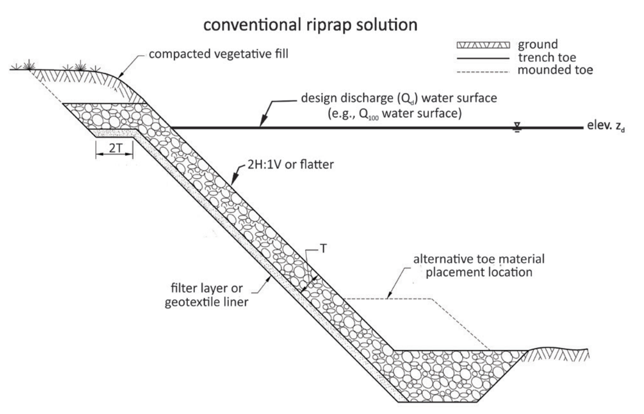
JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

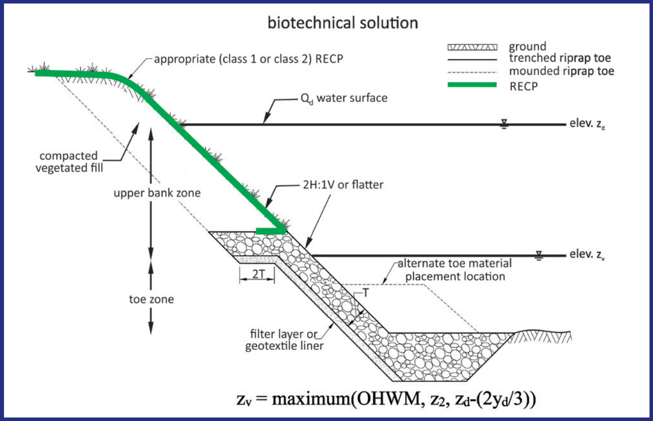
Approaches to the Design of Biotechnical Streambank Stabilization

Volume III—Design Guidelines



Erosion-protection method	Velocity, *v* (ft/s)
Revetment riprap	≤6.5
Class 1 riprap	$6.5 < v < 10$
Class 2 riprap	$10 \leq v \leq 13$
Energy dissipator	>13

RECP class	Maximum permissible cross-sectionally averaged velocity, *v* (ft/s)	
	Bend flow	Straight-reach flow
Class 1 (ECTC classes 3B and 4 ECB)	4.5	6
Class 2 (ECTC classes 5B and 5C TRM)	7.5	10



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16. Abstract

A conceptual framework for the design of biotechnical streambank revetment is proposed. It is intended to be simple in practice, flexible in being widely applicable, familiar in retaining cer-tain aspects of current practice while being patterned after other aspects, and encouraging a more environmentally sensitive approach to reliable streambank protection for INDOT projects. It distinguishes between a toe zone, where traditional hard armoring techniques such as those already included in the INDOT standard designs are more appropriate, and an upper bank zone where vegetation-based techniques would typically be applied. Default techniques are identified to simplify the choice of measures for 'routine' problems, but more case-specific techniques may also be selected. Primary techniques that offer immediate protection on their own are also distin-guished from supplementary techniques that are used only in combination with other (primary) techniques.

The boundary between the toe zone and the upper bank zone is proposed to be the maximum of the ordinary high water mark (or bankfull elevation), the elevation corresponding to the 2-year discharge, and the elevation corresponding to the point that is one third up the slope from the bank toe at the design discharge (for streambank protection). For the upper bank zone, for bank slopes up to 2H:1V, regrading and revegetation with herbaceous species together with the use of rolled erosion control products (RECPs) is proposed as the default. The other (non-default) main primary technique for the upper bank zone is the vegetated mechanically stabilized earth (VMSE, or vegetated reinforced soil slope VRSS, or soil lifts) option (where revegetation with herbaceous species is also considered standard). This requires more engineering and construct-ion effort but is appropriate for those projects where a more vertical (up to maximum bank slope of 1H:1V) solution is desired. The supplementary techniques to be included are live staking to be used with the regrading option, and brush-layering to be used with the VMSE option.

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EXECUTIVE SUMMARY

APPROACHES TO THE DESIGN OF BIOTECHNICAL STREAMBANK STABILIZATION: VOLUME III—DESIGN GUIDELINES

Introduction

The Indiana Department of Transportation (INDOT) seeks to diversify the range of standard approaches to streambank protection to include more environmentally sensitive biotechnical techniques emphasizing the use of vegetative elements. In this report, a conceptual framework for the design of biotechnical streambank revetment is proposed based on a literature review and a field assessment of Indiana projects. It is intended to be simple in practice, flexible in being widely applicable, and familiar in retaining certain aspects of current practice while being patterned after other aspects. Consistent with the current INDOT standard designs, the proposed design guidelines are limited to revetment-only solutions, as they are intended as alternatives to the current designs. A specific streambank stability problem may also require other types of solutions, such as in-stream structures, which were considered beyond the scope of this study.

Findings

The proposed framework distinguishes between a toe zone, where traditional hard-armoring techniques such as those already included in the INDOT standard designs are more appropriate, and an upper bank zone where vegetation-based techniques would typically be applied. The boundary elevation, z_v, between the toe zone and the upper bank zone is proposed in general to be the highest of

a. the ordinary high water mark (or equivalently the bankfull stage),
b. the stage corresponding to a 2-year discharge (Q_2),
c. the elevation corresponding to one third (from the bank toe) of the local depth at the bank toe under design discharge conditions.

In specific techniques, this boundary may be higher but will not be lower. This boundary is a reference level and is not necessarily where vegetative elements begin and hard-armor elements end. It is recommended that the hard-armor region extend a short distance above this reference level to allow for post-installation self-adjustment, e.g., settlement, of the hard armor.

Default techniques are identified to simplify the choice of measures for "routine" problems, but more case-specific techniques may also be selected. Primary techniques that offer immediate protection on their own are also distinguished from supplementary techniques that are used only in combination with primary techniques. Default techniques must be primary. For the toe zone, the recommended default is rock riprap as its numerous advantages have made it the current effective default (for the entire streambank). For the upper bank zone, for bank slopes up to 2H:1V, regrading and revegetation with herbaceous species together with the use of rolled erosion control products (RECPs) is proposed as the default. The restriction to streambanks with 2H:1V or flatter is consistent with a similar restriction on rock riprap.

Similar to the different classes of riprap to be used for different flow velocity conditions, two classes of RECPs were defined for use depending on different flow velocity conditions and whether the protected bank is on the outside of a bend or in a relatively straight reach. A class 1 RECP is a 100% biodegradable erosion control blanket (ECB) with a typical functional longevity of 24 months or more and a minimum permissible unvegetated shear stress of 2 lb/ft^2. For more severe conditions, where a class 1 RECP is inadequate to resist the erosional stresses, a class 2 RECP, which is a permanent turf reinforcement mat (TRM), with a minimum permissible design (fully vegetated) shear stress of 8 lb/ft^2, is recommended. Maximum permissible cross-sectionally averaged velocities for the two standard RECP classes were obtained from a design equation for riprap developed by the U.S. Army Corps of Engineers, based on specified shear stresses and relatively conservative choice of parameter values, for bend flows and for straight-reach flows.

Where default options cannot satisfy design constraints, such as a desire for steeper streambank profile, other primary techniques may be applied. For the toe zone, other hard-armor techniques as described in the INDOT 2013 Hydraulics Design Manual may be applied. For the upper bank zone, the only other non-hard-armor primary technique proposed as a standard design involves the use of vegetated mechanically stabilized earth (VMSE). These, also referred to as vegetated reinforced soil slope (VRSS), or vegetated encapsulated soil lifts, or simply soil lifts, consist of soil encapsulated or wrapped in a facing element or fabric such as an RECP, or a combination of RECPs, that also act a reinforcing element. The choice of fabric wrap would be based on the criteria developed for RECPs. In cases where bank stability must be ensured, such as in the immediate vicinity of a valuable structure, the option to use hard-armor techniques, preferably in a vegetated version, such as the combined use of joint planting with rock riprap, or using vegetated gabions, also remains open for the upper bank zone.

Supplementary techniques are defined as those that may provide environmental/ecological bene-fits, and though they may also enhance bank stability, these positive effects on bank stability are not relied on in the protection design. They are considered optional but are highly recommended. Two supplementary techniques are proposed, each appropriate for the two primary biotechnical techniques: (i) live staking, used with the regrading/revegetation with the RECP primary-technique default option, and (ii) brush layering, used with soil lifts.

Transitions between hard-armor and vegetation-based revetments, and also between protected and unprotected reaches, should receive due attention as experience with riprap revetment and biotechnical techniques has shown that failure of the revetment can often be traced to these transitions.

Implementation

It is suggested that a task force be formed to oversee the implementation of the proposed INDOT standard. The task force should include INDOT staff and representatives from the broader community of regulatory agencies, designers, consultants, and construction companies. Because the proposed standard relies heavily on the use of rolled erosion control products, INDOT standard specifications will need to be developed at the beginning of the implementation process. It is recommended that such INDOT standard specifications be based on the already available FHWA FP-03 standard specifications for these products.

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1. INTRODUCTION AND PROJECT OVERVIEW

Current streambank-protection measures as recommended in the INDOT (2013b) Design Manual (Chapter 203-6.06, to be referred to as INDOT2013-203-6.06) are coming under increasing scrutiny by regulatory agencies, motivated by a desire for more environmentally sensitive approaches. A number of such measures are described in INDOT2013-203-6.06, but these may all be classified as exclusively hard-armor solutions. A hard-armor solution is one that relies on (relatively) rigid rock or concrete elements forming an immobile armor above the underlying erodible bank, thus protecting the bank from damage by a flow event. These conventional techniques are considered effective from the narrow perspective of streambank protection, and have therefore been widely applied. The environmental effects of (exclusively) hard-armor approaches have been discussed (Fischenich, 2003; see also the literature review for this project, Lyn & Newton, 2015) and local-scale as well as regional-scale effects remain an active research topic. Hard-armor solutions to the bank-erosion problem represent a significant human intervention on the natural riverscape, and as a general rule, it might be attempted where practical to reduce or minimize the human footprint (in accordance with the avoid-minimize-mitigate philosophy). In response to the increasing regulatory pressures, INDOT would like to broaden the palette of techniques that should be considered for bank-protection problems to include biotechnical approaches that introduce vegetative elements as part if not necessarily all of the solution.

Standard references on biotechnical techniques for streambank stabilization such as Gray and Sotir (1996) or USDA Natural Resources Conservation Service (1996, referred to as NEH-650), describe a large number of different techniques (with varying terminology), but give limited guidance on the choice of technique. Case studies, such as are found in Goldsmith, Gray, and McCullah (2013) and also USDA (2007, referred to as NEH-654), can be helpful but give little justification for the choice of technique(s), or do not give sufficient engineering information to support the choices. Various decision-matrix schemes or similar aids have been proposed, such as that in the Washington State Aquatic Habitat Guidelines Program (2002, referred to as WISPG2002) or in McCullah and Gray (2005), where an expert-systems software tool was developed to recommend appropriate techniques depending on responses to a questionnaire. In part due to the attempt at a comprehensive solution for all types of conditions, such decision aids still tend to be rather cumbersome in use. The aim of the present work is more modest in that it is limited specifically to typical Indiana conditions and practices, and its scope is limited in other respects, as will be explained in greater detail below (e.g., to revetment-type solutions), and thus will not consider solutions such as in-stream structures.

The proposed design guidelines are based on a literature review (Lyn & Newton, 2015), visual inspection of both INDOT and non-INDOT Indiana sites where biotechnical streambank stabilization techniques have been applied (Newton & Lyn, 2015), and consultation with regulatory agencies and designers with experience in Indiana. It is intended as a basis for a supplement/update of INDOT2013-203-6.06. This report is organized as follows. Chapter 2 summarizes the current design guidelines in INDOT2013-203-6.06, highlighting aspects that would be changed, and others that will not be changed. The chapter ends with an outline of the principles of the proposed approach. Chapter 3 details of the proposed design guidelines.

2. THE GENERAL APPROACH

2.1 Summary of the Current Guidelines

INDOT2013-203.6.06 focuses on bank protection, and is intended to apply to a design discharge, Q_d, exceeding 50 cfs. Q_d is not precisely specified; instead a range, 10% EP to 1% EP (where EP is the exceedance probability), is given. It notes that a hydraulically worse condition regarding bank erosion may occur at less than the largest flow event. Six revetment types are dealt with: (i) riprap, (ii) wire-enclosed rock or gabions, (iii) pre-cast concrete block including articulating concrete blocks, (iv) partially grouted riprap, (v) grouted-fabric-slope pavement, and (vi) soil cement. These may all be classified as hard-armor techniques, and the possibility of integrating vegetative elements is mentioned only for pre-cast concrete blocks. Of these revetment options, riprap may be considered the default; INDOT2013-203.6.06 recommends that "Rock riprap revetment should be used due to its low cost, environmental considerations, flexible characteristics, and widespread acceptance." The rock riprap option will be the primary focus of this summary because of its default status. In addition to the general advantages listed above, the wide applicability and relatively simple design of riprap add to its popular appeal as a revetment solution. Any proposed alternative to an exclusively riprap solution should certainly strive for similarly wide applicability and design simplicity.

Although a number of important design details enter into a successful riprap revetment scheme, the main riprap characteristic of interest is the stone size. Standard equations are available for computing an appropriate stone size depending on channel and flow characteristics (see Lagasse, Clopper, Zevenbergen, & Ruff, 2006). The approach recommended in INDOT2013-203-6.06 depends solely on the average stream velocity (Figure 2.1), relying on Indiana-specific standardized riprap classes (Figure 2.2). As is argued in Appendix A, the INDOT design guideline may be interpreted as a substantial simplification of the available standard equation(s), and may not be conservative.

In addition to the stone size or riprap class, other aspects of riprap design should be highlighted as they may be relevant to any alternative approach. The maximum recommended slope for rock riprap is 2H:1V; hence, near-vertical eroded banks will need to be regraded for (rock) riprap to be a viable option. If a more vertical solution is desired, then other options, such as articulated concrete blocks (slopes up to 1.5H:1V) or gabions (slopes up to

Erosion-Protection Method	Velocity, v (ft/s)
Revetment Riprap	≤ 6.5
Class 1 Riprap	$6.5 < v < 10$
Class 2 Riprap	$10 \leq v \leq 13$
Energy Dissipator	> 13

Figure 2.1 Selection criteria for riprap classes depending on stream velocity (taken from Figure 203-2D in INDOT Hydraulics and Drainage Manual).

1H:3V), will need to be considered. The vertical extent of protection is given in terms of the design high-water elevation (presumably corresponding to the chosen design discharge) plus freeboard, which may vary depending on site conditions and type of protection. Some guidance regarding the streamwise (longitudinal) extent of protection is given, specifically for a channel bend, in terms of the channel width and the location of the bend apex. The designer is however cautioned to use actual observations of erosion in deciding on the streamwise extent of protection. The treatment of the upstream and downstream edges as well as the toe (and to a lesser extent the head) of the riprap layer receives attention because weakness in the edge regions often ultimately lead to failure of the entire riprap armor.

2.2 General Features of Proposed Guidelines: Technique Selection

A primary aim of the proposed standard design guidelines is simplicity in application. The goal is an approach comparable in ease-of-use to that of current revetment design in general, and rock riprap design in particular. The simplicity (compared to other decision-support or screening schemes for bank protection, such as those reviewed in Lyn and Newton (2015)) is achieved in large part by narrowing the scope of the problem/project. The revetment design described in INDOT2013-203-06.6 implicitly assumes that a pure revetment solution has been chosen; this is also assumed in the proposed guidelines. As a result, possible solutions such as in-stream structures, are not considered, and other issues such as those arising from large-scale streambed instabilities such as degradation, or from drainage problems, will not be directly addressed in this work. The proposed guidelines are not intended to apply to all streambank-stabilization problems, but only those for which the current purely hard-armor revetment solutions would have been expected to be successful (for bank protection). The proposed techniques may have broader range of applicability than this, but may require additional measures.

Although the narrowed problem scope eliminated a number of solution options, a further reduction in number of options and hence greater simplicity was achieved by limiting consideration to those techniques deemed to be the most widely applicable, and most useful in a standard design. Techniques that might be chosen only for a very narrow set of conditions were not pursued. Preferred techniques should also have been reliably implemented in Indiana in a number of past projects (both INDOT and non-INDOT). A distinction was also made between those techniques that might be categorized as primary and those categorized as supplementary. A primary technique is aimed specifically at bank stabilization, and so offers immediate protection, even if partially or wholly unvegetated. The traditional rock riprap revetment would be categorized as a primary technique, but so would the more bioengineering-oriented bank regrading/reshaping combined with a rolled erosion control product (RECP) such as an erosion control blanket (ECB) or a turf reinforcement mat (TRM), plus revegetation with herbaceous species. The degree of immediate protection will vary, in the case of riprap with stone size, and in the case of regrading, with the type of RECP used. In distinct contrast, a supplementary technique, typically a pure vegetative element, does not offer immediate protection, and is invariably used in combination with a primary technique. Examples would include the use of live stakes, or live fascines. The distinction between primary and supplementary techniques implies that the former is required, while the latter might be considered optional. As a result, the attention in the present study is focused on the primary techniques.

The specification of a default option, where technically justified, will also simplify the revetment design

Size, in.	Percent Smaller		
	Revetment	Class 1	Class 2
30			100
24		100	85-100
18	100	85-100	60-80
12	90-100	35-50	20-40
6	20-40	10-30	0-20
3	0-10	0-10	0-10
Minimum Depth of Riprap	18 in.	24 in.	30 in.

Figure 2.2 INDOT standard riprap class gradation specification (taken from INDOT Standard Specifications).

process. As indicated in the preceding section and INDOT2013-203-6.06, riprap is essentially the current default. The default option would be the first to be considered in the design process, and for routine problems a satisfactory revetment solution can typically be found with the default. Other options would be investigated if no acceptable solution is found with the default. Non-default solutions are not precluded, but may face additional scrutiny during review and require additional technical analysis and justification, especially if they are also non-standard.

