised to the 1/6 power. This formula was based on data compiled from gravel-bed streams and fixed-bed (no bedforms) channels and is not to be used where n changes significantly with depth (Marcus et al., 1992). Many researchers have attempted to improve this relationship, either through revisions of Strickler's formula or by developing new formulas. For example, Meyer-Peter and Muller (1948) developed an expression for Manning's n based on a larger particle size, D_{90} (diameter for which 90 percent of the particles are finer in a given sample). Limerinos (1970) developed an expression relating both particle diameter and hydraulic radius, partly capturing channel shape and flow depth effects, to hydraulic roughness.

A second approach for characterizing Manning's n for bare earth is to characterize a roughness coefficient for various soil types. Because a variety of soil types is found across the state, the ability to relate a roughness characteristic to individual soil types would be valuable. To implement this method, the designer would need to be provided with soil information prior to design. This approach can be seen in a version of Fortier and Scobey's maximum allowable velocity chart, published by the Federal Highway Administration in Highways in the River Environment (Richardson et al., 1990), which has been expanded to include a column of Manning's n values for the corresponding soil types.

Cowan (1956) developed a system of calculating Manning's n which involves defining a base value for a given channel, n_o, based on sediment size. In addition to the base value, modifying values for channel irregularities are selected based on channel properties by the designer using visual assessment. The sum of the base n_o and all modifying n_i values will provide the overall n value used for the ditch line. No measurements are needed for the assessment of hydraulic roughness based on this approach. Because Cowan's approach utilizes visual assessment, the approximation of Manning's n will be relative to the observer's engineering judgement.

Conventionally, Manning's n for a rough surface has been regarded to remain constant and independent of the flow depth. However, this may not be true (Yen, 1992). Because shallower flows are more influenced by roughness elements than deeper flows, flow depth should not be ignored when calculating hydraulic roughness in shallow flows. Since flows in road ditches are typically not very deep, this aspect deserves attention. The FHWA publication HEC-15 (Chang et al., 1988) includes a chart listing Manning's roughness as a function of flow depth and lining type. The published depth ranges are typical of flow depths in roadside ditches.

Vegetated Linings

Estimating roughness coefficients for vegetated (grass) linings can be difficult. Hydraulic roughness for vegetated linings are characterized as a function of flow depth, blade stiffness, and plant density. Vegetation height can greatly affect hydraulic roughness in roadside ditches and, as a result, ditch capacity. However, vegetation height in ditch lines can vary, depending on maintenance practices. Because hydraulic resistance is dependent on the selected species, various types of vegetation have been classified into five resistance classes. Using HEC-15, Manning's n can be calculated according to vegetation class, ditch hydraulic radius, and channel slope. Seeding density standards need to be considered to aid in the accurate approximation of hydraulic roughness. HEC-15 contains graphs and equations that can be used to compute

Manning's n for vegetated linings. Table 4 is an adaptation of the table found in HEC-15 (Chang et al., 1988).

Cowan's (1956) method of establishing a base value and adding modifiers can also be used to approximate hydraulic roughness of vegetated channels. Visual approximations must be used to assess the extent of hydraulic resistance offered by the lining.

Synthetic linings
Manufacturers of synthetic linings publish hydraulic roughness coefficients for their products. This information will be the most accurate to use in design. During the design process for roadside ditches, the manufacturer of a selected class of lining is not known. Therefore, it may be useful to know a general value of Manning's n for various classes of synthetic linings, independent of manufacturer. Tables 5 and 6 display Manning's n values for various products produced by *Synthetic Industries* and *North American Green*. Although there are many manufacturers of synthetic linings, only two were selected to appear in this report for illustration purposes because of their widespread use on Virginia highways. Information for other products can be obtained directly from the manufacturer. When the manufacturer of a synthetic lining to be used in a design becomes known, the designer should check stability and capacity criteria to ensure an adequate design.

Stability Criteria
There are two methods currently being used by hydraulic engineers for determining the stability of roadside drainage ditches with respect to erosion. They are the Maximum Allowable Velocity Method and the Tractive Force Method.