There may be a tradeoff between simplicity in design and "efficiency." The simplicity of a "standard" default design intended for routine applications will be achieved by choosing rather conservative values for a number of relevant parameters. A more "efficient" solution could be achieved with greater design effort leading to a less conservative solution. Depending on the specific circumstance, the added effort may not be cost-effective.

2.3 General Features of Proposed Guidelines: Specific Techniques

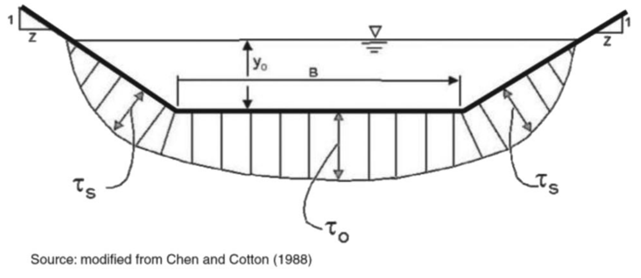
The preceding section described the general aspects of selecting a suitable technique. Specifying a default and reducing the number of different techniques for inclusion as a recognized standard technique simplify the design process. This section discusses the desired features in the techniques to be included as standard, and particularly the default technique. Standard techniques should be broadly applicable, with a range of applicability comparable to those currently included in INDOT2013-203-6.06. Specialized techniques may provide technically superior solutions for special site conditions, but by their nature may be applicable only for limited situations. At this time, it would not be worthwhile to consider them as standard techniques. The proposed guidelines will not preclude such special solutions, but these may require additional analysis and justification. Candidates for consideration as standard techniques should also have some history of being reliably implemented in Indiana. As newer techniques are introduced and become recognized, they may be added to the list of standard techniques.

Another desirable feature for candidate techniques would be a quantified erosion resistance, preferably according to a standard testing protocol and/or large-scale testing. Rock riprap has been intensively studied at a range of scales and standard equations have been developed by various government agencies to relate precisely stone size to flow (and riprap) characteristics. Although permissible velocities for various biotechnical techniques may be found in the literature (e.g., those compiled by Fischenich (2001) or NEH-654), the testing protocols are rarely specified and unlikely to be standardized. The uncertainties in the published values are large. It would also be convenient and simple if, like rock riprap, a technique could be used for a range of flow conditions by choosing different characteristics for the same basic technique (e.g., stone size in the case of rock riprap).

Two other desirable features of candidate techniques are familiarity and "naturalness." Familiarity is closely related to simplicity in that a technique that has familiar aspects often appears to be simpler. This may be especially important where a successful installation is concerned. The second is a preference for solutions that, all other technical requirements being satisfied, are more natural, or where the human "footprint" is minimized. This preference would be consistent with the original motivation for considering alternative approaches to a pure hard-armor approach, namely the search for a more environmentally-sensitive solution.

2.4 General Features of Proposed Guidelines: A Zonal Approach

A common theme found in the literature (Lyn & Newton, 2015) on biotechnical streambank stabilization is the importance of the toe zone for the overall stability of a streambank. The concept of different streambank zones has appeared in Coppin and Richards (1990), Biedenharn, Elliott, and Watson (1997), and NEH-654. The toe zone is expected to experience the largest shear stress, τ, and thus would be subjected to the largest "load" where surficial erosion is concerned as shear stress causes sediment to become mobile. This is illustrated qualitatively in Figure 2.3 (taken from Lagasse et al., 2006), which shows the distribution of boundary shear stress along the wetted perimeter. On the bank, the shear stress attains a maximum on the lower part of the bank (the toe zone), and then decreases to zero near the free surface. The USACE riprap design equation (U.S. Army Corps of Engineers, 1991; see Appendix A and also Lagasse et al., 2006) is based on the velocity (and local depth) at a point that is 20% upslope on the bank as the location of greatest concern. There is also the implication that the design of protection for the upper bank, i.e., the bank above the toe zone, may need to satisfy less stringent requirements than the design of protection for the toe zone. The symmetric (about the channel centerline) boundary shear stress distribution in Figure 2.3 applies specifically to a relatively straight channel; for a channel bend, the shear stress distribution would likely be skewed, with the location of maximum shear stress shifted to the



Source: modified from Chen and Cotton (1988)

Figure 2.3 Boundary shear stress distribution in a trapezoidal channel (taken from Lagasse et al., 2006; modified from Chen & Cotton, 1988).

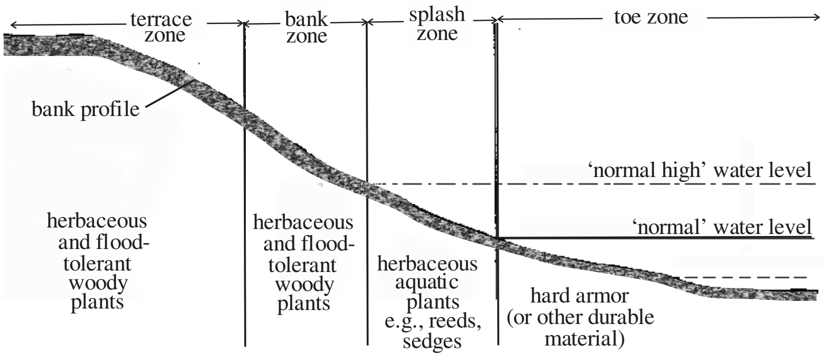


Figure 2.4 Zones according to appropriate vegetation (adapted from Allen & Leech, 1997).

outer bank. Other factors, such as cross-sectional geometry, may also influence the details of the boundary shear stress distribution.

Mass failure, a major contributing mechanism of streambank erosion, is not necessarily confined to the toe zone, but local erosion (due to the larger shear stresses) in the toe zone can precipitate mass failure. Further, if such events do occur in the toe zone, they are likely to result in more significant erosion than if they occur in upper bank regions.

From the perspective of biotechnical protection, different bank regions can also be defined based on the duration that a bank region is under water and consequently the type of vegetation, if any, that can grow under the prevailing conditions (Allen & Leech, 1997; Coppin & Richards, 1990). In the lowest part, which is submerged most of the time (assuming a perennial stream), vegetation is unlikely to be sustained. Allen and Leech (1997; see Figure 2.4) apply the term "toe zone" to the region between the bed and the "average normal stage," which is "often flooded greater than 6 months of the year," and is more suitable for hard-armor rather than vegetative protection. According to Allen and Leech (1997), the splash zone is the bank region "between normal high water and normal low-water" (i.e., above their toe zone), but is also expected to be inundated at least six months of the year. In their splash zone, similar to the marginal (or reed bank) zone of Coppin and Richards (1990), emergent aquatic herbaceous plants that are highly water-tolerant, such as reeds and sedges, can survive. Allen and Leech's bank zone is located above the "normal high-water" level, and is under water for "at least a 60-day duration once every 2 to 3 years." In their bank zone, which corresponds roughly to the damp (seasonal) flooding zone of Coppin and Richards (1990), both herbaceous as well as woody species can grow. The chosen species should be flood-tolerant, and be able to withstand submerged conditions for several weeks. Allen and Leech (1997) define a terrace zone (similar to Coppin and Richards (1997) dry flooding zone) lying above the bank zone that is only occasionally flooded. Appropriate vegetation for their terrace zone is the same as for the bank zone, but may also include larger trees.

2.5 Summary

The current design guidelines, emphasizing the use of riprap, are discussed as a potential model in their simplicity, wide applicability, and familiarity, for the proposed design guidelines for biotechnical approaches. A zonal model which distinguishes between a toe region and an upper bank region is introduced as a possible basis, with the upper bank region appropriate for vegetative elements, while the toe zone is suited to hard-armor elements.

3. THE PROPOSED DESIGN GUIDELINES: DETAILS

3.1 Overview Chart

A flowchart for the design process is given in Figure 3.1. As discussed in Chapter 2, the scope of the proposed guidelines has been restricted to that comparable to INDOT2013-203-6.06. The preliminary planning and assessment stage is critically important for the success of a streambank stabilization project, but will not be discussed in this work. The establishment of clear project goals and priorities, the consideration of fluvial geomorphological issues and erosion mechanisms, and implications for stabilization are discussed in Biedenharn et al. (1997), NEH-654, and Fischenich and Allen (2001), and the interested reader is directed to those references for guidance in the preliminary planning. Non-revetment measures, such as in-stream structures and those addressing drainage, intended to address the mechanisms not associated with the direct action of streamflow are also excluded. Such solutions, which are described in more comprehensive works, such as Gray and Sotir (1996) and NEH-650 and WISPG2003, should be considered if appropriate, either instead of or in addition to the revetment-only solutions offered here. Depending on project goals and priorities, the do-nothing option may also be justified. The restriction to design discharges larger than 50 cfs is taken from INDOT2013-203-6.06, and excludes very small channels. The following assumes (like INDOT2013-203-6.06) that a revetment option has been decided upon as either part or as the sole component of a streambank stabilization approach. The

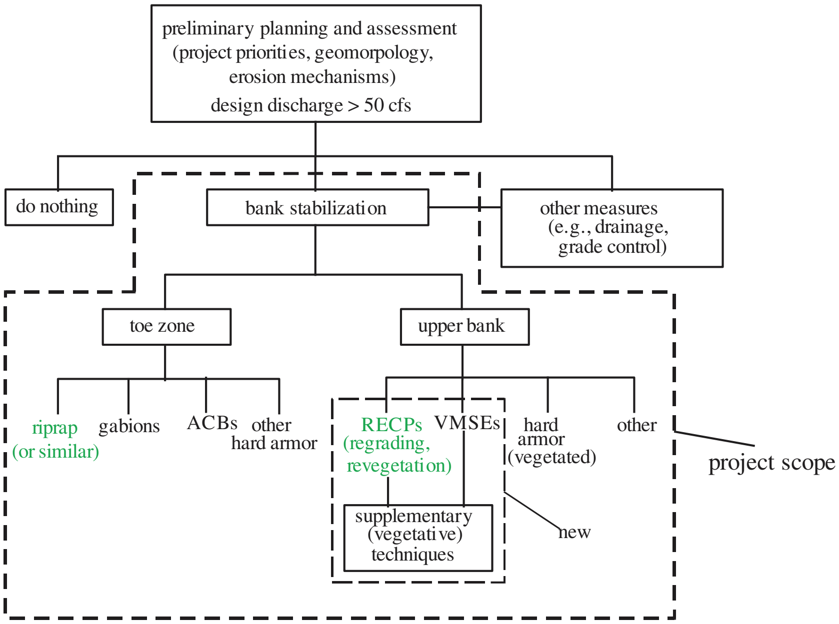


Figure 3.1 Flowchart for proposed design process.

scope of the present work is as shown in Figure 3.1 enclosed within the dashed line.

Similar to Allen and Leech (1997), a zonal approach is taken. This is implicit in many of the approaches reviewed. While more refined definitions of the different streambank zones can be made, only two zones are considered, the toe zone and the upper bank zone. The precise boundary between these two zones will be discussed below, and may differ from other studies. Different revetment options appropriate to the flow and inundation conditions characterizing each zone may be considered. A feature of the proposed design guidelines is the specification of a default or preferred option, which would be that considered most widely applicable. The default for the toe zone is rock riprap. The default for the upper bank zone is regrading and protection with rolled erosion control products (RECPs), combined with herbaceous revegetation (see Figure 3.1).

Other "standard" options for those situations where the default option is considered unsuitable, are also listed. An "other" option is also included to provide flexibility where a specialized solution is required. Non-standard options may require additional justification or consultation with INDOT and/or other regulatory agencies. After the primary protection measure has been decided, supplementary vegetative measures that will reinforce bank stability and enhance environmental aspects can be determined.

3.2 Details of the Guidelines: Defining the Zones

In the following, the elevation of the boundary between the toe zone and the upper bank zone is denoted as z_v (Figure 3.2), and is distinguished from the stage or water surface elevation, denoted as z_d, corresponding to the design discharge (Q_d). In the literature, z_v is often defined in terms of either the bankfull depth (NEH-650) or the ordinary high water mark, OHWM (Allen and Leech (1997) used this definition for their splash zone, which this report combines with their toe zone). Although the concepts of bankfull depth and OHWM are conceptually distinct, they are often used interchangeably. A useful discussion of the identification of OHWM and the relationship to the bankfull depth, with specific application however to the state of Washington, is given in Olson and Stockdale (2010). For the present purposes, a precise identification of the OHWM (or bankfull discharge) is not necessary. Rather two conditions are considered: (i) herbaceous—and possibly other—non-aquatic vegetation should be able flourish in the upper bank region, and (ii) for the design event, the hard-armor solution in the toe zone should sustain the brunt of the shearing forces causing surficial erosion of the streambank.

In principle, the OHWM may be used for the definition of z_v, but proper identification of OHWM may be challenging, and a recurrence-interval based criterion provides a simpler and more straightforward approach that can be used to check or even as an alternative to the OHWM. In the literature, the OHWM (or the bankfull stage) has been associated with discharge with a range of recurrence intervals, from one to two years. For Indiana streams, Jansen (1977) found a range of 0.9 year to 3.9 years for the recurrence interval for bankfull discharge, with a mean of 1.3 years, while for Ohio streams, Sherwood and Huitger (2005) found a wider range of 1 year to 9.65 years with a similar mean of 1.8 years (a median of 1.4 years). A practical and generally conservative specification in terms of recurrence intervals would be the water surface elevation, z_2,

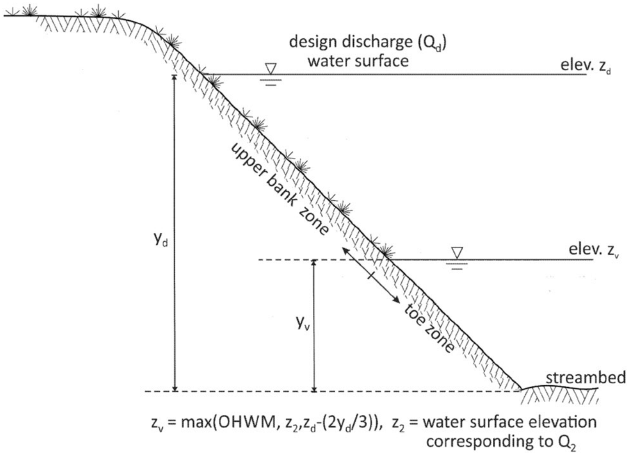


Figure 3.2 Definition of the toe zone and the upper bank zone.

corresponding to a 2-year discharge, denoted as Q_2. The OHWM (or the Q_2) criterion addresses the condition that the upper bank be suitable for non-aquatic vegetation, but does not address the second condition concerning shearing forces. An additional criterion is therefore specified, namely that, for the design discharge, Q_d, in current use in INDOT2013-203-6.06(03) which may range from a 10-year ($Q_d = Q_{10}$) or a 100-year ($Q_d = Q_{100}$) event, the upper bank zone lies above the point that is one third up the bank slope (expressed as z_d-($2y_d/3$), in terms of z_d, and the local depth, y_d, at the bank toe). This criterion is adapted from the USACE riprap design equation, which is based on the velocity that occurs at a location that is 20% up the bank slope, presumably the location of the largest shearing forces on the streambank. Shearing forces are expected to decrease in magnitude as the water surface is approached. If the upper bank is defined as lying above the point 33% up the bank slope, then it should be exposed to shearing forces less than the maximum.

The boundary between the toe zone and the upper bank zone, z_v, is the highest of (i) the OHWM, (ii) the water surface elevation corresponding to a discharge with a 2-year recurrence interval, i.e., Q_2, and (iii) the point that is 33% up the slope for the design discharge for streambank protection chosen according to INDOT 2013-203-6.06(03), or

$$z_v = \text{maximum}(\text{OHWM}, z_2, z_d - (2y_d/3)) \qquad (3.1)$$

In routine cases, it is expected that both the OHWM and z_2 will be higher than z_d-($2y_d/3$) and so z_v will be the higher of the OHWM and z_2. Equation 3.1 is the proposed basic definition. Specific techniques may require a more refined definition, such as presented for the vegetated mechanically stabilized earth (VMSE) technique. In the engineering plans involving biotechnical techniques examined as part of the study, how z_v, i.e., the elevation above which the vegetative elements were installed, was defined was not always clear. In those cases, where the criterion was explicitly specified, such as the Cool Creek project (INDOT No. 0101234), it was typically the bankfull discharge stage (here equivalent to the OHWM).

The boundary defined above between the toe zone and the upper bank zone is not intended to mark the boundary for the hard-armor portion of the biotechnical solution, but rather should be taken as a reference elevation. It is recommended that hard armor should extend to a limited region above this reference elevation. Further, for smaller projects, the upper bank (and the toe) zone will generally be subjected to a uniform treatment. For larger projects, as the shearing forces decrease when the water surface is approached, different treatments that might better match the variable shearing forces in the upper bank zone might be justified.

3.3 Details of the Guidelines: The Default Primary Techniques

3.3.1 The Toe Zoe: The Riprap Default

As mentioned in Sec. 2.1, riprap may be considered the current default revetment solution not only for the toe zone but for the entire slope (INDOT2013-203-6.06(03)). Riprap is attractive as a solution for the toe zone for the same reasons that make it attractive as a general solution: it is widely applicable and standard practices in its design and implementation are well established and familiar to the engineering and construction community. Its resistance to erosion can be quantified in a standard manner. For any given design condition, a safety factor for given stone size can be evaluated. One specific advantage of rock riprap, compared to other standard hard-armor techniques, such as gabions or articulated concrete mats, is that due to its more granular nature it can adjust to minor localized failure, settlement, and surface irregularities. As a result of this "self-healing" aspect, the riprap blanket should extend a limited distance above the toe zone boundary. In the event of some settlement or other vertical self-adjustment after installation, the riprap blanket will still cover the entire toe zone. Rock riprap does have its limitations as a revetment solution; INDOT2013-203-6.06(03) recommends that it be limited to streambank slopes less than 2H:1V. Hard-armor options confined to the toe zone do not distinguish themselves by any marked environmental or ecological advantage.