Maximum Allowable Velocity Method
This method centers on the use of Manning's Equation (Eqn. 1, Section 1) and the Continuity Equation (Eqn. 2, Section 1) to predict the flow depth and velocity for a given ditch geometry and slope.

In Virginia, the velocity predicted by Manning's equation is compared with the maximum allowable velocity, found in Table 2, for the particular soil comprising the ditch lining. Should the predicted velocity exceed the maximum allowable velocity, the designer will need to make appropriate revisions to the current design to satisfy stability requirements. Appropriate modifications could include adjustments to the ditch geometry, lining requirements, slope, etc.

Tractive Force Method
The other method currently used by some states to define ditch stability is based on the maximum tractive force that can be applied by the flowing water on the ditch boundary (Eqn. 4, Section 1).

Should the maximum applied tractive force exceed the forces resisting movement of the soil, erosion will occur. When very fine grain particles are evaluated (e.g., clay particles), particle interactions such as cohesiveness will also need to be considered. The designer should be knowledgeable of theories and principles applied using the tractive force design method to insure accurate results.

Table 4a. Manning's n for vegetated condition – English[+]

Retardance Class	Cover*	Condition	Manning's Roughness Relationship **
A	Weeping lovegrass	Excellent stand, tall (average 30 inches)	$n = \dfrac{r^{\frac{1}{6}}}{15.8 + 19.97 \log(r^{1.4}S^{0.4})}$
	Yellow bluestem Ischaemum	Excellent stand, tall (average 36 inches)	
B	Kudzu	Very dense growth, uncut	$n = \dfrac{r^{\frac{1}{6}}}{23.0 + 19.97 \log(r^{1.4}S^{0.4})}$
	Bermuda grass	Good stand, tall (average 12 inches)	
	Native grass mixture (little bluestem, blue gammaand other long and short Midwest grasses)	Good stand, unmowed	
	Weeping lovegrass	Good stand, tall (average 24 inches)	
	Lespedeza sericea	Good stand, not woody, tall, (average 19 inches)	
	Alfalfa	Good stand, uncut (average 11 inches)	
	Weeping lovegrass	Good stand, unmowed (average 13 inches)	
	Kudzu	Dense growth, uncut	
	Blue gamma	Good stand, uncut (average 13 inches)	
C	Crabgrass	Fair stand, uncut (10 to 48 inches)	$n = \dfrac{r^{\frac{1}{6}}}{30.2 + 19.97 \log(r^{1.4}S^{0.4})}$
	Bermuda grass	Good stand, mowed (average 6 inches)	
	Common lespedeza	Good stand, uncut (average 11 inches)	
	Grass-legume mixture-summer (orchard grass, redtop Italian ryegrass, and common lespedeza)	Good stand, uncut (average 6 to 8 inches)	
	Centipede grass	Very dense cover (average 6 inches)	
	Kentucky bluegrass	Good stand, headed (6 to 12 inches)	
D	Bermuda grass	Good stand (cut to 2.5-inch height)	$n = \dfrac{r^{\frac{1}{6}}}{34.6 + 19.97 \log(r^{1.4}S^{0.4})}$
	Common lespedeza	Excellent stand, uncut (average 4.5 inches)	
	Buffalo grass	Good stand, uncut (average 3 to 6 inches)	
	Grass – legume mixture – fall, spring (orchard grass, redtop, Italian ryegrass, and common lespedeza)	Good stand, uncut (4 to 5 inches)	
	Lespedeza sericea	After cutting to 2 inch height, very good stand before cutting	
E	Bermuda grass	Good stand (average 1.5 inch height)	$n = \dfrac{r^{\frac{1}{6}}}{37.7 + 19.97 \log(r^{1.4}S^{0.4})}$
	Bermuda grass	Burned stubble	

* Covers classified have been tested in experimental channels. Covers were green and generally uniform.

** Hydraulic radius, r, in feet.

[+] Table adapted from FHWA HEC-15 (Chang et al., 1988).

Table 4b. Manning's n for vegetated condition – Metric +

Retardance Class	Cover*	Condition	Manning's Roughness Relationship **
A	Weeping lovegrass	Excellent stand, tall (average 76 cm)	$n = \dfrac{1.22r^{\frac{1}{6}}}{30.2 + 19.97\log(r^{1.4}S^{0.4})}$
	Yellow bluestem Ischaemum	Excellent stand, tall (average 91 cm)	
B	Kudzu	Very dense growth, uncut	$n = \dfrac{1.22r^{\frac{1}{6}}}{37.4 + 19.97\log(r^{1.4}S^{0.4})}$
	Bermuda grass	Good stand, tall (average 30 cm)	
	Native grass mixture (little bluestem, blue gamma and other long and short grasses)	Good stand, unmowed	
	Weeping lovegrass	Good stand, tall (average 61 cm)	
	Lespedeza sericea	Good stand, not woody, tall, (average 48 cm)	
	Alfalfa	Good stand, uncut (average 28 cm)	
	Weeping lovegrass	Good stand, unmowed (average 33 cm)	
	Kudzu	Dense growth, uncut	
	Blue gamma	Good stand, uncut (average 28 cm)	
C	Crabgrass	Fair stand, uncut (25 to 120 cm)	$n = \dfrac{1.22r^{\frac{1}{6}}}{44.6 + 19.97\log(r^{1.4}S^{0.4})}$
	Bermuda grass	Good stand, mowed (average 15 cm)	
	Common lespedeza	Good stand, uncut (average 28 cm)	
	Grass-legume mixture-summer (orchard grass, redtop Italian ryegrass, and common lespedeza)	Good stand, uncut (15 to 20 cm)	
	Centipedegrass	Very dense cover (average 15 cm)	
	Kentucky bluegrass	Good stand, headed (average 15 to 30 cm)	
D	Bermuda grass	Good stand, cut to 6 cm	$n = \dfrac{1.22r^{\frac{1}{6}}}{49.0 + 19.97\log(r^{1.4}S^{0.4})}$
	Common lespedeza	Excellent stand, uncut (average 11 cm)	
	Buffalo grass	Good stand, uncut (average 8 to 15 cm)	
	Grass – legume mixture – fall, spring (orchard grass, redtop, Italian ryegrass, and common lespedeza)	Good stand, uncut (10 to 13 cm)	
	Lespedeza sericea	After cutting to 5 cm height, very good stand before cutting	
E	Bermuda grass	Good stand (average 4 cm height)	$n = \dfrac{1.22r^{\frac{1}{6}}}{52.1 + 19.97\log(r^{1.4}S^{0.4})}$
	Bermuda grass	Burned stubble	

* Covers classified have been tested in experimental channels. Covers were green and generally uniform.
**Hydraulic radius, r, in meters. + Adapted from FHWA HEC-15 (Chang et al., 1988). Equations from FHWA HEC-22 (Young et al., 1996).

Table 5. Manning's n for Selected Lining Products – Unvegetated Condition* – English with Metric in parentheses

Synthetic Lining Class	North American Green Product Name	NAG Manning's n, Flow Depth Range – ft: 0-0.5 (0-0.15)	NAG 0.5-2 (0.15-0.6)	NAG > 2 (> 0.6)	Synthetic Industries Product Name	SI Manning's n, Flow Depth Range – ft: 0-0.5 (0-0.15)	SI 0.5-2 (0.15-0.6)	SI > 2 (> 0.6)
EC-2 Water Velocity 2.5 - 4.0 fps (0.8 – 1.2 mps)	S-75 SC-150 C-125	0.055 0.050 0.022	0.028 0.025 0.014	0.021 0.018 0.014				
EC-3 Type A Water Velocity 4.0 - 7.0 fps (1.2 – 2.1 mps)	C350	0.040	0.025	0.020	Landlok 1050	Values not available, similar to Landlok 1060		
EC-3 Type B Water Velocity 7.0 - 10.0 fps (2.1 – 3.0 mps)	P-300	0.034	0.024	0.020	Landlok 435,450, 460 Landlok 1060	0.035 0.036	0.025 0.026	0.021 0.020
EC-3 Type C Slopes 3:1 and flatter	C350	0.040	0.025	0.020	Landlok 1050	Values not available, similar to Landlok 1060		
EC-3 Type C Slopes steeper than 3:1					Pyramat 4700	0.038	0.028	0.024