3.3.2 The Upper Bank Zone: The Regrading/ Revegetation with Rolled Erosion Control Product (RECP) Default

The default option for the upper bank zone is regrading with herbaceous species revegetation (WISPG2003). It has the similar restriction as riprap of a maximum streambank slope of 2H:1V. This is a simple technique that should be as broadly applicable as rock riprap since both have the same streambank slope restriction. The main erosion issue that arises with regrading/revegetation is the unprotected state prior to the establishment of vegetation. This can be addressed by the use of rolled erosion control products (RECPs), which provide both immediate erosion protection during the initial unvegetated state and contribute to the establishment of vegetation.

A wide range of RECPs of both channel and slope protection is commercially available, and so their general installation should already be familiar to contractors. In addition, their physical characteristics, such as tensile strength, flexibility, light penetration, and ultraviolet light resistance, can be evaluated through standard testing methods. Performance measures, such as their erosion resistance in terms of sediment loss and their ability to promote vegetation growth, have been obtained under standard if limited conditions (Texas Transportation Institute 2001; see Appendix B for sample results). RECPs can be divided into two main types. Temporary or degradable RECPs (also called erosion control blankets, ECBs) have a functional longevity or lifetime specified as being typically less than 36 months. The second type is permanent or non-degradable RECPs, or turf reinforcement mats (TRMs). The Erosion Control Technology Council (ECTC) has a more refined classification with five main product classes. This classification was adopted by the FHWA (2003) in their standard specification, FP-03 Sections 713.17 and 713.18 (see Appendix C). This classification is based on different functional longevities for ECBs (from 3 months to 36 months), and on design shear stresses for TRMs (from 6 lbf/ft^2 to 10 lbf/ft^2). INDOT currently does not have any detailed specifications for RECPs, and it is recommended that INDOT should consider adopting the FHWA sample specifications.

Only two product classes are proposed for in the standard design guidelines in order to simplify the selection of an appropriate RECP. The first class is a 100% biodegradable (photodegradable is not sufficient) ECB with a typical functional longevity of 24 months or more and a minimum permissible unvegetated shear stress of 2 lbf/ft^2. These characteristics correspond to those of classes 3B and 4 of the ECTC (and FHWA (2003) FP-03 713.17) standard classification, with the additional restriction of 100% biodegradability. This would be the preferred alternative because it provides the more environmentally/ecologically benign solution. Under certain flow conditions, the resulting erosional forces may exceed those that this type of ECBs is capable of safely resisting, necessitating an alternative solution. The second class is a permanent TRM, with a minimum permissible design (fully vegetated) shear stress of 8 lb/ft^2, which would correspond to classes 5B and 5C of the ECTC (and FHWA (2003) FP-03 713.17) standard classification. The ECTC criterion for permissible shear stress is based on the unvegetated state for ECBs and the fully vegetated state for TRMs, though some manufacturers will also specify a permissible shear stress for the unvegetated or partially vegetated state. Further, the ECTC specification also indicates a maximum slope of 1.5H:1V for these two RECP classes (even 1H:1V for ECTC class 4 and 0.5H:1V for ECTC classes 5B and 5C) though for slope rather than channel applications. To be more conservative, it is recommended that a maximum slope of 2H:1V is specified for the use of these RECPs in a conventional application.

One desirable characteristic may be termed wildlife "friendliness," which would measure the extent to which an RECP might pose a danger to wildlife, such as snakes and small animals. For example, they may become trapped or entangled within the RECP matrix. This has not been considered because no broadly accepted standard is currently available.

The selection of riprap stone size in INDOT2013-203-6.06(03) is simplified compared, e.g., to the USACE riprap design equation, in that only three stone size classes are distinguished. Both approaches, like other engineering approaches, share the basis in permissible velocity rather than in permissible shear stress. Shear stress tends to be a more direct and reliable indicator of potential erosion. For example, the ECTC classification of RECPs specifies permissible shear stress, not permissible velocity. Nevertheless, velocity, especially cross-sectionally averaged velocity, v, is for practical design more convenient. For the proposed two classes of RECPs for INDOT streambank stabilization standards, the following specification based on v and the USACE riprap design equation is recommended. Details of the technical justification are given in Appendix A. Two cases are explicitly considered: (i) flows in bends, and (ii) flows in straight reaches (Table 3.1). A straight reach is defined here by the condition that, for the design discharge, the ratio of the radius of curvature (R_c) of the channel centerline to the main channel top width, (W_c), at the bend entrance is greater than 12 (i.e., R_c / $W_c > 12$; see Figure 3.3 for a sketch defining R_c and W_c). These quantities can be estimated from aerial photographs or topographical maps.

TABLE 3.1
Maximum permissible cross-sectionally averaged velocities in ft/s for the different standard classes of RECPs.

	Maximum permissible cross-sectionally averaged velocity, v (ft/s)	
RECP class	**Bend flow**	**Straight-reach flow**
Class 1 (ECTC classes 3B and 4 ECB)	4.5	6
Class 2 (ECTC classes 5B and 5C TRM)	7.5	10

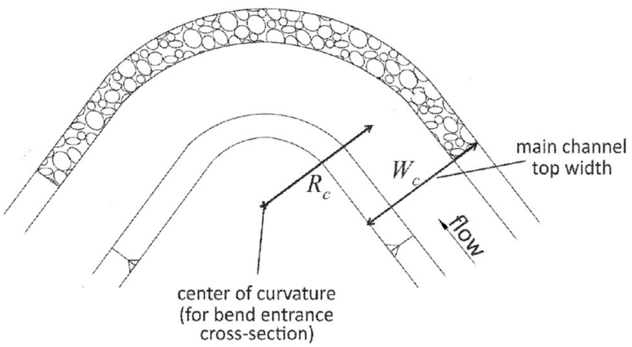


Figure 3.3 Sketch of bend flow showing radius of curvature, R_c , and main channel top width, W_c.

The values given in Table 3.1 were obtained from a more complete design equation (see Appendix A) relating the maximum permissible cross-sectionally averaged velocity to a maximum permissible shear stress, involving the flow depth at the bank toe and the ratio, R_c / W_c. The choice of relatively extreme values of these variables should yield conservative values (comparable to or even exceeding in conservativeness the current INDOT riprap design guidelines) in Table 3.1. Commercial specifications are often substantially higher, especially for turf reinforcement mats (TRMs), e.g., for the Landlok 300 TRM product, for a partially vegetated maximum permissible shear stress value of 8 lbf/ft^2 (the TRM value in Table 3.1 is based on this), a maximum permissible velocity value of 15 ft/s is given (compared to 7.5 ft/s for bend flows and 10 ft/s for straight-reach flows in Table 3.1). Qualifications are often given; for example:

> "Maximum permissible velocity and shear stress has been obtained through vegetated testing programs featuring specific soil types, vegetation classes, flow conditions, and failure criteria. These conditions may not be relevant to every project nor are they replicated by other manufacturers." (Landlok 300 specifications)

Although the RECP in question may exceed the minimum class requirements defined above and therefore can sustain larger erosive forces, it should be remembered that the large-scale flume tests on which such manufacturers' specifications are based are typically of short-duration (30 mins) in straight channels, and so should be interpreted accordingly.

The values given in Table 3.1 are based on conservative choices of variable values, and may be overly conservative; instead of the values in Table 3.1, Equation A.5 (or Figures A.1 and A.2) in Appendix A may be used for a more customized though not necessarily more reliable estimate. Engineering judgment still needs to be exercised as the equation and the values in Table 3.1 do not account for all conceivable conditions. For example, local flow features such as a tributary flow seriously impinging on a streambank, or large woody debris frequently striking the bank may warrant extra protection and a more conservative choice than is called for in the equation in Appendix A or the values in Table 3.1.

It was also suggested earlier that, for projects where streambanks are high and the area of the upper bank zone requiring protection is extensive, the application of a combination of class 1 and class 2 RECPs can be recommended. The more erosion resistant class 2 RECP would be used in the lower half of the upper bank zone where larger shear stresses are expected, while the more environmentally sensitive 100% biodegradable class 1 RECP would be adequate for the smaller shear stresses in the upper half of the upper bank zone. This requires a refinement of maximum permissible velocity values, as summarized in Table 3.2, which are approximately 25% above those in Table 3.1. It is also possible that, for those conditions, where the requirements of Table 3.1 are all exceeded, but those of Table 3.2 are not, class 2 RECP can be installed on the upper half of the upper bank. For conditions exceeding all those in Table 3.2, the application of RECPs might still be considered, but the recommended default is the current rock riprap option.

The current typical riprap installation (slightly modified from Figure 203-6K of INDOT Chapter 203) is compared in Figure 3.4 with the proposed riprap + RECP solution. It assumes that the specified maximum permissible velocity condition on the RECP as summarized in Table 3.1 is satisfied. The two solutions differ mainly in that the riprap in the proposed solution is limited to the toe zone. This may be at an elevation well below the water surface elevation corresponding to the design discharge. In the upper bank zone, the streambank is protected initially by the RECP and later by vegetation (and possibly also still by the RECP in the case of a TRM).

3.4 Details of the Guidelines: The Other (Non-Default) Primary Techniques

3.4.1 The Toe Zone: Other Options

INDOT2013-203-6.06(03) describes other hard-armor streambank protection techniques in addition to riprap,

TABLE 3.2
Maximum permissible cross-sectionally averaged velocities in ft/s for the different standard classes of RECPs to be installed only in the upper half of the upper bank zone.

	Maximum permissible cross-sectionally averaged velocity, *v* (ft/s)	
RECP class	**Bend flow**	**Straight-reach flow**
Class 1 (ECTC classes 3B and 4 ECB)	5.7	7.5
Class 2 (ECTC classes 5B and 5C TRM)	9.2	12.2

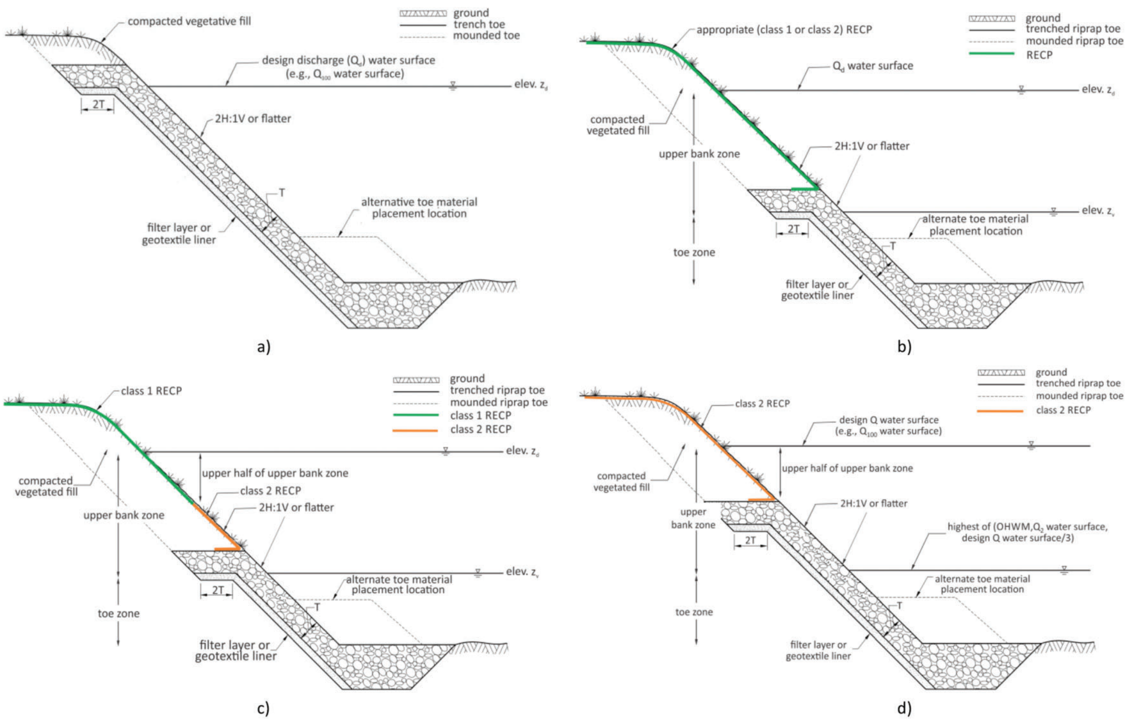


Figure 3.4 (a) Current standard riprap design, (b) proposed standard design with regrading/revegetation and (uniform) RECP, (c) variant of regrading/revegetation design with combination (class 1 + class 2) RECPs, (d) high-velocity variant of regrading/revegetation.

and any of these could be considered for the toe zone. Two of these other techniques will be discussed in detail as they may be especially relevant to an environmentally sensitive approach to streambank protection. The first is referred to in INDOT2013-203-6.06(03)-1b as wire-enclosed rock, but is also commonly known as gabions, either in a mattress or blanket form or in a stacked block form. The prime advantage of gabions is the steep bank slope that can be achieved, which can be crucial in situations where right of way is limited or where the presence of structures or other assets precludes regrading to a flatter slope. In INDOT2013-203-6.06, design recommendations are given for gabion mattresses for bank slopes up to 1H:3V (compared to the recommended maximum value of 2H:1V for rock riprap). The disadvantage is the greater construction and possibly engineering effort. A concern (TDOT, 2012) regarding gabions is the vulnerability to abrasion or other causes of breakage of the wire encasing the stones. Another consideration arising in smaller streams in a natural setting is that the appearance of gabion blocks may be unappealing, and a more natural aesthetic is desired. Vegetated gabions are also available, but these may be a more attractive option in the upper bank zone than in the toe zone, where non-aquatic plant species are not expected to flourish.

The second type of hard armor is referred to as precast-concrete block in INDOT2013-203-6.06(03)-1c, or more specifically the type that is joined together, and hence is also known as articulated concrete mats. In INDOT2013-203-6.06, articulated concrete mats are recommended up to a bank slope of 1.5H:1V. It offers another alternative to rock riprap where regrading is not feasible. Although the open-celled version of articulated concrete mats does offer the possibility of establishing vegetation, this is less of an advantage in the toe zone. There is some anecdotal evidence (Buffington, IDNR, personal communication) that the articulated concrete mats may be more wildlife-friendly than rock riprap, and this may also be taken into consideration in the choice of a hard-armor solution.

3.4.2 The Upper Bank Zone: The Vegetated Mechanically Stabilized Option

In Chapter 3.3.2, regrading plus revegetation was designated as the default primary option for the upper bank zone due to its simplicity, wide applicability, and familiarity to engineers and constructors. Its recommended maximum bank slope of 2H:1V was consistent with that of the default (rock riprap) option for the toe zone. Where a more vertical solution is desired, the maximum bank slope limitation of the regrading option may be too restrictive, and for such cases the option of the vegetated mechanically stabilized earth (VMSE) may be considered as a primary biotechnical solution.

The vegetated mechanically stabilized earth technique (also commonly known as vegetated soil lifts, or vegetated reinforced soil slope or VRSS technique or vegetated geogrids) is part of a family of well-established geotechnical techniques of mechanical stabilization or reinforcement of soils. The basic engineering and construction should already be familiar to larger firms with geotechnical slope stabilization expertise. Elias, Christopher, and Berg (2001; to be referred to as NHI-43) provide an overview of design and construction using VRSS. It does not discuss streambank protection, but does discuss vegetation and soil bioengineering treatment of the face or the exposed earth surface, including examples. Chapter 410-8 (see Appendix D) of the INDOT Design Manual also discusses reinforced soil slopes (taken in large part from Elias et al. (2001)) though to a more limited extent than NHI-43.

The key feature of mechanical stabilized earth (MSE) systems is a reinforcement element or inclusion, typically in a grid- or net-like form, embedded horizontally (or nearly horizontally) in compacted soil, vertically spaced in approximately regular intervals to form soil layers (see Figure 3.5a for a sketch). This element performs in a manner analogous to reinforcement bars in concrete in that reinforcement is "placed parallel to the principal strain direction to compensate for soil's lack of tensile resistance" (NHI-43). Any potential mass failure at a failure surface would be resisted by the reinforcement elements, provided that the failure surface intersects at least one of these elements. Primary reinforcement elements are more extensive than secondary elements that reinforce a more limited region. A second feature is a facing element, which is applied to the face of the soil layer that would otherwise be exposed and unprotected. The facing element may be a rigid feature such as a retaining wall or a gabion, but could be an RECP in the present context, which is more closely related to reinforced soil slope (RSS) applications (Figure 3.5b). If a continuous geotextile reinforcement element is chosen, then a separate facing element may not be needed though an RECP may still be considered for added protection in a channel application. A third component of an MSE or RSS system is the backfill. Whereas the quality and characteristics of backfill for MSE walls with rigid facing elements are important due to concerns about the possible damaging effects of backfill deformation, for RSS applications, backfill quality and characteristics are less important, and with some caution, most on-site soils are likely adequate (NHI-43 Chapter 6.2).

A standard streambank-protection design with restrictions to moderate bank slope (a maximum of 1H:1V) and smaller heights (less than a total of 8 ft) may not require a detailed geotechnical analysis. It is rarely performed in practice but some geotechnical judgment should be exercised. The basic engineering and construction aspects will be similar to that for RSS applications. The minimum recommended length of reinforcement is 3 ft, with a typical height of 12-in (a maximum of 18-in) for a soil lift layer (NEH-650; WISPG2003). While the implementation shown in Figure 3.5b and Figure 3.5c is standard in geotechnical practice, and has also been recommended for streambank protection (NEH-650; Sotir and Fischenich, 2003), another practice seems more prevalent in the latter context where bank slope is moderate and heights are smaller. Heavy-weight woven coir matting is used as both reinforcement and facing elements with burlap backing to retain the fines in the soil lift layer, but the shorter part is placed on the bottom, while the longer part is wrapped over the face and placed on top of the soil lift layer (Figure 3.6), in contrast to the configuration shown in Figure 3.5c.

As with the regrading/revegetation technique, the question arises concerning the maximum permissible cross-sectionally averaged velocities (or shear stresses). Unlike RECPs deployed in more conventional configurations, standard large-scale flume tests have not been performed with RECPs when used to wrap soil-lift faces. The Tennessee DOT Drainage Manual (2012) suggests that the manufacturers' specification of maximum permissible shear (developed from conventional RECP application) is applicable to soil lifts with faces wrapped with RECPs. Sotir and Fischenich (2003) suggests a maximum permissible velocity of 3 ft/s to 5 ft/s under unvegetated conditions and 8 ft/s under fully established vegetation conditions. This is consistent with the values in Table 3.1, but the empirical basis of this suggestion or to what extent it could be applied to flows with sharp bends is unclear. The values given in Table 3.1 may be used with caution, but it is recommended that the magnitudes be reduced to reflect the greater uncertainty.

Different example configurations with gabions and articulated concrete mats are given in INDOT2013-203-6.06. Only one is shown in Figure 3.7a with a gabion block as toe protection and gabion mattresses as bank protection. A modified version of the all-hard-armor (Figure 3.7a) configuration in which the gabion mattresses are terminated at the top of the toe zone, and

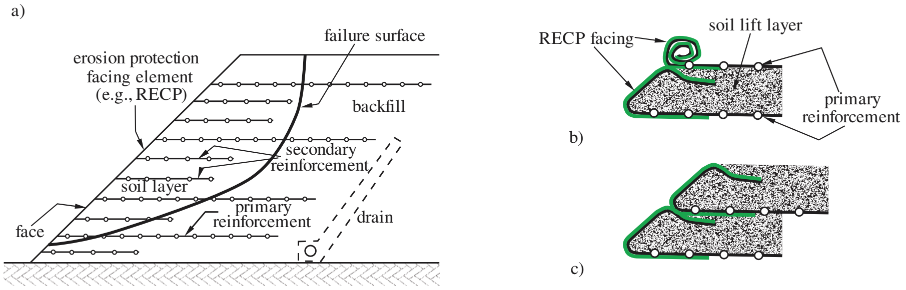


Figure 3.5 Sketch defining (a) terms for a general reinforced soil slope; (b) individual soil lift layer filled with soil, and another reinforcement element on top yet to be filled—also shown is the primary reinforcement element wrapped around the face together with an appropriate RECP; and (c) two completed soil lifts. (Adapted from NHI-43—see also INDOT Chapter 410.8, Figure 410-8A).

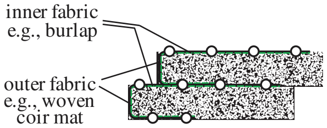


Figure 3.6 Two soil lift layers in a variant commonly found in streambank protection (staking not shown).

soil lifts are installed above that point is shown in Figure 3.7b. Similarly, Figure 3.7c shows a configuration similar to Figure 3.7b, with however gabion mattresses stacked horizontally on top of each other. Another variant with articulated concrete mats replacing the gabions in the toe zone is shown in Figure 3.7d. These examples are not necessarily the most common, but merely illustrate possible solutions where steeper banks might be preferred. In one of the Indiana examples discussed below, the toe zone constituting the base of the soil lifts was formed from a simple stone aggregate, somewhat like Figure 3.7c, but not necessarily using gabion-type enclosures.

Figure 3.7c also illustrates a few optional measures that might be considered in designing VMSE-type solutions. The soil lifts can be inclined downward from the horizontal into the streambank, as this will reduce the lateral earth forces tending to destabilize the soil mass. Secondary reinforcement geogrids can also be added. As loads are highest in the bottom-most layers, the density of reinforcement, alternatively the thickness of the soil lift layer, can be varied to some extent, with the thinnest layers at the bottom and the thickest layers at the top. For small number (3 to 4) and small total height (3 ft to 5 ft) of lifts and moderate bankslopes (flatter than 1H:1V), such measures may not be necessary. For more extreme conditions, these measures may give an added measure of security to the design.

3.4.3 The Upper Bank Zone: The Other Options

The other primary techniques considered as standard for the upper bank zone are the conventional or vegetative versions of hard-armor techniques. These are available for those applications where vegetation would be unlikely to flourish, e.g., under a bridge, or where vegetation might be undesirable, e.g., in the immediate vicinity of a bridge where easy access for periodic inspection should be maintained, or where uncertainty in performance must be minimized, such as where high-value assets or even lives might be at risk. Although the performance of the two standard biotechnical options, regrading/revegetation with RECPs and vegetated mechanically stabilized earth, is thought be comparable with conventional hard-armor techniques for the upper bank zone, there is a greater uncertainty associated with them. If a hard-armor solution is chosen for the upper bank zone, then vegetative versions should be considered. These would include joint staking with rock riprap, vegetated gabions, and vegetated articulated concrete mats.

3.5 The Upper Bank Zone: Supplementary Techniques

Supplementary techniques in this study are those that offer little or no immediate bank protection, and are combined with other primary techniques. Only two such techniques will be included in INDOT standards: (i) live stakes, to be applied with the regrading/revegetation with

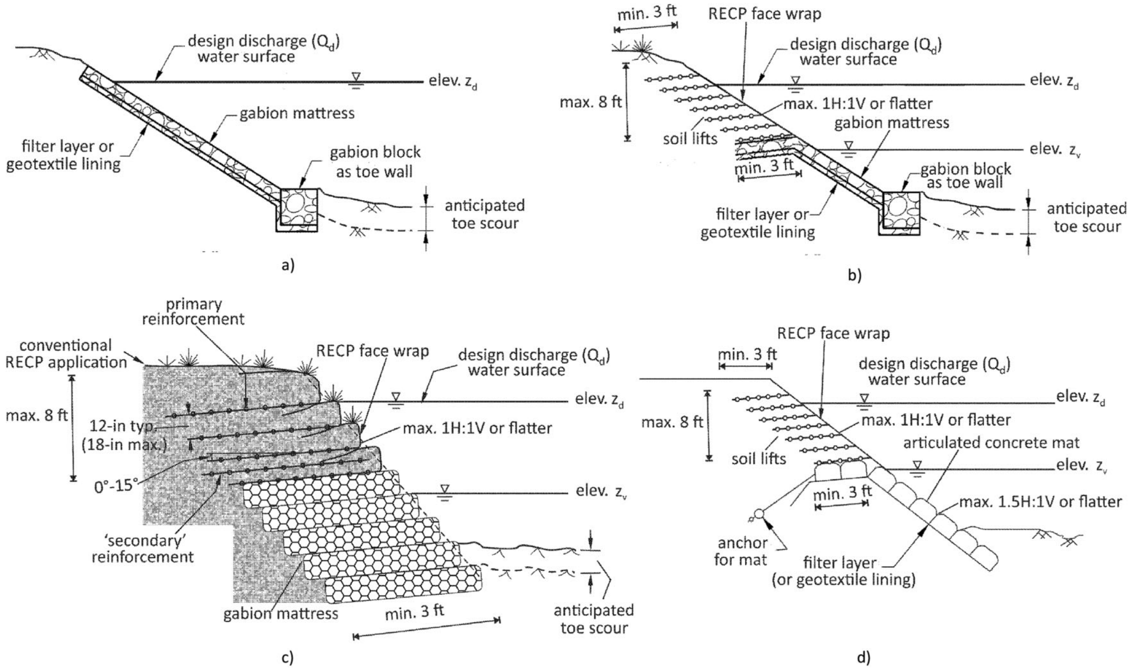


Figure 3.7 (a) Current example gabion revetment design from INDOT2013-203-6.06; (b) example design as in (a) but with gabions only in toe zone and vegetated mechanically stabilized earth (VMSE) or soil lifts for the upper bank zone; (c) variant of (b) with stacked gabion mattresses; and (d) variant of (b) using articulated concrete blocks rather than gabions for the toe zone.

RECP option, and (ii) brushlayering, to be applied with the vegetated mechanically stabilized earth (or similar) option. Despite their different names, the two techniques may be considered the same, differing primarily in their installation. Further, though they may be considered optional, they are highly recommended. Brushlayers (or similar) have become standard practice when soil lifts are installed.

The main primary techniques, regrading/revegetation with RECPs and vegetated mechanically stabilized earth, in their default form are assumed to involve only shallow-rooted herbaceous species that, when established, will contribute to resist surficial erosion. In contrast, the two supplementary techniques to be discussed involve more deeply rooted woody species that should enhance the stability of the soil mass as they become established. They may be viewed as acting like natural, indeed living, geogrid-like reinforcing elements. On the other hand, being natural, their strength characteristics are highly variable and uncertain, and for the present purposes, are not relied on in streambank-protection design. This is the case for the regrading/revegetation standard option where the restriction (maximum 2H:1V) on the bank slope minimizes the need for additional stabilization of the soil mass. Their "design" in terms of spacing and placement is not critical for bank stability and may be based on environmental/ecological and landscaping concerns rather than on purely bank protection concerns. Successful growth and establishment will require matching of species to the prevailing soil, moisture and lighting conditions, as well as the application of approved harvesting, storage, and planting time. Plant and landscaping expertise is recommended for design and construction.

3.5.1 The Upper Bank Zone: Live Staking (For Use with Regrading/Revegetation with RECP Option)

Live stakes refer to dormant, live, rootable woody cuttings, typically 2 ft–3 ft long, 1/2-in to 1-1/2-in in diameter, that are tamped or staked at right angles into the soil until the stake is ≈70%–80% buried with the sharpened thicker end into the soil. Figure 3.8a shows the just planted condition installed on a regraded cut slope through an RECP, while Figure 3.8b shows the rooted condition when a dense network of roots has already developed, and the leaves above the soil surface could potentially enhance resistance to surficial erosion by locally reducing the velocity and promoting sediment deposition. Gray and Sotir (1996) suggest stake spacing of 2 ft to 3 ft apart with a density of 2 to 4 stakes per square yard (see also NEH-650, which relies on the earlier Gray and Sotir). Table 3.3, taken from Sotir and Fischenich (2007), suggests similar though refined stake spacing depending on bank slope and soil characteristics (cohesive or non-cohesive).

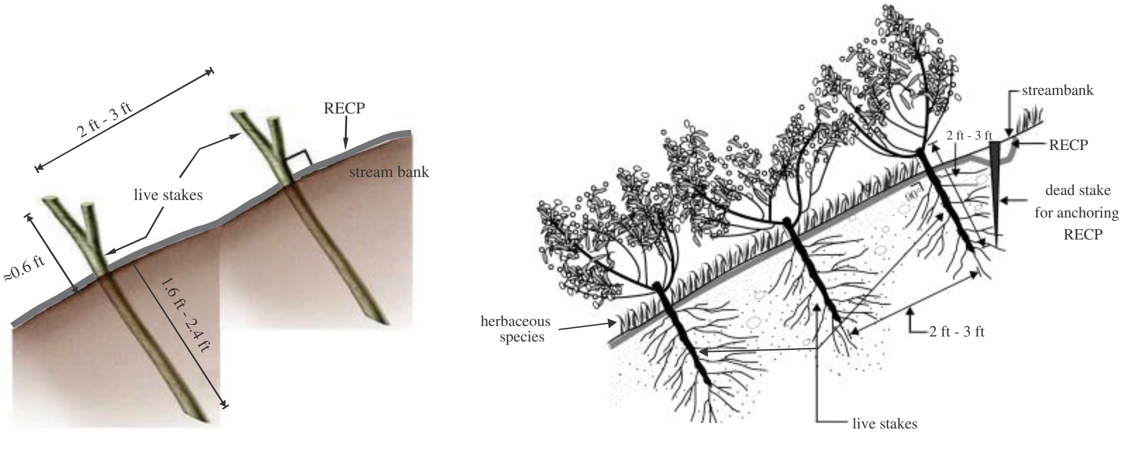
3.5.2 The Upper Bank Zone: Brushlayering (for Use with the VMSE Option)

Although they may not be considered essential to the VMSE option (revegetation with herbaceous species might be sufficient), brushlayering (or similar) has become standard in streambank protection practice whenever the VMSE option is chosen. The term is usually applied to a layer of live cuttings or branches

TABLE 3.3
Live stakes spacing recommended in Sotir and Fischenich (2007).

	Spacing—feet O.C.[1]	
	Soils	
Slope Steepness[2]	**Cohesive**	**Non-Cohesive**
1:1	2 to 3	N/A
2:1	3 to 4	2 to 3
3:1 or flatter	4 to 6	3 to 5

[1] O.C. = On center.
[2] Assumes stable slope
Note: Recommended to be used with an erosion control fabric.



a) b)

Figure 3.8 Live stakes in (a) an initially planted condition through an RECP, and (b) an established condition with dense root network over herbaceous species (adapted from NEH-650).

(also sometimes called whips in the context of willows and cottonwood) between individual soil lift layers. Physically, the whips differ from live stakes in being typically of smaller diameter (less than 1-in) and longer (possibly exceeding 5-ft in length), and their installation also differ in that they are usually placed lengthwise extending from the back of the fill past the face of the fill rather than being tamped into the soil. Further, rather than being planted individually as with live stakes, the much more flexible (and longer) whips are typically installed in layered bundles (Figure 3.9b), and so are particularly suited for fill slopes and soil lift applications.

3.5.3 The Upper Bank Zone: Other Non-Standard Techniques

Other biotechnical techniques that might be classed as supplementary have been implemented in Indiana (Newton & Lyn, 2015). These include the use of coir rolls or logs and live fascines. In the field assessment (Newton & Lyn, 2015), the benefits of such techniques were debatable or marginal, and so for simplicity these are not included in the recommended standard techniques. Because these non-standard techniques when properly installed are not considered to have any significant negative impact, they may be thought of as optional once the standard techniques have been implemented.

3.6 The Upper Bank Zone: Two Indiana Examples

Two primary biotechnical techniques have been proposed for inclusion as INDOT standard streambank stabilization methods for the upper bank zone: (i) the default regrading/ revegetation with RECP option, with notable restriction (same as rock riprap) to bank slopes that are 2H:1V or flatter, and (ii) the vegetated mechanically stabilized earth (VMSE, or reinforced soil slope, VRSS) option, where due possibly to horizontal constraints a more vertical solution is desired. The standard design for VMSE is still limited to bank slopes of 1H:1V or flatter. Two supplementary techniques, one for each primary technique, were proposed: (i) live staking to be applied with the regrading/revegetation with RECP option, and (ii) brushlayering to be applied with the VMSE option. The conventional rock riprap solution would be the default option for the toe zone. Two Indiana examples that have used these techniques are discussed. The choice of these examples does not endorse their overall design or imply that the particular features and their implementation are in any way typical; rather they illustrate a number of details that were highlighted in the preceding.

The first involves bank protection along a reach of the West Fork White River (project location: latitude 38.941603°, longitude -86.997389°) as part of an I-69 mitigation project (INDOT Project 1005457, Contract No. 34267), with plans prepared by Bernardin Lochmueller and Associates and dated 9/26/12. Several features may be noted on the examples located in the project plans shown in Figure 3.10.

1. Substantial regrading of the bank to a generally though not necessarily flatter profile (ranging from 3H:1V to 6H:1V)
2. Riprap (class 2) in the toe zone, (a definition of the toe zone was not specified)
3. Turf reinforcement mat (TRM) in the region above the riprap (the specific type of TRM was not specified),
4. Live staking with willow stakes through the TRM
5. Erosion control blanket (ECB) in the region landward of the TRM (which should not be considered part of the streambank) (the specific type of ECB was not specified)
6. Live staking with cottonwood stakes through the ECB

From the information available on the plans, the actual design details are broadly consistent with the proposed standard design. Further information from the hydraulics/hydrology analysis, such as the design discharge, the stage and cross-sectionally averaged velocity

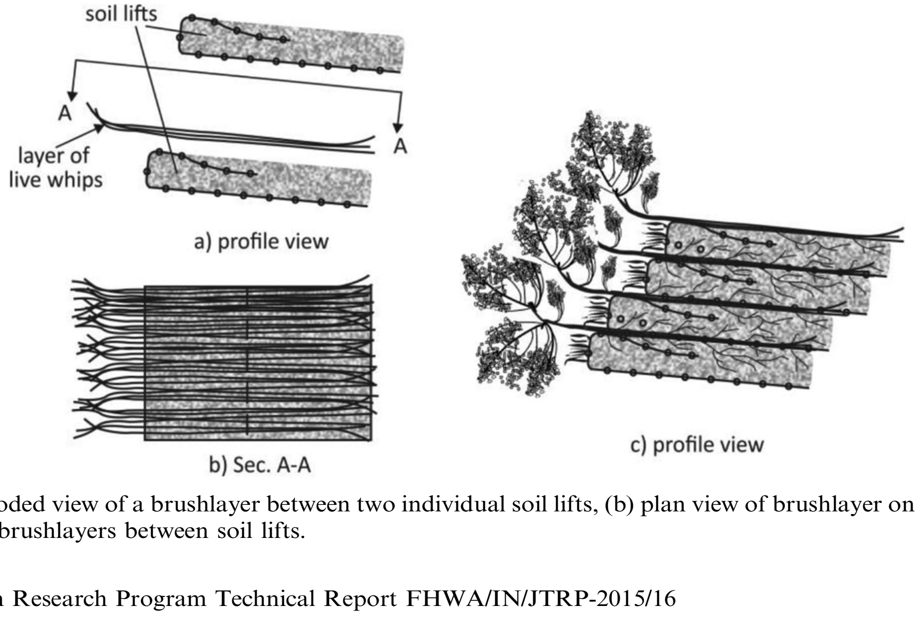


Figure 3.9 (a) Exploded view of a brushlayer between two individual soil lifts, (b) plan view of brushlayer on top of a soil lift, and (c) fully established brushlayers between soil lifts.