* Many manufacturers of synthetic liners are approved by VDOT for use on Virginia highways. *North American Green* and *Synthetic Industries* were included in this report because of their predominant use in Virginia.

Table 6. Manning's n for Selected Lining Products - Vegetated Condition* - English with Metric in parentheses

Synthetic Lining Class	North American Green				Synthetic Industries			
	Product Name	Manning's n Flow Depth Range – ft 0-0.5 (0-0.15)	0.5-2 (0.15-0.6)	> 2 (>0.6)	Product Name	Manning's n Flow Depth Range – ft 0-0.5 (0-0.15)	0.5-2 (0.15-0.6)	> 2 (>0.6)
EC-2 Water Velocity 2.5 - 4.0 fps (0.8 – 1.2 mps)	S-75 SC-150 C-125	Values not available						
EC-3 Type A Water Velocity 4.0 - 7.0 fps (1.2 – 2.1 mps)	C-350 Phase 2**	0.044	0.044	0.044	Landlok 1050	Based on FHWA HEC-15 (Chang et al., 1988)		
	Phase 3	0.049	0.049	0.049				
EC-3 Type B Water Velocity 7.0 - 10.0 fps (2.1 – 3.0 mps)	P-300 Phase 2**	0.044	0.044	0.044	Landlok 435, 450, 460			
	Phase 3	0.049	0.049	0.049	Landlok 1060			
EC-3 Type C Slopes 3:1 and flatter	C-350 Phase 2**	0.044	0.044	0.044	Landlok 1050			
	Phase 3	0.049	0.049	0.049				
EC-3 Type C Slopes steeper than 3:1					Pyramat 4700			

*Many manufacturers of synthetic liners are approved by VDOT for use on Virginia highways. *North American Green* and *Synthetic Industries* were included in this report because of their predominant use in Virginia.
** Phase 2 @ 6 months vegetated growth

Discussion

Hydraulic Roughness Coefficients

The current practice recommended by the Virginia Department of Transportation for selection of hydraulic roughness coefficients is to apply a single value of Manning's n for each lining condition. The recommended n value for bare earth condition in Virginia is 0.03, for lined (synthetic or fully vegetated) ditches a value of 0.05, and for paved ditches a value of 0.015. The current method of design in Virginia is straightforward and easily applied by design engineers. However, the values of Manning's n are applied independent of hydraulic roughness variables (such as soil type, flow depth, vegetation type).

Results of this research show that many parameters influence hydraulic roughness. For the bare earth condition, several methods have been proposed in literature on how to best approximate hydraulic roughness. It appears from the published literature that relating Manning's n to soil type is the most effective means of defining hydraulic roughness for a bare soil lining, allowing flexibility to account for roughness elements of various soils. This approach has been published in 2 ways: characterizing by a representative particle size or by USDA soil type. Many researchers have related a statistical particle diameter to hydraulic roughness. The formula published by Meyer-Peter and Muller (See Table 2) can be valuable in relating Manning's n and particle diameter (D_{90}) for nonuniform sediments. The results generated by this approach are not valid for shallow flows where hydraulic roughness changes significantly with flow depth. Also, roughness coefficients have been published for soil types listed in the Maximum Allowable Velocity table by Fortier and Scobey (Richardson et al., 1990). Both approaches, unlike current VDOT practice, recognize the variability of hydraulic roughness associated with different soil types.

Of the methods used to characterize Manning's n for vegetated (grass) linings presented here, the most effective method appears to be the approach outlined in FHWA HEC-15 (Chang et al., 1988) and presented in Table 4 of this report. This calculation procedure captures the effects of species variation, height of vegetation, slope and hydraulic radius that each influence hydraulic roughness. The current VDOT practice is to apply a single hydraulic roughness coefficient of 0.05 to all design project calculations involving vegetal lining in roadside ditches, despite any variability that may be present.

Values of Manning's n published by manufacturers of synthetic linings will be the most accurate for use in designing roadway ditches with geosynthetics. In Virginia, synthetic linings are divided into three main classes (EC-2; EC-3A; and EC-3B) based on strength. Information concerning Manning's n for individual products should be obtained directly from the manufacturer. Data from two manufacturers of synthetic linings (*North American Greene* and *Synthetic Industries*) indicates that shallow flow depths can have significant influence on hydraulic roughness. For flow depths of 0.15m to 0.6m (0.5 ft – 2 ft), a typical depth range for roadway ditches, an average hydraulic roughness coefficient, taken independent of liner strength classes assigned by Virginia, for these two manufacturers is 0.024. Because the designer assigns a liner class rather than a specific brand of liner, it is important for the designer to be able to best approximate a hydraulic roughness coefficient for the class of lining specified. Collecting hydraulic roughness coefficients from all manufacturer products approved in Virginia can best facilitate this need.

Stability Criteria

From this research, it was found that currently two methods of determining erosion resistance of roadside drainage ditches are widely used – Maximum Allowable Velocity and Tractive Force. In Virginia, the Tractive Force Method is used mainly for design of riprap-lined ditches, and not for stability analysis of unlined ditches. This method, if used correctly, can provide good results for engineers designing unlined roadside drainage ditches. However, use of the Tractive Force Method employed in the FHWA computer program HYDRAIN-HYCHL (Young et al., 1996) is presently accurate only for coarser particles. Caution should be used when applying the program to design ditches lined with fine-grained soils.

Design of roadway drainage ditches in Virginia is performed using the Maximum Allowable Velocity Method stability criteria, where the expected velocity for the 2-year storm is calculated – typically for each 100 ft reach of ditch – and compared to the maximum allowable listed for the soil lining (Table 2). This method has been used and validated for various soil types and conditions from field experience over many years. However, some difficulties have been encountered by VDOT hydraulic engineers in implementing this stability criterion.

The USDA Textural descriptions used in Table 2 do not describe soils as specifically as AASHTO classifications. Textural descriptions are open to interpretation as to which type of soil actually exists on site; they often widely overlap the more specific AASHTO classifications. This can lead to confusion about which maximum allowable velocity value to use.

In meetings with personnel from the nine VDOT Construction Districts it appeared that while there is a standardized methodology throughout Virginia, there is often some confusion about the classification of soil, and hence which maximum allowable velocity from Table 2 should be used. While soils information is available from VDOT Materials Section reports, it is often not available at the time when roadside ditch design is taking place. Consequently, ditches often are designed without the use of this important piece of information.

Although mandated for use by VDOT, the AASHTO classification system is not consistently used for classification of soils in roadside ditch design. When AASHTO soil classifications were checked against USDA Textural soil descriptions, it became clear that accurate correlations between the two systems could not be made. Consequently, the effectiveness of the maximum allowable velocity table is minimized when soil reports using AASHTO classifications are distributed.

There is insufficient data currently available to compute recommend maximum allowable velocity values on a completely rational basis. An effort was made to update Table 2 (Table 2.8.1 in the Drainage Manual (VDOT, 1991)) by cross-checking USDA Textural soil descriptions with AASHTO soil classifications (Table 7). Maximum water velocities used in Virginia were compared with velocities used in nearby states and with average velocity values used in Virginia. In most cases, after determining the AASHTO classification, it was found that the presently used maximum allowable velocities were on the conservative side, in comparison with the other states reviewed, and new maximum velocities were selected to generally represent the average values currently in use.

These new maximum velocity values can be considered as reasonable guidelines for the present. Further research into the erodibility of these soils will provide more definitive values of maximum water velocity tolerated by each soil type.