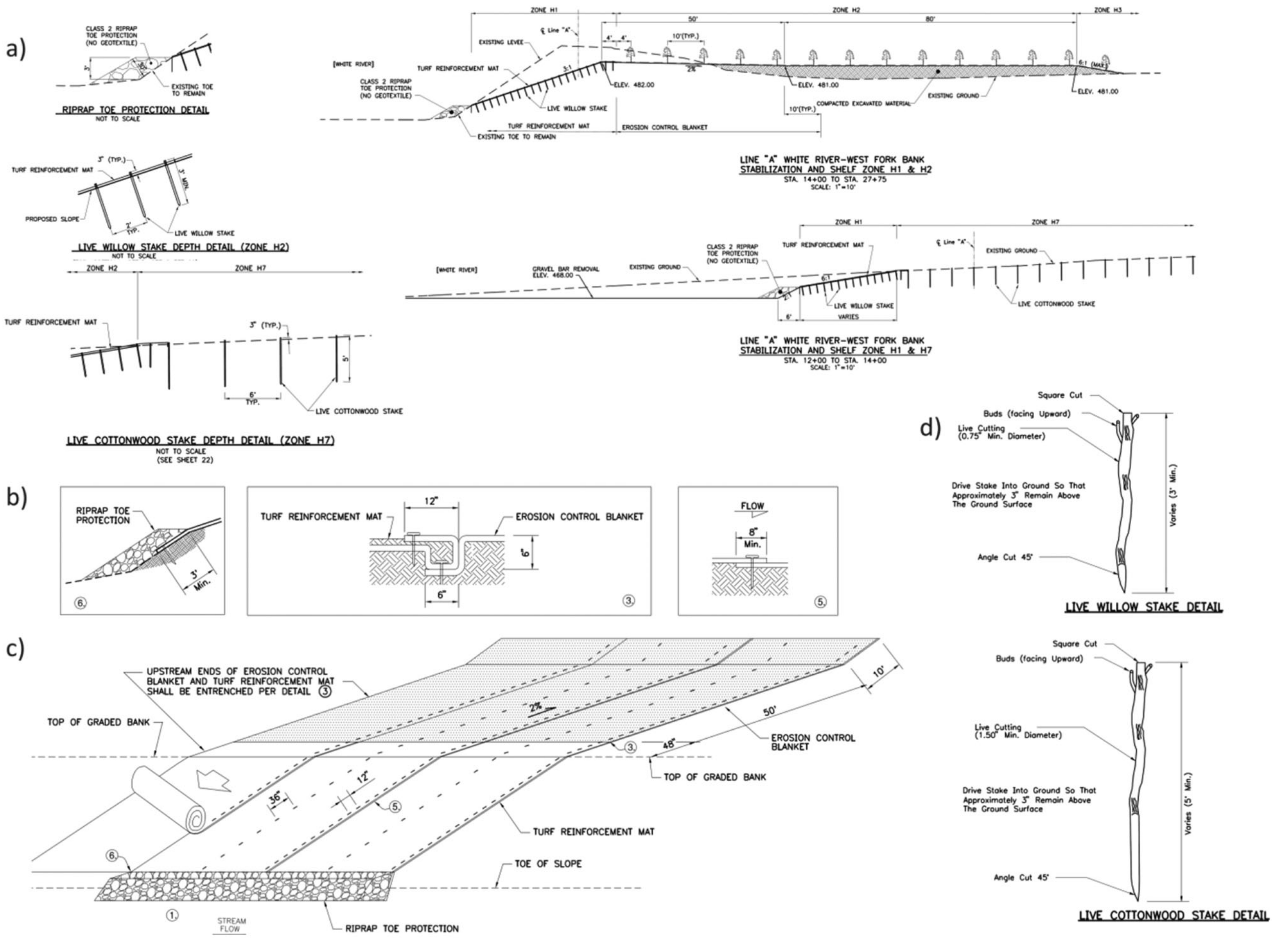


Figure 3.10 (a) Profile view of regrading with details of live staking, (b) details of riprap toe, joining of TRM and ECB, and overlap of adjacent rolls, (c) view of combination of riprap at toe, TRM at mid-height, and ECB at top, installed perpendicular to flow, and (d) details of live stakes.

corresponding to the design discharge, and the choice of specific TRM and ECB would be necessary to make a more precise assessment. As noted in the field site assessment (Newton & Lyn, 2015) part of this study, due to the relatively recent installation, a long-term assessment of the effectiveness of the design was not possible, but vegetation growth and establishment so far have been considered acceptable.

The second example is a stream restoration project for the town of Plainfield near Indianapolis. It used mainly soil lifts as a bank stabilization technique. The site is located on White Lick Creek (project location: latitude: 39.67456°, longitude: -86.39119°) with plans prepared by Banning Engineering and J. F. New, and dated June 2006. Figures 3.11 and 3.12 show two plan sheets that provide the most detailed description found of actually constructed soil lifts, even including a construction sequence for the soil lift installation. Several features may be noted in Figures 3.11 and 3.12.

1. Hard-armor toe/base, consisting of revetment riprap as base for the soil lifts, and class 1 riprap as facing elements; although the design water level is shown as being below the level of the soil lifts, how this water level is obtained (e.g., OHWM) is not specified;
2. Soil lifts at an average bank slope of 1H:1V are shown, with uniform height 18-in, and a maximum total height of 6-ft (hence maximum of 4 lifts) are installed on the rock base;
3. The facing/reinforcing element is a 900-g/m^2 coir fabric (typically this would satisfy the ECTC and FHWA (2003) FP-03 713.17 Type 4 (ECB) specifications, and if 100% coir should also be 100% biodegradable), with an inner fabric specified as NAG S-150, which is a photodegradable short-term (functional longevity of 12 months) ECB that would satisfy the ECTC and FHWA FP-03 713.17 Type 2 specifications;
4. In addition to the 900-g/m^2 coir outer fabric + NAG S-150 inner fabric, an additional Mirafi 5XT geogrid is also used as additional reinforcing element for each soil lift; all of these elements are anchored into the original bank slope by staking at 2-ft spacing;
5. Above the lifts, a NAG-C125BN which is a 100% biodegradable ECB satisfying ECTC and FHWA (2003) FP-03 713.17 Type 4 (ECB) specifications is applied; interestingly it is applied horizontally, which is more typical of channel applications;
6. Instead of the conventional brushlayering between soil lifts, Figure 3.11 shows shrubs at 2-ft centers; the detailed

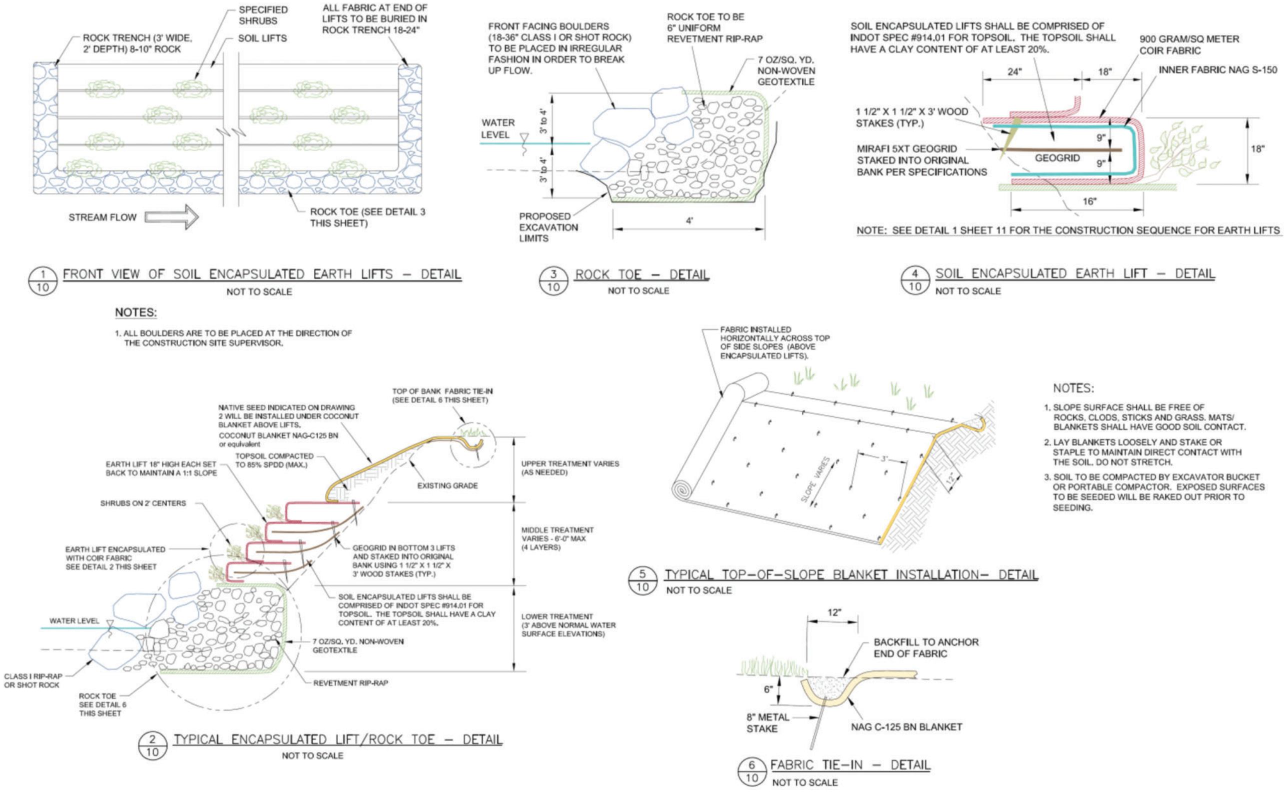


Figure 3.11 Details of a VMSE (or soil lifts) example, including front view with upstream and downstream edge treatments, riprap toe, soil lift with geogrid and facing elements, overall installation including rock toe and soil lifts, and top of slope ECB installation including tie-in.

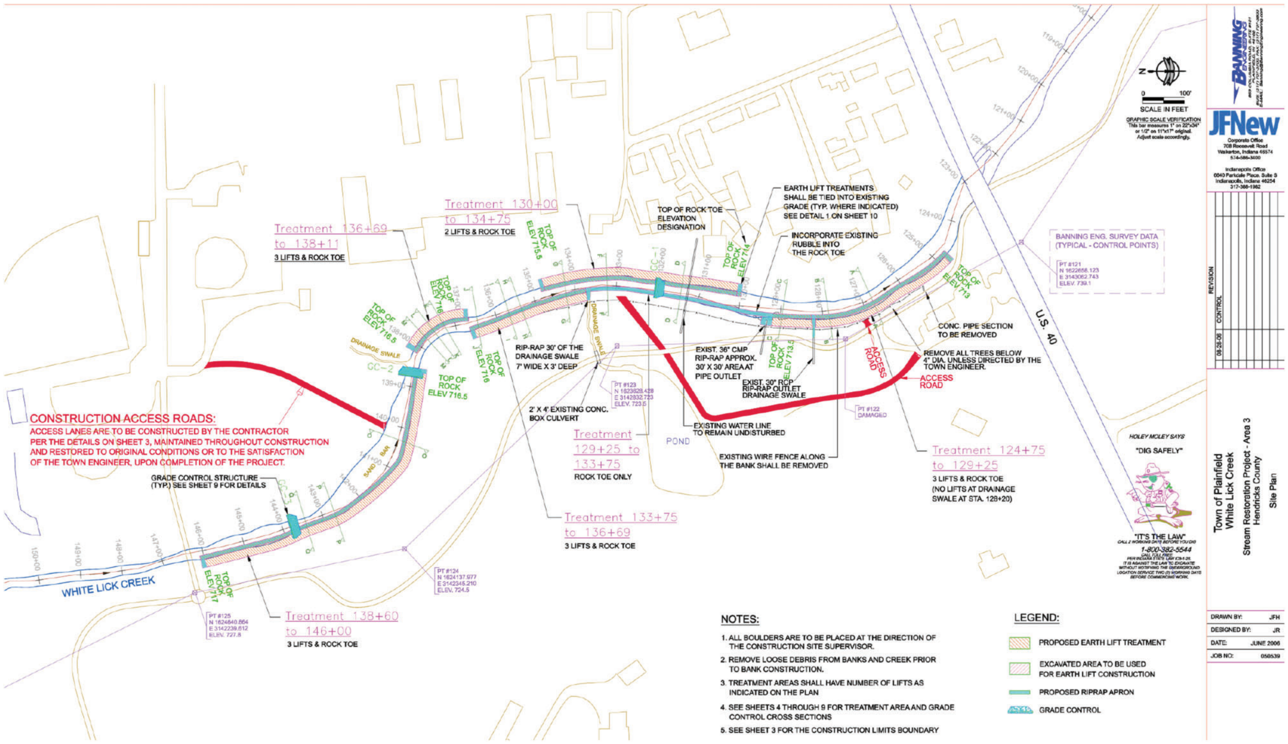


Figure 3.12 Overall view of project using soil lifts as main streambank stabilization measure, but also including in-stream grade control structures.

planting plan however indicates a choice of vegetation between soil lifts varying with the planting time, from live cuttings at 6-in centers to bare-root seedlings on 12-in centers to shrubs at 24-in centers;

7. Attention is also paid to the upstream and downstream edges of the soil lifts treatment, as they begin or end in a rock trench, in which all soil lift fabrics are buried; lengths of treatment sections ranged from ≈140 ft to ≈740 ft, and for the most part was confined to the outer bank;
8. Although not necessarily relevant to the present discussion, in-stream grade-control structures also formed a part of the overall design.

From the available information, the design details are consistent with the proposed standard design for soil lifts (or VMSE), including a maximum bank slope of 1H:1V or flatter, a maximum individual soil lift height of 18-in, a maximum total height of soil lifts less than 8 ft. There is no indication in the plans of the soil lifts being installed at a slight angle to the horizontal. Further information not given, such as the design discharge, the stage and cross-sectionally averaged velocity corresponding to the design discharge, would be required to determine if the reinforcing and facing elements (and other RECPs) are consistent with the proposed design guidelines. The site has been 6 to 7 years in operation, and has been subjected to a number of high flows (if not the design flow). As noted in the field site assessment (Newton & Lyn, 2015), the soil lift treatment has suffered some damage, typically to the lowest soil lift and in bends. Whether this could have been avoided or at least minimized by starting the soil lifts at a higher elevation, i.e., a more judicious delineation of the toe zone, or by using a more erosion-resistant RECP, e.g., a TRM instead of an ECB, as a facing element, or both, or whether following the proposed guidelines for these choices would have resulted in a better solution, remains questions that cannot be resolved with the available information. Despite the damage and the needed repair, the client (the Town of Plainfield) as represented by the Town Engineer, was overall pleased with the outcome and would recommend the biotechnical option for bank stabilization.

3.7 Other Considerations

A concern that should be examined is that the streambank stabilization within the project reach can be successful but that unintended upstream and/or downstream consequences, such as an exacerbation of erosion and/or deposition, might occur. The choice of a biotechnical option should not cause more problems than might have been caused by the choice of current methods, or than might have occurred “naturally” in the absence of the stabilization intervention. The primary consideration is that the conveyance and sediment transport capacity should not be substantially changed. For larger streams, this is less likely to be an issue as the change due to the stabilization intervention is expected to be small. For smaller streams, more caution would be appropriate. Aggressive regrading or other measures that might results in substantial changes in channel cross-section should be pursued with caution. Vegetation will increase flow resistance over the unvegetated state and as a result this would compensate to a certain extent for the larger cross-sectional area resulting from regrading to a flatter bank slope. On the other hand, filling in the channel and adding vegetation, as is sometimes the case with vegetated mechanically stabilized earth (VMSE) applications, might together result in increased sediment transport capacity, and other measures such as regrading the opposite bank might be considered.

3.8 Summary

This chapter gives details of the proposed modification of the current streambank protection measures recommended in INDOT2013-203-6.06. The proposed modification aims to provide greater flexibility in designing environmentally sensitive protection measures. The first step defined the boundary between the toe zone and the upper bank zone with an emphasis on a straightforward application. The second step established the default options for the toe zone, rock riprap, and for the upper bank zone, regrading/revegetation with RECP. Because INDOT does not currently have specifications for RECPs, the FHWA specifications are recommended for adoption. Two classes of RECPs are recommended: (i) a 100% biodegradable ECB of minimum functional longevity of 24 months, and (ii) a (“permanent”) TRM with a minimum permissible shear stress of 8 lbf/ft^2. Permissible cross-sectional velocities for these RECPs, similar to those currently available for riprap design, are based on the USACE equations. Recommended values are proposed for different cases such as flows in bends and in straight reaches, and for regions in the lower and upper half of the upper bank zone. The other non-default primary techniques are then presented: gabions and articulated concrete mats for the toe zone, and vegetated mechanically stabilized earth, i.e., soil lifts, using RECPs as fabric wrap or facing element, as well as vegetated hard-armor for the upper bank zone. Two standard supplementary techniques for the upper bank zone are provided: live stakes for the regrading/revegetation with RECP option, and brushlayers for the soil lift option.

4. SUMMARY, CONCLUSIONS, AND IMPLEMENTATION PLANS

Based on a literature review (Lyn & Newton, 2015) and a field assessment of INDOT and non-INDOT sites (Newton & Lyn, 2015), design guidelines for applying biotechnical techniques to streambank stabilization are proposed. The recommended techniques are not necessarily intended as applicable for all projects, and may not give the “optimum” solution for any specific project, but should provide an adequate solution for “routine” problems. A customized solution, tailored to the specific project, may provide a technically superior solution but will generally require more in-depth analysis and engineering design effort. It may also be subjected to greater scrutiny by INDOT and the regulatory agencies. Standard guidelines will evolve as more information becomes available, and a larger body of experience is accumulated. As a result, recommended values may be revised, and other techniques may be added.

4.1 Proposed Design Guidelines

A proposed standard design for biotechnical streambank stabilization has been developed for possible adoption by INDOT. The main features are:

1. The delineation of a toe zone and an upper bank zone—this is based on the highest of
   a. the ordinary high water mark (or equivalently the bankfull stage),
   b. the stage corresponding to a 2-year discharge (Q_2),
   c. the elevation corresponding to one third (from the bank toe) of the local depth at the bank toe under design discharge conditions; and
   d. for the case where vegetated encapsulated soil lifts (or vegetated mechanically stabilized earth or vegetate reinforced soil slope) are to be implemented, and where the standard design specifies a maximum total height (e.g., 8 ft) of the soil lifts, the elevation corresponding to the maximum total soil lift height below the design discharge stage.
   The boundary between the toe zone and the upper bank zone is a reference level, and is not necessarily where vegetative elements begin and hard-armor elements end. It is recommended that the hard-armor region extend a short distance above this reference level, to allow for post-installation self-adjustment (e.g., settlement, of the hard armor).
2. In the toe zone, a hard-armor (such as rock riprap) technique is required, while in the upper bank zone, a vegetative technique (such as regrading/revegetation with RECP) is preferred.
3. Primary techniques are distinguished from supplementary techniques in that primary techniques offers immediate bank protection and can be used alone, while supplementary techniques must be used in combination with a primary technique.
4. Default options are specified as the preferred primary technique for each zone:
   a. For the toe zone, rock riprap would be the default option, and would be designed in the same manner as is currently being done in INDOT2013-203-6.06, with the same restriction to a maximum bank slope of 2H:1V.
   b. For the upper bank zone, regrading/revegetation with RECP would be the default option, with the same restriction of a maximum bank slope of 2H:1V; the selection of the RECP class is according to Tables 3.1 and3.2. Different maximum permissible velocities are applicable, depending on whether the bank being protected is part of a bend, or a straight reach. In larger projects, a combination of both classes of RECPS may be considered.
5. If design constraints, such as a desire for a bank profile steeper than 2H:1V, make the default options not feasible, then other primary techniques may be applied:
   a. For the toe zone, other hard-armor techniques may be applied, such as wire-encased rock or gabions, or articulated concrete mats; additional design variations are available (including a rock riprap solution with a maximum toe zone bank slope of 2H:1V), but the general principles in INDOT2013-203-6.06 for hard-armor techniques are available as a guide.
   b. For the upper bank zone, the only other non-hard-armor primary technique proposed to be included involves the use of vegetated mechanically stabilized earth (VMSE). These, also referred to as vegetated reinforced soil slope (VRSS), or vegetated encapsulated soil lifts, or simply soil lifts), consist of soil encapsulated or wrapped in a facing element or fabric such as an RECP (or a combination of RECPs), that also act a reinforcing element. They may be viewed as similar to gabion mattress but have soil rather than rock within the wrap, and a fabric (or other geotextile) wrap rather than wire-mesh enclosure. These lifts are laid horizontally (or angled slightly downward from the horizontal) and stacked vertically to achieve an average bank slope of 1H:1V or flatter, and have a maximum individual height of 18-in and a maximum total height of 8-ft. The choice of fabric wrap would be based on the criteria developed for RECPs. Separate reinforcing elements, such as geogrids, may also be installed in addition to the fabric wrap.
   c. For the upper bank zone, the option to use hard-armor techniques, preferably in a vegetated version, such as the combined use of joint planting with rock riprap, or using vegetated gabions, or vegetated open-celled articulated concrete mats, is available for those cases in which bank stability is of paramount importance, i.e., the consequences of bank instability would be catastrophic, and the uncertainty in performance of bank stabilization measures must be minimized.
6. Supplementary techniques are those that may provide environmental/ecological benefits, and though they may also enhance bank stability, these positive effects on bank stability are not relied on in the protection design. They are considered optional, but are highly recommended. Two supplementary techniques are proposed, each appropriate for the two primary biotechnical technique:
   a. Live staking, used with the regrading/revegetation with RECP primary-technique default option, in which dormant live woody cuttings, ranging in diameter of 1/2-in to 1-1/2-in and 2-ft to 3-ft long, are staked through the RECP either randomly or at regularly intervals in a staggered triangular pattern (e.g., with 2-ft center-to-center spacing).
   b. Brushlayering, used with soil lifts, in which dormant live woody cuttings, typically of smaller diameter and longer than those used for live stakes, termed whips when the cutting is willow or cottonwood, are installed as a layer between individual soil lifts.

7. The treatment of transitions between hard armor and vegetation-based revetments and also between protected and unprotected reaches should receive due attention as experience with riprap revetment has shown that failure of the revetment can often be traced to these transitions.

4.2 Implementation

It is suggested that a task force be formed to oversee the implementation of the proposed INDOT standard. The task force should include INDOT staff and representatives from the broader community of regulatory agencies, designers, consultants and construction companies. Because the proposed standard relies heavily on the use of rolled erosion control products, an INDOT standard specifications will need to be developed at the beginning of the implementation process. It is recommended that such an INDOT standard specifications be based on the already available FHWA (2003) FP-03 standard specifications for these products.

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APPENDIX A: RELATING MAXIMUM PERMISSIBLE SHEAR STRESS TO MAXIMUM PERMISSIBLE VELOCITY FOR STREAMBANK PROTECTION

In a recent evaluation, the USACE design equation (U.S. Army Corps of Engineers, 1996; also to be referred to as USACE EM-1601) for rock riprap was identified as the most reliable of the available methods (Lagasse et al., 2006) for selecting the stone size, and so was chosen as the basis for relating maximum permissible shear stress to the maximum permissible velocity for RECP applications. The USACE equation can be expressed as

$$\frac{d_{30}}{y_{ss}} = C_{sf}\,C_s C_v C_t \left[\frac{v_{ss}}{\sqrt{K_{ss}\,g\,(s_g-1)\,y_{ss}}}\right]^{2.5} \tag{A.1}$$

where d_{30} = the stone size for which 30% is smaller by weight, y_{ss} = the local depth at a point 20% upslope from the toe of the revetment, C_{sf} = a safety factor (with value larger than 1), C_s = a stability coefficient, C_v = a velocity distribution coefficient, C_t = a (riprap) blanket thickness coefficient, v_{ss} = the depth-averaged velocity at a point 20% upslope from the revetment toe (i.e., at the same point where y_{ss} is defined), K_{ss} = a sideslope correction factor, g = the acceleration due to gravity, and s_g = specific gravity of the stone.

Equation A.1 can be interpreted as a combination of a Shields criterion for incipient motion of coarse material (so that the maximum permissible shear stress is proportional to stone size) with a power-law flow resistance model similar to but not identical to a Manning-Strickler model. This motivates then its use to obtain a relation between maximum permissible shear stress and maximum cross-sectionally averaged velocity appropriate for application to streambank protection. The Shields criterion for coarse material is expressed as

$$\tau_p = C_\theta \rho g (s_g-1) d_{50} = C_\theta \rho g (s_g-1)(1.2 d_{30}) \tag{A.2}$$

where C_θ = a proportionality constant, typically taken in FHWA manuals as 0.047, ρ = density of water, and d_{50} = the stone size for which 50% is smaller by weight, and the relation, $d_{50} = 1.2 d_{30}$, from Lagasse et al. (2006) has been used. Equation A.2 can be substituted in Equation A.1 to eliminate d_{30}, and solving for v_{ss} then yields

$$v_{ss} = \left[\frac{(\tau_p/\rho)}{C_\theta C_{sf} C_s C_v C_t}\right]^{0.4} \left[g(s_g-1)y_{ss}\right]^{0.1} K_{ss}^{0.5} \tag{A.3}$$

To simplify this relationship, values of various constants are chosen: $C_\theta = 0.047$, $C_s = 0.375$, $C_t = 1$ (Lagasse et al. 2006). For RECPs, it is argued that the sideslope correction factor is not relevant, and so $K_{ss} = 1$. Both the velocity coefficient, C_v, as well as the ratio, v_{ss} / v, where v is the cross-sectionally averaged velocity, are assumed to vary with the ratio of the channel radius of curvature (R_c) to the channel top width (W_c) at the entrance of the bend as follows:

$$C_v = \max\{1.283 - 0.2\log(R_c/W_c), 1\},$$
$$v_{ss} = v[\max\{1.74 - 0.52\log(R_c/W_c), 1\}] \tag{A.4}$$

Substituting Equation A.4 into Equation A.3, and with the above choices for the model constants, leads to

$$v = 4.8\left[\frac{(\tau_p/\rho)}{C_{sf}\max\{(1.283 - 0.2\log(R_c/W_c), 1\}}\right]^{0.4} \left[\frac{(gy)^{0.1}}{\max\{(1.74 - 0.52\log(R_c/W_c), 1\}}\right] \tag{A.5}$$

which is valid for any consistent system of units.

To obtain the values listed in Table 3.1, the maximum permissible shear stress for each RECP class (τ_p = 2 lbf/ft^2 for class 1, and τ_p = 8 lbf/ft^2 for class 2) are used with relatively extreme values of $R_c / W_c = 3$ (flows in bend) and $R_c / W_c = 12$ (straight-reach flow; for $R_c / W_c > 12$, the permissible velocity is increased from the values in Table 3.1 and so the latter is considered conservative), and y = 3 ft. The only other parameter in Equation A.5 to be selected is the equivalent "safety factor," C_{sf}; Lagasse et al. (2006) suggests a standard value of $C_{sf} = 1.1$ for rock riprap (note that USACE EM-1601 specifies $C_{sf} = 1.1$ as a *minimum*). For the class 1 RECP, this value was also chosen, as the maximum permissible shear stress for class 1 RECP is based on the unvegetated state, but for class 2 RECP, a higher value of $C_{sf} = 1.3$ was chosen as the maximum permissible shear stress for class 2 RECP is based on the fully vegetated state. The variation of v with y for a range of values of C_{sf} is plotted in Figure A.1 for flow in a bend ($R_c / W_c = 3$ assumed) and straight-reach flow ($R_c / W_c = 12$ assumed) and compared with the value of the maximum permissible value proposed in Table 3.1. The curves based on Equation A.5 lie to the right of the proposed values (vertical lines) for realistic depths at the revetment toe ($y > 3$ ft), implying that the proposed values are more conservative than those determined from Equation A.5.

In Chapter 3.3, the problem of estimating the shear stresses in the upper half of the upper bank zone arose in a discussion of the possibility of applying different classes of RECPs in the lower half and the upper half of the upper bank zone. No general theoretical model is available for the distribution of shear stress on a general streambank. A simplified estimate can be made by assuming, as is consistent with the USACE riprap design equation, that the maximum shear stress, $\tau_{\text{bank, max}}$ =, on the bank is attained at a point located 20% upslope from the toe of the revetment and that this decreases *linearly* to zero at the free surface. This implies that the variation of the bank shear stress, $\tau_{\text{bank, max}}$, with distance, l, from the revetment toe can be expressed as

$$\tau_{\text{bank}} = \frac{5\tau_{\text{bank,max}}}{4}\left(1 - \frac{l}{L_b}\right), \frac{l}{L_b} \geq \frac{1}{5} \tag{A.6}$$

where L_b is the total distance upslope from the toe of the revetment to the water line on the bank (so that $l = L_b$ defines the water line where $\tau_{\text{bank}} = 0$). This model suggests that for $l \geq 2\,L_b / 3$, the local bank shear stress, $\tau_{\text{bank}} \leq 0.4\,\tau_{\text{bank, max}}$. This simple result may however underestimate the actual shear stress due to the simplifying linear approximation, and so instead the more conservative estimate is made that $\tau_{\text{bank}} \leq 0.6\,\tau_{\text{bank, max}}$. Thus, for RECPs to be installed in the upper half of the upper bank zone, the maximum permissible (cross-sectionally averaged) velocity is determined from Equation A.5 is applied with however τ_p replaced with $\tau_p / 0.6 = 1.67\,\tau_p$. The results for τ_p = 2 lbf/ft^2 for class 1, and τ_p = 8 lbf/ft^2 for class 2 are given in Table 3.2.

It is also of interest to examine the current INDOT Chapter 203-6.06(03) guidelines for stone sizing in light of the USACE design equation (Equation A.1). Figure A.2 shows the results of applying Equation A.1 with $C_{sf} = 1.1$ and assuming d_{30} = 0.5 ft, 0.75 ft, and 1 ft, representing respectively INDOT's revetment class, class 1, and class 2 riprap (see Table 1.1), for the two values of R_c / W_c = 3 and 12 used in the RECP computations. Also included in Figure A.2 are the vertical lines (v = 6.5 ft/s, 10 ft/s) corresponding to the INDOT guidelines for the different riprap classes. From Figure A.2, the current INDOT riprap guidelines may not be as conservative as might be thought, especially for flows in sharp or even moderate bends ($R_c / W_c \leq 12$). Except for the case of revetment class riprap for $R_c / W_c = 12$, the curves based on Equation A.1 lie to the left of the INDOT maximum permissible velocity values for the different standard riprap classes). The effects of flow in bends is separately dealt with in INDOT Chapter 203-6.06(03), where reference is made to the FHWA publications, HEC-15 and HDS-4 for "guidance in the design of channels in a bend." Although not shown, the INDOT recommended values would be considered conservative for $R_c / W_c > 25$, i.e., a straight channel. The results based on Equation A.1 for INDOT riprap classes reinforce the claim that

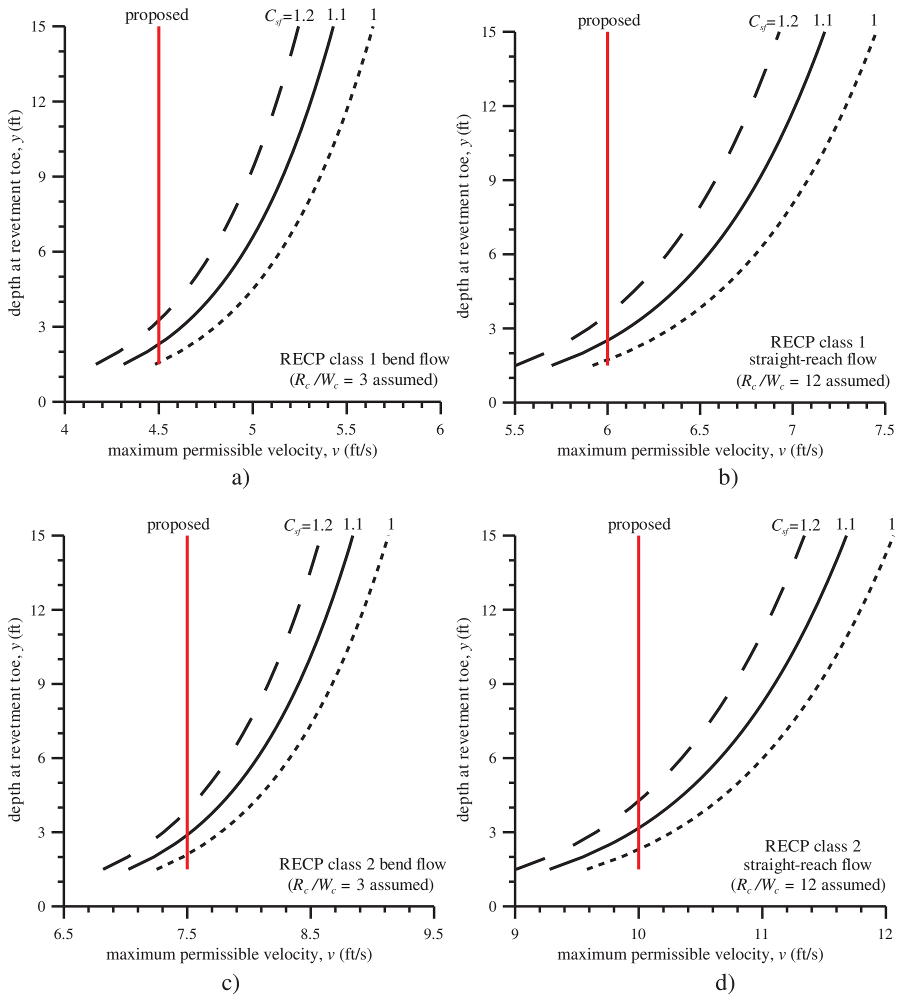


Figure A.1 Comparison of proposed maximum permissible velocity guidelines for standard RECP classes with estimates based on the USACE equation (Equation A.5) assuming different values of the “safety factor”: (a) class 1 RECP, for bend flows (R_c / W_c = 3 assumed), (b) class 1 RECP, straight-reach flows (R_c / W_c = 12 assumed), (c) class 2 RECP, for bend flows (R_c / W_c = 3 assumed), and (d) class 2 RECP, straight-reach flows (R_c / W_c = 12 assumed).

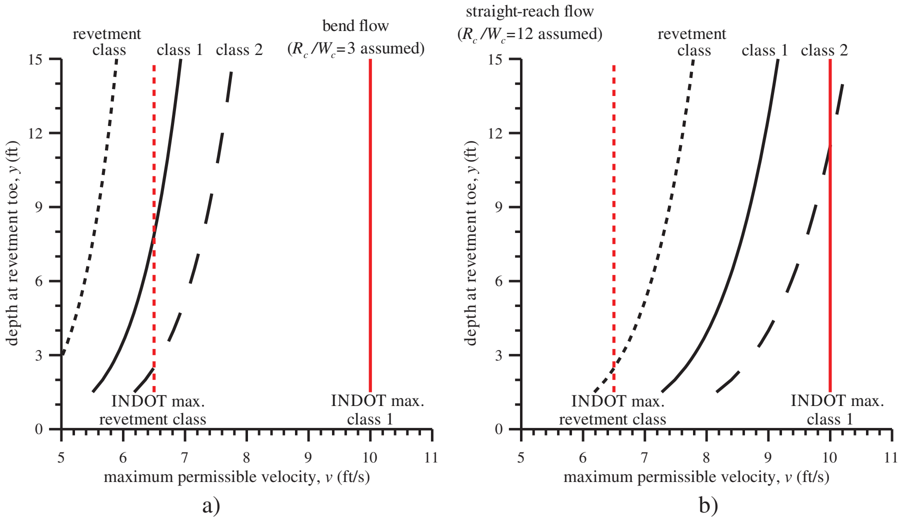


Figure A.2 Comparison of INDOT permissible velocity guidelines for standard riprap classes with estimates based on the USACE equation (Equation A.1, using C_{sf} = 1.1): (a) for bend flows (R_c / W_c = 3 assumed), and (b) straight-reach flows (R_c / W_c = 12 assumed).

the proposed values for the standard RECPs in Table 3.1 should be conservative.