Table 7a. Recommended maximum water velocities and Manning's n as a function of soil type and flow depth – English

AASHTO+ classification	AASHTO Soil Description	Fortier and Scobey soil description	Maximum Water Velocity (fps)	**Manning's n - Flow Depth** 0.5–2.0 ft
	BROKEN ROCK and **COBBLES**	Cobbles and Shingles	5.5	0.030
A-1-a	Stone fragments or **GRAVEL**, with or without well-graded[1] binder[2]	Coarse gravel, non-colloidal	4.5	0.025
		Fine gravel	3.5	0.020
A-1-b	Coarse **SAND**, with or without well-graded[1] binder[2]	Graded loam to cobbles when non-colloidal	4.0	0.030
A-2 (A-2-4, A-2-5, A-2-6, A-2-7)	Mixture of **GRAVEL** and **SAND**, with silty or clay fines[3], or nonplastic silt fines	Graded silts to cobbles when colloidal	4.5	0.030
		Sandy loam, non-colloidal	2.0	0.020
A-3	Fine **SAND**, without silty or clay fines; e.g. beach sand or stream-deposited fine sand	Fine Sand, non-colloidal	1.5	0.020
A-4	Non to moderately plastic[4] **SILT**; mixtures of silt, sand, and/or gravel, with a minimum silt content of 36%	Silt loam, non-colloidal	2.3	0.020
		Alluvial silts, non-colloidal	2.3	0.020
A-5	Moderately to highly plastic[4] **SILTY** soil; mixtures of silt, sand, and/or gravel, with a minimum fines[3] content of 36%	Ordinary firm loam	2.5	0.020
A-6	Plastic[4] **CLAY** soil; mixtures of clay, sand, and/or gravel, with a minimum fines[3] content of 36%	Alluvial silts, colloidal	3.5	0.025
A-7	Moderately to highly plastic **CLAY**; mixtures of clay, sand, and/or gravel, with a minimum clay content of 36%	Stiff clay, very colloidal	4.0	0.025

1) Well-graded – containing a broad range of particle sizes with no intermediate sizes missing.
2) Binder – soil particles consisting of fine sand, silt, and clay.
3) Fines – particle sizes finer than 0.074 mm (e.g., silt and clay particles).
4) Plasticity – ability of a soil mass to deform at constant volume without cracking or crumbling.

\+ Relationship between AASHTO classification and Fortier and Scobey description is loosely correlated.

Table 7b. Recommended maximum water velocities and Manning's n as a function of soil type and flow depth – Metric

AASHTO+ Classification	AASHTO Soil Description	Fortier and Scobey Soil Description	Maximum Water Velocity (mps)	**Manning's n - Flow Depth** 0.15–0.61 m
	BROKEN ROCK and **COBBLES**	Cobbles and Shingles	1.7	0.030
A-1-a	Stone fragments or **GRAVEL**, with or without well-graded[1] binder[2]	Coarse gravel, non-colloidal	1.4	0.025
		Fine gravel	1.1	0.020
A-1-b	Coarse **SAND**, with or without well-graded[1] binder[2]	Graded loam to cobbles when non-colloidal	1.2	0.030
A-2 (A-2-4, A-2-5, A-2-6, A-2-7)	Mixture of **GRAVEL** and **SAND**, with silty or clay fines[3], or nonplastic silt fines	Graded silts to cobbles when colloidal	1.4	0.030
		Sandy loam, non-colloidal	0.6	0.020
A-3	Fine **SAND**, without silty or clay fines; e.g. beach sand or stream-deposited fine sand	Fine Sand, non-colloidal	0.5	0.020
A-4	Non to moderately plastic[4] **SILT**; mixtures of silt, sand, and/or gravel, with a minimum silt content of 36%	Silt loam, non-colloidal	0.7	0.020
		Alluvial silts, non-colloidal	0.7	0.020
A-5	Moderately to highly plastic[4] **SILTY** soil; mixtures of silt, sand, and/or gravel, with a minimum fines[3] content of 36%	Ordinary firm loam	0.8	0.020
A-6	Plastic[4] **CLAY** soil; mixtures of clay, sand, and/or gravel, with a minimum fines[3] content of 36%	Alluvial silts, colloidal	1.1	0.025
A-7	Moderately to highly plastic **CLAY**; mixtures of clay, sand, and/or gravel, with a minimum clay content of 36%	Stiff clay, very colloidal	1.2	0.025