Finally, other approaches to relating maximum permissible shear stress and maximum permissible (cross-sectionally averaged) velocity may be mentioned. An approach very similar to that used in obtaining Equation A.5 may be based on the FHWA HEC-11 (Brown & Clyde, 1989) riprap design equation. This is not discussed further here as Lagasse et al. (2006) have compared the performance of the USACE equation (Equation A.1) with the HEC-11 equation and concluded that Equation A.1 was the more conservative. A different approach (Miller, Fischenich, & Thornton, 2012) combines the Manning's equation and the equation for cross-sectionally averaged boundary shear stress, $\bar{\tau}_b$, for uniform flow:

$$v = \frac{1.49}{n} R_h^{2/3} S_0^{1/2}, \quad \text{and} \quad \bar{\tau}_b = \rho g R_h S_0 \tag{A.7}$$

where n is the Manning's n, R_h is the hydraulic radius and S_0 is the bed slope (Miller et al., 2012), and US customary units are to be used. Because the maximum permissible velocity must be related to the maximum shear stress, $\tau_{\max}$, Miller et al. (2012) recommended the following relationships between $\tau_{\max}$ and $\bar{\tau}_b$:

$$\begin{aligned} \tau_{\max} &= 1.5\bar{\tau}_b, \text{ for straight channels,} \\ &= 2.65\left(\frac{R_c}{W_c}\right)^{-0.5}\bar{\tau}_b, \text{ for flow in bends} \end{aligned} \tag{A.8}$$

The latter model is suspect as it suggests that $\tau_{\max}$ for a rather sharp bend (e.g., R_c / W_c = 4) is smaller than for a straight channel. The resulting equation for maximum permissible (cross-sectionally averaged) velocity is similar in structure to Equation A.1, but also requires a specification of a Manning's n for the channel. The estimate of a maximum permissible velocity according to this approach is for typical values of Manning's n generally less conservative than that based on Equation A.5.

APPENDIX B: FHWA SPECIFICATIONS FOR RECPS

The following is taken from the FHWA "STANDARD SPECIFICATIONS FOR CONSTRUCTION OF ROADS AND BRIDGES ON FEDERAL HIGHWAY PROJECTS (FP-03)" and may be considered as a template for the specification of rolled erosion control products (RECPs).

713.17 **Temporary Rolled Erosion Control Products**. Furnish temporary rolled erosion control products conforming to Table 713-3 and the following. See the Erosion Control Technology Council website (ECTC.org) for commercially available products that may conform to these specifications.

a. Type 1.A, ultra-short term mulch control netting. Furnish a mulch control netting consisting of rapidly degrading photodegradable synthetic mesh or woven biodegradable natural fiber netting with a 3-month typical functional longevity designed for use on geotechnically stable slopes with gradients up to 1V:5H and channels with shear stresses up to 0.25 pounds per square foot.

b. Type 1.B, ultra-short term netless erosion control blanket. Furnish an erosion control blanket composed of processed rapidly degrading natural or polymer fibers mechanically interlocked or chemically adhered together to form a continuous matrix with a 3-month typical functional longevity designed for use on geotechnically stable slopes with gradients up to 1V:4H and channels with shear stresses up to 0.50 pounds per square foot.

c. Type 1.C, ultra-short term single-net erosion control blanket and open weave textile. Furnish one of the following materials: (1) an erosion control blanket composed of processed degradable natural or polymer fibers mechanically-bound together by a single rapidly degrading, synthetic or natural fiber netting to form a continuous matrix or (2) an open weave textile composed of processed rapidly degrading natural or polymer yarns or twines woven into a continuous matrix. The material must have a 3-month typical functional longevity and be designed for use on geotechnically stable slopes with gradients up to 1V:3H and channels with shear stresses up to 1.50 pounds per square foot.

d. Type 1.D, ultra-short term double-net erosion control blankets. Furnish an erosion control blanket composed of processed natural or polymer fibers mechanically-bound between two rapidly degrading, synthetic or natural fiber nettings to form a continuous matrix, with a 3-month typical functional longevity designed for use on geotechnically stable slopes with gradients up to 1V:2H and channels with shear stresses up to 1.75 pounds per square foot.

e. Type 2.A, short-term mulch control netting. Furnish a mulch control netting consisting of photodegradable synthetic mesh or woven biodegradable natural fiber netting with a 12-month typical functional longevity designed for use on geotechnically stable slopes up to 1V:5H and channels with shear stresses up to 0.25 pounds per square foot.

f. Type 2.B, short-term netless erosion control blanket. Furnish an erosion control blanket composed of processed degradable natural or polymer fibers mechanically-interlocked or chemically-adhered together to form a continuous matrix with a 12-month typical functional longevity designed for use on geotechnically stable slopes with gradients up to 1V:4H and channels with shear stresses up to 0.50 pounds per square foot.

g. Type 2.C, short-term single-net erosion control blanket or open weave textile. Furnish one of the following materials: (1) an erosion control blanket composed of processed degradable natural or polymer fibers mechanically-bound together by a single degradable synthetic or natural fiber netting to form a continuous matrix; or (2) an open weave textile composed of processed degradable natural or polymer yarns or twines woven into a continuous matrix. The material must have a 12-month typical functional longevity and be designed for use on geotechnically stable slopes with gradients up to 1V:3H and channels with shear stresses up to 1.50 pounds per square foot.

h. Type 2.D, short-term double-net erosion control blankets. Furnish an erosion control blanket composed of processed natural or polymer fibers mechanically bound between two natural fiber or synthetic nettings to form a continuous matrix with a 12-month typical functional longevity designed for use on geotechnically stable slopes with gradients up to 1V:2H and channels with shear stresses up to 1.75 pounds per square foot.

i. Type 3.A, extended term mulch control netting. Furnish a mulch control netting consisting of a slow degrading synthetic mesh or woven natural fiber netting with a 24-month typical functional longevity designed for use on geotechnically stable slopes with gradients up to 1V:5H and channels with shear stresses up to 0.25 pounds per square foot.

j. Type 3.B, extended term erosion control blanket or open weave textile. Furnish one of the following materials: (1) an erosion control blanket composed of processed slow degrading natural or polymer fibers mechanically-bound together between two slow degrading synthetic or natural fiber nettings to form a continuous matrix; or (2) an open weave textile composed of processed slow degrading natural or polymer yarns or twines woven into a continuous matrix. The material must have a 24-month typical functional longevity and be designed for use on geotechnically stable slopes with gradients up to 1V:1½H and channels with shear stresses up to 2.00 pounds per square foot.

k. Type 4, long-term erosion control blanket or open weave textile. Furnish one of the following materials: (1) an erosion control blanket composed of processed slow degrading natural or polymer fibers mechanically-bound together between two slow degrading synthetic or natural fiber nettings to form a continuous matrix; or (2) an open weave textile composed of processed slow degrading natural or polymer yarns or twines woven into a continuous matrix. The material must have a 36-month typical functional longevity and be designed for use on geotechnically stable slopes with gradients up to 1V:1H and channels with shear stresses up to 2.25 pounds per square foot.

713.18 **Permanent Rolled Erosion Control Products**. Furnish permanent turf reinforcement mats conforming to Table 713-4 and the following. See the Erosion Control Technology Council website (ECTC.org) for commercially available products that may conform to these specifications.

a. Type 5.A, permanent turf reinforcement mat. Furnish a non-degradable turf reinforcement mat with sufficient thickness, strength and void space for permanent erosion protection and vegetation reinforcement on geotechnically stable slopes with gradients up to 2V:1H, channels with design shear stresses up to 6.0 pounds per square foot, and other areas where design flow conditions exceed the limits of natural vegetation.

b. Type 5.B, permanent turf reinforcement mat. Furnish a non-degradable turf reinforcement mat with sufficient thickness, strength and void space for permanent erosion protection and vegetation reinforcement on geotechnically stable slopes with gradients up to 2V:1H, channels with design shear stresses up to 8.0 pounds per square foot, and other areas where design flow conditions exceed the limits of natural vegetation.

c. Type 5.C, permanent turf reinforcement mat. Furnish a non-degradable turf reinforcement mat with sufficient thickness, strength and void space for permanent erosion protection and void space for permanent erosion protection and vegetation reinforcement on geotechnically stable slopes up to 2V:1H, channels with design shear stresses up to 10.0 pounds per square foot, and other areas where design flow conditions exceed the limits of natural vegetation.

TABLE 713-3

Temporary Rolled Erosion Control Products.

	Rolled Erosion Control Product Type											
Property	**1.A(1)**	**1.B**	**1.C**	**1.D**	**2.A(1)**	**2.B**	**2.C**	**2.D**	**3.A(1)**	**3.B**	**4**	**Test Method**
Typical functional longevity(2) (months)	3	3	3	3	12	12	12	12	24	24	36	N/A
Minimum tensile strength(3) (pounds per foot)	5	5	50	75	5	50	50	75	25	100	125	ASTM D 4595
Maximum "C" factor(4)	0.10 at 1V:5H	0.10 at 1V:4H	0.15 at 1V:3H	0.20 at 1V:2H	0.10 at 1V:5H	0.10 at 1V:4H	0.15 at 1V:3H	0.20 at 1V:2H	0.10 at 1V:5H	0.25 at 1V:1½H	0.25 at 1V:1H	ASTM D6459 or other qualified independent test(7)
Minimum permissible shear stress(5)(6) (pounds per square foot)	0.25	0.50	1.50	1.75	0.25	0.50	1.50	1.75	0.25	2.00	2.25	ASTM D6460 or other qualified independent test(7)

(1) Obtain max "C" factor and allowable shear stress for mulch control nettings with the netting used in conjunction with pre-applied mulch material.

(2) Functional longevities are for guidance only. Actual functional longevities may vary based on site and climatic conditions.

(3) Minimum average roll values, machine direction.

(4) "C" factor calculated as ratio of soil loss from rolled erosion control product protected slope (tested at specified or greater gradient, v:h) to ratio of soil loss from unprotected (control) plot in large-scale testing. These performance test values should be supported by periodic bench scale testing under similar test conditions and failure criteria using Erosion Control Technology Council (ECTC) Test Method #2).

(5) Minimum shear stress the rolled erosion control product (unvegetated) can sustain without physical damage or excess erosion (> 1/2-inch soil loss) during a 30- minute flow event in large-scale testing. These performance test values should be supported by periodic bench scale testing under similar test conditions and failure criteria using ECTC Test Method #3.

(6) The permissible shear stress levels established for each performance category are based on historical experience with products characterized by Manning's roughness coefficients in the range of 0.01 to 0.05.

(7) Other large scale test methods determined acceptable by the CO.

TABLE 713-4
Permanent Turf Reinforcement Mats.

	Rolled Erosion Control Product Type			
Properties[1]	**5.A**	**5.B**	**5.C**	**Test Method**
Minimum tensile strength[2][3] (pounds per foot)	125	150	175	ASTM D4595
UV stability (minimum %tensile retention)	80	80	80	ASTM D 4355 (500-hour exposure)
Minimum thickness[2] (inches)	1/4	1/4	1/4	ASTM D 6525
Minimum permissible shear stress[4] (pounds per square foot)	6.0	8.0	10.0	ASTM D 6460 or other[5]qualified independent test

(1) For turf reinforcement mats containing degradable components, obtain all property values on the non- degradable portion of the matting alone.

(2) Minimum average roll values, machine direction only.

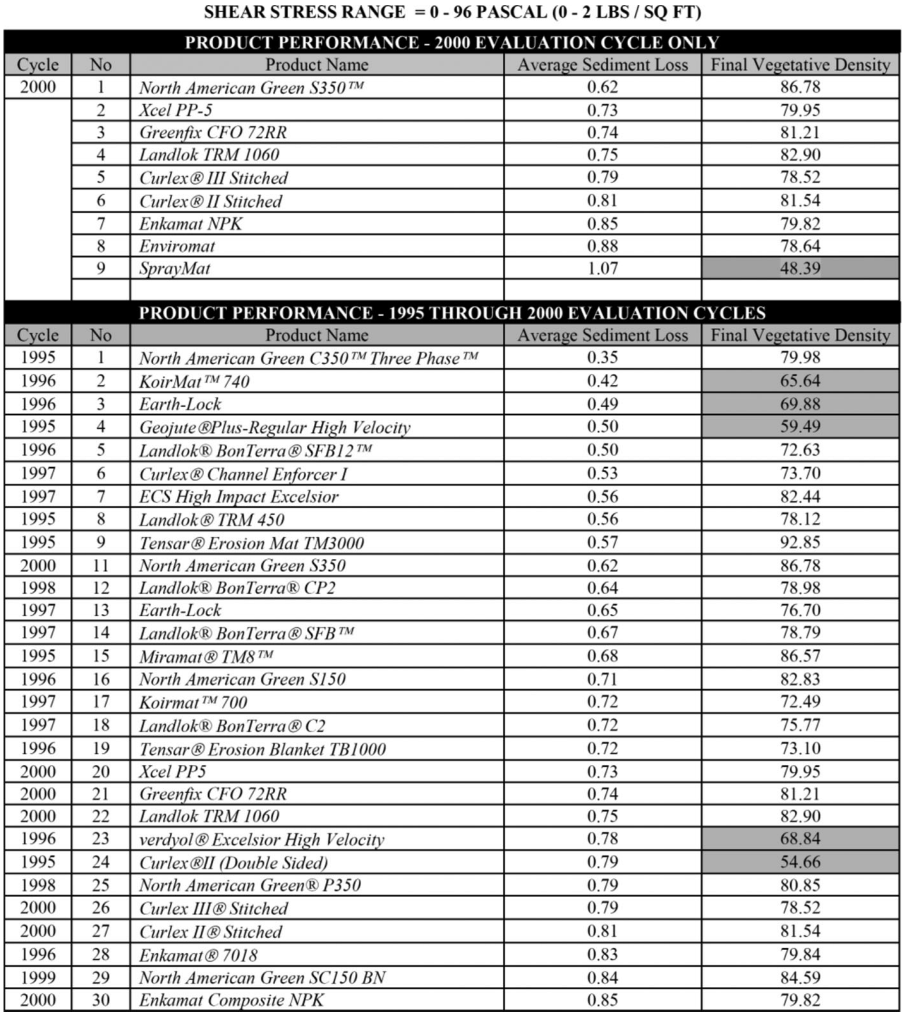
(3) Field conditions with high loading and high survivability requirements may warrant the use of turf reinforcement mats with tensile strengths of 3,000 pounds per foot or greater.

(4) Minimum shear stress the turf reinforcement mat (fully vegetated) can sustain without physical damage or excess erosion (>1/2-inch soil loss) during a 30-minute flow event in large-scale testing. These performance test values should be supported by periodic bench scale testing under similar test conditions and failure criteria using Erosion Control Technology Council Test Method #3.

(5) Other large-scale test methods determined acceptable by the CO.

APPENDIX C: SAMPLE RESULTS OF LARGE-SCALE TESTS ON RECPS (TAKEN FROM TxDOT, 2001)

The following are sample results of large-scale tests on commercial RECPs for channel applications performed at the Texas Transportation Institute Hydraulics and Erosion Control Laboratory, for different shear stress ranges for qualification for use by the Texas Department of Transportation. Two performance measures are used to characterize an RECP: the sediment loss in units of kg per 10 m^2 (the lower the better), and the vegetation density, the average percent vegetation cover at the end of the final round of experiments (the higher the better). A more detailed description of the tests and results may be found at the web site (http://ftp.dot.state.tx.us/pub/txdot-info/mnt/erosion/2001cycle.pdf). Note that the shaded values indicate values that do not meet the performance standards of Texas DOT. The following is not intended as a comprehensive or up-to-date list of performance of commercially available RECPs, but only illustrates the availability of performance data, and it may be noted that other institutions have performed similar tests.