5) Well-graded – containing a broad range of particle sizes with no intermediate sizes missing.
6) Binder – soil particles consisting of fine sand, silt, and clay.
7) Fines – particle sizes finer than 0.074 mm (e.g., silt and clay particles).
8) Plasticity – ability of a soil mass to deform at constant volume without cracking or crumbling.

+ Relationship between AASHTO classification and Fortier and Scobey description is loosely correlated.

SUMMARY OF FINDINGS

As illustrated by the results of this research, it is concluded that ditch erosion on Virginia highways can be reduced by modifying VDOT design practices, conducting additional scientific research, and acting on management issues not currently encompassed by VDOT policies.

Current VDOT practices in the Materials Division and Hydraulics Section often combine to result in ditch designs based on minimal site-specific soil and hydrologic information. VDOT policy does not explicitly emphasize ditch design as an objective of the final soil survey performed by the Materials Division. As a result, insufficient soil information is collected at a project site and is often not reported in a useful format for the hydraulic designer. This, combined with simultaneous project timing, often leaves the hydraulic designer without site-specific soil information for design. To compensate, the hydraulic designers utilize default values (V_{max} and Manning's n) consistently and uniformly for design on projects within a given district, which may not truly characterize actual field conditions and response. A similar issue arises in hydraulic design by the loose application of the Rational Method for determination of peak discharge of design storms. The width of strip for the drainage area beyond the project right-of-way is often interpreted from topographic maps that may not be sufficiently accurate for the intended purpose, or by simply limiting it to an arbitrary value. Peak discharges computed in this manner will be in error of the actual site hydrologic response for the design storm, typically resulting in higher discharge velocities than used for ditch design. A greater emphasis on utilizing site specific information, within the current design context, can lead to more stable ditch designs.

The hydraulic theories used in ditch design rely on quantifying the interaction between flowing water and its boundary (earthen, flexible, or rigid). For ditch capacity issues, this is embodied in the selection of a Manning's roughness coefficient (n). For ditch stability issues, it is embodied in the selection and application of a stability criterion (V_{max}). Hydraulic roughness is a function of many factors such as channel shape and size, flow depth, vegetation characteristics, synthetic lining characteristics, and soil properties. Current VDOT design guidance on selecting a roughness coefficient is largely based on empirical relations using a single factor such as the soil, vegetation, or material type. Current VDOT stability criteria (V_{max}) is largely based on the empirical work of Fortier and Scobey in 1926, relating USDA soil descriptions to irrigation engineers' erosion experience with larger, continuously (sustained) flowing irrigation channels in the western regions of the U.S. Although research to better quantify the interaction between flowing water and its boundary has been in progress for many years, additional scientific research is needed to study materials and conditions prevailing in Virginia, providing improved correlations and design procedures.

Scientific research is also necessary to better understand problematic geographical factors not currently encompassed in ditch design. These factors include the behavior of micaceous soils, the degradation of exposed rock subgrades, the influence of acidic soils and long steep grades. Improved understanding of these factors and their influence on ditch performance would enhance current design procedures and lead to more stable ditch designs.

Current VDOT policies and procedures do not encompass four management issues that influence performance of roadside ditches. First, poor enforcement by local and state agencies of state erosion and sediment control regulations on adjacent private land development, increases ditch discharge flows on VDOT right-of-way above design flows. Ditch erosion and sedimentation have been linked to this problem. Second, current VDOT contract language treats erosion control measures as task-based activities. Once the contractor has performed the task, they have fulfilled the intent of the contract item. VDOT accepts the project before knowing whether vegetation will become established and whether the ditches are stable. Third, a lack of provisions for district involvement in Central Office and Consultant designs. District experience with ditch design and erosion control measures for conditions unique to their district are not realized in projects designed by Central Office or Consultants and has been linked to poor performance of roadside ditches. Fourth, inadequate purchase of right-of-way on roadway projects places restrictions on ditch design that has been linked to ditch erosion, particularly in urban settings. Addressing these non-technical issues can improve roadside ditch performance.