SHEAR STRESS RANGE = 0 - 96 PASCAL (0 - 2 LBS / SQ FT)

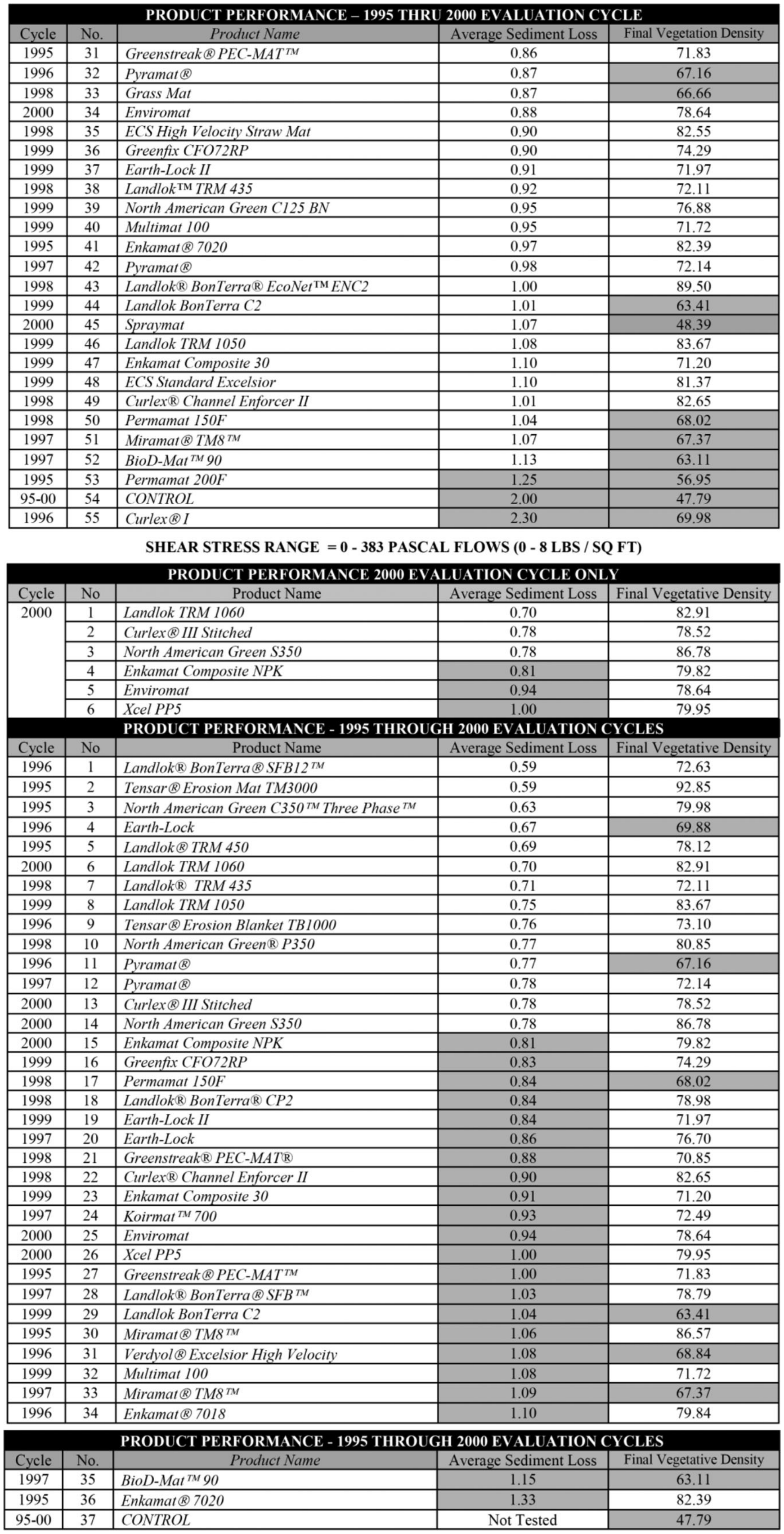
PRODUCT PERFORMANCE - 2000 EVALUATION CYCLE ONLY

Cycle	No	Product Name	Average Sediment Loss	Final Vegetative Density
2000	1	*North American Green S350™*	0.62	86.78
	2	*Xcel PP-5*	0.73	79.95
	3	*Greenfix CFO 72RR*	0.74	81.21
	4	*Landlok TRM 1060*	0.75	82.90
	5	*Curlex® III Stitched*	0.79	78.52
	6	*Curlex® II Stitched*	0.81	81.54
	7	*Enkamat NPK*	0.85	79.82
	8	*Enviromat*	0.88	78.64
	9	*SprayMat*	1.07	48.39

PRODUCT PERFORMANCE - 1995 THROUGH 2000 EVALUATION CYCLES

Cycle	No	Product Name	Average Sediment Loss	Final Vegetative Density
1995	1	*North American Green C350™ Three Phase™*	0.35	79.98
1996	2	*KoirMat™ 740*	0.42	65.64
1996	3	*Earth-Lock*	0.49	69.88
1995	4	*Geojute®Plus-Regular High Velocity*	0.50	59.49
1996	5	*Landlok® BonTerra® SFB12™*	0.50	72.63
1997	6	*Curlex® Channel Enforcer I*	0.53	73.70
1997	7	*ECS High Impact Excelsior*	0.56	82.44
1995	8	*Landlok® TRM 450*	0.56	78.12
1995	9	*Tensar® Erosion Mat TM3000*	0.57	92.85
2000	11	*North American Green S350*	0.62	86.78
1998	12	*Landlok® BonTerra® CP2*	0.64	78.98
1997	13	*Earth-Lock*	0.65	76.70
1997	14	*Landlok® BonTerra® SFB™*	0.67	78.79
1995	15	*Miramat® TM8™*	0.68	86.57
1996	16	*North American Green S150*	0.71	82.83
1997	17	*Koirmat™ 700*	0.72	72.49
1997	18	*Landlok® BonTerra® C2*	0.72	75.77
1996	19	*Tensar® Erosion Blanket TB1000*	0.72	73.10
2000	20	*Xcel PP5*	0.73	79.95
2000	21	*Greenfix CFO 72RR*	0.74	81.21
2000	22	*Landlok TRM 1060*	0.75	82.90
1996	23	*verdyol® Excelsior High Velocity*	0.78	68.84
1995	24	*Curlex®II (Double Sided)*	0.79	54.66
1998	25	*North American Green® P350*	0.79	80.85
2000	26	*Curlex III® Stitched*	0.79	78.52
2000	27	*Curlex II® Stitched*	0.81	81.54
1996	28	*Enkamat® 7018*	0.83	79.84
1999	29	*North American Green SC150 BN*	0.84	84.59
2000	30	*Enkamat Composite NPK*	0.85	79.82

Figure C.1 Sample results from performance tests of RECPs (performed at the Texas Transportation Institute Hydraulics and Erosion Control Laboratory). (*Figure continued on next page.*)



PRODUCT PERFORMANCE – 1995 THRU 2000 EVALUATION CYCLE

Cycle	No.	*Product Name*	Average Sediment Loss	Final Vegetation Density
1995	31	*Greenstreak® PEC-MAT™*	0.86	71.83
1996	32	*Pyramat®*	0.87	67.16
1998	33	*Grass Mat*	0.87	66.66
2000	34	*Enviromat*	0.88	78.64
1998	35	*ECS High Velocity Straw Mat*	0.90	82.55
1999	36	*Greenfix CFO72RP*	0.90	74.29
1999	37	*Earth-Lock II*	0.91	71.97
1998	38	*Landlok™ TRM 435*	0.92	72.11
1999	39	*North American Green C125 BN*	0.95	76.88
1999	40	*Multimat 100*	0.95	71.72
1995	41	*Enkamat® 7020*	0.97	82.39
1997	42	*Pyramat®*	0.98	72.14
1998	43	*Landlok® BonTerra® EcoNet™ ENC2*	1.00	89.50
1999	44	*Landlok BonTerra C2*	1.01	63.41
2000	45	*Spraymat*	1.07	48.39
1999	46	*Landlok TRM 1050*	1.08	83.67
1999	47	*Enkamat Composite 30*	1.10	71.20
1999	48	*ECS Standard Excelsior*	1.10	81.37
1998	49	*Curlex® Channel Enforcer II*	1.01	82.65
1998	50	*Permamat 150F*	1.04	68.02
1997	51	*Miramat® TM8™*	1.07	67.37
1997	52	*BioD-Mat™ 90*	1.13	63.11
1995	53	*Permamat 200F*	1.25	56.95
95-00	54	*CONTROL*	2.00	47.79
1996	55	*Curlex® I*	2.30	69.98

SHEAR STRESS RANGE = 0 - 383 PASCAL FLOWS (0 - 8 LBS / SQ FT)

PRODUCT PERFORMANCE 2000 EVALUATION CYCLE ONLY

Cycle	No	Product Name	Average Sediment Loss	Final Vegetative Density
2000	1	*Landlok TRM 1060*	0.70	82.91
	2	*Curlex® III Stitched*	0.78	78.52
	3	*North American Green S350*	0.78	86.78
	4	*Enkamat Composite NPK*	0.81	79.82
	5	*Enviromat*	0.94	78.64
	6	*Xcel PP5*	1.00	79.95

PRODUCT PERFORMANCE - 1995 THROUGH 2000 EVALUATION CYCLES

Cycle	No	Product Name	Average Sediment Loss	Final Vegetative Density
1996	1	*Landlok® BonTerra® SFB12™*	0.59	72.63
1995	2	*Tensar® Erosion Mat TM3000*	0.59	92.85
1995	3	*North American Green C350™ Three Phase™*	0.63	79.98
1996	4	*Earth-Lock*	0.67	69.88
1995	5	*Landlok® TRM 450*	0.69	78.12
2000	6	*Landlok TRM 1060*	0.70	82.91
1998	7	*Landlok® TRM 435*	0.71	72.11
1999	8	*Landlok TRM 1050*	0.75	83.67
1996	9	*Tensar® Erosion Blanket TB1000*	0.76	73.10
1998	10	*North American Green® P350*	0.77	80.85
1996	11	*Pyramat®*	0.77	67.16
1997	12	*Pyramat®*	0.78	72.14
2000	13	*Curlex® III Stitched*	0.78	78.52
2000	14	*North American Green S350*	0.78	86.78
2000	15	*Enkamat Composite NPK*	0.81	79.82
1999	16	*Greenfix CFO72RP*	0.83	74.29
1998	17	*Permamat 150F*	0.84	68.02
1998	18	*Landlok® BonTerra® CP2*	0.84	78.98
1999	19	*Earth-Lock II*	0.84	71.97
1997	20	*Earth-Lock*	0.86	76.70
1998	21	*Greenstreak® PEC-MAT®*	0.88	70.85
1998	22	*Curlex® Channel Enforcer II*	0.90	82.65
1999	23	*Enkamat Composite 30*	0.91	71.20
1997	24	*Koirmat™ 700*	0.93	72.49
2000	25	*Enviromat*	0.94	78.64
2000	26	*Xcel PP5*	1.00	79.95
1995	27	*Greenstreak® PEC-MAT™*	1.00	71.83
1997	28	*Landlok® BonTerra® SFB™*	1.03	78.79
1999	29	*Landlok BonTerra C2*	1.04	63.41
1995	30	*Miramat® TM8™*	1.06	86.57
1996	31	*Verdyol® Excelsior High Velocity*	1.08	68.84
1999	32	*Multimat 100*	1.08	71.72
1997	33	*Miramat® TM8™*	1.09	67.37
1996	34	*Enkamat® 7018*	1.10	79.84

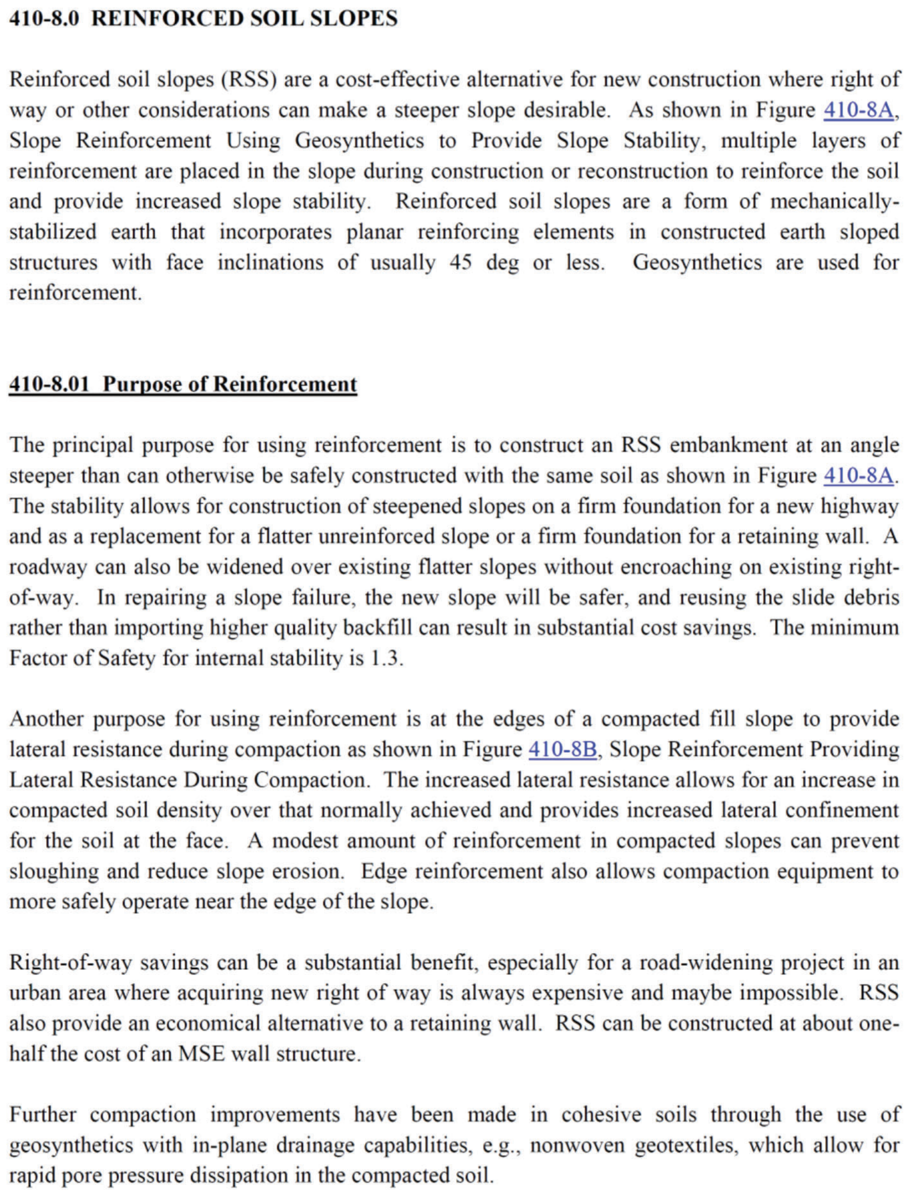
PRODUCT PERFORMANCE - 1995 THROUGH 2000 EVALUATION CYCLES

Cycle	No.	*Product Name*	Average Sediment Loss	Final Vegetative Density
1997	35	*BioD-Mat™ 90*	1.15	63.11
1995	36	*Enkamat® 7020*	1.33	82.39
95-00	37	*CONTROL*	Not Tested	47.79

Figure C.1 *Continued.*

APPENDIX D: SECTION OF INDOT DESIGN MANUAL DEALING WITH REINFORCED SOIL SLOPES

The following is taken from the INDOT 2013 Design Manual Chapter 410 on Earth Retaining Systems.



410-8.0 REINFORCED SOIL SLOPES

Reinforced soil slopes (RSS) are a cost-effective alternative for new construction where right of way or other considerations can make a steeper slope desirable. As shown in Figure 410-8A, Slope Reinforcement Using Geosynthetics to Provide Slope Stability, multiple layers of reinforcement are placed in the slope during construction or reconstruction to reinforce the soil and provide increased slope stability. Reinforced soil slopes are a form of mechanically-stabilized earth that incorporates planar reinforcing elements in constructed earth sloped structures with face inclinations of usually 45 deg or less. Geosynthetics are used for reinforcement.

410-8.01 Purpose of Reinforcement

The principal purpose for using reinforcement is to construct an RSS embankment at an angle steeper than can otherwise be safely constructed with the same soil as shown in Figure 410-8A. The stability allows for construction of steepened slopes on a firm foundation for a new highway and as a replacement for a flatter unreinforced slope or a firm foundation for a retaining wall. A roadway can also be widened over existing flatter slopes without encroaching on existing right-of-way. In repairing a slope failure, the new slope will be safer, and reusing the slide debris rather than importing higher quality backfill can result in substantial cost savings. The minimum Factor of Safety for internal stability is 1.3.

Another purpose for using reinforcement is at the edges of a compacted fill slope to provide lateral resistance during compaction as shown in Figure 410-8B, Slope Reinforcement Providing Lateral Resistance During Compaction. The increased lateral resistance allows for an increase in compacted soil density over that normally achieved and provides increased lateral confinement for the soil at the face. A modest amount of reinforcement in compacted slopes can prevent sloughing and reduce slope erosion. Edge reinforcement also allows compaction equipment to more safely operate near the edge of the slope.

Right-of-way savings can be a substantial benefit, especially for a road-widening project in an urban area where acquiring new right of way is always expensive and maybe impossible. RSS also provide an economical alternative to a retaining wall. RSS can be constructed at about one-half the cost of an MSE wall structure.

Further compaction improvements have been made in cohesive soils through the use of geosynthetics with in-plane drainage capabilities, e.g., nonwoven geotextiles, which allow for rapid pore pressure dissipation in the compacted soil.

Compaction aids placed as intermediate layers between reinforcement in steepened slopes can also be used to provide improved face stability and to reduce layers of more expensive, primary reinforcement as shown in Figure 410-8A.

The use of vegetated-faced RSS that can be landscaped to blend with a natural environment can also provide an aesthetic advantage over a retaining-wall-type structure. However, there are maintenance issues to be addressed such as mowing grass-faced, steep slopes.

For an RSS structure, the choice of slope facing can be controlled with climatic and regional factors. For a structure of less than 30 ft height with slopes of 1:1 or flatter, a vegetative green slope can be constructed using an erosion-control mat or mesh and local grasses. Where vegetation cannot be successfully established or where significant runoff may occur, armored slopes using natural or manufactured materials shall be used to reduce future maintenance.

In terms of performance, due to inherent conservation in the design, RSS are actually safer than flatter slopes designed at the same Factor of Safety. As a result, there is a lower risk of long-term stability problems developing in the slopes. Such problems can occur in compacted fill slopes that have been constructed to low Factors of Safety or with marginal materials, e.g., deleterious soils such as shale, fine grained low cohesive silts, plastic soils, etc. The reinforcement can also facilitate strength gains in the soil over time from soil aging through improved drainage, further improving long-term performance.

410-8.02 Economics

RSS are not normally constructed with rigid facing elements. Slopes constructed with a flexible face can thus readily tolerate minor distortions that can result from settlement, freezing and thawing, or wet-drying of the backfill. As a result, soil which satisfies the requirements for embankment construction can be used in a RSS system. However, a higher-quality material reduces concerns for the durability of the reinforcement, and is easier to handle, place, and compact, which speeds construction.

The performance of RSS is generally not affected by differential longitudinal settlements.

RSS construction with an organic vegetative cover shall be chosen to be consistent with native perennial cover that establishes itself quickly and thrives with available site rainfall, and is maintenance free.

RSS can be cost effective in a rural environment, where right-of-way restrictions exist, or on a widening project where long sliver fills are necessary. In an urban environment, they shall be

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On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,500 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

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