RECOMMENDATIONS

There is insufficient data currently available to provide recommendations for improved design on a completely rational basis. Our recommendations are the best that we can assemble for what was uncovered in this study and embody sound guidance on changes in current practices, procedures, and policies for improving performance of roadside ditches in Virginia. Our recommendations are presented in four major categories: Collection and Reporting of Soil/Rock Data; Hydrologic and Hydraulic Analyses; Management Issues; and Future Research. The order of presentation does not suggest priority.

Collection and Reporting of Soil/Rock Data

- Revise the Material Division's policy on the objectives of a final soil survey to include ditch design.

- Request that Materials Division personnel review the procedures for minimum geotechnical investigations as outlined in the Manual of Instructions (VDOT, 1995) and that proper sampling procedures be observed as outlined in AASHTO T86 (AASHTO, 1990a).

- Require final soil survey reports to present anticipated soil/rock conditions (AASHTO soil classifications and descriptions, or rock descriptions), at road subgrade or ditch line, station by station along a road project.

- Review the Location and Design Division's project development process to determine if the final soil survey can be authorized during the Quality Review for Field Inspection stage (one stage earlier than current, and before authorization of the drainage design), since vertical and horizontal road alignments are essentially established at this stage. This would facilitate timely distribution of the final soil survey report to the hydraulic designers, providing site-specific information at the time of ditch design.

Hydrologic and Hydraulic Analyses

- Request that hydraulic ditch designers review the limitations and proper application procedures of the Rational Method, specifically, proper determination of time of concentration, accurate delineation of actual drainage area, and appropriately accounting for various land uses located within the drainage area.

- Incorporate field data (site-specific information) into design of roadside ditches. Tables have been prepared which account for variation in Manning's n for bare earth and vegetated linings (Tables 3 and 4, Section 4), and are recommended for use in capacity analyses of roadside ditches.

- Use field data (soil information) and the updated maximum allowable velocity (V_{max}) criteria presented in Table 7 of Section 4 for stability analysis of unlined (earthen) ditches.

Management Issues

- Increase interaction with local and state level agencies having jurisdiction over stormwater regulation on private land development to encourage enforcement.

- Develop performance-based contract clauses for erosion control measures, and other incentive contract language.

- The Hydraulics Section should perform periodic review of hydraulic roughness coefficients for approved synthetic linings in use in Virginia to develop approximate representative values for use in ditch design.

- Establish a policy for district level involvement on Central Office and Consultant designs.

- Purchase adequate right-of-way to implement proper roadside ditch designs.

Future Research

- Study the geographical factors identified in this study to understand their influence on ditch performance, and develop rational design procedures to account for their impact.

- Compile improved design procedures and develop seamless new design documents.

- Develop an improved spreadsheet for roadside ditch design that will easily integrate variable hydraulic roughness coefficients along a ditch, and perform more rigorous computations.

- Study vegetation and channel shape effects on Manning's roughness coefficient (n).

- Perform field tests to quantify erodibility of Virginia soils, and develop an improved relationship between soil type (AASHTO classification) and maximum allowable velocity (V_{max}). Eventually, the results of such studies should be confirmed by flume tests.

- Study the influence of soil properties on Manning's roughness coefficient (n), and develop improved relationships.

The conclusions and recommendations presented are based mainly on the ditch design practices and procedures currently employed at the district level. It is presumed that they represent the state of design practice for all highway ditches in Virginia, including VDOT Central Office and consultant designs. Therefore, the recommendations presented should be implemented by all ditch designers of VDOT projects, for uniform improvement of roadside ditch performance on Virginia highways.

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